Seeing Cities in Depth: Subsurface Urban Expansion and the Case for Volumetric Monitoring and Accountability

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Abstract

Urban science can measure surface and aboveground change with increasing precision. Satellites, building-footprint datasets, and emerging three-dimensional products now track urban land, building height, and built volume. Yet these tools still struggle to capture urbanization below ground. This Perspective defines subsurface urban expansion as the extension of urbanization below the local ground surface through the creation, occupation, modification, and governance of underground volume for urban functions. Belowground systems support mobility, drainage, utilities, energy, storage, commerce, and service delivery. They can also create environmental impacts, carbon burdens, social exposures, spatial conflicts, and long-term liabilities that remain difficult to detect through surface-based monitoring. This mismatch is the underground monitoring gap: an observational, data-integration, and accountability problem. Existing underground-space research has shown that the subsurface is a strategic urban resource, while urban monitoring research has improved measurement of surface and aboveground change. The missing link is a framework that treats belowground urbanization as part of the measurable, governable, and publicly accountable city. Closing this gap requires volumetric urban monitoring supported by responsible visibility and directed toward volumetric accountability. Earth observation remains essential, but its value increases when connected with administrative, engineering, environmental, legal, and three-dimensional urban data. Sustainable urban monitoring must account for the full urban volume and make underground risks, responsibilities, and public-interest obligations visible enough to guide better decisions.

Keywords: subsurface urban expansion; underground space; urban monitoring; remote sensing; volumetric urbanization; sustainable infrastructure

1. Introduction: the surface bias in urban monitoring

Urbanization is often measured from above. Satellites detect roads, roofs, impervious surface, land-surface temperature, nighttime lights, and built-up land. These indicators support long-term comparisons of urban expansion and land consumption (Schneider et al., 2010; Seto et al., 2012). Newer datasets map building footprints and assess global building-data completeness (Herfort et al., 2023). Recent three-dimensional products estimate building height, building volume, future built-up volume, and simplified aboveground form (Che et al., 2024; Li et al., 2020; Zhao et al., 2025; Zhu et al., 2025).

This progress has made the vertical city more measurable. Yet most three-dimensional monitoring still focuses on what rises above ground. It captures the footprint and skyline, but not the systems below. Metro tunnels, deep basements, stormwater reservoirs, utility corridors, underground stations, and service networks reshape urban life while leaving little lasting signal in satellite products.

This limitation matters for sustainable infrastructure. Transit tunneling can create deformation risks, utility conflicts, construction disruption, and long-term maintenance obligations. Underground drainage can reduce flooding while creating dependencies on pumps, inspections, emergency access, and groundwater management. These changes are central to urban sustainability, yet they remain weakly represented in conventional indicators.

This Perspective calls this mismatch the underground monitoring gap. It has three layers: an observational gap, because most underground spaces cannot be directly observed from above; a data-integration gap, because information is scattered across permits, engineering records, utility maps, legal documents, and environmental sensors; and an accountability gap, because fragmented visibility makes it harder to assign responsibility, evaluate impacts, and protect public interest.

Existing underground-space research has shown that the subsurface is a strategic urban resource. Existing urban monitoring research has improved measurement of surface and aboveground change. The missing link is a monitoring framework that treats belowground urbanization as part of the measurable, governable, and publicly accountable city. This Perspective addresses that gap by defining subsurface urban expansion, explaining why current monitoring systems undercount belowground growth, and proposing a framework for volumetric monitoring and accountability.

2. Defining subsurface urban expansion

Subsurface urban expansion refers to the extension of urbanization below the local ground surface through the creation, occupation, modification, and governance of underground volume for urban functions. It includes newly excavated spaces and intensified existing systems when they expand urban function, dependency, environmental interaction, or governance responsibility. Intensification can include increased capacity, deeper use, added functions, greater infrastructure dependency, or expanded maintenance and safety obligations within existing underground systems.

Subsurface urban expansion is not limited to megaprojects. It can occur through the cumulative growth of basements, utility corridors, drainage systems, service networks, and underground commercial or transport spaces. It differs from horizontal and vertical urban growth because it can increase urban capacity, infrastructure dependence, environmental disturbance, and public responsibility without changing the visible footprint or skyline. It includes transport systems, basements, service corridors, storage facilities, drainage systems, energy systems, commercial spaces, deep foundations, utility networks, and modified subsurface resources such as groundwater, geothermal heat, geomaterials, and geological storage capacity (Doyle, 2016; Doyle et al., 2016; Li et al., 2013; Sterling et al., 2012).

Several pressures encourage downward growth: high land values, limited surface space, congestion, flood risk, aging infrastructure, and demand for resilient services. Underground space can stack functions within the same surface footprint when planned as part of the wider urban system (Li et al., 2013; Sterling et al., 2012). Metro systems can improve mobility. Stormwater and geothermal systems can support adaptation where local conditions allow (Bayer et al., 2019; Cui & Lin, 2016).

These benefits require careful assessment. The subsurface is finite, crowded, and environmentally active. It contains groundwater, heat flows, soil and rock systems, foundations, utilities, transit infrastructure, archaeological resources, and legal rights. One project can shape future options for decades. Subsurface urban expansion therefore needs monitoring and accountability.

3. Why current monitoring falls short

Urban remote sensing is strongest when change creates surface or aboveground signals. Built-up area, impervious surface, and nighttime lights depend on surface reflectance, surface materials, or emitted light. These indicators are widely used to map urban land cover and urbanization patterns (Goldblatt et al., 2018; Pesaresi et al., 2016; Zhang & Seto, 2013). Building-footprint and height datasets extend this monitoring into aboveground form (Che et al., 2024; Zhu et al., 2025).

These indicators are less effective for completed tunnels, basements, buried utilities, and underground networks. Such systems shape mobility, drainage, energy use, maintenance, and public safety, but often leave no persistent surface signal that common satellite products can map directly. This limitation is clearer now because urban monitoring has entered a three-dimensional phase. Global products can estimate building height and simplified aboveground form. Future urban 3D products can project aboveground built volume (Che et al., 2024; Zhao et al., 2025; Zhu et al., 2025). These advances show that cities are increasingly measured as volumes, while the belowground portion remains weakly measured in mainstream comparative monitoring.

Bobylev (2016) offers an important starting point through indicators such as developed underground volume, underground-space use density, and developed underground volume per person. These measures show that subsurface growth can be quantified. Their limited use in mainstream indicator systems reveals the central problem. Subsurface urbanization can be measured, yet it is rarely integrated into urban monitoring and governance.

Earth observation can still help. InSAR and related persistent-scatterer methods can monitor surface deformation (Crosetto et al., 2016). They have been applied to deformation from tunneling, dewatering, and urban excavation (Ramirez et al., 2022; Serrano-Juan et al., 2017; Wnuk et al., 2021). Optical, SAR, and thermal observations may also flag disturbance or heat-related change. These signals can reveal surface consequences of underground activity, but they do not identify underground extent, depth, function, ownership, maintenance status, or liability.

The deeper obstacle is fragmented data. Relevant information is scattered across permits, basement records, tunnel maps, utility networks, cadastral records, engineering drawings, borehole logs, groundwater sensors, and inspection records. These data often use different formats, access rules, ownership categories, and legal definitions. The underground monitoring gap is therefore also institutional (Peng et al., 2021; Saeidian et al., 2023).

4. What the underground monitoring gap hides

4.1 Hidden growth and spatial conflict

Cities can expand below ground without changing their visible footprint. Basements, tunnels, stations, service corridors, and utility networks can increase urban capacity while surface land cover appears stable (Bobylev, 2016; Sterling et al., 2012). A district may look spatially unchanged from above while its infrastructure load, maintenance demands, emergency risks, and underground land-use intensity increase.

Underground space may appear empty because it is out of sight. In practice, it is often crowded. Foundations, tunnels, utilities, aquifers, archaeological resources, geological hazards, and legal boundaries can compete for the same volume (Volchko et al., 2020; von der Tann et al., 2020). A tunnel, basement, or utility corridor can limit future options by occupying space, shaping access, or constraining later projects.

4.2 Hidden environmental and carbon burdens

Underground construction can alter groundwater flow, soil conditions, and subsidence risk. Basements, tunnels, foundations, and underground walls can block or redirect water (Attard et al., 2016a; Attard et al., 2016b). Dense underground development can also contribute to subsurface heat accumulation and groundwater-temperature change (Hemmerle et al., 2022; Previati & Crosta, 2021). These effects may remain invisible in land-cover maps and accumulate across districts.

Underground infrastructure also carries material and energy demands. Tunnels, stations, basements, and service corridors require excavation, structural materials, waterproofing, ventilation, pumping, and maintenance. These demands can create carbon burdens across construction, operation, and maintenance (Huang et al., 2023). A volumetric assessment should account for materials, emissions, energy use, and long-term maintenance obligations.

4.3 Hidden social exposure and accountability

Underground development can improve mobility, comfort, access, and service reliability. It can also create construction burdens such as noise, dust, vibration, blocked access, and safety risks (Hao et al., 2022; Mir et al., 2022). During operation, underground spaces can raise concerns about air quality, crowding, accessibility, emergency evacuation, and public acceptance (Cui et al., 2023; Kim et al., 2024; Qiao et al., 2019; Zhao et al., 2024).

These impacts are uneven. Some communities may face disruption while receiving fewer benefits. Workers and commuters may rely on underground spaces while having little influence over ventilation, accessibility, safety, or emergency procedures. Residents and businesses may face property, access, vibration, or groundwater-related risks without clear information or dispute channels. Subsurface urban expansion is therefore an environmental justice issue as well as an infrastructure issue.

The accountability problem is equally important. Fragmented information can obscure who owns underground assets, who maintains them, who monitors environmental effects, who is liable for harm, and who can access risk information. Underground infrastructure is often treated as a technical asset. It should also be understood as public-interest space because it shapes exposure, access, safety, and long-term obligations.

5. A framework for monitoring the full urban volume

These hidden changes require a framework that connects where underground systems are located, how they affect the subsurface environment, how they depend on other infrastructure, and who is responsible for them. This Perspective proposes four monitoring dimensions: spatial occupation, environmental interaction, infrastructure interdependence, and governance accountability.

Spatial occupation measures where underground space is occupied, how much volume is used, how deep it extends, and what functions it serves. It builds from indicators such as developed underground volume, underground-space use density, and developed underground volume per person (Bobylev, 2016). Additional indicators may include underground floor area, tunnel length, basement depth, infrastructure density, function mix, and asset age.

Environmental interaction links underground infrastructure with groundwater, soil, rock, heat, groundwater quality, and deformation data. It captures interactions with active subsurface systems, including groundwater flow, subsurface heat, and ground deformation (Attard et al., 2016a; Attard et al., 2016b; Crosetto et al., 2016; Hemmerle et al., 2022).

Infrastructure interdependence captures relationships among tunnels, utilities, basements, foundations, drainage systems, and energy networks. It treats the subsurface as a connected urban system (Peng et al., 2021; Volchko et al., 2020; von der Tann et al., 2020). Measures may include network proximity, conflict zones, co-location opportunities, emergency constraints, maintenance dependencies, and operational dependencies.

Governance accountability connects physical assets with ownership, access rights, easements, permits, inspections, emergency responsibility, data access, and lifecycle maintenance obligations. It should also include affected populations, public access to risk information, complaint and dispute channels, accessibility standards, evacuation requirements, and the distribution of construction burdens and service benefits. Semantic 3D city models, 3D cadastres, BIM-GIS integration, and digital twins can support this work by linking physical assets, legal spaces, and operational data (Cheng et al., 2024; Güler, 2024; Saeidian et al., 2023).

Table 1. Core dimensions of volumetric urban monitoring.

Dimension	**What it measures**	**Example data sources**	**Public-interest question**
Spatial occupation	Underground volume, depth, function, density, and age	Basement records, tunnel maps, permits, utility maps, 3D models	What underground space is occupied, and by whom?

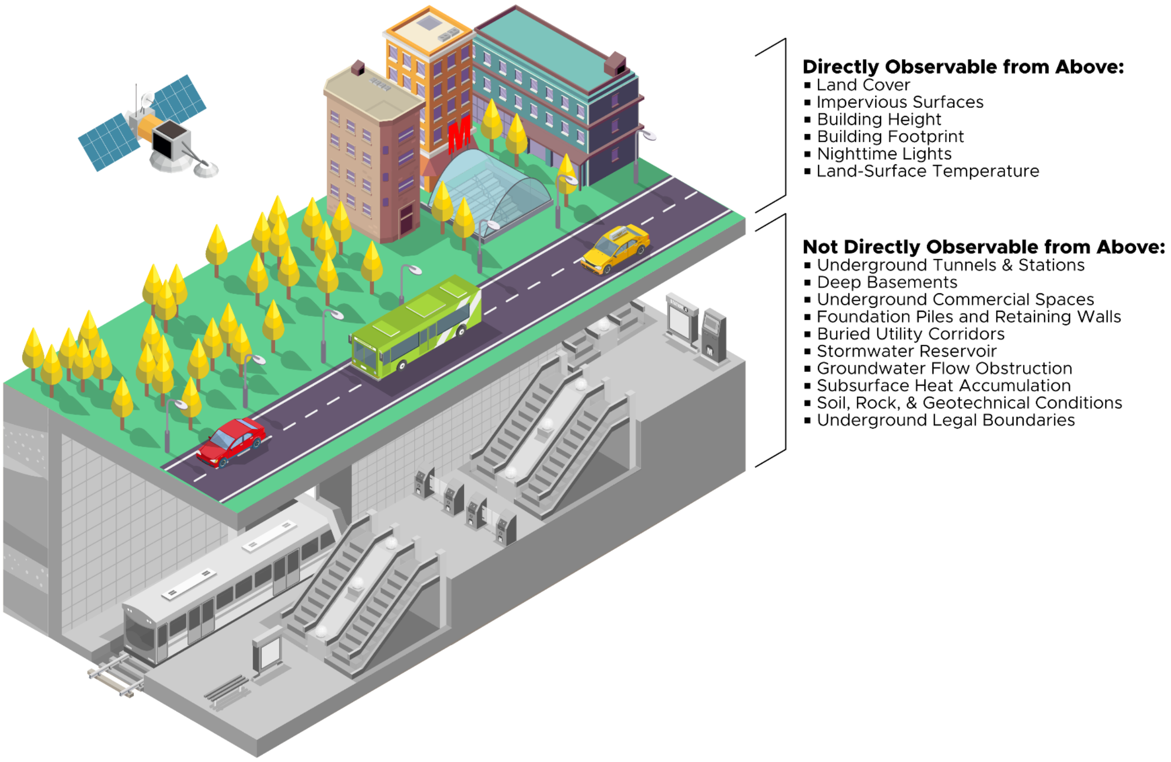
Environmental interaction	Groundwater, heat, deformation, soil, rock, and water-quality effects	Borehole records, sensors, hydrogeological models, InSAR, thermal data	What environmental changes are being produced or intensified?
Infrastructure interdependence	Connections, conflicts, and dependencies among underground systems	Asset maps, BIM-GIS platforms, digital twins, emergency plans	Which systems depend on each other, and where are conflicts likely?
Governance accountability	Ownership, rights, permits, liability, access, maintenance duties, and social exposure	3D cadastres, legal records, easements, inspection databases, complaints, accessibility and emergency records	Who has rights, who bears risk, who benefits, and who is responsible for harm and repair?

The framework should be applied across scales. At the asset scale, it can describe tunnel depth, basement volume, utility condition, and station function. At the parcel or building scale, it can describe rights, permits, easements, and basement extent. At district and city scales, it can reveal groundwater obstruction, heat accumulation, utility congestion, emergency constraints, and the share of critical infrastructure below ground.

The framework should also record uncertainty and data access. Underground data can be incomplete, sensitive, privately held, outdated, or inconsistent across agencies (Peng et al., 2021; Saeidian et al., 2023; Volchko et al., 2020). A useful monitoring system should identify data quality, access restrictions, update frequency, and responsible data stewards. Carbon burdens and social exposure should cut across all four dimensions.

Three terms organize this approach. Volumetric monitoring is the measurement task: accounting for urbanization across surface, aboveground, and belowground space. Responsible visibility is the data-governance task: making underground information visible to the right users at the right level of detail while protecting sensitive data. It can include tiered access, aggregated public indicators, emergency-access protocols, research-use agreements, and community-facing risk summaries. Volumetric accountability is the public-interest outcome: using information to clarify responsibility, reduce harm, and support better decisions.

A. SURFACE-BIASED MONITORING: SURFACE AND ABOVEGROUND SIGNALS OBSERVABLE FROM ABOVE



B. VOLUMETRIC MONITORING AND ACCOUNTABILITY: INTEGRATED EVIDENCE FOR THE FULL URBAN VOLUME

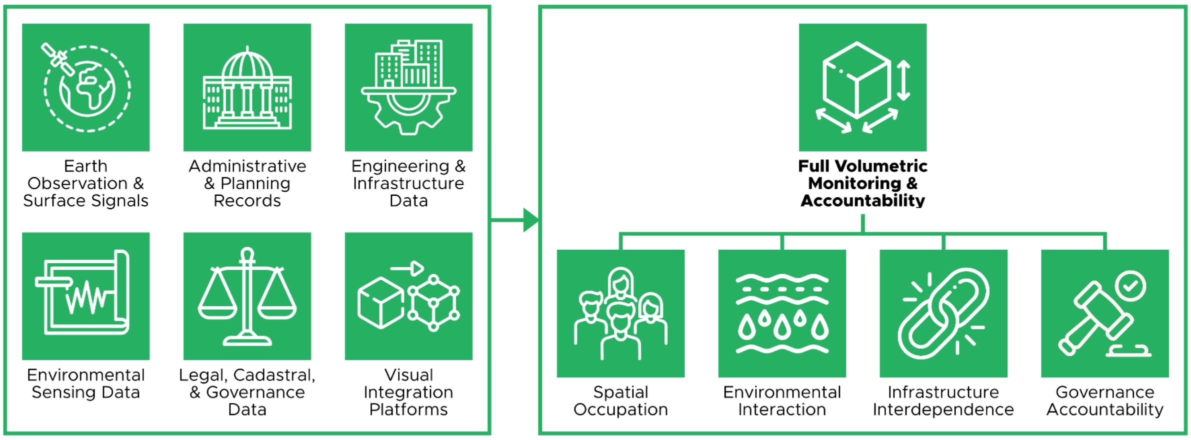


Figure 1. From surface-biased urban monitoring to volumetric monitoring and accountability. (A) Conventional urban monitoring captures surface and aboveground signals observable or inferable from above, including land cover, impervious surface, building footprints, building height, nighttime lights, and land-surface temperature. Belowground systems are not directly observable from above. (B) Volumetric urban monitoring integrates Earth observation with administrative, engineering, environmental, legal, cadastral, and 3D urban data to account for the full urban volume. This approach links spatial occupation, environmental interaction, infrastructure interdependence, and governance accountability.

6. Operationalizing the framework

Operationalizing volumetric monitoring requires a pathway from partial evidence to accountable decisions. Cities do not need complete underground inventories before improving governance. They can begin with available records, high-risk zones, and priority infrastructure corridors. A basic system can compile known tunnels, basements, utilities, permits, and environmental risk areas. An advanced system can add 3D legal models, lifecycle carbon data, environmental sensors, and digital twins.

Four priorities can guide this process. First, researchers should develop shared indicator families for subsurface urbanization, building from measures such as developed underground volume, underground-space use density, and developed underground volume per person (Bobylev, 2016). These indicators should be comparable across cities but flexible across legal systems, infrastructure histories, and planning capacities.

Second, Earth observation should be used as a proxy layer to flag areas where underground activity or risk may require closer investigation. Built-up area, impervious surface, nighttime lights, construction disturbance, SAR change detection, InSAR deformation, and surface-temperature patterns can provide useful screening signals. These signals can guide investigation, but they cannot confirm underground extent, ownership, function, or condition.

Third, administrative, legal, engineering, and environmental data should be linked through shared geospatial standards. Permits, utility maps, cadastral volumes, geotechnical reports, inspection records, groundwater sensors, and deformation data become more useful when linked by location, depth, time, function, and responsibility. Infrastructure agencies can add asset condition, maintenance schedules, and emergency constraints. Planning authorities can define access rules, reporting thresholds, and review procedures.

Fourth, digital tools should be designed for accountability. Digital twins, semantic 3D city models, 3D cadastres, and BIM-GIS platforms are useful when they clarify ownership, maintenance responsibility, data access, and responsibility for harm. A sophisticated model can still fail if it does not identify who can access the data, who updates it, who verifies it, and who is responsible when risks emerge.

Pilot applications can begin in transit corridors, flood-prone districts, dense commercial centers, utility-congested areas, and zones with known subsidence or groundwater stress. These pilots can test how tunnel maps, permits, deformation monitoring, utility records, drainage systems, groundwater sensors, basement records, emergency-access plans, and public-disruption data can inform risk governance. They can also help cities refine data standards and access rules before expanding citywide.

7. Discussion and conclusion

The underground monitoring gap is timely for sustainable cities research. Urban monitoring now measures land conversion, impervious surface, building height, and visible urban form with increasing precision (Che et al., 2024; Goldblatt et al., 2018; Pesaresi et al., 2016; Zhu et al., 2025). These advances have improved how cities are observed from above. They remain less effective for urban systems that extend below ground, including transport, drainage, storage, energy, utilities, and service infrastructure.

The central claim of this Perspective is that subsurface urban expansion is a measurable, governable, and socially consequential form of urbanization. It can reshape land use, infrastructure dependency, environmental risk, public cost, and long-term responsibility without producing clear surface or aboveground signals. A volumetric approach addresses this blind spot by linking four dimensions: spatial occupation, environmental interaction, infrastructure interdependence, and governance accountability.

This blind spot is not only technical. Underground data are often missing, fragmented, or difficult to access. This can weaken oversight and make liabilities harder to trace. It can also make it harder for affected groups to understand or contest potential harm. Underground development can shift risks and responsibilities across communities, agencies, landowners, infrastructure operators, and future users. For this reason, the monitoring gap is also a governance and accountability issue.

The argument has limits. Evidence on underground-space use is strongest in large, infrastructure-intensive cities. Rapidly urbanizing and data-poor cities may have fewer records, weaker coordination, and limited public access to infrastructure information. This means the monitoring gap may be most serious in places where planning capacity and accountability systems are already weak. This should not delay action. It should encourage practical monitoring systems that can begin with partial records, known risks, and priority corridors.

Several research priorities follow from this challenge. Researchers should develop comparable indicators of subsurface urbanization. They should create inventories that link depth, function, ownership, environmental risk, and lifecycle responsibility. They should also test how surface signals can serve as proxies for underground activity or risk. Future work should examine who benefits from underground development, who bears its burdens, and how controlled visibility can protect sensitive information while still supporting planning, emergency preparedness, research, and public oversight.

The policy challenge is to make underground information usable without making sensitive infrastructure data fully public. Volumetric monitoring needs clear institutional rules for data access, record maintenance, accuracy checks, and responsibility when underground risks become public burdens. These rules should clarify who can see specific information, who updates the record, who verifies its accuracy, and who is accountable when harm occurs.

Urban monitoring has learned to measure the footprint and skyline of cities. It now needs to account for depth. Earth observation remains essential because it shows visible urban change and can identify places where underground activity or risk may require closer investigation. Its value increases when connected with permits, cadastral records, engineering drawings, tunnel and utility maps, environmental sensors, lifecycle carbon accounting, 3D city models, and digital twins. The central task ahead is volumetric monitoring and accountability: the capacity to see, measure, and govern the full urban volume before underground risks become public burdens.

Data availability statement

No original datasets were generated or analyzed in this study. This Perspective article draws on published literature and publicly available scholarly sources, all of which are cited in the References section.

Author contributions

AGG was responsible for the conceptualization, literature review, framework development, writing of the original manuscript, and revision of the final manuscript. The author approved the submitted version.

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Conflict of interest

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

Generative AI statement

The author declares that generative AI was used during the preparation of this manuscript. ChatGPT, developed by OpenAI, was used for language editing, structural refinement, and clarity checks. No generative AI tool was listed as an author. The author reviewed and verified all AI-assisted texts and takes full responsibility for the final content of the article.

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