Urban Vulnerability Assessment of Sea Level Rise in Singapore through The World Avatar

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Abstract

This paper explores the application of The World Avatar (TWA) dynamic knowledge graph to connect isolated data and assess the impact of rising sea levels in Singapore. Current sea level rise vulnerability assessment tools are often regional, narrow in scope (*e.g.* economic or cultural aspects only), and are inadequate in representing complex non-geospatial data consistently. We apply TWA to conduct a multi-perspective impact assessment of sea level rise in Singapore, evaluating vulnerable buildings, road networks, land plots, cultural sites, and populations. We introduce OntoSeaLevel, an ontology to describe sea level rise scenarios, and its impact on broader elements defined in other ontologies such as buildings (OntoBuiltEnv ontology), road networks (OpenStreetMap ontology), and land plots (Ontoplot and Ontozoning ontology). We deploy computational agents to synthesise data from government, industry, and other publicly accessible sources, enriching buildings with metadata such as property usage, estimated construction cost, number of floors, gross floor area. An agent is applied to identify and instantiate the impacted sites using OntoSeaLevel, these sites include vulnerable buildings, land plots, cultural sites, and populations at risk. We showcase these sea level rise vulnerable elements in a unified visualisation, demonstrating TWA's potential as a planning tool against sea level rise through vulnerability assessment, resource allocation, and integrated spatial planning.

Highlights

- Development of versatile multi-perspective sea level rise vulnerability assessment tool
- Ontology application for data integration and unified data representation
- Vulnerability assessment of population, land plot, infrastructure and cultural sites
- Sea level rise risk mitigation via integrated planning and asset prioritisation

Contents

1 Introduction

The accelerating pace of sea level rise poses significant threats to coastal urban areas, with immediate effects such as submergence, increased flooding and saltwater intrusion [41]. These effects lead to severe impacts on various urban elements, including structural damage to buildings, disruption of transport mobility, significant population displacement, and induce challenges to future urban planning and development strategies [41]. In addition, sea level rise also threatens non-material aspects of urban life such as cultural sites with heritage value or historical significance, which are often irreplaceable [21]. Heritage sites often reside in coastal areas due to historical human settlement patterns [48], for example there are 77% of the 1092 Cultural World Heritage Sites designated by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) in 2018 are situated in these coastal regions.

Population-dense coastal areas face severe subsidence and are at risk of severe flooding, necessitating extensive flood defences [41]. Low-elevation regions like Southeast Asian deltas and island nations risk significant submergence and displacement [41]. Singapore, a Southeast Asian island state with a high population density of 8,058 people per km^2 as of 2023 [14], has significant infrastructure along its 193 km coastline and faces heightened vulnerability to rising sea levels with issues such as shoreline erosion and coastal flooding [44]. With these aspects, the heightened vulnerability faced by Singapore highlights the urgent need for effective coastal management strategies.

In conducting impact analyses, comprehensive tools are essential to assess the multi-faceted consequences of sea level rise, these tools should account for factors such as population density, existing infrastructure, socio-economic factors, and demographic vulnerabilities to understand the broader implications on communities [36]. Regional vulnerability assessments use data from multiple sources (*i.e.,* flood exposure, vulnerable assets, population at risk, damage) to evaluate sea level rise impacts on coastal communities and infrastructure, directing targeted preventive measures for vulnerable regions. Nevertheless, regional-scale vulnerability analysis often faces challenges such as inconsistencies between detailed ground-level data and broader regional data, which can lead to significant changes in risk estimates across spatial scales [13]. Furthermore, the complexity of integrating diverse, unstructured data sources can hinder precise and actionable assessments [42].

Other tools used for sea level rise vulnerability assessment, such as Geographic Information Systems (GIS), offer detailed insights into vulnerable elements in local areas [24, 36]. However, these GIS-based tools typically provide data for a narrow set of predefined categories, such as demographics or economics, and can create closed data silos that capture only one domain, such as economic or cultural perspective only [36]. Additionally, their centralised maintenance poses challenges for scalability, particularly when integrating more diverse data [29]. Issues such as the lack of data and inconsistencies between datasets further challenge the application of GIS-based tools [55]. Other GIS-based software used to analyse sea level rise impacts typically merge all data products into a single GIS layer [39], which may not be suitable for representing non-geospatial data. Mathematical modelling is another vital tool for evaluating the impacts of sea level rise on coastal areas, employing quantitative methods to project changes in populations and ecosystems [53]. For example, Shukla et al. [53] devised a non-linear mathematical model to analyse the effects of sea level rise on coastal populations. However, these models are often purely theoretical [53] and may lack the detailed, traceable data required for effective urban planning [40].

Data inconsistencies, complexities with cross-domain data, and the narrow focus and scalability issues of GIS-based tools highlight the need for an improved approach to assessing sea level rise vulnerability, combining the granularity and data traceability of conventional GIS methods with the versatility to provide a multi-perspective analysis. The World Avatar (TWA) project addresses these challenges using a dynamic knowledge graph approach to integrate and utilise multi-domain data [1], which is essential for sea level rise impact analysis. By representing cross-domain information with ontologies as the building blocks, new data and knowledge can be seamlessly added with semantic meaning [34], ensuring transparency and traceability amongst disparate data sources.

The purpose of this paper is to provide a multi-domain perspective vulnerability assessment that includes vulnerable infrastructure, affected land plots, population at risk, and vulnerable cultural sites at a country-wide scale and site-specific scale. To do so, the study explores the application of computational agents, knowledge graphs and ontologies to enhance the connectivity of disparate datasets (*e.g.* government data, industry data, open source data) and augment buildings with metadata including property usage, estimated construction cost, gross floor area, building floor. Furthermore, it explores how agents identify and instantiate vulnerable sites based on sea level rise projection scenarios as well as using ontologies to integrate the sea level rise scenario with the instances of each vulnerable site.

The sections of this paper are organised as follows: Section 2 details the problem and prior technical efforts; Section 3 introduces the methodology used and relevant data sources; Section 4 highlights the use cases and results; and Section 5 concludes the work.

2 Background

2.1 Sea Level Rise

Sea level rise is a major consequence of climate change and anthropogenic greenhouse gas emissions, primarily driven by the thermal expansion of seawater, melting of glaciers and ice sheets, as well as freshwater mass exchange between oceans and land water reservoirs [8]. The Intergovernmental Panel on Climate Change (IPCC) reported that the average rate of sea level rise has been steadily increasing between 1901 and 2018 from 1.3 mm/year to 3.7 mm/year [7]. This increase is expected to continue throughout the coming century due to the rise in cumulative carbon emissions across nearly all considered scenarios and modelled pathways [7]. Singapore's Third National Climate Change Study also projects that sea levels around Singapore's coast will continue to rise until 2100 [10]. The impacts of this sea level rise include land erosion, coastal flooding, loss of biodiversity [10], and subsequent economic loss associated with affected land areas and infrastructures [40].

Sea level rise accelerates the deterioration of low-lying buildings and infrastructure networks through coastal flooding, which weakens infrastructural structure and increases the risk of building collapse [3]. Furthermore, these risks on buildings can lead to high costs for repair and reconstruction, as well as decrease property values [40]. Additionally, sea level rise causes populations displacement which disrupts local economies and changes the distribution of communities [3, 22]. Other assets at risk - including cultural sites, historic landmarks, heritage trees, tourist attractions, and museums - carry intangible significance and hold important cultural, historical, and anthropological values [48, 59].

Study has found that resettling coastal populations further inland could endanger additional archaeological sites [33] located inland. This underscores the complexity of sea level rise risk mitigation, and highlights that it requires a multifaceted approach that considers both populations at risk and cultural sites, amongst other factors. At the same time. while most conventional impact analyses focus on the ecological or economic effects of sea level rise, there is a significant lack of research on the concurrent study of the social values that may be lost with the submersion of cultural sites [21]. The narrow focus on specific domains (*i.e.,* economic or cultural only) hinders the holistic understanding of the full spectrum of impacts associated with sea level rise.

Efforts to mitigate sea level rise risk include integrated and localised planning for impact analysis and prevention [18], as well as the implementation of coordinated strategies that consider both current and future climatic conditions [11]. Integrated spatial planning has been implemented to mitigate risks by identifying and limiting development in flood-prone, vulnerable areas [11]. To ensure effective implementation, it is essential to employ interdisciplinary and transdisciplinary approaches, utilising data and knowledge across various scales in coastal risk managing [5, 31]. However, achieving effective risk mitigation is often challenging due to disjoint datasets and the resulting silos. Open-source data required for vulnerability analysis comes from various sources in vastly different formats. Building datasets may come in Geography Markup Language (GML) format, with additional open-source data presented as various user-defined tag and string values [43] that are difficult to integrate. Other datasets sourced from government open data portals may be in Comma-Separated Values (CSV), or GeoJSON formats [20]. This underscores the need for improved interoperability among datasets.

The complexities of sea level rise scenarios highlight the need for an enhanced methodology to create a versatile tool that offers well-rounded insights into localised impact assessment. Such a tool must offer comprehensive insights that account for diverse environmental, social, economic and infrastructural factors [36]. Dynamic knowledge graphs have proven to be a viable solution [1] to address these challenges including data silos, and disparate formats. In addition, ontologies and knowledge graphs have been used to facilitate the synthesis of disparate data types and domains related to sea level rise [25], outlining the suitability of this technology for sea level rise vulnerability assessment.

2.2 The World Avatar

The World Avatar (TWA) aims at creating a digital ‘avatar’ of the world using technologies from the Semantic Web. The world in this idea measures the space of all possible concepts and their realisations. Akroyd et al. [1] gave a very comprehensive overview of the background of this project, as well as the future goals, only the important aspects of the project are introduced here.

TWA consists of a dynamic knowledge graph along with a network of agents that updates with the knowledge graph to simulate the behaviour of the world. The World Avatar makes use of the Resource Description Framework (RDF) and ontologies to represent data. The RDF data model makes statements about resources using triples, or in the form of *subject-predicate-object*. Each resource is represented with an internationalised resource identifier (IRI), ensuring data can be uniquely identified. Directed graphs can be formed with subjects and objects as nodes and predicates as edges, creating actionable knowledge graphs. SPARQL Protocol and RDF Query Language (SPARQL) [60] serves as the standard query language for querying RDF data. This query language is commonly applied for standardisation, accessibility and automation in concepts [32]. Ontologies are used to define the classes for the domains of interest (*e.g.* sea level rise in this work) and the permissible relationships between the classes. They add semantic meaning to the underlying data, allowing inferences to be made.

There are two primary ways to make these graphs queryable. The first method is through triple stores like Blazegraph [4] and RDF4J [16], where triples are explicitly stored in the database. The second method is by using virtual knowledge graphs such as Ontop [62], where the underlying data is stored in relational databases (table form), and the triples are materialised upon query according to rules set by mapping files.

TWA utilises Docker containers in its setup, providing modularity and scalability. Unlike conventional databases, TWA features a network of autonomous agents that operates on the knowledge graph. These agents vary from simple ones that periodically update the graph with new information, such as weather data, to sophisticated agents that perform complex simulations. These simulations include producing air quality estimates and optimising district heating networks [27], as well as conducting molecular engineering of metal-organic polyhedra [30]. By leveraging ontologies and Docker containers, the system is highly modular. Any agent can be replaced without affecting the overall operation, provided it adheres to the ontologies, ensuring seamless operation.

3 Methodology

3.1 Data Sources

The road network data is retrieved from OpenStreetMap [43]. The land plot data is retrieved from Singapore's Urban Redevelopment Authority (URA) Master Plan 2019 [20]. The cultural sites such as heritage trees, historic sites, tourist attractions, museums, and monuments are retrieved from Singapore's Open Data Portal [20]. The population distribution data is based on the year 2020 census provided by Facebook's Data For Good [56]. Although this study does not account for mobility and migration of population in and out of coastal areas, as well as population growth projection, however using the current population can provide a useful sense of scale and distribution of exposure [37]. Since TWA ingests population data as a raster file, the analysis can be easily updated with a more accurate population projection as it becomes available. The underlying digital elevation model used in this study to model sea level rise is sourced from NASA Shuttle Radar Topography Mission (SRTM) Global 1 arc second elevation model [17].

3.2 Sea Level Rise Model

For this study, a simplistic bathtub inundation model [38] is used to outline the low-lying area, whereby the area below the projected sea level rise is designated as vulnerable. The vulnerable area is derived using the digital elevation model (*i.e.,* NASA SRTM Global 1 arc second elevation model) with the Singapore-specific sea level rise projection height derived from IPCC AR6 [51].

3.3 Computational Resources

In this study, Blazegraph is used as the triple store for the knowledge graph (KG) triples. Blazegraph is integrated with virtual triples using Ontop [6] that leverages PostgreSQL as the underlying database to improve semantic query-ability. These computational services (*i.e.,* Blazegraph, Ontop, PostgreSQL, *etc*) are deployed in a containerised manner to support platform-independent deployment. For data integration and communication within the stack, tools such as GDAL (*i.e.,* for geospatial data manipulation) and NGINX (*i.e.,* for web server and load balancer) are utilised. Additionally, GeoServer (*i.e.,* server for geospatial data) and a custom TWA visualisation interface are provided for visualisation.

3.4 Ontology Development

In this study, Sea level rise ontology (*i.e.,* OntoSeaLevel) is introduced to provide semantic definitions to sea level projections scenarios and its connecting impact to elements defined by other ontologies, as seen in Fig. 1. OntoSeaLevel is developed to closely align with the underlying data of future sea level projections attributes [51], these attributes include Shared Socioeconomic Pathway (SSP), Representative Concentration Pathway (RCP), confidence level, percentage quantile, sea level change height, and projection year. `ontosl:SeaLevelChange` describes the central ontological class that represents sea level change, its associating properties such as the projection year and sea level rise height are described by `ontosl:hasProjectionYear` and `ontosl:hasHeight` respectively. `ontosl:ImpactedSite` class describe vulnerable sites which its corresponding subclass can be concepts defined in other ontological classes, and `ontosl:ImpactedSite` is connected with `ontosl:SeaLevelChange` through the `ontosl:hasPotentialImpact` object property. The subclasses of SSP follow the socioeconomic development narratives in the IPCC guideline [49]. At the same time, the subclasses of RCP definition follow the IPCC guideline [19, 46]. The confidence level follows the IPCC AR5 Uncertainties guideline [35]. In OntoSeaLevel, the percentage quantile defines the statistical likeliness of the projection outcome.

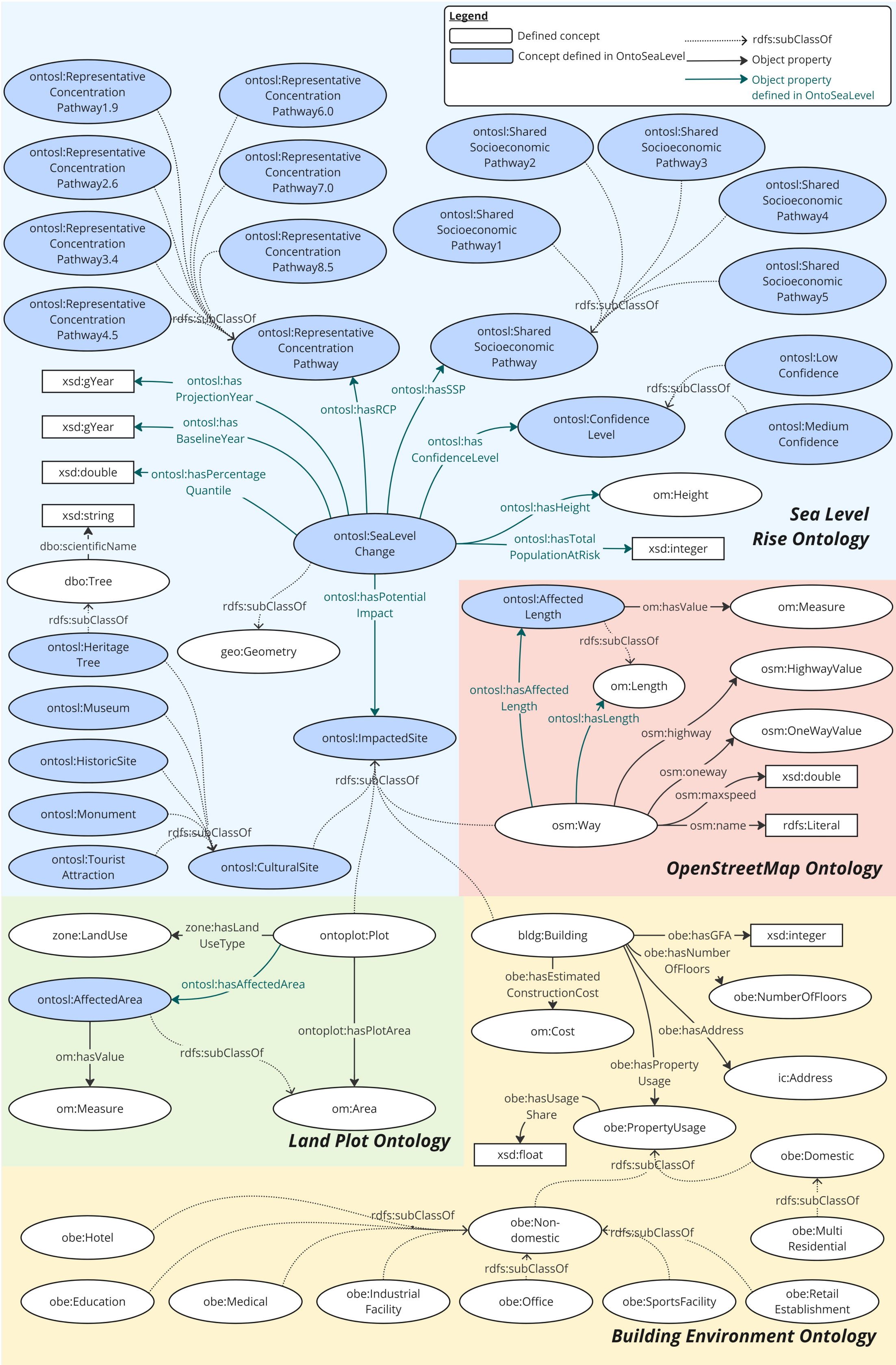


Figure 1: *Outline of Sea Level Rise Ontology (i.e., blue), OpenStreetMap Ontology (i.e., red), Land Plot Ontology (i.e., green), Building Environment Ontology (i.e., yellow).*

OpenStreetMap ontology [12] is used to instantiate OpenStreetMap road network data that includes attributes such as road type, one-way property, road name, and road length. Land plot ontology (*i.e.,* OntoZoning [54] and OntoPlot [52]) defines the plot area and its designated land use type. Building environment ontology (*i.e.,* OntoBuiltEnv) [26] defines building attributes such as estimated construction cost, property usage, usage share, number of floors, and gross floor area.

3.5 Agents

Agents are responsible for enriching the knowledge graph with useful data for analyses later. Five agents were used for this work, they are: 1) OSM agent, 2) Building floor agent, 3) GFA agent, 4) Cost agent and 5) Sea level impact agent. The first four agents are responsible for augmenting information about buildings, whereas the sea level impact agent is responsible for linking different sea level rise scenarios to objects of interest, such as buildings, road networks, land plots, and cultural sites.

Buildings were instantiated in TWA knowledge graph as described in [15], where buildings data is stored in a 3DCityDB database [63] and exposed via Ontop [62], a virtual knowledge graph, as part of TWA. This section describes how agents are used to enrich the knowledge graph, so that data can be queried later to perform potentially useful analyses.

One aspect to be demonstrated in this paper is the analysis of the impacts of sea level rise on buildings based on construction costs. As this data is not publicly available, construction costs of buildings are estimated based on the usage type and their gross floor area (GFA). Note that the focus of this study is to demonstrate the capabilities of TWA in connecting different data sources and not to produce an economic model.

Figure 2 shows the UML diagram of how the knowledge graph is augmented with data by different agents and Table 1 summarises the data added by the agents. The agents are triggered via HTTP POST requests in this work.

Agents obtain the data they need by requesting data from the knowledge graph according to the ontologies described in Section 3.4 with SPARQL queries. In this section, the requests made by agents are presented in plain English and the corresponding SPARQL queries are documented in Appendix A.2.

3.5.1 OSM Agent

The OSM agent was developed to augment instantiated buildings [45]. The agent incorporates building usage and address data from OpenStreetMap (OSM) [43] to enrich building information in the KG via the following process:

1. Equivalent buildings in the KG and the OSM dataset are matched through comparison of the building footprints from the two datasets [45].

2. After a match is found, the agent extracts OSM tags that describe the usage (*e.g.* office and gym) and address information from the OSM data.

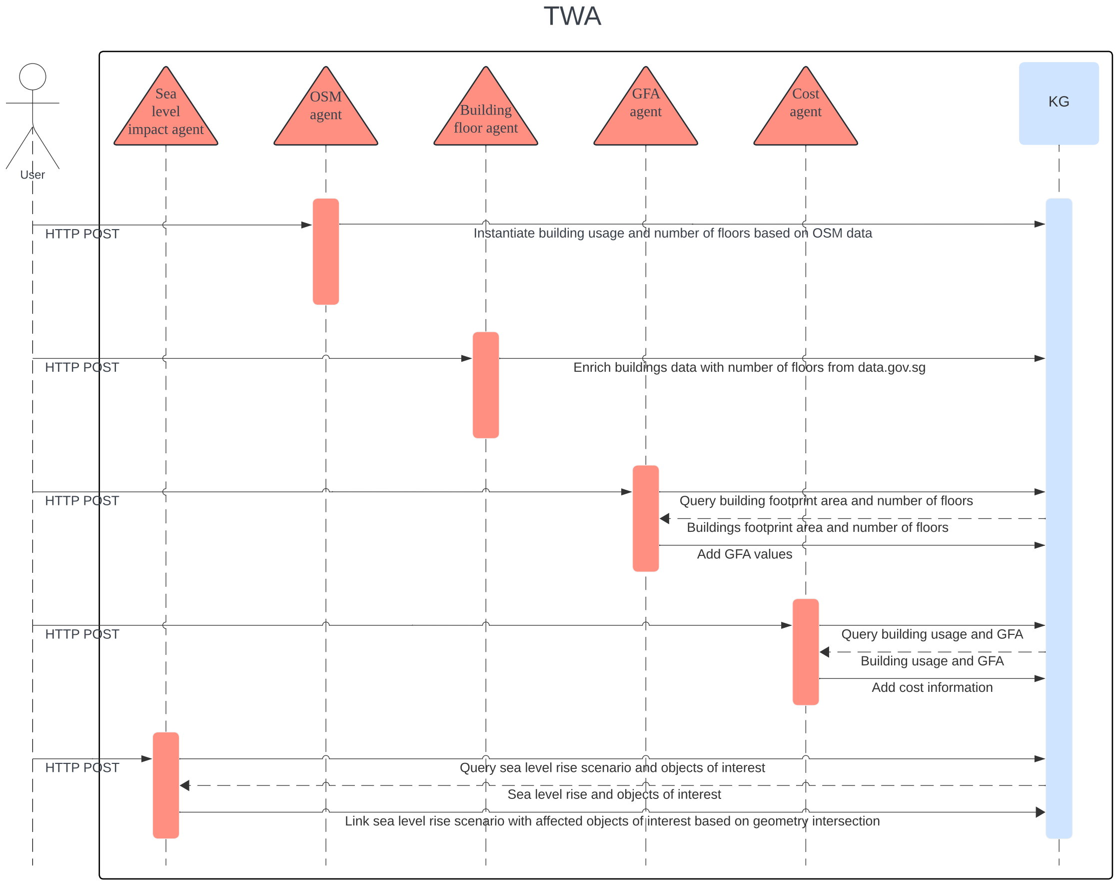


Figure 2: *UML sequence diagram summarising agent interactions.*

3. The agent creates ontological instances of the extracted usage and address information in the KG.

4. The newly created instances are then linked to the corresponding instantiated building in the KG, enriching the KG with usage and address information from OSM.

By having building information linked to the central building concept, the instantiated building in the KG enables consistent building information within TWA for other agents' operation. For example, the added ontological concepts of building usage by OSM agent can be used by the cost agent in Section 3.5.4 to estimate the construction costs of buildings based on property usage. Furthermore, the building address information instantiated by the agent can be used by the building floor agent in Section 3.5.2 to derive number of floor of buildings.

The example of property usage concepts are shown at the bottom of Fig. 1. For example, if an instantiated building in the KG is matched with an OSM building that is tagged as a hotel, the instantiated building will be tagged with the ontological concept `obe:Hotel`. To account for multi-purpose buildings, the OSM agent also instantiates the usage share based on the occupied area. For example, a building may be occupied by offices (60% by area) and retail stores (40% by area), this information is also instantiated in the knowledge

Agent	Data required	Data added to KG
OSM agent	Building footprints from OSM and KG	Building usage, usage share, and address
Building floor agent	Building address	Number of floors
GFA agent	Building footprint area & number of floors	GFA
Cost agent	GFA, building usage & usage share	Construction cost
Sea level impact agent	Elevation, locations of objects of interest, sea level rise	Linkage between sea level rise scenarios with vulnerable objects

Table 1: *Summary of data required by agents and data added by the agents.*

graph via the data property `obe:hasUsageShare` and made available to query.

3.5.2 Building Floor Agent

The main purpose of this agent is to complement buildings with floor data, which is needed to estimate the GFA of buildings by the GFA agent. This agent adds floor data to buildings with two sources of data in this order of priority: 1) Singapore's open data portal [23], and 2) OSM [43].

Floor data from OSM is not added by the OSM agent because if the floor data is present in both datasets, we want to prioritise data from the Singapore's open data portal as it is more credible than OSM.

The Singapore's open data portal contains information on the number of floors of HDB (Singapore's public housing authority) buildings based on addresses. Hence, in order to find the matching building, the agent makes the following request to the knowledge graph:

Give me the address of buildings. (Query 3)

A mock-up of results from Query 3 is given in Table 2. Addresses from the Singapore's open data portal are matched with addresses from the knowledge graph using a fuzzy matching tool [28] so that strings like 'Nanyang Avenue' and 'Nanyang Ave' are treated as equivalents. Once the right building is identified in the knowledge graph, this agent adds the number of floor data to the corresponding building.

[1] Represented by IRIs in actual results, e.g. https://www.theworldavatar.com/kg/Building/8a3f896c-fd75-4643-aa85-43f235458b63

building	streetNumber	streetName
Building1[1]	671C	Jurong West Street 65
Building2	9	Changi North Way
Building3	50	Nanyang Avenue
Building4	48	Springleaf Garden

Table 2: *Mock results of Query 3. The table header is based on the requested variables in the query.*

3.5.3 GFA Agent

The definition of gross floor area (GFA) may vary across different countries, in Singapore, it is defined as the total area of covered floor space, including the half thickness of external walls [58]. In this work, the following simple equation is used to estimate GFA:

$$\mathrm{GFA} = n_{\mathrm{floors}} \times A_{\mathrm{footprint}}, \tag{1}$$

where n_{floors} is the number of floors and $A_{\mathrm{footprint}}$ is the area of the building base footprint. While straightforward, this method of calculating GFA has several limitations. It may overestimate the actual values since certain areas, such as bicycle parking lots and car parks, can be excluded according to Singapore's guidelines [58].

The values required for the calculation are queried from the knowledge graph using the following query:

Give me the number of floors and footprint area of buildings. (Query 5)

Table 3 shows some mock results of Query 5. The GFA for each building is calculated by the agent using the query results and added to the knowledge graph.

building	floor	area
Building1	29	1000
Building2	28	3000

Table 3: *Mock results of Query 5.*

3.5.4 Cost Agent

This agent estimates the construction cost of buildings based on the results generated by the OSM agent, Building floor agent and GFA agent. Construction costs are estimated using GFA of buildings. The construction cost per GFA used in this study was obtained from the industry [2]. The construction cost c of a building b, c_b, is estimated as

$$c_b = \sum_{\mathrm{u}} c_{\mathrm{u}} S_{\mathrm{u},b} \times \mathrm{GFA}, \tag{2}$$

where u indicates a usage type (u $\in$ `obe:PropertyUsage`), c_u is the cost per GFA for a given usage type obtained from [2] and $S_{\mathrm{u},b}$ is the usage share for usage u within building b. The summation acts over all usage types of a building.

Table 4 shows a selection of average construction costs per GFA derived from AIS [2]:

Category	Cost per GFA (SGD/m^2)
Office	5575
Commercial	5690
Industrial	2090

Table 4: *Average construction costs derived from AIS [2].*

To obtain the data required for Equation (2), the following query is made to the knowledge graph:

Give me the usages and GFA of buildings. (Query 6)

building	usage	usageShare	gfa
Building1	`obe:EatingEstablishment`	0.7	110000
Building1	`obe:Office`	0.3	110000
Building2	`obe:IndustrialFacility`	1	120000

Table 5: *Mock results of Query 6.*

Table 5 demonstrates a set of mock results from Query 6 which returns four variables, *i.e.* 'building', 'usage', 'usageShare', and 'gfa'. The value of 'usage' can be any one of the sub-classes of `obe:PropertyUsage` in Fig. 1, whereas 'usageShare' is the fraction of the corresponding usage share, and lastly 'gfa' is the gross floor area. This table shows the usages of two buildings, *i.e.* a building called 'Building1' that is used as an eating establishment with some office space, and a building called 'Building2' that functions as an industrial facility. By considering `obe:EatingEstablishment` as the 'Commercial' category in Table 4, the construction cost of 'Building1' is calculated as:

$$(0.7 \times 5690 + 0.3 \times 5575) \times 110000 = \text{SGD } 622105. \quad (3)$$

This process is repeated for each building, with the resulting values being incorporated into the knowledge graph. While this approach may seem simplistic — given that factors such as location and raw material price fluctuations over the years can impact estimated construction costs — this method provides a baseline for demonstration purposes. As each agent in TWA is deployed as a Docker container, this flexibility allows the Cost agent to be replaced should there be a more precise methodology for representing building value.

3.5.5 Sea Level Impact Agent

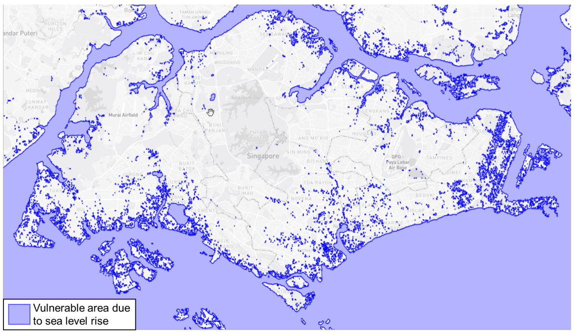
The purpose of this agent is to assess the impacts of a projected sea level rise projection scenario. The agent receives user-defined input parameters of a sea level projection, such as SSP Scenario, RCP value, projection year, confidence level, and statistical percentage quantile. Based on the received inputs, the agent queries the geometrical polygons of the sea level rise projection and assesses if they intersect with the instances of buildings, road networks, land plots, or cultural sites (*i.e.,* monuments, heritage trees, historic sites, museums, and tourist attractions). For the intersected instances, the agent considers it as vulnerable and instantiates the impacted sites (*i.e.,* instances of land plots, buildings, OpenStreetMap road networks, cultural sites) with the instances of sea level rise projection scenario through the object property `ontosl:hasPotentialImpact`. In addition, the agent calculates the affected area and affected length for the intersected land plots and road networks respectively. It also calculates the population at risk by overlaying the sea level projection geometrical area with the underlying population distribution raster. Section 4.2 shows how the results from this agent can be used by executing queries on the knowledge graph.

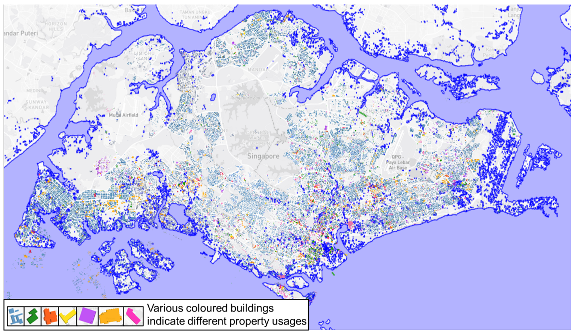
4 Use case

4.1 Impact Assessment and Integrated Spatial Planning

By combining the results of OSM agent, Building floor agent, GFA agent, Cost agent, Sea level impact agent, TWA provides a multi-scale approach to vulnerability assessment, offering both comprehensive and granular insights. In Fig. 3, we demonstrated one of the extreme scenarios based on the SSP5-8.5 low confidence scenario in the year 2150 with a 6.0-meter sea level rise. In the figure, TWA enables a broad, country-level assessment of vulnerabilities of various aspects including buildings, road networks, land plots, cultural sites and population. Additionally, TWA is also capable of detailed, site-specific evaluations as shown in Fig. 4. By integrating diverse datasets into a unified visualisation platform, TWA supports both extensive country-wide assessments and detailed vulnerability assessments. The results shown in the figures are influenced by the quality of the inputs elevation model and sea level rise model, the input model - NASA SRTM elevation model - was taken in the year 2000 and does not capture the recent land reclamation in the southwest region of the island that happened after and therefore the results should be interpreted with caution. However, this limitation does not undermine the objective and results presented in this paper. The intention is to demonstrate the TWA as a proof of concept for sea level rise vulnerability assessment. Should a more accurate elevation model become available, the methodology would remain valid with the updated elevation model that would be substituted.

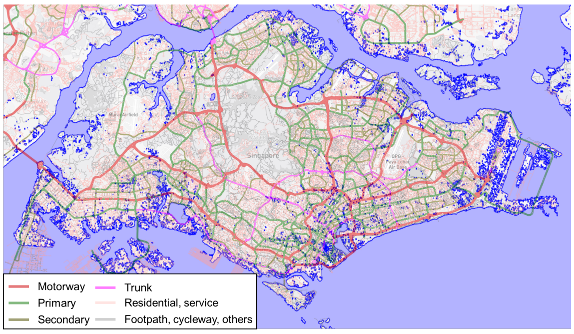
The country-wide vulnerable area visualisation enables planners to identify and prioritise areas that are more heavily affected by potential sea level rise. It serves as a decision support tool to guide and assist planners in making informed decisions. The combination of multiple data such as buildings, road networks, land, cultural sites and population dis-

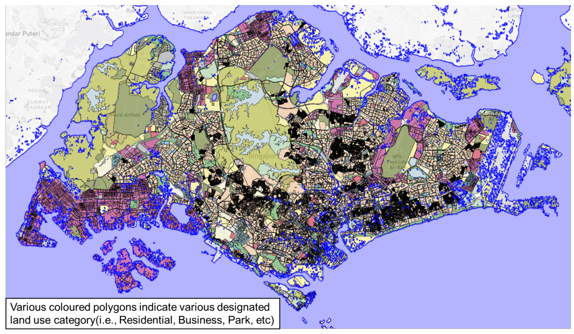




(a) Vulnerable Singapore

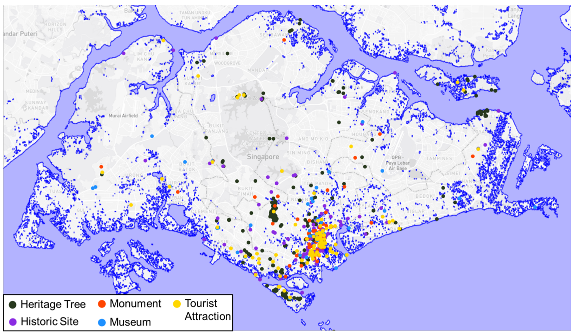
(b) Vulnerable buildings

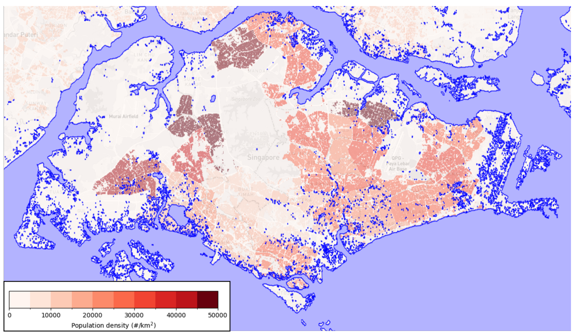




(c) Vulnerable road network breakdown by road types

(d) Vulnerable land plot with designated usages





(e) Vulnerable cultural sites

(f) Vulnerable population distribution

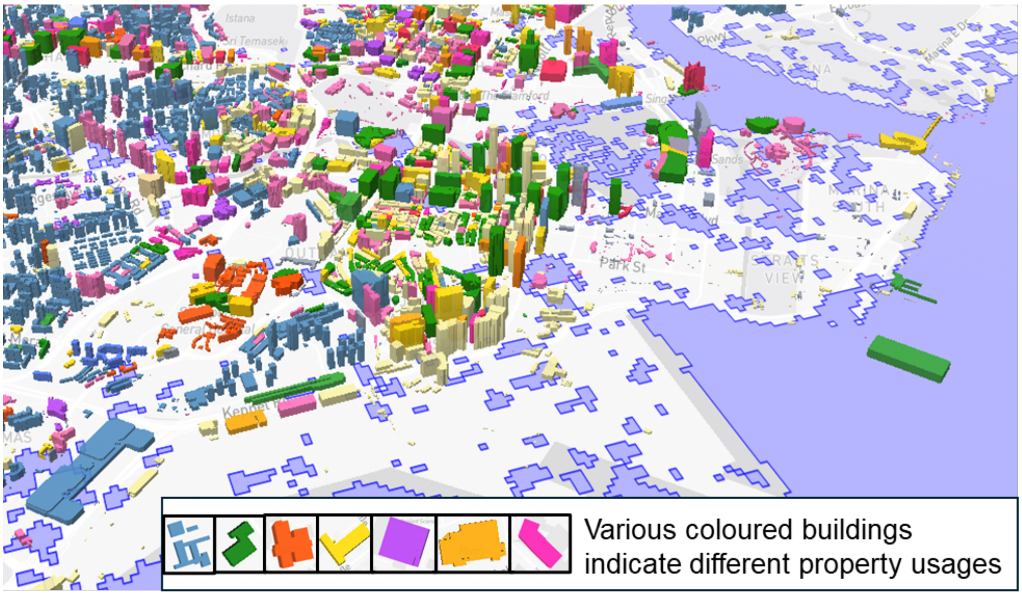
Figure 3: *Impact overview of the SSP5-8.5 low confidence scenario in the year 2150 at the 95th percentage quantile with a 6.0-meter sea level rise.*

tribution provides a better birds-eye perspective, creating a more comprehensive insights representation. The semantic representation behind each of the datasets described using ontologies (*i.e.,* OntoSeaLevel, OntoBuiltEnv, OntoPlot, OntoZone, OpenStreetMap Ontology) provides an in-depth representation of attributes beyond basic GIS representation. The representation of sea level projections and their impacted sites (*i.e.,* buildings, road network, land plot, cultural sites) using ontologies enables to querying of various insights that are relevant to sea level rise risk mitigation such as the populations at risk for a specific sea level rise projection scenario, the type of property usage and its estimated construction cost for the vulnerable buildings, the type of land plot and the area affected by a specific sea level rise projection scenario. The combination of country-wide visualisation support and the use of ontologies for information representation allows for a more precise depiction of datasets. This approach offers administrators both a broad overview visualisation of vulnerable areas from sea level rise and detailed indicators for each impacted asset and element, enabling more effective allocation of funding and resources.

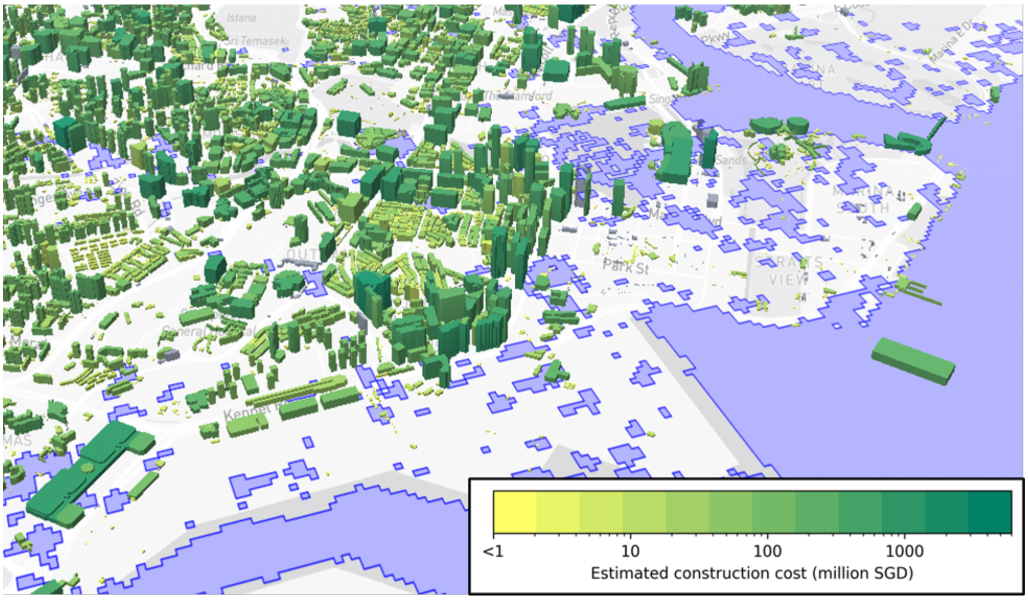
The single unified representation datasets in buildings enable a more accurate and comprehensive representation for decision-makers. The unified representation facilitates the development of a common understanding and perspective of potential impacts on assets and property amongst various stakeholders which is essential for disaster risk mitigation [9]. This enhanced visual overview and augmented urban information facilitate can serve as a platform to communicate information more directly, as 3D representations of disaster risk with accurate scientific representation have shown to be beneficial in engaging stakeholders [9].

Site-specific granular assessment as seen in Fig. 4 allows more precise identification of the properties that are affected. The augmented buildings with property usage and estimated construction cost, offer a more accurate representation of vulnerable areas. This allows administrators to prioritise sea level rise adaptation strategies for buildings that hold more significant value which could be either property usage type, estimated construction cost, gross floor area, or number of floors. One of the applications of having this perspective is that knowing the estimated construction cost of a building, can provide insights into the economic investment and potential financial risks associated with the properties and prioritised for protection. Alternatively, evaluating a building from its property usage type perspective can enable prioritisation of buildings with essential services that are crucial to the community such as healthcare (*i.e.,* hospitals, pharmacies, clinics), emergency services (*i.e.,* police stations, fire stations, police station) or buildings that are important to the economy such as non-domestic (*i.e.,* industrial buildings, hotels, offices, banks). Similarly, the number of floors and gross floor area perspective of buildings enable resource allocation prioritisation for high-rise buildings which may pose greater challenges in terms of relocation, have a higher population density (*e.g.* residential buildings) or require better structural integrity against sea level rise. Ultimately, this site-specific granular assessment facilitates a strategic approach to resource distribution, enhancing the overall urban resilience of the city.

The detailed cultural site also enables urban planners to visualise and assess the impacts of cultural sites with precision as seen in Fig. 5. By knowing the names, locations and descriptions of the cultural sites, planners can prioritise conservation efforts based on the sites' significance and vulnerability to sea level rise. Local administrators can take



(a) Vulnerable buildings by property usage



(b) Vulnerable buildings by estimated construction cost

Figure 4: *Vulnerable buildings based on SSP5-8.5 low confidence scenario in the year 2150 with a 6.0-meter sea level rise.*

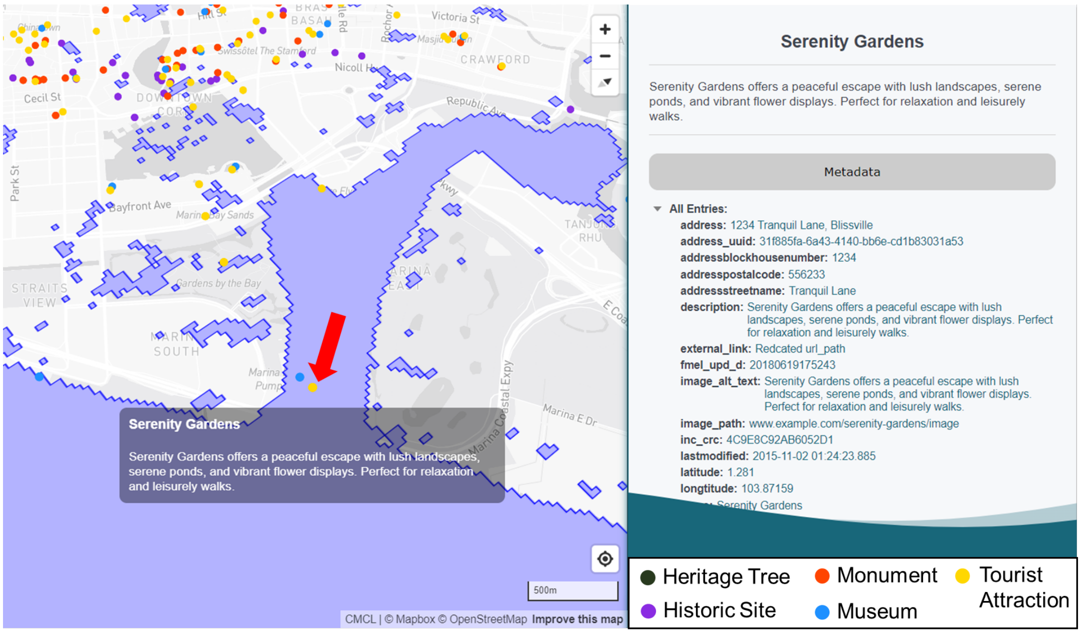


Figure 5: *TWA-VF user-interface on a mocked vulnerable cultural site outlining the site's key attribute such as name, description and address in the side bar.*

protective measures to safeguard and ensure that these significant cultural heritage are preserved with minimal damage. The detailed visualisation also streamlines the selection of adaptation strategies for the specific cultural site type such as whether to relocate or construct protective measures on the selected sites.

Integrated spatial planning with sea level rise risk mitigation requires integration from various data from land use data, infrastructure, planning policy, and demographics [47]. TWA enables the integration of previously isolated data (*i.e.,* population distribution, land plots, buildings, sea level rise vulnerable area) as seen in Fig. 6 in a single visualisation. This unified visualisation enables sea level rise risk mitigation integrated with spatial planning strategies such as avoiding new/high-value developments at vulnerable zones while at the same time considering the underlying land use regulations, population distribution and existing buildings infrastructures and services.

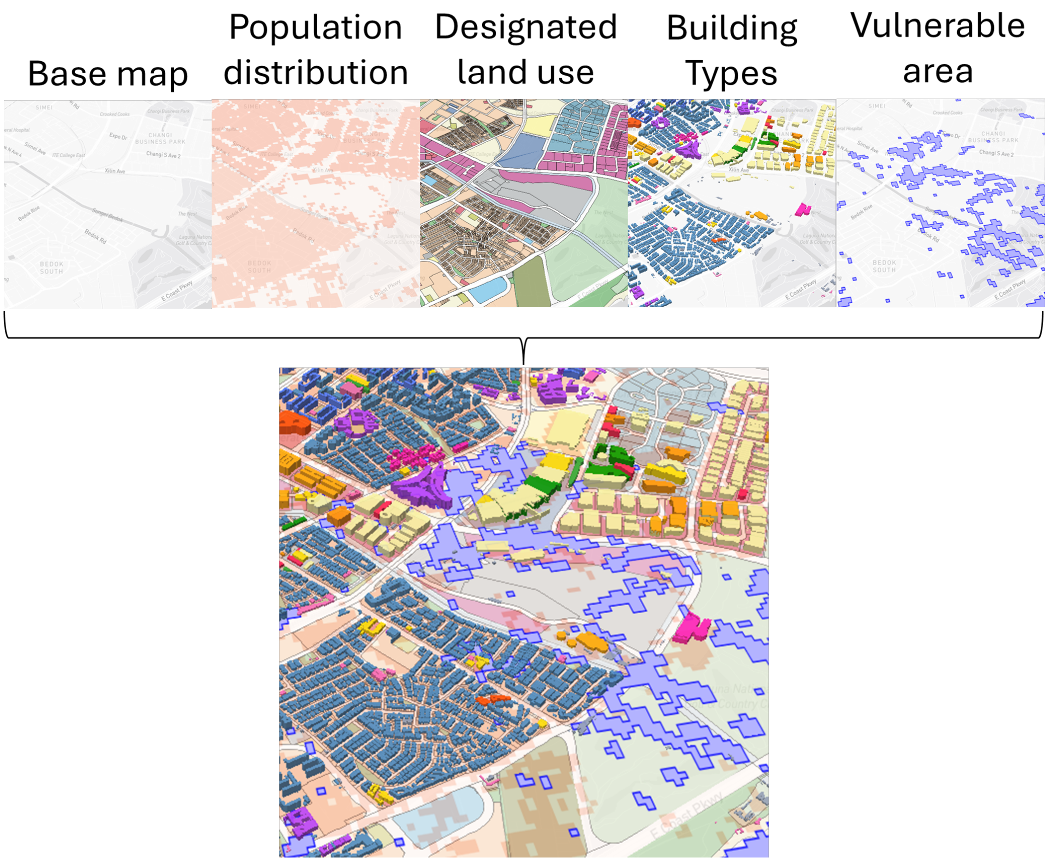


Figure 6: *The combination of population distribution, designated land use, building types, vulnerable area from sea level rise enables a multi-perspective visualisation, enhancing integrated analysis.*

4.2 Data Analysis via Queries

This section demonstrates how the knowledge graph can unlock a wealth of information by providing a single, unambiguous source of truth, eliminating the need to manage heterogeneous data scattered across various locations and formats.

As a demonstration, we show how the total construction cost for the vulnerable buildings can be assessed using SPARQL queries. This is the question we seek to answer:

What is the total cost of the affected buildings based on the SSP5-8.5 low confidence scenario at the 95th percentage quantile, in the year 2150?

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX ontosl: <https://www.theworldavatar.com/kg/ontosealevel/>

SELECT ?scenario
WHERE {
  ?scenario a ontosl:SeaLevelChange;
   ontosl:hasSSP/rdf:type ontosl:SharedSocioeconomicPathway5;
   ontosl:hasRCP/rdf:type ontosl:
       RepresentativeConcentrationPathway85;
   ontosl:hasProjectionYear 2150;
   ontosl:hasConfidenceLevel/rdf:type ontosl:LowConfidence;
   ontosl:hasPercentageQuantile 95.
}
```

Query 1: *SPARQL query to obtain IRI of the SSP5-8.5 low confidence scenario.*

First, the IRI of the scenario is obtained using Query 1. This query requests the value of `?scenario` that adheres to the graph pattern specified in the WHERE clause. It requires `?scenario` to be an instance of the class `ontosl:SeaLevelChange` and to have the following properties that complies to the ontology defined in Fig. 1:

- `ontosl:hasSSP` whose object is of type `ontosl:SharedSocioeconomicPathway-5`;
- `ontosl:hasRCP` whose object is of type `ontosl:RepresentativeConcentration-Pathway85`;
- `ontosl:hasProjectionYear` with the value 2150;
- `ontosl:hasConfidenceLevel` whose object is of type `ontosl:LowConfidence`;
- `ontosl:hasPercentageQuantile` with the value 95.

Assuming the value of `?scenario` from the Query 1 is `<SCENARIO>`, Query 2 shows the query to obtain the total construction costs of buildings impacted by this scenario. The connection between the scenario and buildings, specified in line 8, was established by the sea level impact agent (as described in Section 3.5.5). The triple pattern in line 9 ensures that `?building` is an instance of the `bldg:Building` class. Line 10 shows the triple pattern that retrieves the cost value, adhering to the Ontology of Units of Measure [50]. The function `SUM(?cost) AS ?totalcost` aggregates these costs to provide the total construction cost for the given scenario.

```
PREFIX obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
PREFIX ontosl: <https://www.theworldavatar.com/kg/ontosealevel/>
PREFIX bldg: <http://www.opengis.net/citygml/building/2.0/>
PREFIX om: <http://www.ontology-of-units-of-measure.org/resource/
    om-2/>

SELECT (SUM(?cost) AS ?totalcost)
WHERE {
  <SCENARIO> ontosl:hasPotentialImpact ?building .
  ?building a bldg:Building ;
    obe:hasEstimatedConstructionCost/om:hasValue/om:
        hasNumericalValue ?cost .
}
```

Query 2: *SPARQL query for summing construction costs.*

The link between the Ontology of Units of Measure and the local ontologies is indicated in Fig. 1, in particularly the statement:

```
bldg:Building obe:hasEstimatedConstructionCost om:Cost.
```

The queries shown in this section demonstrate how knowledge graphs can be used to assess the financial impact of environmental changes on infrastructure. Future work could involve automating the generation of such queries through the use of large language models. By translating natural language questions into SPARQL queries, as demonstrated in [57, 64], the process of query creation could become more efficient and user-friendly.

5 Conclusions

In this study, we have augmented The World Avatar to provide a multi-perspective vulnerability assessment on sea level rise in Singapore. We have developed OntoSeaLevel, an ontology to represent sea level rise and its key attributes were developed to describe the relationships of a sea level rise and its broader impact on other urban elements described by other ontologies, such as road networks described by OpenStreetMap ontology, buildings described by OntoBuiltEnv, land plot and designated land use described by Ontoplot and OntoZoning.

We have implemented computational agents to synthesise, integrate and instantiate multiple previously isolated data that exist in various data formats (*i.e.,* GeoJSON, GML, CSV), these data include OpenStreetMap data, cultural sites data, governmental data, and industry data. The building's representation is semantically enriched with integrated information such as property usage, building floor, gross floor area value, and estimated construction cost. A computational agent is applied to identify and instantiate the instances of impacted sites (*i.e.,* vulnerable buildings, land plots, cultural sites, and populations at risk) vulnerable to the sea level rise projection scenario, which the sea level rise projection scenario vulnerable area was derived using a simplistic bathtub inundation model from NASA's Shuttle Radar Topography Mission Global 1 arc second elevation model.

The resulting unified representation of vulnerable buildings, road networks, land plots, cultural sites, and populations at risk from sea level rise through ontologies provides a comprehensive, multi-domain perspective, encompassing both tangible infrastructural and cultural aspects of vulnerable assets. This visualisation enables administrators to perform vulnerability assessment at both a country-wide and localised scale, perform resource allocation prioritisation on significant assets (*i.e.,* either carries more economical value or cultural value), and streamline integrated spatial planning process considering aspects including population distribution, underlying land use, existing infrastructures and vulnerable area.

Future work includes accounting for population growth and changes due to migration. However, the existing available population distribution projections under various shared socioeconomic pathways still lack the granularity needed for meaningful analysis [61]. The current model for sea level rise modelling - bathtub inundation modelling is critically dependent on the quality of the digital elevation model, therefore using a more accurate digital elevation model can lead to significantly improved results. In addition, applying a more sophisticated sea level rise modelling approach that considers factors such as high tide scenarios, extreme weather events, and pluvial flooding can yield a more accurate vulnerability assessment analysis. The results shown in this study strongly depend on the quality of input data models, all analysis published in this paper is based on public domain available data, therefore the findings should be interpreted with caution. In future research, we will collaborate with the National Environment Agency Singapore, and the Nanyang Technological University Singapore to enhance the accuracy of our sea level rise models and analysis.

Declaration of Generative AI and AI-assisted Technologies in The Writing Process

During the preparation of this work the authors used ChatGPT in order to enhance the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data and Code Availability

All the codes developed are available on The World Avatar GitHub repository:
https://github.com/cambridge-cares/TheWorldAvatar.

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The graphical abstract leverages material designed by Freepik.

Nomenclature

GeoSPARQL Geographic Query Language for RDF Data
GML Geography Markup Language
IRI Internationalised Resource Identifier
KG Knowledge Graph
OBDA Ontology-Based Data Access
OSM OpenStreetMap
RDF Resource Description Framework
SPARQL SPARQL Protocol and RDF Query Language
SQL Structured Query Language
TWA The World Avatar

A Appendix

A.1 Namespaces

bldg: <http://www.opengis.net/citygml/building/2.0/>
dbo: <https://dbpedia.org/ontology/>
geo: <http://www.opengis.net/ont/geosparql#>
ic: <http://ontology.eil.utoronto.ca/icontact.owl#>
obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
om: <http://www.ontology-of-units-of-measure.org/resource/om-2/>
ontoplot: <https://www.theworldavatar.com/kg/ontoplot/>
ontosl: <http://www.theworldavatar.com/kg/ontosealevel/>
osm: <https://w3id.org/openstreetmap/terms#>
rdfs: <http://www.w3.org/2000/01/rdf-schema#>
schema: <https://schema.org/>
xsd: <https://www.w3.org/2001/XMLSchema#>
zone: <https://www.theworldavatar.com/kg/ontozoning/>

A.2 SPARQL queries

```
PREFIX ic: <http://ontology.eil.utoronto.ca/icontact.owl#>
PREFIX obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
PREFIX bldg: <http://www.opengis.net/citygml/building/2.0/>

SELECT ?building ?streetName ?streetNumber
WHERE {
  ?building a bldg:Building;
          obe:hasAddress ?address.
  OPTIONAL { ?address ic:hasStreet ?streetName }
  OPTIONAL { ?address ic:hasStreetNumber ?streetNumber }
}
```

Query 3: *SPARQL query to obtain address of buildings.*

```
PREFIX obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
PREFIX bldg: <http://www.opengis.net/citygml/building/2.0/>

SELECT ?building ?floor
WHERE {
  ?building a bldg:Building;
    obe:hasNumberOfFloors/obe:hasValue ?floor.
}
```

Query 4: *SPARQL query to obtain the number of floors.*

```
PREFIX obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
PREFIX bldg: <http://www.opengis.net/citygml/building/2.0/>

SELECT ?building ?floor ?area
WHERE {
  ?building a bldg:Building;
    obe:hasNumberOfFloors/obe:hasValue ?floor;
    obe:hasTotalArea ?area.
}
```

Query 5: *SPARQL query to obtain data required to calculate GFA.*

```
PREFIX obe: <https://www.theworldavatar.com/kg/ontobuiltenv/>
PREFIX bldg: <http://www.opengis.net/citygml/building/2.0/>

SELECT ?building ?usage ?usageShare ?gfa
WHERE {
  ?building a bldg:Building;
    obe:hasPropertyUsage ?property;
    obe:hasGFA ?gfa.
  ?property a ?usage;
    obe:hasUsageShare ?usageShare.
}
```

Query 6: *SPARQL query to obtain building usage and GFA.*

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