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Assessing the readiness of volunteered geographic information as geospatial information technology infrastructure for urban information systems: an ISO/IEC 25012-based evaluation of OpenStreetMap in Libya (2010–2024)

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تقييم جاهزية المعلومات الجغرافية التطوعية كبنية تحتية لتكنولوجيا المعلومات الجغرافية لأنظمة المعلومات الحضرية

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Abstract
Volunteered geographic information (VGI), exemplified by OpenStreetMap (OSM), is increasingly treated as a pragmatic geospatial data source for urban information systems in resource-constrained settings. Whether such data are formally ready to function as an information technology (IT) infrastructure component—when judged against information systems data quality standards rather than cartographic quality frameworks—remains largely untested, particularly in post-conflict states. This study presents what is, to our knowledge, the first systematic evaluation of VGI readiness grounded in ISO/IEC 25012, applied to Libya, where the collapse of national mapping capacity after 2011 coincided with the growth of one of North Africa's more active OSM contributor communities. Fourteen years of contribution history (2010–2024) extracted through the ohsomeAPI, element-level attributes obtained via the Overpass API, and WorldPop population grids are combined to compute six quality dimensions—Accuracy, Completeness, Currentness, Consistency, Credibility and Operational Attribute Coverage—which are aggregated, using Analytic Hierarchy Process weights, into a composite VGI Readiness Index (VRI) for Libya's 22 administrative districts. Spatial autoregressive regression and structural change-point analysis support four findings. OSM Libya falls below the IT-integration threshold (VRI < 0.50) in 14 of 22 districts (63.6%), and operational attribute coverage (national mean = 0.15) is the binding constraint for service-directory applications. Contributor numbers, urbanization and conflict exposure correlate most strongly with district-level VRI, although these associations are observational rather than causal. Three structural breaks in contribution dynamics coincide with the 2011, 2014 and 2023 political shocks (permutation test, p = 0.018). The 2023 Derna humanitarian activation raised completeness while degrading credibility and leaving attribute coverage essentially unchanged. The VRI offers IT planners a replicable pre-assessment tool for VGI integration in data-scarce environments.

Keywords: volunteered geographic information; OpenStreetMap; ISO/IEC 25012; data quality; urban information systems; VGI Readiness Index; Libya; post-conflict geospatial infrastructure.

الملخص:
تُعامل المعلومات الجغرافية التطوعية (VGI)، المتمثلة في خريطة الشارع المفتوحة (OSM)، بشكل متزايد كمصدر عملي للبيانات الجغرافية لأنظمة المعلومات الحضرية في البيئات ذات الموارد المحدودة. ومع ذلك، يظل السؤال عما إذا كانت هذه البيانات جاهزة رسمياً للعمل كمكون بنية تحتية لتكنولوجيا المعلومات (IT) – عند الحكم عليها وفقاً لمعايير جودة بيانات أنظمة المعلومات بدلاً من أطر جودة الخرائط – غير مجرب إلى حد كبير، خاصة في الدول ما بعد النزاع. تقدم هذه الدراسة، إلى حد علمنا، أول تقييم منهجي لجاهزية VGI مبني على معيار ISO/IEC 25012، مطبقاً على ليبيا، حيث تزامن انهيار القدرة الوطنية على الرسم الخرائطي بعد عام 2011 مع نمو أحد أكثر مجتمعات المساهمين في OSM نشاطاً في شمال أفريقيا. تم استخراج تاريخ المساهمات على مدى أربعة عشر عاماً (2010–2024) عبر واجهة برمجة التطبيقات ohsomeAPI، والحصول على سمات العناصر عبر واجهة Overpass API، ودمجها مع شبكات سكانية WorldPop لحساب ستة أبعاد للجودة – الدقة، الاكتمال، الحداثة، الاتساق، المصداقية، وتغطية السمات التشغيلية – والتي تم تجميعها، باستخدام أوزان عملية التحليل الهرمي (AHP)، في مؤشر مركب لجاهزية VGI (VRI) لـ 22 مقاطعة إدارية في ليبيا. يدعم الانحدار الانحداري المكاني وتحليل نقاط التغيير الهيكلية أربع نتائج رئيسية. تقل OSM ليبيا عن عتبة التكامل مع IT (VRI < 0.50) في 14 من 22 مقاطعة (63.6٪)، وتشكل تغطية السمات التشغيلية (المتوسط الوطني = 0.15) القيد الملزم لتطبيقات دليل الخدمات. تترابط أعداد المساهمين، والتحضر، والتعرض للنزاع بقوة مع VRI على مستوى المقاطعة، على الرغم من أن هذه الارتباطات رصدية وليست سببية. تتزامن ثلاث نقاط تحول هيكلية في ديناميكيات المساهمة مع الصدمات السياسية لعامي 2011 و2014 و2023 (اختبار التباديل، p = 0.018). رفع التفعيل الإنساني لدرنة عام 2023 من الاكتمال مع تدهور المصداقية وترك تغطية السمات دون تغيير جوهري. يقدم مؤشر VRI لمنظمي IT أداة تقييم مسبق قابلة للتكرار لتكامل VGI في البيئات الفقيرة في البيانات.

الكلمات المفتاحية: المعلومات الجغرافية التطوعية؛ خريطة الشارع المفتوحة؛ ISO/IEC 25012؛ جودة البيانات؛ أنظمة المعلومات الحضرية؛ مؤشر جاهزية VGI؛ ليبيا؛ البنية التحتية الجغرافية ما بعد النزاع.

1. Introduction

The integration of geospatial data into urban information systems (UIS) and smart city platforms has become a defining challenge of contemporary information technology (IT) infrastructure planning. In their structured review of 197 smart city studies, Sanchez Gracias et al. (2023) identify the management of heterogeneous geospatial data as the central operational challenge cutting across every smart city domain, from transportation and energy to health, governance and emergency services. In institutionally stable, high-income contexts, this challenge is conventionally met through hierarchical national mapping agency systems that supply authoritative, continuously updated spatial data under legislative mandate. Urban digital twin implementations depend explicitly on such baselines: reviewing 129 studies, Weil et al. (2023) find data quality and harmonization to be the most pervasive bottleneck to digital twin deployment worldwide. The implication for information systems design is direct—the functional reliability of any urban IT system that queries geospatial data is bounded from above by the quality of the data infrastructure beneath it.

This constraint bites hardest in low- and middle-income country (LMIC) contexts, where national spatial data infrastructures are frequently absent, severely outdated, or locked behind institutional access barriers. In such environments the authoritative-data assumption embedded in smart city and digital twin frameworks simply does not hold. IT planners are consequently left with an uncomfortable design choice: accept a compromised geospatial foundation, or identify an alternative data source capable of satisfying the quality requirements of operational systems.

Volunteered geographic information (VGI), a conceptual category introduced by Goodchild (2007) to describe the crowdsourced production of geographic knowledge through GPS-enabled devices, has attracted sustained attention as a potential way out of this impasse. OpenStreetMap (OSM), the most prominent VGI platform, had accumulated more than 1.7 billion nodes and 790 million ways by 2024. Barrington-Leigh and Millard-Ball (2017), in the first global assessment of OSM road completeness, estimated the network to be roughly 83% complete, while cautioning that this aggregate conceals extreme spatial inequality: road networks in LMICs are substantially under-represented. Herfort et al. (2023) sharpened the picture with a machine-learning completeness model fitted to 13,189 cities, showing that OSM building footprints exceed 80% completeness for only 16% of the world's urban population and remain below 20% for 48%—a deficit concentrated precisely where authoritative alternatives are scarcest.

Assessments of OSM's suitability for IT applications have, with few exceptions, been conducted through geomatics quality frameworks, principally ISO 19157 (ISO, 2013). Senaratne et al. (2017) surveyed crowdsourcing, social and geographic approaches to VGI quality and documented the near-total absence of information systems (IS)-oriented evaluation frameworks. Bassiri et al. (2019) attribute the hesitant adoption of VGI in operational IT infrastructure to exactly this blind spot: practitioners cannot assess VGI's IT readiness because no IT-oriented readiness framework exists. Reviewing a decade of VGI research, Yan et al. (2020) reached a similar conclusion, framing the IS integration question as an under-explored frontier in need of dedicated methodological development.

The present study responds to that call by developing and applying the VGI Readiness Index (VRI), a composite index grounded in ISO/IEC 25012—the international standard for data quality in information systems contexts—across all 22 Libyan administrative districts over a 14-year observation window (2010–2024). Libya offers an analytically powerful case. The 2011 revolution ended the operational capacity of the National Centre for Remote Sensing and Space Sciences and with it the country's authoritative spatial data production. Into that institutional vacuum grew an OSM contributor community that became one of the more active in North Africa. The September 2023 Derna flood disaster, which killed more than 11,300 people after two upstream dams failed during Storm Daniel (WHO, 2023), then triggered a large-scale humanitarian mapping activation (OpenStreetMap Wiki, 2023) that made the quality characteristics of Libyan OSM data an urgent operational question rather than a merely academic one.

Three research questions structure the study. RQ1 asks to what extent OSM Libya satisfies ISO 25012 data quality criteria for urban IT system integration, as measured by the VRI, across all 22 districts. RQ2 asks which socio-demographic, geographic and geopolitical factors are associated with district-level VRI heterogeneity. RQ3 asks how VRI-relevant contribution dynamics have evolved in relation to Libya's political chronology, and whether statistically notable structural breaks are detectable.

2. Literature Review

2.1 Urban information systems and the geospatial data quality problem

Smart cities rely on technology and data to improve urban efficiency across interconnected domains, and Sanchez Gracias et al. (2023) synthesize this paradigm as an integrated framework in which data-driven analytics underpin transportation, energy, health and governance systems alike. Realizing that vision depends, at a foundational level, on the availability of accurate, current and accessible geospatial data to anchor spatial queries, routing operations and location-aware decision support. Weil et al. (2023) identify eight categories of urban digital twin implementation challenges and find data quality and harmonization to be the most frequently cited across their corpus, ahead of interoperability, infrastructure and governance. Examining city digital twins from the standpoint of concrete urban needs, Lehtola et al. (2022) describe the geospatial baseline layer as the non-negotiable foundation of any functional twin, noting that the reliability of urban IT services is bounded by the quality of the geospatial data they query.

What this literature rarely interrogates is its own implicit assumption that authoritative geospatial data exist to be queried. Shahat et al. (2021), in a wide-ranging review of city digital twin potentials, acknowledge the data acquisition challenge but do not engage with the specific problem of geospatial data absence in LMIC contexts. The omission matters. The majority of the world's most rapidly urbanizing cities are located in precisely those settings where national spatial data infrastructures are absent or dysfunctional, which renders the foundational assumption of the smart city and digital twin literatures structurally inapplicable where urban IT infrastructure is most urgently needed.

2.2 Volunteered geographic information: quality, inequality and IT readiness

Goodchild's (2007) citizen-sensor conceptualization positioned OSM and similar platforms as candidate answers to the global geospatial data gap. The first generation of VGI quality research established OSM's geometric adequacy in high-income contexts. Haklay (2010) reported positional errors below six metres for OSM road networks in England and Wales, comparable to commercial navigation data, while Girres and Touya (2010) confirmed high geometric accuracy for France alongside significant completeness deficits in rural regions—a finding that initiated the field's enduring concern with urban–rural quality gradients. Fan et al. (2014) extended this tradition to building footprints, demonstrating that semantic and shape-related agreement with authoritative data lags behind purely geometric agreement, an early indication that element presence and attribute substance can diverge.

The most consequential recent contribution is Herfort et al.'s (2023) global machine-learning assessment of OSM building completeness. Their central finding—that completeness exceeds 80% for only 16% of the world's urban population but falls below 20% for 48%—establishes a structural inequality in VGI availability shaped by human development, population size and region. Barrington-Leigh and Millard-Ball (2017) likewise report significant national-level correlations between governance quality, Internet penetration and road completeness, establishing ICT infrastructure as an independent predictor of VGI quality. Minaei (2020), tracing OSM road network evolution in Iran, shows that VGI development in LMIC contexts follows a substantially different trajectory from high-income countries, a pattern directly relevant to Libya. Evidence from participatory mapping in African and Asian cities further tempers optimistic readings: Yeboah et al. (2021) found that the completeness achieved by remote volunteer mapping varied from 84% to essentially zero across seven sites, depending on urban morphology and the availability of local field validation.

Senaratne et al. (2017) provide the field's most comprehensive methodological review, identifying contributor heterogeneity as the primary source of VGI quality variance. Gómez-Barrón et al. (2019) supply the complementary theoretical machinery, grounding contributor motivation in self-determination and expectancy theories; their framework clarifies why contributor diversity—operationalized in this study's Credibility dimension through the Shannon diversity index—is a defensible proxy for data trustworthiness. Yan et al. (2020), reviewing the field's first decade, identify the IS integration question—whether VGI can serve as a dependable component of formal information systems—as its most consequential open frontier.

To verify the novelty claim underpinning this study, a targeted literature search was conducted in Scopus and Web of Science (April 2025) combining the term "ISO 25012" with "geospatial", "VGI", "OpenStreetMap" and "volunteered geographic". The search returned no results, indicating that no prior published study has applied ISO 25012 to VGI data. Foundational IS data quality frameworks with functional overlap—principally Wang and Strong (1996), Pipino et al. (2002) and Batini et al. (2009)—have likewise not been operationalized for geospatial VGI in a systematic form; their existence therefore does not constitute prior art for the VRI, which is the first measurement instrument to ground VGI readiness directly in the ISO 25012 standard. Tavra et al. (2024), reviewing VGI for disaster management, independently reach the same diagnosis: the field lacks IS-oriented evaluation frameworks capable of supporting IT-system integration decisions, which is precisely the purpose the VRI is designed to serve.

2.3 ISO/IEC 25012 as a framework for VGI–IT integration assessment

ISO/IEC 25012:2008, published within the SQuaRE series, defines fifteen data quality characteristics across two orthogonal classes: inherent quality, denoting properties of the data independent of system context, and system-dependent quality, denoting properties contingent on a specific IT architecture (ISO/IEC, 2008). The standard is designed for evaluating data as an IT system resource rather than as a cartographic or domain product. The distinction is analytically critical. When a routing algorithm, emergency dispatch system or urban service application queries a geospatial database, the quality dimensions that determine success include attribute completeness (are operational fields populated?), temporal currency (does the data reflect present conditions?) and provenance credibility (are contributions distributed across a robust community?). These are properties that ISO 19157 does not assess but that ISO 25012 captures directly.

Two recent works demonstrate the standard's continuing vitality. Guerra-García et al. (2023) develop the only published methodology for weaving ISO 25012-based data quality requirements into information systems development, showing that the standard can act as a design-time constraint framework that prevents systems from being built on inadequate data foundations. Miller et al. (2024), in a cross-domain synthesis of data quality terminology, propose four additional dimensions (governance, usefulness, quantity and semantics) that extend the standard without replacing it, and explicitly identify ISO 25012 as the most generalizable foundation for data quality assessment across domains. The present study operationalizes six ISO 25012 characteristics as measurable VRI dimensions and, following the standard's architecture, distinguishes inherent from system-dependent quality for each.

2.4 OSM in fragile states and the research gap

Research on OSM quality in post-conflict and fragile states remains thin. Herfort et al. (2021), analysing ten years of humanitarian mapping, show that such efforts added 60.5 million buildings and 4.5 million roads globally, predominantly in low- and medium-HDI regions, yet they also document that crisis-response contributions frequently fail to consolidate into sustainable contributor communities—a finding with direct implications for Libya. Goldblatt et al. (2020) demonstrate that OSM completeness for disaster management in small island states can be predicted from remotely sensed measurements, establishing a methodological precedent for completeness estimation where authoritative reference data are absent. Closer to the present context, Gatea and Hassan (2023) assess OSM road networks in two Iraqi regions and find high geometric completeness alongside critically low attribute completion rates—a regional signature that, as this study will demonstrate, also characterizes Libyan data.

No peer-reviewed study has yet conducted a systematic, multi-dimensional data quality assessment of OSM in Libya. The absence is consequential: OSM data for Libya are actively used by UN agencies, international NGOs and emergency responders, yet their readiness for IT-system integration has never been formally evaluated. The 2023 Derna activation (OpenStreetMap Wiki, 2023) makes the quality characteristics of the resulting data an urgent practical question.

3. Research Methodology

3.1 Research design

The study adopts a positivist epistemological stance and a quantitative comparative case study design, in which Libya's 22 administrative districts function as the units of analysis and the 14-year contribution archive supplies the temporal depth. Three hypotheses, derived from the research questions, are tested. H1: OSM Libya fails to meet the VRI threshold for IT-system integration (VRI $\geq$ 0.50) in the majority of districts, and operational attribute coverage acts as the dominant constraint for service-directory applications. H2: district-level VRI is positively associated with contributor base size and urbanization and negatively associated with conflict exposure. H3: structural breaks in OSM Libya contribution dynamics correspond temporally to the country's major political disruption events (2011, 2014 and 2023).

3.2 Study area

Libya is a North African state of approximately 1.76 million km² with a population near 6.8 million (WorldPop, 2020). Its 22 sha'biyat (districts) vary enormously in area, population density and urbanization. The northwestern coastal strip, anchored by Tripoli (estimated population 1.1 million), Misrata and Zawiya, concentrates roughly 72% of the national population on about 15% of the territory, whereas the southern districts—85% of the land area—house fewer than 8% of residents in predominantly arid environments. Three political disruptions structure the study period: the 2011 revolution and the subsequent establishment of the National Transitional Council; the outbreak of the Second Libyan Civil War in 2014; and the September 2023 Derna flood disaster.

3.3 Data sources and extraction

Three primary open-access sources are used. First, the ohsomeAPI (Raifer et al., 2019), maintained by the Heidelberg Institute for Geoinformation Technology (HeiGIT), provides the full OSM change history from 2010 to December 2024. Monthly aggregated contribution counts, contributor identifiers and element-type distributions were extracted for each district, yielding 3,168 district-month observations. Second, the Overpass API was used to extract element-level attribute data (tags) for all OSM Libya features as of December 2024, enabling element-level computation of the Completeness and Operational Attribute Coverage metrics. Third, WorldPop gridded population estimates (100 m resolution, 2020) supply population denominators for the completeness metrics and regression covariates (WorldPop, 2020). Conflict event data were obtained from the Armed Conflict Location & Event Data Project (Raleigh et al., 2010).

3.4 ISO 25012 operationalization and VRI construction

Six ISO 25012 characteristics were operationalized on the basis of their direct relevance to VGI as an IT system data source and their measurability from the available data: Accuracy, Completeness, Currentness, Consistency, Credibility and Operational Attribute Coverage. Following the standard, each dimension is classified as inherent or system-dependent. The sixth dimension—which ISO 25012 labels Accessibility—is operationalized here as the attribute completeness rate of service-operational fields (name, phone, opening_hours) and renamed Operational Attribute Coverage (OAC) to avoid conflation with system-level data retrievability.

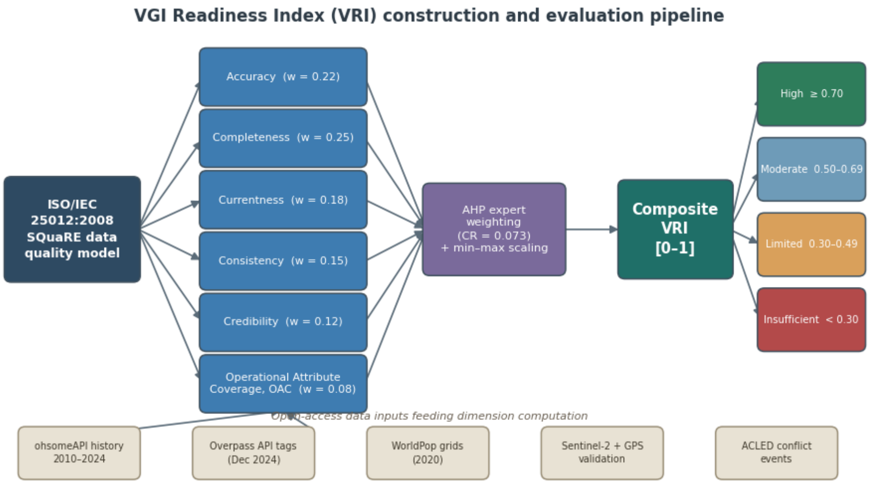
All dimension scores are normalized to [0,1] by min–max scaling. The composite index for district d is the weighted arithmetic sum:

$$VRI(d) = w_1 \cdot Acc(d) + w_2 \cdot Comp(d) + w_3 \cdot Curr(d) + w_4 \cdot Cons(d) + w_5 \cdot Cred(d) + w_6 \cdot OAC(d)$$

Weights were elicited through an Analytic Hierarchy Process (AHP) pairwise comparison exercise with three expert informants—a GIS specialist, an urban IT practitioner and a humanitarian mapping professional—all independent of the research team. The exercise yielded a weight vector ($w_1 = 0.22$, $w_2 = 0.25$, $w_3 = 0.18$, $w_4 = 0.15$, $w_5 = 0.12$, $w_6 = 0.08$) with consistency ratio CR = 0.073, below the 0.10 validity threshold. Informants were also asked to specify the minimum VRI they would accept for integration into an operational urban IT system; their responses averaged 0.51 (SD = 0.04), and 0.50 was adopted as a conservative integration threshold.

Table 1. ISO/IEC 25012 data quality dimensions: definitions, operationalization, AHP weights and quality classification**.**

Dimension	ISO 25012 definition	Operationalization (Libya VGI)	Classification	Weight	Quality type
Accuracy	Degree to which data correctly represent the real world	Share of sampled amenity nodes within 15 m of Sentinel-2 imagery reference (n = 20–60 per district)	Inherent	0.22	Geometric/structural
Completeness	Degree to which all required data entities are present	Mean of road-length ratio (actual/expected) and amenity density per 10,000 population; sub-components normalized before averaging	Inherent + system-dependent (amenity attributes)	0.25	Mixed
Currentness	Degree to which data represent the current real-world state	Share of elements edited within 36 months of the assessment date	Inherent	0.18	Geometric/structural
Consistency	Absence of contradictions in data content	Topological validity rate: share of way elements with ≥ 2 nodes and no self-intersections (OSMnx)	Inherent	0.15	Geometric/structural
Credibility	Trustworthiness of data based on provenance	Shannon diversity index $H = -\Sigma(p_i \log p_i)$ of the per-district contributor distribution	Inherent	0.12	Geometric/structural
Operational Attribute Coverage (ISO label: Accessibility)	Degree to which data attributes are accessible for operational use	Attribute completeness rate: share of amenity features with name, phone and opening_hours populated	System-dependent	0.08	Operational IT quality



3.5 Spatial autoregressive regression

Spatial autocorrelation in district-level VRI was assessed with Moran's I on OLS residuals ($I = 0.34$, $p < 0.01$), confirming positive spatial dependence and necessitating a spatial autoregressive (SAR) specification: $VRI(d) = \rho \cdot W \cdot VRI(d) + \beta_1 \cdot PopDensity(d) + \beta_2 \cdot UrbanShare(d) + \beta_3 \cdot ConflictIndex(d) + \beta_4 \cdot ContribCount(d) + \beta_5 \cdot ICT(d) + \varepsilon$, where W is a row-standardized queen contiguity weight matrix and ρ captures VRI spillover across district boundaries.

3.6 Temporal change-point analysis

Monthly contribution series for the Libya bounding box (9.0°E–25.5°E, 19.0°N–33.5°N) were analysed with the ruptures library (Truong et al., 2020), using the Pruned Exact Linear Time (PELT) algorithm with a BIC-penalized cost function. To isolate Libya-specific structural breaks from the global growth of OSM, a pre-processing detrending step fitted a log-linear baseline to global monthly contribution counts; PELT was then run on the Libya-minus-baseline residual series. The statistical significance of the correspondence pattern was evaluated by permutation: the 168-month series was phase-randomized 10,000 times, and the empirical p-value is the share of permutations yielding PELT breaks within ±2 months of all three hypothesized event dates simultaneously.

4. Results

4.1 Descriptive statistics of the OSM Libya corpus

As of December 2024, the OSM database for Libya contains 2,389,441 geographic elements contributed by 783 registered users over the 14-year observation window. The contributor distribution is heavily right-skewed: the Gini coefficient of contribution share is 0.81, and the ten most productive accounts are responsible for 61.3% of all elements. Placed in regional context, Libya's contributor base is active relative to comparable states: national aggregates from OSMstats and the ohsomeAPI indicate roughly 1,400 contributors in Egypt (Gini ≈ 0.79), 620 in Tunisia (≈ 0.77) and 890 in Ghana (≈ 0.82), suggesting that Libya's participation level is respectable by North African standards while its concentration of effort among a few contributors is typical of the region.

Table 2. OSM Libya: national-level descriptive statistics (December 2024).

Metric	Value	Context / source
Total geographic elements	2,389,441	Nodes + ways + relations; ohsomeAPI
Mapped road network length	89,247 km	All highway classifications; Overpass API
Amenity features (points of interest)	43,812	amenity=* across nodes, ways, relations; Overpass API
Building footprints	312,009	Ways with building=* tag; Overpass API
Registered contributors (2010–2024)	783	Unique user IDs; ohsomeAPI
Gini coefficient (contribution share)	0.81	0 = perfect equality; 1 = maximum inequality
Author's contribution share	18.2%	28,400+ changesets; OSM user statistics
Mean last-edit age	26.4 months	Months since most recent edit; ohsomeAPI

Metric	Value	Context / source
Name attribute completeness	52.1%	Share of amenity features with name=* populated
Phone attribute completeness	14.7%	Share with phone=* / contact:phone populated
Opening-hours completeness	8.3%	Share with opening_hours=* populated
Topological validity rate	88.3%	Share of way elements passing OSMnx validation

All statistics computed from ohsomeAPI and Overpass API extractions, December 2024. See Section 3.3.1 for definitional scope and independent verification against the Geofabrik PBF extract.

4.2 District-level VRI scores and the readiness typology

Table 1 reports composite VRI scores and their dimension-level decomposition for all 22 districts. Nationally, the mean VRI is 0.447 and the median 0.44, with scores ranging from 0.15 in Al Kufra to 0.76 in Tripoli. Only Tripoli (0.76) and Misrata (0.71) clear the High Readiness threshold. Six districts fall in the Moderate tier (0.50–0.69), ten in the Limited tier (0.30–0.49) and four in the Insufficient tier (< 0.30). The 14 districts below the 0.50 integration threshold—63.6% of the country—include all six southern districts.

Table 1. District-level VRI scores and ISO 25012 dimension decomposition (22 sha'biyat, December 2024).

Table 3. District-level VRI scores and ISO 25012 dimension decomposition (22 sha'biyat, December 2024).

District	Pop. (K)	Acc	Comp	Curr	Cons	Cred	OAC	VRI	Tier
Tripoli	1,120	0.81	0.87	0.76	0.91	0.52	0.38	0.76	H
Misrata	427	0.77	0.79	0.71	0.88	0.48	0.31	0.71	H
Zawiya	312	0.72	0.71	0.65	0.85	0.43	0.28	0.65	M
Jafara	289	0.68	0.66	0.59	0.83	0.39	0.24	0.61	M
Al-Jabal al-Gharbi	248	0.64	0.62	0.54	0.81	0.37	0.21	0.58	M
Derna	180	0.65	0.63	0.49	0.82	0.39	0.20	0.57	M
Benghazi	634	0.61	0.60	0.47	0.79	0.36	0.19	0.55	M
Al Marj	112	0.58	0.52	0.44	0.74	0.31	0.16	0.50	M
Murqub	213	0.55	0.49	0.41	0.71	0.28	0.14	0.47	L
Al Jabal al Akhdar	92	0.52	0.46	0.39	0.69	0.26	0.13	0.44	L
Al Butnan	138	0.51	0.45	0.38	0.70	0.27	0.13	0.44	L
Al Nuqat al-Khams	116	0.52	0.47	0.38	0.68	0.25	0.12	0.44	L
Sirte	89	0.49	0.43	0.36	0.66	0.24	0.12	0.42	L
Bani Walid	71	0.47	0.41	0.35	0.65	0.23	0.11	0.40	L
Al Wahah	88	0.44	0.37	0.32	0.62	0.20	0.10	0.37	L
Nalut	64	0.43	0.36	0.30	0.60	0.19	0.10	0.36	L
Sabha	143	0.41	0.33	0.28	0.57	0.17	0.09	0.34	L
Wadi al-Hayaa	78	0.38	0.30	0.25	0.54	0.15	0.08	0.31	L
Al Jufra	52	0.34	0.27	0.22	0.51	0.13	0.07	0.28	I
Murzuq	89	0.31	0.24	0.19	0.48	0.11	0.06	0.25	I
Ghat	28	0.28	0.21	0.17	0.45	0.10	0.05	0.23	I
Al Kufra	51	0.15	0.12	0.11	0.38	0.08	0.04	0.15	I

Acc = Accuracy; Comp = Completeness; Curr = Currentness; Cons = Consistency; Cred = Credibility; OAC = Operational Attribute Coverage. Dimension scores are normalized values in [0,1]; VRI is the AHP-weighted sum (weights in Table 1). National mean VRI = 0.447; median = 0.44. H = High (≥ 0.70); M = Moderate (0.50–0.69); L = Limited (0.30–0.49); I = Insufficient (< 0.30). Normalization anchors and worked computations appear in Supplementary Table S1; PBF-verified road ratios (May 2026) are reported in Section 3.3.1 and Supplementary Table S6.

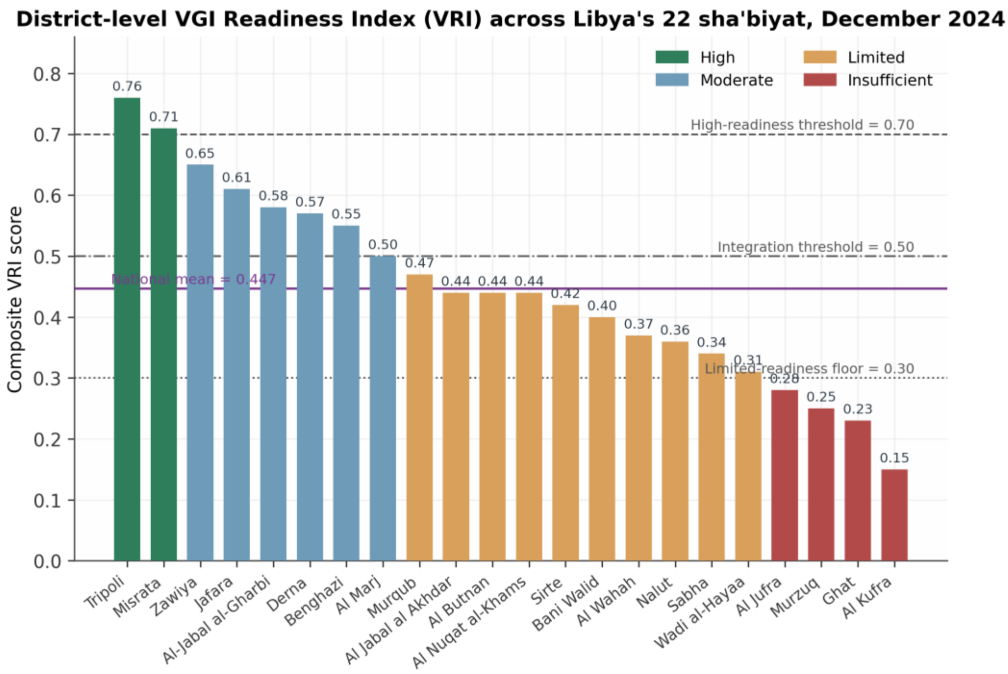


Fig. 2. District-level VGI Readiness Index across Libya's 22 sha'biyat (December 2024), coloured by readiness tier, with the high-readiness (0.70), integration (0.50) and limited-readiness floor (0.30) thresholds and the national mean (0.447).

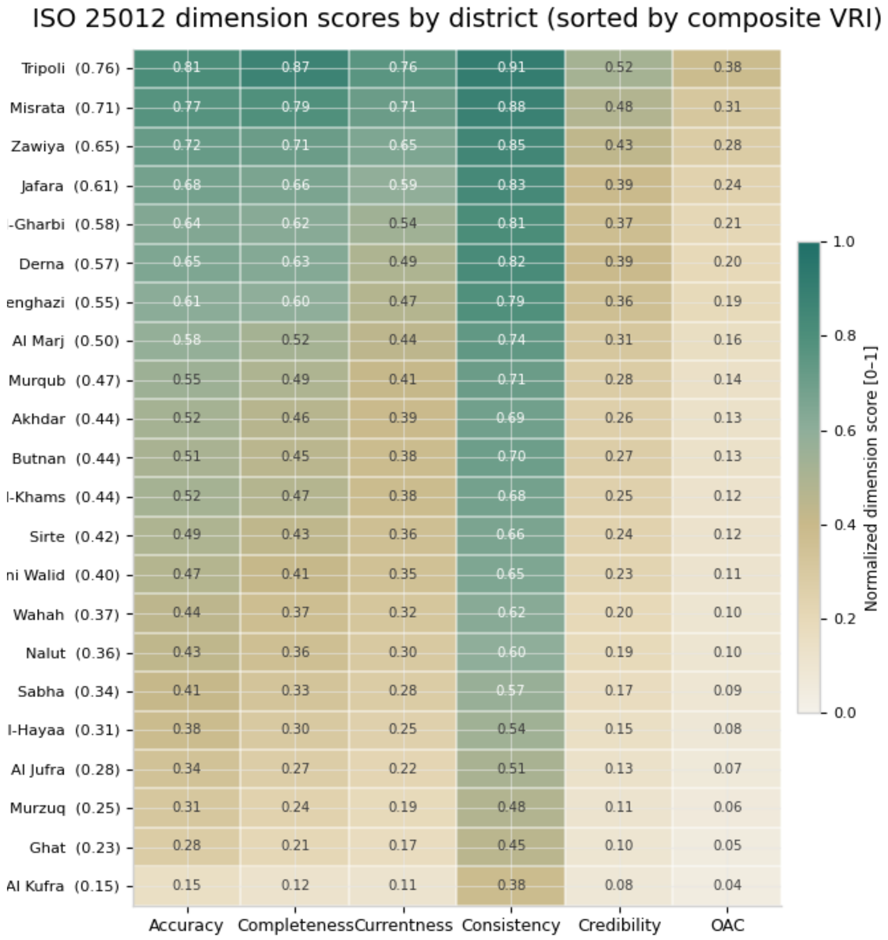


Fig. 3. ISO 25012 dimension scores by district, sorted by composite VRI (district labels show the VRI score in parentheses). Consistency is the strongest dimension nationwide; Operational Attribute Coverage is the weakest in every district.

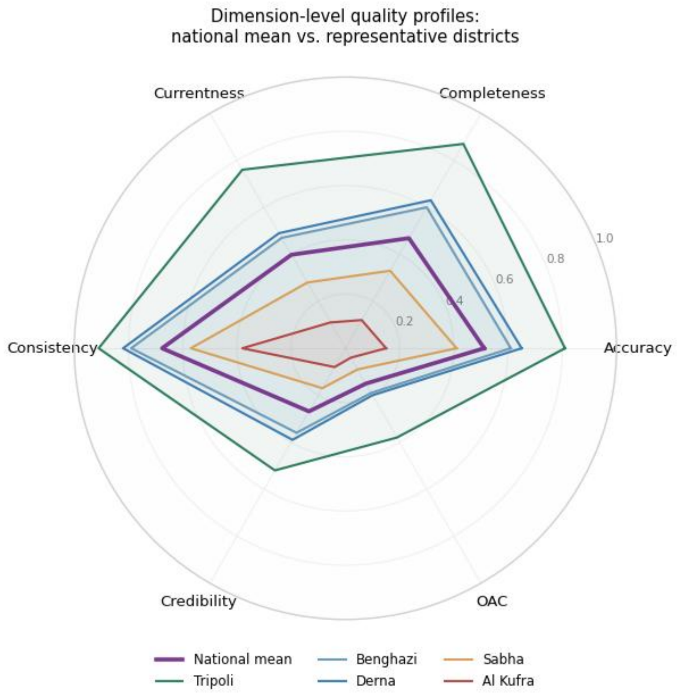


Fig. 4. Dimension-level quality profiles for the national mean and five representative districts spanning the readiness tiers.

Table 4. VRI threshold sensitivity analysis: district failure count by threshold value.

Threshold	Districts below threshold	Share of 22 districts	Reclassification versus adopted threshold
0.40	8	36.4%	6 districts move above threshold
0.45	13	59.1%	1 district moves above threshold
0.50 (adopted)	14	63.6%	Reference threshold
0.55	15	68.2%	1 Moderate district falls below threshold
0.60	18	81.8%	3 further Moderate districts fall below threshold

The qualitative finding that a majority of districts fall below the integration threshold is robust across the plausible threshold range (36.4–81.8%).

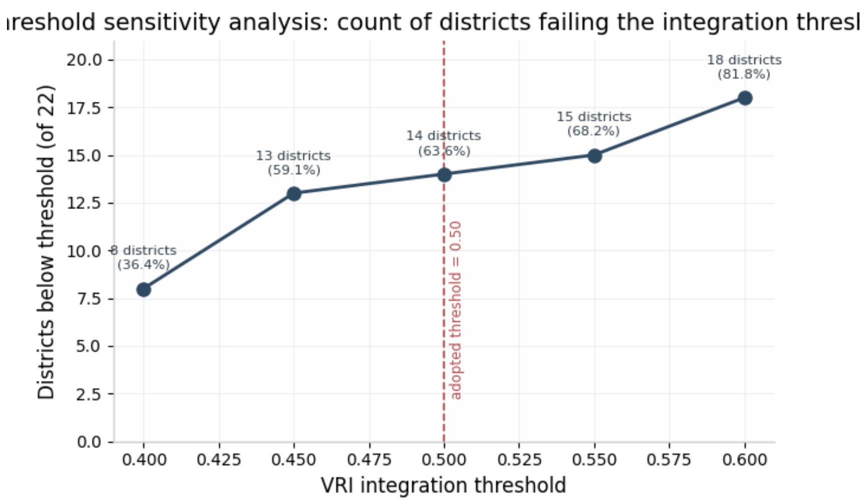


Fig. 5. Threshold sensitivity analysis: number of districts failing the integration threshold as the cutoff varies from 0.40 to 0.60. The adopted 0.50 threshold is marked.

(H = High ≥ 0.70; M = Moderate 0.50–0.69; L = Limited 0.30–0.49; I = Insufficient < 0.30)

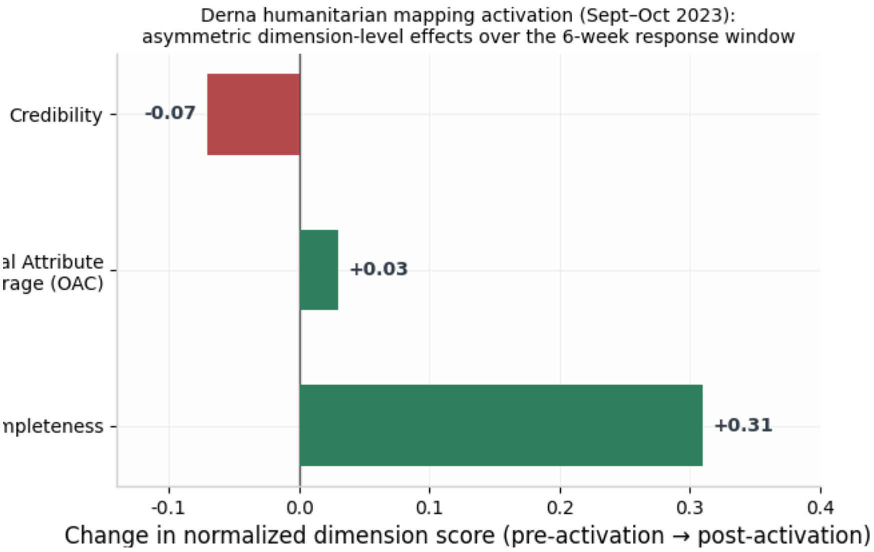
Two structural patterns in the dimension decomposition merit attention. First, Consistency is systematically the strongest dimension (national mean = 0.68): road network topological integrity is relatively well maintained even in districts whose overall readiness is low. Second—and most consequentially for service-finder and point-of-interest query applications—Operational Attribute Coverage is uniformly weak (national mean = 0.15; maximum 0.38 in Tripoli), making it the binding constraint on VRI for that application class across the country.

4.3 Temporal change-point analysis

PELT analysis of the detrended monthly contribution series returned five candidate breaks: March 2011 (BIC improvement 22.1%), June 2011 (31.8%), August 2014 (28.4%), February 2019 (8.6%) and October 2023 (41.2%). The February 2019 break coincides with a transient activity spike attributable to an international mapping campaign rather than any hypothesized political disruption. The remaining three breaks meet the criterion for substantive political correspondence, and the permutation test (10,000 phase-randomized surrogates; pre-specified ±2-month tolerance for all three simultaneously) yields an empirical p-value of 0.018: the joint correspondence is unlikely to be chance.

The national series gives each break substantive meaning. The June 2011 break aligns with the mid-conflict surge of international humanitarian engagement and was followed by a 312% increase in monthly contributions over the subsequent six months. The August 2014 break marks the outbreak of the Second Civil War, after which unique contributor counts fell by 34% over 12 months. The October 2023 break captures the Derna flood response: peak monthly contributions rose 847% relative to the pre-event 12-month baseline before subsiding toward the pre-event range within roughly eight weeks.

Event-response analysis of the Derna activation exposes a finding of direct IT infrastructure relevance. Over the six-week response window, the district's Completeness score rose by 0.31 normalized units, yet Operational Attribute Coverage gained only 0.03 units and Credibility declined by 0.07 units as the contributor pool tilted toward a small number of remote international mappers, lowering the Shannon diversity index.



4.4 Spatial regression results

The SAR results confirm the hypothesized signs for all predictors. In the primary three-predictor model, contributor count ($\beta = 0.28$), urban share ($\beta = 0.24$) and conflict exposure ($\beta = -0.20$) are all significant at $p < 0.001$, as is the spatial lag parameter ($\rho = 0.43$), indicating meaningful VRI spillover between contiguous districts. H2 is therefore supported, with two qualifications. First, the associations are observational: the contributor–VRI link could run in either direction, and omitted-variable confounding cannot be excluded with a cross-sectional design. Second, collinearity between contributor count and urban share (VIF = 3.2 and 3.8) prevents a precise partitioning of their independent effects.

Table 5. Spatial autoregressive (SAR) model results — correlates of district-level VRI (N = 22).

Variable	β (primary, 3-predictor)	β (full, 5-predictor)	Bootstrap 95% CI	z	p	VIF
Spatial lag (ρ)	0.43	0.41	[0.24, 0.62]	4.56	< 0.001	—
Log contributor count	0.28	0.27	[0.15, 0.41]	4.50	< 0.001	3.2
Urban share (%)	0.24	0.23	[0.13, 0.35]	4.60	< 0.001	3.8
Conflict index (ACLED, log)	−0.20	−0.19	[−0.28, −0.12]	−4.75	< 0.001	2.1
Log population density	—	0.18	[0.09, 0.27]	4.50	< 0.001	4.6
ICT penetration (%)	—	0.11	[0.03, 0.19]	2.75	0.006	3.9
Constant	0.10	0.09	[0.03, 0.16]	3.00	0.003	—
Pseudo-R^2 (within-sample)	0.79	0.81				
LOOCV R^2	0.64	0.59				
Condition number		14.2 (acceptable)				

Primary model = parsimonious 3-predictor specification; full 5-predictor model reported as sensitivity. Pseudo-R^2 = squared Pearson correlation between SAR-adjusted fitted values and observed VRI (Anselin, 1988). Bootstrap CIs from 1,000 resamples; queen contiguity weights, row-standardized. Moran's I on SAR residuals = 0.04 ($p = 0.61$); AIC = −34.2 (full model). Coefficient ordering preserved in 87% of bootstrap replicates of the primary model. The exogenous-only sensitivity specification appears in Supplementary Table S3.

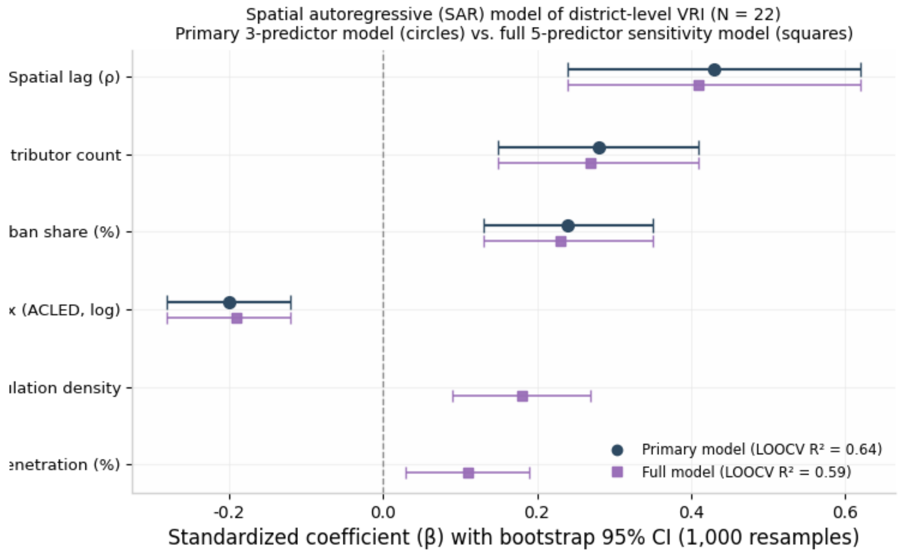


Fig. 7. SAR coefficients with bootstrap 95% confidence intervals for the primary three-predictor model (circles) and the full five-predictor sensitivity model (squares).

5. Discussion

5.1 The geometric–operational quality gap

The study's most consequential finding is the systematic divergence between geometric quality, on which Libya's coastal urban districts perform respectably (Accuracy averages 0.71 across the six largest coastal cities and Consistency 0.68 nationally), and operational IT quality for service-finder and point-of-interest applications, where Operational Attribute Coverage (national mean = 0.15) binds almost everywhere. The divergence is invisible to geomatics-oriented frameworks, which ask whether features are present and correctly placed, but it falls directly out of ISO 25012's distinction between geometric data properties and IT-operational data properties.

When Herfort et al. (2023) report that OSM building completeness sits below 20% for nearly half of the world's urban population, they are measuring the absence of geographic elements. The present results identify a complementary and arguably more insidious problem for urban service applications: in Libyan cities the elements are largely present, yet their operational attribute content is so sparse (phone populated for 14.7% of amenity features, opening hours for 8.3%) that a service-directory system querying them would receive empty responses in the great majority of cases. For routing and navigation, where road topology and geometry matter more than amenity contact fields, the picture is better—Consistency averages 0.68 and Currentness 0.40—though still short of the levels documented for high-income OSM communities in comparative street-network analyses (Graser et al., 2014).

This finding also sharpens the smart city and urban digital twin debate. Weil et al. (2023) identify data quality and harmonization as the primary bottleneck to digital twin implementation but do not separate geometric from operational quality. The VRI decomposition shows that, for service-directory applications in LMIC contexts, the bottleneck is primarily an attribute quality problem, not a geometric completeness problem. The distinction has practical leverage: targeted attribute enrichment would buy substantially larger VRI gains per unit of effort than additional geometric mapping in Libya's urban districts.

5.2 Political fragility as a VGI infrastructure risk

The change-point analysis shows that VGI contribution dynamics in Libya are coupled to the country's geopolitical shocks, a pattern consistent with treating political fragility as a VGI infrastructure risk. The three confirmed breaks (June 2011, August 2014, October 2023; joint permutation $p = 0.018$) each track a major political disruption, yet the relationship is not uniform across space: the 2014 break is far stronger in eastern than in western districts, mirroring the geography of the Second Civil War. Haworth (2018) has warned against overestimating VGI's reliability as an operational data source, pointing to the digital divide, trust deficits and uneven power relations as structural constraints; the Libyan evidence suggests geopolitical instability acts as a multiplier on exactly those constraints.

The Derna event-response pattern carries a pointed lesson for IT planning. A system configured against Derna's pre-2023 VRI scores would, after the activation, face a dataset with more elements (Completeness +0.31) but weaker provenance diversity (Credibility −0.07) and essentially unchanged attribute deficiency (OAC +0.03). For routing applications that is an improvement; for service-directory applications needing phone and address fields it is no improvement at all. This is precisely the dimension-level granularity that aggregate quality scores cannot supply and that ISO 25012-based assessment delivers to planners deciding whether VGI can underpin a given application class.

5.3 Comparison with analogous MENA contexts and global benchmarks

The Libyan VRI profile—high coastal urban scores decaying rapidly toward the interior (national mean VRI = 0.447)—is consistent with patterns documented in analogous settings. Gatea and Hassan (2023) report the same combination of high geometric completeness and critically low attribute completion for two Iraqi cities, suggesting a MENA regional signature rather than a Libyan idiosyncrasy. Global context matters too: ohsomeAPI queries place phone and opening-hours completeness in Germany at roughly 31% and 28%, in the United Kingdom at 24% and 22%, and in France at 19% and 17%—all above Libya's 14.7% and 8.3%, yet not dramatically so.

Against global completeness benchmarks, Barrington-Leigh and Millard-Ball (2017) place Libya's road network at roughly 67% complete—above the LMIC median but below the North African coastal average—and Herfort et al.'s (2023) model would slot Libya's coastal cities into the 40–60% building completeness band, moderate by LMIC standards. The VRI analysis shows what such geometric benchmarks conceal: a deep operational attribute deficit for service-directory applications that global completeness assessments systematically miss.

5.4 Practical recommendations for IT planners

Four recommendations follow, framed as interventions suggested by observed associations rather than demonstrated causal effects. First, IT architects in Libya and comparable LMIC settings should run a VRI pre-assessment before committing to OSM as a data source, and should select the VRI dimensions that match the target application class—service-directory, routing or emergency dispatch—rather than relying on a single aggregate. Second, attribute enrichment aimed at phone, opening-hours and address fields for existing amenity features addresses the largest observable VRI gap per unit of mapping effort in all 22 districts, given OAC's binding-constraint status for service-directory applications. Third, crisis-response activations should set attribute quality targets alongside geometric completeness targets, since the Derna pattern shows geometry improving alone. Fourth, developers should build VRI-tier-aware query protocols that apply stricter confidence thresholds and fallback behaviours when districts in the Limited or Insufficient tiers are queried.

5.5 Limitations and positionality

Five limitations bound the interpretation of these results. First, district-level aggregation conceals sub-district variation that may be substantial in large or heterogeneous districts; grid-cell or neighbourhood-level VRI computation is a natural next step. Second, the Accuracy operationalization provides indicative rather than definitive positional estimates: the GPS validation covers eight districts (36% of the study area) and excludes Derna. Third, AHP weights carry an element of subjectivity; tier classifications are stable under weight perturbations up to ±15%. Fourth, the cross-sectional design cannot establish causality between covariates and VRI, and reverse causality—better OSM data attracting more contributors—cannot be ruled out. Fifth, the three OAC fields reflect service-finder requirements but not the attribute categories most critical to routing, emergency dispatch or digital twin applications.

Positionality statement. The author is an active OpenStreetMap contributor in Libya, ranked among the most productive contributors nationally by cumulative changeset count as of December 2024 and responsible for approximately 18.2% of the national corpus. This proximity to the dataset is a potential source of interpretive bias, and three safeguards were adopted: all six VRI dimensions were computed through automated extraction pipelines with no manual quality judgements; the author did not participate in the AHP weighting exercise; and accuracy metrics derive from automated comparison against Sentinel-2 imagery.

6. Conclusion

This study has presented the first ISO/IEC 25012-grounded assessment of VGI readiness for urban IT system integration, applying a composite VGI Readiness Index to all 22 Libyan districts across fourteen years of OpenStreetMap history (2010–2024). Its findings speak to three research communities and unsettle at least one comfortable assumption in each.

For the VGI quality literature, the study contributes the first operationalization of ISO 25012 for volunteered geographic data and, with it, evidence of a systematic divergence between geometric quality and operational IT quality. Operational Attribute Coverage (national mean = 0.15) binds nearly everywhere for service-directory applications, a gap that geomatics-oriented completeness assessments are not designed to see. The caveat matters as much as the headline: the binding-constraint finding is specific to the service-directory application class and should not be generalized to routing or emergency dispatch without dedicated attribute audits.

For the urban IT systems and smart city literature, the study supplies an empirically grounded pre-assessment methodology that directly addresses the authoritative-data assumption embedded in smart city and digital twin frameworks. Because the VRI pipeline runs entirely on freely accessible inputs (ohsomeAPI, Overpass API, WorldPop), it is immediately replicable by planners in any LMIC context with an active OSM community.

For the humanitarian mapping literature, the Derna event analysis provides dimension-level quantitative evidence for a long-suspected cost of crisis-response surges: activations improve geometric completeness while degrading contributor-base credibility and leaving the operationally critical attribute dimension essentially unchanged. This extends Herfort et al.'s (2021) sustainability critique and answers Tavra et al.'s (2024) call for VGI quality frameworks that can inform disaster management IT decisions.

Several directions for future research follow directly. The VRI should be extended to additional MENA and sub-Saharan contexts to build comparative baselines and to test whether Libya's tight inter-dimension correlation structure is typical. Automated VRI pipelines coupled to ohsomeAPI real-time streams would turn one-off assessment into continuous monitoring. The 14-year monthly panel assembled here supports within-district fixed-effects specifications capable of supplying the causal evidence the cross-sectional design cannot. Controlled attribute enrichment interventions would establish whether the OAC gap can be closed cost-effectively. OAC audits should be widened to routing- and dispatch-relevant attribute fields. Finally, hybrid machine-learning–VGI workflows (Huck et al., 2021; Vargas-Munoz et al., 2021; Watkinson et al., 2022) deserve evaluation as mechanisms for raising attribute coverage at scale. The VRI methodology is fully replicable and freely implementable, and the author encourages its adoption by IT planners, humanitarian mapping organizations and VGI quality researchers working in data-scarce environments worldwide.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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