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

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Perspective

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Abstract

Cities are increasingly measured through surface land cover and aboveground form, even as urban activity expands below ground. This Perspective develops an integrated approach for making that expansion visible and governable. First, it defines subsurface urban expansion as durable growth or intensification of urban activity below the local ground surface through new or expanded occupation, use, or modification of underground volume. Second, it identifies an underground monitoring gap produced by connected failures of observation, data integration, and accountability. Third, it proposes a framework for volumetric urban monitoring that combines four analytical dimensions, two governance mechanisms, and a five-stage implementation cycle. Spatial occupation, environmental interaction, infrastructure interdependence, and governance accountability characterize underground change. Responsible visibility governs sensitive information, and volumetric accountability assigns enforceable lifecycle obligations. Earth observation supports screening, validated proxies, deformation detection, and surface-impact monitoring within a broader evidence system that includes institutional, technical, and in situ information. Applications in New York City, Lyon, and Singapore illustrate how integrated evidence could reveal cumulative effects, coordinate infrastructure, and clarify responsibility. Bringing the subsurface into urban measurement and governance can help cities identify hidden risks earlier and prevent unresolved obligations from becoming lasting public burdens.

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

1. Introduction

Urbanization changes the horizontal extent, vertical form, and functional capacity of cities, yet established monitoring systems capture these dimensions unevenly. Datasets increasingly map visible land cover, built-up land, impervious surfaces, nighttime lights, building footprints, heights, and volumes, while planning models forecast surface land-use transitions and growth hotspots (Goldblatt et al., 2018; Li et al., 2020; Pesaresi et al., 2016; Zhu et al., 2025; Kumar et al., 2025). Belowground urbanization remains weakly represented in established indicators despite these advances (Bobylev, 2016; Sterling et al., 2012).

This omission matters because cities can expand their capacity beneath surfaces that appear stable. Tunnels, basements, utility corridors, drainage systems, energy infrastructure, and storage facilities add occupied volume and intensify urban functions without necessarily altering the visible footprint of development (Bobylev, 2016; Sterling et al., 2012). These changes can affect groundwater, ground stability, subsurface heat, infrastructure dependencies, and long-term financial and institutional obligations (Attard et al., 2016a, 2016b; Peng et al., 2021; Previati and Crosta, 2021; Qiao et al., 2019). Because relevant records are often dispersed across technical systems and responsible institutions, cities may accumulate underground assets and liabilities without a coherent account of their extent, effects, or responsible actors (Bobylev, 2016; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021).

This Perspective treats the subsurface as a measurable and governable dimension of urbanization and makes three linked contributions. It first defines subsurface urban expansion and establishes its conceptual boundaries. It then identifies the underground monitoring gap as a combined failure of observation, data integration, and accountability. Finally, it proposes a volumetric monitoring framework that connects physical change with institutional responsibility through three layers: four analytical dimensions that characterize underground change, two governance mechanisms that regulate information and obligations, and a five-stage cycle that connects evidence with urban decisions. Within this system, Earth observation supports screening and surface-impact analysis, whereas institutional, technical, environmental, and in situ evidence establishes asset characteristics, causal processes, legal status, and responsibility (Crosetto et al., 2016; Güler, 2024; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021).

2. Subsurface urban expansion and the underground monitoring gap

Subsurface urban expansion is durable growth or intensification of urban activity below the local ground surface through new or expanded occupation, use, or modification of underground volume. The concept includes newly excavated spaces and existing systems whose extent, depth, capacity, function, or infrastructural role increases over time. An intervention therefore qualifies when it creates a material and lasting increase in occupied volume or functional intensity. Routine inspection, repair, and like-for-like replacement remain outside the concept unless they enlarge or intensify the system, whereas extensions and capacity increases constitute expansion. Regulatory changes enter the definition only when they accompany a physical or functional change below ground.

Applying the concept to boundary cases requires attention to durability, physical occupation, and functional intensity. Shallow foundations that provide ordinary structural support are generally excluded, but large or deep foundations may qualify when they occupy substantial volume, alter groundwater or ground conditions, constrain future development, or require dedicated oversight (Attard et al., 2016a, 2016b; Volchko et al., 2020). Geothermal installations may also qualify when they create durable energy infrastructure or materially intensify subsurface heat use (Bayer et al., 2019; Doyle et al., 2016). Physical occupation and functional intensification determine inclusion; environmental effects and governance obligations determine wider significance.

The concept complements adjacent fields through its focus on change over time and the links among physical occupation, environmental effects, and institutional obligations. Underground-space development and underground urbanism examine buried facilities, subsurface planning coordinates competing resources and uses, and three-dimensional land administration records volumetric rights, restrictions, and responsibilities (Li et al., 2013; Saeidian et al., 2023; Volchko et al., 2020). Subsurface urban expansion asks how occupation and function increase, which effects follow, and which obligations accumulate across the asset lifecycle.

Earth observation contributes to this agenda through specific and bounded evidentiary roles. InSAR and persistent-scatterer methods can detect ground deformation and selected surface responses associated with underground activity, supporting screening, impact monitoring, and investigation prioritization (Crosetto et al., 2016; Ramirez et al., 2022; Serrano-Juan et al., 2017; Wnuk et al., 2021). Surface observations can also serve as proxy layers when local validation establishes a reliable relationship with a defined subsurface process. Because deformation may arise from several causes, attribution requires project schedules, engineering drawings, groundwater records, boreholes, inspections, and physical models (Crosetto et al., 2016; Peng et al., 2021; Serrano-Juan et al., 2017). Direct measurements and institutional records remain necessary to establish underground extent, depth, function, condition, ownership, legal status, and responsibility (Güler, 2024; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021).

The underground monitoring gap emerges from three connected failures that leave subsurface change incompletely observed and governed. An observational gap arises because many buried systems produce no persistent surface signal (Bobylev, 2016; Sterling et al., 2012). A data-integration gap arises when information is dispersed across incompatible records, spatial references, access rules, and institutions (Saeidian et al., 2023; Yan et al., 2019, 2021). An accountability gap follows when fragmented evidence obscures ownership, maintenance duties, environmental responsibility, liability, and available remedies (Güler, 2024; Peng et al., 2021; Qiao et al., 2019). Acting together, these failures can delay risk detection, weaken coordination, conceal cumulative effects, distribute burdens inequitably, and transfer unresolved obligations to the public (Peng et al., 2021; Qiao et al., 2019; von der Tann et al., 2020). Figure 1 links this conceptual pathway to an iterative implementation cycle.

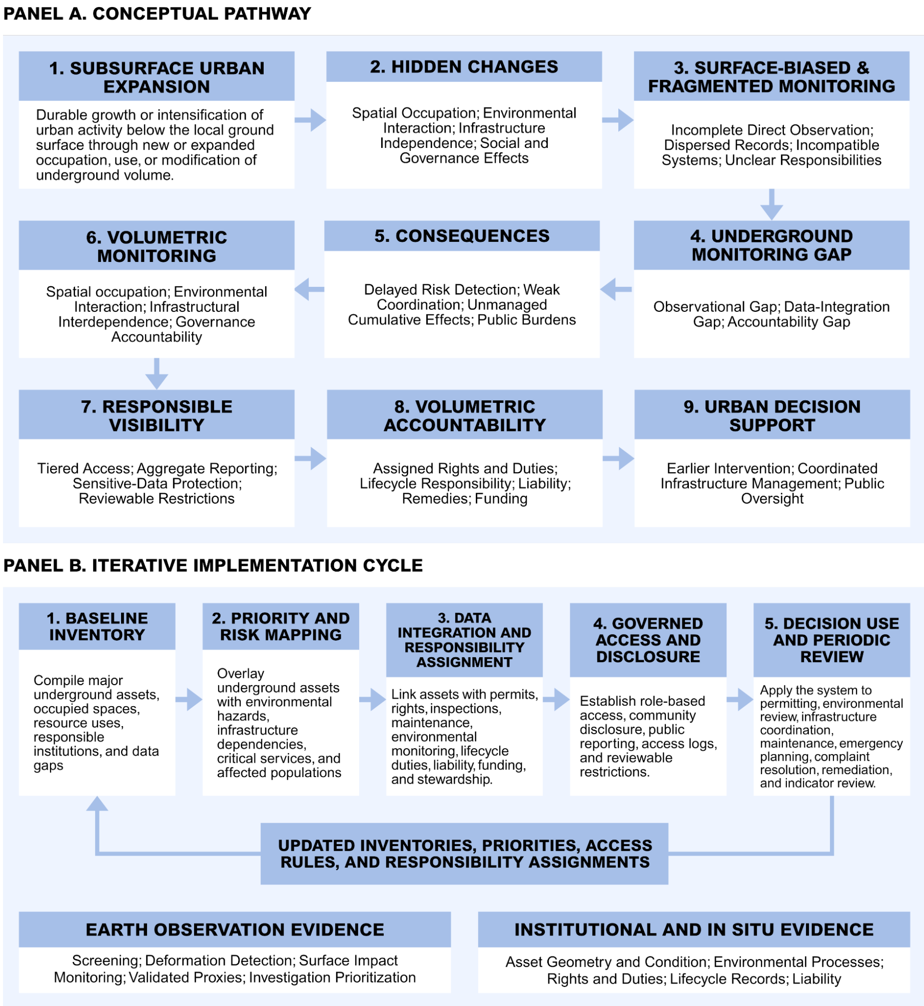

Figure 1. Conceptual pathway and iterative implementation cycle for volumetric urban monitoring. Panel A traces the progression from subsurface urban expansion and hidden spatial, environmental, infrastructural, social, and governance effects to surface-biased monitoring and the resulting observational, data-integration, and accountability gaps. Volumetric monitoring responds by organizing evidence across four analytical dimensions; responsible visibility governs access to sensitive information; and volumetric accountability assigns rights, duties, lifecycle responsibilities, liability, remedies, and funding obligations. Panel B presents the five-stage implementation cycle and shows how Earth observation and institutional and in situ evidence jointly update inventories, priorities, access rules, and responsibility assignments.

3. Volumetric monitoring and accountability

Volumetric urban monitoring treats the city as a three-dimensional system in which surface, aboveground, and belowground processes interact. Four dimensions describe underground occupation, environmental change, infrastructure interdependence, and institutional responsibility. Social consequences cut across them because underground development distributes benefits, disruption, exposure, service risk, information access, and remedies unevenly.

3.1. Four analytical dimensions

Spatial occupation establishes what lies below ground, where it is located, how much volume it occupies, and how these stocks change through time. Measures include volume, depth, floor area, network length, density, age, and function (Bobylev, 2016). Distinguishing stocks from rates of expansion reveals competition for finite space, constraints on future projects, and differences in planning, maintenance, and risk-management demands (Bobylev, 2016; Volchko et al., 2020; von der Tann et al., 2020).

Environmental interaction characterizes how underground development changes groundwater, subsurface temperature, soil and rock conditions, water quality, and ground stability (Attard et al., 2016a, 2016b; Hemmerle et al., 2022; Previati and Crosta, 2021). Underground structures can obstruct groundwater flow, contribute to subsurface heat accumulation, and generate deformation during excavation or dewatering (Attard et al., 2016a, 2016b; Hemmerle et al., 2022; Wnuk et al., 2021). Boreholes and sensors provide direct observations, models support interpretation, and InSAR supplies complementary measurements of surface deformation (Attard et al., 2016a, 2016b; Crosetto et al., 2016; Ramirez et al., 2022). Monitoring records should preserve the distinction among direct measurements, observed surface responses, modeled effects, and inferred causes.

Infrastructure interdependence identifies where underground and surface systems connect, compete for space, or create the potential for cascading failure (Peng et al., 2021; Volchko et al., 2020; von der Tann et al., 2020). Analysis should account for proximity to critical assets, shared corridors, redundancy, maintenance access, service dependencies, and emergency constraints. Engineering drawings, asset inventories, BIM-GIS systems, digital twins, and operational records can support this work (Cheng et al., 2024; Peng et al., 2021). Digital twins gain decision value when verified geometry is linked with environmental observations, legal attributes, lifecycle records, and data-governance controls, including subsurface information in three-dimensional representations of land use and infrastructure (Cheng et al., 2024; Sharma and Dehalwar, 2026).

Governance accountability establishes whether the evidence base identifies ownership, rights, permits, inspections, maintenance duties, emergency authority, liability, remedies, and data stewardship (Güler, 2024; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). It also examines how benefits, disruption, risk, information access, and institutional response are distributed across an asset's lifecycle (Peng et al., 2021; Qiao et al., 2019). This analytical dimension measures whether responsible actors and procedures are visible; volumetric accountability, developed in Section 3.3, turns those assignments into enforceable duties, remedies, and funding obligations.

The four dimensions require complementary, traceable evidence. Shared identifiers, spatial references, metadata, update schedules, and assigned stewards connect technical records, environmental observations, legal information, and field measurements (Saeidian et al., 2023; Yan et al., 2019, 2021). An integrated system should preserve disagreement and classify records as verified, estimated, inferred, outdated, or missing. These classifications determine whether information supports routine planning, requires verification, or remains unsuitable for high-consequence decisions.

3.2. Responsible visibility

Responsible visibility aligns information resolution and safeguards with each user's function and public-interest needs. Emergency responders and operators require detailed operational information, while public authorities require asset-scale records for permitting, coordination, inspection, and maintenance (Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). Researchers may receive controlled data, affected communities need localized impact and response information, and the public needs aggregate indicators of development, compliance, cost, risk, and responsibility (Peng et al., 2021; Qiao et al., 2019; Saeidian et al., 2023).

The principle also requires narrowly justified restrictions and safeguards that remain open to review. Field-, record-, or layer-level controls can protect exact geometry, access points, hazardous zones, and operational vulnerabilities (Saeidian et al., 2023; Yan et al., 2019, 2021). Redaction, aggregation, spatial generalization, delayed release, and access logging can preserve oversight without exposing sensitive systems. Each restriction should identify its purpose, authorized users, permitted resolution, data steward, and review date; emergency protocols may temporarily expand access, but subsequent use should be documented.

3.3. Volumetric accountability

Volumetric accountability converts governed information into enforceable obligations across the full asset lifecycle. Each asset or occupied volume should be linked to identifiable owners, operators, regulators, maintenance authorities, emergency authorities, and data stewards (Güler, 2024; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). Approval and operating records should assign responsibility for monitoring, inspection, renewal, decommissioning, complaints, remediation, liability, and funding (Cheng et al., 2024; Peng et al., 2021; Qiao et al., 2019).

Accountability must also provide procedures through which affected communities can understand risks, raise concerns, and obtain corrective action. Public authorities should disclose localized construction disruption and environmental risk, maintain accessible complaint and dispute-resolution channels, and document remedies. Approval records should assign long-term environmental and structural monitoring, establish intervention thresholds and reporting schedules, and define emergency-access or evacuation duties. Lifecycle reporting should also identify carbon and material burdens, maintenance and renewal costs, and the expected costs of remediation and closure (Cheng et al., 2024; Huang et al., 2023).

These arrangements are especially important where private development can create cumulative or off-site effects that later become public liabilities (Peng et al., 2021; Qiao et al., 2019; Volchko et al., 2020; von der Tann et al., 2020). Before approving such projects, public authorities should establish responsibility, financial assurance, and cost-recovery rules that remain effective through ownership transfer, closure, and decommissioning.

3.4. Indicators and evidence

A practical indicator system should make underground change comparable through measurable stocks, rates, environmental responses, infrastructure dependencies, and institutional performance (Attard et al., 2016a, 2016b; Bobylev, 2016; Cheng et al., 2024; Güler, 2024). Table 1 separates the four analytical dimensions from the two governance mechanisms and presents a compact set of indicators that cities can adapt to local conditions and capacity. Every indicator should specify its unit, baseline, denominator, spatial scale, update frequency, uncertainty, verification status, and data completeness. Absolute totals require normalized measures, environmental indicators require reference conditions and thresholds, and cross-city comparisons require consistent inclusion rules and transparent reporting of record coverage (Bobylev, 2016; Saeidian et al., 2023; Yan et al., 2019, 2021).

Table 1. Core elements, measurable indicators, and evidence for volumetric urban monitoring

Analytical dimensions			
Element	**Core question**	**Illustrative indicators or requirements**	**Principal evidence**
Spatial occupation	What occupies underground volume, where, and for how long?	Developed underground volume (m^3); annual volume change (m^3/year); mean and maximum depth (m); underground floor area (m^2); network length (km); median asset age (years)	Permits; engineering surveys; tunnel and utility maps; basement records; 3D models
Environmental interaction	What environmental change is produced or intensified?	Groundwater-level change from baseline (m); deformation rate (mm/year); subsurface-temperature anomaly (°C); defined water-quality change; monitored area with verified environmental data (%)	Boreholes; sensors; hydrogeological and geotechnical models; InSAR
Infrastructure interdependence	Which systems connect, compete, or create cascading risk?	Conflicts per kilometre of network; assets within a defined critical-proximity threshold (%); direct service dependencies per asset; critical services with backup capacity (%); assets with constrained emergency access (%)	Asset maps; engineering drawings; BIM-GIS systems; digital twins; maintenance and emergency records
Governance accountability	Can responsible actors, rights, duties, and remedies be identified?	Assets with an identified owner and authority (%); inspections completed on time (%); assets with current maintenance schedules (%); median complaint-resolution time (days); assets with assigned liability and remediation responsibility (%)	Cadastres; permits; easements; legal, inspection, complaint, and emergency records
Governance mechanisms			
Element	**Core question**	**Illustrative indicators or requirements**	**Principal evidence**
Responsible visibility	Who needs which information, and under what safeguards?	Records with assigned access classifications (%); restrictions reviewed on schedule (%); public reports issued on schedule (%); documented unauthorized-access incidents	Access-control records; data-sharing agreements; disclosure and review records
Volumetric accountability	Who must monitor, maintain, remedy, and pay across the lifecycle?	Assets with assigned lifecycle duties and funding (%); assets with an identified emergency authority (%); assets with decommissioning plans (%); unresolved liability cases; remediation actions completed (%)	Regulatory decisions; lifecycle plans; financial assurances; liability and remediation records

Note. Each indicator should report its baseline, unit, denominator, spatial scale, observation period, update frequency, uncertainty, verification status, and data completeness. Institutional-performance indicators also require information on reporting coverage, detection capacity, case complexity, and outcome quality. Because high incident or complaint counts may reflect stronger detection and reporting systems, interpretation should consider the process that produced each value.

4. Operational priorities and illustrative cases

4.1. Five-stage implementation cycle

A five-stage iterative pathway translates the framework into urban decision-making. Stage 1 establishes a baseline inventory of major assets, occupied spaces, resource uses, responsible institutions, and data gaps. Each record should document location, depth, function, age, ownership, condition, source, update date, and data quality (Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). Indicators should report inventory coverage, verified geometry, and the currency of condition records.

Stage 2 identifies priority locations by overlaying underground assets with environmental hazards, infrastructure dependencies, critical services, and affected populations. Earth-observation indicators can direct attention toward possible impacts, but technical records, field measurements, and models are needed to verify specific causes (Crosetto et al., 2016; Ramirez et al., 2022; Serrano-Juan et al., 2017; Wnuk et al., 2021). GIS-linked runoff models, for example, can identify areas where drainage demand warrants closer assessment alongside asset geometry, condition, maintenance, and groundwater observations (Patel et al., 2024).

Stages 3 through 5 connect evidence with institutional responsibility, governed access, and decision use. Stage 3 links each asset with permits, rights, inspections, maintenance, environmental monitoring, emergency roles, lifecycle duties, liability, funding, and stewardship (Cheng et al., 2024; Güler, 2024; Peng et al., 2021; Saeidian et al., 2023). Stage 4 establishes role-based access, community disclosure, public reporting, access logs, and reviewable restrictions. Stage 5 applies the system to permitting, environmental assessment, infrastructure coordination, maintenance, emergency planning, complaint resolution, remediation, and periodic review (Peng et al., 2021; Qiao et al., 2019; Volchko et al., 2020). New permits, failures, inspections, measurements, and community reports then update the baseline inventory and priority map.

Implementation can proceed in phases, allowing cities with limited capacity to begin where risk and available evidence are greatest. Transit corridors, flood-prone districts, utility-congested zones, and areas affected by subsidence or groundwater stress provide suitable pilots. Evaluation should examine data completeness, decision relevance, screening accuracy, attribution uncertainty, and cost before coverage expands.

4.2. Illustrative urban cases

The three cases illustrate different entry points for applying the framework with evidence that cities already collect. In New York City, surface flood maps identify inundation hazards, but a volumetric assessment would connect those hazards with subway entrance elevations, tunnel geometry, drainage capacity, passenger exposure, network operations, and institutional duties (Metropolitan Transportation Authority, 2024; Miura et al., 2025). Combining these records would improve understanding of flood propagation through the underground network and clarify responsibility for risk reduction, disruption response, and protective maintenance.

Lyon illustrates the cumulative environmental effects that become visible when records are integrated across parcels. Parcel-level information can identify individual basements and underground structures, while district-scale analysis can evaluate their combined effects on groundwater flow (Attard et al., 2016a, 2016b). This broader view connects physical occupation with observed groundwater change, model uncertainty, and responsibility for mitigation.

Singapore provides an institutional entry point through surveyed utility geometry linked with data quality, legal rights, restrictions, responsibilities, and organizational roles (Yan et al., 2019, 2021). Volumetric monitoring would extend this integration to environmental conditions, infrastructure dependencies, controlled access, and lifecycle obligations. Together, the cases show how cities can connect feasible components around a defined risk or decision and expand the system iteratively.

5. Discussion

The underground monitoring gap changes what counts as urban expansion and what cities must measure to govern it. Dominant indicators capture land conversion, building form, and aboveground volume, but may register little change where underground occupation and functional intensity are increasing (Bobylev, 2016; Goldblatt et al., 2018; Li et al., 2020; Zhu et al., 2025). Groundwater alteration, ground instability, infrastructure failure, public expenditure, and liability can therefore accumulate beneath apparently stable surfaces (Attard et al., 2016a, 2016b; Peng et al., 2021; Qiao et al., 2019).

The framework addresses this mismatch through five linked concepts. Subsurface urban expansion identifies the change; the underground monitoring gap explains why its effects and obligations remain fragmented; and volumetric monitoring organizes the evidence needed to characterize them. Responsible visibility governs access, while volumetric accountability converts evidence into oversight, remedies, funding, and lifecycle responsibility. The contribution is therefore an information architecture that connects three-dimensional measurement with decisions and enforceable obligations.

This architecture also establishes a disciplined role for Earth observation. Surface change and deformation measurements can identify possible impacts, validate proxies, and prioritize investigation, but cannot independently establish underground geometry, function, condition, legal status, or responsibility (Crosetto et al., 2016; Ramirez et al., 2022; Serrano-Juan et al., 2017; Wnuk et al., 2021). Technical, environmental, legal, and institutional evidence supplies these attributes (Güler, 2024; Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). Recording the certainty and provenance of each claim is therefore essential.

Implementation will be uneven because rapidly developing cities may also have incomplete utility records, limited three-dimensional cadastres, sparse long-term monitoring, and weak interagency coordination (Peng et al., 2021; Saeidian et al., 2023; Yan et al., 2019, 2021). These constraints can leave places with the greatest need for information least able to assemble it. Cities can respond by prioritizing high-risk assets, disclosing data quality, assigning responsibility, and establishing repeatable updates before extending coverage.

Comparative research should determine which indicators support consistent cross-city analysis and which require thresholds defined by local geology, infrastructure, governance, and risk tolerance. Apparent differences may reflect development patterns, record coverage, access restrictions, or inconsistent definitions, so studies should assess uncertainty, verification, and reporting capacity alongside indicator values (Bobylev, 2016; Saeidian et al., 2023; Yan et al., 2019, 2021). Pilot applications should test effects on permitting, maintenance, environmental assessment, emergency planning, complaints, and liability decisions.

5.1. Priorities for research and practice

Moving volumetric monitoring from concept to practice requires coordinated changes in research, administration, infrastructure management, and regulation. Researchers, statistical agencies, and monitoring initiatives should incorporate belowground indicators into established accounts of surface and aboveground change. City governments should build phased inventories that connect assets with environmental conditions, affected populations, and responsible institutions, while infrastructure and environmental agencies should document the level of evidentiary certainty required for each decision. Regulators and data authorities should embed responsible visibility, lifecycle duties, community-facing risk disclosure, remedies, and funding requirements in project approval and periodic review.

5.2. Conclusion

Cities need an integrated account of their footprint, skyline, and depth because urban change does not stop at the ground surface. Volumetric monitoring connects measurable indicators and complementary evidence with governed access and enforceable responsibility. Applied iteratively, it can reveal risks earlier, improve coordination across interdependent infrastructure, and clarify who must act throughout the asset lifecycle. These capabilities can help cities expand below ground without allowing unresolved obligations to become lasting public burdens.

Data availability statement

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

Author contributions

AGG was responsible for conceptualization, literature review, framework development, visualization, writing the original manuscript, and revising 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

ChatGPT (GPT-5.6 Thinking, OpenAI) was used during this revision for language editing, structural refinement, condensation, and clarity checks. No generative AI tool was listed as an author. The author reviewed and verified all AI-assisted text and takes full responsibility for the final content of the article.

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