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A Feasibility Assessment of an Extended LADM: Enhancing Land Administration Systems Through Object-Relational Database Management

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ABSTRACT

The modernisation of land administration systems (LAS) is essential for enhancing sustainable land management, particularly in developing countries where the challenges of population growth, climate change, and resource scarcity are most pronounced. This paper evaluates the feasibility of implementing an extended land administration domain model (LADM), tailored to the specific needs of developing countries. This study employs an object-relational database management system, PostgreSQL, with its spatial extension PostGIS, to implement the extended LADM. This approach allows for the incorporation of data elements driven from global initiatives, such as those elements reflecting gender equality, indigenous rights, and informal land tenure, into the LAS framework. The process involves extracting and modifying data definition language (DDL) specifications from enterprise architecture frameworks to align with the specific project requirements. The feasibility of the extended LADM is validated through a series of queries that demonstrate the model's enhanced capabilities in addressing critical land administration challenges. This research contributes to the field by offering a standardized data management framework with a focus on less recognized land ownership rights, ensuring more inclusive and effective LAS.

1 | Introduction

The modernisation of land administration systems (LAS) is a critical component in promoting sustainable land management, particularly in developing countries where challenges such as population growth, climate change, and resource scarcity are most pronounced (Williamson et al. 2010). Despite the efforts of international initiatives and organizations, the absence of legally recognized land information management in various countries highlights the ongoing inefficiencies in LAS (Jahani Chehrehbargh et al. 2023).

The land administration domain model (LADM) (ISO 2012) provides a standardized structure for LAS, but its application in diverse contexts, especially in developing countries, necessitates further extension and adaptation (Van Oosterom et al. 2022).

Although LADM's broad applicability is well recognized, its largely conceptual nature and the absence of detailed implementation guidance present significant challenges in real-world deployment (Rajabifard et al. 2021). Converting LADM from a conceptual framework into a fully operational system demands not only semantic and structural adaptations but also technical integration into modern databases (Kara et al. 2023; Lemmen et al. 2021; Rajabifard et al. 2021; Shahidinejad et al. 2024).

The conceptual data models are critical in identifying objects, their relationships, and their constraints in any given domain,

providing a foundational framework for more detailed data modeling processes (Atzeni et al. 2020). However, without practical implementation guidelines, conceptual models, such as LADM, remain difficult to translate into fully operational physical models. For instance, Bar-Maor and Smyth (2022) noted that converting LADM into a usable physical model within real-world production systems often requires manual adjustments, significant expertise, and adaptations to meet specific local land administration needs. This includes addressing essential aspects like data integrity, referential integrity, and the accurate representation of spatial and temporal relationships, further complicating its implementation.

One of the main objectives of converting a conceptual model into a physical model is to reduce ambiguity and create a more manageable, scalable system (Elmasri 2008). Highlights the importance of physical models for achieving this goal, as they provide more concrete representations of relationships and constraints. However, transforming LADM into a functional physical model within a production system introduces multiple challenges, including ensuring complex relationships, handling large datasets, and integrating spatial data, which often requires specialized tools and a deep understanding of both the data and the specific requirements of local land administration systems (Shahidinejad et al. 2023).

Advances in database management systems, particularly in handling spatial data, provide promising solutions to these challenges. According to Shahidinejad et al. (2024), relational database management systems, such as PostgreSQL/PostGIS and Oracle, have significantly improved the ability to store, manage, and query both 2D and 3D cadastral data. Many of the same database management principles—such as spatial indexing, data integrity, and scalability—are equally applicable to both 2D and 3D data in cadastral systems. This suggests that recent advancements in database technology can be leveraged to improve the digital management of land administration data, offering enhanced processing, storage, and querying capabilities that align with the needs of developing countries.

The use of object-relational database management systems (ORDBMS) like PostgreSQL offers significant advantages for modernizing LAS. These systems allow for the seamless integration of spatial and nonspatial data, enabling land administration professionals to perform complex queries, visualize data, and manage large datasets efficiently (Ramakrishnan and Gehrke 2002). Moreover, the database development lifecycle, which includes stages, such as design, implementation, and evaluation, ensures that the system is continuously optimized for performance and scalability (Coronel and Morris 2019).

The physical schema of a database can be directly derived from the conceptual schema using data definition language (DDL), with the aid of binding rules that guide the transformation process. Tools like enterprise architect (EA) facilitate this conversion by allowing the extraction of DDL from unified modeling language (UML) class diagrams. This helps to generate the necessary SQL scripts for creating the physical database model. However, this process often requires some manual adjustments to ensure that complex relationships, constraints, and spatial data types are accurately implemented within the database system (Shahidinejad et al. 2024).

This study proposes an extension of the LADM, implemented within PostgreSQL with the PostGIS extension, to create a more inclusive and responsive LAS framework. The extended model introduces new data elements and structures that enhance the capacity of LAS to manage issues related to gender sensitivity, indigenous land rights, and informal tenure. The feasibility of this extended LADM is validated through a series of queries and implementations within PostgreSQL, demonstrating its enhanced capabilities in addressing the complexities of land administration. This research offers an LADM-based database management framework for policymakers and land administration professionals seeking to modernize LAS in alignment with global sustainability goals.

The structure of this paper is as follows: Section 2 provides an overview of the LADM and highlights its significance in diverse jurisdictions and the challenges faced during its implementation. Section 3 outlines the methodology for extending the LADM and details its practical implementation within PostgreSQL, emphasizing the role of ORDBMS in supporting the LADM model. Section 4 presents the development of the LADM-based database and queries, illustrating how the model integrates global parameters to address critical land management challenges, especially for vulnerable and marginalized communities. Section 5 focuses on query execution, providing insights into the practical application of the extended model by executing SQL queries within PostgreSQL and visualizing the results using QGIS. Finally, Section 6 concludes with a summary of the research's contributions, emphasizing the successful implementation of the extended LADM and its potential to modernize LAS in developing countries.

2 | Overview of the LADM

A well-designed land administration data model plays a central role in facilitating equitable and inclusive land management, serving as the foundation for integrating, exchanging, and managing data related to rights, ownership, and spatial units (ISO 2012; Lemmen et al. 2015). In response to diverse and evolving tenure contexts, several data models have emerged or been adapted, including the land administration domain model (LADM), the infrastructure for spatial information in Europe (INSPIRE) (Abramic et al. 2018; Sjoukema et al. 2022), and the social tenure domain model (STDM), which functions as a methodology derived from LADM (Antonio et al. 2015; Chen et al. 2024).

STDM was specifically developed to address the needs of socially legitimate but unregistered land tenures, including informal and customary systems. It allows for participatory data collection and flexible representation of land rights that are not formally recorded or tied to surveyed parcels. Although the acronym stands for "model," STDM is best understood as a methodological framework, encompassing formal and informal tenures, spatial elements, and social relationships. It is particularly valuable in community-driven settings where participatory mapping and inclusive land governance are emphasized. Although STDM offers a bottom–up, participatory approach to informal tenure, and prior extensions address specific gaps, the developed LADM provides a unified and technically implementable framework suitable for national-level system reform.

The LADM is an international standard (ISO 19152-1:2024) designed to facilitate the recording, management, and dissemination of land-related information. It serves as a conceptual study employs a framework that provides a standardized way of representing land administration information across different jurisdictions, thereby enhancing interoperability, data exchange, and the overall quality of LAS.

2.1 | Background and Purpose of LADM

LADM was developed to address fragmentation in land administration systems, offering a consistent data model across different legal and institutional contexts (Williamson et al. 2010). Its primary objective is to define standard classes for land parcels, rights, responsibilities, restrictions (RRRs), and associated parties. By offering this common structure, LADM enhances the potential for interoperability and coordinated land governance globally.

The first edition of LADM, published in 2012, laid the foundation for creating a global standard in land administration by addressing the fundamental components of land information. This edition focused on establishing a conceptual framework that could be applied universally, regardless of the legal or administrative differences among countries (ISO 2012).

The implementation of LADM Edition I opens up opportunities for land administration (LA) service providers and vendors in GIS, document management systems, and database management systems (DBMS) to introduce innovative products, services, and applications for LA. This, in turn, enables land registries and cadastral organizations to design, develop, implement, and maintain their systems with improved efficiency (Kara et al. 2023). In response to the evolving demands of modern land administration, a second edition of LADM is currently under development. This upcoming version aims to address several limitations of the first edition, particularly by broadening its scope to include additional domains such as valuation, spatial planning, and marine cadastre. The second edition will also focus on improving support for 3D and 4D cadastres while integrating cutting-edge technological advancements, including blockchain and artificial intelligence, to meet the future needs of land governance (Kalogianni et al. 2022).

2.2 | Structure and Key Components of LADM

LADM is structured into several packages, each of which addresses a specific aspect of land administration. These packages include:

- Party package represents the parties involved in land administration, such as landowners, tenants, and governmental organizations. It includes attributes like names, roles, and relationships between parties.
- Administrative package handles the rights, restrictions, and responsibilities (RRRs) associated with land parcels. It defines how these RRRs are represented and managed within a land administration system, including legal and administrative boundaries.
- Spatial unit package deals with the spatial representation of land parcels, including their geometry, topology, and spatial relationships. It allows for the representation of both 2D and 3D parcels, making it suitable for various types of land tenure systems.
- Surveying and representation subpackage: This package is concerned with the methods and tools used to capture and represent the spatial data associated with land parcels. It includes surveying processes, accuracy standards, and the integration of survey data into the LAS.

The revision of LADM into Edition II represents an evolution of the model to address emerging needs and challenges in land administration. Unlike the first edition, which focused primarily on core elements such as parties, rights, and spatial units, LADM Edition II is structured as a multipart standard. This extension allows for enhanced specificity and adaptability in diverse contexts. The proposed parts of LADM Edition II include (Kara et al. 2023):

- Part 1—Generic conceptual model: Serves as a high-level standard, defining basic terms, structures, and relationships fundamental to land administration. This part provides a common foundation for the entire model, covering core classes like parties, rights, and spatial units, and it maintains compatibility with LADM Edition I.
- Part 2—Land registration: Focuses on land registration with an extended model for land rights, restrictions, and responsibilities (RRRs), including 3D spatial representations. This part refines the elements introduced in Edition I and adds support for mortgage classes and various spatial sources, including survey and design sources.
- Part 3—Marine georegulation: Introduces marine georegulation, aligning with international marine standards like the IHO S-121. It aims to support the registration of rights in marine environments, allowing integration of land and marine cadastres.
- Part 4—Valuation information: Adds structures for managing land and property valuation information, supporting public registries used for taxation and other fiscal functions. It includes classes for valuation units, transaction prices, and valuation procedures.
- Part 5—Spatial plan information: Addresses spatial planning by incorporating zoning and land use planning data. This part includes plan units and blocks to represent different zoning areas and functions within spatial planning hierarchies.
- Part 6—Implementation aspects: Focuses on technical aspects for implementing LADM, in collaboration with the OGC. It supports encoding standards and provides guidance for software and data infrastructure integration.

2.3 | Importance of LADM in Modern Land Administration

The adoption of LADM has significant implications for the modernisation of land administration systems. By providing a common framework, LADM enables the integration of diverse LAS into a coherent system that can support advanced functionalities

such as 3D cadastres, the inclusion of informal and customary rights, and the management of land use and land cover data (Lemmen et al. 2015). This standardization is particularly important in the context of global initiatives aimed at promoting sustainable land management, improving land tenure security, and supporting economic development in developing countries (Williamson et al. 2010).

LADM's inherent flexibility allows it to be tailored to the specific legal and institutional frameworks of different countries, making it an indispensable tool for harmonizing land administration practices on a global scale. Although its applicability extends to developed nations, it is particularly impactful in developing countries, where the need for inclusive, robust, and sustainable land administration systems is most pressing (Zevenbergen et al. 2013).

In LADM Edition I, country profiles from Portugal, Indonesia, Australia (Queensland), Japan, Hungary, the Netherlands, the Russian Federation, and South Korea were included, underscoring the adaptability of LADM across diverse legal frameworks. This number has since grown significantly, with around 50 countries, including China, Malaysia, Brazil, Ethiopia, and Japan, actively developing or implementing LADM-based systems (Kalogianni et al. 2021). These efforts illustrate the expanding role of LADM in managing land tenure challenges across various legal and institutional contexts globally.

LADM country profiles represent cadastral data organization at a conceptual level, but successful implementation requires overcoming practical challenges, particularly in database interoperability. Colombia has made significant progress in LADM implementation, particularly through the integration of INTERLIS tools. Baron et al. (2018) demonstrated how Colombia's LADM profile enables legal independence and modularity, which supports the customisation of land administration systems to fit local legal contexts. Additionally, Morales et al. (2021) worked on designing an all-inclusive land administration system based on LADM, aimed at streamlining land governance and ensuring data interoperability across various sectors. Oukes et al. (2019) identified key obstacles in implementing LADM profiles, such as semantic, syntactic, and schematic differences. In Serbia, Sladić et al. (2020) developed a process model for smoother database implementation. Govedarica et al. (2021) discussed the design and implementation of a LADM-based cadastral information system for Serbia, Montenegro, and the Republic of Srpska. The study highlights the challenges of adapting the LADM to local legal and technical conditions, emphasizing the need for interoperability and integration of cadastral data. By tailoring the system to regional requirements, the authors improved land administration processes and system efficiency. These case studies illustrate how different countries are working through physical model challenges to achieve efficient LADM implementations.

LADM-based studies in Indonesia have significantly advanced land administration by integrating spatial planning and improving cadastral workflows. Indrajit et al. (2021) proposed an extension of the LADM country profile for Indonesia, focusing on integrating spatial planning data. The study applied a design science research method (Hevner et al. 2004) to develop a 3D land-use model for cities like Jakarta and Bandung, adapting it to national data policies. The research aimed to improve the first version of the Indonesian LADM profile and provided a proof-of-concept, enhancing land-use planning and decision-making efficiency. Additionally, Aditya et al. (2021) introduced a LADM-compliant field data collector for cadastral surveys in Indonesia by examining possible collaborative efforts (top–down information and bottom–up field recording and validation) using a mobile application designed for both spatial and legal/administrative data simultaneously. Budisusanto et al. (2013) developed a prototype for 3D cadastre systems, particularly for multilevel apartments, showcasing LADM's potential in managing complex urban land use. Sari (2010) focused on the workflow of maintaining cadastral data in Indonesia using LADM, highlighting its role in data governance. However, there remains a gap in fully considering global initiatives, such as gender equality and indigenous rights, in the implementation of LADM for Indonesia.

2.4 | Limitations, Challenges and Opportunities

To implement physical data models, two primary methods exist: file-based or database storage. Traditional file-based solutions have notable drawbacks, such as data isolation, redundancy, and application dependency (Van Oosterom et al. 2019). They also fail to ensure data integrity, security, consistency, or concurrent access (Shahidinejad et al. 2024). As a result, a robust DBMS is crucial for managing spatial data, including spatial characteristics, models, queries, data types, and indexing (Kalogianni et al. 2020; Salleh et al. 2021; Tekavec et al. 2021). DBMS enables the secure storage, maintenance, and exploitation of cadastral data (Tekavec et al. 2021; Thompson and van Oosterom 2021; Zlatanova and Stoter 2006).

Despite its numerous advantages, the implementation of the LADM is not without its challenges. A significant limitation lies in the complexity of adapting LADM to align with the diverse legal, cultural, and institutional frameworks across different countries. As LASs are inherently local, customizing LADM to reflect country-specific legislation and practices requires substantial expertise and resources. This process often involves redefining certain components, such as rights, restrictions, and responsibilities (RRRs), which can be intricate and time-consuming (Paasch et al. 2015; Rajabifard et al. 2021).

Moreover, the lack of a clear and comprehensive set of implementation guidelines complicates efforts to ensure that the conceptual LADM model translates seamlessly into a functioning system. Countries must often resort to creating their extensions to meet their unique needs, which can create inconsistencies and further complicate system integration (Bar-Maor and Smyth 2022).

The integration of LADM into existing legacy systems is another notable challenge. Many jurisdictions rely on older land information systems that are not designed to be compatible with modern standards like LADM, leading to technical hurdles. Retrofitting these systems to incorporate LADM functionalities requires significant financial and technical investments,

particularly in terms of data migration, system interoperability, and capacity building.

In addition to these structural challenges, LADM's core model must be extended to accommodate emerging issues such as gender equality, indigenous land rights, and informal land tenure. These are pressing concerns, particularly in developing countries, where a large proportion of land rights remain undocumented or outside the formal system. Although LADM provides a solid foundation for recording land rights, its current form is not fully equipped to address these complex social and cultural dynamics. Extending LADM to integrate these considerations—through the inclusion of attributes for gender sensitivity or recognizing collective Indigenous landholdings—is essential for fostering equitable and inclusive land governance (Jahani Chehrehbargh et al. 2022; Kalogianni et al. 2022).

Additionally, technological advancements such as blockchain and artificial intelligence offer promising opportunities to improve the integrity, security, and transparency of land transactions. However, LADM's current architecture lacks explicit guidelines for integrating these technologies, presenting further implementation challenges that need to be addressed in future revisions of the model.

3 | Methodology for Assessing the Feasibility of an Extended LADM

This study evaluates the feasibility of implementing an extended LADM tailored to the specific needs of developing countries, focusing on Indonesia. This work builds upon the findings from two of the author's previous studies: "Identifying Global Parameters for Advancing Land Administration Systems" (Jahani Chehrehbargh et al. 2024b) and "Current Challenges and Strategic Directions for Land Administration System Modernisation in Indonesia" (Jahani Chehrehbargh et al. 2024a). The approach is structured into four key phases: requirement analysis, model design and extension, physical data model implementation, and evaluation, as outlined in Figure 1.

3.1 | Requirement Analysis

The requirement analysis phase relies on the results from two of the author's previous studies to establish a solid foundation for extending the LADM:

- Parameter identification from previous studies: The parameters for extending the LADM were identified based on the findings from the paper "Identifying Global Parameters for Advancing Land Administration Systems". This study provided a detailed analysis of global initiatives such as the United Nations' Sustainable Development Goals (SDGs) and the framework for effective land administration (FELA), highlighting the need for inclusivity in gender sensitivity, indigenous land rights, informal tenure, valuation, and taxation within land administration systems.
- Needs assessment from stakeholder consultations: Insights from the study "Current Challenges and Strategic Directions for Land Administration System Modernisation in Indonesia" were used to refine the model requirements further. This research involved extensive stakeholder consultations, including discussions with policymakers, land administration professionals, and community representatives, to identify the challenges faced in the Indonesian context. These findings were crucial in shaping the extended LADM to address local needs, such as gender equality, indigenous rights, and the management of informal land tenure.

3.2 | Model Design and Extension

Following the requirement analysis, the study focused on extending the LADM to incorporate the identified parameters:

- Conceptual and logical model design: Using the parameters identified in the previous studies, the LADM was conceptually extended to include new classes, relationships, and attributes that support gender equality, indigenous

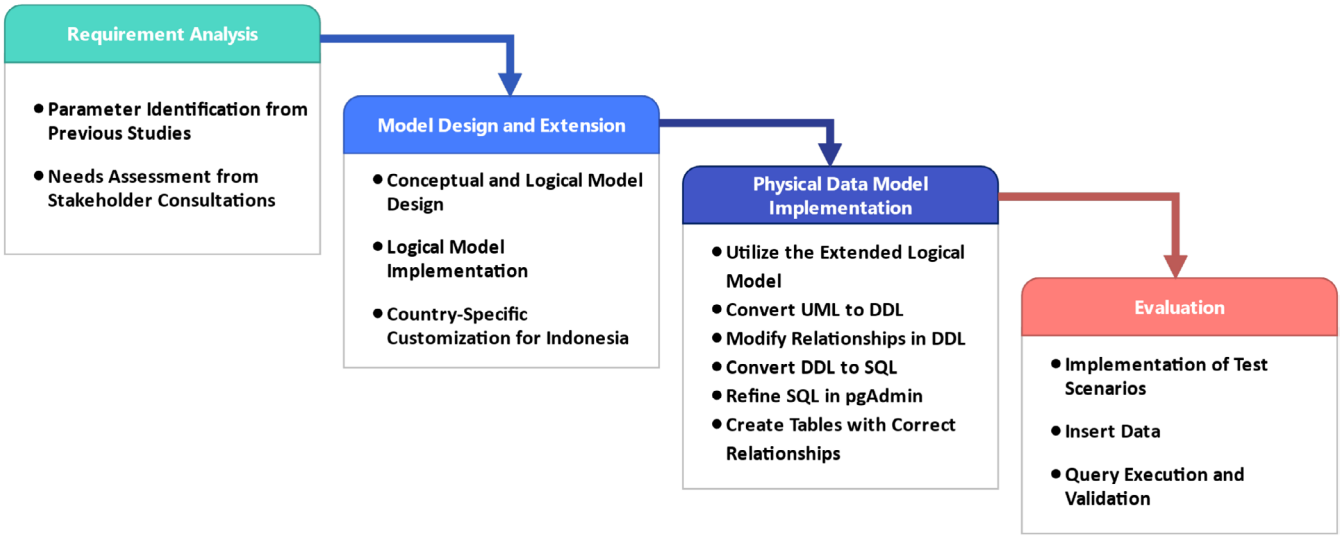

FIGURE 1 | Methodology of assessing the feasibility of an extended LADM.

land rights, informal land tenure, valuation, and taxation. The conceptual model was designed to provide a coherent framework that integrates these parameters, using UML diagrams to represent the relationships and structures.

- Logical model implementation: The conceptual model was translated into a logical model using Enterprise Architect software. This step involved defining the arrangement of data elements and their interconnections, serving as a blueprint for the physical database. The logical model validated the conceptual framework and provided practical insights into implementation challenges, which facilitated the creation of DDL schemas for DBMSs such as PostgreSQL, Oracle, and SQL Server (Shahidinejad et al. 2024).
- Country-specific customisation for Indonesia: The extended LADM was customized to address Indonesia-specific parameters, as identified in the previous study. This customisation involved introducing additional code lists and features that align with the local land governance challenges.

3.3 | Physical Data Model Implementation

The physical data model implementation phase involved translating the logical model into a working database in PostgreSQL, following a series of detailed steps:

- Utilize the extended logical model: The extended logical model developed in enterprise architect software was used as the foundation for creating the physical data model. This model included all necessary classes, attributes, and relationships required to support the extended LADM.
- Convert UML to DDL: The UML diagrams representing the extended logical model were transformed into DDL within the EA software. This step established the initial blueprint for the database structure, detailing how data would be stored, accessed, and managed.
- Modify relationships in DDL: The generated DDL scripts were refined and adjusted to accurately reflect the intended data architecture. This involved modifying relationships between tables, and ensuring that primary and foreign keys were correctly defined to maintain data integrity and consistency.
- Convert DDL to SQL: The refined DDL scripts were converted into SQL code, making them ready for implementation in the PostgreSQL database system. This step translated the logical data structure into executable SQL commands for database creation.
- Refine SQL in pgAdmin: The SQL code was further refined in pgAdmin, focusing specifically on primary and foreign keys to resolve any issues and finalize the database structure. This involved checking for any constraints or dependencies that might impact the database's functionality.
- Create tables with correct relationships: The finalized SQL scripts were executed in pgAdmin to create the database tables. This step ensured that all relationships were correctly established according to the extended logical model, completing the physical model.

3.4 | Evaluation

The evaluation phase focuses on validating the extended LADM through practical implementations and performance assessments:

1. Implementation of test scenarios: To assess the practical viability of the extended LADM, a series of test scenarios were developed. These scenarios were carefully designed to reflect the real-world complexities of land administration in Indonesia, addressing key issues such as gender-sensitive land rights, indigenous land tenure, and informal settlements. Each scenario was structured to evaluate the model's performance in managing and querying these diverse land tenure and governance challenges. For instance, the Indigenous land tenure scenario tested the model's ability to document and protect indigenous rights, whereas the informal settlements scenario evaluated its capacity to track and regularize informal land claims.
2. Data insertion: After the database structure was finalized, the tables were populated with relevant data sets to operationalize the extended LADM. These data sets included sample entries for indigenous groups, gender-specific land ownership records, and informal settlements. The data insertion phase was crucial for simulating real-world land tenure arrangements and assessing the model's robustness. Additionally, the dataset was structured to ensure comprehensive testing, covering a wide range of attributes such as land ownership types, tenure rights, spatial data, and demographic information.
3. Query execution and validation: The extended LADM's capacity to handle complex land administration queries was evaluated through a series of SQL queries. These queries were executed to retrieve data related to specific land tenure scenarios, such as identifying parcels owned by Indigenous communities or tracking land plots with informal rights. The PostgreSQL DBMS was connected to QGIS, an open-source spatial data visualization tool, allowing for the visualization and spatial analysis of query results. This integration provided valuable insights into the spatial distribution of land ownership and rights, further validating the model's applicability in real-world scenarios. The resulting visual representations enhanced the interpretation of land tenure data, facilitating a clearer understanding of ownership patterns and the relationships between different land rights.

4 | Development of LADM-Based Database and Queries

The proposed extension of the LADM integrates several global parameters to enhance LAS in line with international trends and address critical gaps in land management, particularly for vulnerable and marginalized communities, who often face

significant challenges in securing their land tenure and accessing land-related services (Jahani Chehrehbargh et al. 2024b). These parameters include gender equality, Indigenous land rights, valuation and taxation, dispute resolution, informal rights, and specific attributes such as tenure type, boundary type, and data source type. The careful integration of these parameters into the land management paradigm establishes a robust framework essential for promoting sustainability in land governance.

The extended LADM is intentionally designed to support more inclusive and decentralized governance structures. It accommodates tenure types and spatial units beyond formally surveyed parcels, enabling the recording of locally recognized claims, informal arrangements, and overlapping rights—including those held by marginalized and indigenous communities. These elements can be populated through participatory methods, allowing communities to map and validate their land relationships. This capability moves beyond traditional top–down systems by facilitating the co-production of land data between authorities and communities. Although the model does not directly resolve disputes or allocate benefits, it provides a transparent, standards-based framework to surface contested or underrepresented claims, thereby supporting more equitable and inclusive decision-making in sustainable urban development.

To align LAS with the global parameters and enhance its inclusivity and comprehensiveness, the LADM has been extended in several key areas (Jahani Chehrehbargh et al. 2024):

1. Gender equality: The second edition of LADM introduces "sex types" within the party package. This study builds upon this by proposing an extension based on the "gender" attribute in the LA_Party class, which enables the collection of gender-specific data essential for gender-sensitive land administration. This extension not only distinguishes between sex and gender but also includes the "LA_GenderType" attribute to capture a broader spectrum of gender identities, thus fostering a more inclusive and equitable land governance framework. Integrating this gender-sensitive approach within the harmonized LADM II model underscores our commitment to aligning with international standards while addressing critical needs for gender inclusivity in land administration.
2. Indigenous rights: To enhance the recognition and protection of Indigenous land rights, this extension of the LADM introduces an "Indigenous_status" attribute within the LA_Party class to identify individuals or groups as members of Indigenous communities. This attribute is further supported by additional elements such as "Indigenous group" and "Indigenous group type," which, along with specific code lists within the LA_BAUnitType and LA_RightType classes, capture the distinct rights and classifications pertinent to Indigenous groups. Although the second edition of LADM has made progress, it still lacks dedicated provisions for fully registering Indigenous land rights. Our proposed attributes offer a critical step toward bridging this gap.
3. Informal rights: This model extends the LADM by treating informal rights as generalizations under the LA_Right class. Unlike the second edition of LADM, which only includes informal rights as a basic code in the LA_RightType without further development from the first edition, this extension incorporates key attributes such as settlement types, population data, and recorded dates. These enhancements enable more comprehensive documentation of informal tenure arrangements, making the model adaptable to various contexts and significantly improving its capacity to reflect diverse land tenure realities.
4. Valuation and taxation: To integrate comprehensive valuation and taxation processes into LAS, this model introduces new classes, including VM_Valuation, VM_SinglePropertyAppraisal, VM_MassAppraisal, and VM_TransactionPrices. These classes support detailed property valuation and taxation workflows, enabling accurate and consistent property assessments while seamlessly linking valuation registries with cadastral and land registries. Although the second edition of LADM includes a valuation package, we have extended its attributes to incorporate the latest valuation methodologies, detailed further in the body of this paper. Additionally, we recommend elevating the role of taxation within the model, treating it as an integral part of the valuation framework rather than as an external package, to better reflect its critical function in land administration.
5. Specific attributes: Additional attributes such as tenure type, boundary type, and data source type have been added to provide further granularity and adaptability to different land administration contexts. These extensions ensure that the model is adaptable for use across different jurisdictions and land management scenarios.

The proposed extensions to the LADM in this study are designed to align with global initiatives aimed at enhancing land administration systems by addressing diverse land rights and administrative needs. These modifications make the model a more robust and adaptable framework for contemporary land governance, building upon its core structure while incorporating new capabilities to support a broader range of land rights and governance practices. This approach reflects international standards and best practices for equitable and sustainable land management.

To translate these theoretical enhancements into a practical application, the physical data model of the extended LADM was implemented using PostgreSQL and pgAdmin. This implementation involved several key steps to ensure that the model's adaptations were accurately represented within a functional database system. The following sections outline the process and outcomes of each step, emphasizing the technical considerations and the functionality achieved through this comprehensive implementation.

1. Database schema development: The first step involved developing the database schema by converting the extended logical model from UML diagrams into a comprehensive DDL script using Enterprise Architect software. This conversion process in EA is relatively straightforward due to built-in functionalities that automate the transformation from UML to DDL. The resulting DDL script defined the necessary tables, columns, data types, and constraints needed to accommodate the new attributes and

TABLE 1 | Comparison between the automated SQL code and the modified SQL code.

Automated creation of SQL code from DDL by EA	Modified SQL code
CREATE TABLE "Id_indigenousgroup" ("Asing/luarNegeri" varchar(50) NULL, "Bali" varchar(50) NULL, "Banjar" varchar(50) NULL, "Batak" varchar(50) NULL, "Betawi" varchar(50) NULL, "Bugis" varchar(50) NULL, "Butonese" varchar(50) NULL, "Cina" varchar(50) NULL, "Cirebon" varchar(50) NULL, "Dayak" varchar(50) NULL, "Gorontalo" varchar(50) NULL, "Jawa" varchar(50) NULL, "Madura" varchar(50) NULL, "Makassar" varchar(50) NULL, "Melayu" varchar(50) NULL, "Minahasa" varchar(50) NULL, "Minangkabau" varchar(50) NULL, "Nias" varchar(50) NULL, "Other" varchar(50) NULL, "Sasak" varchar(50) NULL, "SukuAsalAceh" varchar(50) NULL, "SukuAsalBanten" varchar(50) NULL, "SukuAsalJambi" varchar(50) NULL, "SukuAsalKalimantanLainnya" varchar(50) NULL, "SukuAsalLampung" varchar(50) NULL, "SukuAsalMaluku" varchar(50) NULL, "SukuAsalNusaTenggaraTimur" varchar(50) NULL, "SukuAsalPapua" varchar(50) NULL, "SukuAsalSulawesiLainnya" varchar(50) NULL, "SukuAsalSumateraLainnya" varchar(50) NULL, "SukuAsalSumateraSelatan" varchar(50) NULL, "Sunda" varchar(50) NULL, "Id_indigenousgroupID" integer NOT NULL, "Groupid" varchar(50) NULL);	CREATE TABLE "Id_indigenousgroup" (Id_indigenousgroupID integer, indigenous_group varchar(50)); INSERT INTO "Id_indigenousgroup" (Id_indigenousgroupID, indigenous_group) VALUES (1, 'Asing/luarNegeri'), (2, 'Bali'), (3, 'Banjar'), (4, 'Batak'), (5, 'Betawi'), (6, 'Bugis'), (7, 'Butonese'), (8, 'Cina'), (9, 'Cirebon'), (10, 'Dayak'), (11, 'Gorontalo'), (12, 'Jawa'), (13, 'Madura'), (14, 'Makassar'), (15, 'Melayu'), (16, 'Minahasa'), (17, 'Minangkabau'), (18, 'Nias'), (19, 'Other'), (20, 'Sasak'), (21, 'SukuAsalAceh'), (22, 'SukuAsalBanten'), (23, 'SukuAsalJambi'), (24, 'SukuAsalKalimantanLainnya'), (25, 'SukuAsalLampung'), (26, 'SukuAsalMaluku'), (27, 'SukuAsalNusaTenggaraTimur'), (28, 'SukuAsalPapua'), (29, 'SukuAsalSulawesiLainnya'), (30, 'SukuAsalSumateraLainnya'), (31, 'SukuAsalSumateraSelatan'), (32, 'Sunda');

classes introduced in the extended LADM, such as "LA_GenderType" for gender-specific data and "Indigenous_status" for recognizing Indigenous land rights. Following the initial schema development, the DDL scripts underwent a refinement process to optimize the relationships between tables, particularly focusing on foreign key constraints and the representation of hierarchical data structures. Although converting UML to DDL in Enterprise Architect software is relatively straightforward due to automated tools, several challenges emerged in accurately reflecting the complex relationships and data hierarchies in the extended LADM. Issues such as defining primary and foreign keys, handling inheritance, and managing multiplicity required manual adjustments to ensure data integrity. Additionally, the automated conversion often created unnecessary rows and redundant columns, requiring optimization. Further challenges included spatial data types, code list classes, indexing, and constraints, all of which needed careful handling during transformation.

2. Conversion of DDL to SQL and SQL refinement in pgAdmin: Following the generation of the DDL scripts, the next step was to convert these scripts into SQL commands compatible with PostgreSQL. This process required modifying the DDL to conform to PostgreSQL-specific syntax and optimizing it for efficient performance. Special attention was needed for code lists and enumerations, which often required changes in the SQL to accurately represent relationships and enforce constraints. The automatically generated SQL scripts did not correctly display the code lists and their associated relationships, necessitating manual adjustments to ensure accuracy. Table 1 shows the comparison between one of the automated SQL codes generated from DDL by Enterprise Architect and the Modified SQL Code for Correct Representation of Code Lists and Their Relationships. This modification was applied to all enumerations of extended LADM.

3. Data insertion and validation: Once the refined SQL scripts were finalised, the database was populated with test data to simulate real-world scenarios. This data included entries representing gender-specific land ownership, Indigenous community land rights, and informal settlements, reflecting the diverse nature of land tenure in developing countries. However, the provided real data from the Ministry of Land Affairs and Spatial Planning of Indonesia (ATR/BPN: Agraria dan Tata Ruang/Badan Pertanahan Nasional), which pertains to 156

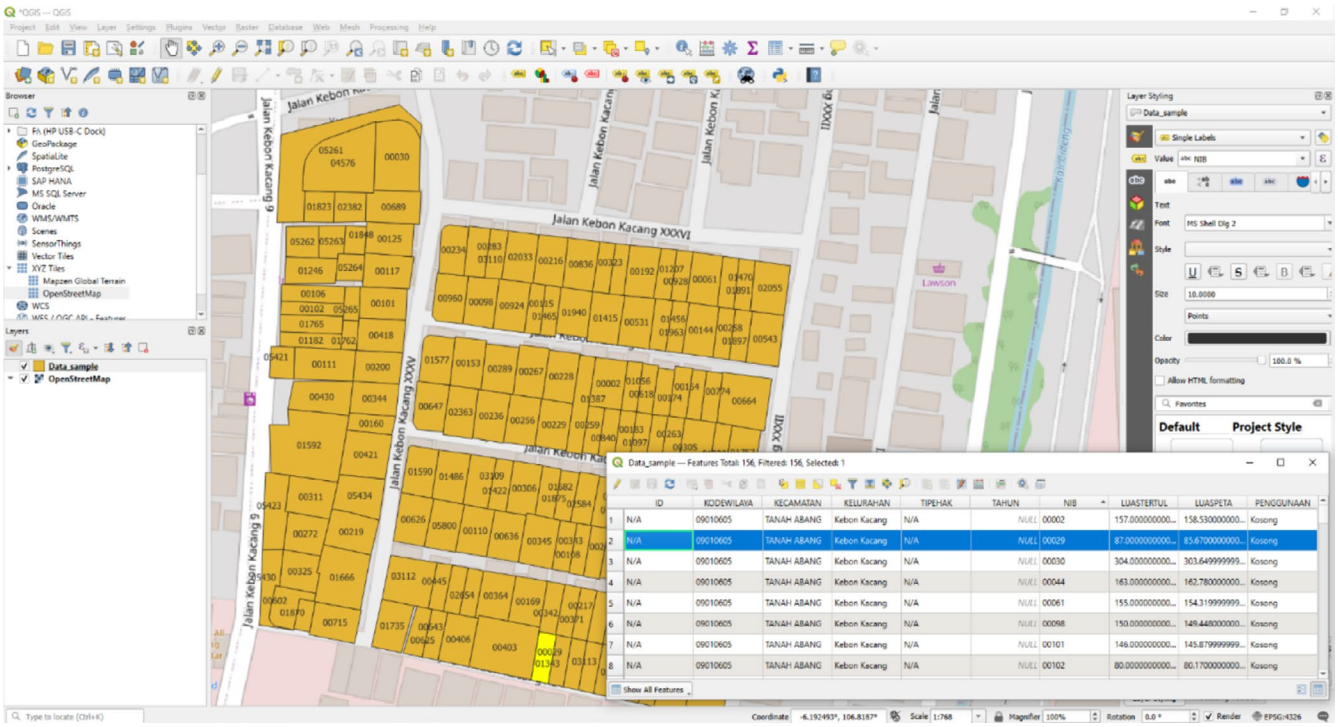

FIGURE 2 | The raw data with related attributes in the Bahasa language.

parcels located in Jakarta, consisted only of NIB (Nomor Identifikasi Bidang: parcel identification numbers), the geometry of parcels, area information, and some region codes. This limitation, possibly due to privacy concerns, meant that essential attributes required for the extended LADM, such as gender-specific data and Indigenous status, were not included in the real dataset. Figure 2 show the original data in QGIS software.

A primary challenge during data insertion was the absence of necessary attributes in the provided real data, which required us to create these attributes ourselves to fully implement the extended model. Ensuring that the test data accurately represented real-world scenarios while conforming to the database schema's constraints and relationships posed additional difficulties. Managing incomplete or inconsistent data entries necessitated the development of strategies to maintain data integrity without compromising the functionality of the database.

5 | Query Execution

To assess the extended model's functionality, a series of SQL queries were executed to evaluate its performance in retrieving and manipulating data related to the new attributes and entities. To further evaluate the model's capabilities, the PostgreSQL DBMS was integrated with QGIS. This integration allowed for the visual representation of query results providing additional insights into the spatial distribution of land rights and other administrative units. By visualizing the query results in QGIS, the model's practical applicability in real-world land administration contexts was further validated. The spatial visualization enhanced the understanding of how land ownership and rights are distributed geographically, offering a valuable tool for policymakers and land administration professionals.

5.1 | Query 1: Identifying Indigenous Parcels Affected by Planned Road Construction

5.1.1 | Scenario Overview

This query identifies parcels within a 15-m buffer zone around a planned road construction site to evaluate the impact on various land rights, particularly those held by Indigenous communities. The 15-m buffer distance used in the query example reflects a typical impact assessment radius applied in urban infrastructure planning, such as for road widening or utility corridor safety zones. Although technically practical, such thresholds should be contextually justified and ethically reviewed, particularly where land rights or compensation decisions are affected. Adaptive or participatory threshold-setting methods should be considered in implementation phases, especially in sensitive tenure contexts. Understanding which parcels fall within this impact zone is crucial for urban planners to make informed decisions regarding compensation, relocation, or other administrative actions required to mitigate the effects of the construction project. The query classifies the affected parcels based on their ownership rights—such as Private, Public, Informal, or Indigenous—and further differentiates them by specific Indigenous group rights where applicable. This detailed analysis is vital for ensuring that development projects respect Indigenous land rights and comply with national and international guidelines, such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP). The extended LADM framework facilitates this analysis by including an “Indigenous_status” attribute within the “La_party” class. These enhancements allow for a comprehensive understanding

of how infrastructure projects might affect Indigenous lands, ensuring that the planning and execution of such projects do not infringe upon Indigenous communities' rights.

5.1.2 | Query Execution

Figure 3 shows the results of the query, which identifies parcels within a 15-m radius of the planned road and categorizes them by their ownership rights. The visual output created in QGIS highlights the spatial distribution of various land rights surrounding the planned road, supporting effective land management and planning decisions. The corresponding code is provided in Table 2.

5.2 | Query 2: Identifying Women-Owned Parcels by NIB

5.2.1 | Scenario Overview

This scenario aims to identify parcels owned by women within the study area by retrieving their corresponding NIB numbers. This data are essential for analyzing land ownership distribution by gender and understanding the role of women in land ownership in Jakarta. Previously, the absence of gender-specific ownership data hindered gender-sensitive analyses, limiting the model's effectiveness in evaluating gender equality in land ownership—a key metric for assessing land administration systems. The extended version of LADM, however, addresses this limitation by introducing a "gender" attribute within the "La_party" class, which records the gender of the parcel owner. This enhancement not only improves the functionality of LADM in supporting local land administration but also aligns with global initiatives such as the United Nations SDGs, particularly SDG 5, which emphasizes achieving gender equality and empowering women.

5.2.2 | Query Execution

Figure 4 shows the query executed in pgAdmin software, with the result table displayed on the left side. Additionally, a visual representation of the query results, generated in QGIS, is shown on the right side of the figure, illustrating the spatial distribution of women-owned parcels across the study area. This visualization enhances the understanding of gender-based ownership patterns, supporting local policy-making efforts in land governance.

5.3 | Query 3: Identifying Rights of Neighboring Parcels Within a 25-Meter Radius

5.3.1 | Scenario Overview

In this scenario, the objective is to identify neighboring parcels within a 25-m radius of a specific parcel (ID: 130) and record their ownership rights. These ownership rights include categories such as informal, indigenous, private, or public. This query is essential for understanding the spatial relationships between parcels and assessing the distribution of different types of land ownership within a specific area. The earlier version of the LADM was not equipped to handle this type of spatial query effectively, as it lacked Indigenous rights. The extended version of LADM overcomes these limitations by incorporating spatial data capabilities and enhanced classification of the right types.

5.3.2 | Query Execution

Figure 5 shows the query executed in pgAdmin software, with the resulting neighboring parcels identified within a 25-m radius of Parcel 130. The ownership rights of these parcels are then recorded in a new table to show in QGIS, which is displayed on the

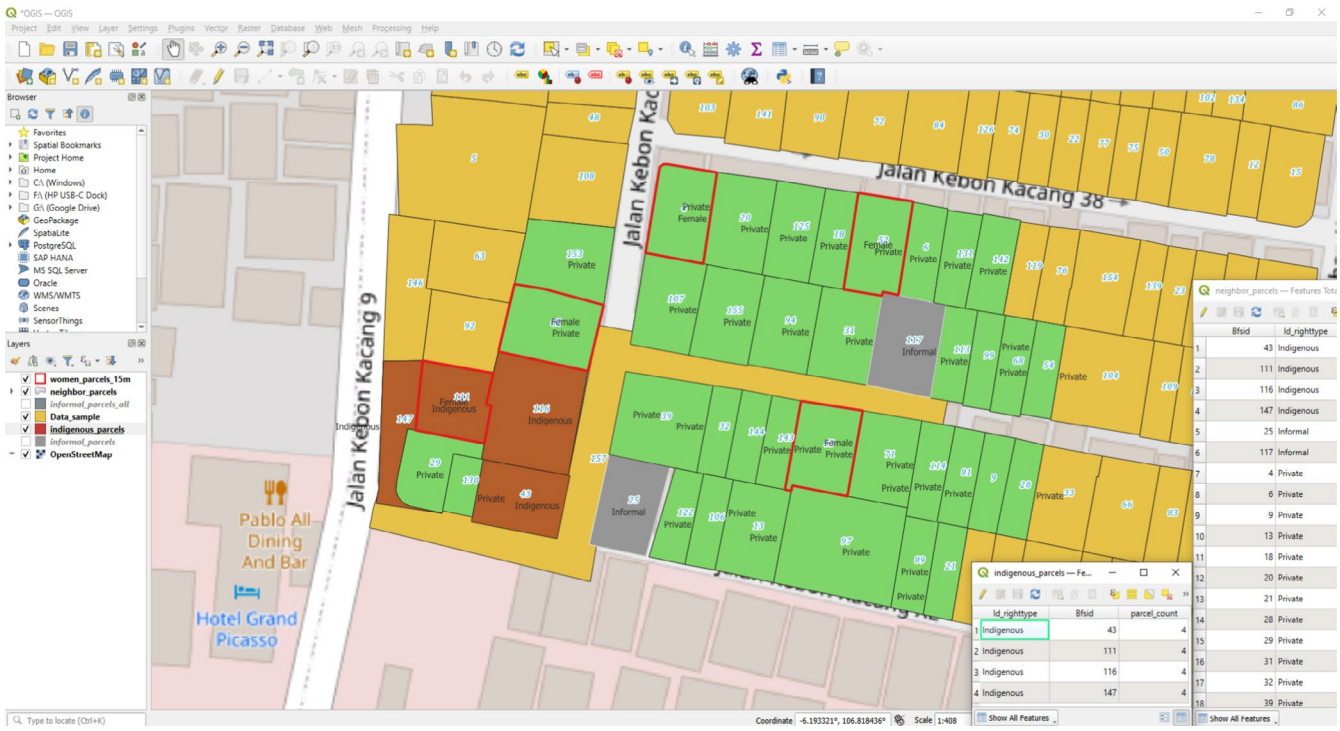

FIGURE 3 | Query execution and spatial distribution of parcels affected by planned road construction.

TABLE 2 | Summary of parcels affected by planned road construction, categorized by ownership rights.

Indigenous parcels	Women Owned parcels	Informal Parcels
-- Drop the table if it already exists DROP TABLE IF EXISTS indigenous_parcels; -- Create the indigenous_parcels table CREATE TABLE indigenous_parcels AS WITH parcel AS (SELECT ST_SetSRID(ST_GeomFromEWKB(decode("Geome", 'hex')), 23834) AS geom FROM "La_boundaryfacestring" WHERE "Bfsid" = 157), neighbors AS (SELECT a."Bfsid", ST_SetSRID(ST_GeomFromEWKB(decode(a."Geome", 'hex')), 23834) AS geom FROM "La_boundaryfacestring" a JOIN parcel p ON ST_DWithin(ST_SetSRID(ST_GeomFromEWKB(decode(a."Geome", 'hex')), 23834), p.geom, 15) WHERE a."Bfsid" != 157) SELECT r."Id_righttype", n."Bfsid", n.geom, COUNT(n."Bfsid") OVER () AS parcel_count FROM neighbors n JOIN "La_right" r ON n."Bfsid" = r."La_spatialunitID" WHERE r."Id_righttype" = 'Indigenous';	-- Drop the table if it already exists DROP TABLE IF EXISTS women_parcels_15m; -- Create the women_parcels_15m table with the required columns CREATE TABLE women_parcels_15m AS WITH target_parcel AS (-- Select the geometry of the target parcel (Bfsid = 157) SELECT ST_SetSRID("Geome", 23834) AS geom FROM "La_boundaryfacestring" WHERE "Bfsid" = 157), neighboring_parcels AS (-- Identify neighboring parcels within a 15-meter radius of the target parcel SELECT a."Bfsid", ST_SetSRID(a."Geome", 23834) AS geom FROM "La_boundaryfacestring" a JOIN target_parcel t ON ST_DWithin(ST_SetSRID(a."Geome", 23834), t.geom, 15) WHERE a."Bfsid" != 157) -- Select parcels owned by women and include required columns SELECT su."Nib" AS NIB, n.geom AS Geome, r."Id_righttype", g."gender" FROM neighboring_parcels n JOIN "Id_spatialunit" su ON n."Bfsid" = su."La_spatialunitID" JOIN "La_party" lp ON su."La_spatialunitID" = lp."La_spatialunitID" JOIN "La_gendertype" g ON lp."Gender" = g."gender" JOIN "La_right" r ON n."Bfsid" = r."La_spatialunitID" WHERE g."gender" = 'Female';	-- Drop the table if it already exists DROP TABLE IF EXISTS informal_parcels; -- Create the informal_parcels table CREATE TABLE informal_parcels AS WITH parcel AS (SELECT ST_SetSRID(ST_GeomFromEWKB(decode("Geome", 'hex')), 23834) AS geom FROM "La_boundaryfacestring" WHERE "Bfsid" = 157), neighbors AS (SELECT a."Bfsid", ST_SetSRID(ST_GeomFromEWKB(decode(a."Geome", 'hex')), 23834) AS geom FROM "La_boundaryfacestring" a JOIN parcel p ON ST_DWithin(ST_SetSRID(ST_GeomFromEWKB(decode(a."Geome", 'hex')), 23834), p.geom, 15) WHERE a."Bfsid" != 157) SELECT r."Id_righttype", n."Bfsid", n.geom, COUNT(n."Bfsid") OVER () AS parcel_count FROM neighbors n JOIN "La_right" r ON n."Bfsid" = r."La_spatialunitID" WHERE r."Id_righttype" = 'Informal';

left side of the figure. On the right side, a visual representation generated in QGIS illustrates the spatial relationship between Parcel 130 and its neighboring parcels, highlighting the different types of land rights. This visualization aids in understanding the proximity and distribution of various ownership categories, supporting local land management and planning efforts.

5.4 | Query 4. Regularization and Upgrading of Informal Settlements

5.4.1 | Scenario Overview

The regularization and upgrading of informal settlements are key priorities for achieving global sustainability goals, such as the United Nations' SDGs, particularly Goal 11, which focuses on making cities inclusive, safe, resilient, and sustainable. Informal settlements, which often lack formal land tenure and access to essential services, present significant challenges for urban planners and policymakers. Identifying parcels within these areas is critical for implementing infrastructure upgrades, improving service delivery, and ensuring equitable land governance. By recognizing and categorizing parcels as "informal," planners can align their efforts with global initiatives aimed at reducing inequality and promoting sustainable urban development.

The extended LADM integrates attributes that cater specifically to informal land rights, offering a more detailed and comprehensive analysis of these tenure types. By leveraging these attributes, this scenario supports global efforts to address informal settlements, aiding in the strategic allocation of resources and the prioritization of areas for regularization.

5.4.2 | Query Execution

Figure 6 displays the execution of the query designed to identify parcels classified as informal settlements within the study area.

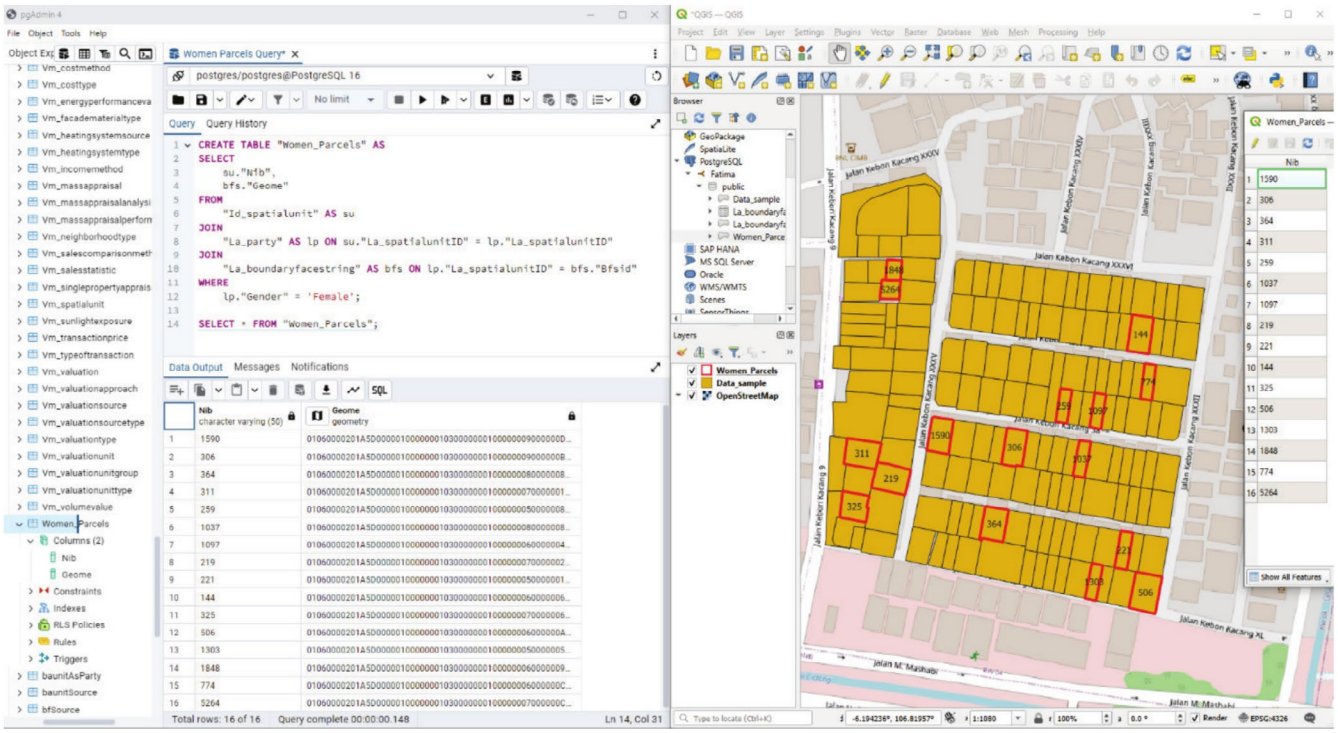

FIGURE 4 | Women-owned parcels query execution in pgAdmin with the distribution displayed in QGIS.

The query utilizes spatial data from the La_boundaryfacestring table and joins it with the La_right table to filter parcels marked as having "Informal" rights. This filtering process allows for the precise identification of parcels that require regularization or upgrading interventions. The SQL command executed in pgAdmin retrieves the NIB, geometry, right type, and spatial unit ID for each informal parcel, ensuring that all necessary information is available for further analysis and planning. The resulting table generated in pgAdmin lists the parcels located within informal settlements, which are subsequently visualized in QGIS to display their spatial distribution.

6 | Implications and Conclusion

The findings of this study underscore the critical need for modernizing LAS in developing countries to better manage land-related information and address various socio-economic and environmental challenges. The extended LADM implemented in PostgreSQL, integrated with pgAdmin, demonstrates enhanced capabilities in addressing key land administration issues such as gender equality, indigenous rights, and informal settlements. This research aligns with global initiatives like the SDGs and the FELA, emphasizing the importance of inclusive and sustainable land management practices.

- Enhanced functionality through LADM extension: The extension of LADM to include attributes for gender sensitivity, indigenous rights, and informal land tenure significantly improves its applicability in diverse land governance contexts, particularly in developing countries. The incorporation of these attributes allows for a more nuanced understanding of land tenure and rights, supporting the needs of vulnerable and marginalized communities. For example, the addition of the "gender" attribute in the LA_Party class enables gender-sensitive analyses, which is critical for promoting gender equality in land ownership and management. Similarly, the inclusion of indigenous rights attributes facilitates the recognition and protection of Indigenous land rights, ensuring compliance with international guidelines such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP).
- Addressing informal settlements: The identification and categorization of informal settlements, as demonstrated in Query 4, are essential for urban planning and the regularization of these areas. Informal settlements often lack formal recognition and access to essential services, which pose significant challenges for urban planners and policymakers. The extended LADM, with its specific attributes for informal rights, enables more precise and comprehensive analyses of land tenure types, thereby supporting strategic planning efforts for infrastructure upgrades, regularizing land tenure, and improving service delivery in informal settlements. This approach not only aligns with global sustainability goals but also provides a robust framework for managing the complexities of informal land tenure.
- Implications for policy and practice: The research findings provide valuable insights for policymakers and land administration professionals seeking to modernize LAS in developing countries. The extended LADM framework offers a scalable and adaptable solution that can be tailored to the specific needs of different countries, ensuring more inclusive and efficient land governance practices. By incorporating global initiatives such as gender equality and indigenous rights into the LAS framework, the extended LADM supports the development of more equitable and sustainable land administration systems. The successful

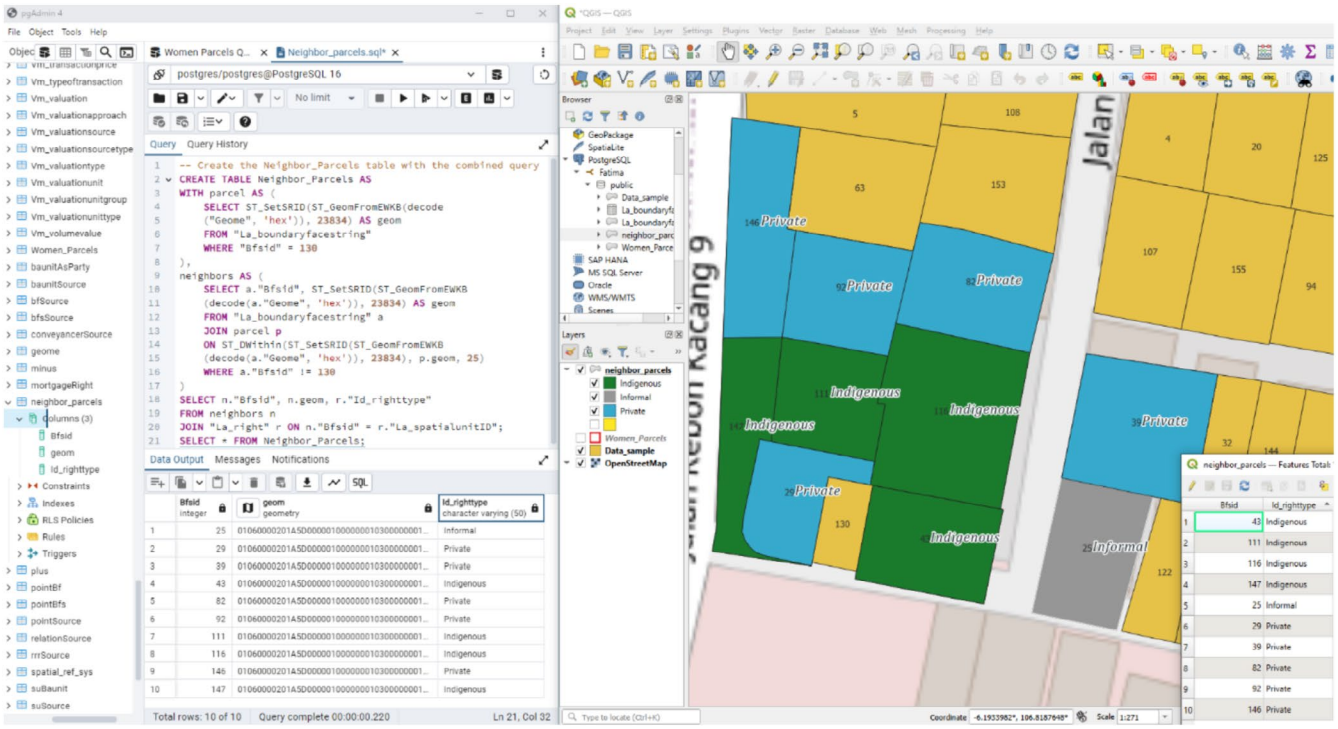

FIGURE 5 | Neighboring parcels query with the distribution and ownership rights.

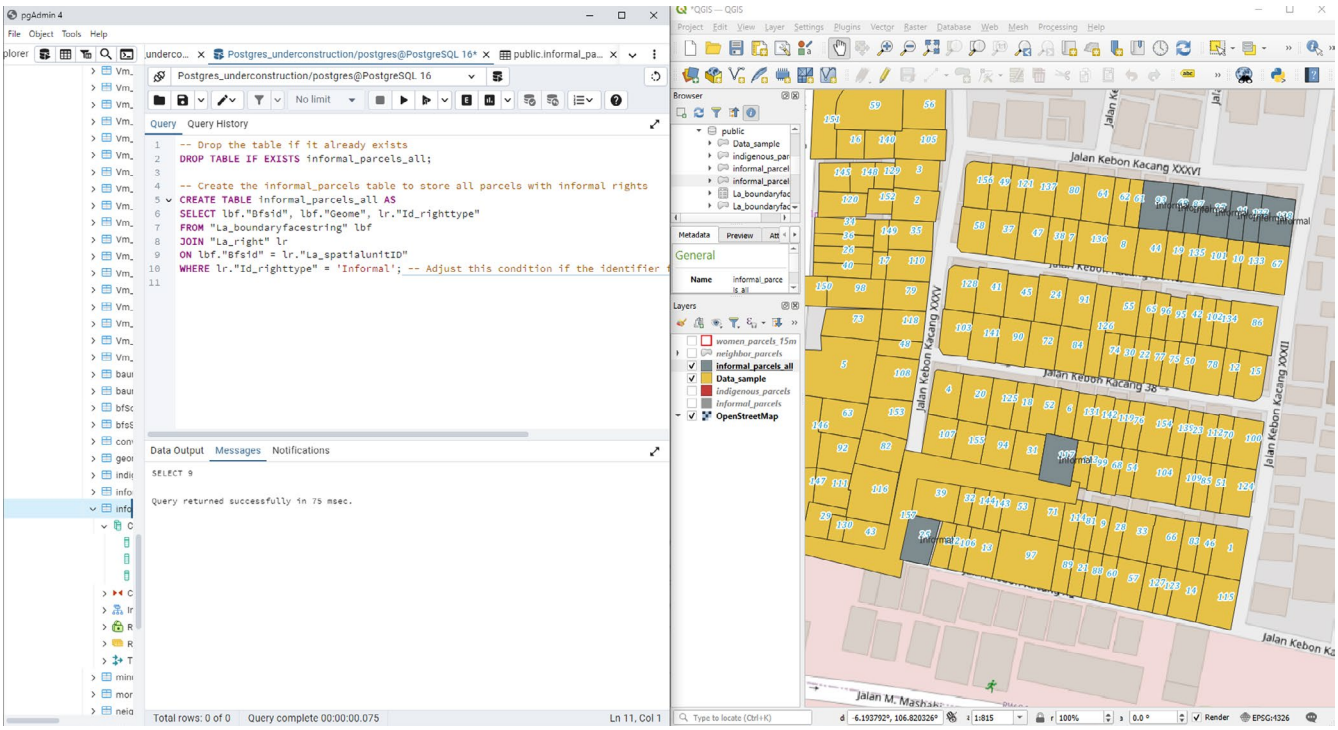

FIGURE 6 | Identification and spatial distribution of informal settlements in the study area.

implementation of the extended LADM in PostgreSQL also demonstrates its technical feasibility, providing a practical tool for land administration professionals to manage diverse types of land rights and governance practices effectively.

This study presents the development and implementation of the land administration database predicated on an extended version of LADM to address critical land data management issues in developing countries. The extended LADM, implemented within PostgreSQL and integrated with pgAdmin, has demonstrated enhanced capabilities in managing data elements related to gender equality, indigenous land rights, and informal settlements. These data elements are often overlooked in traditional LAS, and this work provides a significant step in implementing the

extended LADM standard to support the promotion of inclusive and sustainable land data management.

The study validates the extended LADM through a series of practical tests, such as executing complex SQL queries that assess the implemented database's ability to manage diverse land ownership rights. The results show that the extended LADM is effective in capturing and analyzing land tenure data, particularly for marginalized and vulnerable communities. This standard's flexibility allows it to adapt to various legal and institutional contexts, offering a scalable solution that can be customized to meet the specific needs of different countries. This is especially relevant in developing nations, where formal land tenure systems may be inadequate or fragmented. From a technical perspective, extending LADM and transforming the conceptual model into a physical database presented several challenges, particularly in ensuring data integrity and optimizing performance. However, the successful implementation of the extended model in PostgreSQL demonstrates that these challenges can be overcome with careful planning and technical adjustments. The study also emphasizes the importance of using robust database management systems to handle both spatial and nonspatial data in land administration contexts.

Adapting LADM to fit specific legal frameworks and integrating it with legacy systems require substantial time, expertise, and resources. Additionally, the challenge of gathering and updating the necessary data in developing countries is significant, particularly due to the involvement of multiple agencies with different interests and responsibilities. This complexity makes data collection a key consideration for implementing modern land administration systems. Future work should focus on addressing this issue by exploring methods for data collection and coordination across multiple agencies.

It is important to note that the practical application of the proposed method for modernizing land administration systems (LAS) and incorporating global parameters into LADM requires jurisdictions to first collect and integrate specific data, such as gender-disaggregated ownership information, which are often unavailable, incomplete, or sensitive. This prerequisite creates a challenge not only for this research but also for any future implementation of the extended model in real-world settings. Real-world data would allow for a more robust validation process and might also improve both the design and testing stages. However, due to privacy constraints and restricted access to comprehensive datasets, the use of synthetic data were necessary for this research. Future studies should prioritize collaboration with government agencies and custodians to enable responsible access to real-world data for further validation.

This study primarily focuses on the technical feasibility of extending the LADM through implementation in an object-relational database; however, we recognize that ethical and governance considerations are central to achieving inclusive and equitable land administration systems. Although the operationalisation of fairness principles—such as conflict resolution and prioritization in multiparty claims—lies outside the technical scope of this paper, we have taken measures to enable future ethical integration. This includes support for anonymisation of sensitive data, schema design that can represent overlapping or contested claims, and alignment with international data protection standards such as GDPR. The model also provides a framework for documenting areas of potential conflict, including disputes over infrastructure improvements and overlapping claims between indigenous communities. By surfacing such issues transparently, the system enables more informed, inclusive, and conflict-sensitive planning. We further highlight the future potential of incorporating participatory data collection mechanisms, such as those from the social tenure domain model (STDM) and fit-for-purpose land administration (FFP-LA), to strengthen bottom–up governance and ensure representation of diverse community perspectives.

Looking ahead, future enhancements are essential to support dynamic land rights, temporally shifting spatial units, and increasingly complex governance demands. In particular, non-sedentary populations and climate-sensitive tenure systems require flexible data models capable of representing evolving land relationships. Future research will explore the incorporation of 3D and 4D cadastre components—first by modeling volumetric land parcels, then extending to temporal attributes and versioned objects that align with developments in LADM Edition II. This would enable the representation of seasonally valid rights, time-bounded claims, and responsive governance structures. Additionally, ensuring cross-jurisdictional scalability will be crucial for managing diverse legal frameworks. Emerging technologies such as blockchain and artificial intelligence also hold significant promise for enhancing the integrity, transparency, and automation of land administration systems, offering new pathways for securing land tenure and improving governance outcomes.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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