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Visualization of Sea Level Rise with Spatial Analysis for A Future Scenario of Istanbul

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Abstract Recently, statistics on earth's surface temperature point toward high record temperatures that lead to Sea Level Rise (SLR) and degradation of land surface area. These situations cause other spatial objects (land and marine properties) to be affected by changes in their physical properties (including geometries and locations). Thus, this study attempts to investigate various aspects related to land and marine spatial objects/properties with respect to qualitative analyses of SLR together with visualization using the city of Istanbul as a case study. This study also discusses a brief experiment utilizing the Multi Error Removed Improved Terrain Digital Elevation Model (MERIT DEM), existing building footprints, simulated bathymetry, and land use datasets. The experiment reveals the prediction of the SLR according to the Intergovernmental Panel on Climate Change (IPCC) report. Additionally, in this article, the aim is to serve as a reference for near future research in the context of geospatial components, SLR and Land Administration Area Model (LADM) as object modelling tools.

Keywords Coastal Flooding · Elevation Data · LADM · SLR · Visualization

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Introduction

Istanbul, the largest city in Türkiye, is located in the northwest of the country and is surrounded by the Black Sea to the north and the SoM to the south. The Strait of Istanbul, which connects the Asian and European continents, passes through this megacity, and the ancient city center was established on the peninsula on the shores of the Golden Horn. Istanbul's unique geostrategic location and, especially, its specific waterways have had great importance in terms of trade, transportation and cultural interaction throughout its history. This geographical location, intertwined with the sea; in addition to the Islands region in the Sea of Marmara (SoM), the settlements and the estuary along the coastline of Istanbul, have caused the city to live in a predominantly marine climate. Humid air masses originating from the seas in Istanbul cause summers to be hot and humid, and winters to be mild and rainy (Couper 1989).

However, recent research has shown that this critical location also makes it one of the cities that will be affected by the negative consequences of climate change. In most of the models and scenarios prepared with Istanbul as the center, it has been reported that many devastating effects of climate change are expected in the future, from temperature increase to drought, from sea level rise to heavy rainfall (Karaca and Nicholls, 2008; Nigussie and Altunkaynak 2018; Toros et al. 2017; Büyüksalih, et al., 2019; Kurt and Xingong, 2020; Türe and Ar 2024; Büyüksalih and Gazioğlu, 2024). Therefore, more detailed research is required for each of these effects.

This study aims to visualize the sea level rise (SLR) for a future scenario of the city of Istanbul with spatial analyses via 3D geospatial components (land–marine). This investigation deals with two levels of SLR (3 and 15 meters) to illustrate the potential impacts of SLR on land–marine properties. The scenario of land–marine properties and the related components such as spatial data, georeferenced and datum, data management/analysis, data quality including visualization and dissemination are key components of the SLR research. Later, these components can be utilized for the visualization of the SLR scenario using datasets such as the Multi-Error-Removed Improved-Terrain Digital Elevation Model (MERIT DEM), existing building footprints (with heights), and land use. The literature (Atilola 2012; Boulus and Wilson 2023; Satpalda 2023) shows that all aspects need to be investigated; however, the three most important ones, which are data management/analysis, data quality, and visualization, will be the focus. In this study, the belief is held that climate change and global warming issues are very much related to the geospatial components (aspects). Tools such as GIS software (ArcGIS Pro) could be utilized for analysis.

This study reveals several major aspects of 3D land-marine properties' components, especially the qualitative analyses based on several datasets. SLR could cause severe problems, especially in areas with less coastal protection and bring the possibility of losing land to the sea. For example, the Sea of Marmara coastlines along with highly developed, industrialized, and built-up districts of Istanbul live with this danger. Esti-mating the effect and dimension of this phenomenon requires the application of global digital elevation models (GDEMs) together with other thematic map layers (including satellite images, line maps, 3D models, and socioeconomic datasets) in the GIS environment. In this way, predictions can be made regarding the influence of SLR on land use/land cover together with human settlements along the coast, and it will be possible to generate a coastal zone management for the area to deal with the threats brought by environmental disasters.

Section 3 discusses the 3D land–marine components, and Section 4 describes GIS analyses related to SLR effects on Istanbul as a case study area. Section 5 and Section 6 contain discussion and conclusion, respectively.

Climate Change Impact on Coastal Areas: SLR

One of the many direct and indirect effects of global climate change is SLR. Like many effects, SLR, which is an increasing threat especially for coastal areas, is also being tried to be predicted by researchers. In order to protect the economic, social and environmental security of cities, measures should be planned and implemented to cope with these effects (Tribbia and Moser 2008). With this motivation, scientific studies on SLR are increasing and vital feedback is provided to decision makers (Gornitz 1995; Titus and Narayanan 1995; Raper et al. 1996; Darwin and Tol 2001; Gazioğlu et al., 2010; Church and White 2011; Simav et al., 2013; Cazenave et al. 2014; Frederikse et al. 2020; Falkenberg and Dupont 2023; Turner et al. 2023; Völz and Hinkel 2023; Zhang et al. 2023; Zhou and Hawken 2023). Worldwide measurements show that global mean sea level has risen by an average of 0.18 m (range 0.10–0.25 m) over the last 100 years (Warrick et al. 1996). Although it is unclear to what level this increase will increase in the future, it is clear that its catastrophic effects depend on our climate adaptation.

The two main causes of SLR due to climate change are thermal expansion and melting of land glaciers. Between 1971 and 2018, 50% of the observed SLR was due to thermal expansion, 22% by ice loss from glaciers, 20% by the melting of ice sheets, and 8% by the decrease in water storage (Intergovernmental Panel on Climate Change (IPCC), 2021). As the ocean water warms, it expands by 0.01%, followed by a

SLR of 0.3 m (Pachauri et al. 2014). The roles of the large terrestrial ice sheets of Greenland and Antarctica in the global climate system are vital (Shepherd et al. 2018). As dramatic evidence: melting caused by extreme heatwaves caused the Greenland ice sheet to lose mass for the 26th consecutive year, and in September 2022, it rained instead of snow for the first time. Other, Arctic sea ice extent decreased by a record 43% between 1979 and 2019 (NSIDC 2023). Since 2011, the ice area in the Arctic Ocean has reached its lowest level since 1850 and the global mean sea level has risen at its fastest pace in the last 3000 years since 1900 (Lee et al. 2023). The sixth Assessment Report of the IPCC (Lee et al. 2023) shows that anthropogenic greenhouse gas (GHG) emissions are responsible for about 1.1 °C of warming since 1850–1900 and finds that global temperature is expected to reach or exceed 1.5 °C of warming on average over the next 20 years. Furthermore, as an overview, the changes in mean SLR from past to present have been evaluated and future directions have been presented with scenarios by the IPCC (Solomon et al. 2007; Pachauri et al. 2014). According to the very high GHG emission scenarios in the reports, global SLR is up to 1.01 m by 2100. Moreover, according to the 2023 AR6 Report and NASA, the SLR change will be up to 2 m by 2150 under the highest scenario (SSP5–8.5). It is also stated that the increase will reach 3 meters in 2300 according to the optimistic scenario and 7 meters according to the worst-case scenario (Lee et al. 2023; NASA 2023).

According to Kirezci et al. (2020), in the case of an RCP8.5 scenarios without coastal protection or the necessary SLR climate change adaptation; there will be an increase in the risk of flood disasters for 48% of the Earth's land area, 52% of the global population settlements and 46% of global assets by 2100. As additional info, 68% of global coastal flooding will be due to tidal and storm events, and 32% will be due to regional SLR.

SLR will increase the degradation of coastal ecosystems, coastal erosion, saltwater intrusion into estuaries and aquifers, and flooding of low-lying land. Coastal erosion, one of these chain effects, will cause dune destruction, including coastal plateaus, and will make coasts more vulnerable to strong storms and waves (Mimura 2013). It should not be forgotten that the habitats of many species will also be destroyed as a result of the destruction of these coastal areas; sea turtle nests in sandy areas are one of the most concrete examples of this (Pink 2018). On the other hand, an aquifer, which is a valuable freshwater reservoir, may not be able to drain the salt water mixed with it for years. The result is of course catastrophic, a series of serious problems starting with the deterioration of groundwater quality and the restriction of access to clean and safe water. Moreover, this contaminated water will pose a threat to human health with the parasites it contains and will pave the way for many epidemics that are easily transmitted through water (UN-Water 2021). Such a change in coastal ecosystems will make impossible the dynamics of adaptation of living things to the environment in which they live. In the long term, SLR is essentially a total extinction for coastal life (coastal cities, coral reef drowning, mangroves, nesting habitat destruction, salt intrusion) (Roy et al. 2023; Woodroffe and Webster 2014). For this reason, SLR stress faced by coastal life ranks high among the measures to be taken against the devastating effects of global climate change.

Sea level, routinely measured in all oceans by high-precision satellite altimetry in recent years, shows clear evidence of a global increase in SLR (Cazenave et al. 2014). And there are an estimated 680 million people worldwide living in coastal areas threatened by SLR, and by 2050 this population is expected to triple, with 50% of the world's population living within 100 km of coastal areas (Zhou and Hawken 2023). This population faces multiple evolving hazards, including the associated risks of SLR on infrastructure systems; disruption of transport services in coastal cities, lack of access to electricity and water resources, and ongoing cascading failures (Hinkel et al. 2018). Therefore, it will be necessary to take a holistic approach that interacts with climate-related risks to prevent insensitive urban development, cope with large-scale infrastructure and coastal change (Hinkel et al. 2018).

3D Land–Marine Components

The geospatial components related to 3D land–marine properties are introduced in this section. These components include spatial data, georeferenced-datum, and data management and analysis. The other components, such as data quality and dissemination of information, are not fully described; however, they will be partly described implicitly within the following sections. Figure 1 illustrates the major components related to 3D land–marine properties. The following sections describe the major components.

Symbols, Units and Abbreviations

Geospatial data availability has grown significantly in recent years with diverse sources such as satellites, aerial imagery, drones, GPS devices, and sensors. According to the UN-GGIM (2020), the development of 3D land–marine properties related to climate change (SLR) warrants 3D spatial data updating. However, there can be several challenges to obtaining accurate and up-to-date data (land–marine) where the data access needs to be balanced with privacy and

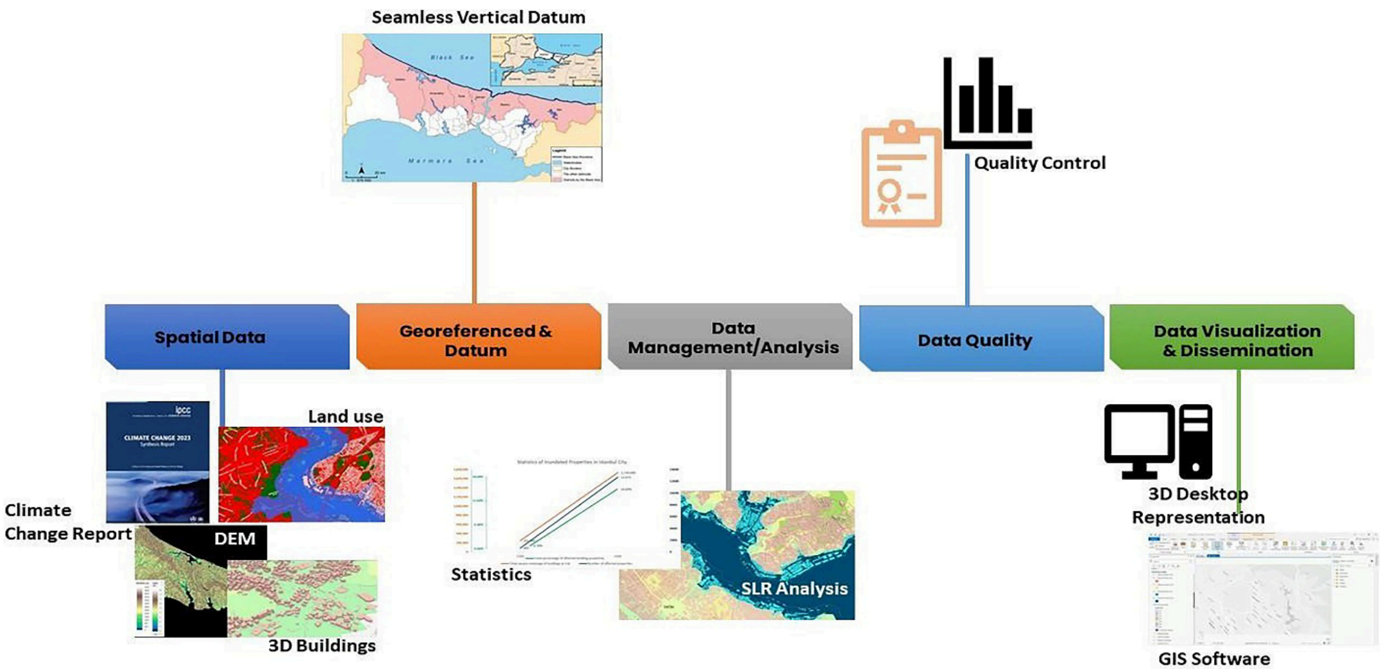

Figure 1. The 3D land-marine components.

security concerns. Additionally, land–marine objects spanning both terrestrial (land) and marine (ocean) environments are inevitably difficult to obtain. For instance, marine data collection is often monitored by different government agencies, research institutions, and private organizations; thus, it is hardly accessible, as stated by Trice et al. (2021). Spatial data related to 3D land–marine properties such as bathymetry, 3D buildings, digital elevation models (DEMs), land-use, and transportation networks (railways, tram, metro, highways, and roads) are crucial for visualizing the scenario of SLR. The bathymetry data comes from the General Bathymetric Chart of the Ocean (GEBCO) and is publicly available within the International Hydrographic Organization (IHO) and the Inter-governmental Oceanographic Commission (IOC) of UNESCO.

Spatial data (2D and 3D) related to land and marine environments, such as marine cadaster, have a crucial role in the delineating and modelling of the SLR (partly). The modelling as practiced by several stakeholders is quite comprehensive and able to answer major queries related to land– marine scenarios. In this case, it is advisable to cooperate with the Land Administration Domain Model (LADM), as reported by Kara et al. (2024). The LADM is able to provide the systematic connection between the features of the situation (the relationship between various classes where it can be extended and adapted to specific situations in land–marine administration). The 3D land– marine properties could be encoded with detailed information on legal rights, re-strictions, and responsibilities (RRR). This study describes the LADM modelling approach for the land–marine scenario toward the end of this study (see section LADM for SLR).

Georeferenced & Datum

In general, the integration of marine and land features requires analyzing spatial information that delineates the boundary and interactions between these two environments. For example, 3D land–marine properties require data integration between DEMs and bathymetry to illustrate the situation. However, different georeferenced data (land and marine) may create issues during the integration where different datums (i.e., lowest astronomical tide [LAT] for marine and mean sea level [MSL] for land) require conversion to a common datum and are also error prone; geoid based as seamless vertical datum can be applied. The dynamic interactions and dependencies of these environments can be achieved by the integration of land and sea through georeferenced data and datum. Figure 2 shows the situation in which the joining of land and the sea surface occurs. The red line represents the shoreline, indicating the distinction between land and sea areas where it can be approximated by defining the MSL at zero value.

Data Management & Analysis

Managing 3D land–marine spatial data deals with all the key components, including data processing, database, data analysis, and visualization. Data processing in this case involves the generation of contours with classification and coastline extraction from DEMs. The classification illustrates

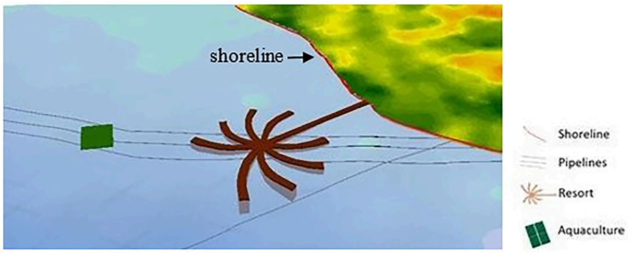

Figure 2. The situation in which the joining of land and the sea surface occurs.

the elevation of topography at different levels; the same goes for the bathymetry data. Other aspects of data processing include joining land use

and 3D property data as part of enriching attributes of the 3D buildings. The integration of these data simulates the SLR with different height levels (3 and 15 meters), including visualization of the inundated area. Details of the analysis are described in Section 3.0.

The SLR case study: Istanbul

Climate change poses significant challenges to coastal cities worldwide, with rising sea levels threatening the viability of coastal communities, infrastructure, and ecosystems. As a prominent coastal metropolis situated at the crossroads of Europe and Asia, Istanbul is particularly vulnerable to the impacts of SLR. Understanding the localized effects of SLR on Istanbul is essential for informing adaptation strategies and enhancing the city's resilience to future climate change. This section aims to assess the potential impacts of SLR on the city of Istanbul, focusing on the years 2100 and 2300.

Topographic data for Istanbul was obtained from MERIT DEM, which provided the detailed elevation information necessary for simulating SLR-induced inundation. Fig.3 shows MERIT DEM, which shows the 3D topography of the city of Istanbul. Coastline data were utilized to delineate the boundary between land and sea and to identify coastal areas susceptible to SLR impacts. Geographic Information System (GIS) modelling techniques were employed to simulate the spatial distribution of SLR impacts on Istanbul. Utilizing the topographic data and SLR scenarios, inundation maps were generated to visualize the extent of coastal flooding under different SLR scenarios. Vulnerability assessments were conducted to identify high-risk areas and infrastructure vulnerable to SLR-induced hazards, integrating factors such as elevation and land use into the analysis.

Simulation of Sea Level Rise Impacts

The GIS-based modelling approach employed in this study facilitated the simulation of SLR impacts on Istanbul for the years 2100 and 2300. Inundation maps were generated to visualize the spatial extent of coastal flooding under the projected SLR scenarios of 3 m (meters) for 2100 and 15 m

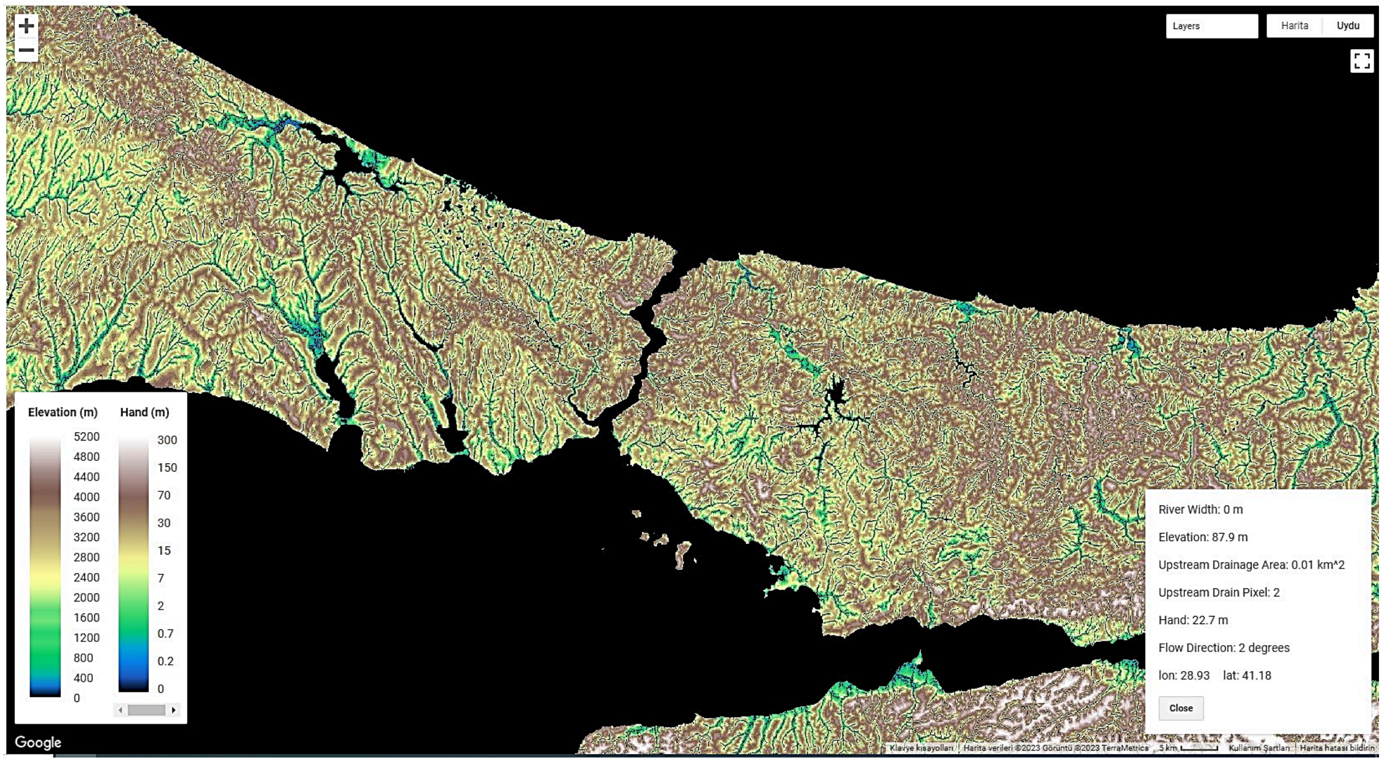

Figure 3. MERIT DEM showing Istanbul city 3D topography

for 2300. Figure 3 illustrates the simulated inundation zones for an area in Istanbul under these scenarios, showing the potential impact of inundation.

In Figure 4(a), representing the year 2023, minimal inundation is observed, with coastal areas largely unaffected by rising sea levels. However, as depicted in Figure 4(b) for the year 2100, significant expansion of inundation zones is evident, with coastal districts experiencing partial submergence and encroachment of water into inland areas. Figure 4 (c) provides a glimpse into the distant future, projecting the inundation zones for the year 2300, where the most severe SLR scenario results in widespread inundation of coastal areas and substantial land loss. The delineation of inundation zones illustrates the extent to which coastal properties are susceptible to inundation, with some properties partially covered by water and others fully submerged due to the elevation of the water level. Visualization underscores the urgency of implementing adaptation measures to mitigate the adverse impacts of SLR on coastal communities, infrastructure, and ecosystems.

The analysis provides valuable insights into the projected impact of SLR on building properties in Istanbul, as depicted in Figure 5. Assessing a total of 85,199 building properties across the Fatih and Beyoğlu districts, the projections indicate that by the year 2100, approximately 661 properties —constituting 0.78% of the total—may face the threat of SLR-induced impacts. Looking ahead to 2300, this number escalates significantly to 12,672 properties, accounting for approximately 14.89% of the total building stock. Moreover, the total square meterage of buildings at risk sees a substantial increase from 247,000 square meters in 2100 to a staggering 1,730,000 square meters by 2300. These findings underscore the mounting threat posed by SLR to coastal urban areas, emphasizing the urgent need for proactive measures to mitigate the risks and safeguard vulnerable com- munities and infrastructure in the face of future climate challenges.

Figure 6 presents a cross-sectional profile of the area, offering a visual representation of both the predicted SLR and the current sea level as of the year 2023. This detailed depiction includes buildings situated atop the terrain, providing a three-dimensional context for understanding the potential impacts of rising sea levels on coastal infrastructure. The blue line delineates the water level corresponding to a projected SLR of 15 m, revealing areas susceptible to inundation. Notably,

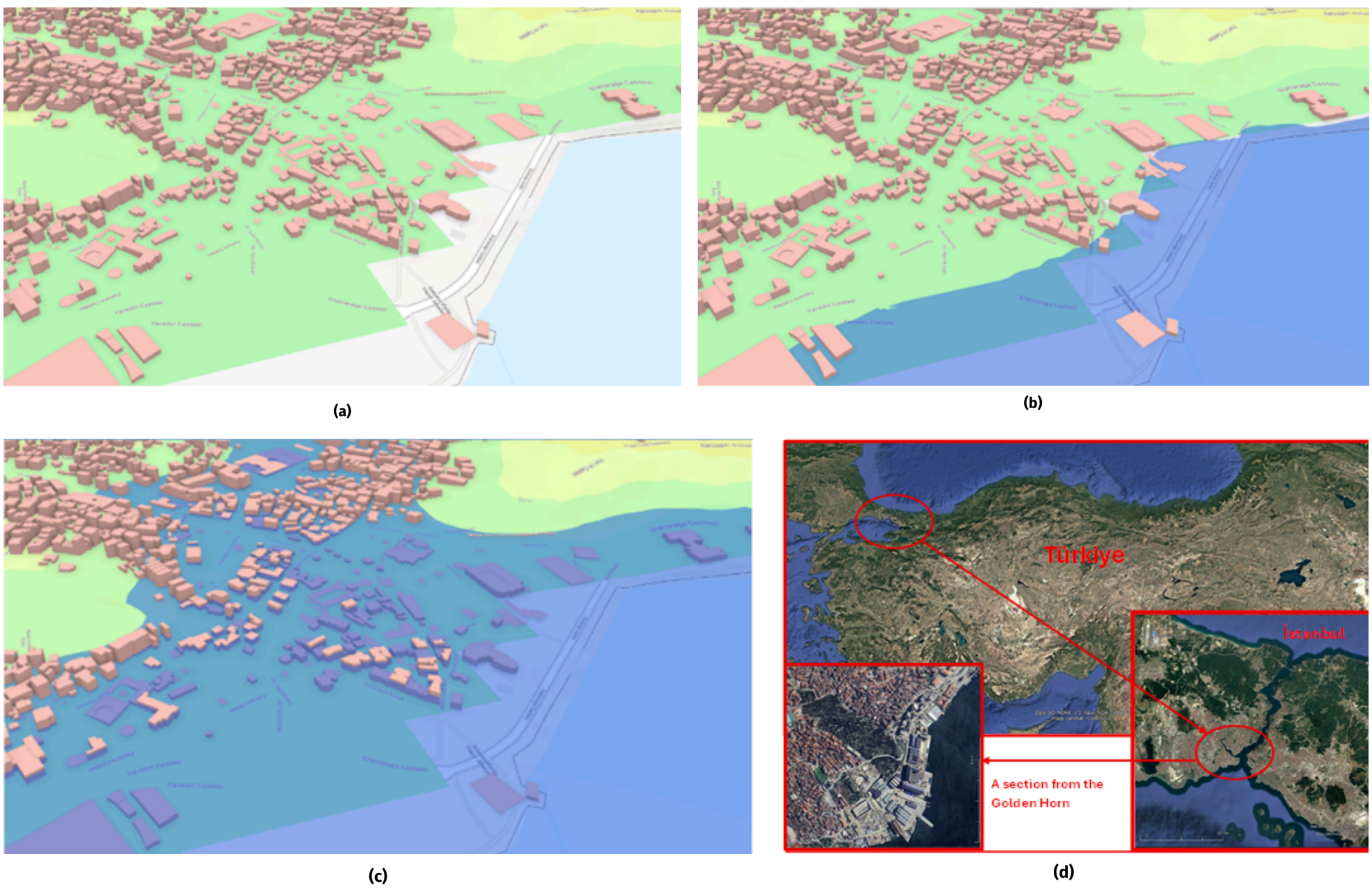

Figure 4. Simulated Inundation Zones in 3D View for Istanbul City under SLR Scenarios: (a) Year 2023, (b) Year 2100, and (c) Year 2300 (d) from the Golden Horn to Beyoglu

some buildings are partially submerged, underscoring the implications of SLR on urban landscapes and the imperative for adaptive strategies to mitigate risks and safeguard vulnerable communities and assets.

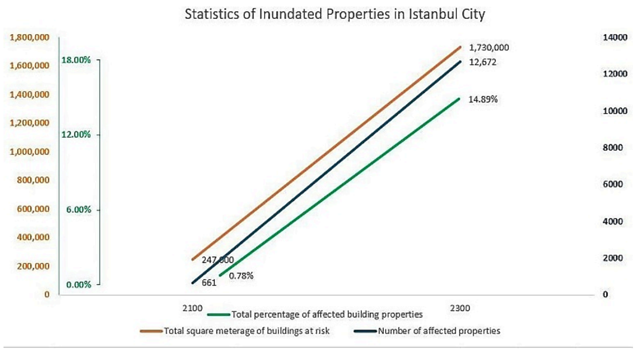

Figure 5. The Statistics of Potential Impacts of SLR on Building Properties (yellow is square meters, black is number of buildings, Green is the share in the total building stock ratio)

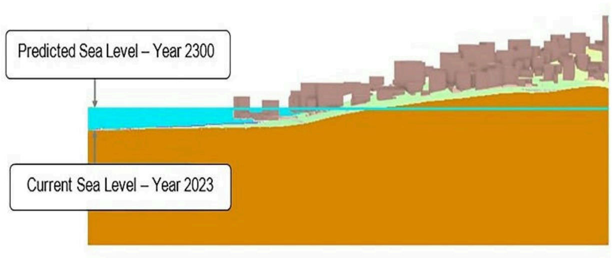

Figure 6. Cross Section of Sea Level and Land (15 m Sea Level Rise) in Fatih and Beyoglu Areas.

Figure 7 comprises two images, (a) and (b), which provide a comprehensive depiction of the land affected by SLR in the districts of Fatih and Beyoglu in Istanbul. Image (a) is a map illustrating the extent of land impacted by SLR, with areas affected by a 3 m rise depicted in light blue and those affected by a 15 m rise shown in dark blue. This visualization offers an overview of the projected impacts of rising sea levels on land cover within the study area. Meanwhile, image (b) offers a closer look at specific areas within Fatih and Beyoğlu, featuring a three-dimensional view of buildings atop the map.

Land Use/Properties Analysis

The land use map as illustrated in Figure 8 classifies various land cover types within the Fatih and Beyoglu districts, providing valuable insights into landscape composition and distribution. Grassland, the first class, denotes areas dominated by grasses, herbs, and non-woody vegetation, often utilized for grazing livestock or for recreational purposes. Cropland, the second class, encompasses areas designated for agricultural cultivation, indicating intensive human activity related to food production and farming practices. Built-up areas, the third class, represent urban or densely developed regions characterized by buildings, infrastructure, and roads, reflecting urbanization and settlement patterns. Sparse vegetation and barren landform the fourth class, signifying areas with minimal plant growth or vegetation loss due to environmental conditions or human disturbance. Permanent water bodies, the fifth class, encompass lakes, rivers, and other aquatic ecosystems, highlighting the presence of water resources within the landscape. Lastly, herbaceous wetlands, the sixth class, indicate areas with saturated soil conditions and herbaceous vegetation, such as marshes and wet meadows, which support diverse plant and animal species. Understanding the distribution and extent of these land cover categories is vital for land management, environmental monitoring, urban planning, and natural resource conservation.

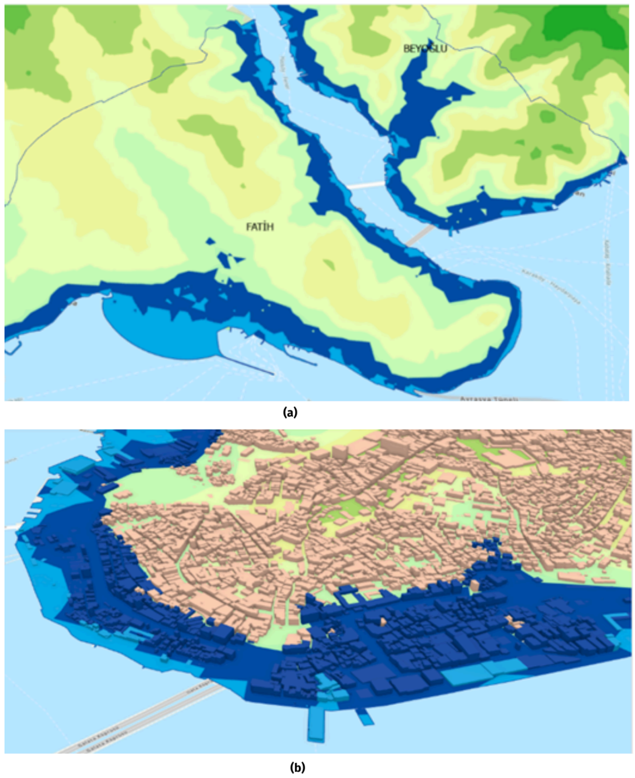

Figure 7. (a) The Affected Land Areas for 3 m (Light Blue) and 15 m (Dark Blue) Rises. (b) A Close-Up with 3D Buildings, Colored to Indicate Inundation Levels.

Based on the data analysis conducted for the districts of Fatih and Beyoğlu, the projected impacts of SLR in the years 2100 and 2300 have been assessed. Table provides a breakdown of the square meters of land area affected by SLR in two different scenarios: a 3 m rise by 2100, and a 15 m rise by 2300.

In 2100, under the 3 m sea level rise scenario, the analysis indicates significant impacts across various land cover types.

Built-up areas, encompassing urban and developed regions, are projected to experience the most substantial impact, with approximately 991,857 square meters affected. This is followed by grassland, cropland, bare/sparse vegetation, permanent water bodies, and herbaceous wetlands, each experiencing varying degrees of impact.

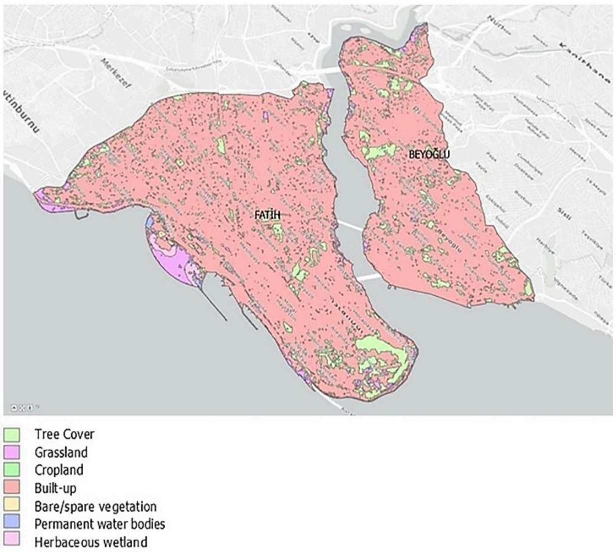

Figure 8. Land-Use Map of Fatih and Beyoglu Districts Consists of Six Classes.

Looking further ahead to 2300, the projected sea level rise of 15 m exacerbates the impacts on the landscape of Fatih and Beyoğlu. Built-up areas are anticipated to bear the brunt of the impact, with a staggering 4,883,878 square meters affected, highlighting the vulnerability of urbanized regions to rising sea levels over the long term. Other land cover types, including grassland, cropland, bare/sparse vegetation, permanent water bodies, and herbaceous wetlands, also show increased areas of impact compared to the 2100 scenario.

Table 1. Projection of land use affected by SLR in the districts of Fatih and Beyoğlu for year 2100.

Land Use	Year 2100 (m²)	Year 2300 (m²)
Grassland	376,770	546,398
Cropland	5,136	17,937
Built-up	991,857	4,883,878
Bare/sparse vegetation	62,507	108,516
Permanent water bodies	114,577	130,222
Herbaceous wetland	124,593	124,593

These findings underscore the importance of proactive measures to mitigate the impacts of SLR on coastal areas such as Fatih and Beyoğlu. Urban planning strategies, adaptation measures, and coastal management initiatives will be crucial for enhancing resilience and ensuring the sustainable development of these vulnerable regions in the face of future climate change impacts.

Risk Map: High, Middle, Low

Figure 9 is a map delineating areas of varying risk levels concerning SLR susceptibility. In this visualization, yellow shading designates regions with a medium risk, red denotes areas of high risk, and grey signifies low-risk zones. The categorization of risk is contingent upon land elevation and the potential impact of SLR, with high-risk areas identified as those likely to be significantly affected by a 3 m rise in sea level, while medium-risk areas anticipate a rise of 15 m. Conversely, low-risk areas, characterized by their elevated position and distance from coastlines, demonstrate a diminished susceptibility to SLR impacts. This risk map serves as a valuable tool for urban planners, policymakers, and stakeholders to prioritize mitigation and adaptation strategies, directing attention to areas most vulnerable to the consequences of rising sea levels.

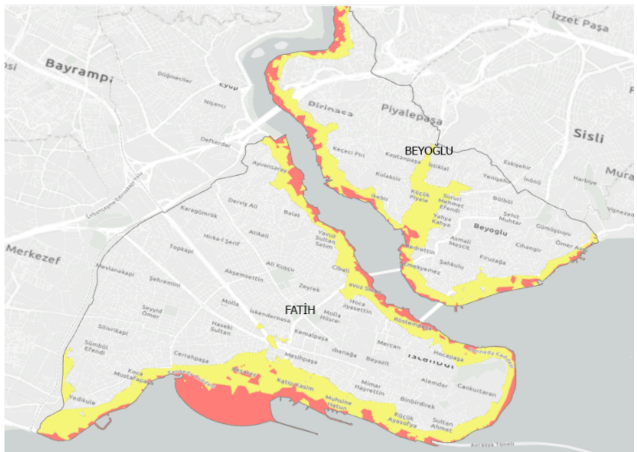

Figure 9. Risk Map Depicting Areas Prone to SLR Impacts in the Fatih and Beyoglu Districts. Yellow Shading Represents Medium-Risk Areas; Red Indicates High-Risk Zones; and Gray Signifies Low-Risk Regions.

LADM for SLR

The aspects within SLR, such as marine spatial data, the affected area, and the vulnerability, can be mapped via LADM (together with Part 3: Marine Geo-regulation); it is one of the modules within the new LADM Edition II (Kara et al. 2024), as illustrated in Figure 9. Classes with white color represent basic classes of LADM, and the blue color represents the SLR classes with their respective cardinality. The proposed conceptual model could be further developed to incorporate 3D visualization, as indicated in Figure 11. Recent literature (Kara et al. 2024; Zamzuri et al. 2022) shows that the relationships of objects or situations could be established

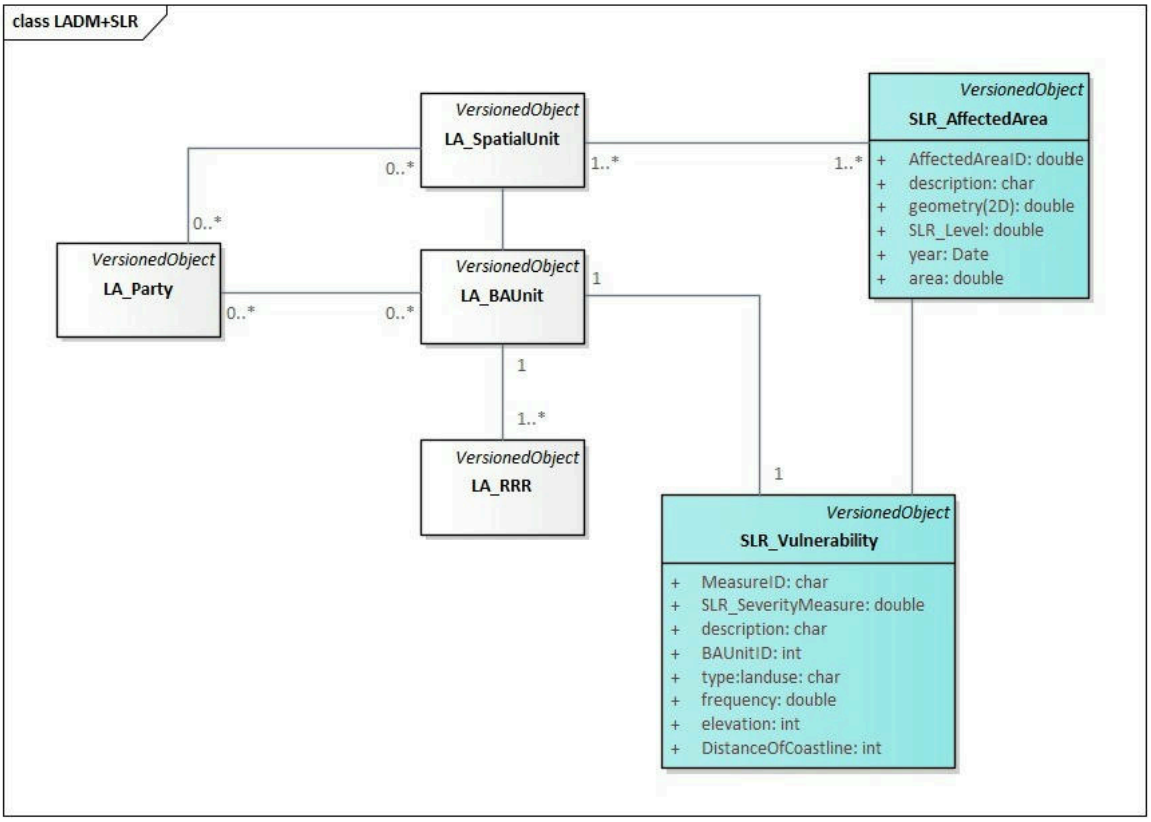

Figure 10. Conceptual model for integrating LADM with SLR.

and defined with LADM modelling tools for land and marine environments where models provide clear linkages between the classes (in this case, SLR situations).

Figure 10 illustrates an example of a conceptual model integrating LADM with SLR. The basic classes from LADM like LA_Party, LA_BAUnit, LA_RRR, and LA_SpatialUnit are retained. Several classes regarding SLR, such as SLR_AffectedArea and SLR_Vulnerability could be incorporated to represent the scenario of SLR. The description of the classes is as below:

(1) SLR_AffectedArea: The inundated areas affect-ed by SLR (the possible attributes such as Affecte-dAreaID, description, geometry (2D), SLR_Level, year, and area)

(2) SLR_Vulnerability: Assessment of LA_BAUnit vulnerability to SLR (the possible attributes such as MeasureID, SLR_SeverityMeasure, description, BAUnitID, type:landuse, frequency, elevation, and DistanceOfCoastline)

The LA_BAUnit is associated with SLR_Vulnerability to evaluate the risk level. The SLR_AffectedArea represents the impacted area by difference of SLR together with SLR_SeverityMeasure for measuring the valuation of inundated areas.

This conceptual model (integration of LADM and SLR) could be utilized for the development of a system for the authorities for handling and managing the land–marine administration situation. Thus, the SLR situation of Istanbul could be visualized by incorporating 3D visualization tools such as CesiumJS.

The above Figure 11 attempts to illustrate the conceptual framework of the system development by incorporating LADM and SLR for the Istanbul scenario. The data sources (cadastral, buildings, and topography) form major components for spatial data. The database could be developed by incorporating LADM through Post-greSQL and PostGIS adapted from (2019). The developed database will be exported as CityGML or IFC for-mat together with 3D visualization. In the end, the system (web and apps) could be utilized to disseminate the 3D land–marine information to the end users (authorities and other users) via OpenAPI technology.

Discussions

In this study, application of the MERIT DEM and GIS datasets to determine the vulnerability of Istanbul coastlines along the SoM against the SLR has been realized based on the scenarios given in the recent IPCC report. MERIT DEM is based on the SRTM dataset but with enhanced vertical accuracy (Jarvis et al. 2008). Figure 4 shows the qualitative analyses of the SLR for Istanbul (Fatih and Beyoglu districts) based on the years 2023, 2100, and 2300, respectively. In the year 2100, Figure 4

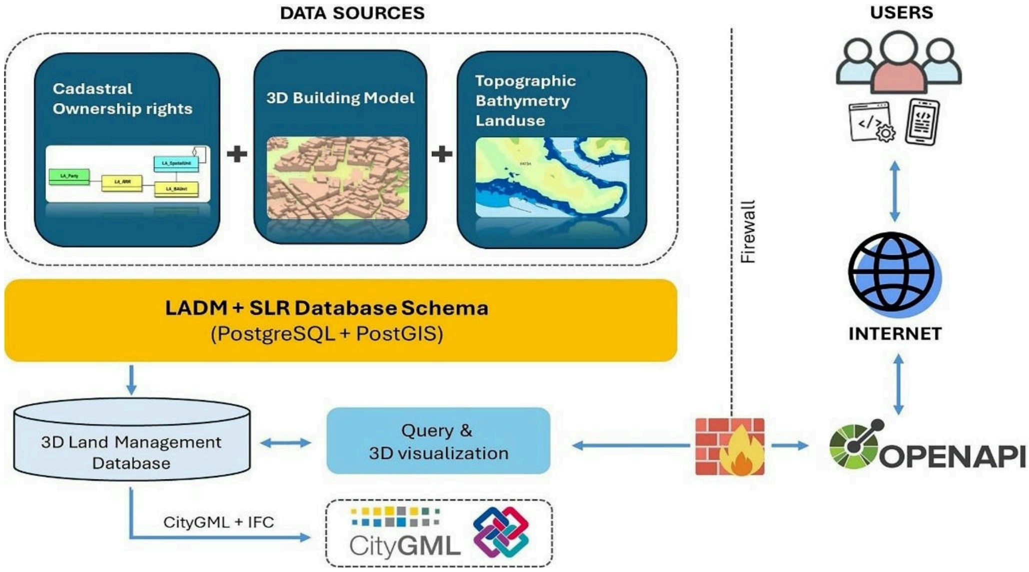

Figure 11. SLR framework with LADM.

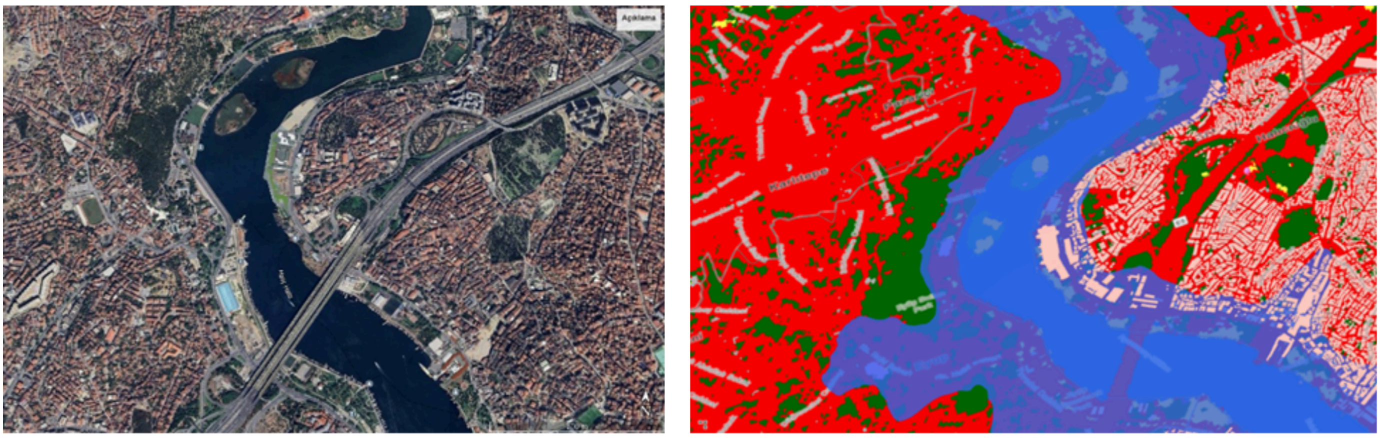

Figure 12. (a) Satellite Image Showing the Golden Horn (Around the Golden Horn Bridge) (b) ESA Worldcover Data With 10 m Resolution and Generated in 2021 Using V200 of the Algorithm: Built-Up Area (Red), Tree Cover (Green), Grassland (Yellow), and the In- undated Areas (Light Blue).

(b) illustrates the prediction of a 3 m SLR, i.e., a maximum of 200 m of inundated land from the coastline. The inundated areas depend on the terrain elevation. For the year 2300, Figure 4 (c) illustrates the visualization of a 15 m SLR, i.e., a maximum of 600 m of inundated land from the coastline. Figure 5 illustrates the statistics of potential impacts of SLR on building properties, and a cross-section of the profile for both predicted SLR and the current SLR of the year 2023 are shown in Figure 6.

Figure 12 shows the Fatih and Beyoglu districts based on land use cover with inundated areas. These districts of Istanbul contain the main historic sites (especially Fatih); Beyoglu has the famous Taksim Square, Istiklal Street, Galata Tower, and Pera area, which are major tourist hubs. In addition, one of the main transportation networks (M2 metro line) here connects to the Marmaray line at Yenikapi station for the Anatolian site. Also, the Fatih district includes the Eminönü area, where many people, especially tourists, gather for shopping; the main local bus station for going to different parts of Istanbul is also there with boats and ships carrying people to Uskudar and Kadikoy. Areas like Halic and the bridges (Unkapani and Galata) obviously face some risks.

It is important to address this issue within the framework since quality data generates accurate buildings/properties information. High data quality ensures that the data can be trusted and effectively used for analysis, decision-making, and other applications. Several authors discussed this issue, as reported by (1991) and more recently by Stoter (2020). Stoter emphasized that the presence of data quality issues, specifically 3D data errors, hinders data sharing with other applications or platforms. She pointed out that modelling software can play a crucial role in incorporating ISO 19107 as 3D geometry standards to prevent and minimize these errors and suggested that the application of automatic repair algorithms could be explored as a potential solution to address this issue. In light of this, the utilization of management processes and tools to maintain and improve the quality of the data is indispensable. MERIT DEM, which we used for SLR analysis, has a large grid spacing of 90 m (3 arcsec). However, according to Chai et al. (2022) and Jarvis et al. (2008), it produced a high geometric accuracy of about 3 m even in the forested area when the DEMs data from dense lidar point clouds were used as a reference. It is obvious that the produced risk map might not be accurate enough for the intended detailed application. Inevitably, the more accurate the DEMs, the better the risk map analysis outcome. Other aspects, like timeliness (recent) and completeness, also play an important part, with the more recent data reflecting the situation better. In the case of Istanbul, we utilized quite recent data (2018 for DEMs, 2021 for ESA WorldCover data, district boundaries data, and building data).

Other important aspects, like visualization and dissemination, need to include several tools for queries of relevant information regarding land–marine properties management. For example, queries in inundated areas lead to fast evacuation routes and regions (higher ground). Moreover, the severity of affected buildings can be obtained by a proper query analysis. Detail visualization requires a 3D view to support some perspectives (i.e., the different levels of inundated buildings), which are hardly visualized in 2D view, including in animation of the dynamic SLR. Above all, authorities such as the Türkiye Disaster and Emergency Management Authority (AFAD) should have a system for information dissemination and visualization on various platforms, such as mobile and web portals. The proposed LADM conceptual model with SLR could be co-developed, conforming with Open API and OGC requirements as indicated in the overall framework (see Figure 11). Those components could trigger the development of an early warning system.

Conclusions

The study clearly shows that the SLR in Istanbul case together with geospatial components, especially DEMs data, helps and improves visualization of the phenomena. Obviously, the experiments and analyses carried out in this study could be improved with up-to-date and more accurate data, especially in integrated coastal area planning. It is essential to consider the effects that are likely to occur in the future due to numerous climate change effects, which are almost inevitable, unlike in past years when natural hazards were less prevalent. Among these effects, the complete destruction of infrastructure along the coast and the decrease in agricultural productivity stand out as primary concerns. In urban areas, the deterioration of the coastal line will result in an escalating impact toward the city from point zero, necessitating infrastructure activities not only to mitigate the effects but also to compensate for the damage incurred and to reduce urban vulnerability.

For this purpose, various infrastructural solutions can be developed to prevent water from moving inland in coastal areas due to sea level rise. In physical coastal infrastructure, raised land barriers can be created to prevent the sea from advancing inland, with dikes and dikes. In addition, movable flood barriers and more breakwaters can protect the coastline from wave erosion. Coastal plants and coastal ecosystems can naturally slow down water movement. It may also be possible to slow down sea level advancement by re-nourishing eroded shores with sand and gravel. Urban planning and infrastructure adaptation are of vital importance, especially for the Istanbul metropolis. For this reason, constructing new infrastructure at higher elevations can reduce the risk of flooding. By optimizing rainwater drainage channels and drainage systems, the impact of water moving into the inner regions can be limited. Finally, gradually moving settlements in risky areas to safer areas can be a long-term solution. Of course, such measures require consideration of both engineering and ecological compatibility when combating sea level rise.

This study demonstrates the types of data that can be used for decision support mechanisms. It also indicates that point-based planning in urban areas is not highly effective and emphasizes the necessity of adhering to a sea-level change parameter that aligns with the geographical reality of the city in regional planning. The early focus of coastal properties was primarily on beach communities that historically bore the brunt of shore-line changes and coastal storms. However, insufficient attention has been paid to the loss of coastal wetland ecosystems, which are rapidly diminishing due to hindrances to their natural migration caused by inland development blocking estuarine habitats amidst rising sea levels. With urban areas increasingly exposed to these changes, major population centers face escalating risks. It is seen that by 2100, 70% of the world's population will be connected to the coast. The increasing population along the coast and the associated socio-economic demands will need to be shaped against the SLR.

Several aspects, such as dynamic elements of topography (earthquake and tectonic plate movements), weather, ocean currents, and human activities, may influence the SLR and need to be considered in any system development. Other major points, such as valuation of properties, land use, population, and epoch data are well connected for future scenarios. We strongly believe time (temporal) also plays a crucial role in these very dynamic phenomena.

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