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GEOSCIENCE LITERACY FOR SUSTAINABLE DEVELOPMENT IN GHANA

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Abstract

Geoscience knowledge and information are indispensable, especially for developing countries like Ghana in need of modern strategies to tackle sustainability issues. This paper discusses how Geoscience literacy can help achieve some of the United Nation's Sustainable Development Goals (SDGs) in Ghana, focusing on the areas of water, geohazards, mineral resources, and the environment, as well as geoheritage, geoconservation and geotourism. We propose a National Awareness Program in Geoscience and Sustainable Development focused on promoting environmental protection and disaster risk prevention and mitigation culture rather than emergency response. We recommend Geoscience literacy geared towards natural resource development and management and teaching the nexus between geoscience and society building. We also suggest using geotourism as a source of national revenue generation rather than the continuous exploitation of our natural resources. This will ultimately contribute significantly to achieving the SDGs for the country and provide a template for other developing countries where these recommendations align with their SDGs.

Keywords

geoscience education, sustainable development goals, natural resources, environment, Ghana

Introduction

Geosciences involve studying Earth's processes, materials, and structures and are important in sustainable development globally (Scown, 2020; Senger, 2024). The Earth's natural processes can result in natural hazards or natural disasters such as earthquakes, volcanic eruptions, solar variations, ocean current variations, flooding, and drought, which have negative effects (change in biodiversity, pollution, climate issues, water quality issues, diseases, change in habitat or habitat loss etc.) on the natural environment and affect human and wildlife (Keller and DeVecchio, 2019; Mata-Lima et al., 2013). Also, human-induced actions, such as energy generation, urbanisation, mineral extraction, deforestation, agricultural practices, and transportation infrastructures, profoundly impact the environment, leading to environmental degradation, climate variability/change, and adverse health consequences (Cheung and Lo, 2018; Evseeva et al., 2021; Oznobikhina, 2022; Singh et al., 2021; Wolman, 2022). These activities contribute to global warming through greenhouse gas emissions, deforestation, and industrial production with industrial plants in urban areas particularly impacting human health and ecological balance. The interdependence between people and the environment has become more evident, emphasizing the need for a holistic understanding of human-environment relationships to address environmental problems and health impacts (Rani, 2024). Policymakers and researchers must consider the increasing risks of these multifaceted environmental changes to develop strategies to mitigate negative impacts and promote sustainable development. Rajendran (2010) noted that human activities have the potential to exceed crucial boundaries within the Earth system, leading to the potential destabilization of the planet.

Several scholars (Gill et al., 2019; Gyang and Ashano, 2010; Williams et al., 2023) have elucidated and illustrated the importance of education in earth and environmental sciences towards fostering sustainable development in the African context. These studies have underscored the significance of active community involvement and the effectiveness of public literacy alongside localized applications in addressing geological challenges. This underscores the critical need for a combination of broad knowledge and specific utilization of geosciences in national and community development. Geoscientists are indeed playing a key role in addressing critical issues such as disaster prevention, water resource management, soil preservation, energy shift, urban development, and educational enhancement (de Mulder and Cordani, 2023; Stewart, 2022). Notably, the realm of geosciences has contributed significantly to the comprehension and resolution of natural resource and environmental dilemmas in Ghana (Pabi, 2024). The geological and geophysical characteristics of Ghana, known for its abundance of mineral resources, influence gravitational variations and govern geophysical aspects across diverse regions (Manu et al., 2022). Mining operations, particularly in the Pra Basin, have led to heightened levels of toxic heavy metals like arsenic, cadmium, and mercury, impacting water quality and posing health hazards to the public (Arhin et al., 2018; Lemenkova, 2022). Investigations into soil chemistry in regions like Wassa and Prestea-Huni Valley reveal elevated concentrations of elements such as arsenic, cobalt, and copper, underscoring the interplay of geological and human-induced factors on soil quality and potential health consequences (Arhin et al., 2018). The burgeoning field of medical geology is increasingly recognized as a vital discipline in addressing environmental and health challenges stemming from geological processes, emphasizing the neces-

sity for interdisciplinary cooperation to alleviate geological health issues in Ghana (Kazapoe et al., 2021).

In developing countries such as Ghana, geoscience knowledge and preparedness to tackle sustainable development goals, geohazards, and climate issues are woefully inadequate (Adjarko et al., 2014; Adomako and Ampadu, 2015; Nyarko and Petcovic, 2021; Sapah et al., 2023). Adjarko et al. (2014) outlined significant challenges in the incorporation of environmental sustainability into construction procurement at the local government level in Ghana. Adomako and Ampadu (2015) conducted a comprehensive analysis of the impact of agricultural practices on environmental sustainability in Ghana. Their findings showed that the relationship between agricultural practices and environmental sustainability presents serious challenges including the deterioration of soil, water, air and biodiversity. These practices not only pose health hazards to both farmers and consumers but also contribute substantially to high levels of carbon emissions into the atmosphere thereby accelerating the process of climate change. This critical issue has not received much attention from relevant stakeholders. Apronti et al. (2015) investigated the link between theory and practice in Ghana's basic schools' science syllabus about Disaster Risk Reduction (DRR) and found significant gaps between the disaster pedagogy outlined in the syllabi (theory) and that which occurs in practice. While the theory outlines active and innovative techniques for teaching, learning, and evaluating DRR lessons, this does not reflect in the practical application of these techniques in the real world. Similarly, Nyarko and Petcovic (2021) found that teachers in Ghana lack adequate understanding of climate issues such as ozone depletion and global warming. Also, Allotey et al. (2017) carried out a field survey to assess how artisanal masons who form the group responsible for the construction of a large percentage of buildings in Ghana view the risk associated with earthquake disasters. This study found that earthquake education is lacking and is a critical factor that needs to be addressed in Ghanaian society. Other evidence of the general lack of geoscience knowledge and geoscience literacy in Ghana, is presented in Sapah et al. (2023), which showed the lack of geoscience content in the formal educational curriculum of elementary and high schools in Ghana and how this affects geoscience literacy in Ghana. Due to this lack of preparedness, misconceptions and inadequate resources, people often do not appreciate the extent of geoscience risks, impacts and mitigation practices.

Therefore, literacy in geosciences in Ghana's pursuit of sustainable development objectives cannot be overemphasized. It is not only required in facilitating the identification and development of geoscience issues such as new freshwater aquifers, forecasting contamination pathways, and combating groundwater pollution (Freyssinel, 2023) but also contribute to improving soil fertility by utilizing local rock and mineral materials to enhance agricultural productivity and food security. Understanding geohazards, creating hazard maps, and implementing geoscience literacy initiatives help in reducing vulnerability to natural disasters. The expertise of geoscience professionals has been useful in diverse fields including but not limited to assessing hydrocarbon potential, promoting safe resource extraction, and developing alternative energy sources for sustainable energy practices. Geomorphological mapping, rock characterization, and geological site investigations aid in sustainable construction practices while geochemical monitoring of pollution migration supports environmental management and biodiversity conservation efforts. These diverse applications of geoscience not only contribute to sustainable development but also create opportunities for socio-economic growth through various geoscience-related jobs and enterprises.

This paper provides a commentary that highlights some links between sustainable development and the role of geoscience knowledge and literacy in attaining these goals in Ghana. It is worth noting that while we draw on global examples, most of our analysis and synthesis in this article is based on discussions, observations and experience from the African continent and Ghana.

Materials and Methods

Geoscience Education and Sustainable Development

Sustainable development is an essential concept aiming to balance economic, social, and environmental needs for the well-being of current and future generations. It involves various dimensions such as global governance, infrastructure management, geodiversity and biodiversity conservation, waste management, and socio-cultural considerations (Abdullah, 2024; Moktadir and Ren, 2023). The essence of sustainable development lies in strengthening ecological systems, improving human living standards within environmental limits, and enhancing social well-being while protecting the environment (Kupchenia, 2022). This concept has emerged as a response to the negative consequences of past development approaches and aims to address issues like resource depletion, pollution, climate change, and social injustices (Huifang, 2022). Sustainable development is about environmental conservation and fostering strong, healthy, and just societies by meeting diverse needs, promoting well-being, social cohesion, and equality of opportunities (Bera, 2020; Huifang, 2022). Its global significance is underlined by the need to guarantee a sustainable future for all, considering the interconnectedness of environmental, social, and economic systems (Darvishi et al., 2023).

Geoscience literacy is critical in achieving sustainable development goals (SDGs) by providing the required knowledge and skills to address environmental challenges and promote sustainable practices. In Kenya for instance, geoscience education is highlighted as instrumental in accelerating the critical goals of Vision 2030 and the SDGs, emphasizing the need to embed sustainability concepts into the curriculum and increase the number of trained geoscientists (Williams et al., 2023). Practical activities in geosciences, such as studying

natural calamities and exploring the interconnected global system, have instilled attitudes of responsible global citizenship and solidarity among students, contributing to sustainable development efforts (Freyssinel, 2023). Lunn (2023) asserts that integrating geodiversity and biodiversity education towards SDG 15 in upper secondary schools demonstrates the interdisciplinary approach needed to raise awareness of Earth Sciences issues and their impact on achieving the SDGs. Projects like the Geo-School initiative in Brazil emphasize the importance of geologic knowledge in forming a sustainable society (Freyssinel, 2023). Similarly, the Geo-Escola Project in Sao Jose do Rio Preto highlights the significance of adopting geosciences for professional and citizen knowledge, essential for sustainability (Carneiro et al., 2007). Furthermore, the Caminhos Geologicos Project in Rio de Janeiro focuses on disseminating geological knowledge to the population through various strategies, including educational projects in schools and scientific events, to promote geoconservation and bridge the gap in geology education (Piranha et al., 2009). By involving students in practical activities related to natural calamities, as seen in the Next Land STEM project, geosciences can instill attitudes of solidarity and responsible global citizenship, crucial for sustainable development (Mansur, 2009). This means that promoting geosciences literacy for sustainability through educational projects is crucial for engaging students in understanding environmental challenges and fostering a culture of sustainability.

Geoscientists possess the knowledge, skills, and competencies necessary to advance each of the SDGs, including addressing issues like water resources, soil conservation, poverty alleviation, urban planning, waste management, energy resources, mineral exploration, disaster risk reduction, and education (de Mulder and Cordani, 2023; Lunn, 2023). Although minerals are essential to many aspects of daily life and play a crucial role in human development, sustainable development, and the global economy, they are often overlooked in the Sustainable Development Goals (SDGs). To address these oversights and ensure equitable access to minerals globally, it is prudent to integrate concepts such as "mineral exploitation," "mineral security," and "mineral poverty" into the SDG agenda (Franks et al., 2022). Indeed, initiatives like the Geosciences Sustainability Atlas aim to raise awareness about the significant contributions of geoscientists to sustainability and emphasize the importance of their involvement in achieving the SDGs (Kavvada et al., 2022). In Ghana, Geoscience literacy is crucial in promoting sustainable development by fostering environmental insight and geoethical responsibility (Owusu-Agyeman, 2021). However, the current landscape in Ghana's higher education institutions reveals challenges in incorporating sustainability practices, including a lack of transdisciplinary approaches and limited sustainability education in departments (Akua-Sakyiwah, 2022; Asumadu, 2022; Beoku-Betts, 2020). To address these challenges, Sapah et al. (2023) recommended transformative changes to the curriculum, starting at the elementary school level. These changes aim to prepare students to effectively tackle Ghana's environmental issues and contribute meaningfully to the country's sustainable development goals. By combining geoscience literacy with sustainability principles and promoting a collaborative academic culture, Ghana can strengthen its ability to achieve sustainable development through informed and responsible actions.

Geoscience in Africa

A nation's location and territory on the Earth's surface directly impacts its economic and social planning and development. This is because, its interactions, internal structure dynamics, and morphology will determine the source of its natural resources (i.e., mineral, groundwater, and energy resources), distribution of natural geohazards (e.g., volcanoes, earthquakes, and landslides) soil types, climate and others. In addition, knowledge and understanding of the characteristics of a nation's geological environment among citizens, the future workforce, and policymakers will inform the quality of decisions concerning land use, economic planning, and development in Africa.

The continent of Africa hosts some of the world's stable crust and oldest rock formations and rich mineral resources (Graham and Ovadia, 2019; Jessell et al., 2018). Given these resources and the importance of geoscience literacy, Africa has the potential to contribute significantly to global geoscience and environmental issues related to energy use. It however appears that the production and application of Geoscience education in Africa are not advancing (Davies, 2010; Martínez-Frías and Mogessie, 2012; North et al., 2020). For example, although Africa has some of the most fertile lands on the planet, aridity and desertification are also prevalent over the continent which has rendered much of the continental soils highly weathered and infertile with high acidic content and levels of iron and aluminium oxides above the recommended thresholds. However, expertise, research, and education to help mitigate these problems remain scant from the African perspective. We further argue that the development of geoscience and its related benefits to the African continent is limited by a lack of interest and relevant knowledge in the management of the continent's resources and environment (Davies, 2010; Kay et al., 2013; North et al., 2020) by its central governments. Olufadewa et al. (2020) emphasize that most countries in West Africa spend less than 0.25% of their GDP on scientific research.

For example, most countries around the world have a geological survey usually tasked with geological mapping, mineral resource investigation, geohazards mapping, and the development and maintenance of databases related to these. They are also expected to educate and use this knowledge to assist in developmental endeavors. However, Kay et al. (2013) in their study revealed that most geological surveys in Africa are not equipped to undertake these tasks. They identified only six African countries based on their ability to actively acquire and disseminate geoscientific data and carry out active geo-

scientific work. This means that the African continent needs to build its geoscience capacity to develop knowledge and use sustainable local management practices for its mineral resources. To do this and achieve other SDGs, it is essential to provide opportunities for economic, scientific, academic, social, cultural, and professional growth and development, especially in geoscience in mobilizing information, knowledge, skills, and initiatives towards sustainable development (Martínez-Frías and Mogessie, 2012). Some of these goals are being achieved through notable efforts such as the UNESCO initiative in Earth Sciences Education for Africa (Missotten et al., 2009) in developing cooperation among African nations in Geoscience education. However, more needs to be done.

Results and Discussion

Geoscience and Sustainable Development in Ghana

Ghana, located in West Africa just north of the Gulf of Guinea, is bordered by Côte d'Ivoire to the west, Burkina Faso to the north, and Togo to the east (Figure 1). In 2021, Ghana's population was 30.8 million, with 50.7% female and 49.3% male (Ghana Statistical Services, 2023). About 57% of the population lives in urban areas, and 60% are between the ages of 15 and 64 (Ghana Statistical Services, 2023). The country is rich in natural resources, including precious metals, industrial minerals, and hydrocarbons. As a lower middle-income country, Ghana's economy is driven by services, which account for 47% of its GDP, followed by industry at 32% and agriculture at 21% (Ghana Statistical Services, 2023).

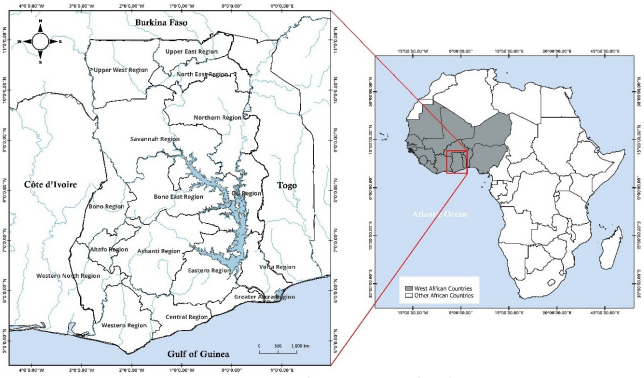

Figure 1. Location map of Ghana.

Mapping the UN SDGs onto Ghana's specific developmental challenges reveals a complex interplay between global aspirations and local realities. The Ghanaian context emphasizes the importance of localizing the SDGs through effective coordination among stakeholders at the local government level (Annan-Aggrey et al., 2022). Collaboration between higher educational institutions and cultural arts institutions in Ghana showcases informal yet impactful partnerships that transcend traditional boundaries, contributing to sustainable education and economic growth (Bello, 2022). Furthermore, the enforcement of environmental laws in Ghana directly aligns with SDGs related to environmental sustainability, emphasizing the need for strong management and accountability in sustainable development efforts (Aboagye et al., 2022). Recognizing Africa's agency in steering sustainable development priorities, particularly through initiatives like the African Agenda 2063, highlights the importance of aligning global SDGs with regional agendas for more effective project design and monitoring in sub-Saharan Africa (Garfias Royo et al., 2022). Assessing the level of public awareness about the SDGs among Ghanaians underscores the need for improved communication strategies to enhance understanding and engagement with all SDGs across different demographic groups in Ghana (Odoom et al., 2023).

To achieve sustainable development in Ghana, it is crucial to understand and manage the socio-economic and environmental impacts of geoscience activities. Mining activities in Ghana, particularly artisanal and small-scale mining, have been found to have both positive and negative impacts on the country. While mining impacts economic development by creating jobs and income for communities, it also poses environmental challenges such as land degradation and water pollution, affecting the livelihoods of residents in mining areas (Owusu et al., 2016; Shubita et al., 2022). Also, efforts to curb illegal mining and restore the environment through ecological restoration projects can boost the economy by creating jobs and increasing household income, thus enhancing the country's local economies and environmental integrity. Geoscience in Ghana embodies a multifaceted interaction between promoting economic well-being and preserving the environment, necessitating meticulous oversight and collaboration with other disciplines for lasting measures.

As outlined in various research papers, sustainable development in Ghana is intricately linked to the implementation of the SDGs. The SDGs, particularly goals 6, 7, 12, 13, 14, and 15, directly address environmental sustainability and the enforcement of environmental laws in Ghana (Aboagye et al., 2022). Additionally, the significance of trees and forests to SDGs has been highlighted, emphasizing the importance of conserving these resources for sustainable growth (Mensah et al., 2022b). Furthermore, the contribution of non-timber forest products (NTFPs) to economic development in Ghana, especially in the eastern region, underscores the need for policies that promote their sustainable management to achieve the SDGs (Akomaning et al., 2023). Ensuring access to clean and affordable water, as per SDG 6.1, is also crucial for Ghana's sustainable development journey, with efforts needed to address challenges such as water contamination and inadequate waste disposal facilities.

The Ghanaian society in meeting the SDGs requires that certain important necessities be provided. This includes: (i) a sufficient supply of clean water (ii) management of waste for a healthy environment (iii) reliable energy supply, and (iv) mitigating risk action toward natural and human-made hazards. Due to the low level of geoscience literacy in the country, it is crucial to regularly create awareness and educate the public on geoscience issues critical to the needs of Ghanaian society.

For example, our current knowledge of geoscience and readiness to deal with geohazards or natural disasters are woefully inadequate. This inadequacy is concerning because these hazards and disasters continuously pose significant risks to our development and progress. Flooding, mass movement and earthquakes are natural disasters that occur in Ghana and are copiously documented (Amponsah et al., 2020; Oteng-Ababio, 2013; Owusu et al., 2016). In the following sections of this paper, we provide some specific anecdotal and evidence-based suggestions on how knowledge in geoscience can be applied to achieving the SDGs for sustainable development in Ghana.

Water

Increased clean water demand comes with increasing population and modern developments. Surface and groundwater are the main sources of clean water supply globally. Surface water is however more prone to the threat of pollution as well as both the direct and indirect effects of climate change, mainly due to anthropogenic activities (Van Vliet et al., 2021). Surface water bodies in Ghana are being polluted through human activities including illegal mining activities, improper water disposal, open defecation, bad agricultural practices etc., poor waste management and untreated runoffs. As such, the poor quality of most surface water bodies in Ghana renders them unusable for drinking and domestic supply despite their availability (Abanyie et al., 2020; Bessah et al., 2021; Darko et al., 2023; Doamekpor et al., 2015). This means that a huge amount of money and expertise are required for an extensive chemical treatment to be useful for drinking and domestic supply. Groundwater as an alternative, globally constitutes the largest (about 98%) freshwater reservoir that is readily available to humans all year round (Margat and Van der Gun, 2013). Securing safe water supplies in Ghana would not be possible without groundwater. Apart from this, groundwater proves to be of better quality as it is protected from surface polluting activities and thus is key in achieving the SDG, either directly or indirectly. Ghana, like other regions, relies heavily on groundwater to meet the country's water supply needs, especially in the northern parts, during the dry seasons, and in many rural communities. However, the downward movement of chemicals such as poly-fluoroalkyl substances (PFAS), lead, and arsenic from mining tail dams and agricultural practices continues to be a threat to the underground water system in Ghana.

The exploration and exploitation of groundwater for drinking and domestic water supply in Ghana predate about a century, when a few indigenes employed local technology to access groundwater through hand-dug wells (Gyampoh and Asante, 2011). The narrative has changed today, and many homes have private, mechanized boreholes thus increasing volumes of groundwater discharge. Details on the use and mode of abstraction in the country are well documented (Banoeng-Yakubo et al., 2010; Obuobie et al., 2018). Hydrogeological maps of Ghana developed by various researchers (Banoeng-Yakubo et al., 2010; Dapaah-Siakwan and Gyau-Boakye, 2000) indicate that groundwater occurs in all geologic formations under varying conditions noting that the development of the resource must be tailored to exact geology and hydrogeology being explored. Banoeng-Yakubo et al. (2010) provide five distinct hydrogeological provinces in Ghana: The Pan African Province, the Birimian Province, the Coastal Sedimentary Province, the Voltaian Province, and the Crystalline Basement Granitoid Complex. This classification establishes the Pan-African and Birimian Provinces as more productive and of excellent quality of water for domestic, agricultural and industrial uses than the other provinces. Although the use of groundwater in the country has increased tremendously, the citizenry still lacks basic knowledge and understanding of the sustainable utilization of this vital resource (Banoeng-Yakubo et al., 2010; Owusu et al., 2016). Though recharge estimates determined in various parts of the country (Addai et al., 2016; Obuobie et al., 2012; Yidana and Chegbeleh, 2013) suggest promising fortunes for groundwater resources development, others have indicated a decline in water levels owing to the combined effects of climate change and impacts of anthropogenic activities in some parts of the country (Amisigo et al., 2014; Marke, 2013; Mensah et al., 2022a).

We suggest that some questions that should be central to groundwater exploitation in Ghana include but are not limited to: i) How much of the resource is available in the country and how can it be used sustainably to enhance rural livelihoods? ii) How can the resource be managed sustainably to meet the growing water supply needs of the populace and forestall devastating human and/or ecological consequences, which may result from over-exploitation? iii) How can these vulnerable resources be protected from polluting activities and if polluted, how can it be restored? We emphasize here that the responses to these and many other questions should rest not only with geoscientists but also on law enforcement institutions, communities and consumers who are mandated to ensure sustainable exploitation and protection of our groundwater resources. As emphasized by Raghavendra and Deka (2015), sustainable development of groundwater resources requires the efficient management of existing sources to serve contemporary needs without jeopardizing the chemical and physical characteristics, storage, and recovery of groundwater aquifers for future generations. Unfortunately, nearly 57% of the world's major aquifers have plunged to critical levels of sustainability (Sun et al., 2022) and many countries have become pragmatic in exploring and exploiting their groundwater resources (Wijnen et al., 2012). It is therefore instructive that for effective and sustainable management of the resource especially within saprolite (i.e. weathered bedrock that produces and stores groundwater) and adjoining units, further and intensive hydrogeological research is done to constrain the characteristics of the various hydrogeological provinces to provide adequate foundation to establish safe yields and advise on optimum abstraction levels. It is also important to strictly enforce the policy framework that guides the exploration and exploitation of groundwater under the Drilling

Licence and Groundwater Development Regulations (LI 1827) in Ghana. Additionally, there needs to be strong collaboration between institutions to govern and manage this valuable resource effectively. Training communities and policy makers on groundwater exploration, pollution pathways, and aquifer management can improve water resource sustainability. For example, promoting hydrogeological literacy can enhance community-led groundwater recharge projects, especially in drought-prone areas like the northern parts of Ghana (SDG 6: Clean Water and Sanitation).

In ensuring the sustainable development of groundwater resources, the threats of climate change and increasing adverse anthropogenic activities certainly call for prudent measures in developing and managing the resource, both quantitatively and qualitatively. Urgent policy actions would help protect the resource and ensure its availability for sustainable development. The multiple applications of geoscience can provide the necessary knowledge, skills, research and expertise to support this endeavor.

Geohazards

Geohazards are adverse geological processes and conditions that can cause significant damage or loss of property and life. These hazards are related to short and long-term geological and environmental processes. The impact of geohazards on Ghanaian lives and economy is enormous. Floods (landscape, human-induced and climate-induced), severe storms, landslides, subsidence, and drought (Figure 2), claim lives, injure many, and destroy homes and livelihoods. This is particularly true for the case of urban flooding in Ghana (Forson et al., 2023; Korah and Cobbinah, 2017; Quaicoe and Sapah, 2025). In 2010, Ghana recorded unprecedented flooding which affected 55 communities and displaced about 700,000 people. Also, about 3234 homes were destroyed while 23,588 acres of farmland were flooded. These damages amounted to an estimated total cost of US$116,340.22 (Mensah and Ahadzie, 2020; National Disaster Management Organization (NADMO), 2010). Extant research documents the human and socio-economic impacts of flooding in Ghana and attributes these large-scale impacts to climate-induced rainfall, poor urban planning, waste and drainage management and lack of preparation and literacy (Abeka et al., 2019; Amoako and Inkoom, 2018; Asumadu-Sarkodie et al., 2015; Campion and Venzke, 2013; F.Y. et al., 2014; J.K., 2016; Tabiri, 2015; Tasantab, 2019).

Ghana is also prone to earthquakes and other seismic hazards (Ahulu et al., 2018; Asare-Bediako et al., 2023). Even though Ghana is situated on the stable West Africa Craton, it has experienced destructive earthquakes documented as far back as 1615 with magnitudes ranging from 1.0 to 6.8 (Ahulu et al., 2018; Ambraseys and Adams, 1986; Asare-Bediako et al., 2023; Junner, 1941; Quaah, 1980). Seismic activity is mostly concentrated in the southern part of Ghana (Figure 3). The tectonic setting of the southern part of Ghana is characterized by fault systems that trigger seismic activity. Prominent among these seismic events is the 6.5 magnitude, June 22, 1939, earthquake, that was felt throughout the entire country, resulting in major destruction and loss of lives. The most damage to life and property occurred in the capital city, Accra, where 16 people were killed, and 133 injured with hundreds of thousands of pounds of weight of construction damage. Other notable events include the 4.7 Magnitude, March 11, 1964, earthquake, the 4.7 magnitude, February 14, 1997, earthquake and its 4.1 magnitude, 6 March 1997 aftershock (Ahulu et al., 2018). Earthquakes of magnitude <4.5 have since occurred with the most recent being a 4.0 magnitude earthquake felt in Accra and its environs on the 12th of December 2022 (Frimpong, 2022). Despite these, Ghana's preparedness for a major seismic event is woefully inadequate (Amponsah et al., 2020; Awere and Addai, 2022).

Figure 2. Images showed; a) A flooding event in Accra (retrieved from the National Disaster Management Organization (NADMO) website). b) The aftermath of a landslide that occurred in Adaklu in the Volta region of Ghana, in 2017, destroying farmlands (*retrieved from citifmonline.com*). c) Drought impacted lands (*retrieved from The United Nations Convention to Combat Desertification UNCCD's Ghana National Drought Plan document*). d) The aftermath of the 1939 earthquake which occurred in Ghana (*retrieved from Ghana facts and History @Ghana museum twitter page*).

The responsibility for disaster management lies not only with one organization; rather, it calls for collaboration and coordination of experts, professionals and agencies from different sectors. Geoscientists have the requisite knowledge and expertise to support a multi-disciplinary methodology and help state institutions frame policies that will raise public awareness, minimize hazards and reduce people's vulnerability to natural disasters. Also, if Geoscientists are involved at the right time during the mitigation planning processes, the impacts of these disasters will be averted. The Geoscientists are responsible for preparing vulnerability maps and identifying hotspots and impact areas for management decision support. In addition, geoscientists can collaborate with various state agencies and modern technological advancements to develop early warning systems to promote preparedness and protective actions for geohazards.

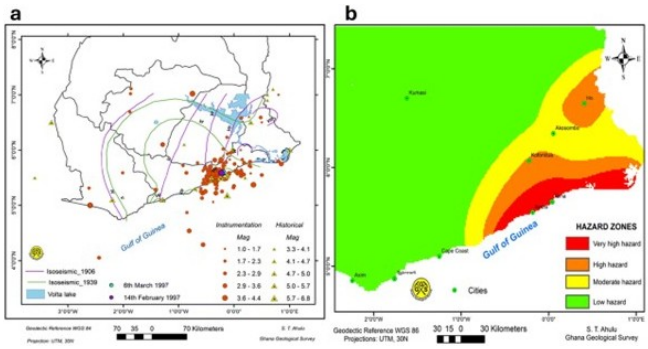

Figure 3. Images from Ahulu et al. (2018) showed; a) Seismicity of southern Ghana with isoseismic lines prepared for the 20 November 1906 and 22 June 1939 events. b) Seismic hazard zones in southern Ghana.

Some questions that should be central to help promote geohazard education and research in Ghana include but are not limited to: i) How can coastal erosion and sea-level rise affect the socio-economic and environmental stability of coastal communities in Ghana? ii) What is the current seismic risk profile of major urban places, and what is the extent of preparedness, prevention and mitigation strategies for potential earthquake occurrences in Ghana? iii) How can land use and climate patterns change affect the frequency and severity of floods in Ghana, and what are the consequences for disaster risk management? iv) What major factors contribute to landslide susceptibility in the hilly and mountainous regions of Ghana, and how can these regions be effectively monitored and managed? v) How does deforestation influence hydrological cycles and water resources, and what are the prolonged implications for flooding, water availability and quality in Ghana? Educating stakeholders on climate-related geohazards and geohazard monitoring enables early warning systems. For example, understanding seismic activity and land subsidence can inform urban planning in coastal cities like Accra, reducing disaster risks (SDG 13: Climate Action; Agenda 2063 Aspiration 1: Sustainable environments; CPESDP Pillar 7: Climate Resilience).

Mineral resources and the environment

Ghana is a nation blessed with many mineral resources including Gold, Diamond, Bauxite and Manganese, Iron ore, Limestone, Feldspar, Lithium, Quartz, and Salt. There are also minor deposits of Ilmenite, Magnetite, and Rutile (Kastning, 2011; Kesse, 1985). The presence and distribution of mineral and energy resources are intricately linked to geoscience, making the expertise of geoscientists important in the identification and extraction of these resources in a manner that is both economically feasible and environmentally sustainable, thus, contributing substantially to the socio-economic development of the country. These resources, if sustainably exploited, will enhance the well-being of the people, and bring prosperity to a nation (Ericsson and Löf, 2019). Civilization today increasingly depends on mineral and fossil energy resources which are non-renewable and vary in their availability, cost of production, and geographical distribution.

Ghana's most commercially exploited mineral is Gold, which accounts for about 95% of the country's mineral revenue. Manganese, Bauxite, and Diamonds are the other commercially exploited minerals in Ghana. Ghana is Africa's largest gold producer, overtaking South Africa in 2019 with 4.8 million ounces in output (International Trade Administration, 2022). Ghana has been mining gold since the 1900s and its earnings form a greater portion of the country's foreign exchange earnings - 47.2% of gross foreign exchange earnings which represents about 5.7% of the gross domestic products (GDP) as of 2019 (Ghana Chamber of Mines, 2019) and provide both direct and indirect employment to many.

Both legal large-scale and artisanal mining and illegal mining, popularly known as "Galamsey" activities impact the environment both during and after their active lifetime. Mining-related environmental impacts vary with the type of mine and the nature of exploited minerals. For example, surface mining causes more rapid environmental destruction compared to underground mining. This is because it involves the large-scale removal of vegetative cover which leads to rapid soil degradation, resulting in the loss of soil fertility and altered topography. Dust from stockpiles and tailings causes contamination of air, and land, alteration of surface water quality, and sedimentation of drainage channels. The combination of complex metals and the seepage of effluents into the environment pose a threat to human and aquatic life. The quality and quantity of groundwater are impacted by seepage and changing recharge rates due to ore removal. Additionally, underground mining poses a long-term risk of subsidence, which can cause engineering problems for buildings and structures on the surface. Additionally, abandoned mine openings such as shafts, inclines, and pits, concealed by vegetation, are dangerous to life. Aboka et al. (2018) reported that the effects of mining on local mining communities depend on the processes by which the mining activities are carried out, safety precautions taken, and health and environmental risk assessments conducted before, during and after mining is completed. Thus, substandard mining practices may precipitate health hazards that may counter the positive economic benefits of the mining activities.

By law, one must obtain a mining license to conduct any mining-related activity (reconnaissance, prospecting, exploration, or mining) in Ghana (Minerals and Mining Act 703 of 2006). However, illegal mining is prevalent despite efforts by various governments to curtail such activities. Illegal mining in Ghana constitutes mining activities in which individuals without mining licenses and/or concessions operate uncontrolled with substandard mining practices within the concessions of large-scale mining companies or in areas barred from mining (Obeng et al., 2019; Yiridomoh, 2021). Though positive arguments have been made for illegal mining such as its role in providing employment and a source of livelihood for people, the devastating uncontrolled operations involved in recent times have had devastating effects on the environ-

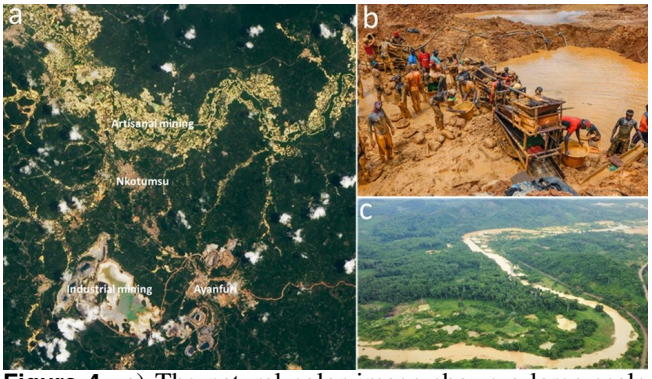

Figure 4. a) The natural-color image shows a large-scale mine and several artisanal mines in the Central Region of Ghana. The image was captured on March 29, 2020, by the Operational Land Imager (OLI) on Landsat 8. The mines lie within the Ashanti gold belt, one of the richest gold regions in West Africa (*NASA Earth Observatory, 2021*); b) This Image shows illegal small-scale mining activities being carried out (*Photo credit: Africa feeds*); c) Drone Image of the polluted river Pra in Ghana. This pollution has occurred over the years due to illegal small-scale mining activities (*Photo credit: Trading Ghana's Water for Gold, 2014*)

ment, particularly on Ghana's water bodies and agricultural land (Figure 4) (Adiyah, 2014; Ofosu et al., 2020; Owusu-Ansah and Smardon, 2015; Schueler et al., 2011; Yiridomoh, 2021). This can be attributed to the profitability of gold mining and dwindling employment opportunities in the formal sector all resulting in a surge of illegal miners. Similarly, small-scale/Artisanal mining although legal, has been shown to have an increasing destructive impact on the environment (Barenblitt et al., 2021) compared to large-scale industrial mining.

Studies have shown that although large-scale industrial mines cover a wider area than individual small-scale or artisanal mining sites including "Galamsey" sites, their collective impact on the landscape surpasses those of larger mines. For instance, Barenblitt et al. (2021) estimated that the vegetation lost to "Galamsey" and small-scale mines in the southwestern forest zones of Ghana from 2005 to 2019, amounts to 25% and is virtually seven times more than industrial mines. Mercury and heavy metals used in these types of mining activities pollute the drinking and domestic water supplies for communities, causing major health concerns, including kidney and neurological disorders, for those consistently exposed. Organizing training workshops for mining communities on geochemical health risks (e.g., mercury exposure in Prestea) would be very beneficial. This aligns well with SDG 12: Responsible Consumption and Production; Agenda 2063 Aspiration 1: Equitable resource governance, and CPESDP Pillar 6: Environmental Sustainability.

Further, poorly managed mine pits, abandoned pits and improperly closed pits also pose health hazards long after mining has been completed. Abandoned mines with associated Acid Mine Drainage (AMD) discharges pose a threat to ground and surface water as well as soil. Many abandoned mines, and their associated waste, are an ongoing source of AMD and toxic heavy metals that have long-term harmful impacts on sources of community water supply such as rivers, streams and groundwater, as well as on aquatic life (Bennett, 2016; Gigantone et al., 2020; Liu et al., 2021). Aside from health hazards and risks, the closure or abandonment of mine pits may come with socio-economic implications for the local communities within which mining takes place. For example, the loss of jobs in the mines may mean loss of income and livelihoods for families which may in turn affect other aspects of social life within the community (Stacey et al., 2010; Zobrist et al., 2009). As at now, no mine in Ghana is known to have been completely closed in terms of meaningful remediation works after it has reached its exploration limit. However, there have been several reported cases of mine being abandoned for over 10 years under the pretext of care and maintenance before takeovers. The standard practice in many countries involves ensuring that mines, after closure, are left in conditions with minimal long-term environmental impacts. In Ghana, mines are expected to follow the Minerals and Mining Law (PNDCL 153), Ghana's Mining and Environmental Guideline, and the Ghana Environmental Protection Act 1994 (Act 490) and follow internationally accepted best environmental practices. This, however, does not seem to be the case. From all these, it can be agreed that mining, if not conducted properly, is an antagonist to environmental management and sustainability. Thus, a good resolution of these challenges is key to the development of mineral resources consistent with the pillars of sustainability.

This is where knowledge, skills, expertise, and experiences in geoscience come into play. Geoscientists identify, locate, and extract mineral resources economically while minimizing the environmental and health impacts of these processes. Geoscientists such as Geologists, Geochemists, Hydrogeologists, Engineering Geologists, Geophysicists etc., play an important role in providing solutions to environmental problems associated with mining (Koscova et al., 2018; Lai et al., 2021; Plumlee, 1997). This can be achieved through education and outreach, research and policymaking. Geoscientists can make available to the relevant policymakers, mining companies, mining communities, the public and other stakeholders their findings and opinions on the most appropriate protocols regarding mining in Ghana. geoscience education and outreach in mining communities are important to influence the mindset and social practices that harm the environment. This aligns well with SDG 13: Climate Action, Agenda 2063 Aspiration 1: Sustainable environments, and CPESDP Pillar 6: Environmental SustainabilityEducation and outreach can also be a means of the dissemination of solution-orientated information to already affected local mining communities. Geoscientists through research and collaborations with appropriate agencies can provide data, mitigation and monitoring solutions on environmental issues associated with mining such as water quality, post-mining land use, physical stability, waste management,

soil and geochemical stability and Public Health. Such valuable data and information can assist governmental agencies by providing them with useful data to aid in setting up policies and guidelines for prevention, mitigation, and monitoring. Such data and information can also be used to improve and review the current legislature, regulations, monitoring program, risk management, cost and securities and the social aspects associated with mining.

Geoheritage, Geoconservation and Geotourism

Geoheritage, Geoconservation and Geotourism are concerned with the preservation of sites or areas of geologic features with significant scientific, educational, cultural, or aesthetic value. Recent decades have seen growing awareness within the global geoscientific community in relation to the perception, preservation and protection of diverse geological elements and geological heritage. This has led to the development of the concepts of Geodiversity, Geoparks, Geotourism, Geoheritage, and Geoconservation (Kaur, 2022). These global initiatives have resulted in the conservation of some important geological heritage and have demonstrated that they can provide a new path for sustainable development (Kaur, 2022). Works of Gill (2016) and Gill and Smith (2021) have demonstrated the relevance of aspects of geoscience such as Geoheritage, Geoconservation and Geotourism to achieving each of the 17 SDGs.

The Geology of Ghana is particularly interesting and important because of the age, tectonics and lithologic characteristics of the supracrustal rocks, resulting in spectacular geological sites. Apart from its rich geological history, there is also major economic interest in the geology of Ghana due to its mineral, oil, and water resources. Despite the major advantages of the geology of Ghana, Ghana has no known Geoheritage and or Geotourism sites. Ghana has made some attempts at Geoconservation. There are two parks listed on the UNESCO World Heritage List and six Ramsar sites recognized by the Ramsar Convention. These places are conserved either for tourism or their environmental importance. None of these sites, however, have a Geoeducation component. Even though in the Laws of Ghana, the Ghana Geological Survey Authority ACT, 2016 ACT 298 has made provisions via Regulation (e) for Geoconservation, no sites have been identified and developed as Geoconservation sites by law. We argue that geological sites can be identified, mapped, described and documented for Geoheritage, Geoconservation, Geoeducation and Geotourism in Ghana.

Currently, many countries are trying to diversify sources of foreign direct investment and national incomes, from mining or any activities which are deemed environmentally unsustainable and are increasing their effort on non-mine inflows from tourism. All over the world, tourists have found more serenity and solace in geology-based touristic features such as crater lakes, waterfalls, canyons, and spectacular rocks. For example, the Grand Canyon National Park in Arizona, the Yosemite National Park in the Sierra Nevada mountains,

Figure 5. Shows some geological formations in Ghana, that can be developed to enhance Geotourism in Ghana. a) Mount Afadza, the tallest mountain in West Africa (*retrieved from Sanza, 2019*) b) Kintampo fall (*retrieved from viewGhana.com)*. c) Wulin Mushroom rock (*retrieved from Ghanaweb.com*). d) Gambaga escarpment, a 100km long line of cliffs with caves, prehistoric paintings, and carvings (*retrieved from Haun, 2019*). e) Wli waterfall, the highest waterfall, in West Africa (Degue, 2011). f) Lake Bosomtwi, the only natural lake in Ghana formed by impact cratering (*retrieved from ghana.arocha.org*). g) Afram fault escarpment, part of the Kwahu Afram plains and mountains.

USA, and the sandstone landforms of the Karoo Basin in South Africa are all major geotourist sites that provide large revenues for their respective countries. Ghana can follow the examples of other countries and develop famous geoscience sites such as Lake Bosomtwi (the only natural lake in Ghana), the Boti, Akaa, Kintampo, Fuller, and Wli waterfalls as well as the beautiful scenery along the Akwapim range and the Massif sandstones exposures in Gambaga, Damongo and Kintampo as massive geotourism sites. Similarly, the Kwahu Plateau to the south of the Voltaian Sedimentary Basin, mount Afadja (the highest mountain in Ghana), and the Atiwa range among other scenic places can also be developed into national parks or geoparks (Figure 5). The potential for tourism and the enhancement of the rural economy through geotourism will be achieved through intentional policies that factor in geoscience knowledge and geoscientists. For example, training guides to interpret geological features at Lake Bosomtwi (meteorite crater) and Kintampo Waterfalls and educating lawmakers on UNESCO Global Geopark criteria to protect sites like the Gambaga Escarpment would greatly promote geotourism. This initiative in line with SDG 8: Decent Work and Economic Growth, Agenda 2063 Aspiration 5: Cultural

identity and tourism, and CPESDP Pillar 2: Economic Transformation; Pillar 4: Social Development.The potential for geoscience-based tourism to develop and grow our national and rural economies, alleviate poverty, and enhance sustainable rural livelihood in the country is enormous. Policy and decision-makers need to use geoscience as a key pillar for stemming the acute rural poverty in parts of the country.

Recommendations and Proposed Initiatives

From the above examples given about the role of geoscience in achieving the SDGs, which is not exhaustive, we have demonstrated clearly the importance of geoscience in the sustainable development of Ghana. As such, geoscience literacy should be instituted in the fabric of Ghanaian society, especially at all school levels and institutions charged with the responsibility to coordinate and implement SDGs. We are of the view that, geoscience awareness, education and literacy geared towards sustainability is very important to promote and support the SDGs in Ghana. We therefore propose the following initiatives to promote geoscience literacy in Ghana for sustainable development.

Establishment of a National Geoscience and Sustainable Development Awareness Program

To effectively harness the potential of geosciences in supporting Ghana's SDGs, it is imperative to develop a comprehensive national geoscience and sustainable development awareness program. This initiative, named National Awareness Program in geoscience and Sustainable Development (NAP-GSD), should aim to increase public understanding of geoscience concepts, promote responsible resource management, and foster disaster risk reduction culture across all sectors of society.

This program should be analogous to the National Disaster Management Organization (NADMO) but with a broader focus on sustainability, disaster prevention and mitigation through geoscience information and education rather than emergency response.

Key components of the program may include:

Public Education Campaigns: Utilize mass media (i.e., radio, television, social media, and print outlets) to disseminate information on geological hazards, mineral resources, water resources, and environmental conservation. Campaigns should be tailored to local contexts and languages to maximize reach.

Curriculum Integration: Incorporate geoscience topics into primary, secondary, and tertiary education curricula. Develop age-appropriate teaching materials and practical activities that foster curiosity and understanding of Earth sciences from an early age.

Community Outreach and Engagement: Organize workshops, seminars, and field visits for local communities, artisanal miners, farmers, and other stakeholders. These activities should focus on hazard awareness, sustainable resource use, and climate resilience.

Capacity Building for Educators and Community Leaders: Train teachers, local leaders, and community health workers in basic geoscience concepts and disaster preparedness to serve as local champions of geoscience literacy.

Partnerships and Stakeholder Involvement: Collaborate with government agencies, universities, research institutions, NGOs, the private sector, and traditional authorities to ensure a coordinated and sustainable approach. In addition to their core mandate NAP-GSD is expected to encourage and facilitate collaborations between the Ghanaian geoscientific community and civil society to actively show the great potential of geosciences in the building of a safer, healthy, and wealthy Ghana.

Promotion of Geoheritage, Geoconservation, and Geotourism

Identification and Preservation of Geoheritage Sites: Conduct national assessments to identify and protect sites of geological, paleontological, or geomorphological significance. Establish designated geoheritage zones to promote awareness and conservation.

Development of Geotourism: Leverage Ghana's unique geological features to attract eco- and geo-tourists, creating employment opportunities and generating revenue for local communities. Develop interpretive centers, guided tours, and educational materials to enhance visitor experience.

Development of a Community Geo-Guide Training Program: This program is designed to empower local community members to become skilled and confident leaders in geotourism. The program focuses on providing participants with a strong foundation in geology, storytelling, communication, and sustainable tourism practices.

Through a combination of classroom learning, hands-on activities, and field practice, participants will gain the knowledge and skills needed to develop and lead engaging geotourism experiences that showcase the unique geological and cultural heritage of their region. This program aims to foster local ownership of geotourism initiatives, promote environmental stewardship, and create economic opportunities for the community.

Formulation of a National Geoscience Policy

Ghana's development is guided by multiple strategic frameworks, notably the SDGs, Agenda 2063 of the African Union, and the Coordinated Programme of Economic and Social Development Policies (CPESDP).

To leverage geosciences effectively in achieving these ambitious visions, a targeted policy approach is essential - one that mainstreams geoscience literacy across sectors, enhances institutional capacity, and fosters public engagement.

Key policy recommendations are as follows:

Formalize Geoscience Education and Capacity Building as a National Priority: Enact legislation that mandates the integration of geoscience literacy into the national education curriculum at all levels (i.e., primary, secondary, and tertiary). This should include the development of nationally approved teaching modules, practical fieldwork, and community out-

reach programs. The implementation agency should be the Ministry of Education, in collaboration with the Geological Survey Authority, Ghana Institution of Geoscientists, and academia. Such a policy would lead to an increased public awareness and a skilled workforce capable of addressing Ghana's specific geological challenges, aligned with SDG 4 (Quality Education) and SDG 13 (Climate Action).

Establish a National Geoscience and Sustainable Development Policy Framework: Develop a comprehensive policy document that explicitly links geoscience activities with national development goals, emphasizing responsible resource management, disaster risk reduction, and environmental sustainability. The policy should delineate roles for government agencies, industry, academia, and civil society, with dedicated funding for geoscience research, community education, and geoheritage conservation. Such a policy will result in a coordinated national strategy that aligns geoscience research and education with SDGs 6, 13, 15, and Agenda 2063 priorities, fostering an enabling environment for sustainable development.

Institutionalize Multi-Stakeholder Engagement and Community Participation: Establish regional and community-based geoscience councils composed of local leaders, scientists, educators, and civil society actors. These bodies should oversee local hazard mitigation, resource management, and geoheritage promotion. These bodies would create incentives and capacity-building programs for community leaders and artisanal miners to adopt sustainable practices informed by geoscience knowledge. It is expected that this policy would lead to enhanced local resilience, improved resource sustainability, and community-driven conservation aligned with SDG 11 (Sustainable Cities and Communities) and SDG 15 (Life on Land).

Leverage Technology and Innovation for Data-Driven Decision-Making: Invest in geospatial data infrastructure, including GIS, remote sensing, and hazard modeling platforms, accessible to policymakers, researchers, and communities. Establish a National Geospatial Data Center that consolidates geological, hydrological, and hazard data, and develops user-friendly tools for disaster preparedness and resource management. It is expected that this will enhance capacity for evidence-based policymaking, disaster risk reduction, and sustainable land use planning.

Conclusion

Implementing these integrated initiatives will foster a culture of geoscience literacy across Ghana, empowering citizens, policymakers, and stakeholders to make informed decisions that promote sustainable development, resilience to natural hazards, and responsible resource management. An informed society equipped with geoscience knowledge is essential for building a resilient Ghana that thrives economically, socially, and environmentally.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abanyie, S. K., Sunkari, E. D., Apea, O. B., Abagale, S., and Korboe, H. M. (2020). Assessment of the quality of water resources in the upper east region, ghana: a review. *Sustainable Water Resources Management*, 6(4):52.

Abdullah, I. Y. (2024). Employing sustainable development to build societies.

Abeka, E., Asante, F. A., Laube, W., and Codjoe, S. N. A. (2019). Contested causes of flooding in poor urban areas in accra, ghana: an actor-oriented perspective. *Environment, Development and Sustainability*, 22(4):3033–3049.

Aboagye, E. M., Effah, K. O., and Mensah, F. (2022). Achieving sustainable development goals. *RISUS - Revista de Inovação e Sustentabilidade*, 13(4):135–145.

Aboka, Y., Cobbina, S., and Doke, A. (2018). Review of environmental and health impacts of mining in ghana. *Journal of Health Pollution*, 8(17):43–52.

Addai, M. O., Yidana, S. M., Chegbeleh, L. P., Adomako, D., and Banoeng-Yakubo, B. (2016). Groundwater recharge processes in the nasia sub-catchment of the white volta basin: Analysis of porewater characteristics in the unsaturated zone. *Journal of African Earth Sciences*, 122:4–14.

Adiyah, F. (2014). The effects of illegal small-scale gold mining ("galamsey") activities on the water quality of the akantansu and sintim rivers in the asutifi north district of the brong ahafo region of ghana. Master's thesis, Kwame Nkrumah University of Science and Technology.

Adjarko, H., Osei-Poku, G., and Ayarkwa, J. (2014). Challenges to the incorporation of environmental sustainability issues into construction procurement at the local government level of ghana. *International Refereed Journal of Engineering and Science (IRJES)*, 3(11):42–52.

Adomako, T. and Ampadu, B. (2015). The impact of agricultural practices on environmental sustainability in ghana: a review. *Journal of Sustainable Development*, 8(8):70–85.

Ahulu, S., Danuor, S., and Asiedu, D. (2018). Probabilistic seismic hazard assessment of southern part of ghana. *Journal of seismology*, 22(3):539–557.

Akomaning, Y. O., Darkwah, S. A., Živělová, I., and Hlaváčková, P. (2023). Achieving sustainable development goals in ghana: The contribution of non-timber forest products towards economic development in the eastern region. *Land*, 12(3).

Akua-Sakyiwah, B. (2022). A contextual approach to institutional change.

Allotey, N. K., Adom-Asamoah, M., Kumi, A., Nyasapoh, M. A., and Dompreh, C. Z. (2017). Earthquake risk: The opinion of ghanaian local artisians.

Ambraseys, N. and Adams, R. (1986). Seismicity of west africa. *Annals of Geophysics*, 4(B6):679–702.

Amisigo, B. A., McCluskey, A., and Swanson, R. (2014). Modeling impact of climate change on water resources and agriculture demand in the volta basin and other basin systems in ghana.

Amoako, C. and Inkoom, D. (2018). The production of flood vulnerability in accra, ghana: re-thinking flooding and informal urbanization. *Urban Studies*, 55:2903–2922.

Amponsah, P., Opoku-Ntim, I., and Nortey, G. (2020). Seismic risk in ghana: efforts and challenges. *Arabian Journal of Geosciences*, 13:1–5.

Annan-Aggrey, E., Arku, G., Atuoye, K., and Kyeremeh, E. (2022). Mobilizing communities of practice for local development and acceleration of the sustainable development goals. *Local Economy*, 37(3):219–229.

Apronti, P. T., Osamu, S., Otsuki, K., and Kranjac-Berisavljevic, G. (2015). Education for disaster risk reduction (drr): Linking theory with practice in ghana's basic schools. *Sustainability*, 7(7):9160–9186.

Arhin, E., Webrah Kazapoe, R., Mahamuda, A., and Kazapoe, R. (2018). Medical geology and health: An approach to address diseases related to natural environment-reviewing the ghanaian situation. *Topics: Medical Geology and Natural*.

Asare-Bediako, B., Boateng, C. D., Danuor, S. K., Opoku, N., Arthur, L. N. B., and Anokwa, Y. M. (2023). An overview of seismic activities in ghana: A systematic review.

Asumadu, G. (2022). Examining sustainability education in economics, accounting and finance in tertiary institutions in ghana. *Modern Economy*, 13(12):1521–1532.

Asumadu-Sarkodie, S., Owusu, P. A., and Rufangura, P. (2015). Impact analysis of flood in accra, ghana. *Advances in Applied Science Research*, 6:53–78.

Awere, G. K. and Addai, G. A. (2022). Assessing households' preparedness for earthquakes in gbawe, accra. *Journal of Environment and Earth Science*, 12(11).

Banoeng-Yakubo, B., Yidana, S. M., Ajayi, J. O., Loh, Y., and Asiedu, D. (2010). Hydrogeology and groundwater resources of ghana: A review of the hydrogeological zonation of ghana.

Barenblitt, A., Payton, A., Lagomasino, D., Fatoyinbo, L., Asare, K., Aidoo, K., Pigott, H., Som, C., Smeets, L., Seidu, O., and Wood, D. (2021). The large footprint of small-scale artisanal gold mining in ghana. *Science of the Total Environment*, 781:146–644.

Bello, M. (2022). Connecting knowledge and practice for sustainable development.

Bennett, K. (2016). Abandoned mines—environmental, social and economic challenges.

Beoku-Betts, J. (2020). Science as a development tool in ghana: Challenges, outcomes, and possibilities for women academic scientists.

Bera, S. (2020). Sustainable urban development: Meaning and significance. *Galore International Journal of Applied Sciences and Humanities*, 4:29–33.

Bessah, E., Raji, A. O., Taiwo, O. J., Agodzo, S. K., Ololade, O. O., Strapasson, A., and Donkor, E. (2021). Assessment of surface waters and pollution impacts in southern ghana. *Hydrology Research*, 52(6):1423–1435.

Campion, B. and Venzke, J. (2013). Rainfall variability, floods and adaptations of the urban poor to flooding in kumasi, ghana. *Natural Hazards*, 65:1895—-1911.

Carneiro, C. D. R., Barbosa, R., and Piranha, J. M. (2007). Bases teóricas do projeto geo-escola: uso de computador para ensino de geociências. *Brazilian Journal of Geology*, 37(1):90–100.

Cheung, L. T. O. and Lo, A. Y. H. (2018). Environment and development. *Asian Geographer*, 35(2):121.

Dapaah-Siakwan, S. and Gyau-Boakye, P. (2000). Hydrogeologic framework and borehole yields in ghana. *Hydrogeology Journal*, 8(4):405–416.

Darko, H. F., Karikari, A. Y., Duah, A. A., Akurugu, B. A., Mante, V., and Teye, F. O. (2023). Effect of small-scale illegal mining on surface water and sediment quality in ghana. *International Journal of River Basin Management*, 21(3):375–386.

Darvishi, Y., Karami, H., and Goodarzian, F. (2023). Sustainable development in oxygenated fuels.

Davies, T. C. (2010). Geoscientific and environmental health issues in africa. *International Geology Review*, 52(7–8):873–897.

de Mulder, E. F. J. and Cordani, U. G. (2023). Geoscience for sustainable development; the next decade.

Degue, J. (2011). Wli waterfall: A tourist attraction worth visiting. `https://www.modernghana.com/news/329381/1/wli-waterfall-a-tourist-attraction-worth-visiting.html`.

Doamekpor, L. K., Darko, R., Klake, R. K., Samlafo, V. B., Bobobee, L. H., Akpabli, C. K., and Nartey, V. K. (2015). Assessment of the contribution of road runoffs to surface water pollution in the new juaben municipality, ghana. *Journal of Geoscience and Environment Protection*, 4(1):173–190.

Ericsson, M. and Löf, O. (2019). Mining's contribution to national economies between 1996 and 2016. *Mineral Economics*, 32(2):223–250.

Evseeva, O., Evseeva, S., and Dudarenko, T. (2021). The impact of human activity on the global warming. *E3S Web of Conferences*, 284:11–17.

Forson, E. D., Amponsah, P. O., Hagan, G. B., and Sapah, M. S. (2023). Frequency ratio-based flood vulnerability modeling over the greater accra region of ghana. *Modeling Earth Systems and Environment*, 9(2):2081–2100.

Franks, D. M., Keenan, J., and Hailu, D. (2022). Mineral security essential to achieving the sustainable development goals. *Nature Sustainability*, 6(1):21–27.

Freyssinel, I. (2023). Promoting geosciences education for sustainability by educational project. https://doi.org/10.5194/EGUSPHERE-EGU23-4156.

Frimpong, E. (2022). Accra experiences moderate earth tremor of magnitude 4.0. https://www.graphic.com.gh/news/general-news/earth-tremor-hits-accra.html.

F.Y., L., K., K.-Y., D., O., and P., G.-B. (2014). Flood pulse alterations of some river basins in ghana. *Ghana Journal of Science*, 12:19–32.

Garfias Royo, M., Diep, L., Mulligan, J., Mukanga, P., and Parikh, P. (2022). Linking the un sdgs and african agenda 2063: Global goals and local priorities for africa. *World Development Sustainability*, 1:100010.

Ghana Chamber of Mines (2019). Performance of the Mining Industry in 2019. https://ghanachamberofmines.org/wp-content/uploads/2020/05/Performance-of-the-Mining-Industry-in-2019.pdf.

Ghana Statistical Services (2023). Newsletter quarterly gross domestic product (qgdp) first quarter 2023.

Gigantone, C. B., Sobremisana, M. J., Trinidad, L. C., and Migo, V. P. (2020). Impact of abandoned mining facility wastes on the aquatic ecosystem of the mogpog river, marinduque, philippines. *Journal of Health and Pollution*, 10(26).

Gill, J. C. (2016). Geology and the sustainable development goals. *Episodes: Journal of International Geoscience*, 40(1):70–76.

Gill, J. C., Mankelow, J., and Mills, K. (2019). The role of earth and environmental science in addressing sustainable development priorities in eastern africa. *Environmental Development*, 30:3–20.

Gill, J. C. and Smith, M. (2021). *Geosciences and the sustainable development goals*. Springer Nature.

Graham, E. and Ovadia, J. S. (2019). Oil exploration and production in sub-saharan africa, 1990-present: Trends and developments. *The Extractive Industries and Society*, 6(2):593–609.

Gyampoh, B. A. and Asante, W. (2011). A mapping and documenting indigenous knowledge in climate change adaptation in ghana. Technical report, Africa Adaptation Programme (AAP); United Nations Development Programme (UNDP). https://doi.org/10.13140/RG.2.1.4818.6640.

Gyang, J. D. and Ashano, E. C. (2010). The role of geosciences in sustainable development of an expanding urban region: A case study of the jos-bukuru urban region, north central nigeria. *Pacific Journal of Science and Technology*, 11(2):664–670.

Huifang, T. (2022). Sustainable development.

International Trade Administration (2022). Mining industry equipment. https://www.trade.gov/country-commercial-guides/ghana-mining-industry-equipment.

Jessell, M., Baratoux, D., Siebenaller, L., Hein, K., Maduekwe, A., Ouedraogo, F., Baratoux, L., Diagne, M., Cucuzza, J., Seymon, A., and Sow, E. (2018). New models for geoscience higher education in west africa. *Journal of African Earth Sciences*, 148:99–108.

J.K., O.-A. (2016). The influences of land use and sanitation infrastructure on flooding in kumasi, ghana. *GeoJournal*, 81(4):555–570.

Junner, N. (1941). The accra earthquake of 22nd june, 1939. *Gold Coast Geological Survey, Bulletin*, 13:3–41.

Kastning, T. (2011). Basic overview of ghana's emerging oil industry. https://library.fes.de/pdf-files/bueros/ghana/10496.pdf.

Kaur, G. (2022). Geodiversity, geoheritage and geoconservation: a global perspective. *Journal of the Geological Society of India*, 98(9):1221–1228.

Kavvada, A., Ishida, C., Juárez, J., Ramage, S., Merodio, P., and Friedl, L. (2022). Earth observation applications and global policy frameworks.

Kay, P., Hoatson, D. M., Huleatt, M. B., and Lewis, B. (2013). Assessment of mineral potential, geoscience survey capacity, risk, and geological aid in africa, asia, latin america, and the pacific. Technical Report 2012/064, Geoscience Australia.

Kazapoe, R. W., Arhin, E., and Amuah, E. E. Y. (2021). Known and anticipated medical geology issues in ghana. *Ecofeminism and Climate Change*, 2(4):169–184.

Keller, E. A. and DeVecchio, D. E. (2019). *Natural hazards: earth's processes as hazards, disasters, and catastrophes*. Routledge.

Kesse, G. O. (1985). *The mineral and rock resources of Ghana*. A.A. Balkema, Rotterdam Boston.

Korah, P. I. and Cobbinah, P. B. (2017). Juggling through ghanaian urbanisation: flood hazard mapping of kumasi. *GeoJournal*, 82:1195–1212.

Koscova, M., Hellmer, M., Anyona, S., and Gvozdkova, T. (2018). Geo-environmental problems of open pit mining: Classification and solutions. *E3S Web of Conferences*, 41:01034.

Kupchenia, L. (2022). Concept of sustainable development in the system of international environmental law. *ScienceRise*, 2(20):29–33.

Lai, F., Beylot, A., Navarro, R., Schimek, P., Hartlieb, P., Johansson, D., and Villeneuve, J. (2021). The environmental performance of mining operations: Comparison of alternative mining solutions in a life cycle perspective. *Journal of Cleaner Production*, 315:128030.

Lemenkova, P. (2022). Geophysical mapping of ghana using advanced cartographic tool gmt. *Kartografija i Geoinformacije*, 20(36):16–37.

Liu, H., Wu, Q., Chen, J., Wang, M., Zhao, D., and Duan, C. (2021). Environmental impacts related to closed mines in inner mongolia. *Sustainability*, 13(23):13473.

Lunn, J. (2023). Geoscientists make a difference. *EoS*, 104.

Mansur, K. L. (2009). Projetos educacionais para a popularização das geociências e para a geoconservação. *Geologia USP. Publicação Especial*, 5:63–74.

Manu, E., de Lucia, M., Schleicher, A. M., Kempka, T., and Kühn, M. (2022). Geochemical evolution and reaction mechanisms controlling groundwater chemistry in the pra basin (ghana). In *EGUGA*, pages 22–427.

Margat, J. and Van der Gun, J. (2013). *Groundwater around the world: a geographic synopsis*. Crc Press.

Marke, A. (2013). Literature review on the impact of climate change on economic development in northern ghana. `https://www.peaksexercise.org.uk/`.

Martínez-Frías, J. and Mogessie, A. (2012). The need for a geoscience education roadmap for africa. *Episodes: Journal of International Geoscience*, 35(4):489–492.

Mata-Lima, H., Alvino-Borba, A., Pinheiro, A., Mata-Lima, A., and Almeida, J. A. (2013). Impacts of natural disasters on environmental and socio-economic systems: What makes the difference? *Ambiente & Sociedade*, 16:45–64.

Mensah, H. and Ahadzie, D. K. (2020). Causes, impacts and coping strategies of floods in ghana: a systematic review. *SN Applied Sciences*, 2:1–13.

Mensah, J., Awabil, G., Graham, A. Y., and Mensah, A. N. (2022a). Relevance of trees and forests to sustainable development: Perspectives of key rural actors in selected communities, ghana. *Visegrad Journal on Bioeconomy and Sustainable Development*, 11(2):79–88.

Mensah, J. K., Ofosu, E. A., Akpoti, K., Kabo-Bah, A. T., Okyereh, S. A., and Yidana, S. M. (2022b). Modeling current and future groundwater demands in the white volta river basin of ghana under climate change and socio-economic scenarios. *Journal of Hydrology: Regional Studies*, 41:101–117.

Missotten, R., Gaines, S. M., and de Mulder, E. F. (2009). Unesco's new earth science education initiative for africa. In *AGU Fall Meeting Abstracts*, volume 2009, pages U11B–0023.

Moktadir, M. A. and Ren, J. (2023). Leveraging environmental, social, and governance strategies for sustainable tannery solid waste management towards achieving sustainable development goals. *Sustainable Development*.

National Disaster Management Organization (NADMO) (2010). Disaster management.

North, M. A., Hastie, W. W., and Hoyer, L. (2020). Out of africa: The underrepresentation of african authors in high-impact geoscience literature. *Earth-Science Reviews*, 208:103262.

Nyarko, S. C. and Petcovic, H. L. (2021). Ghanaian preservice science teachers' knowledge of ozone depletion and climate change, and sources of their knowledge. *International Journal of Science Education*, 43(10):1554–1575.

Obeng, E., Oduro, K., Obiri, B., Abukari, H., Guuroh, R., Djagbletey, G., Appiah-Korang, J., and Appiah, M. (2019). Impact of illegal mining activities on forest ecosystem services: local communities' attitudes and willingness to participate in restoration activities in ghana. *Heliyon*, 5(10):e02617.

Obuobie, E., Agyekum, W., Appiah-Adjei, E. K., Upton, K., O Dochartaigh, B. E., and Bellwood-Howard, I. (2018). Hydrogeology of ghana. `https:`

/ / www.bgs.ac.uk / africagroundwateratlas / country-profiles/ghana/.

Obuobie, E., Diekkrueger, B., Agyekum, W., and Agodzo, S. (2012). Groundwater level monitoring and recharge estimation in the white volta river basin of ghana. *Journal of African Earth Sciences*, 71:80–86.

Odoom, D., Mensah, E. O., Dick-Sagoe, C., Lee, K. Y., Opoku, E., and Obeng-Baah, J. (2023). Examining the level of public awareness on the sustainable development goals in africa: An empirical evidence from ghana. *Environment, Development and Sustainability*, 26(3):1–18.

Ofosu, G., Dittmann, A., Sarpong, D., and Botchie, D. (2020). Socio-economic and environmental implications of artisanal and small-scale mining (asm) on agriculture and livelihoods. *Environmental Science and Policy*, 106:210–220.

Olufadewa, I. I., Adesina, M. A., and Ayorinde, T. (2020). From africa to the world: Reimagining africa's research capacity and culture in the global knowledge economy. *Journal of Global Health*, 10(1).

Oteng-Ababio, M. (2013). 'prevention is better than cure': assessing ghana's preparedness (capacity) for disaster management. *Jàmbá: Journal of Disaster Risk Studies*, 5(2):1–11.

Owusu, P. A., Asumadu-Sarkodie, S., and Ameyo, P. (2016). A review of ghana's water resource management and the future prospect. *Cogent Engineering*, 3(1):1164275.

Owusu-Agyeman, Y. (2021). Formation of a sustainable development ecosystem for ghanaian universities. *International Review of Education*, 67(3):333–362.

Owusu-Ansah, F. and Smardon, R. C. (2015). Mining and agriculture in ghana: A contested terrain. *International Journal of Environment and Sustainable Development*, 14(4):371–397.

Oznobikhina, L. A. (2022). Assessment of the impact of industrial activities on environmental quality and public health. *IOP Conference Series: Earth and Environmental Science*, 979(1):012151.

Pabi, O. (2024). The adoption and applications of earth observations and allied geoinformation systems for environmental management in ghana. *European Journal of Environment and Earth Sciences*, 5(5):16–22.

Piranha, J. M., Dal, C., and Carneiro, R. (2009). O módulo são josé do rio preto do projeto geo-escola - uma experiência educacional diferenciada. *Brazilian Journal of Geology*, 39(3):533–543.

Plumlee, G. S. (1997). The environmental geology of mineral deposits. In Plumlee, G. S., Logsdon, M. J., and Filipek, L. F., editors, *The Environmental Geochemistry of Mineral Deposits: Part A: Processes, Techniques, and Health Issues Part B: Case Studies and Research Topics*, pages 1–27. Society of Economic Geologists.

Quaah, A. O. (1980). *Microseismicity, past seismic activity and seismic risk in Southern Ghana*. PhD thesis, University of London.

Quaicoe, J. and Sapah, M. S. (2025). A novel approach of the application of drainage morphometry and analytical hierarchy process to the flood susceptibility assessment of the ungauged kakum river basin, using remote sensing data. *Modeling Earth Systems and Environment*, 11(1):1–15.

Raghavendra, N. S. and Deka, P. C. (2015). Sustainable development and management of groundwater resources in mining affected areas: A review. *Procedia Earth and Planetary Science*, 11:598–604.

Rajendran, C. (2010). Challenges in earth sciences: the 21st century. *Current Science*, 99(12):1690–1698.

Rani, P. (2024). A multidimensional exploration of the interplay between human health and environmental factors. *Shodh Sari*, 3(3):225–237.

Sapah, M. S., Asiedu, D. K., and Loh, Y. S. A. (2023). Geoscience education in ghana: status and recommendations. *Episodes Journal of International Geoscience*, 47(1):1–9.

Schueler, V., Kuemmerle, T., and Schröder, H. (2011). Impacts of surface gold mining on land use systems in western ghana. *Ambio*, 40:528–539.

Scown, M. W. (2020). The sustainable development goals need geoscience. *Nature Geoscience*, 13(11):714–715.

Senger, K. (2024). Sustainable development goals and the geosciences: A review. *Earth Science, Systems and Society*, 4.

Shubita, M., Ahmed, S., and Essel-Paintsil, M. (2022). The economic impact of corporate social responsibility on the development of indigenous communities: evidence from ghana's mining sector. *The International Journal of Organizational Analysis*, 31(1):196–214.

Singh, D., Karambelas, A., Chhatre, A., DeFries, R., Kinney, P., and Davis, K. F. (2021). A systems lens to evaluate the compound human health impacts of anthropogenic activities. *One Earth*, 4(9):1233–1247.

Stacey, J., Naude, A., Hermanus, M., and Frankel, P. (2010). The socio-economic aspects of mine closure and sustainable development: Literature overview and lessons for the socio-economic aspects of closure-report 1. *Journal of the Southern African Institute of Mining and Metallurgy*, 110(7):379–394.

Stewart, I. S. (2022). Integrating "the triangle of geography, geology, and geophysics" into sustainable development. *Jordan Journal of Earth and Environmental Sciences*.

Sun, J., Hu, L., Li, D., Sun, K., and Yang, Z. (2022). Data-driven models for accurate groundwater level prediction and their practical significance in groundwater management. *Journal of Hydrology*, 608:127–630.

Tabiri, M. O. (2015). Perennial problem of floods in accra: what is the way forward? *International Journal of Advanced Research in Education and Technology*, 2:198–201.

Tasantab, J. C. (2019). Beyond the plan: how land use control practices influence flood risk in sekondi-takoradi. *Jàmbá: Journal of Disaster Risk Studies*, 11(1):1–9.

Van Vliet, M. T., Jones, E. R., Flörke, M., Franssen, W. H., Hanasaki, N., Wada, Y., and Yearsley, J. R. (2021). Global water scarcity including surface water quality and expansions of clean water technologies. *Environmental Research Letters*, 16(2):024020.

Wijnen, M., Augeard, B., Hiller, B., Ward, C., and Huntjens, P. (2012). Managing the invisible: Understanding and improving groundwater governance. Water papers, World Bank.

Williams, R., Raji, M., Gill, J., Olaka, L., Omuombo, C., Odhiambo, C., and James, H. (2023). A roadmap to strengthen geoscience education for sustainable development in kenya. In *EGU General Assembly Conference Abstracts*, pages EGU–14209.

Wolman, A. (2022). Salud y medio ambiente. *Revista de La Facultad de Medicina*, 65(3):8–18.

Yidana, S. M. and Chegbeleh, L. P. (2013). The hydraulic conductivity field and groundwater flow in the unconfined aquifer system of the keta strip, ghana. *Journal of African Earth Sciences*, 86:45–52.

Yiridomoh, G. Y. (2021). “illegal” gold mining operations in ghana: Implication for climate-smart agriculture in northwestern ghana. *Frontiers in Sustainable Food Systems*, 5:479.

Zobrist, J., Sima, M., Dogaru, D., Senila, M., Yang, H., Popescu, C., Roman, C., Bela, A., Frei, L., Dold, B., and Balteanu, D. (2009). Environmental and socioeconomic assessment of impacts by mining activities-a case study in the certej river catchment, western carpathians, romania. *Environmental Science and Pollution Research*, 16(1):14–26.