LADM Based 3D Temporal Approach for Coastal Cadastre

Yusuf H. Atulukwu [1], Muhammad Imzan Hassan [1], Ainn Zamzuri [1], Alias Abdul Rahman [1], Mehmet Alkan [2]

[1] 3D GIS Research Lab, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia - yusufatulukwu@graduate.utm.my; imzan@utm.my; ainnalfatihah@gmail.com; alias@utm.my

[2] Dept. Geomatic, Faculty of Civil Engineering, Yildiz Technical University, Istanbul, Türkiye - alkanmehmet4461@gmail.com

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Abstract

Effective coastal cadastre management requires an advanced framework capable of addressing spatial and temporal complexities arising from the evolving nature of coastal environments. This paper presents an LADM-based 3D Temporal approach for coastal cadastre to enhance the management of coastal property rights, jurisdictional boundaries, and land-sea interactions. The proposed framework integrates three-dimensional spatial data with temporal attributes, enabling precise representation and tracking of changes in coastal parcels, maritime zones, and shoreline boundaries. The LADM-based model is structured within a spatial database for practical implementation, ensuring seamless interoperability with GIS-based visualization and web-based monitoring tools. This approach strengthens cadastral decision-making by addressing key challenges such as shifting shorelines, overlapping land-sea rights, and the evolving legal status of marine parcels. From a legal and policy standpoint, this framework supports harmonizing land and marine tenure systems, promoting regulatory compliance, dispute resolution, and jurisdictional coordination among stakeholders. Implementation of an LADM-based 3D Temporal cadastre within a structured database framework enhances transparency, facilitates adaptive marine governance, and ensures legal clarity in coastal property administration. The findings underscore the critical need for a legally robust cadastral model to support sustainable coastal management and equitable access to marine resources.

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1. Introduction

The 3D Temporal marine cadastre data model integrates three-dimensional spatial data with time-based information to improve marine and coastal management (Alkan Mehmet, 2024),(Polat et al., 2020). It captures the horizontal extent (latitude and longitude), vertical depth or elevation (seabed, water column, and airspace), and temporal changes such as shoreline shifts, tides, and evolving legal boundaries. This model addresses key challenges, including spatial conflicts from overlapping marine activities, temporal overlaps from time-sensitive uses, and changes like sea-level rise and sediment movement (Abdul Rahman et al., 2024). Recent advancements have expanded this framework into a 4D marine cadastre (Gürsoy Sürmeneli, Alkan, et al., 2022), enabling more effective management of overlapping uses, resolution of time-sensitive conflicts, and adaptation to environmental changes (Polat et al., 2020). Integrating 3D spatial data with temporal attributes, enhances boundary management, resource allocation, shoreline monitoring, and climate impact assessment. It also supports marine spatial planning and conflict resolution through transparent, time-based records (Kyriazi, 2018a), (White et al., 2010). By incorporating depth and time, this model strengthens marine governance, spatial planning, and sustainability, ensuring that marine and coastal resources are managed efficiently and equitably (United Nations Committee of Experts on Global Geospatial Information Management [UN-GGIM], 2024).

Coastal erosion is a major environmental challenge threatening land tenure security, particularly in low-lying coastal regions. The gradual retreat of shorelines leads to loss of land, changes in cadastral boundaries, and potential disputes over property ownership (Abdul Rahman et al., 2024), (Yadav et al., 2018). These changes can result in legal ambiguities, where landowners face difficulties in asserting their rights over eroded or submerged parcels (Musa et al., 2023). In Malaysia, coastal areas, especially in Terengganu, are highly vulnerable to erosion due to climate change, rising sea levels, and human activities such as uncontrolled development and sand mining. Kampung Pengkalan, a coastal settlement in Terengganu, has experienced significant shoreline retreat, leading to the loss of residential and commercial properties (Hamzah et al., 2023). Traditional static cadastral systems struggle to accommodate these changes, as land parcels are typically recorded with fixed boundaries that do not reflect the nature of coastal landscapes.

Traditional land tenure systems struggle to accommodate the loss or transformation of land parcels, leading to inconsistent cadastral records. Property owners and administrators face challenges in updating these records to reflect physical land changes, as traditional cadastral systems are static and designed for stable, land-based environments. They rely on fixed coordinates, survey markers, and legal descriptions, which become problematic in coastal areas where shorelines are constantly shifting.

Key limitations of traditional cadastral systems in coastal areas include their inability to adapt to temporal changes, resulting in outdated records that do not reflect erosion-induced boundary shifts. Legal and administrative uncertainties arise due to unclear regulations on submerged or eroded parcels, leading to ownership disputes. Inefficiencies in spatial data management stem from the lack of integration with the land administration system (LAS) and remote sensing, limiting coastal monitoring. Additionally, these systems fail to incorporate maritime boundaries, making them inadequate for managing land-sea interactions.

These challenges underscore the need for a spatially enabled cadastral system that integrates shoreline changes, marine property rights, and adaptive legal frameworks (Fang et al., 2024; Janečka & Souček, 2017; Rajabifard et al., 2018).

The Land Administration Domain Model (LADM) (Figure 1), introduced by ISO 19152, is an internationally recognized standard that provides a standardized and flexible framework for land administration by integrating spatial, legal, and temporal attributes. It enables spatial and temporal updates in cadastral records, ensuring more accurate and dynamic land management. It is a conceptual framework that underpins land administration systems. As a conceptual framework, LADM supports land administration through its three core components: parties (individuals and organizations), basic administrative units (rights, responsibilities, and restrictions), and spatial units (parcels, legal spaces of buildings, and utility networks). Additionally, a sub-package for surveying, geometry, and topology representation further refines its capability (Kara et al., 2024), (Lemmen, Abdullah, et al., 2021).

The growing complexity of marine governance, particularly in areas with overlapping rights, dynamic coastal boundaries, and competing marine activities, has highlighted the limitations of traditional land administration systems in managing marine spaces. In response to these challenges, the Land Administration Domain Model (LADM) has been extended to include marine spaces through the publication of ISO 19152-3:2022, also known as LADM Part 3: Marine Georegulation.(Land, 2024)(Body et al., 2022)

This extension provides a formal and standardized approach for representing legal marine spaces, including maritime boundaries, exclusive economic zones (EEZs), and marine tenure arrangements. It introduces the ability to model legal objects in three dimensions and overtime (3D+T), allowing for the inclusion of dynamic elements such as shoreline migration, tidal fluctuations, and time-bound marine licenses. LADM Part 3 supports legal and hydrographic data interoperability, facilitating more integrated marine spatial planning and regulation.

Despite its comprehensive structure and international relevance, the implementation of LADM Part 3 remains limited. Many coastal nations have not yet developed customized coastal cadastre systems that operate this model. Key barriers include institutional fragmentation, gaps in legal frameworks for marine tenure, limited technical capacity, and a lack of integration between marine and terrestrial spatial databases. Nonetheless, LADM Part 3 serves as a critical foundation for the development of harmonized, rights-based marine spatial data infrastructures, offering a pathway toward more effective marine governance.

Unlike traditional cadastral models, the LADM supports temporal updates in both land and marine records through its LA_Source class, which enables the recording and management of temporal events. This functionality is particularly relevant for managing coastal properties affected by shoreline retreat, a challenge often overlooked due to the absence of temporal classifications in conventional systems.

The absence of a LADM-based 3D Temporal marine cadastre model limits the ability to:

i. Track and document the transition of cadastral parcels from terrestrial to marine status, assessing partial, significant, or complete impacts.
ii. Monitor and manage TOLs dynamically, ensuring compliance with marine zoning regulations and legal tenure requirements.
iii. Incorporate real-time coastal monitoring data to support sustainable marine governance and decision-making.

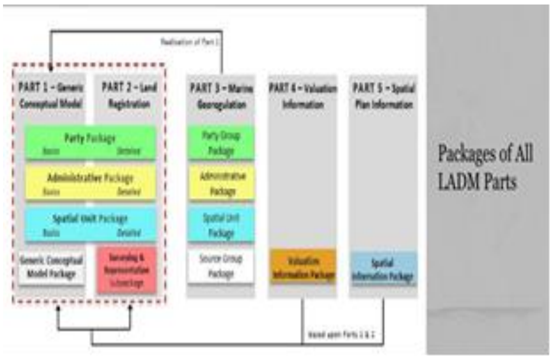

Figure 1. Packages of All LADM Parts. (Kara et al., 2024; Land, 2024; van Oosterom, 2023)

The Land Administration Domain Model (LADM), introduced by ISO 19152, provides a standardized framework for spatial, legal, and temporal data management, allowing for more adaptive and responsive cadastral systems (Janečka & Souček, 2017; Rajabifard et al., 2018; Lemmen, Abdullah, et al., 2021;. Kara et al., 2024).

Existing studies highlight the critical need for integrating temporal dimensions in land administration (Gürsoy Sürmeneli et al., 2022; Thompson & van Oosterom, 2021; Ho & Hong, 2021). Traditional cadastral models often struggle to accommodate dynamic coastal changes, particularly in regions affected by shoreline retreat and the associated issues of marine property rights (Cole & Wilson, 2016; Flego et al., 2021).

1.1 Marine Cadastre and Temporal Dimensions

The marine cadastre is a specialized land administration system developed to manage spatial information associated with marine environments, including the seabed, water column, and sea surface (Sutherland, 2004; Binns, 1995; Binns et al., 2004; Fraser et al., 2003). In Malaysia's dynamic coastal regions, such as Terengganu, this system must accommodate complex spatial and temporal variability driven by both natural processes and anthropogenic activities. To effectively capture these dynamics, the integration of three-dimensional (3D) and temporal data models is essential, enabling the accurate representation of marine spatial units and their evolution over time(Rahman et al., 2012). Temporal data is especially critical in coastal zones where shoreline changes, tidal fluctuations, and seasonal variations are prevalent. The proposed LADM-based 3D Temporal coastal cadastre addresses this need by incorporating spatiotemporal data that accurately documents land status changes resulting from land reclamation, coastal landfilling, and shoreline rehabilitation efforts (Zulkifli et al., 2019). In erosion-prone areas like Kampung Pengkalan, coastal cadastre capabilities are vital for tracking coastal retreat and enabling proactive and responsive governance.

This framework is built upon the ISO 19152 Land Administration Domain Model (LADM) Edition II and III, extending its core classes to incorporate legal and administrative components, particularly the management of rights, restrictions, and responsibilities (RRRs) (Lemmen et al., 2021; Lemmen et al., 2015). This integration ensures the legal validity of spatial data while enhancing its utility in administrative decision-making. The LADM-based 3D Temporal coastal cadastre thus supports the continuous tracking of spatial units through time (3D + T), maintaining spatial-temporal integrity and enabling more transparent and effective marine resource management. In the Malaysian context, practical applications include: (i) improved coastal management through detailed spatial and temporal analytics; (ii) enhanced environmental monitoring to support climate adaptation and sustainable development goals; and (iii) more accountable and efficient resource allocation, including for aquaculture zones and fishing sites. Importantly, the proposed model ensures that the principles of the National Land Code (NLC) are extended to marine spaces, thus promoting integrated governance and sustainable development. This case-specific implementation illustrates the potential of a LADM-based 3D Temporal approach to strengthen adaptive marine spatial planning and coastal governance in Malaysia.

This study introduces a LADM-based 3D Temporal approach for coastal cadastre, developed to address the complex spatial and legal challenges of managing dynamic coastal and marine environments. By extending the Land Administration Domain Model (LADM) to incorporate three-dimensional spatial units and temporal attributes, the proposed framework supports an accurate representation of marine parcels, shifting shoreline boundaries, and evolving tenure arrangements. This LADM-based 3D Temporal model integrates real-time monitoring data, legal and administrative components, and spatial information systems to enhance marine property governance, improve transparency in leasing, and strengthen regulatory enforcement. The approach is particularly relevant in erosion-prone coastal areas such as Kampung Pengkalan, where land–sea interfaces are subject to continuous change. Through the integration of land administration systems (LAS) and remote sensing technologies, the model facilitates continuous monitoring and spatial analysis of coastal dynamics, enabling a responsive and adaptive cadastral system. Ultimately, the framework aims to enhance tenure security, support informed decision-making, and reduce land-use conflicts in Malaysia's coastal zones.

Furthermore, this study presents the proposed framework in alignment with the ISO 19152 and LADM Part III marine georegulation (Land, 2024) standards, ensuring robust and interoperable management of dynamic coastal and marine spaces.

The data model extends the core LADM conceptual classes Party (LA_Party), Administrative (LA_RRR, LA_BAUnit), and Spatial Unit (LA_SpatialUnit) to incorporate three-dimensional marine parcels and temporal components essential for tracking changes over time and includes the integration of real-time monitoring data, legal zoning constraints, and tenure dynamics driven by shifting coastal boundaries. Designed to accommodate various land and seabed tenure types, the framework upholds spatial-temporal integrity, promotes transparency in marine leasing, and strengthens regulatory enforcement mechanisms. Enabling detailed spatial analysis and continuous observation of coastal changes, the model supports evidence-based governance in vulnerable areas such as Kampung Pengkalan. The alignment with the LADM standards also ensures compatibility with existing land administration systems and facilitates future expansion to support marine cadastre initiatives globally.

The remainder of the paper is structured as follows: Section 2 covers the Literature review, Section 3, the Methodology, Section 4 presents the Initial results and case study overview, and Section 5 provides the Conclusion and recommendations.

2. Literature Review

Traditional cadastral systems struggle to accommodate shifting shorelines, leading to outdated records and legal uncertainties over eroded or submerged parcels. Designed for stable land environments, these systems rely on fixed coordinates and lack integration with GIS and remote sensing, limiting coastal monitoring. Additionally, the absence of maritime boundary considerations makes them inadequate for managing land-sea interactions.

A fundamental issue is that Malaysia's current cadastral framework does not include a systematic mechanism for updating property boundaries in response to shoreline shifts. As a result, cadastral records quickly become outdated, leading to land tenure conflicts, governance challenges, and complications in compensation or land reclamation efforts (Dong et al., 2024; Bagheri et al., 2021). Dimopoulou & Elia, (2012)**,**(Williamson et al., n.d.), declared that a modernized cadastral approach that integrates spatiotemporal changes in coastal environments is most desirable

Accordingly, Fang et al., (2024; Janečka & Souček, (2017; Rajabifard et al., 2018) agree that addressing these challenges requires a dynamic, spatially enabled cadastral system that integrates shoreline changes, marine property rights, and adaptive legal frameworks

Other significant advancements include integrating spatial and temporal data for marine cadastres. Kara et al. (2023) emphasized the adaptation of LADM for coastal management, while Lemmen et al. (2021) extended LADM to dynamic marine environments within socio-legal contexts. Oosterom et al. (2019Discuss advances from 2D to 3D cadastres, incorporating 4D elements to address evolving property rights on a global scale. The current Malaysian 3D marine cadastre data model (A. Zamzuri et al., 2022) did not incorporate the temporal component needed to accelerate the documentation of temporal changes and administration of tenure, such as temporal occupation license, leading to administrative inefficiencies and governance challenges.

The extension of LADM to marine and temporal aspects offers a structured approach to integrating spatial dimensions into a unified framework (Mehmood et al., 2022; Vranić et al., 2021).

Studies highlight LADM's potential for dynamic marine environments by enabling efficient land and marine data management while facilitating data sharing and interoperability (Atazadeh et al., 2021; Gürsoy Sürmeneli et al., 2022). Peter Van Oosterom & Stoter, (2010) introduced a five-dimensional geographic data model (3D+time+scale), focusing on formalizing geographic information within a conceptual 5D continuum.

Coastal erosion is recognized as a natural process exacerbated by climate change, sea-level rise, and human activities, resulting in shoreline retreat, land loss, and cadastral boundary shifts. This phenomenon challenges land tenure security and property rights, particularly in coastal regions like Malaysia, where static cadastral boundaries fail to accommodate dynamic coastal landscape changes (Uşak et al., 2024). Studies have shown that shoreline retreat can lead to legal disputes over land ownership, especially when property boundaries extend into submerged areas or are altered by erosion (Passeri et al., 2015).

2.1 The Malaysian National Land Code 1965 and Coastal Cadastre Framework

Malaysia is a coastal nation gifted with crucial natural resources located within Peninsular and East Malaysia. However, the management of marine property rights, leasing, and governance faces significant challenges, particularly due to the dynamic nature of coastal changes such as erosion, accretion, and sea level rise. In Peninsular Malaysia, all 11 states adhere to the Torrens System, as outlined in the National Land Code 1965 (NLC 1965), which provides a land title registration system ensuring legal ownership, security, and government oversight. Under this system, the land register is the final authority, guaranteeing ownership and minimizing disputes. Despite these frameworks, Malaysia's Temporary Occupation License (TOL) system, governed under Section 65 of the NLC 1965, facilitates the short-term leasing of foreshore and seabed areas for aquaculture, tourism, and port development. While the system is vital for supporting economic activities, several limitations persist. Specifically, there is a pressing need to clearly define permit conditions, evaluate investment costs and returns, and assess the status and disposition of investments upon permit expiration. Furthermore, Section 40 of the NLC 1965 dictates that coastal land permanently submerged by natural processes is reclassified as foreshore or seabed, reverting to state ownership (Mohamed et al., 2023;Marzukhi et al., 2018;Halid & Hassim, 2024). However, the current cadastral system lacks the necessary mechanisms to systematically track and analyze these land-to-sea transitions. The absence of integrated spatiotemporal tracking systems within both the TOL framework and cadastral records hinders enforcement, complicates tenure management, and undermines effective marine spatial governance (Yahaya et al. 2011). Additionally, the jurisdictional boundaries set by the United Nations Convention on the Law of the Sea (UNCLOS), extending beyond three nautical miles, introduce further uncertainties regarding property rights and zoning enforcement (Halid & Hassim, 2024). Moreover, conflicts between land use zoning under Local Plans and tenure conditions governed by the NLC and the Town and Country Planning Act 1976 (Act 172) highlight the need for regulatory harmonization (Mohamed et al., 2023;Marzukhi et al., 2018). Existing 3D marine cadastre models, which primarily rely on static spatial representations, fail to incorporate temporal components essential for tracking cadastral property evolution over time. This limitation complicates the accurate monitoring of marine parcel changes, leading to legal uncertainties, tenure insecurity, and administrative challenges (N. A. A. Zamzuri et al. 2021; Ashraf Abdullah et al. 2014).

Scholars such as Gürsoy Sürmeneli, Koeva, et al. (2022), Flego et al., (2021), Thompson & van Oosterom, (2021), Ho & Hong, (2021) and Cole & Wilson (2016) underscore the critical need for integrating temporal dimensions into land administration, particularly in dynamic marine environments.

This gap is particularly relevant in Malaysia, where the current National Land Code may require reevaluation to incorporate a customized LADM-based coastal cadastre data framework that enhances tenure security (Mohamed et al., 2023;Marzukhi et al., 2018;Halid & Hassim, 2024).

It must be noted that static land tenure systems struggle to address parcel loss and transformation, leading to inconsistencies in cadastral records. Also, property owners and land administrators face difficulties in updating cadastral records to align with physical land changes, highlighting the need for an adaptive mechanism.

To address the challenges of implementing LADM Part 3, several international strategies and best practices have been identified. Foremost is the harmonization of legal and institutional frameworks to formally recognize marine rights, restrictions, and responsibilities (RRRs) alongside terrestrial tenure. Countries such as Canada and the Netherlands have successfully integrated marine legal spaces into national cadastre systems through collaborative and cross-sector governance. A modular, phased implementation approach that begins with pilot projects in priority coastal zones can progressively build technical and institutional capacity. In parallel, the use of interoperable spatial standards, such as ISO 19152 and IHO S-121, facilitates the integration of legal, hydrographic, and planning datasets. Capacity building and stakeholder engagement, particularly among land surveyors, marine authorities, and local communities, are essential to ensure long-term adoption and relevance.

Building on these global lessons, this research proposes an enhanced LADM-based 3D Temporal Marine Cadastre Data Model tailored to the Malaysian context. The model integrates spatiotemporal attributes, real-time monitoring data, and marine legal frameworks within the scope of the National Land Code. By embedding temporal components within an LADM-compliant structure, the proposed system aims to improve transparency in leasing, strengthen regulatory enforcement, and enhance governance over Malaysia's dynamic coastal and marine environments.

The next Section, 3, discusses the methodology.

3. Methodology

The study follows a process of data collection of satellite images, bathymetry data from the General Bathymetry chart of the ocean (Gbeco), cadastral lots from the mapping authority, orthophotos via drone technology, while possible attribute classes were obtained from the LADM and Malaysians' 3D MCDM, respectively. Temporal data integration ensures that the model incorporates temporal data to represent the changing nature of the coastal shoreline. This also allows for the simulation of future shoreline shifts based on historical trends and predictive models. The outputs of these models are integrated into the 3D Temporal cadastre to project future erosion impacts and property losses.

The adopted possible classes were used for the development of the LADM-based 3D Temporal Coastal cadastre conceptual data model. The temporal event class, marine parcel, cadastral parcel lot, and other necessary classes were integrated into the spatial unit of the LADM structured model while maintaining the Party package and administrative package, and the other Spatial unit packages of the LADM, respectively.

The study utilizes a 3D Temporal cadastre model, developed within the Land Administration Domain Model (LADM) framework, to visualize the shoreline transformations over time. The model will integrate both real-world and simulated data to provide a more accurate representation of coastal changes and their impact on property management. This model aims to link land administration processes with temporal and spatial shoreline changes, forming the basis for the creation of a 3D Temporal cadastre. It outlines how cadastral boundaries and property rights will be tracked over time, incorporating both real-world and simulated data.

The core of the methodology involves the design and development of a 3D Temporal cadastre data model within the Land Administration Domain Model (LADM) framework, beginning with the conceptual model development.

The proposed model validation of the proposed LADM-based 3D+T Marine Cadastre Model will be conducted through data accuracy assessment, model testing, and legal framework evaluation in the following key areas:

i. Spatial and temporal accuracy validation to compare the model's spatial and temporal representations with ground-truth data such as satellite imagery and bathymetric surveys. The focus is to ensure precise tracking of marine parcel boundaries, detect changes over time (partial, significant, or full submersion), and maintain consistency with real-world coastal dynamics.
ii. Legal and Governance Compliance Validation objective is to assess the model's alignment with Malaysia's National Land Code (NLC 1965), TOL leasing rules, UNCLOS, and marine zoning laws focusing on verifying that the model accurately represents ownership transitions, leasing rights (TOL), and jurisdictional changes for submerged lands.
iii. LADM Compliance and Data Model Integrity's objective is to evaluate the model structure against ISO 19152 LADM standards, ensuring components like LA_Parcel, LA_Right, and LA_BAUnit properly capture 3D+T attributes. The focus is to validate the integration of temporal changes within LADM structures to facilitate seamless land-to-marine transitions.
iv. Database and System Performance Validation objective is to test the PostGIS spatial database for its ability to handle 3D+Temporal queries, updates, and real-time data ingestion while focusing on ensuring the system efficiently processes marine parcel changes without performance bottlenecks.
v. Usability and Decision-Support Validation's objective is to assess the visualization and analytical tools (e.g., 3D Web GIS dashboard) designed for marine parcel management. The focus is to evaluate the usability of the system for land administrators, marine authorities, and policymakers, ensuring it supports effective decision-making, respectively.

3.1 Data Modelling

The development process starts by organizing real-world concepts and their interrelationships into a structured format. A Unified Modeling Language (UML) class diagram is employed to construct the conceptual model, capturing the logical associations among entities. From this model, relevant classes are identified, categorized, and their fundamental relationships are defined to support subsequent database development.

A key objective of this work is to address the inadequate representation of marine properties in the current systems. As outlined in Table 1, these classes and their associated groups are drawn from both the Land Administration Domain Model (LADM) parts 1 & 3 and Malaysia's national profile, forming the basis of the conceptual model. By integrating new classes that capture the unique characteristics of marine environments such as marine parcels ("marine layer units"), coastal parcels (cadastral lots), and temporal elements, this enhanced system extends the existing Malaysian 3D marine cadastre data model for a customized LADM-based 3D Temporal coastal cadastre data model. Additionally, metadata and interoperability classes support efficient data exchange, which is enabled by LADM Part 3, with a dedicated survey data class that ensures data accuracy.

The development of the involves the identification and classification of relevant LADM classes (Table 1), followed by the use of Enterprise Architect and UML to construct the conceptual data model. The framework was structured around the core LADM packages: LA_Party, LA_RRR, LA_BAUnit, and LA_SpatialUnit. While LA_Party, LA_RRR, and LA_BAUnit retained their original LADM designations, LA_SpatialUnit was adapted into LMC_SpatialUnit to accommodate additional specialized classes, LMC_MarineSpatialUnit, and LMC_CadastralParcel. LADM Part 3, Marine Georegulation, LA_Source, serves as a Temporal event class, and as such, our LMC_TemporalEvent with her data will function from there (LA_Source), stored with relevant temporal attribute data respectively. This modification preserves the integrity of the LADM structure while extending its capacity to represent both land and marine property units within a unified

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system. The model thus enables an individual to simultaneously hold rights over land cadastral lots and marine parcels, supporting integrated coastal land administration within an LADM 3D Temporal coastal framework. The model should, when queried, be able to show the dual ownership of parcels, either a marine or a land parcel, respectively.

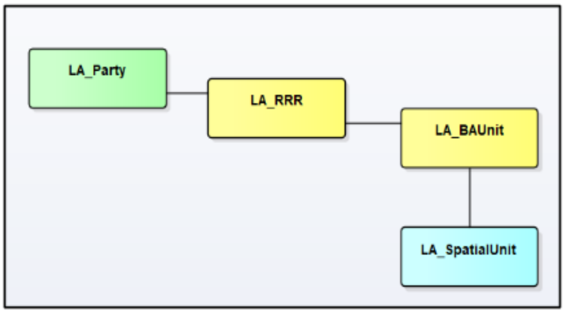

Figure 2. LADM classes

3.1.1 Potential LADM Classes

The possible classes for adoption into the LADM-based 3D Temporal coastal cadastre model are shown in the table below, describing the proposed conceptual data model

Group/ Packages	Sub-Classes
Party	LA_Party LA_GroupParty
Administrative	LA_BAUnit LA_AdministrativeSource LA_RRR LA_Right LA_Responsibility LA_Restriction
Spatial Unit	LA_Source LMC_MarineSpatialUnit LMC_MarineParcel LMC_SeaSurface LMC_AboveSeaSurface LMC_Seabed LMC_UnderSeabed LMC_WaterColumn LMC_CadastralParcel MC_SurveyData MC_Metadata_Interoprability LMC_TemporalEvent

Table 1. Potential LADM classes

Table 1 outlines the potential and possible classes for integration in the Conceptual Data model of the proposed LADM-Based coastal cadastre. Three-Dimensional with Temporal Marine Cadastre Data Model based on the LADM standard. The identified classes were classified into the Party, Administrative, and spatial units, respectively.

The development of the conceptual model (Figure.8) follows. The conceptual design defines the data management structure within the 3D Temporal Coastal Cadastre Conceptual data model, developed based on the LADM framework and structured for database implementation. It delineates the relationships among entities to support a comprehensive integration of land and marine cadastral information. The design adheres to the LADM conceptual model while being specifically adapted to the Malaysian cadastral registration system through a tailored country profile. Unified Modeling Language (UML) was employed to formally represent the entities, attributes, and their interrelationships within the model.

The UML diagram illustrating the proposed 3D Temporal Coastal Cadastre model is the initial result of this research.

The modelling of LADM Packages and the Logical Data Model development was next. The LADM-based 3D Temporal Coastal Cadastre Data Model was developed by adapting existing marine cadastre models and the Malaysian LADM Country Profile. Specific entities and attributes were added to accurately represent real-world coastal scenarios. The Logical Data Model (LDM) defines the structure and relationships of the data independently of physical storage, while the conceptual model (Figure 9) details the attributes of various classes leading to the creation of the 3D Temporal Marine Cadastre Logical Data Model based on the LADM framework.

Class development is discussed beginning with LA_Party, LA_RRR, and LA_SpatialUnit. Here, the LADM Packages are transformed from the traditional LADM LAs to MCs. The Party Package (LA_Party) (Figure.3) represents people and organizations with a legal or administrative relationship to land. For example, natural people, companies, government agencies, and include party identifiers, roles, and groups. The LADM LA_Party inherits wholly the existing attributes with additional customized attributes for the marine environment, including pID as class identifier with green color of the LADM.

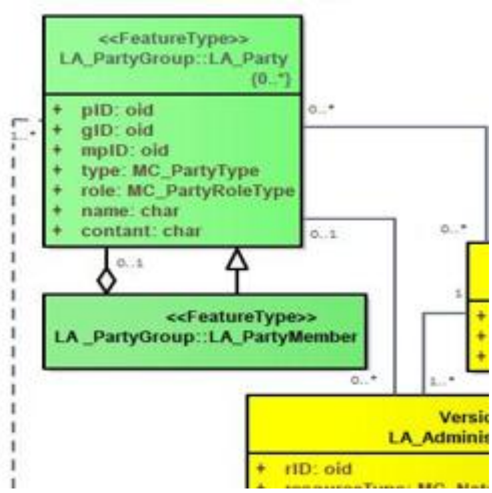

Figure 3. LA_Party(Green)

The Administrative Package LA_RRR, LA_BAUnit, in Yellow (Figure 4). The traditional LADM LA_AdministrativeSource retains its LADM LA status. The RRRs are Rights (ownership, lease), Restrictions (no-built zones), Responsibilities (maintenance duties), while BAUnit (Basic Administrative Unit), A group of RRRs related to one or more spatial units, which captures legal relationships and administrative facts.

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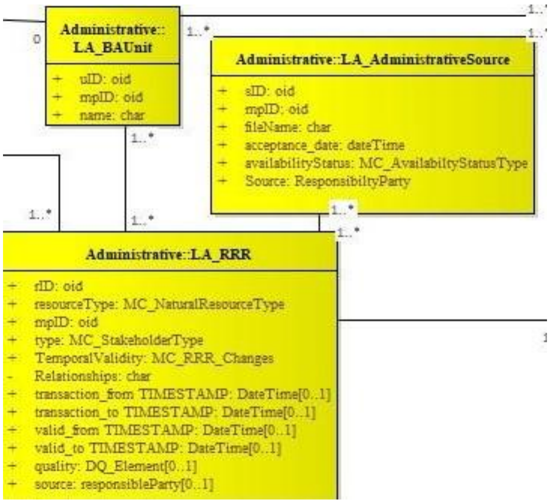

Figure 4. LA_BAUnit, LA_AdministrativeSource Classes (Yellow)

The Spatial Unit Package (LA_SpatialUnit) (Figure 5), in the Land Administration Domain Model (LADM), the Spatial Unit Package defines a spatial unit as an area or volume of land, water, or space that is identified and delineated for land administration. A spatial unit may represent a physical entity, such as a land parcel, building plot, or marine area, as well as a legal space, including three-dimensional property units like condominium volumes or vertical zones within the marine water column. It may also include non-physical or overlapping spaces, such as rights-of-way or zones with multiple legal claims. Each spatial unit is uniquely identified and linked to associated legal parties, rights, restrictions, responsibilities, and administrative records. The geometric representation of a spatial unit, whether a point, polygon, or 3D volume, can be stored directly within the system or referenced externally through integrated spatial databases. In the context of a marine cadastre, spatial units may encompass vertical segments of the water column or seabed parcels designated for activities such as aquaculture, navigation, or resource extraction. This flexible and consistent conceptualization of spatial extent supports integrated administration across both terrestrial and marine domains.

Our core intention for the coastal cadastre integration was carried out in the spatial unit based on the LADM provisions for extension of additional classes to accommodate such for the cadastral framework. The core classes here are the cadastral parcel, marine parcel, and

Temporal event integration was handled within the LA_Source; here, the LA_Source was enhanced with temporal event attributes for coastal and marine objects based on LADM part 3 georegulation. The LA_Source connects all the units specifically the LA_Party, LA_Adminstrative Source, LA_BAUnit, LA_RRR, LMC_SpatialUnit, LMC_MarineParcel and LMC_CadastralParcel respectively. All are invariably dependent and store their data in the LA_Source for processing and queries.

Each of these classes has unique identifiers for database creation and linking appropriately with other LADM units, which ensures that various forms of query or queries can be carried out with expected output and results. The Marine parcel classes and the cadastral parcel classes have their sub-classes with their attributes customized based on their code list.

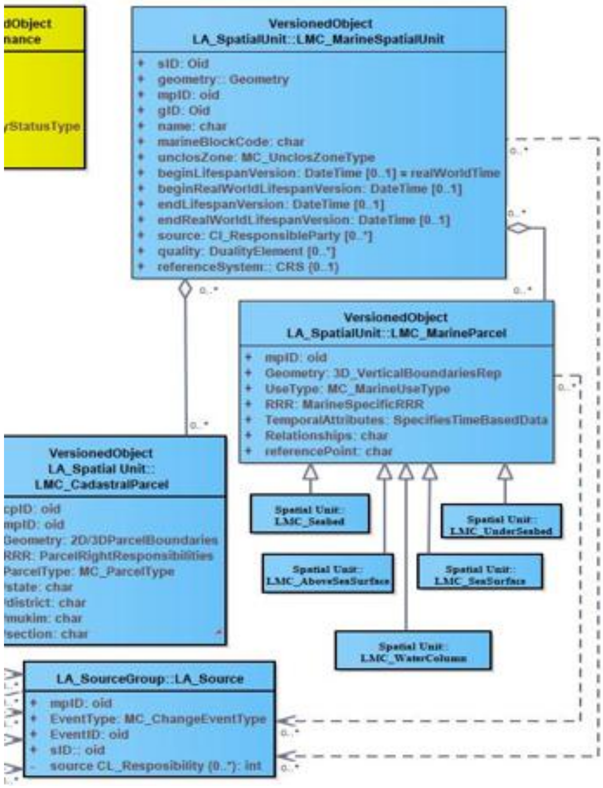

Figure 5. LMC_MarineSpatialUnit (Blue)

Figure 5 illustrates the spatial unit involving cadastral parcel classes and marine parcel classes, with the marine spatial unit acting as an ontology class that connects the cadastral parcel class to the marine parcel class. This structure facilitates the integration of the temporal class event, along with its corresponding attribute data.

The Cadastral Parcel Unit Class (figure 6) consists of the main LMC_CadastralParcel class and two sub-classes of MC_SurveyData, MC_Metadata_Interoperability, with their attributes to enable proper documentation of cadastral parcel lots and how data can be exchanged, respectively. Through the ontology of the Marine spatial unit, both the cadastral parcel and the marine parcel are brought together thereby integrating the land and marine parcel into views, determining the effect of reclamation of land to marine, marine to marine occasioned by shoreline shifts and particularly the shifting or 'moving boundary' of the sea situation and the effects on 3D marine properties. Also, issues on temporal occupation license TOL, and use of seabed, especially the legal provisions based on the Malaysian National Land Code of 1965, the UNCLOS declaration of the law sea, the various definitions of nautical mile by various nations, and the universal declaration.

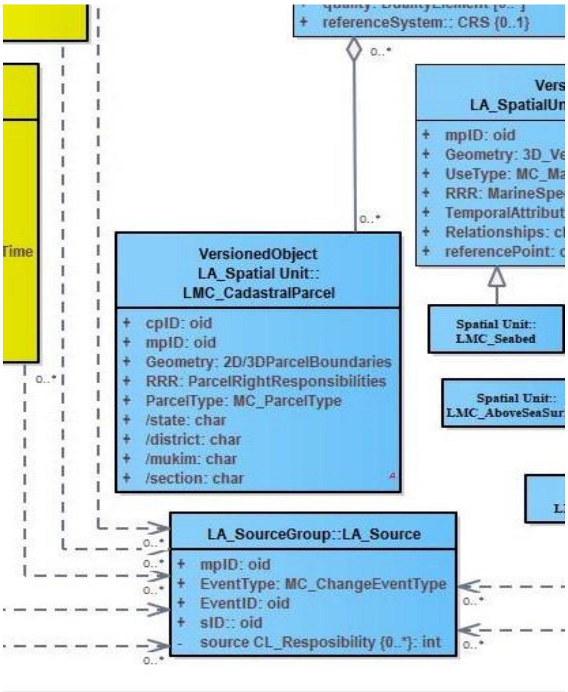

Figure 6. MC_CadstralParcel with Attributes

The Marine Parcel unit (Figure 7) class consists of the main marine parcel class and five sub-classes with their attributes to enable proper documentation of various RRRs, respectively. The sub-classes include LMC_Seabed, LMC_UnderSeabed, LMC_SeaSurface, LMC_AboveSeaSurface and LMC_WaterColumn respectively. The class has mpID as an identifier.

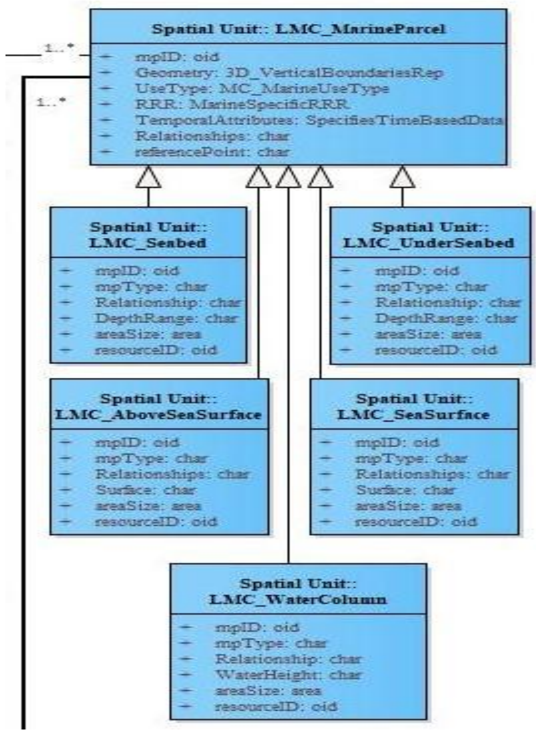

Figure 7. LMC_MarineParcel & sub-classes

The Logical Conceptual Data Model (Figure.9) represents an abstract blueprint of how data is structured, focusing on the organization of entities, attributes, and their relationships without tying it to specific technologies or databases. In the context of an LADM-Based 3D Temporal coastal Cadastre, it defines how cadastral elements such as marine parcels, rights, and parties are logically linked within a framework based on the Land Administration Domain Model (LADM). This model ensures consistency, supports spatial-temporal queries, and facilitates integration with legal and administrative data for effective marine property management.
This work recognizes LADM part 3, marine georegulation provisions for temporal events in the LA_Source, therefore customized with relevant temporal attributes to allow us to achieve the aim of this research work. These integrations are expected to enable the cadastre system to track changes over time, ensuring that historical data and legal clarity are maintained. The ontology of this class will capture time-based changes affecting CadastralParcels and MarineParcels, such as shoreline movement, sea-level changes, shifting boundaries, and the Temporal Occupation Licenses (TOL). Also, the temporal perspective ensures that both the legal and spatial dimensions of marine and coastal land administration are accurately tracked over time. The temporal event class within LA_Source has an identifier EventID to ensure linkage with other classes.

The developed framework is further discussed, detailing the attributes within various classes and their intended functions in the developed cadastre. Furthermore, the specifics of the framework are discussed below

a. LMC_MarineSpatialUnit

Represents a distinct, legally defined section of marine space, which may include the seabed, water column, and airspace above.

Attributes:

- ParcelID: Unique identifier for each marine parcel.
- Geometry: 3D representation, including vertical boundaries (depth from seabed to surface).
- UseType: Designation (e.g., fishing, conservation, navigation).
- RRR: Marine-specific rights, restrictions, and responsibilities.
- TemporalAttributes: Specifies time-based data, such as seasonal restrictions, shifting boundaries, or changing rights.

Relationships:

IsWithin: Connects MarineParcels to larger marine zones or administrative areas.

IsAssociatedWith: Links to CadastralParcels for parcels spanning both land and marine environments

▪ LMC_ MarineParcel classes

The marine layer geometries allow the system to model properties in a 3D context, making it possible to *manage Rights, Restrictions, and Responsibilities (RRR)* across different layers of the marine environment. It represents 3D volumes that define the spatial extent of a property unit within the marine environment. The sub-classes here include

LMC_Seabed, LMC_UnderSeaBed, LMC_WaterColumn, LMC _SeaSurface, and LMC_AboveSeaSurface are designed to capture specific layers of the marine environment. The general class attributes are for the sub-classes to inherit in addition to their specific attributes.

General Class Attributes:

- **mpID**: Unique identifier for the marine unit. (mpID, i.e., marine proper identifier)
- **LMC_MarineType**: Type of volume (e.g., seabed, under seabed, water column, sea surface, and above sea surface).
- **Boundaries**: Define the 3D coordinates that outline the volume.
- **Owner**: Identifies the legal entity owning or having rights to the volumetric unit
- **Relationships**: Connections to adjacent volumes (e.g., vertically or horizontally linked).

Specifically,

a) The LMC_Seabed, & LMC_UnderSeabed, representing the portion of the marine property extending along the seabed, is relevant for activities like drilling, mining, and underwater construction, with *DepthRange* as its customized attribute.

b) The LMC_WaterColumn defines the vertical space between the seabed and the surface, capturing the water body, which has *WaterHeight* as a customized attribute.

c) The LMC_SeaSurface, & LMC_AboveSeaSurface represent the top layer of the marine environment, including the sea surface and immediate airspace, and have *SurfaceArea* as the customized attribute, respectively

▪ LMC_TemporalEvent Classes (within the LA_Source)

The marine environment is dynamic, with properties often subject to temporal changes. The temporal event classes are expected to enable the cadastre system to track changes over time, ensuring that historical data is retained, and legal clarity is maintained. In this research, the Ontology captures time-based changes affecting CadastralParcels and MarineParcels, such as shoreline movement, sea-level changes, and shifting boundaries.

LMC_TemporalEvent

Attributes:

- EventID: Unique identifier for each event.
- EventType: Type of change (e.g., erosion, accretion, regulatory update).
- TransactionTime (tmin, tmax): This indicates when a change is recorded in the

system (i.e., when the transaction was created or modified)

- ValidTime (vmin, vmax), which indicates the actual period during which the property state or legal rights are valid, regardless of when they were recorded.
- EventStartTime/EndTime: Temporal attributes indicating when the event starts and ends.
- Archival History: A lot of historical changes, including past states and transactions.

Relationships:

Affects: Connects the event to CadastralParcel or MarineParcel classes, showing which parcels are impacted by the change.

IsLinkedTo: Relates to RRR, adjusting rights and restrictions over time.

▪ LMC_CadastralParcel Classes

Represents the core concept of a land parcel as traditionally used in cadastres, including spatial boundaries and ownership or legal attributes.

Attributes:

- ParcelID: Unique identifier for each parcel.
- Geometry: 2D or 3D spatial representation of the parcel's boundaries.
- Ownership: Information on the owner(s) and their rights or jurisdiction
- RRR (Rights, Restrictions, and Responsibilities): Legal information detailing the rights and responsibilities associated with the parcel.
- TemporalLink: Links to LMC_TemporalObject to ensure the tracking of changes over time.
- lot_status: Status of the lot (e.g., active, disputed, protected, submerged, threatened)
- area: Total area of the lot (calculated based on the boundary coordinates)
- ownership: Details of ownership or jurisdiction

Relationships:

IsAdjacentTo: Links to nearby or neighbouring CadastralParcels or MarineParcels.

OverlapsWith: Defines any overlapping areas (e.g., in intertidal zones).

▪ MC_SurveyData

This class captures spatial measurement and survey data needed to maintain accurate boundaries in both land and marine parcels.

Attributes:

- SurveyID: Unique identifier for survey data.
- Method: Survey technique used (e.g., bathymetric, topographic).
- Accuracy: Precision of the survey, crucial for legal and administrative purposes.
- Timestamp: Date and time of the survey.

Relationships:

IsSourceFor: Links survey data to the SpatialUnit, showing the origin of boundary definitions.

▪ MC_Metadata_Interoperability

This class ensures metadata organization, use, and enables data exchange based on international standards.

Attributes:

- externalSystemID: oid
- DataSource: DataOriginSataliteBathymetrySurveys
- dataCollectionDate: Date
- AccuracyLevel: ReliabilityAccuracy
- DataUpdate_Frequency: DataUpdateRecords
- translation rules:ISO_DataCollectionStandard
- Relationship

Section 4 is the Initial Results and Discussions

4. Initial Result and Discussions

4.1 The Initial Results

The initial result of this research is hereby presented, which includes the conceptual framework and the logical data model or detailed conceptual data model as figures 8 and 9
Figure 8 is the LADM-based 3D Temporal Conceptual Coastal Cadastre data model framework, while Figure 9 is the developed LADM-based 3D Temporal coastal cadastre logical data model.
The developed LADM-Based 3D Temporal coastal cadastre logical data model introduces new classes of MC_MarineSpatialUnits, MC_CadastralParcel, along with their sub-classes, MC_SurveyData, and MC_Metadata_Interoperability, and the MC_MarineParcel class. The MC_MarineParcel class, in turn, includes the sub-classes MC_SeaSurface, MC_AboveSeaSurface, MC_Seabed, MC_UnderSeabed, and MC_WaterColumn. Temporal events are handled within the LA_Source, ensuring that changes to property status, boundaries, and rights are consistently recorded over time, supporting legal continuity and historical clarity.
The adopted approach was designed to facilitate the comprehensive management of marine properties by integrating advanced volumetric geometries, robust temporal attributes, and flexible cadastral lot structures, respectively

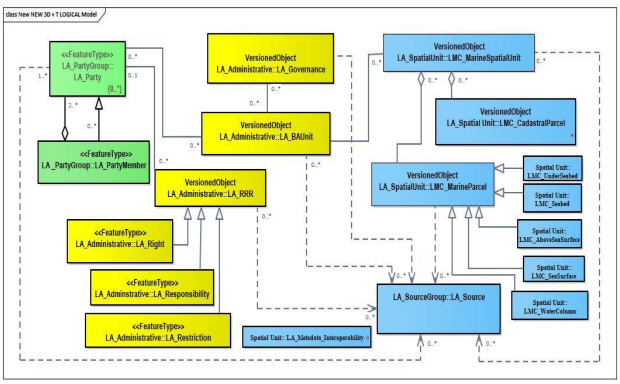

Figure 8. LADM-based 3D Temporal Conceptual Coastal Cadastre data model

The model enables the visualization and quantification of shoreline transformations over time. By integrating real-world and simulated data, it will provide a more accurate representation, cadastral documentation with a temporal context of coastal changes and their impact on property management and governance.

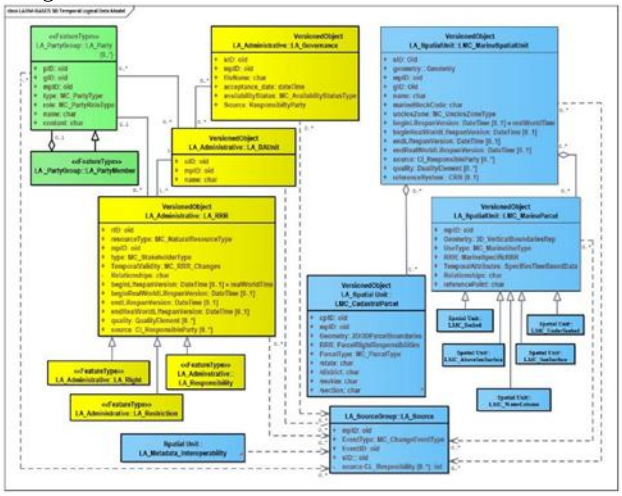

Figure 9. LADM-based 3D Temporal Logical Coastal Cadastre data model (appendix 1)

4.2 Case Study Overview: 3D Property Situation in Kampung Pengkalan Kuala Maras, Terengganu

The case study overview of 3D property situations justifying the necessities for a customized coastal cadastre.
The 3D cadastral situations of properties of our case study were examined from the following scenarios (Figure 12) of 2024 and 2025, respectively. Our first discussions would be centered on the satellite Imagery of 2024 and the physical photo of our study area, highlighting the threatening situations of our cadastre. The scenario is the integration of the two images showing both pre- and post-erosion activities.

Figure 10. Temporal changes of Kampung Pengkalan Kuala Maras shoreline and Property Situation as of 2024 and January 2025

As of 2024, properties (pink), roads (green), and the shoreline (deep blue) in Kampung Pengkalan Kuala Maras aligned with the cadastral register. By January 2025, erosion had completely erased these features and properties physically, therefore becoming figurative in our cadastre. Figure 10. illustrates this drastic transformation, comparing May 2024 pre-erosion satellite imagery with the post-erosion scenario, which shows the total loss of properties, buildings, roads, and shoreline. These changes raise legal and administrative concerns about property rights, compensation, and land reclassification.
Authorities must update the cadastral register, maps, and land titles while deciding whether submerged parcels remain legally recognized or become public domain. Issues on compensation, resettlement, and policy adjustments in the marine cadastre must be addressed.
Noticed that before the coastal changes, the cadastral boundaries of this area were well-defined based on the available historical records and satellite imagery. However, without regular updates, coastal cadastral records become outdated. Lost

properties now transformed into marine parcels under government jurisdiction, creating legal conflicts where two sets of RRR (Rights, Restrictions, and Responsibilities) apply, one for the original land parcel and another under marine regulations.

Malaysia's cadastre system is yet to fully address these situations, requiring cadastre updates, fair compensation policies, alternative land allocations, and setback zones for risk reduction.

Figure 11 is the 3D visualization of situations of properties for both cadastral parcels and simulated marine parcels in blue, highlighting shoreline changes from 2008, 2024, and 2025, emphasizing the urgent need for continuous updates in coastal cadastral management. It visualizes the affected and at-risk properties, showing cadastral lots (brown) transitioning into marine parcels (blue). The shoreline positions from 2008 (red), 2024 (yellow), and 2025 (pink), along with the road network (dotted green), highlight significant land loss.

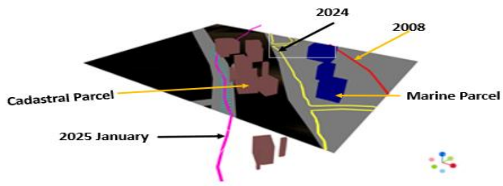

Figure 11. 3D view of land–sea interactions at Kampung Pengkalan Kuala Maras, Terengganu

Figure 12. 3D view of land–sea interactions at Kampung Pengkalan Kuala Maras, Terengganu

Figures 11 and 12 illustrate land-sea interactions in a 3D view, showcasing both cadastral lots and marine parcels along with shoreline positions with distance measured in a yellow line across different periods, specifically 2008, 2024, and January 2025, at the case study location of Kampung Pengkalan Kuala Maras, Terengganu**.** This transformation from traditional land cadastres to an integrated marine cadastre underscores the necessity for an LADM-based 3D Temporal approach in managing coastal cadastral information effectively.

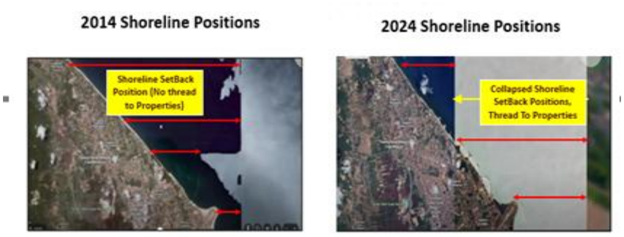

Figure 13. Shoreline shift, 2014-2024 showcasing temporal movement at Kampung Pengkalan, Maras, Terengganu, Malaysia

Figure 14. Query of Shoreline positions of our case study, Kampung Pengkalan Kuala Maras, Terengganu

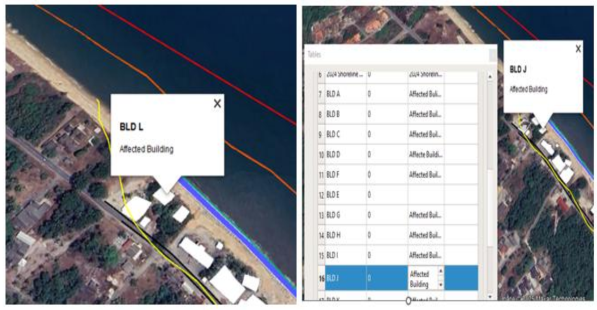

Figure 15. Query of Building properties with attributes of our case study, Kampung Pengkalan Kuala Maras, Terengganu

The next section discusses the conclusions and recommendations

5. Conclusion and Recommendations

This study has demonstrated that shoreline retreat and coastal dynamics significantly affect cadastral property boundaries, contributing to tenure insecurity, legal conflicts, and governance challenges in coastal regions. The research presents an LADM-based 3D Temporal coastal cadastre model that offers a spatiotemporal framework for integrated land and marine property management.

The model employs marine layer geometries to represent property units in the marine environment, enabling accurate assignment and management of Rights, Restrictions, and Responsibilities (RRR) across the marine domain. Key sub-classes such as LMC_Seabed, LMC_UnderSeabed, LMC_WaterColumn, LMC_SeaSurface, and LMC_AboveSeaSurface encapsulate distinct marine layers with attributes like DepthRange, WaterHeight, and SurfaceArea, supporting complex marine use cases like drilling, navigation, and offshore construction. Furthermore, tracking temporal changes, including shoreline shifts and sea-level variations, will preserve legal continuity and historical accuracy.

Additional components such as LMC_CadastralParcel, MC_SurveyData, and MC_Metadata_Interoperability enhance spatial precision and metadata exchange, promoting interoperability and adaptability across systems. The model's implementation within the context of Terengganu's vulnerable coastal areas highlights its practical relevance and necessity for comprehensive coastal cadastre systems.

To strengthen land administration and resilience in erosion-prone coastal zones, the following recommendations are made:

Legal reforms are needed to accommodate dynamic shoreline changes and integrate temporal marine property definitions into existing cadastral laws.
Enhanced spatial data infrastructure and the adoption of real-time monitoring technologies are crucial for effective marine and coastal land governance.
Participatory coastal governance frameworks, involving stakeholders at local and national levels, are vital for inclusive decision-making and tenure security.

Predictive modeling tools should be incorporated to forecast future coastal changes, enabling proactive planning and mitigation strategies.
Future research will focus on model validation, scalability, integration with real-time monitoring systems, and policy adaptation mechanisms, ensuring the model's readiness for wider application and long-term sustainability in coastal and marine property management.

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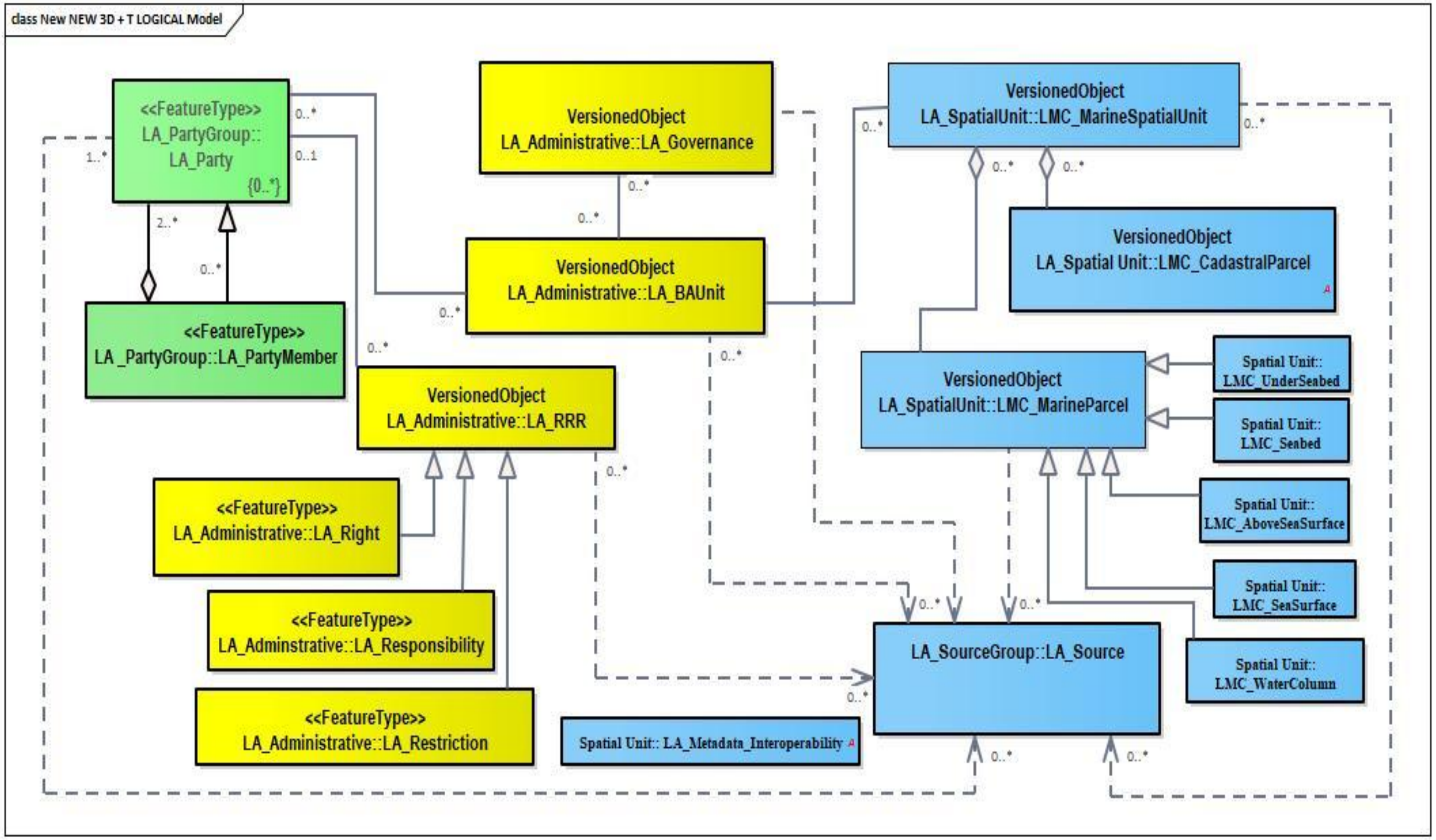
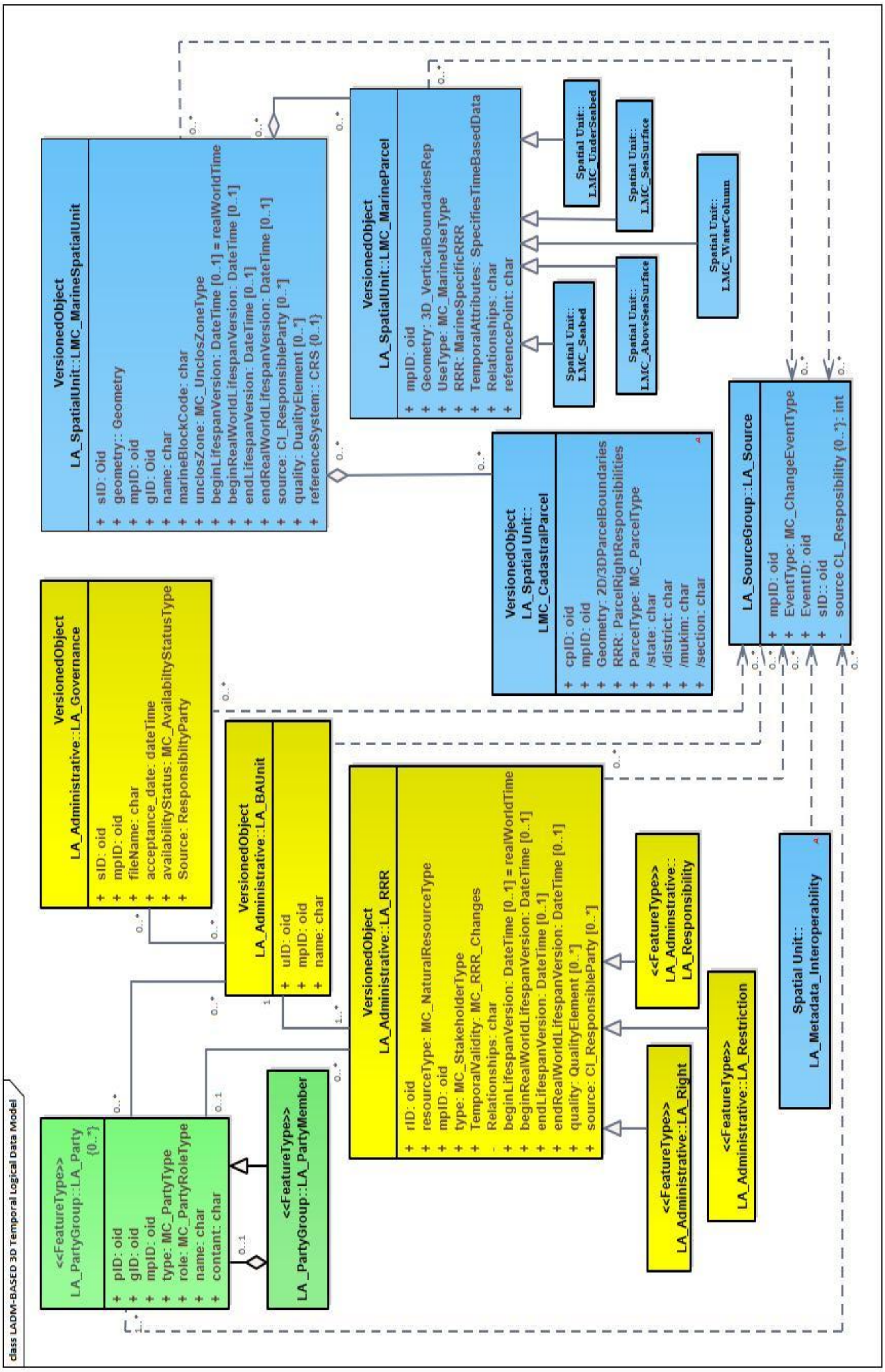
Appendix 1: LADM-Based 3D Temporal Coastal Cadastre
Appendix 1: 2D View of Study Area
Appendix 2: Shoreline Positions to Properties
Appendix 4: Land-Sea Interaction with Cadastral Lots and Marine Parcels
Appendix 5: Concurrent 2D & 3D Property Vie**ws**

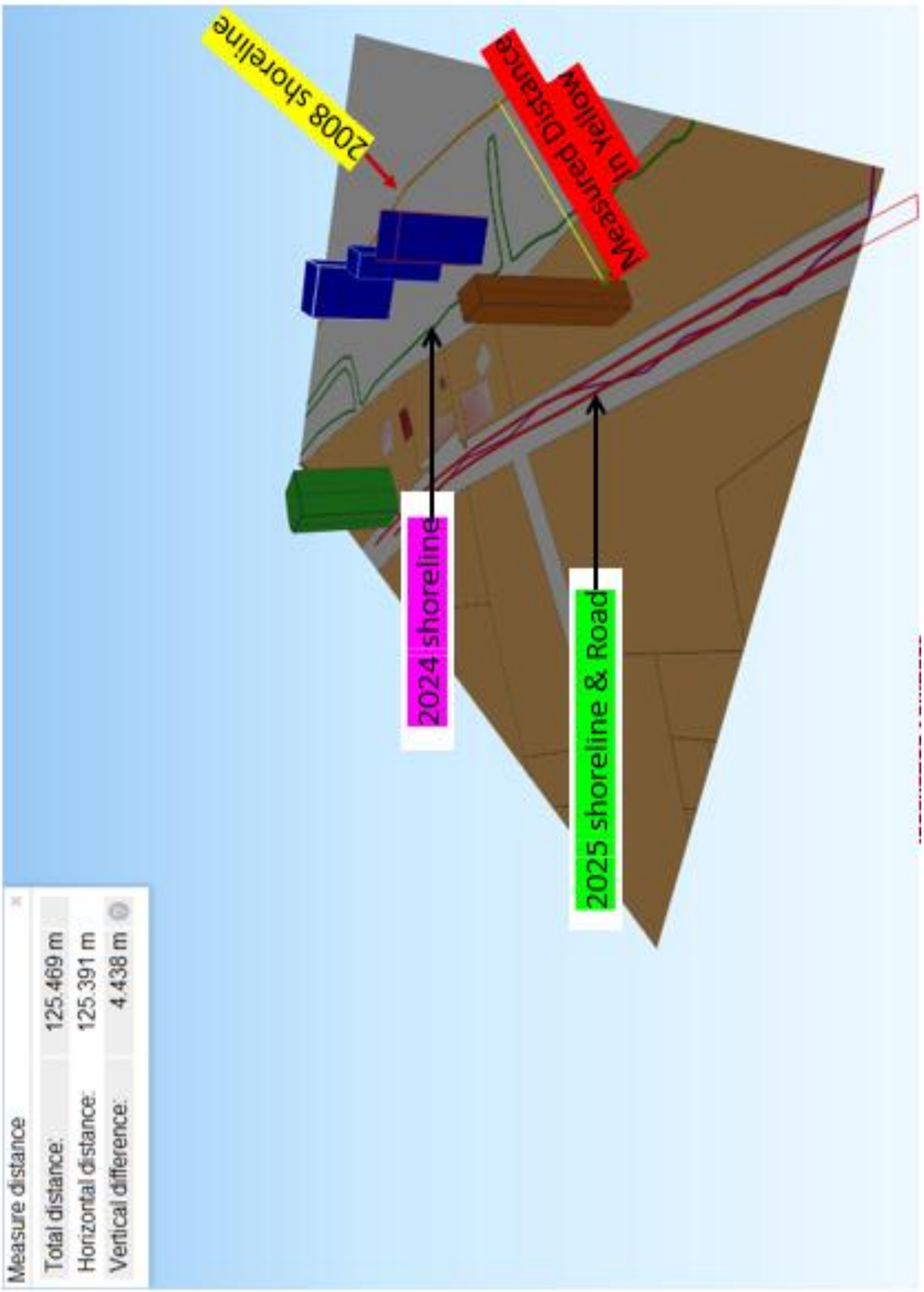
Appendix 1: LADM-Based 3D Temporal Coastal Conceptual Cadastre Model



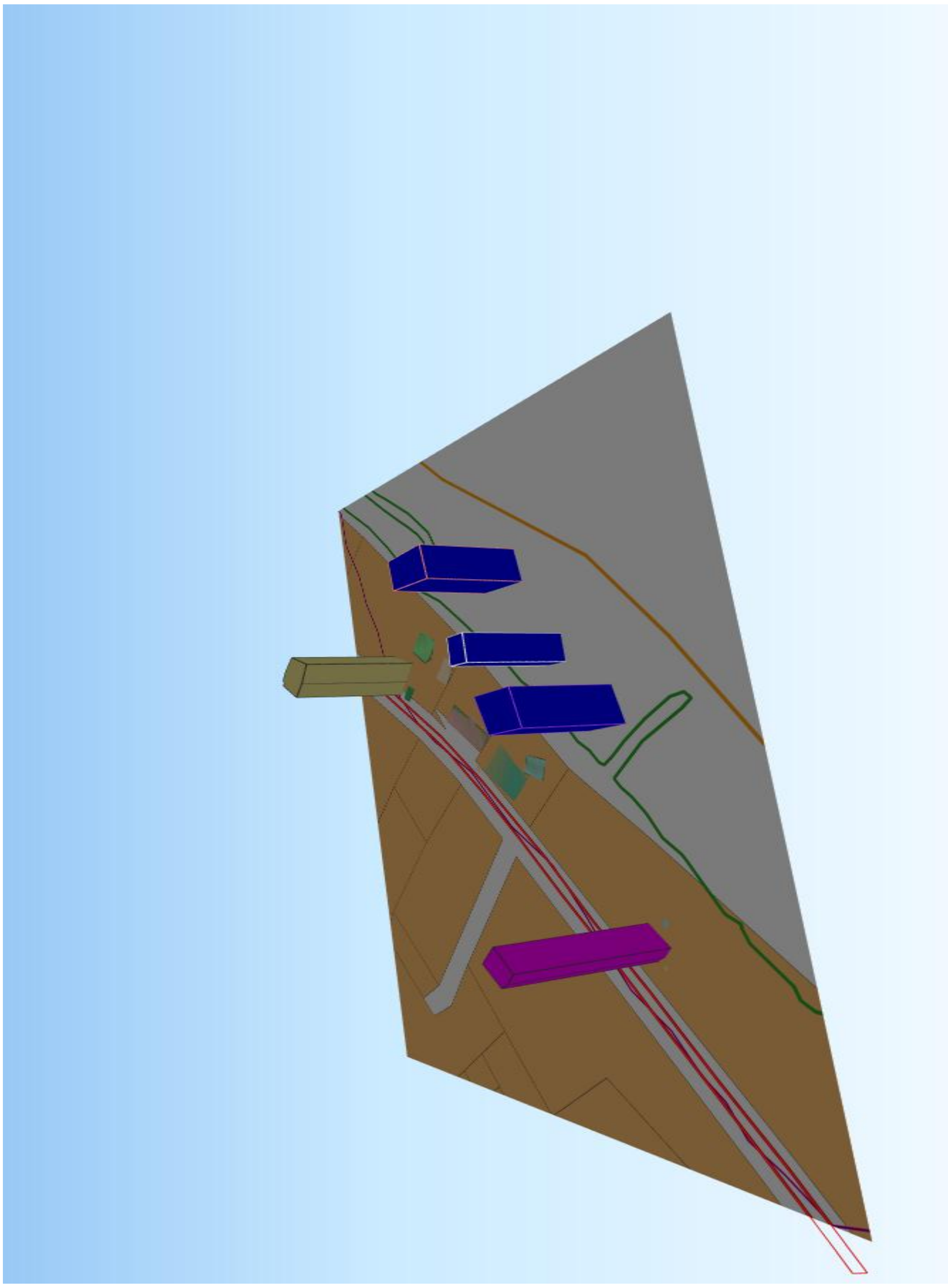
Appendix 2: Detailed LADM-Based 3D Temporal Coastal Conceptual Cadastre Model



Appendix: 3: Shoreline Positions to Properties



Appendix 4: Land-Sea Interaction with Cadastral Lots and Marine Parcels (Cadastral lots in Brown, marine Properties in Blue)



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Appendix 5: Concurrent 2D & 3D Property Views