

REVIEW

Urban Geology: Challenges and Opportunities in Rapidly Expanding Cities

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ABSTRACT

The study of geological materials, processes, and groundwater systems in relation to the built environment is known as urban geology and is growing in significance as the surface area of cities and their subsurface complexity continue to expand rapidly. This is a review of the existing knowledge on the geological nature of urban settings and the assessment of the obstacles and opportunities presented in fast-growing cities. Cities also tend to cover a wide range of different sedimentary sequences and altered topography, as well as have a large amount of artificial substrate that makes stratigraphy difficult to understand, geotechnics difficult to predict, and hydrogeology harder to connect. Rapid urbanization may increase geohazards, such as landslides, floods, seismic shaking impact, sinkholes, and land subsidence caused by groundwater extraction. Simultaneously, urbanization stresses groundwater resources and predisposes them to long-term contamination in the underground, which is determined by the heterogeneity of geological formations and the historical background of infrastructure. The review emphasizes the role of urban geology in reducing risk via hazard zonation, site characterization and monitoring, and sustainable development via geology-informed land-use planning, resilient infrastructure design, and strategic control of the use of subsurface space for transport, utilities, and to develop low-carbon energy resources like geothermal systems. The solution to the urban underground data problem is greatly enhanced by progress in remote sensing, near-surface geophysics, and 3D geological modeling, but cannot be effectively adopted due to gaps in data, fragmented governance, and a lack of cross-disciplinary integration. In order to achieve safer and more sustainable cities, there is a

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ARTICLE INFO

Received: 26 February 2026 | Revised: 26 April 2026 | Accepted: 30 April 2026 | Published Online: 19 May 2026
DOI: <https://doi.org/10.30564/jees.v8i5.13247>

CITATION

Xiao, F., 2026. Urban Geology: Challenges and Opportunities in Rapidly Expanding Cities. *Journal of Environmental & Earth Sciences*. 8(5): 185–199. DOI: <https://doi.org/10.30564/jees.v8i5.13247>

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need to strengthen urban geological databases, policy frameworks, and capacity building.

Keywords: Urban Geology; Artificial Ground; Geohazards; Groundwater; Subsurface Planning

1. Introduction

The process of urbanization is one of the most dramatic and fastest changes on the surface of the earth in the twenty-first century. This statistical evidence has shown that over half the world population now lives in cities, and that it is expected to keep growing at a pace that is even in the developing and emerging economies. For the purposes of this review, “rapidly expanding cities” are defined as urban agglomerations experiencing annual population growth exceeding 2.5% or land consumption rates surpassing 3% per decade, based on UN-Habitat and World Bank classifications. Four typological dimensions are distinguished: (i) demographic scale, megacities (>10 million) versus mid-sized (1–10 million) versus emerging (<1 million); (ii) geographic setting, coastal (vulnerable to sea-level rise and saline intrusion), inland riverine (flooding and alluvial sediments), and arid/semi-arid (groundwater depletion); (iii) governance context, formal planned expansions versus informal/peri-urban settlements (where geological data are typically absent); and (iv) growth driver, industrial, administrative, or climate migration. This growth is not only horizontal or longitudinal, but also growing deeper and deeper underground, altering the natural landscapes, geological systems, and geodynamic processes on a new scale and scale never before seen. Cities are becoming increasingly in contact with the geological environment, and geology is an essential, although seldom represented, aspect of sustainable urban development^[1–3].

Urban geology is an interdisciplinary discipline that studies the relationships between geological processes, materials, and structures and the built urban environment. It includes the investigation of natural geologic settings, including bedrock, soils, groundwater, and geohazards, and artificial modifications, including artificial ground and excavations, land reclamation, and underground infrastructure. In contrast to traditional geology, which may be preoccupied with relatively undisturbed natural systems, urban geology deals with complicated, highly altered environments in which natural and human-made processes co-exist and interrelate. This complexity sets considerable challenges and specific

opportunities for scientific research and practical implementation^[4].

The booming urban areas exert more and more pressure on geology. Comprehensive land-use modification alters both surface and subsurface environments, disturbs the natural drainage pattern, and changes the sedimentary and geochemical cycle. Another implication of large-scale construction works such as high-rise buildings, transportation systems, and underground systems is the significant loading of the ground and the need to have an in-depth insight into the subsurface. Simultaneously, the increase in water, energy, and raw material needs contributes to exerting pressure on the geological resources, which frequently results in the depletion of groundwater, land subsidence, and the worsening of the environment. They are especially acute in the megacities and urban areas with rapid development, when planning and regulatory frameworks might not be able to keep up with the development^[5,6].

The geological hazards are a major threat to the human population and infrastructure. Urbanization can further increase the exposure of cities to earthquakes, landslides, flooding, coastal erosion, and sinkhole formation, which are all dangerous in nature. Human and economic concentration increases the possible impact of such events and makes geological processes a serious socio-economic risk. Climate change further increases these risks since it changes the way precipitation changes, sea level, and the occurrence of extreme weather, thus compounding human interactions between geology and cities. The mitigation and understanding of such hazards involve sound geological knowledge incorporated in urban planning, engineering design, and risk management^[7].

Although geology is a very critical subject, it is often not applied in decision-making in cities. Urban development has commonly been economically, politically, and socially motivated, with geological constraints dealt with in a reactive manner, such as when the structure fails or when there is an environmental disaster. Comprehensive geological information in most cities, and specifically in the fast-urbanizing areas, is incomplete, outdated, or unavailable to planners and

policymakers. Where there is data, there may be communication barriers with the geoscientist, engineer, urban planner, and decision maker to their successful use. Consequently, urban areas can be built in geologically unsound locations, which can make them more susceptible in the long term and more expensive to maintain^[8].

Simultaneously, the fast-growing cities provide great opportunities for developing urban geology. Urban environments are a human-earth system interaction on a massive scale and are real-world laboratories. The development of geospatial technologies, remote sensing, geophysics, and data integration has increased the possibilities to describe the conditions of the urban subsurface in finer detail and more accurately. The latest trends of increasing focus on sustainable development, resilience, and climate adaptation have provided new geological requirements for urban policy and planning. The idea of nature-based solutions, resilient infrastructure, and smart cities is becoming more and more dependent on geological insights in the optimization of land use, resource management, and mitigation of risks^[9].

One of the more significant urban geological frontiers is the subsurface. The surface space is becoming unavailable, and cities are growing downwards in an attempt to support transportation systems, utilities, energy storage facilities, and waste disposal facilities. Subsurface space is an area that should be carefully examined in terms of geological conditions, hydrogeological regimes, and long-term geomechanical behavior in order to be used sustainably. Urban geology offers the scientific justification in the form of balancing the competing subsurface applications; reducing the environmental impact, and also reducing pollution and loss of human lives. Also, cities have major secondary resources, including building materials and geothermal energy, which can be integrated into the strategies of the circular economy when managed correctly^[10,11].

The purpose of this review is to synthesize the existing body of knowledge on urban geology within the framework of rapidly growing cities and discuss all the challenges and opportunities presented by it. It explores the geological peculiarities of the urban setting, the major threats and limitations of faster urban development, and how geological knowledge can contribute to sustainable and resilient urban development. This article attempts to discuss the importance of urban geology in tackling modern challenges faced by the

urban environment by combining geological, engineering, environmental science, and urban planning^[2,12].

The structure of the review is organized as follows. **Figure 1** presents a conceptual framework linking natural geological conditions, anthropogenic modification, and the resulting risks and opportunities that define urban geology in rapidly expanding cities. Section 2 presents the geological properties of the urban settings, including the natural and artificial elements. Section 3 provides an examination of the key issues of rapidly growing cities and focuses on the geohazards, resource management, and risks connected with climate. Section 4 will discuss opportunities and how urban geology can be applied in planning, reducing risks, and sustainable use of resources. Lastly, Section 5 makes conclusive remarks and points to the main research gaps and future directions. In this synthesis, the review highlights the need to have geological knowledge incorporated in the urban development strategies to aid in safer, more resilient, and sustainable cities^[13–15].

2. Geological Characteristics of Urban Environments

2.1. Natural Geological Framework of Cities

Regional tectonic location, lithology, geomorphology, and hydrogeological regime are the main factors that control the geological basis of a city. A lot of large cities have traditionally been built along rivers, coasts, or along plains, which are tectonically stable, and thus settlement was concentrated where water, fertile soil, and transport networks were favorable. This leads to the common overlays of sediments, which in urban areas are very unconsolidated and could either be alluvium, deltaic, or coastal sands, which do not have the same mechanical and hydraulic characteristics as the underlying bedrock. These are the geological natural environments that directly impact the formulation of urban development due to their impact on the stability of the ground, the ground-bearing capacity, the availability of groundwater, and the vulnerability to geological hazards^[1].

The long-term mechanical behavior of the subsurface is established through bedrock geology, which involves how it responds to building and other infrastructure loading. Competent rock units are typically hard and offer good conditions

for foundations and underground constructions, but weak or highly fractured rocks can be a problem of deformation, inflow of water, and instability. Thick layers of unconsolidated sediments, on the contrary, tend to settle and compact,

especially under anthropogenic loading or groundwater deposition. Knowledge of the variance of such materials in space is therefore critical to safe and cost-effective urban growth.

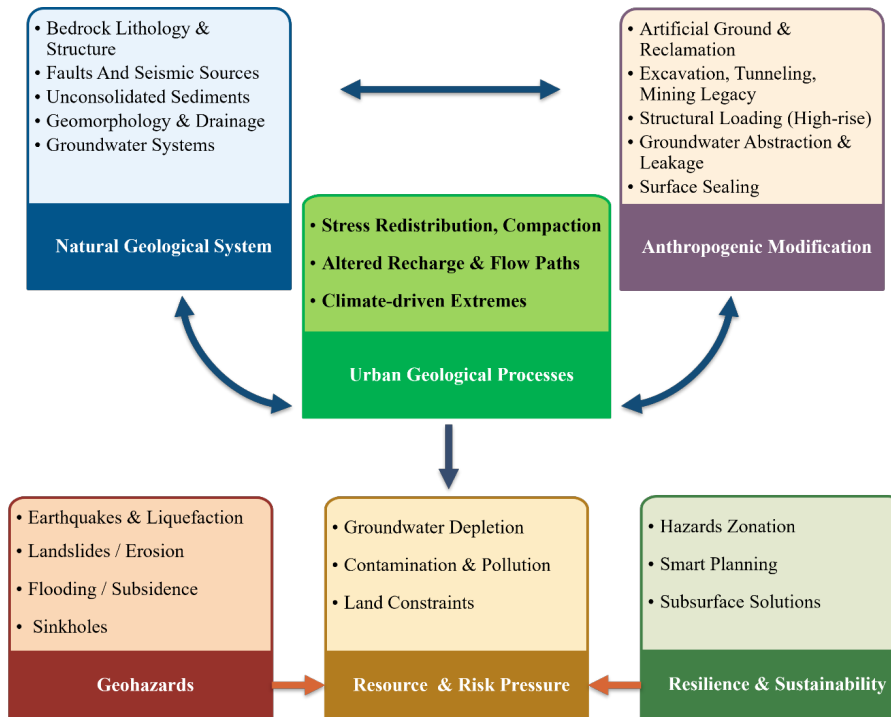


Figure 1. Conceptual Framework of Urban Geology in Rapidly Expanding Cities.

Urban geomorphology is manifested in natural landforms, which are inherited, and those that have been modified by human activity. Even with high levels of urbanization, hillslopes, floodplains, terraces, and coastal features have an impact on drainage patterns and hazard exposure. The steep slopes, reclaimed land, or flood plain areas in cities that are rapidly growing in population are the areas in which construction usually takes place, which puts a high value on the geomorphological evaluation. These features are also important in the transportation of sediment, erosion, and the interaction of surfaces and the subsurface, influencing the stability of the urban structure and the quality of the environment^[16].

2.2. Urban Stratigraphy and Anthropogenic Deposits

The anthropogenic deposits, also known as the artificial ground, are one of the most peculiar aspects of urban geological settings. Construction fill, demolition waste, reclaimed

land, and reworked natural sediments, which have been deposited or altered by human activity, are all represented by these deposits. The urban stratigraphy is thus generally very complex, heterogeneous, and highly variable at short distances, and it represents various periods in the development and land-use change.

Artificial ground may be a wide range of different compositions, densities, and engineering characteristics, and is not always as consistent as natural geological formations. Poorly compacted fill material can experience long-term settlement, and buried debris and organic matter can decay or collapse, resulting in ground instability. The historical records of land reclamation and infilling in most old cities are not complete, and it is hard to precisely define the nature of the subsurface unless the area is examined in detail. Such uncertainty is a major challenge to foundation design and underground construction, as well as infrastructure maintenance^[17].

Successive stages of human adjustment are usually

characterized by stark contrast between natural and anthropogenic strata in urban stratigraphy. The contrasts may impact groundwater movement, movement of contaminants, and geotechnical behaviour. The identification and mapping of artificial ground as a formal stratigraphic unit has been a significant addition to the geological study of contempo-

rary cities, which allows better reflection of the underground conditions and enhances the use of geological information in urban planning procedures^[1,18,19]. Collectively, the main geological elements that are found in urban areas and the meaning of these elements in the planning, engineering, and environmental aspects of them are summarized in **Table 1**.

Table 1. Core Components of Urban Geology and Their Engineering and Environmental Significance.

Urban Geological Component	Typical Urban Expression	Why it Matters in Rapidly Expanding Cities	Common Indicators/Datasets
Bedrock geology	Fractured rock, weathered profiles, fault zones	Controls foundation behavior, excavation stability, seismic site response	Geological maps, boreholes, structural mapping, seismic refraction
Unconsolidated sediments	Alluvium, deltaic clays, coastal sands	Settlement potential, liquefaction susceptibility, groundwater storage	CPT/SPT logs, grain-size, geophysics, hydrostratigraphy
Geomorphology	Floodplains, terraces, slopes, coastal barriers	Governs flooding, erosion, slope instability, drainage pathways	DEMs, geomorphic mapping, remote sensing
Artificial ground	Fill, reclamation, demolition debris, made ground	Heterogeneity drives differential settlement and uncertainty	Historical land-use, geotechnical reports, GPR, utility records
Urban soils (technogenic soils)	Mixed/compacted soils, altered horizons	Reduced infiltration, contamination storage, ecosystem constraints	Soil surveys, geochemistry, permeability tests
Groundwater system	Altered recharge, leakage, pumping cones	Subsidence, flooding, contaminant transport	Piezometers, pumping records, water chemistry, isotope tracers

2.3. Urban Soils and Geochemical Alterations

The urban soils vary significantly compared to the natural soils because of excavation, mixing, compaction, and contamination. Original soil profiles in most cities have been cut off or even eliminated and replaced by technogenic soils, which record human activities in lieu of natural processes of pedogenic development. These soils are usually characterised by changed physical and chemical characteristics such as low permeability, high bulk density, and a higher level of pollutants.

The combination of industrial emissions and traffic-related pollutants, construction materials, and waste disposal practices causes geochemical changes in the urban environment. Accumulation of heavy metals, hydrocarbons, and other contaminants in soils and sediments is harmful to human health and the ecosystem. These contaminants are highly associated with land-use history, geology, and hydrology, with an essential focus on the combined geological and environmental evaluations.

Urban soils are also very important in the regulation of surface water infiltration, vegetation support, and mediation of interactions between the surface and subsurface. Poor soil structure and diminished infiltration ability may enhance surface runoff and flooding, especially during heavy rainfall. It

is important to note that to manage stormwater, design green infrastructure, and restore urban ecosystems, it is important to understand the geological and geochemical properties of urban soils^[20–22].

2.4. Groundwater Systems in Urban Areas

The urban geological environment is one of the important elements of the environment, supplying water, controlling the subsurface environment, and affecting the geotechnical stability. Urbanization brings dramatic changes to the natural groundwater systems by covering the surface with impermeable material, creating artificial drainage systems, and abstraction. Such changes may interfere with recharge, alter groundwater flow patterns, and alter hydraulic gradients^[4,23].

In urban centers that have fast growth rates, the most common cause of ground subsidence is the extraction of groundwater, especially where the ground is composed of compressible sediments. The buildings, roads, and underground infrastructure can also be damaged by subsidence, and in the long run, this will have an economic and social cost. On the other hand, in certain urban areas, the decline in industrial groundwater consumption has caused the groundwater to rise and, therefore, endanger the basement and struc-

tural degradation. Both situations demonstrate that the city's groundwater systems are dynamic and complicated.

The quality of groundwater is also a significant issue in urban areas. Sewers, industrial locations, landfills, and polluted soils may serve as a source of consistent pollution. The transport and attenuation of contaminants is highly dependent on the geological heterogeneity aspect of the presence of low-permeability layers or preferential flow paths. Good groundwater management thus needs a high level of geological characterization, along with constant monitoring and adaptive management^[24].

2.5. Methods for Investigating Urban Geological Conditions

An urban geological environment is characterized based on the integration of both conventional geological methods and new technology. The data of boreholes, geological mapping, and geotechnical studies are still considered as the main sources of information, yet they can hardly be utilized in the urban setting because of limited accessibility and great cost. This has led to the increasing reliance of urban geology on the incorporation of a wide variety of datasets to obtain a complete picture of the subsurface.

Non-invasive techniques of imaging subsurface structure and determining areas of weakness or heterogeneity include geophysical techniques, including seismic surveys, electrical resistivity, and ground-penetrating radar. The concepts of remote sensing and geographic information systems allow for the examination of surface features, changes in land use, and geomorphological processes at varying scales. The development of three-dimensional geological modeling has developed the capacity to visualize and communicate complex underground urban states to non-specialist stakeholders^[25].

Geologists, engineers, planners, and policymakers should work closely together in order to effectively investigate the geological conditions of the city. The sharing of data, standardized mapping of the man-made ground, and the creation of accessible urban geological databases are progressively accepted as the constituent elements of sustainable urban management. These methods give the issue of rapid urban growth a critical basis by enhancing the knowledge of the geological properties of the areas under cities, and therefore, offering solutions to the challenges and opportunities

presented by such growth^[26,27].

3. Challenges in Rapidly Expanding Cities

3.1. Urban Geohazards and Risk Amplification

Blistering urban development is one of the factors that influence the natural balance of geological systems and often result in excessive and more frequent geohazards. Cities accumulate populations, infrastructure, and economic resources in fairly small territories, which increases the scope of possible effects of geological processes. The threat of earthquakes, landslides, flooding, coastal erosion, and sink-hole formation is especially dangerous within urban areas, where even the occurrence of a moderate earthquake will cause disproportionate damage and loss^[28].

These hazards may be increased by urban development, by altering the natural landforms and underground conditions. Construction can cause destabilization of hillsides and landslides, especially where weak or weathered material forms the underlying base, excavation, slope cutting, and loading. Land reclamation and channelization in floodplains and coastal areas can increase flood risk by reducing natural storage capacity and altering sediment dynamics. Local geological situations also determine seismic risk since unconsolidated ground and artificial underground can enhance the magnitude of the ground movement, exposing structures and infrastructure to greater susceptibility.

The ambiguity in characterizing hazards and assessing risk increases the challenge of managing urban geohazards. The incomplete history records, geological heterogeneity, and inadequate monitoring networks can be barriers to the proper prediction of hazard behavior. With the development of cities, which are growing very fast, planning is usually done reactively instead of taking preventive measures against the hazards, since the information on the geological aspects of the area is not available to individuals^[29-31].

3.2. Ground Instability, Subsidence, and Deformation

In numerous rapidly developing cities, the problem of ground instability is an omnipresent issue that can be caused by geological factors as well as human actions. The load-

ing of compressible soils, the existence of a heterogeneous artificial ground, and the variation of groundwater levels may cause settlement and deformation of the ground. These processes can evolve with time, and hence, they can hardly be noticed until substantial damage has been caused^[32].

One of the most common urban ground deformations is land subsidence associated with groundwater extraction. In sedimentary basins, which are made of deposits with a high clay content, pumping over time may cause irreversible compaction, causing urban districts to settle differently. Subsidence may undermine the integrity of structures, the transport infrastructure, and drainage systems, and at the same time augment flood exposure in low-lying regions. In coastal urban areas, subsidence along with the rise in sea

level is particularly dangerous to the resilience of the urban area.

Collapse as a part of karst processes, degradation of abandoned underground workings, and long-term settlement of ill-conceived fill materials are other types of ground instability. These hazards need comprehensive knowledge of the conditions of the subsurface and the development with time in order to identify and manage them. In most cities, however, legacy information is disjointed or unavailable, which constrains the success of mitigation measures^[1,33]. To make it clearer, the geohazards prevailing in urban areas, the geological mechanisms controlling them, how urban development increases their risk, and the most common methods of mitigating the problem are summarized in **Table 2**.

Table 2. Major Geohazards in Rapidly Expanding Cities: Mechanisms, Urban Amplifiers, Impacts, and Mitigation Options.

Hazard	Dominant Geological Controls	How Rapid Urbanization Amplifies Risk	Typical Impacts in Cities	Common Mitigation/Management Approaches
Earthquake ground shaking & site effects	Sediment thickness, Vs30, basin geometry, fault proximity	Dense exposure; poor code compliance; variable artificial ground	Structural damage; lifeline failure	Microzonation, seismic codes, retrofit programs
Liquefaction	Saturated sands/silts, shallow groundwater	Reclamation, rising groundwater, poor compaction	Tilting, settlement, utility rupture	Ground improvement, drainage, foundation redesign
Landslides	Slope angle, weak strata, weathering, discontinuities	Slope cuts, loading, vegetation removal, storm runoff	Road/rail disruption; casualties; property loss	Slope stabilization, zoning, drainage control, monitoring
Flooding (river/urban pluvial)	Floodplain geomorphology, soil infiltration, channel capacity	Impervious cover, constrained waterways, loss of storage	Inundation; contamination mobilization	Flood zoning, retention basins, green infrastructure, early warning
Land subsidence	Compressible sediments, aquifer-system compaction	Intensive groundwater pumping; high-rise loading	Differential settlement; flood exposure	Pumping controls, managed aquifer recharge, InSAR monitoring
Sinkholes/karst collapse	Carbonate dissolution, cavities, fluctuating groundwater	Leaking pipes, dewatering, concentrated loads	Sudden collapse; infrastructure failure	Ground investigation, grouting, water management, risk zoning

3.3. Groundwater Depletion and Quality Degradation

The high rate of urbanization puts so much pressure on the groundwater supplies that the amount extracted seems not to be sustainable. Groundwater is a valuable source of domestic, industrial, and agricultural water in most cities, especially where there is a shortage of surface water supplies or even unpredictability. Excessive use may cause a drop in the water table, decreased water flow into rivers, and lead to poor quality of dependent ecosystems, which have long-term environmental and socio-economic implications^[34].

The degradation of the quality of groundwater is also a

very serious challenge. In urban areas, there are sophisticated sources of contamination, such as industries, fuel facilities, dumping grounds, and dilapidated sewage systems. The concentration of pollutants can remain in the underground for decades and move through complex geological routes, posing a risk to drinking water sources. Cleaning up the contaminated groundwater is very technical, expensive, and time-consuming, especially when it is found in crowded built environments where access is limited. The extreme weather conditions and climate variability contribute to more problems in managing urban groundwater. Extensive droughts may put a strain on the underground water supply, whereas heavy precipitation can move the contaminants or fill the

drainage channels, which subsequently causes the entry of contaminated water into the aquifers. These antagonizing forces emphasize the importance of combined geological and hydrological approaches in addressing groundwater management of fast-growing urban areas^[35–38].

3.4. Engineering Geology Conflicts in Dense Urban Settings

The boundary between engineering and geology is growing more complicated with the growth and thickening of urban areas, both vertical and underground. The high-rise buildings, deep foundations, tunnels, and underground facilities put a high burden on the geological environment, and the precise characterization of the ground conditions and long-term behaviour is necessary. Time and financial limitations in the rapidly growing urban centres might restrict the amount of geological research, leaving more chances of unexpected issues associated with the ground^[1].

Conflict between engineering and geology is usually caused by the differences between design assumptions and the reality of the subsurface conditions. Delays in construction, cost increases, and hazards may be experienced due to the geological heterogeneity, the existence of artificial ground, and surprising groundwater inflows. Subsurface construction is a business that is very sensitive to this sort of uncertainty because even a small change in lithology or structure can result in a big effect on stability and water control.

The combination of several projects in the constrained urban space adds to these difficulties. Connections between neighboring foundations, tunnels, and underground utilities may cause a change in stress patterns and groundwater flows, causing complex interactions that would not be predictable. To overcome these problems, it is necessary to not only investigate the specific sites but also the geological structures of cities that will assist in organizing planning and design^[39].

3.5. Climate Change and Emerging Geological Risks

Climate change is becoming an important issue that determines urban geological challenges. Evolution in the strength of precipitation, temperature, and sea level has a direct impact on geological processes that form the basis

of urban stability^[40]. Heavy rains may also lead to more common and severe instances of erosion, landslides, and amplified floods, especially in places that have been altered in their drainage systems and surfaces that are impermeable.

In coastal urban areas, the increase in sea level and storm surges increases their interaction with the urban geology and marine processes. Intrusion of saline waters into the coastal aquifer, erosion of recovered lands, and disruption of coastal sediments have become increasingly threatening to infrastructure and water supply. They can normally interact with underlying geological weaknesses, including soft sediments and subsidence, and increase their effects^[41].

There are also new uncertainties brought by climate change to long-term urban planning. Geological environments that were once seen as stable can change under new climatic regimes and disrupt the traditional design criteria and risk evaluations. The inclusion of climate forecasts in urban geological research is still a major methodological and institutional dilemma, but it is a must in improving the resilience of fast-growing cities^[42].

3.6. Data Limitations and Governance Challenges

One of the basic problems of resolving urban geological problems is associated with the data availability, quality, and access. In most urban centers that are rapidly growing, the information on geology is sparse, old, or gathered to support solitary projects without an amalgamation into an urban system. The lack of standardized data management systems inhibits the possibility of constructing overall subsurface models and also evaluating cumulative effects at the city level.

Additional barriers to the application of geological knowledge include governance and institutional barriers. Land use, infrastructure, water management, and hazard mitigation responsibilities are frequently spread between different agencies and create incoherent decision-making. Even in cases where the geological information exists, gaps between geoscientists, planners, engineers, and policymakers may lead to poor usage of geological information.

To overcome these difficulties, technical solutions are not sufficient, but institutional innovation is also needed. Inclusion of urban geology in the planning regulations, establishment of common data platforms, and encouragement

of interdisciplinary cooperation are necessary steps to handling the geological threat in rapidly growing cities in a more efficient way. By solving scientific and governance-related challenges, cities would be in a better position to predict and manage the geological problems related to sudden urban development^[43].

4. Opportunities and Applications of Urban Geology

4.1. Geological Input to Urban Planning and Land-Use Management

Urban geology provides a scientific platform of knowledge on which urban planning and land-use decisions rely. Geological evaluations are able to inform the spatial arrangements of urban growth, as well as avoid exposure to risks by determining geological constraints and opportunities at an early stage. The planners with geological maps, subsurface models, and hazard zonation can be equipped with the necessary data on ground stability, the vulnerability to floods, and also the availability of resources, and develop strategies for development that will be more consistent with the natural environment^[44].

The use of geological information in the planning process in fast-growing cities can assist in preventing construction in areas that are unsuitable due to geological conditions, such as unstable slopes, floodplains, or areas that can be subjected to subsidence. In cases where development cannot be avoided in such locations, urban geology assists in designing the right mitigation measures and adaptive land-use approaches. This active intervention is in contrast to the conventional reactive measures to geological issues and may allow saving much in the long-term economic and social expenses.

The city level of the application of urban geology also allows the planning of infrastructure networks and transportation corridors, as well as green spaces. The attainment of more balanced and resilient patterns of urban growth that are sensitive to both surface and subsurface restrictions can be achieved by considering geological conditions as well as social and economic aspects by urban planners^[45]

4.2. Risk Reduction and Urban Resilience Building

The reduction of geological risk and increase in urban resilience are two of the most crucial uses of urban geology. Geological evaluations are used to determine, estimate, and control hazards that include earthquakes, landslides, floods, and ground deformation. Zoning rules, when applied to building codes and emergency planning, provide a direct contribution to the safety of lives and property, with geological knowledge being a part of it.

The idea of urban geology facilitates resilience because cities can predict the effects of extreme events and can design infrastructures to withstand geological pressure. Engineering solutions using site-specific studies and area hazard models are based on the local conditions of the ground, whereas long-term monitoring of ground processes results in adaptive management when the situation changes. Such strategies are especially useful in situations of climate change when past trends cannot be trusted as predictors of risk in the future.

Urban geology also helps in social and institutional resilience, in addition to physical protection. The effective communication of geological dangers and uncertainties assists in creating awareness among the people and enhances informed judgment by the stakeholders. Through the integration of geological knowledge into city governance systems, cities can enhance their ability to react to both immediate disasters and gradual geological alterations^[46].

4.3. Sustainable Use of Subsurface Space

With surface space becoming more limited, the urban subsurface is offering a significant source of infrastructure and services necessary in contemporary cities. Urban geology is a scientific foundation for the sustainable development of the underground space, which includes transportation tunnels, utility corridors, energy storage facilities, and waste management systems. The geological factors that determine the suitability of the subsurface for such uses are the strength of rocks, fracture patterns, groundwater conditions, and long-term geomechanical behaviour. **Table 3** gives a screening summary of frequently used applications in the subsurface, depth ranges of application, requirements based on geology, and major risks^[47,48].

Table 3. Subsurface Urban Functions and Geology-Based Suitability Considerations.

Subsurface Use	Typical Depth Range (Indicative)	Geological Requirements	Main Geological/Hydro-geological Risks	Suitability Screening Criteria
Metro/road tunnels	10–50+ m	Predictable strata, manageable groundwater, stable rock/soil	Water inflow, face instability, settlement at surface	3D geology model, groundwater regime, stiffness contrasts
Utility corridors	1–10 m	Excavatability, limited contamination, shallow stability	Differential settlement, corrosion environment, utility clashes	Artificial ground mapping, contamination screening, service density
Deep foundations	Variable	Competent bearing layers or rockhead accessibility	Pile refusal variability, scour, negative skin friction	Rockhead map, compressibility profile, groundwater trends
Underground storage (water/energy)	Variable	Low-permeability confining units or engineered containment	Leakage pathways, uplift pressure, induced deformation	Hydrostratigraphy, permeability anisotropy, stress regime
Geothermal (shallow)	20–300 m	Thermo-hydro suitability, heat conductivity, stable groundwater	Thermal interference, groundwater contamination pathways	Thermal properties, aquifer sensitivity, spacing guidelines
Stormwater infiltration systems	1–5 m	Permeable soils, clean vadose zone, safe groundwater separation	Mobilization of contaminants, clogging	Infiltration tests, soil geochemistry, groundwater protection zones

Subsurface space strategic planning needs a combined knowledge of the competing uses of subsurface space and conflicts. Urban geology facilitates this procedure through the capacity to provide three-dimensional descriptions of the subsurface environment and the evaluation of the aggregate effects of numerous underground buildings. This is a holistic view of the subsurface that ensures that subsurface functions are not interfered with and there is minimal possibility of unexpected geological or environmental effects.

Besides infrastructure, the subsurface has the potential of providing low-carbon energy sources, such as shallow geothermal power systems and underground thermal storage. Such technologies have the potential to serve the sustainability of urban interests when properly oriented by good geological assessment and the reduction of risks to the environment. The concept of urban geology, therefore, plays a key role in realizing the potential of the subsurface as a useful and multifunctional resource of the urban environment^[49].

4.4. Urban Georesources and Circular Economy Approaches

Cities hold important geological reserves that can be utilized to make the cities more sustainable and circular economies. Construction and infrastructure projects leave excavated materials, which can be reused or recycled as aggregates and fill, and therefore, less primary natural resources are used, and also waste is minimized. Urban geology gives the guidelines on how to determine the quality, quantity, and

appropriateness of these secondary resources.

Identification and management of urban georesources involve a lot of knowledge on both natural geology and anthropogenic deposits. Geological characterization assists in identifying materials that can be reused and those that are potentially dangerous to the environment or that are potentially harmful to engineering. Through the realization of georesource measurements in urban development, cities will be able to minimize material transportation, decrease the amount of greenhouse gas emissions, and encourage the efficient utilization of the existing local resources^[50].

Urban geology helps to manage the sustainable usage of groundwater and geothermal resources, which are becoming considered as the major parts of urban resilience and energy transition strategies. Geological knowledge can be used to make the city less geographically limited and more dynamic to achieve long-term sustainability when correlated with the principles of the circular economy^[51].

4.5. Technological Advances and Data Integration

The current technological developments have provided immense possibilities for using urban geology in the fast-developing urban centers. In urban settings, the processes in geology can be observed in much detail and continuously by means of high-resolution remote sensing, geophysical imaging, and sensor networks. Such instruments can further improve the skills of identifying ground deformation,

tracking groundwater processes, and evaluating the effects of urban development in almost real-time.

The use of geological data in digital systems and 3D representations of cities has enhanced communication between geoscientists and other non-expert stakeholders. Planning and engineering databases can be connected to urban geological models to facilitate the analysis of scenarios and

evidence-based decision-making. All the most common data sources and investigative techniques, along with their advantages, weaknesses, and their most appropriate uses in urban settings, are summarized in **Table 4**. This integration is especially useful in urban environments where several projects and processes are interconnected in a limited space^[25,52,53].

Table 4. Data and Methods for Urban Geological Characterization: Strengths, Limitations, and Best-Fit Applications.

Method/Data Source	What it Resolves Best	Typical Resolution/Scale	Strengths in Cities	Common Limitations	Best-Fit Applications
Boreholes & geotechnical logs	Stratigraphy, strength parameters	Site to corridor scale	Direct ground truth; engineering relevance	Sparse, expensive, inconsistent metadata	Foundations, tunneling design, calibration of models
CPT/SPT & in situ testing	Soil behavior, liquefaction metrics	Site scale	Quantitative, comparable metrics	Limited in coarse/very hard strata	Seismic microzonation inputs; settlement estimates
Near-surface geophysics (ERT, MASW, GPR)	Layering, stiffness, voids, utilities	Site to neighborhood	Non-invasive; fills gaps between boreholes	Interpretation uncertainty in noisy urban settings	Artificial ground mapping; sinkhole screening
Remote sensing (LiDAR, optical)	Surface morphology, change detection	City scale	Rapid coverage; repeated observations	Limited direct subsurface sensitivity	Geomorphology, drainage, slope mapping, land-use change
InSAR deformation mapping	Subsidence/uplift patterns	City to regional	Time-series deformation monitoring	Needs coherence; interpretation requires context	Pumping-related subsidence; construction impacts
3D geological / hydrogeological models	Integrated subsurface understanding	City scale	Communication tool; scenario testing	Data-hungry; requires governance/data standards	Planning, subsurface zoning, cumulative impact assessment

Despite these advances, the effective use of technology depends on institutional capacity and data governance. An integrated workflow linking data acquisition, 3D subsurface modeling, risk and resource assessment, and planning-oriented decision support is summarized in **Figure 2**. Urban geology is most effective in situations where technological

tools are integrated into collaborative systems that facilitate data sharing, standardization, and sustainable maintenance. Cities can be more resilient to the management of geological challenges and the opportunity of using emerging opportunities by relying on technological innovation and combined data systems^[54].

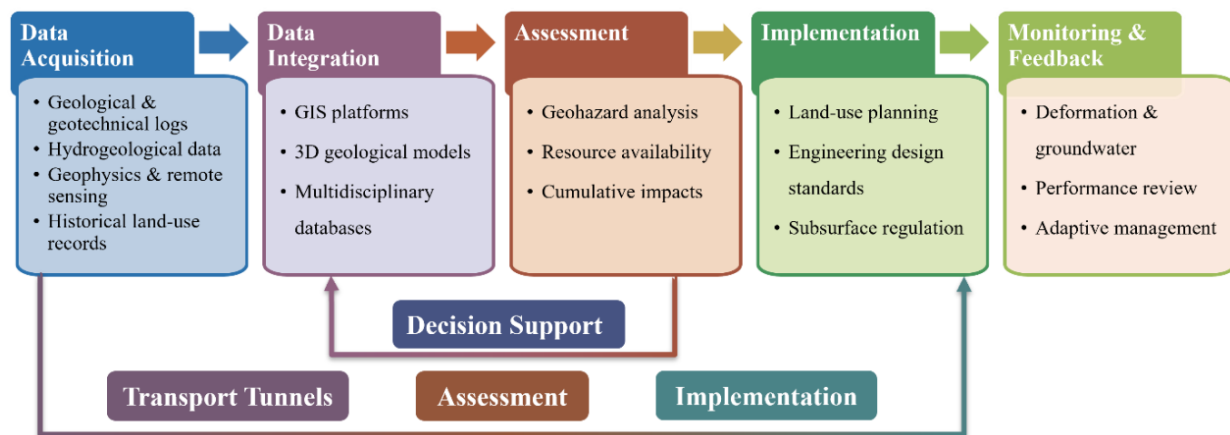


Figure 2. Workflow for Integrating Urban Geology into Resilient City Planning and Management.

4.6. Education, Policy Integration, and Capacity Building

Institutional and human capacity development is what eventually determines whether urban geology is successful or not. Training and educational programs with more interdisciplinary skills are required in order to train geoscientists to be effective in urban environments. Simultaneously, more geological awareness among decision-makers, planners, and engineers can enhance the adoption of geological knowledge in decision-making.

Policy integration is another significant source of improving the role of geology in urban development. The introduction of geological evaluations to the planning regulations, environmental impact evaluations, and infrastructure requirements can institutionalize the factor of taking into account the subsurface conditions and geological risks. These policies offer a regular structure for implementing geological expertise in various industries and levels. Capacity building is also applicable in community involvement and communication with society. Cities should bring geological information closer to city dwellers by making information interesting and applicable to citizens, to create more awareness of geological hazards and resources. This expanded concept enhances more accommodating and stronger urban development, and affirms the worth of urban geology as the bedrock of a sustainable city plan^[55–57].

5. Conclusions

Urban geology has become one of the most important areas of interest to study and operate complex relations between the geological systems and growing cities. With the ongoing urbanization that is transforming the surface and subsurface of the earth, the geological circumstances are becoming a determining factor in the safety, functionality, and sustainability of the urban environments. The review has shown how natural geological structures, anthropogenic changes, and dynamics interact to produce the peculiarity of urban geological structures, as well as conditioning the risks and opportunities of contemporary cities.

Rapid urbanisation can increase geological difficulties by concentrating people and facilities in regions that are frequently covered by uneven and susceptible geological structures of the soil. Geohazards, ground instability, groundwater

depletion, and climate-related risks are not independent phenomena, but they interact with each other and change on both natural and human impact bases. The effects of poor geological consideration are often long-term in nature, and they appear in the form of structural damage, worsening of the environment, and socio-economic vulnerability. The solution to these obstacles needs to be a paradigm shift between the reactive approach to solving problems and the proactive approach to geologically-informed urban development.

Simultaneously, the fast pace of urban development provides important prospects for further development of geological knowledge. Urban geology offers the necessary instruments for land-use planning, mitigation of hazards, and sustainable utilization of underground space and resources. Geology can also make a direct contribution to the larger urban sustainability objectives by aiding resilient infrastructure design and facilitating circular economy approaches, as well as by informing climate adaptation efforts. The development in technology in data acquisition, modeling, and visualizing data has further advanced the ability to describe tricky urban underground situations and to incorporate geological data in decision-making.

Although this has been developed, there are still significant loopholes in bringing urban geology into policy and practice. Information constraints, institutional disintegration, and communication hurdles remain to restrict the utilization of geological data in most cities with high growth rates, especially in the developing world. To overcome these challenges, there should be concerted actions to enhance the availability of data, interdisciplinary partnerships, and the geological experience should be integrated into urban governance systems. Capacity building and education are also valuable so that specialists as well as decision-makers are able to interact with urban geological issues.

The current and upcoming studies of urban geology ought to aim at finding standard methods of describing artificial ground, an enhanced city-scale ground model, and integrating climate change forecasts into geological risk analysis. It will be necessary to focus more on monitoring and adaptive management in the long term to comprehend how urban geological systems change. It can also be beneficial to conduct related studies in various geographic and socio-economic settings to understand some of the best practices that can be transferred and the solutions specific to the situa-

tion.

To sum up, urban geology is a key concept in overcoming the challenges and seizing the opportunities inherent in the high rate of urban growth. The identification of the subsurface as a part of the urban system and the processes of planning and policy making can help cities to be more resilient, less prone to risk, and more likely to develop more sustainable developmental strategies. With the ongoing process of urbanization taking place at a faster pace all over the world, the relevance of urban geology will only grow, hence its significance in holding the key to the future of cities.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

All data were presented in the article.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

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