

Empirical Urban Growth Dynamics (2000–2025) and A Conceptual Architectural Framework for Spatial Digital Twins in Secondary African Cities: A Case Study of Owerri, Nigeria

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Abstract

Rapid urban expansion in secondary cities of Sub-Saharan Africa has intensified pressure on land resources and infrastructure, exposing the limitations of conventional planning systems reliant on periodic assessments. While Geographic Information Systems (GIS), Remote Sensing (RS), and Artificial Intelligence (AI) have improved monitoring, their integration into continuous Spatial Digital Twin (SDT) environments remain limited in Nigeria. To address this gap, this study presents an empirical baseline analysis and formulates a conceptual Spatial Digital Twin framework for sustainable urban growth monitoring in Owerri Metropolis, Nigeria. Historical land use and land cover dynamics between 2000 and 2025 were first quantified using multi-temporal Landsat imagery in Google Earth Engine via Random Forest classification to establish the empirical foundation. Based on observed growth patterns, the study identified key spatial, environmental, and administrative data requirements and formulated a five-layer system architecture. Comprising Physical Environment, Data Acquisition, Spatial Integration, Analytical Intelligence, and Application layers, the framework establishes an architectural roadmap for integrating multi-source spatial data, scenario simulations, and predictive analysis into local planning. The practical utility of the framework is demonstrated through targeted applications in urban expansion tracking, flood hazard evaluation, and Sustainable Development Goal (SDG) 11 monitoring. This study provides a scalable, transferable blueprint to guide municipal authorities rather than claiming an active, fully deployed live software or sensor environment.

Keywords: Spatial Digital Twin; Sustainable Urban Development; Urban Growth Monitoring; Artificial Intelligence; Internet of Things; SDG 11.

1. Introduction

The twenty-first century has witnessed unprecedented urban expansion, with cities emerging as the primary centres of economic growth, technological innovation, and human development. According to the United Nations, more than half of the global population currently resides in urban areas, and this proportion is projected to increase to nearly 70% by 2050 as urban centres continue to absorb rapid population growth [7]. While urbanization creates opportunities for economic diversification and improved access to infrastructure and services, it also exerts enormous pressure on land resources, housing, transportation systems, water resources, and ecological environments [12]. In many developing countries, urban expansion has occurred faster than the capacity of planning institutions to manage it, resulting in uncoordinated land conversion, environmental degradation, increasing disaster risks, and declining urban sustainability. Consequently, cities are increasingly seeking innovative approaches that enable continuous monitoring, predictive analysis, and evidence-based planning to support sustainable urban development.

Traditional urban planning systems have relied largely on periodic surveys, static geographic information system (GIS) databases, conventional remote sensing products, and manual planning procedures to monitor urban growth [18]. Although these approaches have significantly improved the understanding of land use dynamics over the past decades, they often provide only retrospective snapshots of urban change and are unable to represent the continuously evolving interactions between the physical environment, infrastructure systems, and human activities. Furthermore, planning decisions based solely on periodically updated spatial datasets frequently struggle to respond to rapidly changing urban conditions, particularly in rapidly growing cities where land conversion occurs within relatively short timeframes [14]. Recent advances in geospatial technologies, cloud computing, artificial intelligence (AI), Internet of Things (IoT) sensing, Building Information Modelling (BIM), and three-dimensional city modelling have created new opportunities for developing dynamic digital representations of cities that can continuously integrate, analyse, and visualize urban information for decision support.

Among these emerging technologies, the concept of the Spatial Digital Twin (SDT) has gained considerable attention as a next-generation framework for smart and sustainable urban management. A Spatial Digital Twin is a dynamic digital representation of a physical city that continuously integrates multi-source geospatial information, sensor observations, analytical models, and planning databases to mirror real-world urban conditions in near real time [23]. Unlike conventional GIS platforms, which primarily support spatial visualization and analysis, Spatial Digital Twins facilitate bidirectional interactions between the physical and digital environments by enabling continuous data synchronization, scenario simulation, predictive modelling, and policy evaluation. Recent applications have demonstrated the potential of Spatial Digital Twins in flood risk management, infrastructure monitoring, transportation optimization, environmental assessment, utility management, and smart city governance [27]. By integrating remote sensing, GIS, artificial intelligence, IoT, and semantic three-dimensional city models into a unified platform, Spatial Digital Twins provide planners with an intelligent decision-support environment capable of anticipating future urban conditions rather than merely documenting past changes.

Despite the growing adoption of Spatial Digital Twin technologies in Europe, North America, and parts of Asia, their application within Sub-Saharan Africa remains extremely limited. Most African cities continue to depend on fragmented spatial databases, isolated planning systems, and periodic land use assessments that rarely communicate with one another [17]. In Nigeria, urban growth studies have predominantly concentrated on land use and land cover change detection, urban expansion modelling, flood susceptibility mapping, and infrastructure assessment using GIS and remote sensing techniques [11] [14] [15]. While these studies have substantially improved understanding of urban growth processes, they generally stop at mapping and prediction, offering limited guidance on how diverse geospatial datasets can be integrated into a continuously evolving digital environment capable of supporting real-time planning decisions. This gap is largely due to institutional data silos, infrastructure constraints, and the lack of a structured architectural roadmap tailored to data-constrained secondary cities. Consequently, there remains no comprehensive Spatial Digital Twin framework specifically designed to address the unique planning challenges of rapidly expanding secondary cities in Nigeria.

Over the past two decades, Owerri metropolis has experienced extensive physical growth driven by population increase, commercial development, institutional expansion, and transportation infrastructure [3] [11] [19]. This expansion has transformed large areas of vegetation, agricultural land, and wetlands into built-up environments, increasing surface impermeability and placing considerable pressure on drainage systems, transportation networks, and public infrastructure. The encroachment of development into environmentally sensitive areas, particularly along the river corridors, has contributed to recurrent urban flooding, ecosystem degradation, and increasing exposure to environmental hazards [20] [25]. Managing these interconnected challenges requires planning systems capable of integrating historical urban dynamics with continuously updated spatial information to support proactive rather than reactive decision-making.

Against this background, this study establishes a 25-year empirical geospatial baseline (2000–2025) and formulates a conceptual Spatial Digital Twin framework for sustainable urban growth monitoring in Owerri Metropolis, Nigeria. Historical urban growth patterns between 2000 and 2025 are first processed and quantified using multi-temporal satellite imagery to provide the empirical foundation required for framework formulation. Based on this baseline, the study identifies the geospatial, environmental, infrastructural, and administrative datasets required to support a functional Spatial Digital Twin and proposes a five-layer system architecture that integrates Geographic Information Systems, Remote Sensing, Artificial Intelligence, Internet of Things technologies, and urban planning databases into a unified decision-support platform. Rather than presenting an operational software deployment, this paper delivers a structured architectural roadmap demonstrating how integrated spatial intelligence can support urban expansion tracking, flood risk management, and evidence-based planning decisions in secondary African cities.

2. Materials and Methods

2.1. Study area

Owerri Metropolis is located in southeastern Nigeria and comprises Owerri Municipal, Owerri North, and Owerri West Local Government Areas (LGAs) of Imo State. The metropolis serves as the administrative capital of Imo State and functions as an important commercial, educational, and transportation hub within southeastern Nigeria. Geographically, the metropolitan area lies approximately between Latitudes 5°25'N and 5°35'N and Longitudes 6°55'E and 7°10'E, covering an estimated land area of about 537 km² [4] [11]. The study area experiences a humid tropical climate characterized by distinct wet and dry seasons, with mean annual rainfall exceeding 2,000 mm and average temperatures ranging between 24°C and 30°C. The metropolis is drained principally by the river network, whose extensive floodplains and wetlands perform critical ecological and hydrological functions. The underlying geology consists predominantly of the Benin Formation (Coastal Plain Sands), which supports productive groundwater systems but is highly susceptible to erosion and flooding due to its loose sandy formations [4] [19] [26]. Rapid population growth and increasing commercial activities have accelerated the expansion of residential developments, transportation infrastructure, and public facilities throughout the metropolis. This expansion has resulted in significant conversion of vegetation, agricultural land, and wetlands into built-up areas, creating increasing pressure on natural ecosystems and urban infrastructure. These characteristics make Owerri an appropriate case study for developing and demonstrating a Spatial Digital Twin framework capable of supporting sustainable urban growth monitoring and planning.

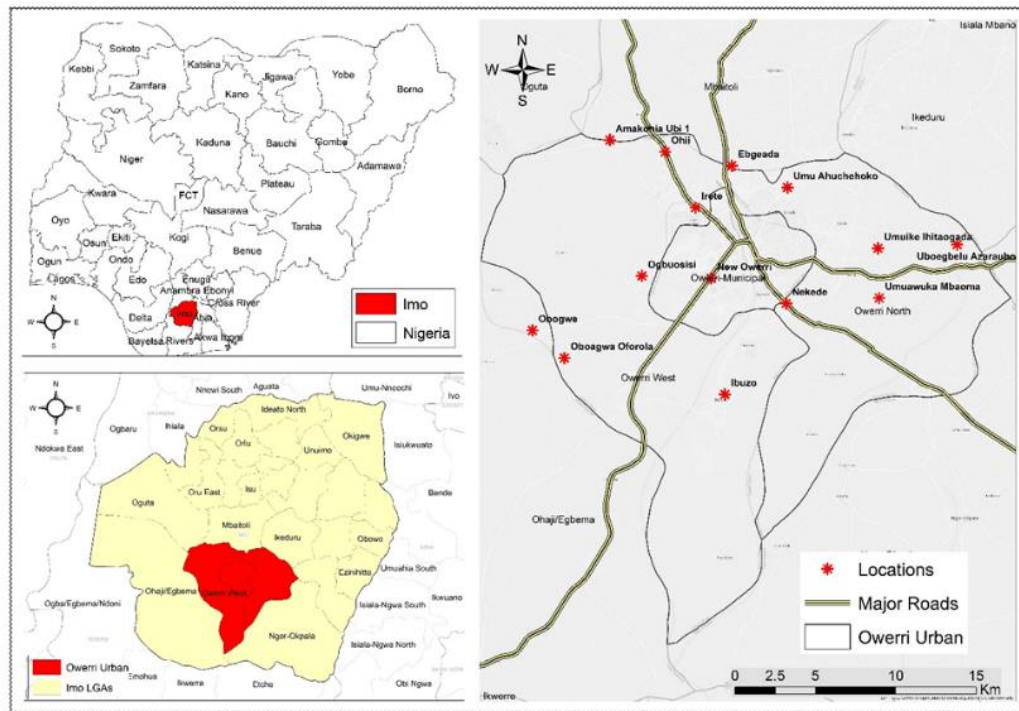


Fig 1: Map showing the Owerri Urban Area, Imo State

2.2. Research Design

This study adopted a framework development research design that combines empirical geospatial analysis with conceptual systems architecture to formulate a Spatial Digital Twin (SDT) for sustainable urban growth monitoring. The research followed a four-phase methodological workflow that integrates historical urban growth assessment, geospatial data requirement analysis, digital twin architecture development, and planning application demonstration (Fig 2). Rather than implementing a fully operational, live hardware digital twin, the study establishes an empirical baseline from satellite observations and formulates a conceptual framework detailing the technical architecture, data integration schemas, and operational workflows required to support future implementation [21]. The methodological pipeline is structured into two distinct domains: (1) an Empirical Baseline Phase, comprising remote sensing classification, accuracy assessment, and spatial driver extraction; and (2) a Conceptual System Design Phase, specifying the five-layer architectural roadmap, data stream protocols, and scenario mapping guidelines for future prototype implementation.

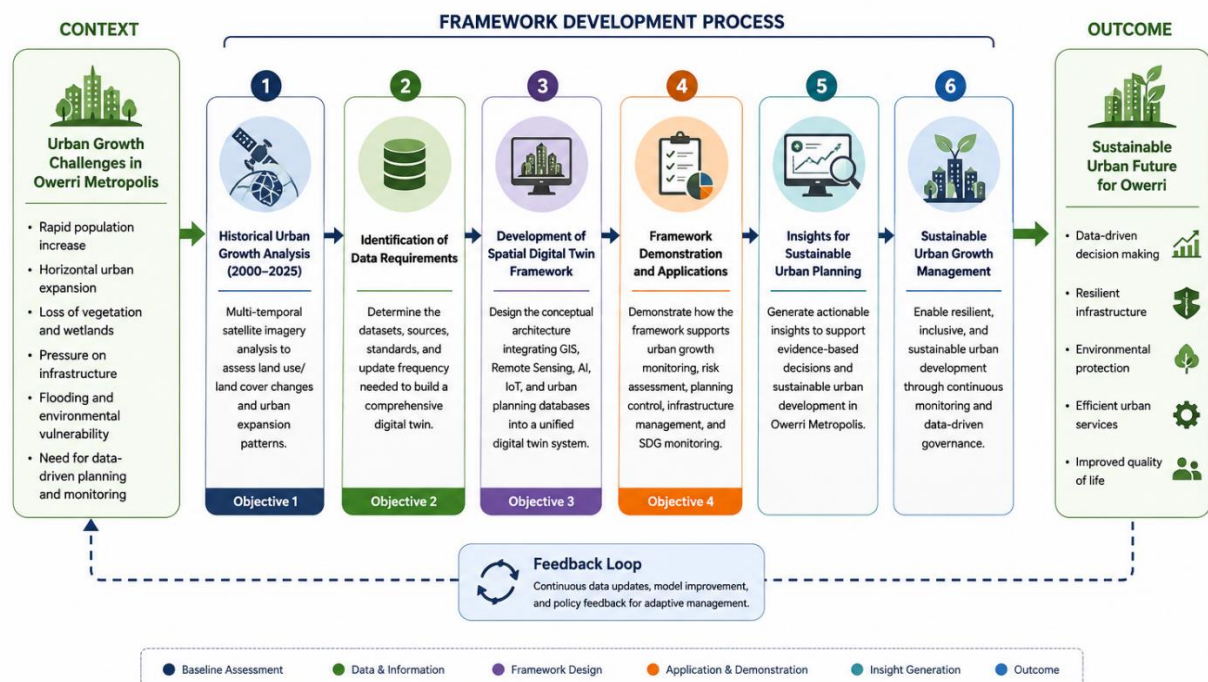


Fig 2: Overall methodological framework adopted for developing the proposed Spatial Digital Twin Framework for sustainable urban growth monitoring in Owerri Metropolis (Author's Analysis, 2026)

2.3. Overall Methodological Framework

The development of the proposed Spatial Digital Twin framework consisted of four interconnected phases.

Phase I: Historical Urban Growth Assessment:

The first phase established the historical urban growth baseline upon which the Digital Twin framework was developed. Multi-temporal Landsat satellite imagery covering the years 2000, 2010, 2020, and 2025 was processed within the Google Earth Engine (GEE) cloud computing environment. Standard image preprocessing procedures, including atmospheric correction, cloud masking, geometric correction, and image compositing, were performed before land use and land cover (LULC) classification. The Random Forest machine learning algorithm was employed to classify the imagery into six land use classes comprising built-up areas, vegetation, agricultural land, wetlands, bare land, and water bodies. Post-classification comparison techniques were subsequently applied to quantify urban expansion and land cover transitions between the study years. The resulting LULC maps provided the empirical evidence required to identify major urban growth trends and establish baseline conditions for the proposed framework.

Sensor Normalization and Radiometric Harmonization

To address potential spectral shifts across the multi-decadal imagery suite (Landsat 7 ETM+, Landsat 8 OLI, and Landsat 9 OLI-2), all scenes were converted to Surface Reflectance (SR) using the USGS LEDAPS (for Landsat 7) and LaSRC (for Landsat 8 and 9) atmospheric correction algorithms. Because subtle bandpass discrepancies exist between the TM/ETM+ and OLI/OLI-2 sensors, cross-sensor radiometric harmonization was conducted following Roy et al. (2016). Landsat 8/9 Operational Land Imager data were transformation-aligned to the Landsat 7 ETM+ spectral response using ordinary least squares (OLS) regression coefficients applied across the visible, near-infrared (NIR), and shortwave-infrared (SWIR) bands. Furthermore, topographically induced illumination variation was corrected using the C-correction topographic normalization model supported by the 30 m SRTM Digital Elevation Model. Cloud cover, shadow, and scan-line corrector (SLC-off) gaps were masked using the C Function of Mask (CFMask) algorithm prior to spectral feature extraction.

Accuracy Assessment Protocol

Quantitative validation of the Random Forest multi-temporal classifications was conducted using a stratified random sampling framework across each historical image year (2000, 2010, 2020, and 2025). For each epoch, a minimum of 50 reference points per LULC class (Built-up, Forest, Agriculture, Wetland, Waterbody, Bare Surface) were selected, yielding a minimum sample size of $N = 500$ points per mapping year. Reference ground truth was derived from historical high-resolution Google Earth historical imagery, field survey GPS points, and topographic maps. Error matrices (confusion matrices) were constructed to compute Overall Accuracy (OA), Producer's Accuracy (PA), User's Accuracy (UA), and the Kappa coefficient (kappa) according to Equations (i) to (iv):

$$OA_i = \frac{\sum_{i=1}^r n_{ii}}{N} \times 100 \quad (1)$$

$$\kappa = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_{i+} \cdot x_{+i})}{N^2 - \sum_{i=1}^r (x_{i+} \cdot x_{+i})} \quad (2)$$

$$PA = \frac{\text{Correctly Classified}}{\text{Total reference pixels for the class}} \times 100 \quad (3)$$

$$UA_i = \frac{n_{ii}}{n_{i+}} \times 100 \quad (4)$$

where x_{ii} represents diagonal entries in the confusion matrix, N is total sample count, and x_{i+} and x_{+i} denote row and column marginal totals.

Phase II: Identification of Digital Twin Data Requirements

The second phase focused on identifying the multi-source datasets required to support a operational Spatial Digital Twin for Owerri Metropolis. Relevant datasets were identified through an assessment of digital twin literature, smart city architectures, and local urban planning information requirements. The identified datasets were grouped into thematic categories including remote sensing data, topographic data, transportation networks, cadastral information, utility infrastructure, hydrological data, socio-economic information, environmental observations, and municipal planning records [5] [8] [28]. For each dataset, the required spatial resolution, data format, acquisition source, update frequency, and operational role within the proposed framework were defined to establish an interoperable data integration roadmap.

Phase III: Development of the Spatial Digital Twin Framework

The third phase involved the conceptual design of the proposed Spatial Digital Twin framework. Drawing upon established digital twin architecture principles, the framework was designed as a five-layer system:

- 1) Physical Urban Environment Layer
- 2) Data Acquisition and Sensing Layer
- 3) Spatial Database and Integration Layer
- 4) Analytical Intelligence Layer
- 5) Application and Decision Support Layer

The relationships among these components were designed to establish a continuous flow of information from the physical city to the virtual environment, enabling the integration, analysis, visualization, and interpretation of urban information for planning purposes.

Phase IV: Framework Demonstration and Planning Applications

The final phase demonstrated the practical application of the proposed framework through representative urban planning scenarios relevant to Owerri Metropolis. These scenarios illustrate how the Spatial Digital Twin could support sustainable urban management by integrating historical urban growth information with continuously updated geospatial datasets. The demonstration focused on selected plan-

ning applications including urban growth monitoring, flood risk assessment, development control and building permit verification, infrastructure management, environmental monitoring, and Sustainable Development Goal (SDG) 11 reporting. These applications were used to illustrate the potential of the proposed framework as a decision-support system for proactive urban planning and management.

2.4. Data Sources

Table 1 outlines the empirical datasets analyzed in this study alongside the target operational data streams proposed for future system integration.

Table 1: Multi-source Spatial Data Framework for Owerri Metropolis

Data Classification	Dataset Category	Dataset Source	Primary Purpose / Role
Primary Empirical Datasets (Analyzed in this Study)	Satellite Imagery	Landsat 5, 7, 8, 9 (USGS / GEE)	LULC classification & historical growth assessment (2000–2025)
	Elevation Data	SRTM DEM (USGS)	Terrain, slope, and hydrological baseline modeling
	Administrative Boundaries	Owerri LGA Boundaries from Office of the Surveyor-General of the Federation (OSGOF)	Spatial reference, clipping, and zonal statistics
	Road Network	OpenStreetMap / Imo State Geographic Information Service (IMOGIS)	Transportation layout and physical connectivity baseline
	River Network	Digitized Hydrology (IMOGIS)	River floodplain mapping
Target Operational Data Streams (Proposed Framework Architecture)	Population Data	National Population Commission	Demographics and urban expansion density indicators
	Cadastral & Planning Data	Ministry of Lands / Owerri Capital Development Authority (OCDA) / IMOGIS	Parcel management, building permits, and zoning compliance
	Meteorological Observations	Nigerian Meteorological Agency (NiMet)	Hydro-meteorological monitoring and flood early warning
	Real-Time IoT Streams	Water level / Weather sensors (Proposed)	Streamflow monitoring and continuous environmental telemetry

The 30-meter SRTM DEM utilized in this study provides a preliminary macro-level elevation profile for spatial contextualization. It is explicitly recognized that 30-meter SRTM DEM data and impermeability indices alone do not constitute a calibrated hydrological model. Within the proposed framework, these static topographies serve as structural baseline inputs, intended to be coupled with finer-resolution elevation models (e.g., UAV LiDAR) and physical runoff modeling in future operational phases.

2.5. Conceptual Framework Development

The conceptual Spatial Digital Twin (SDT) framework was formulated using a systems integration design that bridges geospatial data structures, artificial intelligence, urban planning repositories, and digital municipal infrastructure into a unified architectural roadmap. Rather than representing independent components, the system architecture specifies interconnected subsystems designed for continuous data exchange via standardized models and interoperable spatial databases [28]. The proposed framework emphasizes structural scalability, interoperability, and adaptability, establishing a theoretical design that can incorporate expanded datasets and analytical modules as municipal data infrastructure matures. Consequently, this architecture serves as a conceptual blueprint to guide the future technical implementation and empirical prototyping of Spatial Digital Twins in Owerri and comparable rapidly urbanizing secondary cities across Sub-Saharan Africa.

3. Results

3.1. Historical Urban Growth Dynamics in Owerri Metropolis (2000–2025)

The historical land use and land cover (LULC) assessment established the baseline spatial conditions required for developing the proposed Spatial Digital Twin (SDT). Analysis of multi-temporal satellite imagery revealed that Owerri Metropolis experienced substantial urban expansion between 2000 and 2025, accompanied by significant transformation of its natural landscape. Built-up areas expanded from 54.12 km² (10.08%) in 2000 to 244.80 km² (45.61%) in 2025, representing an overall increase of 190.68 km² or approximately 352.33% during the study period. This rapid growth occurred primarily along the major transportation corridors connecting Owerri with Onitsha, Aba, and Okigwe, reflecting the outward expansion of residential, commercial, and institutional developments [13]. Conversely, natural vegetation experienced a substantial decline from 358.64 km² (66.82%) in 2000 to 140.33 km² (26.14%) in 2025, while wetland areas decreased dramatically from 29.03 km² to only 1.56 km², representing a loss of more than 94% of the original wetland extent (Table 2). These changes indicate increasing pressure on environmentally sensitive ecosystems and highlight the growing conflict between urban development and ecological conservation. Agricultural land exhibited a moderate increase during the latter part of the study period, whereas bare land and water bodies showed comparatively smaller fluctuations. Accuracy range between 93.18% in 2000 to 99.15% (Table 3). Overall, the observed urban growth pattern reflects predominantly horizontal expansion characterized by the conversion of vegetated landscapes and wetlands into impervious built-up surfaces. Such development has important implications for stormwater generation, biodiversity conservation, groundwater recharge, and flood vulnerability. More importantly, the results demonstrate that urban growth within Owerri is occurring at a pace that cannot be effectively monitored through periodic mapping alone [16] [29]. Continuous observation, timely data integration, and predictive planning tools are therefore required to support sustainable urban management. These findings provide the empirical justification for the development of the proposed Spatial Digital Twin framework.

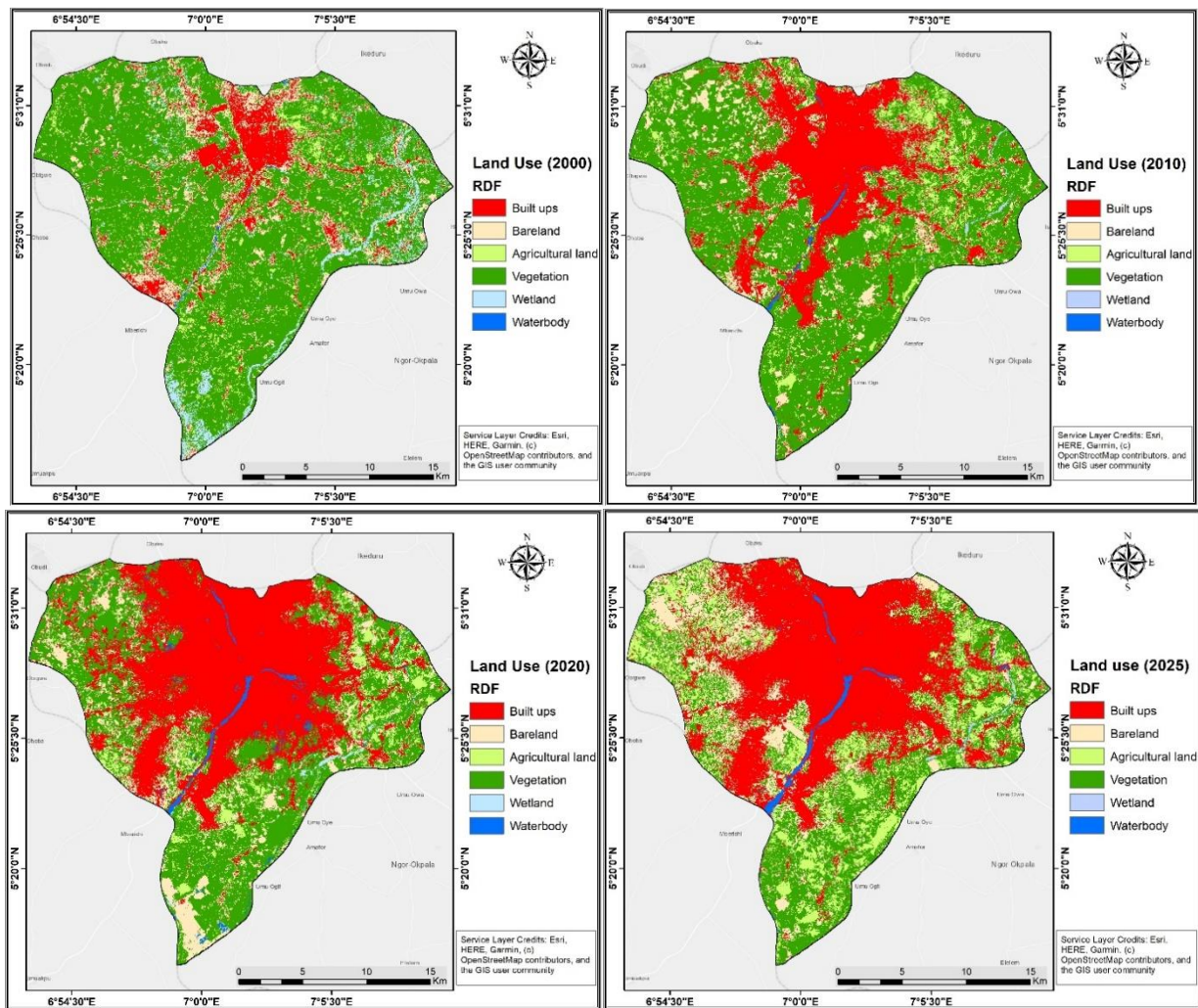


Fig 3: LULC Projection (2000-2025)

Table 2: Spatio-Temporal Distribution of Green Infrastructure in Owerri Urban (2000–2025).

LULC Class	2000 Area (sq km)	2000 %	2010 Area (sq km)	2010 %	2020 Area (sq km)	2020 %	2025 Area (sq km)	2025 %	Net Change (sq km)
Built-up	54.12	10.08	138.86	25.87	237.85	44.31	244.80	45.61	+190.68
Bareland	72.91	13.58	64.94	12.10	67.33	12.54	74.65	13.91	+1.74
Agricultural	20.74	3.86	32.98	6.14	26.80	4.99	68.75	12.81	+48.01
Vegetation	358.64	66.82	296.35	55.21	194.74	36.28	140.33	26.14	-218.31
Wetland	29.03	5.41	1.38	0.26	2.52	0.47	1.56	0.29	-27.47
Waterbody	1.32	0.25	2.26	0.42	7.52	1.40	6.68	1.25	+5.36
Total Area	536.77	100.0	536.77	100.0	536.77	100.0	536.77	100.0	--

Table 3: Multi-Temporal Random Forest Classification Accuracy Summary (1990–2025)

Year	Sensor	Total Sample Points (N)	Overall Accuracy (OA, %)	Kappa Coefficient (κ)	Overall User's Accuracy Range (%)	Overall Producer's Accuracy Range (%)
2000	Landsat 7 ETM+	500	93.80%	0.9140	89.1% – 97.0%	88.6% – 96.5%
2010	Landsat 7 ETM+	500	94.20%	0.9210	90.2% – 97.5%	89.4% – 97.1%
2020	Landsat 8 OLI	500	96.40%	0.9510	93.0% – 98.8%	92.5% – 98.2%
2025	Landsat 9 OLI-2	520	99.15%	0.9878	97.5% – 100.0%	96.8% – 100.0%

3.2. Data Requirements for the Proposed Spatial Digital Twin Framework

The second objective of this study was to identify the geospatial and non-spatial datasets required to support the development of a comprehensive Spatial Digital Twin for Owerri Metropolis. The review of existing digital twin architectures, together with local planning requirements, indicates that an effective SDT depends on integrating heterogeneous datasets originating from multiple sources rather than reliance on a single geospatial database.

The identified datasets include Earth observation imagery, digital elevation models, cadastral information, transportation networks, hydrological features, demographic statistics, municipal planning records, meteorological observations, utility infrastructure, and real-time sensor data. Each dataset contributes a distinct function within the digital twin environment. Earth observation imagery provides periodic updates on land use dynamics and urban expansion, while digital elevation models support terrain analysis, drainage modeling, and flood

simulations. Cadastral and planning records provide information on land ownership, zoning regulations, and development approvals, enabling the framework to evaluate proposed developments against statutory planning requirements.

As a conceptual application scenario, the Spatial Digital Twin framework is structured to ingest external hydrological model outputs (e.g., HEC-RAS hydraulic profiles, SWMM runoff simulations, and in-situ stream gauge telemetry along the rivers). While detailed hydrodynamic modeling and peak discharge calculations fall outside the empirical scope of this historical baseline study, the framework's architecture specifies the data ingestion pipelines required to map hydro-meteorological risk once localized physical modeling data become available. Table 4 summarizes these proposed datasets, their technical specifications, primary sources, update frequencies, and functional roles within the Spatial Digital Twin architecture.

Table 4: Data Requirements for Owerri SDT [2] [5] [8] [23] [27]

Dataset Category	Dataset Layer Name	Technical Specifications & Formats	Primary Source Origin	Update & Sync Frequency	Integration Status & Role in SDT Framework
Remote Sensing	Landsat 8/9 & Sentinel-2	30m & 10m bands; GeoTIFF format	USGS Earth Explorer / ESA	Quarterly pull	Analyzed Baseline: Tracks macro-scale LULC transitions and urban sprawl boundaries.
Topography	SRTM DEM & LiDAR Point Clouds	30m DEM; high-density LAS/LAZ formats	USGS / Drone Survey Services	Static (DEM) / Bi-annual (LiDAR)	Analyzed Baseline: Extracts slope and elevation models for flood and runoff simulations.
Fluvial & Hydrology	River Vectors	Polylines and polygon buffers; Shapefile (.shp)	Digitized from Ortho-photos	Static	Analyzed Baseline: Delineates strict environmental "No-Build" zones and hazard boundaries.
Socio-Demographic	Census & Pop. Growth Rates	Tabular records; JSON/.csv formats	NPC Nigeria / World Bank	Decennial / Annual estimates	Analyzed Baseline: Calculates population growth rates (PGR) and per-capita infrastructure demand.
Sensing (In-Situ)	Water Level & Rain Gauge Streams	JSON time-series data; MQTT payload protocol	IoT Telemetry Networks	Hourly push to Apache Kafka	Target Future Integration: Provides real-time river levels and precipitation for early flood warnings.
Municipal Cadastre	Digital Cadastral & Layout Plans	Vector features; Post-GIS spatial format	Imo Ministry of Lands / IMOGIS	Real-time transaction sync	Target Future Integration: Integrates parcel boundaries and spatial layout plans.
Fiscal & Legal	CofO Registries & Property Geotags	Database records with lat/long metadata	IMOGIS / IIRS	Real-time stream update	Target Future Integration: Enables spatial tax auditing and boundary verification.

3.3. Proposed Spatial Digital Twin Framework for Sustainable Urban Growth Monitoring

The principal contribution of this study is the development of a concept for Spatial Digital Twin framework designed specifically for sustainable urban growth monitoring in Owerri Metropolis. The proposed architecture is designed to ingest real-time feeds, integrate geospatial technologies, urban planning information, artificial intelligence, and digital infrastructure into a unified decision-support environment capable of supporting continuous urban observation and predictive planning. The proposed framework is organized into five interconnected layers that collectively represent the flow of information between the physical city and its digital counterpart (Fig 4).

- 1) The Physical Layer: Represents the real-world urban environment and comprises buildings, transportation infrastructure, drainage systems, utilities, vegetation, water bodies, and other physical assets distributed throughout the metropolis. These components constitute the entities monitored within the digital twin environment.
- 2) The Data Acquisition and Sensing Layer: Captures information describing the state of the physical environment through multiple observation platforms. Satellite imagery, unmanned aerial vehicles (UAVs), Global Navigation Satellite Systems (GNSS), meteorological stations, river level sensors, mobile mapping systems, and municipal survey data collectively provide both periodic and real-time observations required for updating the digital representation of the city [9].
- 3) The Spatial Database and Integration Layer: Functions as the central repository for storing, managing, and harmonizing heterogeneous datasets acquired from multiple sources. The integration of PostgreSQL/PostGIS with semantic three-dimensional city models based on the CityGML standard facilitates interoperability between spatial datasets while supporting efficient storage, retrieval, and spatial querying of urban information [29].
- 4) The Analytical Intelligence Layer: Constitutes the computational engine of the framework. Machine learning algorithms, spatial analysis techniques, urban growth models, flood simulation models, and environmental assessment tools process integrated datasets to detect urban change, predict future development patterns, assess environmental risks, and evaluate planning scenarios [1]. Rather than functioning as isolated analytical tools, these models interact continuously with the central database to generate updated planning intelligence.
- 5) The Application and Decision Support Layer: Provides planners and decision-makers with an interactive environment for visualizing urban conditions, monitoring infrastructure, assessing development proposals, simulating future scenarios, and supporting evidence-based policy formulation. By integrating analytical outputs with three-dimensional visualization technologies, the framework transforms complex geospatial information into practical planning knowledge that can support sustainable urban governance.

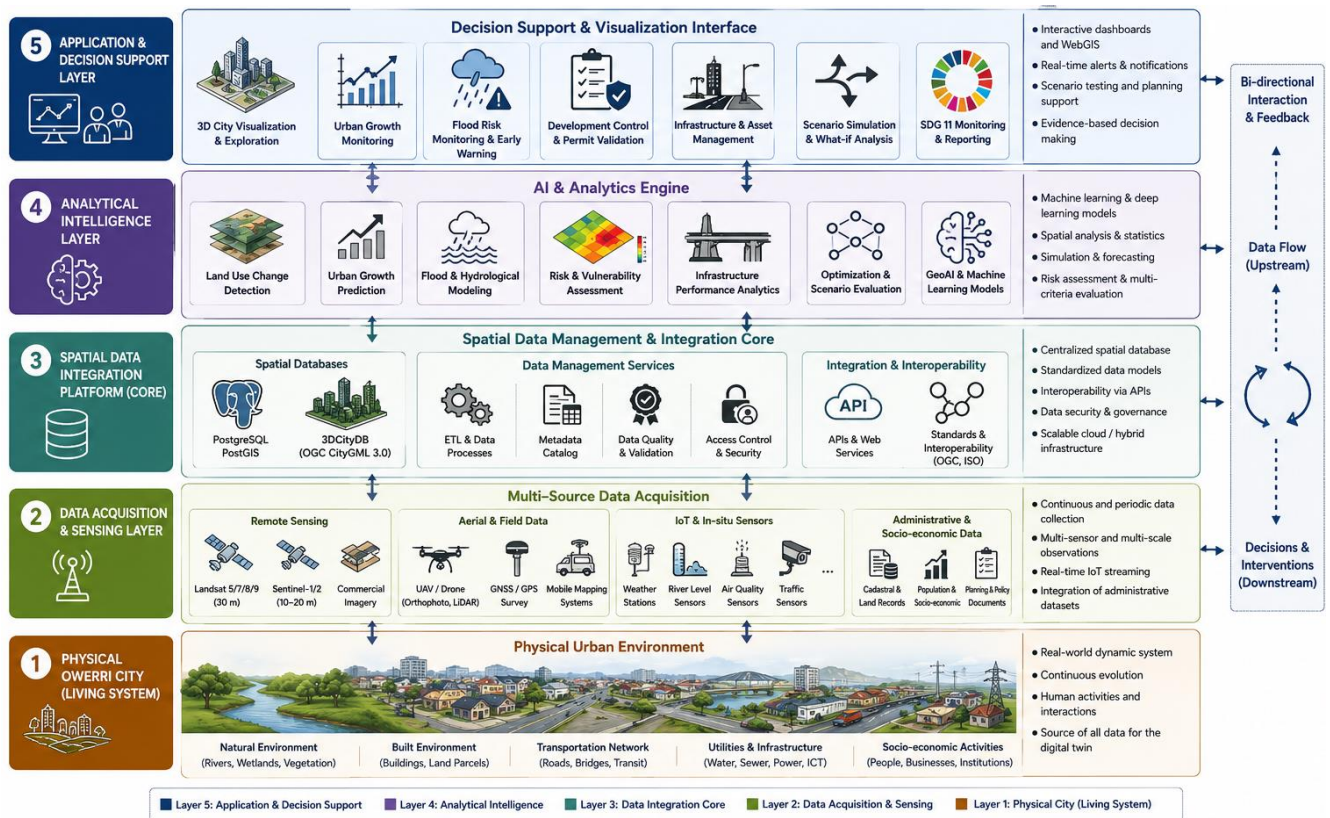


Fig 4: Architecture of the proposed Spatial Digital Twin Framework (OSDTF) illustrating the integration of physical urban systems, multi-source data acquisition, spatial data management, analytical intelligence, and decision-support components for sustainable urban growth monitoring

4. Discussion

4.1. Potential Planning Applications and Implementation Strategy

Primary Core Applications (Static/Empirical Baseline)

The primary application involves continuous urban growth monitoring, where periodic satellite imagery and administrative datasets are automatically incorporated to detect newly developed areas, identify informal settlements, and quantify changes in land use patterns [24]. Simultaneously, the framework directly addresses urban flood risk management. By combining digital elevation models, river vectors, and land cover impermeability metrics, the framework enables planners to simulate runoff conditions, delineate flood hazard zones, and evaluate the hydrological impacts of proposed developments before construction begins [6] [10] [22]. The flood risk assessment capabilities discussed in this framework represent theoretical application scenarios rather than empirical hazard delineations. Inferring flood vulnerability strictly from 30-meter SRTM DEM elevation profiles and land surface impermeability metrics provides an initial spatial indicator of runoff potential, but lacks physical hydrodynamic precision [20]. To achieve operational flood hazard mapping, future deployments must integrate high-resolution terrain models, local soil permeability parameters, rainfall-runoff modeling, and hydrodynamic river channel simulations along the drainage basins.

Secondary Horizon Applications (Conceptual System Potential)

Beyond core growth and flood modeling, the architecture establishes a foundation for digital development control (evaluating building plans against statutory setback regulations), spatial tax auditing, infrastructure asset management, and Sustainable Development Goal (SDG) 11 monitoring [5]. These advanced functions represent long-term operational horizons as local spatial data infrastructures achieve full digital maturity, involving automated permit checks, real-time hydrometric early warnings, and live traffic/infrastructure monitoring.

Institutional Constraints and Phased Deployment Roadmap

To ensure the proposed framework remains practically viable in the context of Owerri, implementation must account for local institutional and technical constraints. Factors such as power supply stability, internet bandwidth limitations, agency data-storage (e.g., between Ministry of Lands, OCDA, and IMOGIS), and initial capital investment for IoT sensor hardware represent operational challenges. To overcome these hurdles, a Phased Deployment Roadmap is formulated:

- Phase 1: Baseline Static Integration (Years 1–2): Operationalize the core PostGIS database using existing GEE satellite workflows, SRTM elevation data, and digitized municipal records. Establish inter-agency data sharing protocols.
- Phase 2: Hybrid Digital Synchronization (Years 3–4): Introduce high-resolution drone mapping, digitize building layout approvals, and link municipal tax registries to spatial parcel units.
- Phase 3: Live Sensor & IoT Deployment (Years 5+): Deploy in-situ river gauge telemetry and weather stations along the river corridors, enabling full cyber-physical feedback loops and automated flood early warning systems (Fig 5).

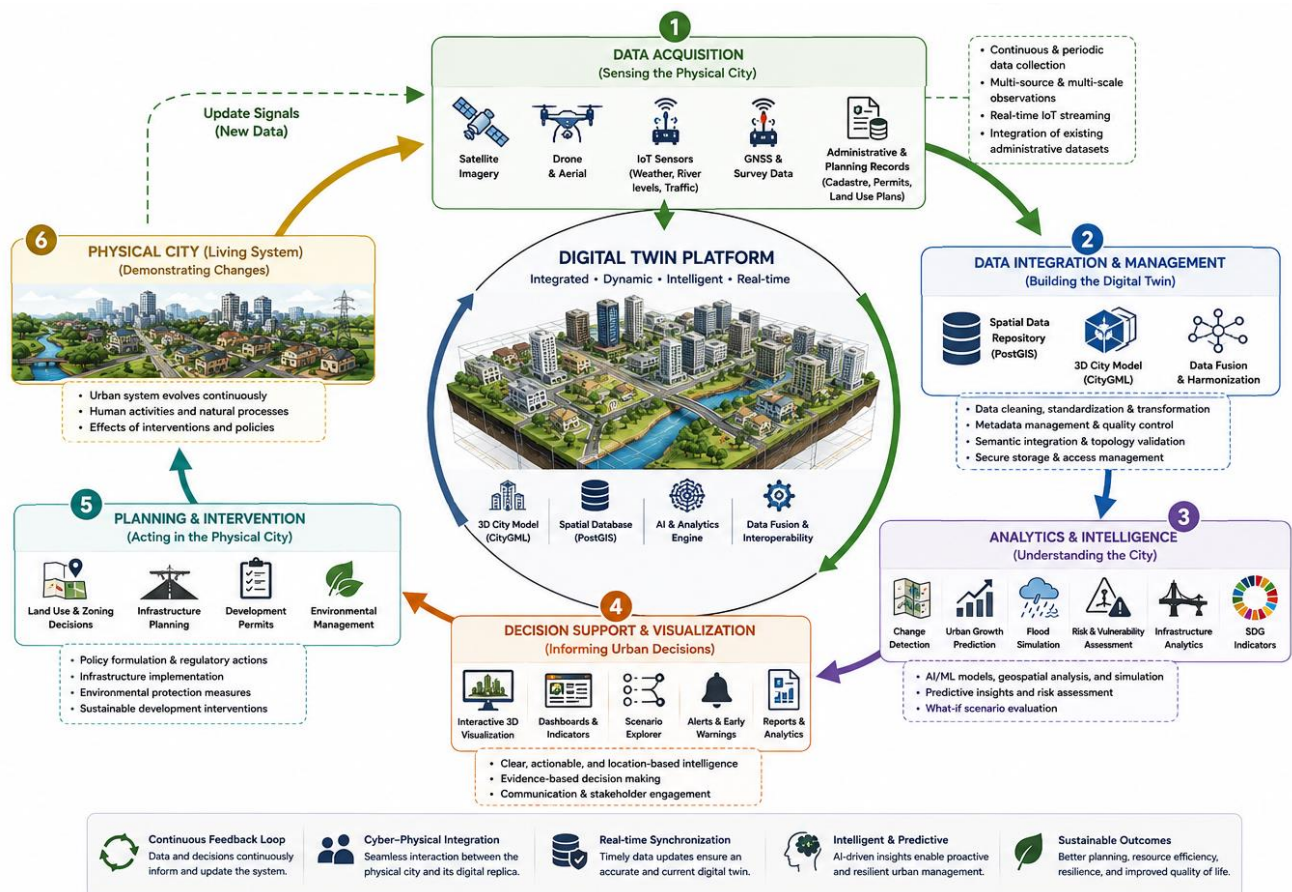


Fig 5: Operational workflow of the proposed Spatial Digital Twin illustrating the cyber-physical feedback loop from urban data acquisition through analytics, decision support, planning intervention, and continuous updating of the physical city.

4.2. Implications for Sustainable Urban Planning and Scientific Novelty

The findings of this study demonstrate that sustainable urban management requires moving beyond isolated, periodic land-use mapping. While conventional satellite remote sensing provides essential historical baselines, its standalone capacity for continuous monitoring, predictive forecasting, and real-time decision support remains constrained. The proposed Spatial Digital Twin (SDT) framework addresses these limitations by specifying a conceptual blueprint capable of progressively assimilating multi-source geospatial datasets into an integrated planning environment [29]. For rapidly urbanizing secondary cities, where institutional capacity and data infrastructures are often constrained, this framework formulates a practical roadmap for transitioning toward data-driven urban governance. By conceptualizing the integration of Earth observation, machine learning pipelines, administrative planning records, and localized sensing technologies, the framework outlines how planning authorities can better anticipate urban growth vectors, safeguard environmentally sensitive zones, and optimize infrastructure deployment.

The primary methodological contribution of this research lies in contextualizing Digital Twin architectures for data-constrained urban environments. Standard urban digital twin paradigms developed in high-resource Western or megacity contexts assume continuous real-time telemetry, dense IoT sensor networks, and centralized enterprise GIS databases. Such operational assumptions do not hold in secondary African cities like Owerri, which are characterized by rapid informal spatial growth, non-continuous sensor coverage, and delayed cadastral updates. This study advances spatial planning methodology by decoupling digital twin functionality into a tiered data-maturity model. It illustrates how static Earth observation baselines (Phase 1) can be systematically linked with periodic, low-cost UAV mapping (Phase 2) prior to physical IoT sensor integration (Phase 3). The scientific novelty resides not in replicating established Digital Twin concepts, but in structural adaptation, formulating a data-feed spatial framework tailored to the operational realities of rapidly expanding cities in the Global South. Furthermore, while contextualized using Owerri Metropolis, the integrated design offers a transferable approach for secondary cities across Sub-Saharan Africa facing comparable planning dynamics.

5. Conclusion

The rapid physical transformation of Owerri Metropolis over the past two decades underscores a critical vulnerability in conventional urban planning: static, periodic mapping cannot keep pace with dynamic, real-world urban expansion. The observed loss of natural buffer zones along the river corridors demonstrates that uncoordinated spatial growth is actively compounding environmental risks, particularly urban flooding and infrastructure strain. Reviewing land use monitoring, while valuable for documenting past change, leaves municipal authorities in a continuously reactive posture, unable to intervene before unsustainable development occurs.

To solve this operational gap, this study formulated a conceptual Spatial Digital Twin framework as an architectural blueprint for data-driven urban governance. By structuring an integrated five-layer system, spanning multi-source data acquisition, central spatial database harmonization, predictive spatial analytics, and interactive decision support, the paper provides a clear roadmap for transitioning secondary African cities from static GIS sources to continuous spatial intelligence platforms. Ultimately, the proposed framework demonstrates that achieving resilient, sustainable urban growth requires bridging the divide between multi-source geospatial data and real-time planning interventions.

To bridge the gap between this conceptual architecture and practical urban deployment, the following action-oriented recommendations are proposed:

- 1) Institutionalize an Integrated Urban Spatial Data Infrastructure (SDI): To support the framework's central data layer, key planning authorities, including the Imo State Ministry of Lands, Owerri Capital Development Authority (OCDA), and Imo State Geographic Information Service (IMOGIS), must establish interoperable database protocols. Breaking down existing agency data silos is the mandatory first step toward continuous spatial monitoring.
- 2) Establish a Phased High-Resolution Data Acquisition Pipeline: Rather than relying on low-frequency satellite updates, municipal institutions should establish routine geospatial update schedules utilizing unmanned aerial vehicle (UAV/drone) surveys and ortho-photo mapping. Regular high-resolution data capture serves as the necessary bridge toward updating 3D city models and cadastral registries.
- 3) Pilot Low-Cost Telemetry Networks in High-Vulnerability Corridors: To make the sensing layer functional without overwhelming municipal budgets, authorities should prioritize targeted deployments of in-situ IoT sensors (such as automated river-level gauges along the river basins). These micro-deployments will validate real-time data streaming for early flood warnings prior to city-wide sensor rollouts.
- 4) Enact Spatial Data Governance and Capacity Building Policies: Technical deployment must be matched by institutional readiness. Imo State planning bodies should formulate clear governance frameworks addressing spatial data sharing, cybersecurity, and system maintenance, while conducting continuous technical training for municipal staff to ensure long-term operational sustainability.
- 5) While this work establishes the empirical baseline and formulates the architectural blueprint for an SDT in Owerri, it does not claim a deployed software system. Future research must focus on developing a software prototype for Phase 1 data ingestion, executing pilot testing of the framework on specific high-density municipal layouts and performing empirical functional testing and validation of the proposed GeoAI models using live or simulated municipal streams.
- 6) A key limitation of the present baseline study is the reliance on coarse-resolution SRTM elevation metrics without coupled physical hydrological modeling. Future research would need to prioritize coupling calibrated hydrodynamic models (such as HEC-RAS or hydro-GIS extensions) with localized river gauge telemetry to validate flood hazard predictions within the Owerri urban catchment.

In summary, this study contributes to spatial science by establishing a transferable, data-feed framework that enables secondary African cities to build spatial digital baselines despite resource and data constraints. The framework bridges the gap between empirical earth observation and municipal decision-support roadmaps.

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