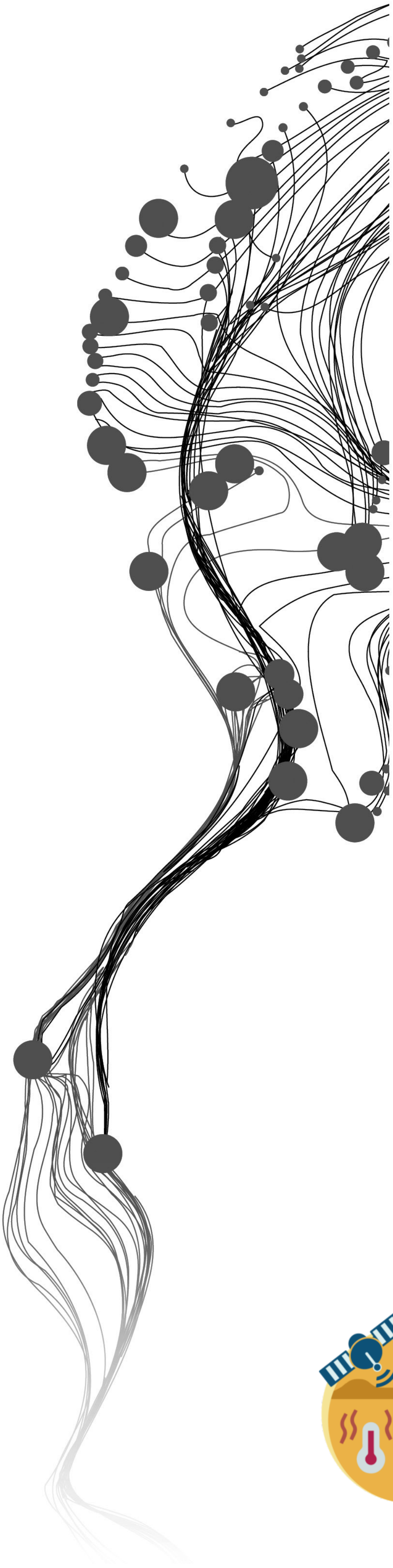
GEO-TWIN: ENHANCING FLOOD RISK MANAGEMENT THROUGH 3D DIGITAL TWIN

A.Y. ALI
August, 2025

SUPERVISORS:

Dr. Mila Koeva (PGM)

Dr. Bastian van den Bout (AES)
Dr. Eefje Hendriks (AES)



GEO-TWIN: ENHANCING FLOOD RISK MANAGEMENT THROUGH 3D DIGITAL TWIN

A.Y. ALI
Enschede, The Netherlands, August, 2025

Thesis submitted to the Faculty of Geo-information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: M-SE

SUPERVISORS:
Dr. Mila Koeva (PGM)
Dr. Bastian van den Bout (AES)
Dr. Eefje Hendriks (AES)

THESIS ASSESSMENT BOARD:
Dr. Monika Kuffer (UT-ITC,BMS) (chair)
Prof. Dessislava Petrova-Antonova (External Examiner)

ABSTRACT

This thesis presents GeoTwin, an open source browser-native 3D digital twin platform for flood risk visualization and analysis in Small Island Developing States (SIDS), with Dominica as a use case. GeoTwin combines a rapid flood simulation service (FastFlood) with a WebGL-based 3D rendering pipeline to show flood scenarios and impacts to stakeholders.

From the client, users set up a simulation and request results from the FastFlood service. The platform downloads the resulting water-height GeoTIFF and processes it into a grid of flood polygons for near real-time visualization. Flood layers are rendered using the engine's terrain-hugging pipeline and a dedicated water shader to show semi-transparent, terrain-conforming inundation surfaces over 3D context layers. An embedded impact analysis module sums up precomputed affected buildings per flood grid cell into impact indicators (e.g. buildings at risk, estimated occupants, economic value) with category reporting and simple threshold-based risk levels.

GeoTwin's architecture prioritizes accessibility (no plugins, commodity hardware), transparency (open source implementation) and stakeholder-oriented design. The prototype shows an end-to-end workflow simulation request, raster processing, terrain-conforming rendering and impact analysis all in a web application. The contribution is a practical, lightweight framework to operationalize flood scenarios into a 3D environment, where 2D maps are insufficient for effective communication and planning.

- Github: https://github.com/Geo-Twin/GeoTwin
- GeoTwin webpage: geotwin-production.up.railway.app

Keywords

Digital Twin, Flood Risk Management, 3D Visualization, Small Island Developing States (SIDS), WebGL, Open-Source, Stakeholder Engagement, Disaster Risk Reduction, Dominica, FastFlood.

ACKNOWLEDGEMENTS

Alhamdulillah ! This journey has been a winding path, and I could not have navigated it without the constellation of people who lit the way(Litrally).

My new chapter began when I moved to Amsterdam. I arrived without a clear plan, but through my partner, Li Xue, I was welcomed by her friends who quickly became my own. Thank you to Stefan for pushing me to apply for a Master's degree, and to his girlfriend, Danru, for always being postive. That encouragement led me to an open day at the University of Twente, where program director Thomas Groen spoke of creating "empathetic engineers" to solve "wicked problems." I knew I had found my place.

To my supervisors, who guided me while navigating their own momentous life events: thank you. To Mila, I feel so lucky you chose me as your student. Your compassionate guidance, even when I was slacking, helped me achieve so much. To Bastian, thank you for shaping this thesis from its core ideas to its code while welcoming a new baby. Your dedication is inspiring. And to Eefje Hendriks, who returned in my final months with a newborn, thank you for your sharp, critical feedback; I am a better writer and researcher because of it. A huge thank you to Irene for the constant encouragement during our weekly ESA meetings, and to Cees, Guiliano, Jarno, and Malavika for the unforgettable fieldwork, and my heartfelt gratitude to Lin for making us feel at home in Dominica. The entire ITC community has been incredible.

This thesis was written across two cities, and I had a support system in both. To my roommates in Enschede, thank you for making our apartment a home. To my Amsterdam crew, Pengyu, Yichun, James, Jeewon, and Niclas, thank you for the weekly hotpots(at Pengyu's) and the friendship that kept me sane. To my classmate Austin, my study buddy for nearly a year: as I write this, you are still texting me, "one last push, and you're done!" Thank you, my friend. I hope you are having a good time in Scotland. I also owe a debt of gratitude to the Volks Hotel for the work that kept me afloat.

To my family across the world: to my uncle back in the States, Uncle Ahmed, your financial support has been a lifeline I can never repay. To my three younger sisters, Iman, Siham, and Nebila, your belief in me has been a constant source of strength. To my cousins Affi, Jamal, and Fahad, thank you for always being there. To my aunt in Amsterdam, Aunt Hawa, thank you for your kindness; I hope to make up for lost time. To my Mom and Dad, whom I have not seen in eight years: I miss you and I hope to see you both very soon.

And finally, to my partner, Effy. I cannot imagine this without you. You have been my constant support and strength through my ACL recovery and the final weeks of writing. You are the reason I am here.Thanks to an offer from Adriano & Luigi, this work is now a stepping stone into a PhD. I look forward to what the future holds.

> *What's meant for you will reach you even if it's beneath two mountains, and what's not meant for you won't reach you even if it's between your two lips.*
>
> — *Imam Al-Ghazali*

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

1.1 PROBLEM DEFINITION

Flooding remains one of the most pervasive and destructive hazards globally, with an increasing impact on urban and rural communities as a consequence of global population growth and the intensification of climate change. Globally, economic losses from weather- and climate-related extremes have increased significantly in recent decades, with floods accounting for a significant proportion of these damages (Doocy et al., 2013; European Environment Agency, 2023). This trend is driven by a confluence of anthropogenic climate change, with global temperatures projected to increase by 1.5 - 4.5 °C by the year 2100 (Intergovernmental Panel on Climate Change, 2014), and socioeconomic factors such as rapid urbanization and population growth (Doocy et al., 2013; Pachauri et al., 2014). Small Island Developing States (SIDS) are particularly vulnerable due to their geographical position and extension, concentrated assets, and limited access to resources, leading to disproportionately high disaster losses relative to their population and Gross Domestic Product (GDP) (Bradshaw et al., 2009; Cashman & Nagdee, 2017). This study aims to introduce an open-source, web-native digital twin platform for flood risk management in Dominica.

Dominica, known as the "*Nature Isle of the Caribbean*," exemplifies this vulnerability. With annual average losses from disasters estimated at 7.9% of GDP, among the highest in the Caribbean region(Bank, 2018), the nation faces persistent risk. Its rugged mountainous terrain, deep river valleys, and exposure to Atlantic hurricanes mean that Dominica is at risk of multiple hydrometeorological hazards, including intense rainfall, riverine and flash flooding, coastal storm surges, and landslides (Panwar et al., 2024; Slinger-Friedman, 2017). Coastal settlements such as Roseau, Pointe Michel, Coulibistrie, and Canefield are particularly exposed, as economic activity and population are concentrated in narrow alluvial plains adjacent to steep basins and the sea (Slinger-Friedman, 2017). The historical record highlights the frequency and severity of flood impacts: Tropical Storm Erika (2015) triggered widespread landslides and floods, displaced thousands and destroyed key infrastructures, while Hurricane Maria (2017) damaged 90% of the built environment, causing catastrophic losses in housing, public assets, and livelihoods (Doocy et al., 2013; Mankowski, 2023). In both cases, cascading hazards, such as co-occurrence landslides and river surges, amplified the scale of the disaster, overwhelming local coping capacities (Cashman & Nagdee, 2017).

During recent years, the Faculty of Geo-Information Science and Earth Observation (ITC) of the University of Twente has been working on improving understanding of multihazard events and challenges in the Caribbean, particularly Dominica (Rajendran, 2024), including the

EO4MULTIHAZARDS project [1] and the PARATUS project [2]. Table 3.1 shows a list of previously collected datasets from this long-lasting collaboration, and work in Dominica, emphasizing the importance of stakeholders and authorities' collaboration. This work, being part of the EO4MULTIHAZARDS, contributes to the understanding of the flood risk communication in Dominica.

According to Cha et al., 2020, by year 2100, the climate projections indicate a 20 - 30% increase in both frequency and intensity of extreme precipitation events, leading to a doubling of Category 4 - 5 hurricanes in the eastern Caribbean. In future warming scenarios, this can increase the risk of acute and compound flooding (Nabukulu et al., 2024; Pachauri et al., 2014). These hydro-climatic trends are compounded by anthropogenic drivers: rapid urban expansion, informal housing construction, and insufficient drainage infrastructure, all of which increase the exposure of people and assets to flood hazards (Huong & Pathirana, 2013; Panwar et al., 2024). Recent work has shown that in other tropical, data-scarce urban centers, the doubling of impervious surface area can result in a near doubling of peak flood depths, highlighting the critical influence of land use and planning on disaster risk (Huong & Pathirana, 2013). In Dominica, similar patterns of unregulated development, limited enforcement of planning codes, and persistent socioeconomic constraints have led to increased settlement in high-risk floodplains and coastal margins (IMF, 2021; Slinger-Friedman, 2017).

A robust understanding of flood risk in these environments requires knowledge of the physical hazard and a systematic assessment of exposure, vulnerability, and coping capacity (UNISDR, 2017; Westen & Greiving, 2017). Building on established frameworks in disaster risk reduction, risk is systematically quantified as the probability-weighted interaction between hazardous events (e.g., flood depth, duration, and velocity), the spatial distribution of exposed people and assets, the intrinsic vulnerability of buildings and infrastructure, and the effectiveness of coping and adaptive capacities at the household and institutional levels (UNISDR, 2017; van Westen et al., 2008; Westen & Greiving, 2017). Furthermore, risk communication is a critical component of building disaster management systems, because of the challenging nature of communicating uncertainty under disaster event (Fakhruddin et al., 2020). In Dominica, limited local resources, gaps in technical expertise, and the absence of high-frequency, high-resolution monitoring data further constrain risk reduction efforts, leaving decision-makers reliant on static flood maps, post-event field surveys, and fragmented GIS data (Panwar et al., 2024; Slinger-Friedman, 2017).

Existing SIDS practices frequently center on conventional two-dimensional (2D) flood mapping using desktop GIS and hydraulic models. While these are valuable for hazard zoning and regulatory purposes, these approaches suffer from critical limitations: they typically employ depth-averaged hydraulic models that cannot capture the complex three-dimensional (3D) fluid dynamics of urban flooding, including vertical acceleration and turbulence at infrastructure interfaces (Teng et al., 2017); in short, they cannot visualize flood depth in complex urban terrain and are slow to update following new hazard or land use information (K. Beven, 2012; Brunner & of Engineers, 2016; Schumann et al., 2009). Furthermore, technical barriers, including proprietary software requirements, computational overhead, and a lack of user-friendly interfaces, restrict access to local planners, emergency managers, and the wider community as non specialist residents and civil-society actors who rely on flood information for preparedness, response, or recovery but are outside formal planning and emergency agencies (Blair et al., 2019; Fuller et al., 2020a; Mankowski, 2023). The "last mile" of flood risk communication, delivering actionable, spatially explicit in-

---

[1] EO4MULTIHAZARDS project page: https://eo4multihazards.gmv.com/

[2] PARATUS project page: https://www.paratus-project.eu/

formation to all stakeholders in a timely and understandable way, remains a persistent challenge, especially during rapidly evolving events such as flash floods and hurricanes (Doocy et al., 2013; Ramos et al., 2010).

This combination of natural, socioeconomic, and technological factors defines the acute, multifaceted flood risk context in Dominica and other SIDS. This underscores the urgent need for innovative, accessible decision-support tools (Bakhtiari et al., 2023) that can integrate diverse geospatial and hydro-meteorological data, visualize dynamic scenarios in three dimensions, and communicate risk effectively to a range of stakeholders and at-risk communities (Mankowski, 2023; UNISDR, 2017; van Westen et al., 2008). Addressing these gaps forms the scientific and practical motivation for this study.

The next section critically examines the limitations of existing research and practice in SIDS flood risk management, highlighting unresolved challenges in data integration, real-time modelling, and user-centered communication (Stewart, 2024) that motivate the development of new digital twin solutions.

1.2 RESEARCH GAP

Despite decades of international research and investment exceeding US$1 billion annually in flood risk reduction(UNISDR, 2017), significant gaps persist in the science and practice of flood risk management for Dominica. The conventional workflow, which includes hazard mapping, exposure analysis, and scenario-based planning, relies heavily on static, two-dimensional outputs derived from hydrodynamic models and satellite imagery (K. Beven, 2012; Brunner & of Engineers, 2016; Schumann et al., 2009). While such approaches remain foundational for zoning and regulatory purposes, they are increasingly misaligned with the evolving needs of decision-makers and affected communities, particularly in highly dynamic and data-constrained island contexts (Blair et al., 2019; Doocy et al., 2013; Fuller et al., 2020a).

A critical bottleneck lies in the integration of heterogeneous datasets. Effective flood risk assessment requires the fusion of high-resolution topographic data (e.g., LiDAR, DEMs or drone-derived DSMs), accurate building inventories, detailed infrastructure networks, and both historical and near-real-time precipitation data (Huong & Pathirana, 2013; Mankowski, 2023; Panwar et al., 2024). However, in practice, these datasets are often incomplete, outdated, inconsistently formatted, or distributed across fragmented institutional silos (UNISDR, 2017; van Westen et al., 2008; Westen & Greiving, 2017). The resulting uncertainty in exposure and vulnerability mapping is rarely communicated clearly to stakeholders, hampering the effectiveness of early warnings, emergency responses, and long-term resilience planning (Doocy et al., 2013; Ramos et al., 2010). When building risk communication systems, elements shown in Figure 1.1 should be considered equally (Fakhruddin et al., 2020).

Another major challenge is the slow update cycle and lack of interactivity inherent in traditional desktop-based GIS and hydraulic modelling environments. High-fidelity hydrodynamic models, such as HEC-RAS[3] or MIKE FLOOD[4], provide detailed flood extents and depths, but require extensive expert input, high computational resources, and time-consuming scenario gener-

---

[3] HEC-RAS: https://www.hec.usace.army.mil/software/hec-ras/

[4] MIKE FLOOD: https://www.dhigroup.com/technologies/mikepoweredbydhi/mikeplus-2d-overland

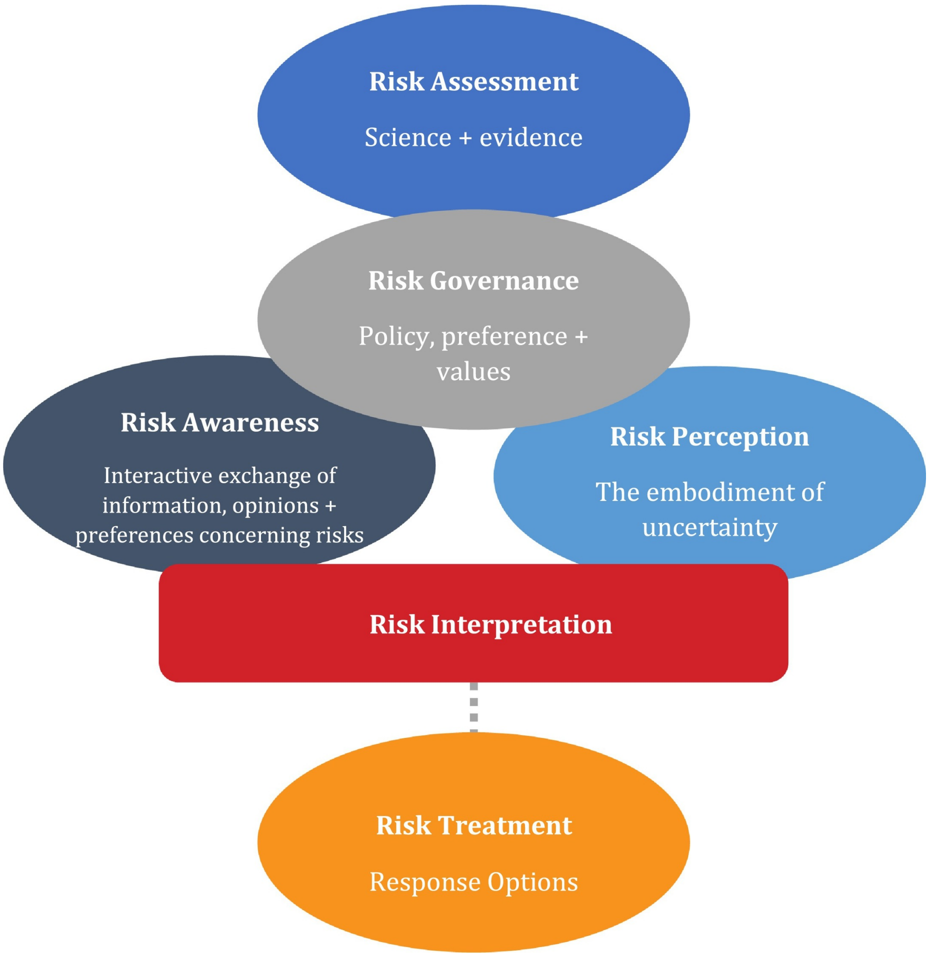


Figure 1.1: Risk communication framework for early warning systems *Source: Bapon, 2020.*

ation (Blair et al., 2019; Brunner & of Engineers, 2016). This delay limits their utility for real-time situational awareness or community engagement, particularly in the context of rapidly evolving hazards such as flash floods, tropical cyclones, or compound events (floods coupled with landslides or storm surges) (Mankowski, 2023; Nabukulu et al., 2024; Panwar et al., 2024). Existing 2D dashboards also fail to visualize vertical variations in flood depth and overlook the spatial complexity of urban terrain and building typologies that critically shape local impacts (Fuller et al., 2020a; Haynes et al., 2018).

A growing body of literature highlights the potential of 3D, web-native visualization platforms, often used as a foundation for "digital twins", to transform risk communication and support decision-making in disaster management (Barrile et al., 2025; Fan et al., 2021; Fuller et al., 2020a; Westen & Greiving, 2017). In parallel, VR/AR has matured for immersive, site-specific risk communication, typically as presentation layers rather than continuously updating, data-integrated systems. In this context, digital twins, as shown in Figure 1.2, refer to integrated, interactive, and dynamically updated virtual models of real-world environments, combining geospatial data, real-time sensor feeds, and simulation outputs in an accessible 3D interface (Fuller et al., 2020a; Petrova-Antonova & Ilieva, 2019; Tao et al., 2019). Recent studies have demonstrated that such platforms can enhance public understanding of risk, foster scenario-based planning, and support iterative, participatory engagement with a broader spectrum of stakeholders, including those with limited technical expertise (Riaz et al., 2023; Yin et al., 2024). However, most operational digital twins for flood management remain either (i) proprietary, requiring significant licensing costs and computational resources (e.g., ESRI flood simulation[5], Tygron[6], and 3DI[7]), (ii) limited to "showcase" demonstrators in desktop GIS (e.g., Blender-based 3D models), or (iii) focused on high-income urban centers with extensive data and institutional support (Barrile et al., 2025; Blair et al., 2019; Mankowski, 2023). In SIDS and other data-scarce settings, open-source, browser-based platforms that integrate locally relevant datasets and support real-time, user-driven exploration of risk scenarios are still very rare (Dembski et al., 2020; Mankowski, 2023; Westen & Greiving, 2017).

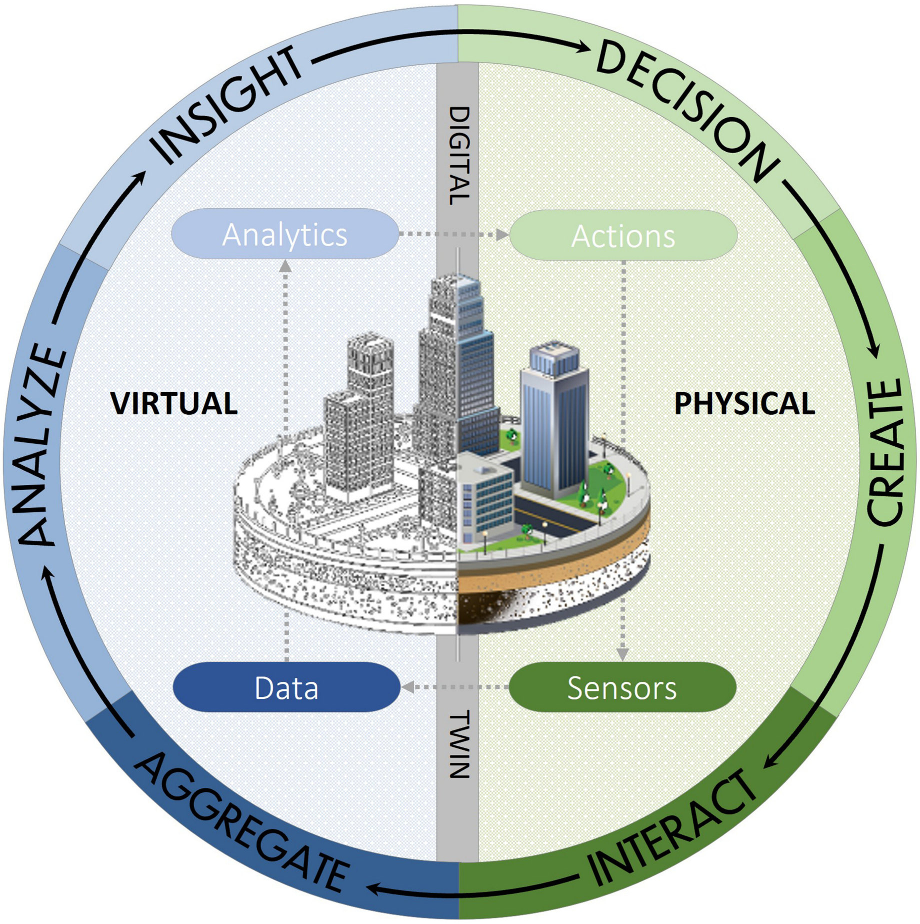


Figure 1.2: The role of the digital twin in the urban planning and decision-making process of the physical city. *Source: Petrova-Antonova and Ilieva, 2019.*

Moreover, the effectiveness of new digital tools depends on technical capability and their adoption and sustained use by local stakeholders. Studies in technology adoption theory emphasize that user acceptance is influenced by factors such as perceived usefulness, ease of use, trust in data, organizational capacity, and the perceived gap between scientific outputs and actionable decision support (Charalabidis et al., 2025; Fuller et al., 2020a; UNISDR, 2017). In the Caribbean, recent participatory research (van den Bout & Koeva, 2025) underscores the need for platforms that

---

[5] ESRI 3D flood simulation: https://pro.arcgis.com/en/pro-app/latest/help/mapping/simulation/simulation-in-arcgis-pro.htm

[6] Tygron: https://www.tygron.com/en/

[7] 3DI: https://3diwatermanagement.com/for/3d-digital-twins/

are both technically robust and tailored to the socio-institutional realities of SIDS, including diverse user needs, frequent data gaps, and limited IT capacity (Panwar et al., 2024; Riaz et al., 2023; UNISDR, 2017).

In summary, the literature highlights the following challenges: integrating diverse, multi-scale datasets; enabling interactive, real-time scenario analysis; communicating complex 3D risk information in ways that are actionable for decision-makers and communities; and ensuring local adoption and sustainable use(Farsi et al., 2019). These interlocking gaps set the stage for the present research, which aims to design, implement, and evaluate an open-source, browser-native digital twin/GeoTwin specifically tailored to the flood risk context of Dominica and comparable SIDS.

The following section reviews the scientific foundations of digital twin approaches in disaster management and critically examines their advantages and limitations for bridging the above research gaps.

1.3 DIGITAL TWIN AS DECISION SUPPORT (DTDS)

The term “digital twin” traces its conceptual roots to NASA’s Apollo program in the 1960s, where identical physical spacecraft models were employed to simulate and test mission scenarios in parallel with real missions (Liu et al., 2019). The formal term “digital twin” was later introduced by John Vickers of NASA in the early 2000s and by Grieves in the context of manufacturing as a dynamic, digital representation that mirrors a physical system and allows for real-time monitoring, simulation, and analysis (Fuller et al., 2020a; Grieves, 2014; Grieves & Vickers, 2017). Building on the urgent challenges outlined in Section 1.2, the concept of a digital twin has emerged as a pivotal technological innovation for advancing flood risk management; however, the development of digital twins for flood risk management is still under-explored (Bakhtiari et al., 2023), as shown in Figure 1.3. Unlike VR/AR, which typically require head-mounted displays or other dedicated devices, digital twins can be delivered through standard web browsers using HTML5/WebGL, lowering equipment and access barriers for stakeholders and the public. Therefore, we focus on digital twins as an equipment-light platform for decision support.

In environmental and geospatial sciences, digital twins are defined as dynamic, data-driven virtual replicas of real-world geospatial and infrastructural systems that are updated in near real-time through the integration of heterogeneous datasets, computational models, and stakeholder interactions (Fuller et al., 2020a; La Guardia & Koeva, 2023; Zhang, 2024). This extension from their engineering origins is not merely semantic: in the context of flood risk, a digital twin can continuously fuse data streams, such as rainfall, river stage, hydrodynamic simulation output, and infrastructure status, with high-fidelity, interactive 3D terrain and city models (Ariyachandra & Wedawatta, 2023; La Guardia & Koeva, 2023; Rajendran, 2024). This results in a platform where decision-makers, planners, and non-technical stakeholders can visualize complex flood scenarios, interrogate the spatial distribution of hazards and vulnerabilities, and anticipate the potential effects of interventions before a disaster strikes.

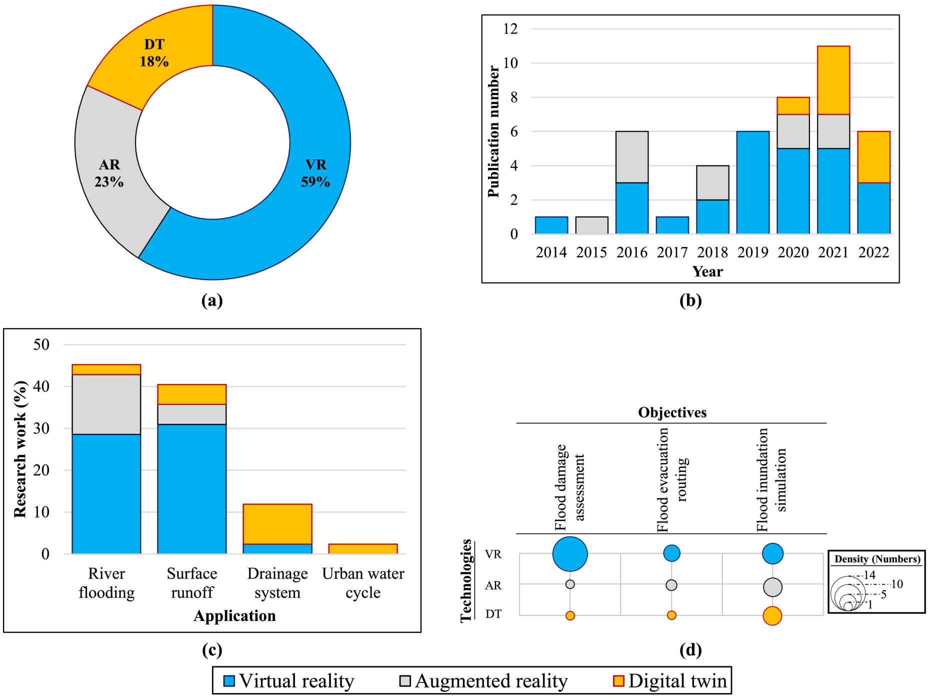


Figure 1.3: Dashboard of the recent digital visualisation technologies: (a) proportional breakdown, (b) timeline distribution, (c) application distribution, (d) objective distribution *Source: Bakhtiari et al., 2023.*

Key functional attributes of digital twin decision support systems (DT-DSS) for flood resilience include:

1. **Real-Time Synchronization:** Continuous ingestion of forecast or observational data to update simulations and visualizations with minimal latency, supporting proactive warning and response (Ariyachandra & Wedawatta, 2023).
2. **Multi-Resolution Modelling:** Integration of models across scales, from detailed building-level inundation to catchment-wide hydrology, through federated data architectures that preserve coherence across resolutions (Tan et al., 2024).
3. **3D User-Centric Interfaces:** Browser-based, plugin-free 3D viewers that abstract technical complexity and present actionable metrics (e.g. impacted building count, depth exceedance thresholds) within an intuitive, navigable environment (Ge & Qin, 2025).
4. **Scenario Management:** Built-in tools for defining, storing, and comparing multiple flood scenarios, enabling quantitative evaluation of mitigation alternatives such as levees, detention basins, or building retrofits (Dharmarathne et al., 2024).

Existing 3D web-based solutions such as F4Map[8] and Cesium-based platforms[9] are either proprietary or challenging for customization, making them less ideal for building a digital twin platform. Furthermore, these solutions often present significant hurdles for resource-limited agencies

---

[8] F4Map demo zoomed in on Dominica: https://demo.f4map.com/#lat=15.3972264&lon=-61.3929237&zoom=12

[9] CesiumJS: https://cesium.com/platform/cesiumjs/

in SIDS due to licensing, technical, and cost constraints (La Guardia & Koeva, 2023; Rajendran, 2024). Therefore, these limitations lead research advocates for open-source, browser-based, modular digital twin architectures designed with stakeholder co-design and iterative prototyping to democratize access and genuinely improve resilience in data and capacity-limited contexts (Forcada, 2025; Fuller et al., 2020a; La Guardia & Koeva, 2023). Moreover, although 2D GIS dashboards are effective for planning, they do not fully leverage the spatial insights afforded by 3D interactions, such as vertical cross-section analysis or immersive exploration of inundation dynamics around critical infrastructure (Costabile et al., 2021).

The present project aims to address these limitations by delivering a fully web-native, open-source DT-DSS, GeoTwin. To achieve fully web-native platform, FastFlood[10] is chosen because of its rapid flood simulation in the web (1500 times faster than traditional models with over 97% accuracy), and WebGL[11] is chosen for its high performance 3D rendering capabilities with any compatible web browser without the need of plug-ins. GeoTwin integrates live data feeds, external hydrodynamic outputs (FastFlood API), and advanced 3D WebGL visualization in a single platform. By adhering to open standards (for example, WebGL 2.0, GeoJSON, and OGC APIs) and modular design principles, GeoTwin democratizes access to sophisticated flood decision support, empowering SIDS stakeholders to anticipate flood impacts, evaluate interventions, and enhance community resilience without the need for specialized software installations (Weil et al., 2023).

To avoid ambiguity in this study, we adopt the term "GeoTwin" to refer specifically to a geospatial digital twin for flood risk management. While digital twin frameworks and nomenclature vary across fields, GeoTwin is used here both as the name of the platform developed for Dominica and as an analytic construct throughout this work. This approach reflects recent best practices in the digital twin literature, which distinguishes between industrial digital twins and urban (geospatial) digital twins, and enables a focused comparison with related work in urban and disaster resilience (La Guardia & Koeva, 2023; Zhang, 2024).

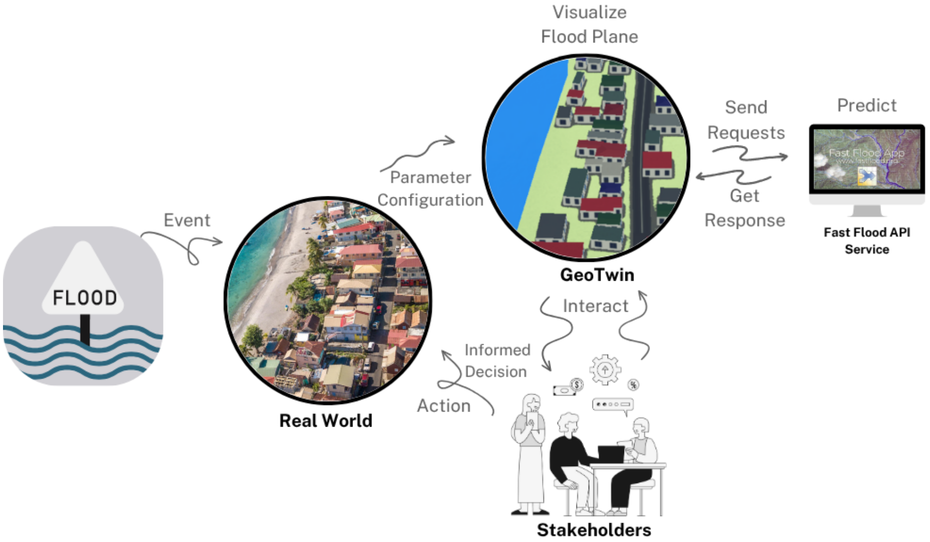


Figure 1.4: Overview of the proposed GeoTwin workflow. *Source: Author(2024).*

To provide a clear overview of the GeoTwin's operational flow, Figure 1.4 illustrates the core

---

[10] FastFlood: https://fastflood.org/
[11] WebGL: https://www.khronos.org/webgl/

components and data interactions between GeoTwin, stakeholders and the FastFlood (van den Bout et al., 2023) API. The workflow highlights how heterogeneous data sources, ranging from static geospatial layers to real-time hydrodynamic outputs, are ingested, processed, and rendered within a unified 3D environment. It also emphasizes the modular integration of external simulation services, web-based visualization pipelines, and user-centric decision support tools. This overview serves as a foundation for understanding the subsequent technical and evaluation sections of this study.

As mentioned at the beginning of this chapter, the aim of the study is to develop a platform, GeoTwin, to support the flood risk decision-making process. Specifically, how digital twin-based flood risk predictions can be effectively communicated to stakeholders in Dominica by integrating real-time data with 3d visualization techniques, timely and visually clear information to support informed decision-making.

1.4 RESEARCH OBJECTIVES AND QUESTIONS

This study addresses the following main research question / main objective:

How can Digital Twin–based flood hazard predictions be made accessible, accurate, visually intuitive, and real-time to support flood risk decision-making by key stakeholders in Dominica?

To answer this, the study is structured into three sub-objectives, each with associated research questions.

Sub-objective 1: To identify stakeholder requirements for a Digital Twin platform supporting flood risk management in Dominica.

(i) What are the functional needs and expectations of local stakeholders (meteorological staff, disaster managers, planners) for a Digital Twin platform?

(ii) Which data sources, formats, and systems are currently used by the stakeholders, and how should these be integrated with the platform?

Sub-objective 2: To design a 3D Digital Twin Platform (GeoTwin) for flood risk decision support.

(i) Which key features and functionalities should GeoTwin provide (e.g., real-time visualization, scenario simulation)?

(ii) How can GeoTwin integrate diverse geospatial and hydrological datasets into a unified 3D environment?

(iii) How does GeoTwin support decision-making workflows for flood impact assessment and mitigation?

Sub-objective 3: To evaluate the GeoTwin prototype against existing solutions.

(i) How does GeoTwin perform in terms of spatial accuracy, usability, and efficiency compared to current 2D GIS dashboards and Digital Twin platforms?

(ii) What are the perceived strengths and weaknesses identified by stakeholders during evaluations?

(iii) Which future enhancements are prioritized by end users for improving flood resilience?

1.5 THESIS STRUCTURE OVERVIEW

The following chapters present the scientific and technical development of GeoTwin. The thesis is organized as follows.

- **Chapter 2: Literature Review.** Flood-modelling approaches in resource-constrained contexts, web-based 3D visualization tools, and existing digital twin frameworks for infrastructure resilience are reviewed. Identifies critical gaps, real-time integration, and browser-native twins that GeoTwin addresses.
- **Chapter 3: Study Area and Data.** Describes Dominica's physical geography, flood history, and the geospatial datasets (OSM footprints, LiDAR DEMs, FastFlood API samples) used in the study. Presents fieldwork insights and stakeholder requirements elicited from workshops and interviews.
- **Chapter 4: Methodology & System Architecture.** Details the conceptual framework, GeoTwin multi-layer design (data acquisition, preprocessing, visualization), planned integration with FastFlood, and field-driven co-design and validation protocol.
- **Chapter 5: Results.** Reports performance benchmarks (frame rates, load times), accuracy assessments (Hurricane Maria case IoU and depth error metrics), and usability feedback (System Usability Scale scores, thematic analysis of stakeholder interviews).
- **Chapter 6: Discussion.** Findings are interpreted in light of the research questions, limitations (data quality, browser constraints, SIDS-specific challenges) are discussed, and future directions (multi-hazard modules, real-time sensor feeds, landslide visualization) are proposed.
- **Chapter 7: Conclusion.**

Chapter 2

Literature Review

2.1 FLOOD MODELING APPROACHES FOR SMALL ISLAND DEVELOPING STATES (SIDS)

The analytical core of any flood-focused Digital Twin is its hydrological and hydraulic modelling engine. The choice of this engine is a critical decision that dictates the system's data requirements, computational demands, predictive accuracy, and ultimately, its feasibility within a specific operational context. For a SIDS like Dominica, characterized by steep catchments, rapid runoff dynamics, and significant data scarcity, a careful and critical evaluation of modelling paradigms is essential. This section comparatively analyzes physically-based, conceptual, and data-driven models to establish a justification for the modelling approach best suited for integration into the GeoTwin framework.

Distributed and Physically-Based Models

Physically-based hydraulic models represent the most rigorous approach in terms of physical realism and detail. Industry-standard models such as HEC-RAS and MIKE FLOOD are capable of simulating one-dimensional (1D) and two-dimensional (2D) unsteady flow by numerically solving the Saint-Venant equations or their derivatives (Brunner & of Engineers, 2016). These models can provide highly detailed predictions of flood extent, depth, and velocity, and can explicitly represent complex hydraulic structures like bridges and culverts. However, their primary drawback lies in their data requirements. Accurate simulation with these models necessitates high-resolution Digital Elevation Models (DEMs), detailed river channel bathymetry, and extensive data on land use and friction coefficients (K. J. Beven, 2012). In data-scarce environments like many SIDS, acquiring such comprehensive datasets is often prohibitively expensive and logistically challenging, representing a major barrier to implementation (Schumann et al., 2009).

Conceptual Rainfall-Runoff Models

In contrast, conceptual rainfall-runoff models offer a more pragmatic alternative for data-limited regions. Widely used methods like the Soil Conservation Service Curve Number (SCS-CN) method and the Rational Method are designed with simplified, lumped-parameter structures that represent catchments using empirical relationships (USDA, 1986). These models require significantly fewer parameters and less input data, primarily relying on time series of rainfall and catchment characteristics. While they do not provide the same level of detailed hydraulic information as physically-based models, their parsimony and computational efficiency make them suitable for preliminary assessments, especially in ungauged basins common in SIDS contexts.

Machine Learning-Based Methods

The growing availability of environmental data and advancements in computational power have increased the development of data-driven modelling techniques in hydrology. Artificial Intelligence (AI) and Machine Learning (ML) algorithms, such as Support Vector Regression (SVR) and Random Forest (RF), can learn complex, non-linear relationships directly from data without relying on explicit physical process representation (Mosavi et al., 2018).

More recently, hybrid models that combine different AI architectures, such as a Convolutional Neural Network (CNN) with a Recurrent Neural Network (RNN), have shown exceptional promise for river flood prediction by capturing both spatial and temporal data complexities (Kusuma et al., 2022; Wang et al., 2023; Zhao et al., 2024), by capitalizing on the strengths of both models. For example, the CNN component can efficiently extract features from spatial data, such as satellite imagery and topographical information, which are vital for assessing flood risk areas (Bentivoglio et al., 2022; Chen et al., 2021). The RNN component, on the other hand, processes sequences of time-dependent data, such as historical river discharge rates and rainfall patterns, thereby enhancing the model's predictive capacity over time (Janizadeh et al., 2019; Mienye et al., 2024). This dual approach allows for a more nuanced understanding of flooding events, combining immediate spatial characteristics with historical temporal trends (Choi & Shin, 2022; Noor et al., 2022). However, their performance is fundamentally dependent on the availability of long, high-quality historical datasets for training, which are often lacking in SIDS.

This analysis concludes that the most pragmatic path for GeoTwin is to leverage a rapid modelling approach that balances physical representation with data scarcity. A rapid 2D hydraulic model, such as the one used by the FastFlood API, provides results without the demand for a large amount of data, compared to traditional complex models, making it suitable for the SIDS context (van den Bout et al., 2023). In summary, Table 2.1 provides a comparative overview of flood modelling methods and their suitability to build a GeoTwin platform.

Table 2.1 Comparative analysis of flood modelling methods and their suitability for SIDS.

Model Type	**Example(s)**	**Underlying Principle**	**Key Data Requirements**	**Strengths**	**Weaknesses**	**Suitability for DT in SIDS Context**
Physically-Based Hydraulic	HEC-RAS, MIKE FLOOD	Solves shallow water equations (e.g., St. Venant) for 1D/2D flow.	High-resolution DEM, detailed channel bathymetry, cross-sections, roughness coefficients.	High physical realism, detailed output (depth, velocity), explicit structure representation.	Very high data requirements, computationally intensive, requires specialized expertise.	Low. Prohibitively high data and resource demands for initial implementation.
Conceptual Rainfall-Runoff	SCS-CN, Rational Method	Represents catchment using empirical relationships and lumped parameters.	Time series of rainfall, catchment area, soil type, land use.	Low data requirements, computationally efficient, suitable for ungauged basins.	Lower physical realism, provides outlet discharge only (not detailed hydraulics), requires calibration.	Medium. Feasible for high-level runoff estimation but lacks spatial detail for inundation mapping.
Machine Learning-Based	SVR, Random Forest, CNN-RNN	Learns statistical relationships between input (e.g., rainfall) and output (e.g., flow) data.	Long, high-quality historical time-series data for training and validation.	Can capture complex non-linear patterns, with high predictive accuracy if well-trained.	“Black box” nature (low interpretability), performance highly dependent on data quality and quantity.	Medium. Potential is high but constrained by the lack of extensive historical datasets.
Rapid 2D Hydraulic	FastFlood	Solves simplified 2D shallow water equations on a grid, optimized for speed.	DEM, rainfall data, basic land cover/infiltration parameters.	Provides spatially explicit results (depth, extent), computationally efficient.	Lower hydraulic detail than complex models, relies on simplified physics.	High. A pragmatic and feasible option that aligns well with data availability and the need for rapid scenario analysis in SIDS.

2.2 ADVANCES IN WEB-BASED 3D GIS AND VISUALIZATION TECHNOLOGIES

The effectiveness of a Digital Twin for flood risk management is based on model accuracy and its ability to communicate complex and dynamic information. Traditional 2D maps are often inadequate for conveying the true scale of a 3D phenomenon like flooding. On the other hand, 3D geospatial data with modern web technologies has created an opportunity to build interactive and immersive visualization platforms that bridge the gap between expert analysis and stakeholder understanding.

WebGL enables rendering interactive 3D graphics in a web browser. It provides low-level GPU access and a rich ecosystem of high-level, open-source JavaScript libraries. For geospatial visualization, the following shows a list of widely adopted libraries built on the WebGL API that can load and render real-world coordinate systems, allowing for the globe and maps to be visualized in 3D:

- **CesiumJS:** A premier open-source library for creating high-precision 3D globes and maps, with robust support for streaming massive 3D datasets (e.g., entire cities) and time-dynamic data, making it ideal for visualizing flood evolution (Cesium, 2012).
- **Three.js:** A flexible, general-purpose 3D library that provides the building blocks for creating custom 3D scenes, though it requires more boilerplate code for geospatial context compared to specialized libraries like CesiumJS ((Mr.doob) & Authors, 2010).
- **deck.gl:** A WebGL-powered framework optimized for the visual exploratory analysis of large datasets through an intuitive, layer-based paradigm, excellent for rendering data-rich overlays like sensor points or flow vectors (Uber Technologies, Inc., 2016).

The purpose of this visualization is to enhance usability and stakeholder engagement. Research shows that 3D representations significantly reduce the cognitive effort required for non-technical stakeholders to interpret a situation compared to abstract 2D maps, leading to improved understanding and decision-making (Amirebrahimi et al., 2016). This can be further enhanced by incorporating **Physically Based Rendering (PBR)**, a methodology that achieves a high degree of realism by simulating the physical properties of light interaction with materials, such as their roughness, reflectivity and transparency (Chavez, 2023; Pharr et al., 2004), see Figure 2.1.

Such realistic visualizations, sometimes incorporated into “serious games” or immersive Virtual Reality (VR) simulations, are increasingly used for flood education, public outreach, and studying human risk perception in controlled settings (Aksa et al., 2025).

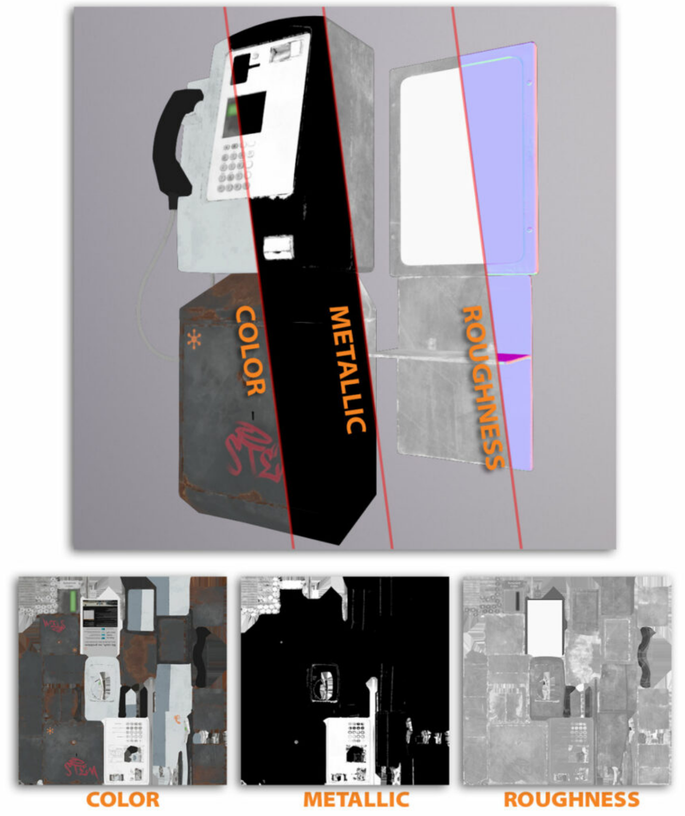


Figure 2.1: A visual breakdown of the material attributes in the PBR workflow. The main texture maps needed are color, metallic, and roughness. A normal and opacity map was also used. *Source: Chavez, 2023.*

2.3 DIGITAL TWIN FRAMEWORKS FOR FLOOD RISK MANAGEMENT AND INFRASTRUCTURE RESILIENCE

For academic precision, a true Digital Twin is distinguished from a static *Digital Model* by a dynamic data flow; it is further distinguished from a *Digital Shadow* (one-way data flow) by having a **bidirectional** data flow, where the physical system informs the virtual model, and the virtual model can provide insights to influence the physical system (Fuller et al., 2020b). This closed-loop feedback mechanism is the defining feature that elevates a DT to an active, intelligent management system (Tao et al., 2019).

The application of DT technology in hydrology and flood risk management is a growing field. City-scale frameworks are being developed to integrate flood forecasting with urban infrastructure, enabling analysis of cascading disruptions and enhancing situational awareness (Park et al., 2024). By providing a platform for “what-if” scenario simulation, DTs allow stakeholders to test the efficacy of different mitigation strategies in a virtual environment before committing resources in the real world (Riaz et al., 2023).

Chapter 3

Study Area and Data

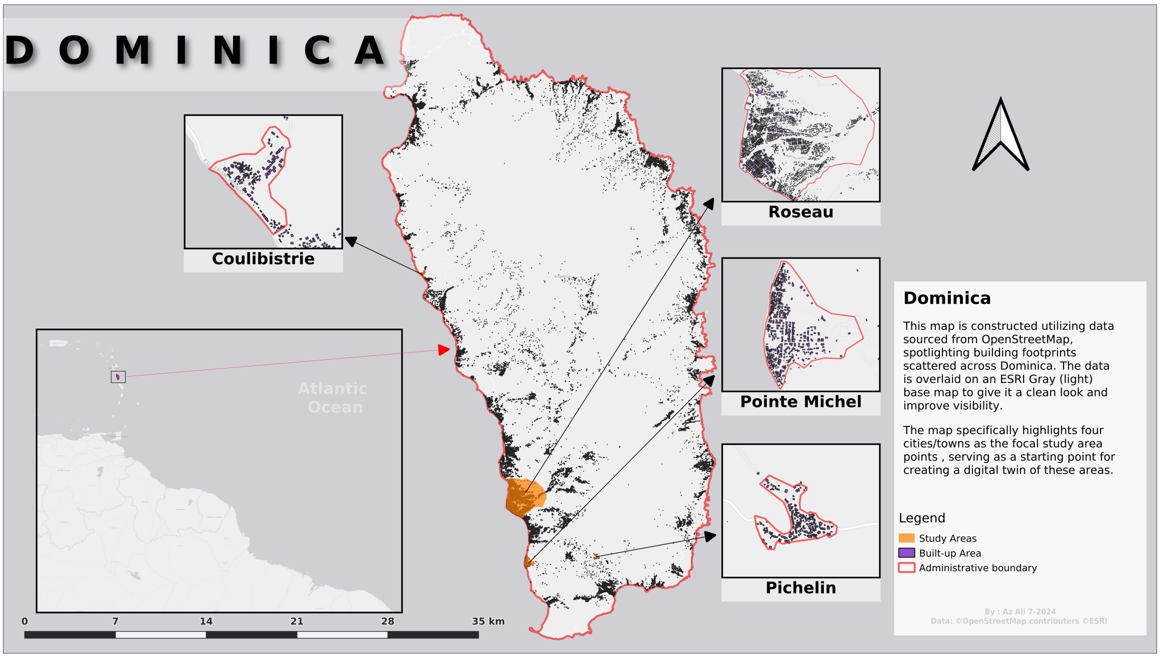
3.1 GEOGRAPHIC CONTEXT AND PHYSICAL ENVIRONMENT

The Commonwealth of Dominica is a sovereign island nation in the Lesser Antilles, spanning approximately 750 km^2. Its volcanic origins have produced a landscape dominated by a central spine of steep, forested mountains and deeply incised river valleys (Slinger-Friedman, 2017). Peaks rise above 1,400 meters, and more than 365 rivers and streams radiate from the interior to the coast, forming a dense hydrological network (Government of the Commonwealth of Dominica, 2017). Coastal areas are characterized by narrow alluvial plains, which concentrate most of the population and economic activity. This topography creates conditions for rapid runoff and flash flooding, as intense rainfall is quickly channeled through steep catchments to low-lying communities (Cashman & Nagdee, 2017). Figure 3.1 provides an overview of Dominica's geographic context, buildings, and key coastal settlements where flood exposure is most severe. The key urban centers vulnerable to flooding, such as Roseau, Coulibistrie, Pointe Michel, and Pichelin (with the exception of being non-coastal settlements), are marked on the map for reference.

Dominica's tropical climate features high temperatures and humidity year-round, with a pronounced wet season from June to November that coincides with the Atlantic hurricane season (Slinger-Friedman, 2017). The island is subject to frequent extreme precipitation events, often associated with tropical waves, storms, and hurricanes, which can deliver large volumes of rainfall in short periods. The combination of steep terrain and erodible volcanic soils makes landslides a common secondary hazard, often exacerbating flood impacts by damming rivers or depositing debris into channels (Government of the Commonwealth of Dominica, 2017).

3.2 SOCIO-ECONOMIC LANDSCAPE AND CRITICAL INFRASTRUCTURE

Dominica's population was recorded as 71,293 in the 2011 census (Dominica Central Statistics Office, 2011), with the highest density in and around the capital, Roseau, situated in the parish of St. George (Dominica Central Statistics Office, 2011). Settlement patterns place a significant proportion of residents and infrastructure in areas exposed to flood hazards. The economy is primarily based on agriculture and tourism, both of which are highly sensitive to hydro-meteorological extremes. Critical infrastructure, including the main seaport, airport, road networks, hospitals, and utilities, is also located in these coastal zones, increasing the risk of systemic disruption during flood events (Cashman & Nagdee, 2017). The interdependence of these systems amplifies the potential for cascading failures.



This map is constructed utilizing data sourced from OpenStreetMap, spotlighting building footprints scattered across Dominica. The data is overlaid on an ESRI Gray (light) base map to give it a clean look and improve visibility.

The map specifically highlights four cities/towns as the focal study area points , serving as a starting point for creating a digital twin of these areas.

Figure 3.1: Study Area Location. *Source: Author(2024).*

3.3 HISTORICAL FLOOD EVENTS AND IMPACTS

Dominica has experienced a series of severe flood events with major humanitarian and economic consequences. In August 2015, Tropical Storm Erika delivered approximately 320 mm of rainfall in less than 12 hours, as reported by the Dominica Meteorological Service and confirmed in peer-reviewed analyses (Pasch et al., 2018). The event resulted in over 30 fatalities, displaced thousands, and caused damages estimated at US$483 million (about 90% of GDP at the time) (Bank, 2018; Government of the Commonwealth of Dominica, 2015). Critical infrastructure, including the main airport and numerous bridges, was destroyed, isolating communities for weeks (Government of the Commonwealth of Dominica, 2015).

In September 2017, Hurricane Maria, a Category 5 storm, made direct landfall, bringing extreme winds and torrential rainfall that led to island-wide flooding and landslides. Over 90% of the built environment was damaged or destroyed, with economic losses totaling US$1.37 billion (226% of GDP) (Government of the Commonwealth of Dominica, 2017). These events highlight the destructive power of compound hazards and the urgent need for improved prediction to prevent loss and damage and to develop resilience-building measures.

3.4 AVAILABLE GEOSPATIAL DATASETS

The GeoTwin framework operates as a visualization platform of the final outputs of simulations carried out with FastFlood. While GeoTwin itself directly processes contextual geospatial data such as building footprints, its primary function is to render the flood hazard layers generated by the FastFlood API. Therefore, to provide a complete picture of the data used in the entire workflow, this section describes a list of data used by GeoTwin, along with a list of geospatial and meteorological datasets used by FastFlood.

- **Digital Elevation Models (DEM):** High-quality terrain data is the foundation for any credible flood simulation. The FastFlood simulation engine utilizes modern, high-quality global DEMs such as the *Copernicus DEM at 30m resolution (Copernicus30)*. For specific high-risk locations like Dominica, the global DEM is supplemented with much higher-resolution local data where available, including processed *LiDAR* data, to ensure the most accurate topographic representation possible for overland flow paths (FastFlood.org, 2025).

- **Land Cover:** The hydrological calculations within FastFlood incorporate land cover data to determine surface roughness and infiltration parameters. These are derived from established global datasets such as the *ESA Climate Change Initiative (CCI) Land Cover*, which provides a classification of surface types (e.g., urban, forest, agriculture) (ESA, 2017).

- **Satellite Imagery:** While not directly processed by GeoTwin, multispectral imagery from platforms like **Sentinel-2** serves as a foundational input for the land cover products used by FastFlood. This imagery is crucial for the upstream processes of land use classification and monitoring environmental changes that affect hydrological responses (Drusch et al., 2012).

- **Soil Parameters:** In addition to ESA, infiltration parameters used by FastFlood are also derived from global datasets like **SoilGrids**, which provides gridded information on soil properties such as sand, silt, and clay content. These parameters are essential for estimating soil infiltration capacity, a key factor in determining the volume of rainfall that becomes surface runoff (Hengl et al., 2017).

- **Precipitation Data:** Accurate rainfall data is the primary driver for flood simulations. Data from multiple sources is available for GeoTwin, including API endpoints for:
  - *Global Precipitation Measurement (GPM) IMERG:* Provides near-real-time, high-resolution satellite-based precipitation estimates, essential for forecasting and monitoring developing storm events (Huffman et al., 2019).
  - *Local Rain Gauges:* Where available, historical and real-time data from gauges in Dominica can be used for model calibration and validation, providing critical ground-truthed measurements.
  - *ERA5 Reanalysis:* A global climate reanalysis dataset that provides a long-term, consistent historical record of precipitation, useful for simulating past events and understanding long-term climate trends (Hersbach et al., 2020).

- **Building and Infrastructure Data:** While the hazard layer is provided by FastFlood, the 3D environment and context layers are processed directly by GeoTwin. The following datasets can be used as a foundation to render buildings and their information:
  - *OpenStreetMap (OSM):* A global, open-source database providing building footprints, road networks, and river networks. While coverage can be variable, it serves as a crucial baseline for exposure analysis (OpenStreetMap contributors, 2017).
  - *Local GeoJSON Data:* An interpolated dataset of previously collected datasets from ITC Twente, and classified buildings from data collected in the context of the EO4MULTIHAZARDS project. The distribution of the dataset are shown in Figure A.2, A.3, A.4, and A.5 in Appendix A.

- **Real-time Sensor Data:** While not yet fully implemented for Dominica, the GeoTwin architecture 4.5 is designed to accommodate future integration of Internet of Things (IoT) data streams, such as real-time river level or flow rate sensors, weather stations, and community-based monitoring devices. This planned expansion will enable real-time data assimilation and dynamic model updating, further enhancing the digital twin's predictive and decision-support capabilities (Park et al., 2024).

- **FastFlood API Simulation Data (Consumed by GeoTwin):** The final, crucial dataset ingested by GeoTwin is the hazard data generated by the FastFlood API. The service returns flood depth and extent as a **GeoTIFF** raster, which is then directly processed and visualized within the GeoTwin platform as the primary output of the simulation workflow (van den Bout et al., 2023).

Table 3.1 describes the list of datasets that are available, and commonly used (Rajendran, 2024) to build a GeoTwin platform. In our framework, we utilize these datasets strategically for optimization purposes; details can be found in Chapter 4.

Table 3.1 Summary of datasets available for developing a GeoTwin framework. The source and availability of data are also specified.

Dataset	Format	Source/License	Description
DSM	Tiff (.tif)	ITC, University of Twente	Raster file of Digital surface model
Buildings	Shapefile (.shp)	OpenStreetMap	Vector file of buildings
Road network	Shapefile (.shp)	ITC, University of Twente	Vector file of roads
River network	Shapefile (.shp)	ITC, University of Twente	Vector file of river network
Bridges	Shapefile (.shp)	Dominica - Engineering Department	Vector file of bridge locations
Elevation, Land cover, Infiltration, Rainfall	Raster	FastFlood app (various sources)	Raster files from SRTM (Elevation), Sentinel-2 (Land cover), ECMWF (Rainfall forecast), Soilgrids.org (Soil data for infiltration)
Historical precipitation records	Text file	UT-ITC (previous projects)	During Hurricane Maria and Tropical Storm Erika
Geological / Hydrogeological data	Raster	PARATUS project	Geological and hydrogeological layers
UAV data	Raster	Previous projects	Available only for certain regions of interest
Disaster databases (incl. flood hazard maps)	Raster/Vector	UT-ITC	Detailed inventory for Hurricane Maria and Tropical Storm Erika

Chapter 4

Methodology and System Architecture

4.1 METHODOLOGICAL FRAMEWORK

The development of the GeoTwin platform is guided by a Design Science Research (DSR) methodology. DSR, as shown in Figure 4.1, is a problem-solving paradigm focused on the creation and evaluation of innovative IT artifacts, such as models, methods, and systems, that are designed to address specific, real-world problems (Hevner et al., 2004). This approach was explicitly chosen because the primary objective of this thesis is to build and evaluate a functional and effective technological solution (GeoTwin) to solve the practical problem of inadequate flood risk decision support in Dominica. The DSR process is inherently iterative, involving cycles of building the artifact, evaluating its utility in the target environment, and refining it based on feedback to generate new knowledge about both the problem domain and the potential solution space. To address the research questions, the methods section is structured into three phases that correspond directly to **RQ1–RQ3**, as depicted in Figure 4.2

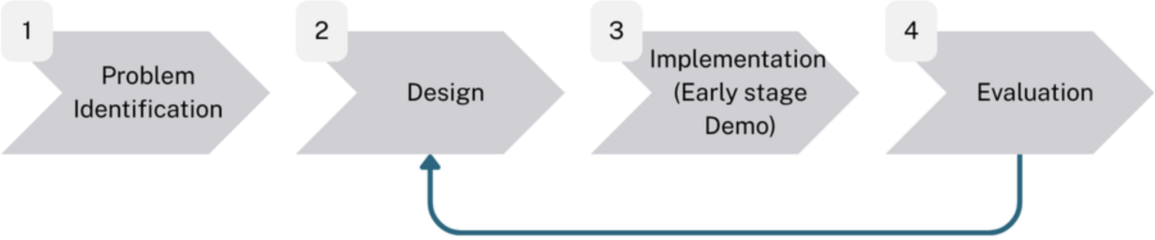


Figure 4.1: Design Science Research (DSR) methodology. *Adapted from: Bilandzic and Venable, 2011.*

This methodology involves the principle of co-design, which ensures that the developed artifact is technically sound, practically relevant and usable for its intended stakeholders. The requirements and functional specifications for GeoTwin were directly informed by the stakeholder workshops and unstructured interviews conducted in Dominica, from the field work by ITC Twente in 2025, as well as the questionnaire survey (van den Bout & Koeva, 2025) from 2024. Details are in the section 4.2.2 below.

Table 4.1 Research questions, methods, data, analysis, and outcomes

Research Question	**Research Method**	**Data**	**Data Analysis**	**Outcomes**
(**RQ1**.i) Functional needs and expectations of stakeholders	Qualitative & Quantitative Stakeholder Analysis; Co-design Workshops	Interviews; Questionnaire survey responses; Workshop notes	Thematic analysis of interviews; Descriptive statistics of survey preferences	Validated user requirements and functional specifications
(**RQ1.ii**) Existing data sources, formats, and integration needs	System & Workflow Analysis; Document Analysis; Literature review	Interview transcripts; Technical documentation	Identification of data gaps and format issues	A list of datasets used by GeoTwin
(**RQ2.i**) Key features and functionalities of GeoTwin	Design Science Research (DSR); Participatory Workshops; Iterative Prototyping	User requirements from **RQ1**	Feature prioritization through stakeholder feedback	Defined feature set for GeoTwin
(**RQ2.ii**) Dataset integration into a unified 3D environment	Artifact Construction; System Architecture Design	OSM, GeoJSON datasets; FastFlood API outputs; Technical library specs	Development and testing of preprocessing pipelines; Rendering engine performance profiling	Functional data pipeline and 3D rendering system handling heterogeneous datasets
(**RQ2.iii**) Supporting decision-making workflows	Scenario-Based Evaluation	Stakeholder defined use-cases	Design of novel decision-support use cases grounded in stakeholder practices	A feature that automates stakeholder's workflow
(**RQ3.i**) GeoTwin performance vs. current solutions	Performance Benchmarking; Comparative Analysis; Usability Testing	System performance logs; existing static maps; Stakeholder task-based feedback	Quantitative benchmarking on FPS, memory; Qualitative usability comparisons	Validated efficiency and usability on standard hardware; Added value over 2D workflows
(**RQ3.ii**) Stakeholder perceptions on strengths and weaknesses	Qualitative Thematic Analysis	Interview transcripts; Workshop feedback sessions	Thematic coding to identify strengths, weaknesses, barriers	Strengths and weaknesses
(**RQ3.iii**) Prioritized future enhancements	Participatory Requirements Elicitation	Feedback from interviews and workshops; Prioritization exercises	Analyzing stakeholder feedback	Prioritized roadmap for future GeoTwin development based on user needs

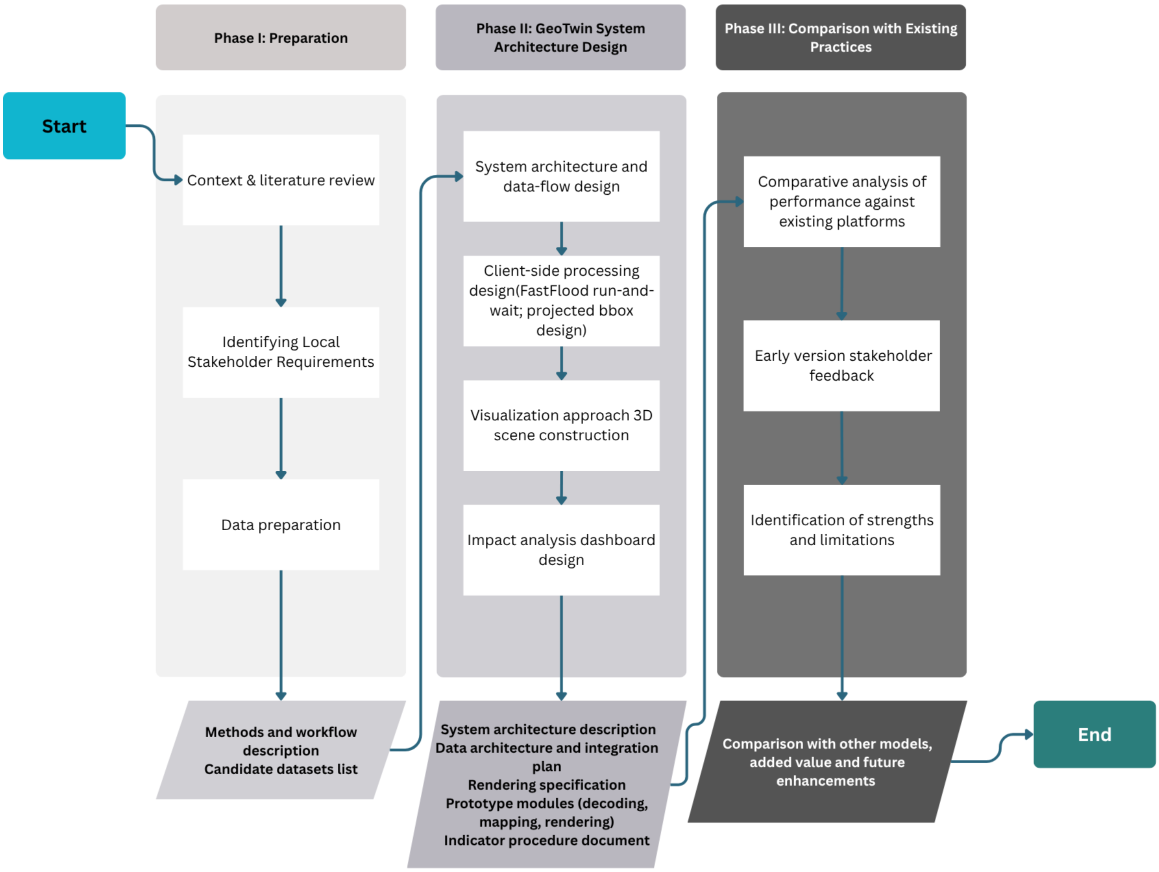


Figure 4.2: Methodological Flowchart of the research.

4.2 PHASE I: PREPARATION

4.2.1 Stakeholder Classification

This study builds upon an earlier classification developed by Rajendran, 2024 on the topic, successfully classifying stakeholders in Dominica by dividing them into four quadrants based on the two axes of interest and importance. For example, Quadrant A represents low interest and high importance, and Quadrant D represents high interest and low importance. The detailed classification is in Figure 4.3.

4.2.2 Methods of Identifying Local Stakeholder Requirements and Expectations

The following methods are used to identify local stakeholder requirements and expectations.

Unstructured Interviews: In April 2025, the author conducted five in-person, unstructured interviews in Dominica as art of ongoing ESA and PARATUS project activities. Participants were key informants from government agencies, technical departments, and non-governmental organizations directly involved in disaster management and infrastructure planning. Their roles, institutions, and expertise are summarized in Table 4.3. These stakeholders' positions on the clas-

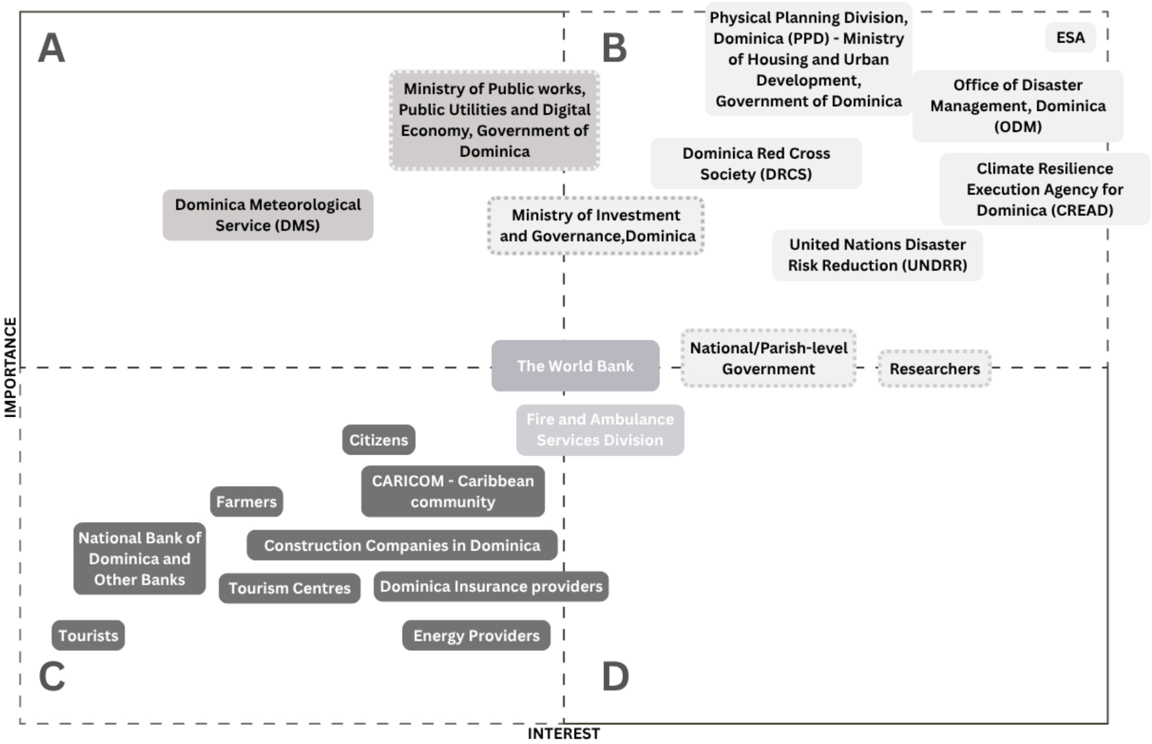


Figure 4.3: Stakeholder classification matrix. *Adapted from: Rajendran, 2024*

sification matrix are shown in the Appendix A.2. Because the goal was exploratory needs discovery, when shown to an early stage version of GeoTwin, conversations were open-ended rather than guided by a fixed questionnaire about the platform. The key topics touched upon are (1) current disaster management workflows and decision contexts, (ii) data availability and quality, (iii) technology use and integration barriers, (iv) resource and regulatory constraints, and (v) desired capabilities for analysis and visualization.

Interviews were video-recorded (with consent) and transcribed verbatim, then imported into ATLAS.ti[1] for analysis. Guided by the study's research questions, an a priori codebook of 32 codes was defined to structure the analysis, which included a hierarchical family *Stakeholder Insights* with the subcodes *Opportunities* and *Barriers*. The full code list and definitions are shown in Table 4.2. Quotations were assigned to codes and examined for frequencies and code-document distributions. Specific quotations and visualizations derived from these outputs are reported in Chapter 5. This unstructured design was chosen to include tacit practices and latent needs that fixed-response surveys often miss. To reduce interpretive bias, we used explicit code definitions and presented quotations alongside counts to ground interpretations.

Talk and Discussion situated in the ESA Workshop: A talk was given at the ESA workshop for the EO4MultiHazard project to gather feedback on early-stage concepts of the GeoTwin platform. This participatory method allowed users to directly engage with mock-ups and prototypes, providing immediate feedback on the usability of proposed features.

Questionnaire Survey: To complement the qualitative data, a structured questionnaire (van

---

[1] https://atlasti.com

Table 4.2 Codebook for stakeholder interview analysis

Code	Comment
3D Usability	Preference for clear, intuitive 3D visualization by non-experts.
Community DRR	Community plans, first responders, and local hazard maps.
Community Engagement	Plans for engaging with the communities.
Data Sources	Data sources identified by stakeholders.
Disaster Management Challenges	Solutions to managing disaster.
Early Warning Gap	Alerts issued reactively; need predictive thresholds.
Education and Information	Informing community with disaster-related knowledge.
Emergency Preparedness	Prepare for hazard emergency.
Feature requirement	Features needed for tools that can help with disaster management.
Funding Challenges	Challenges when curating funds.
Future Enhancements	Prioritized additions: sensors, socio-economic layers, analytics.
GIS Capacity	Limited in-house GIS capability; need simple tools.
Hazard Impact	Impact of previous hazards.
House Impact	Building- and road-level exposure identification.
Multi-hazard	Interest in extending beyond floods to landslides, fires, seismic.
Needs for Improvement	Need to have improvement over disaster management.
Needs for Technology	Situations when need technology.
Post-Event Updates	Need to refresh GIS/asset layers after major events.
Project Context	Context of the GeoTwin project.
Regulatory Compliance	EIAs/codes/monitoring influence siting and design.
Resource Constraints	Funding/staff shortages; reliance on volunteers/partners.
Road Safety	Safety issues regarding roads.
Safety Awareness	Community awareness of the safety.
Scenario Planning	"What-if" simulations for planning, response, and training.
Stakeholder Context	Context provided by stakeholders, including projects they are working on.
Stakeholder Insights	Insights from stakeholders on disaster management.
Stakeholder Insights: Opportunities	Opportunities for tool building.
Stakeholder Insights: Barriers	Hurdles for having better disaster management.
Technology Integration	Points regarding integrating technology into their workflow.
Tool requirement	Requirement for specific tools.
Training Needs	Requirement for onboarding and ongoing user training.
Usability Definition	What is considered as useful.

Table 4.3 Overview of interviewed stakeholders

Stakeholder ID	Stakeholder Role	Institution/Organization Type	Relevant Expertise
S1	GIS Officer	Dominica Meteorological Service	Hydrology, GIS systems
S2	Director General	Dominica Red Cross	Community resilience, disaster response
S3	Civil Engineer	Physical Planning Division	Project HRP planning, construction regulation
S4	Chief Physical Planner	Physical Planning Division	Land use regulation, EIA oversight
S5	Local Government Commissioner	Ministry of Culture, Youth Sports, and Community Development	Community disaster planning, governance

Figure 4.4: Presenting GeoTwin to stakeholders in Dominica

den Bout & Koeva, 2025) written by supervisors of this project from a previous study in the MSc Thesis of Rajendran, 2024 was used since this work is a continuation of a similar research theme. This survey, which was conducted at four different events, yielded a total of 34 responses from participants, including experts in planning, disaster management, geospatial fields, MSc students in relevant domains, and a stakeholder in Dominica, with the aim of identifying requirements, needs, and expectations for a 3D decision support tool for flood risk management.

4.2.3 Data preparation

A robust data preprocessing and transformation pipeline is essential to convert the raw input datasets into a harmonized, analysis-ready format suitable for the GeoTwin environment. This workflow is designed to overcome the common challenge of integrating heterogeneous data by automating the steps required for spatial alignment and optimization for web-based visualization.

The first step in the workflow is the harmonization of coordinate reference systems. All geospatial datasets are reprojected to a common system, Web Mercator (EPSG:3857), the standard for web mapping applications. This ensures that building footprints, road networks, and flood layers align correctly with the terrain model.

Next, 2D vector data is transformed into renderable 3D meshes. Building footprints from OSM and local GeoJSON files are processed using a procedural extrusion algorithm. This algorithm takes the 2D polygon of each building and extrudes it vertically to a specified height. The choice to use procedural generation was made to minimize the need for pre-existing 3D models, which are rarely available for Dominica.

Raster data from the FastFlood API is decoded on the client. When a user runs a simulation, the GeoTIFF file containing water height is fetched and processed with a GeoTIFF decoder in the browser. The raster band is read into typed arrays and mapped to the simulation area extent. This client-side approach enables interactive updates without heavyweight backend infrastructure.

The human-readable pseudocode in Algorithm 1 illustrates the core logic of the data transformation pipeline.

Algorithm 1: Data Processing and Loading Pipeline

```
Input: dataSources: collection of geospatial datasets
Output: scene: fully prepared 3D scene object
// Phase 1: Harmonize Vector Data
harmonizedBuildings ← REPROJECT(dataSources.osmBuildings, EPSG:3857);
harmonizedRoads ← REPROJECT(dataSources.osmRoads, EPSG:3857);
// Phase 2: Generate 3D Meshes from Vectors
buildingMeshes ← {};
foreach footprint ∈ harmonizedBuildings do
    if footprint.attributes.height exists then
        height ← footprint.attributes.height;
    else
        height ← defaultHeight;
    mesh ← EXTRUDEPOLYGON(footprint.geometry, height);
    buildingMeshes.append(mesh);
// Phase 3: Prepare Terrain Data
terrainDEM ← LOADDEM(dataSources.dem);
// Phase 4: Add Data to Rendering Engine
scene.add(buildingMeshes);
scene.setTerrain(terrainDEM);
return scene
```

4.3 PHASE II: GEOTWIN SYSTEM ARCHITECTURE DESIGN

The GeoTwin system is designed as a modular, multi-layer, web-native application to ensure scalability, maintainability, and accessibility without requiring specialized client-side software. The architecture separates flood simulation, raster processing, and visualization into interoperable modules. The overall system architecture of GeoTwin, illustrating the modular layers and data flow, is depicted in Figure 4.5.

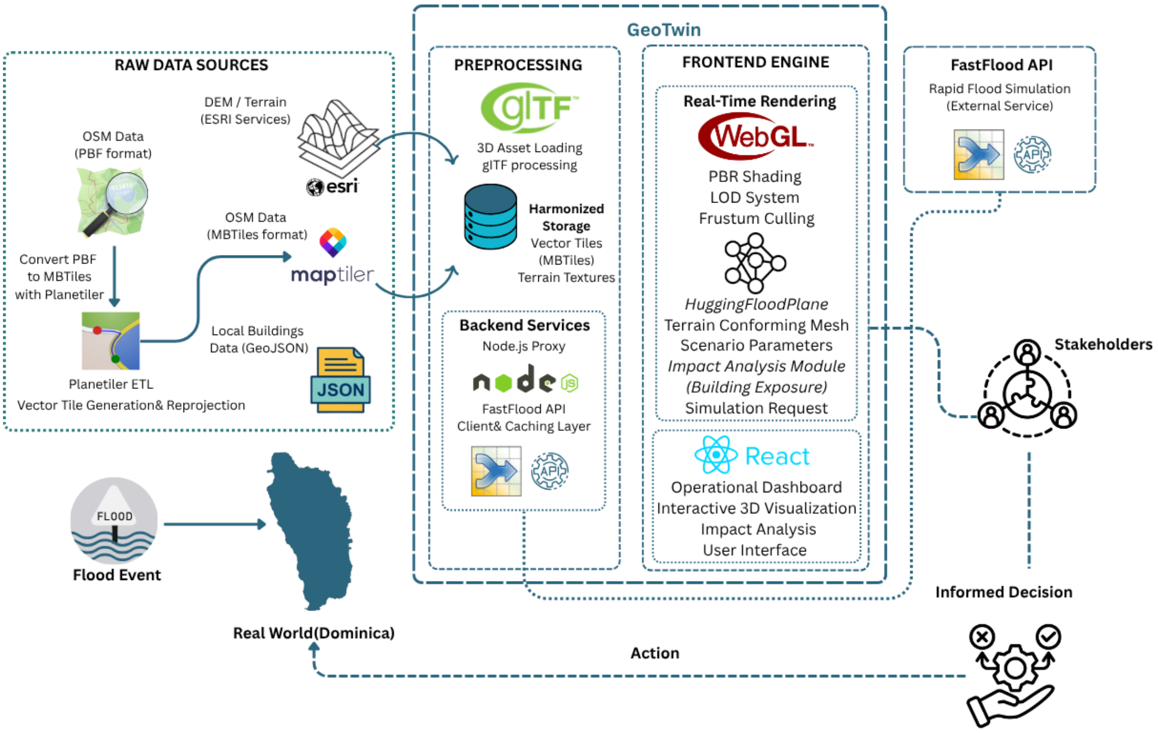


Figure 4.5: System Architecture of GeoTwin.

4.3.1 Frontend and Backend Stack

The UI component is a browser-based application built using modern web technologies. The interface is developed with React[2], a declarative JavaScript library for building user interfaces, and written in TypeScript for enhanced code quality and maintainability. The 3D rendering is powered by a custom WebGL2 engine, which communicates directly with the system's GPU to deliver high-performance, interactive visualizations (Herman et al., 2017).

The lightweight backend is implemented using Node.js[3], serves as an intermediary for handling data requests and interfacing with external services.

---

[2] https://react.dev/

[3] https://nodejs.org/en

4.3.2 FastFlood API Integration and Hazard Modeling

The interaction with the API is handled via standard HTTP requests from the client. From the GeoTwin interface, a user can define a set of simulation parameters (e.g., return period, duration). The FastFlood service processes the request and returns a JSON payload listing output files (e.g., `whout.tif` for water height). The client downloads the GeoTIFF bytes and processes them into a grid of flood polygons aligned to the requested area. These polygons contain per-cell water height and bounding boxes used for rendering and analysis (van den Bout et al., 2023). Algorithm 2 shows the concept of how flood planes are rendered.

Algorithm 2: Terrain-Conforming Flood Mesh Generation (concept)

```
Input: floodRaster: Raster grid containing water height
       AreaBbox: Projected bounding box of the simulation area
Output: tiles: terrain-conforming flood tiles
for each flooded cell $(i, j)$ do
    worldQuad ← CELLTOWORLDQUAD(i,j, areaBbox);
    depth ← WATERHEIGHT(i,j);
    tile ← BUILDPROJECTEDTILE(worldQuad, height = depth);
    ADDSMALLZOFFSET(tile);
    tiles.append(tile);
return tiles
```

4.3.3 Building Classification

To be able to analyze buildings affected by flooding in the 3D scene, building details were interpolated from open building datasets, such as OSM, Open building map (gfz, n.d.), stored in local GeoJSON sources . Missing values of building type classification, including their occupancy type, were generalized based on the footprint characteristics and the area. Other concurrent work done by the ESA project in 2025, classified building datasets for major settlements, was also incorporated.

In the current prototype, building values are also used as part of the building information. These values are first calculated arbitrarily based on the square foot area of the building footprint and material costs per square meter. Subsequently, the values are generalized to all 38,557 buildings in the GeoJSON datasets. These calculations are approximations for demonstration purposes. In the future, local governments can prepare datasets in such a manner and upload them to the platform for accurate affected building calculation.

4.3.4 Impact Analysis

The impact analysis aggregates precomputed affected buildings from flooded grid cells and summarizes exposure. For affected assets, the flood-processing step annotates each flooded grid cell with any intersecting buildings (coordinates, occupancy where available). The primary metrics are computed as follows. Let B_{aff} be the set of unique affected buildings across all flooded cells.

Then:

$$\text{buildingsAtRisk} = |B_{\text{aff}}| \quad \text{peopleAffected} = \sum_{i \in B_{\text{aff}}} \text{occ}_i \quad \text{economicLoss} = \sum_{i \in B_{\text{aff}}} \text{value}_i$$

$$\text{highRiskArea} = |P| \times 19.1 \times 19.1 \text{ m}^2$$

where P is the set of flooded pixels converted to tiles. A simple risk level is assigned: HIGH if buildingsAtRisk > 100, MEDIUM if > 50, else LOW.

4.4 PHASE III: COMPARISON WITH EXISTING PRACTICES

The evaluation of the GeoTwin prototype is conducted through a twofold approach to address **RQ3**.

First, a comparative analysis is performed to benchmark GeoTwin's features, architecture, and accessibility against other established 3D platforms. This involves a detailed feature and architectural comparison against leading commercial solutions in the flood risk sector, namely ESRI ArcGIS, Tygron, and 3Di, to situate GeoTwin within the current technological landscape.

Second, a qualitative assessment is conducted based on the feedback gathered from stakeholders during unstructured interviews and discussions where an early version of GeoTwin was presented. The transcribed feedback is analyzed to identify the perceived strengths, weaknesses, and potential adoption barriers of the platform. This analysis also serves to identify and prioritize future enhancements as suggested directly by the end-users.

4.5 SUMMARY OF METHODOLOGICAL CONTRIBUTIONS

The methodological framework presented in this chapter aims to address the proposed research objectives and the gaps identified in the literature. The choice of a DSR approach, informed by co-design principles, ensures that the outcome is both technically innovative and practically relevant to the needs of end users in Dominica.

Phase I introduces the methods used for qualitative stakeholder analysis and data preparation. Phase II details the system architecture and end-to-end flow (simulation request, GeoTIFF decoding, terrain-conforming rendering, and impact analysis). Phase III reflects on comparison against existing solutions based on qualitative feedback.

Chapter 5

Results

As mentioned in the Chapter 4, this project involved a series of unstructured interviews with five local stakeholders in Dominica, representing public institutions and community organizations actively engaged in flood risk management and climate resilience. Based on these interviews in the fieldwork and technology identified in the literature, the GeoTwin platform was developed and deployed as a functional 3D digital twin for flood risk decision support. The open-sourced code repository is available at: *https://github.com/Geo-Twin/GeoTwin*. Together, these deliverables provide insight into the requirements, design priorities, and expected utility of a digital twin platform for SIDS, addressing the research questions outlined in Section 1.4.

5.1 RQ1: LOCAL STAKEHOLDER REQUIREMENTS AND EXPECTATIONS

5.1.1 Qualitative Analysis Overview

As mentioned in Section 4.2.1, the qualitative analysis of the interview process was conducted using the manually defined codes in Table 4.2.

The treemap of code frequency over the interview transcripts is shown in Figure 5.1. The most frequent codes include *Community DRR*(29) and *Stakeholder Context*(23), which categorize stakeholders' plans and their relevant work contexts beyond these, challenges such as *Resource Constraints* (20), *Stakeholder Insights: Barriers* (21), and *Disaster Management Challenges* (15) repeatedly appear in the conversations, indicating that the main obstacles to improving disaster management are resource-related, including funding (*Funding Challenges*) (8).

Complementing the treemap, the Sankey diagram in Figure 5.2 visualizes the code-document distribution derived from the manual code-quote assignments. Most codes are spread relatively evenly across stakeholders, indicating broad coverage for topics such as *Stakeholder Context*, *Emergency Preparedness*, and *Resource Constraints*. However, a few codes show visibly thicker inflows from specific participants, suggesting role-specific emphases. For example, *Regulatory Compliance* comes primarily from S4 (planner), and *Road Safety* from S5 (commissioner), whereas *GIS Capacity* is concentrated in S1 and S3, who have engineering-based roles.

Figure 5.3 shows frequent terms across the interview transcripts. The dominance of words such as *community*, *challenge*, *Dominica*, *building*, *road*, *house*, *resilience*, *rainfall*, *river*, and *risk* aligns with the highest-frequency codes (e.g., *Community DRR*, *Emergency Preparedness*). Terms like *need*, *local*, *working*, and *time* further reflect an operational focus and resource constraints.

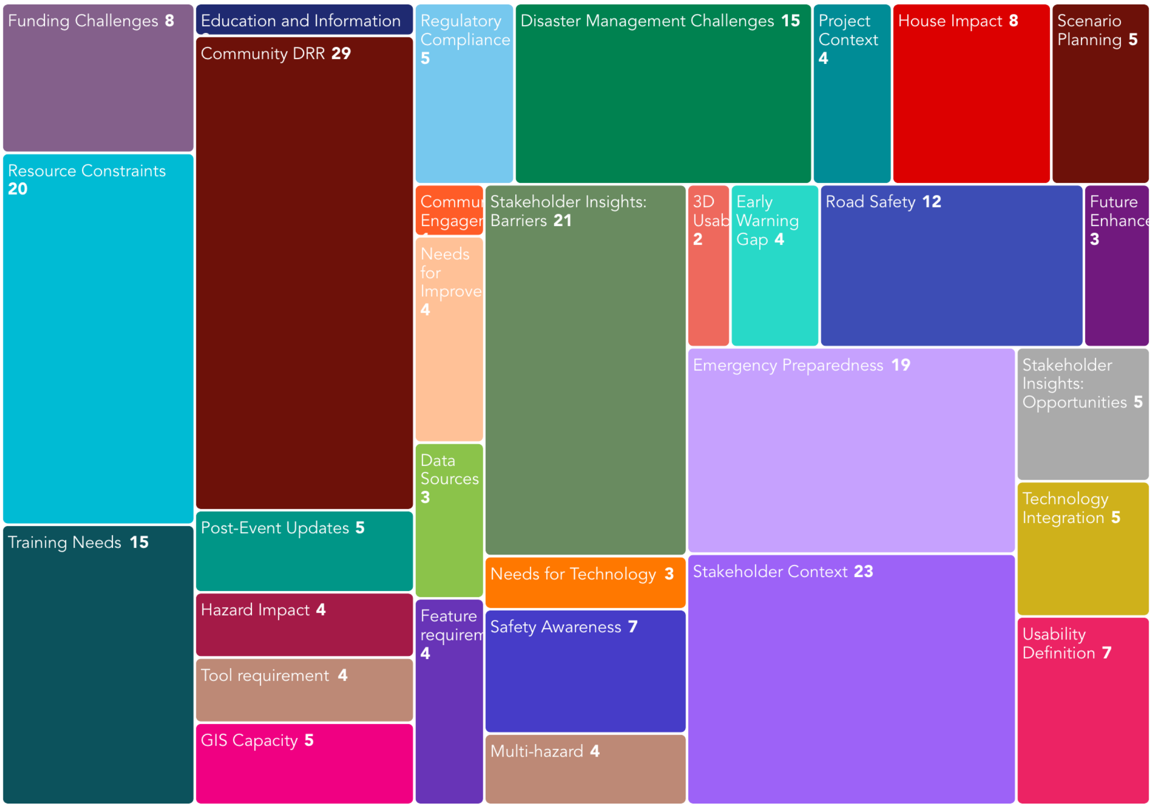


Figure 5.1: The treemap of code frequency over interview verbatim.

The word cloud is shown as descriptive context to illustrate interview vocabulary. Substantive interpretation relies on coded quotations, frequencies, and coverage. The code used to generate this word cloud can be found in the Appendix A.7.

5.1.2 (i) What are the functional needs and expectations of local stakeholders (meteorological staff, disaster managers, planners) for a Digital Twin platform?

During the interview with the public planning department, the stakeholder expressed that their primary objective is emergency preparedness.

"Well, our goal is during events like hurricane. That's especially the worst one we have in this region. Not to have losses, no people, no houses, no buildings. So to stay safe during the event and start again." - S3

However, despite this, there is currently no early warning system used in Dominica. Warnings are issued only after a flood happens, according to the GIS officer from the Dominica Meteorological Service.

"...so we do not really alert the community when a flood is expected or is going to occur. It's always after the fact when a flood is occurring is then we [are] issuing a warning that a flood is occurring but it's nothing before that. So we do not really give an early warning." - S1

Figure 5.2: The Sankey Diagram of code-document distribution.

For flood mapping, stakeholders need to go to the field to measure the extent of the damage, which shows limited use of digital tools for flood early warning.

"... Well, we do not really have [tools], it's only after [flooding]. Afterwards, we could go on the field and see where the river actually extended to and then try to get the coordinates of the extent of the rivers, and put it on the map to see which areas are most vulnerable or more at risk to the flooding." - S1

When asked which tools they use to make these maps, the stakeholder mentioned QGIS, but with very limited capacity:

"QGIS. ... we don't have a GIS unit. So it's probably one or two people that are trained in QGIS.

Figure 5.3: Word cloud of stakeholder interviews.

... I'm one of those that do a little mapping. Not much. So I'm one of those that are trained in the field ... trained in QGIS." - S1

These conversations reveal a need for tools that can be operated by personnel without specialized GIS or hydraulic modeling expertise, thereby lowering the workload on the limited number of people working on flood risk communication.

When it comes to 3D visualization, stakeholders also expressed how 3D visualization could potentially help with their current workflow, especially for visualizing flood depth, ideally, parameterized with a hypothetical scenario, to see the extent of the damage.

"... if we have a certain amount of [heavy storm], I don't know, [let's say] 100 millimeters of rainfall, in maybe an hour, we could know how high the water would get." - S1

Furthermore, the stakeholder questionnaire survey carried out in April 2024 within the ESA EO4MULTIHAZARDS project reinforced this, revealing a clear preference among 90% of respondents for interactive 3D visualizations over static 2D maps for both planning and operational use (van den Bout & Koeva, 2025).

Furthermore, an interview with the Dominica Red Cross stakeholder emphasized the importance of technology integration into their workflows, as well as technical expertise in using these tools.

"...in the development of our hazard maps. Before, you know, we used to just use hand-drawn maps, walk through the communities, and, you know, just get a sketch of the community and actually draw the homes and everything, you know. So now that we have some of our volunteers trained and we use the GIS, we have the GIS tools that we can go out and actually take the coordinates of the houses and then use the technology to produce the maps." - S2

These results directly address the research question, emphasizing the need to create a tool that is novel by being open source with 3D visualization.

5.1.3 (ii) Which data sources, formats, and systems are currently used by the stakeholders, and how should these be integrated with the platform?

Stakeholders reported the use of a variety of tools, including QGIS, which is also mentioned in the previous interview above, for analyzing and mapping data. Furthermore, KoboToolbox is used for data collection.

"Yeah, using Kobo and the other software available to our volunteers, so that helps a lot." - S2

To unify data from these tools, GeoTwin supports loading and displaying building attributes stored as GeoJSON.

However, loading large GeoJSON or Shapefiles has slow load times and high network bandwidth usage, which is a critical requirement for users with limited internet connectivity. According to the stakeholder from the Red Cross, mobile devices are often used for collecting and processing information.

"we train the volunteers, the information is all on their phone, so you don't have to be using the long assessment forms to go out and collect the information, and they could just quickly access, you take a photo, you get all the data." - S2

Therefore, to optimize the delivery of building footprint data, this research utilizes vector tiles in the MBTiles format, generated using the open-source tool Planetiler(Barry, n.d.). This choice was made because vector tiles store geographic data in small, pre-processed chunks, which allows the frontend application to efficiently request and render only the data needed for the current map view and zoom level. The MBTiles file for Dominica, derived from OpenStreetMap, is a self-contained SQLite database that can also be served locally or from a simple web server.

5.2 RQ2: GEOTWIN DESIGN

5.2.1 (i) Which key features and functionalities should GeoTwin provide (e.g., real-time visualization, scenario simulation)?

Section 5.1 first addresses RQ1 by identifying stakeholders' functional needs and expectations: (1) an open-source platform for flood-risk communication; (2) 3D visualization; and (3) a lightweight system.

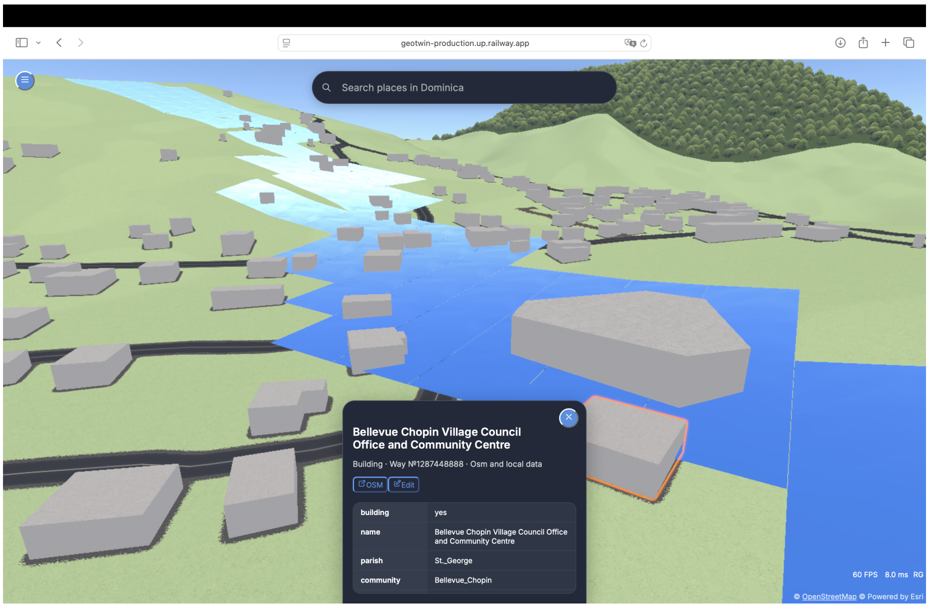
Building on these, GeoTwin focuses on these features: near-real-time visualization for early warning and parameterized flood scenario requests.

Furthermore, another key features that is suggested by the stakeholders is to have building-level impact analysis.

"And which houses that will be flooded or not. ... So, showing which houses are vulnerable is one of, you think, good features that the tool should have." - S1

Based on the stakeholder requirements, along with the literature review, the key features of GeoTwin include:

Near-real-time 3D visualization: GeoTwin supports 3D flood rendering on the fly, incorporating near-real-time data from FastFlood, see Figure 5.4.



Bellevue Chopin Village Council Office and Community Centre

Building · Way №1287448888 · Osm and local data

building	yes
name	Bellevue Chopin Village Council Office and Community Centre
parish	St._George
community	Bellevue_Chopin

Figure 5.4: Flooding rendered in 3D scene.

Scenario parameters: The panel allows users to run a pre-defined demonstration of flood simulation in the Grand Bay area, as shown in Figure 5.5. Moreover, the panel also allows users to manually select simulation parameters, including rain intensity, storm duration, sea level rise, river flow rate, return period, and resolution, see Figure 5.6.

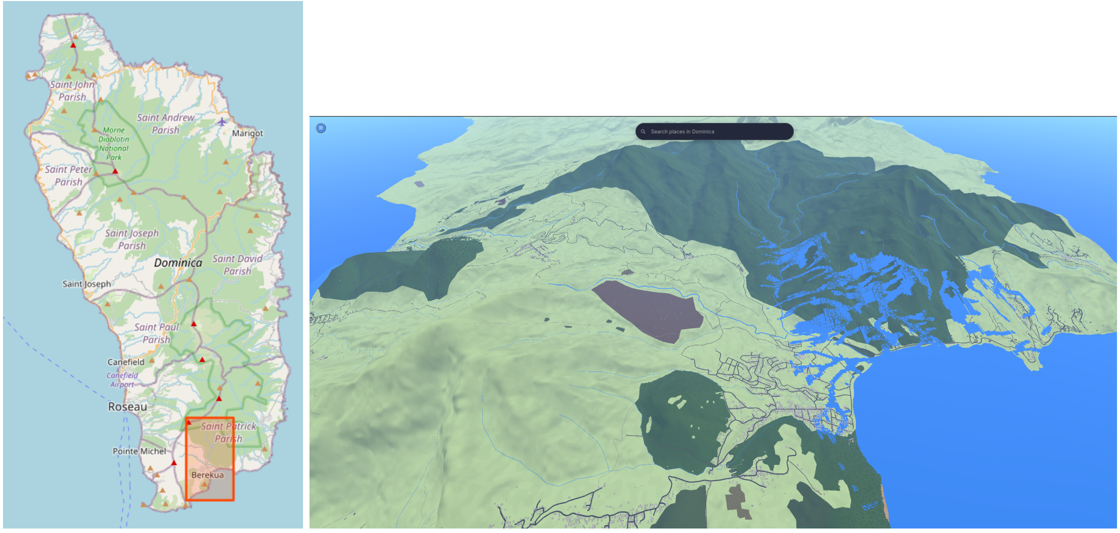
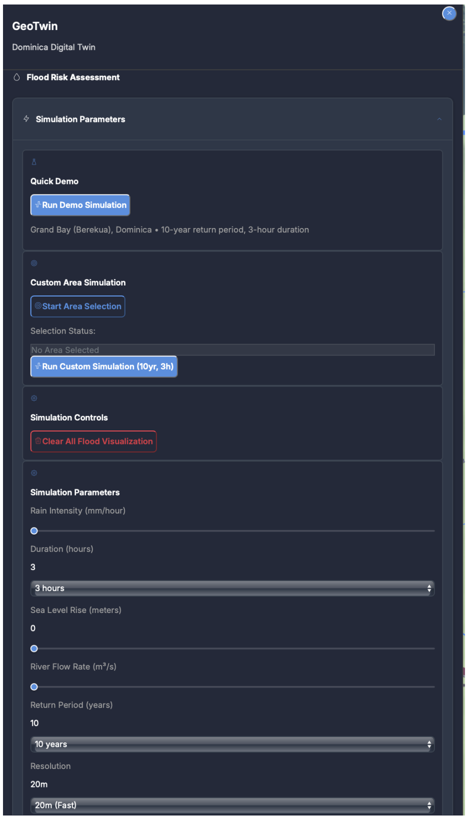


Figure 5.5: A demonstration of flood simulation in Grand Bay area, shown in GeoTwin.

On Click Building Information: This feature of GeoTwin displays the on-click information



Grand Bay (Berekua), Dominica • 10-year return period, 3-hour duration

Selection Status: No Area Selected

Rain Intensity (mm/hour)

Duration (hours): 3 — 3 hours

Sea Level Rise (meters): 0

River Flow Rate (m^3/s)

Return Period (years): 10 — 10 years

Resolution: 20m — 20m (Fast)

Figure 5.6: GeoTwin simulation parameter panel.

of every Dominican building, including the occupancy type, roof type, roof shape, and construction type, as displayed in Figure 5.4.

Impact analysis: Buildings at risk and other exposure metrics are aggregated from the computed flood grid. Figure 5.7 shows the panel with key impact information. The final output can also be exported as PDF files with the building way ID (unique building identifier used in OSM).

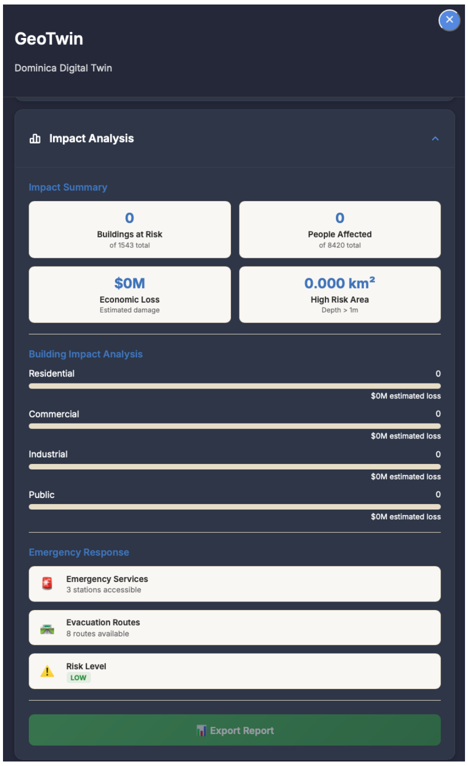
5.2.2 (ii) How can GeoTwin integrate diverse geospatial and hydrological datasets into a unified 3D environment?

GeoTwin implements a client-side workflow summarized as follows:

FastFlood outputs: The client posts a simulation request (run-and-wait). From the returned file list, `whout.tif` (water height) is downloaded as an ArrayBuffer and decoded into per-pixel depths, dimensions, and bounding box.

Flood grid: Each flooded pixel is converted to one world-space quad (two triangles) with a single flood depth value, using the GeoTIFF bounding box and pixel indices to compute coordinates in projected meters. Edge cells are tagged via 8-neighbor checks and shallow edges are clamped minimally for visibility.

Elevation: Terrain tiles are fetched from ESRI's ArcGIS REST ImageServer (WorldElevation3D/Terrain3D) and decoded with LERC to build ring-based height textures in the renderer.



GeoTwin
Dominica Digital Twin

Impact Analysis

Impact Summary

0
Buildings at Risk
of 1543 total

0
People Affected
of 8420 total

$0M
Economic Loss
Estimated damage

0.000 km²
High Risk Area
Depth > 1m

Building Impact Analysis

Residential 0
$0M estimated loss

Commercial 0
$0M estimated loss

Industrial 0
$0M estimated loss

Public 0
$0M estimated loss

Emergency Response

Emergency Services
3 stations accessible

Evacuation Routes
8 routes available

Risk Level
LOW

Figure 5.7: GeoTwin impact analysis panel.

Rendering: For each flooded cell, a terrain-conforming projected mesh is built (height = floodDepth) and positioned at the cell center with a small vertical offset to prevent z-fighting. Buildings and context layers are rendered alongside for interpretation.

Development Environment & Deployment Stack

The front end is a React (TypeScript) single-page application with a custom WebGL2 rendering engine; GeoTIFFs are downloaded as ArrayBuffers and decoded client-side, with a small proxy/microservice used for GeoTIFF processing where needed. The user interface components are sourced from the Mantine UI library, selected for its comprehensive set of accessible and customizable components. The build system utilizes Webpack 5 to bundle the TypeScript and React code into optimized static assets for the browser.

The backend consists of a lightweight proxy server built with Node.js, which handles communication with the external service, the FastFlood API. The app can be containerized (Docker) for deployment.

This full-stack, open-source approach is a self-contained, easily distributable, and sustainable platform that does not impose licensing costs or proprietary dependencies on its users. Moreover, GeoTwin can be easily reproduced for a different area by providing corresponding area datasets in MBTile format.

In summary, the technology stack used in GeoTwin is in Table 5.1.

Table 5.1 GeoTwin Technology Stack

Component	Technology/Library	Purpose in GeoTwin
Frontend Framework	React	Core library for building the user interface
Language	TypeScript	Provides static typing for robust, scalable code
3D Graphics API	WebGL2	Low-level API for GPU-accelerated 3D rendering in the browser
UI Components	Mantine UI	Provides a comprehensive set of accessible UI components
State Management	Recoil	Manages application state in a scalable way
Backend Runtime	Node.js	Runs the backend proxy server for API communication
Module Bundler	Webpack	Bundles and optimizes frontend code for production
Containerization	Docker	Packages the application for consistent deployment

Data Integration and Preprocessing Pipeline

The data integration pipeline is implemented through a series of specialized modules designed to handle differences in formats, coordinate reference systems, and spatial resolution across vector, raster, and elevation data.

Vector Data Processing: Building footprints and infrastructure layers are sourced from OpenStreetMap (OSM) and local GeoJSON files. These datasets are reprojected to Web Mercator (EPSG:3857) and processed to generate 3D mesh geometries through vertical extrusion based on attribute-derived or DEM-estimated building heights. For performance and scalability, vector layers are converted into MBTiles format using Planetiler (Barry, n.d.). This tiled SQLite format enables the frontend to load only features within the viewport, optimizing browser-based rendering (Ali, 2025).

Elevation Data: Terrain elevation is retrieved from ESRI's public WorldElevation3D/Terrain3D services as tiled heightmaps. These are processed into GPU-ready texture arrays and used in real-time by terrain and flood shaders to accurately render topography in the 3D scene.

Flood Raster Data: Hazard data from the FastFlood API arrives as GeoTIFF rasters, which encode water depth per pixel. These are processed client-side in the browser using the `geotiff.js` library. Upon receipt, the `whout.tif` is decoded to access band 0 as water depth, along with width, height, and bounding box. Pixels above a 0.001 m threshold are converted to world quads, and the flood depth values are stored in a `Float32Array`. This array is then used to generate a terrain-following flood surface through the rendering engine (see Algorithm 3). This client-side processing avoids server bottlenecks and enables fast feedback during scenario exploration.

All datasets are harmonized into the Web Mercator projection to ensure alignment in the 3D viewer. The pipeline is designed to support automated ingestion and processing, allowing the platform to respond rapidly to updated data and simulation results.

Algorithm 3: Client-side flood raster to world grid

```
Input: waterHeightRaster, width, height, bbox = [minX, minY, maxX, maxY]
Output: floodCells (list of quads with depth)
floodCells ← [ ];
cellWidth ← (maxX - minX)/width;
cellHeight ← (maxY - minY)/height;
for $y \leftarrow 0$ to $height - 1$ do
    for $x \leftarrow 0$ to $width - 1$ do
        $d$ ← waterHeightRaster[$y \cdot width + x$];
        if isfinite($d$) and $d > 0.001$ then
            worldMinX ← minX + $x\cdot$ cellWidth;
            worldMaxX ← minX + $(x+1)\cdot$ cellWidth;
            worldMinY ← maxY - $(y+1)\cdot$ cellHeight;
            worldMaxY ← maxY - $y\cdot$ cellHeight;
            edge ← isEdge(x,y);
            depth ← edge ? $\max(d, 0.0015)$ : $d$;
            floodCells.append(quad(worldMinX,worldMinY,worldMaxX,worldMaxY,
              depth));
```

HuggingFloodPlane Terrain-Conforming Flood Mesh System

Each flooded pixel is represented as one projected mesh tile (two triangles) positioned at the pixel's world-space center: - height parameter = floodDepth, - final elevation at render time $= H_{\text{terrain}}(x, z)$ + floodDepth + ϵ, - $\epsilon \approx 0.01$ m to prevent z-fighting.

This process ensures that the flood surface "hugs" the terrain with sub-meter accuracy, showing how water fills valleys, flows around hills, and interacts with topographic features. A visualization of flood rendering over a terrain is in Figure 5.8.

Rendering Engine

The GeoTwin visualization is powered by a custom real-time rendering engine built with WebGL2. The engine is designed for high-performance rendering of large-scale geospatial scenes and incorporates several advanced graphics techniques and optimization strategies.

The engine uses a Physically Based Rendering (PBR) pipeline to achieve a high degree of visual realism. PBR simulates the physical properties of light and materials, using textures for albedo (base color), normal (surface detail), roughness, and metalness to create more intuitive and believable scenes (Pharr et al., 2004). This is crucial for stakeholder buy-in, as a more realistic representation of their environment can enhance their understanding and trust in the simulation.

Moreover, the renderer uses:

- a terrain/hugging projection path for terrain-conforming objects (roads, flood tiles),

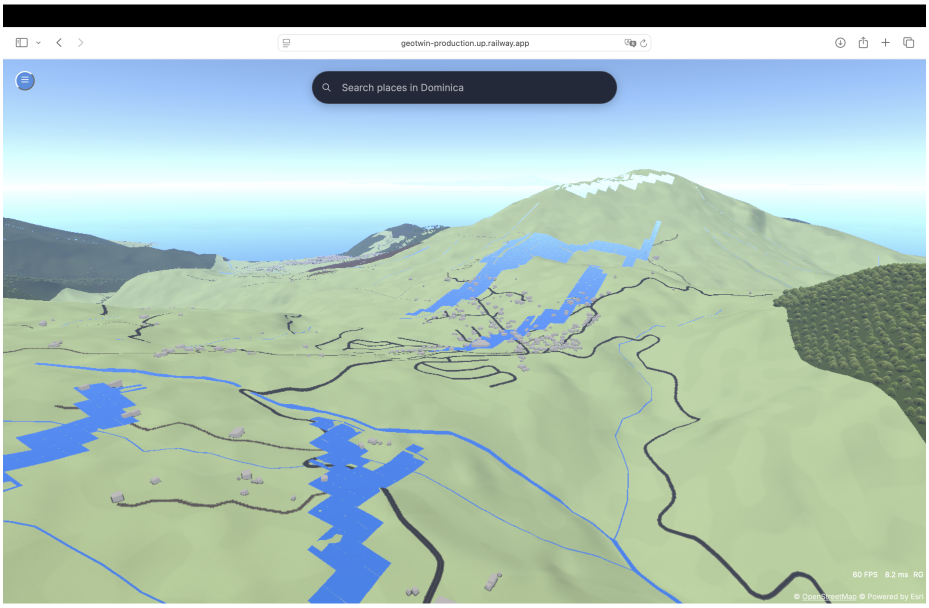


Figure 5.8: Flood tile rendering over a terrain.

- ESRI-derived ring height textures sampled in shaders,
- water material and other shaders from ShaderToy [1] for flood visualization,
- 3D artifacts from steam [2],
- a building LOD system to manage detail and memory.

To maintain interactive frame rates (targeting 60 FPS), the engine implements several critical optimization strategies:

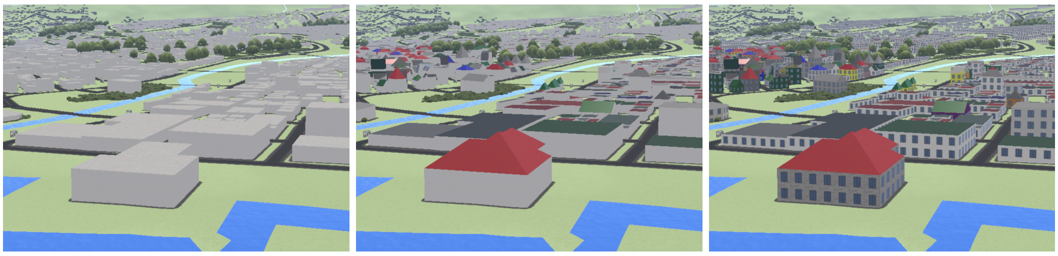
- **Frustum Culling:** Objects outside the camera's current view are not sent to the GPU for rendering, dramatically reducing the processing load. This strategy comes from the library used within WebGL.
- **Level of Detail (LOD):** A three-tier LOD system is implemented for buildings as shown in the Figure 5.9. At a distance (LOD 1), buildings are rendered as simple, untextured blocks. At mid-range (LOD 2), they are rendered with correct roof shapes but simplified facades. Up close (LOD 3), they are rendered with full detail and PBR materials. This dynamic simplification significantly reduces the number of polygons per frame.
- **Texture Streaming and Caching:** A TexturePool system manages the loading and unloading of high-resolution textures based on their visibility and distance from the camera. This prevents the GPU memory from being overloaded with textures that are not currently needed, a critical factor for running on hardware with limited VRAM. A custom feature adapted from the Three.js library.

---

[1] https://www.shadertoy.com

[2] https://steamcommunity.com/app/255710/workshop/

- **Batch Instancing:** Repetitive objects, such as trees, are rendered using GPU instancing. This technique allows thousands of instances of the same object to be rendered in a single draw call, dramatically reducing the communication overhead between the CPU and GPU(see Algorithm 4 for the instanced rendering workflow). This optimization is modified and adapted from the Three.js library.



(a) LOD1 (b) LOD2 (c) LOD3

Figure 5.9: LOD Tiers for Building Rendering in GeoTwin.

Algorithm 4: Batched Rendering Workflow for Instanced Objects

```
Input: scene: The current 3D scene graph
Input: camera: The active camera object defining the view frustum
foreach objectType ∈ {trees, streetlights} do
    visibleInstances ← empty list;
    foreach instance ∈ scene.getInstances(objectType) do
        if camera.isInFrustum(instance.boundingBox) then
            visibleInstances.append(instance);
    instanceDataBuffer ← CREATEBUFFERFROM(visibleInstances);
    UPDATEGPUBUFFER(objectType.instanceBuffer, instanceDataBuffer);
    DRAWELEMENTSINSTANCED( objectType.mesh, instanceCount =
      len(visibleInstances) );
```

Integration with FastFlood API

The client submits a run-and-wait request with parameters (return period, duration, optional rain/ocean/flowRate, resolution, projected bbox). From the returned file list, `whout.tif` is selected and downloaded as an ArrayBuffer. The GeoTIFF is decoded (client-side; proxy fallback exists if needed), the flood grid is generated, and terrain-conforming tiles are created and rendered, as shown in the Algorithm 5. An example of area selection and visualization of FastFlood output is shown in Figure 5.10.

Algorithm 5: FastFlood → decode → render → impact

```
Input: params: return_period, duration, resolution, bbox, [rain, ocean, flowRate]
Output: updated scene and metrics
files ← runAndWait(params);
url ← select(files, “whout.tif”);
buf ← download(url);
raster ← decodeGeoTIFF(buf);
floodCells ← rasterToWorldGrid(raster);
buildProjectedMeshes(floodCells);
updateImpactMetrics(floodCells);
```

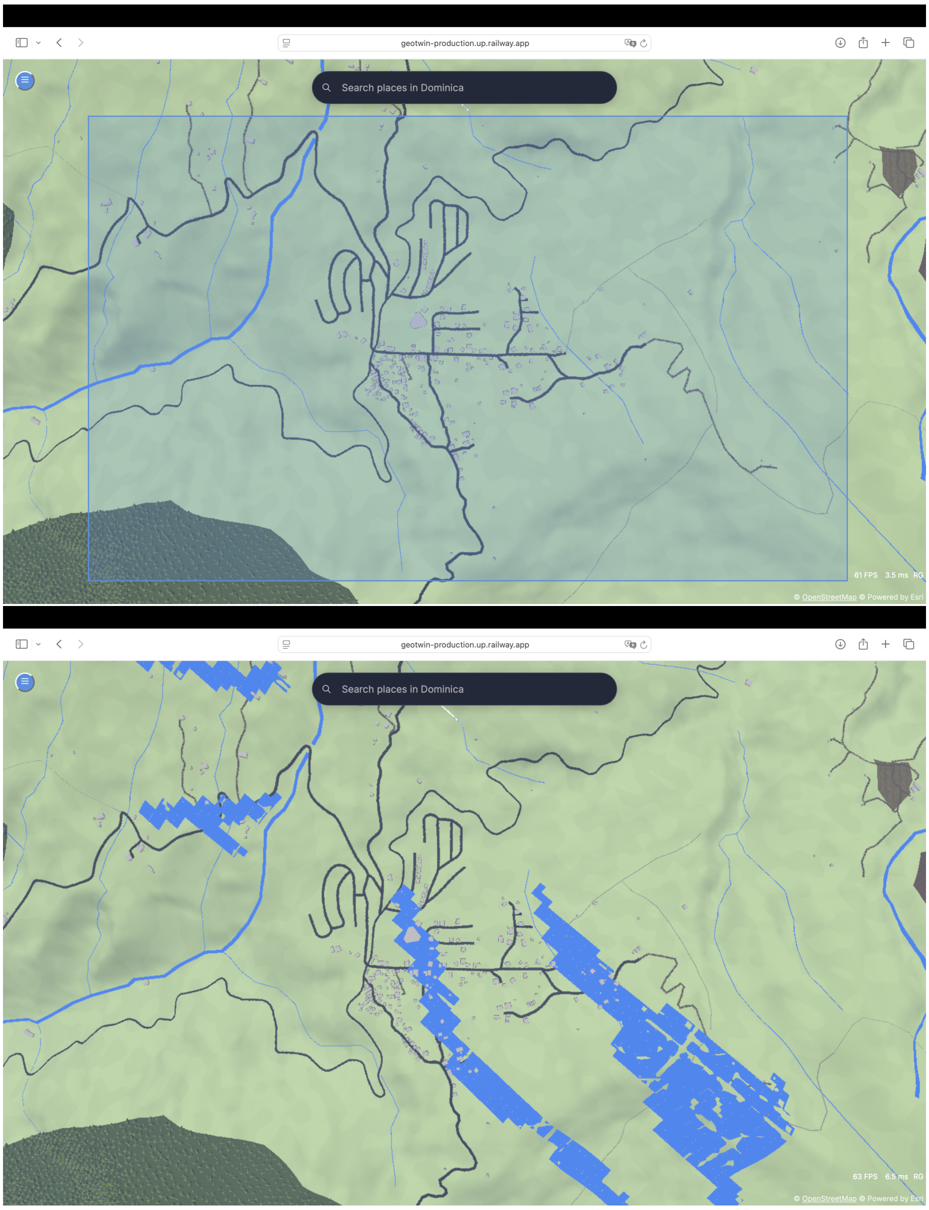
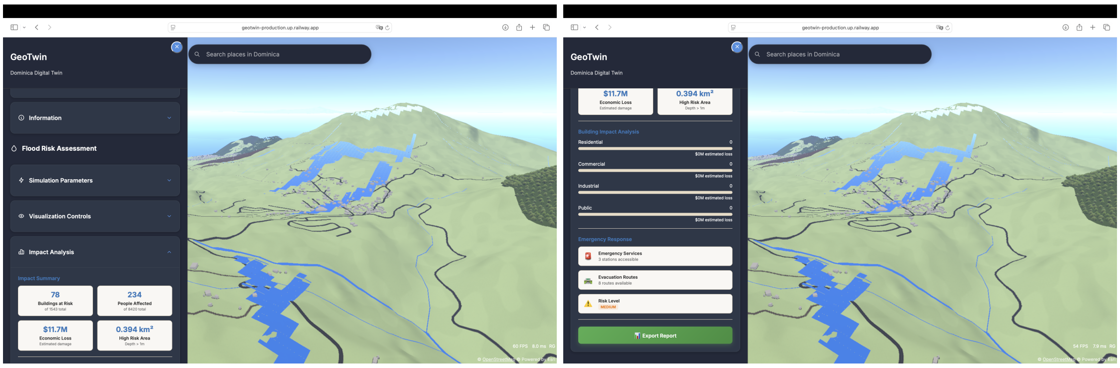


Figure 5.10: FastFlood integration pipeline visualization.

5.2.3 (iii) How does GeoTwin support decision-making workflows for flood impact assessment and mitigation?

Impact screening is computed from the flood grid. For each flooded cell, the system queries buildings near the cell's center (and corners if needed), attaches any found to that cell, and aggregates exposure metrics for the dashboard. One example of impact analysis and estimation after flood simulation is shown in Figure 5.11. Furthermore, a generated PDF report can be found in Appendix A.5, Figure A.10. As a proof of concept, the prototype generates reports that provide decision-makers and flood risk communicators with measurable, easy-to-comprehend results that can be readily shared with local stakeholders to raise awareness.



78 Buildings at Risk of 1543 total

234 People Affected of 8420 total

$11.7M Economic Loss Estimated damage

0.394 km² High Risk Area Depth > 1m

Residential 0 $0M estimated loss

Commercial 0 $0M estimated loss

Industrial 0 $0M estimated loss

Public 0 $0M estimated loss

Emergency Services 3 stations accessible

Evacuation Routes 8 routes available

Risk Level MEDIUM

Figure 5.11: Impact analysis and export sections in panel.

5.3 RQ3: EVALUATION AGAINST EXISTING SOLUTIONS

The evaluation of GeoTwin is twofold. First, its performance and features are compared against established commercial and specialized 3D flood visualization platforms to benchmark its technical novelty and utility. Second, feedback from stakeholders provides a qualitative assessment of its perceived strengths, weaknesses, and potential future enhancements.

5.3.1 (i) How does GeoTwin perform in terms of spatial accuracy, usability, and efficiency compared to current 2D GIS dashboards and Digital Twin platforms?

As established through stakeholder interviews, the primary tool for flood risk visualization in Dominica is QGIS, used to create static, 2D maps that are typically distributed as PDFs after an event. While effective for reporting, this method lacks the interactivity and predictive capabilities needed for preparedness and early warning, a gap that stakeholders explicitly identified.

GeoTwin provides an interactive 3D environment for scenario-based analysis. To evaluate its position among other 3D platforms, GeoTwin was compared against three leading solutions in the flood risk management sector: ESRI's ArcGIS platform (specifically its 3D visualization capabilities), Tygron, and 3Di. The comparison, summarized in Table 5.2, focuses on key architectural and accessibility differences.

A fundamental distinction lies in the rendering architecture. Commercial platforms like Tygron and 3Di perform the intensive hydrodynamic calculations and 3D rendering on powerful

Table 5.2 Comparative Analysis of Flood Visualization Platforms (focus: 3D flood visualization)

Feature	GeoTwin	ESRI ArcGIS	Tygron	3Di
Architecture	Client-side WebGL2 (browser)	Desktop (Pro), Server (Enterprise), SaaS/browser (Online)	Desktop client + cloud/SaaS; web interfaces	Browser (3Di Live) + desktop (QGIS Modeller); server compute
Licensing	Open-source (MIT)	Proprietary (licenses/subscription)	Proprietary (SaaS)	Proprietary (subscription)
Core function	3D flood visualization	Full GIS suite incl. 3D Scene Viewer	Urban planning & simulation (incl. water/flood)	Hydrodynamic modeling & visualization
Accessibility	Browser; no install	Browser & desktop; license/subscription	Desktop client & web; subscription	Browser (Live) & desktop (Modeller); subscription
Data integration	GeoJSON, vector tiles	OGC (WMS/WFS/WMTS/WCS, OGC API–Features), GeoPackage, GeoJSON (tools), shapefile, rasters; Esri geodatabases	GeoJSON; WFS/WMS; GeoTIFF; CityGML; I3S/SLPK; ArcGIS links	QGIS vectors/rasters for models; outputs NetCDF (CF), GeoTIFF
3D performance / efficiency	Client-side WebGL2; lightweight	Large or unoptimized web scenes, or running without browser GPU hardware acceleration, can render slowly.	Rendering city-scale 3D scenes in the Tygron Client can be slow on machines without a discrete GPU; the vendor strongly advises a GeForce RTX 3050 or better.	Enabling many detailed layers (e.g., manholes) and zooming out can degrade performance and make the browser viewer slow.

server-side GPUs. The user's browser acts as a thin client, streaming the resulting video or rendered frames. This approach allows for highly accurate fluid dynamics animations but introduces significant costs, reliance on high-speed internet, and a proprietary "black box" environment.

In contrast, GeoTwin clearly operates entirely on the client-side, leveraging the user's local GPU via WebGL2. This design choice makes it fundamentally different:

- **Open-Source and Free:** Eliminates licensing fees, a major barrier identified by stakeholders (*Funding Challenges*).
- **Lightweight and Accessible:** Runs in any modern web browser without requiring powerful servers, specialized software installations, or high-bandwidth streaming.
- **Transparent and Adaptable:** The open-source nature allows for local adaptation and integration with other tools, empowering local experts rather than creating dependency on a single vendor.

While GeoTwin does not perform hydrodynamic simulations itself, it serves as a powerful, open-source platform for visualizing the outputs of external models like FastFlood, democratizing access to 3D flood risk insights.

5.3.2 (ii) What are the perceived strengths, weaknesses, and adoption barriers identified by stakeholders during evaluations?

During the development process, an early version of GeoTwin was presented to stakeholders. The feedback was instrumental in shaping the final prototype. The primary strength identified was its visual interactivity and 3D perspective, which was perceived as a significant improvement over static 2D maps. Stakeholders noted that the ability to "see" the potential height of water against familiar buildings and landmarks would be a powerful communication tool. As S1 from the Meteorological Service noted, a key need is to know *"how high the water would get"* for a given rainfall scenario, a question the 3D visualization directly answers.

However, stakeholders also identified critical adoption barriers. The most prominent was the concern over reliable internet connectivity, especially in rural areas or during a disaster. The reliance on a web-based platform, while accessible, is a potential weakness. Furthermore, while GeoTwin is designed to be user-friendly, stakeholders emphasized the need for continuous training and support to build technical literacy and ensure the tool is used effectively. Long-term sustainability, including platform maintenance and data updates, was also raised as a concern.

This feedback highlights that while the technology itself is a strength, successful adoption hinges on addressing the surrounding socio-technical context, including infrastructure, training, and institutional support.

5.3.3 (iii) Which future enhancements are prioritized by end users for improving flood resilience?

Stakeholder feedback and ESA workshop discussions pointed to several clear priorities for future development. These enhancements aim to evolve GeoTwin from a scenario-based tool to a more comprehensive, real-time, and multi-hazard risk management platform.

The most frequently requested enhancement was real-time sensor integration. Stakeholders expressed a strong desire to connect the platform to live data streams from rainfall gauges and river level sensors. This would enable the digital twin to reflect current, real-world conditions, transforming it into a genuine early warning system that could trigger alerts based on live data, moving beyond pre-computed scenarios.

Second, stakeholders suggested designing the platform to incorporate multi-hazard analytics. While the current focus is on flooding, Dominica faces a complex risk landscape that includes landslides, seismic activity, and hurricanes. Users prioritized the addition of landslide susceptibility layers and the ability to visualize the potential for cascading events, such as heavy rainfall triggering both floods and landslides.

Finally, a key priority was interoperability with existing systems. Stakeholders, particularly from the planning and emergency response sectors, emphasized the need for a platform to connect with their inventory systems for critical infrastructure (e.g., hospitals, shelters, utilities) and to integrate with emergency telecommunication networks. This would allow the platform to not only visualize physical impacts but also to support logistical planning, such as identifying accessible evacuation routes or assessing the status of critical facilities during an emergency.

5.3.4 Limitations

A critical reflection on the research reveals several methodological and system-level limitations. These constraints define the current boundaries of the work and provide a clear roadmap for future research.

First, the accuracy of the flood hazard visualization is entirely dependent on the outputs of the FastFlood model. This model employs simplifications to achieve computational speed, trading a degree of hydraulic precision for interactivity (van den Bout et al., 2023). This can result in a "pixelated" or grid-like appearance of the floodwater, as shown in Figure 5.12, which does not represent the fluid nature of water. Consequently, the results are best suited for strategic planning and rapid response scenarios, not for detailed engineering design.

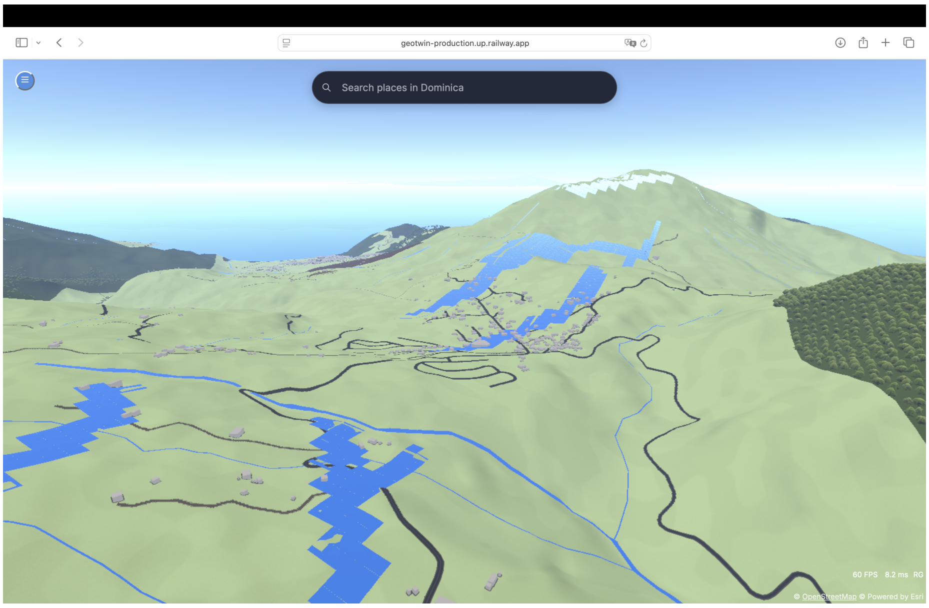


Figure 5.12: Example of pixelated flood visualization due to the underlying raster data from the hydrodynamic model.

Second, the impact analysis is currently limited to physical exposure. It does not yet incorporate socio-economic vulnerability data to model differentiated impacts on various population groups. Integrating such layers is a critical next step. This research is part of the broader ESA EO4MULTIHAZARDS project, which aims to advance multi-risk assessment by combining EO data with local knowledge [Deliverable D4.1 of the ESA-funded project EO4MULTIHAZARDS]. Future work could integrate the detailed building stock, roof type, and economic cost data being developed by other researchers within the project to create a more holistic and equitable risk assessment.

Third, the current prototype does not yet integrate real-time sensor data. While the architecture is designed to accommodate such streams, its absence means the platform operates in a scenario-based mode rather than as a true real-time monitoring system. This represents a key step in advancing the tool's maturity.

Fourth, due to logistical constraints, it was not possible to conduct extensive, longitudinal user analytics to formally measure the platform's impact on decision-making processes over time. The stakeholder feedback, while positive, is primarily qualitative and based on interview interactions.

Finally, it is crucial to clarify GeoTwin's role as a Digital Twin. According to the OASCITIES MIM framework (oascities, n.d.), a Local Digital Twin "leverages either historical data, near real-time data, or real-time data, enabling visualization, analysis, simulation, and reasoning for supporting decision-making." GeoTwin clearly falls within this definition. However, it is a visualization and integration platform, not a hydrodynamic solver. It is designed to consume, process, and intuitively display the outputs of external models; it does not perform the complex fluid dynamics calculations itself. This distinction is fundamental to its lightweight, accessible design and is a deliberate architectural choice, not a duplication of the first limitation regarding model accuracy.

Chapter 6

Discussion

6.1 GEOTWIN GEMINI PRINCIPLES ANALYSIS

This research developed GeoTwin, a 3D digital twin prototype designed to support flood risk management in Dominica. This work is situated within the broader context of the European Space Agency (ESA) EO4MULTIHAZARDS project, which aims to advance multi-risk assessment by integrating Earth Observation data with local stakeholder knowledge [Deliverable D4.1 of the ESA-funded project EO4MULTIHAZARDS]. The need for such a tool was identified through ongoing collaboration within the project, and its development was pushed forward through the combined work on building stock characterization, risk analysis, and visualization. This chapter discusses the outcomes of the GeoTwin implementation, evaluated through the lens of the Gemini Principles, and reflects on the findings and their implications for disaster risk management in Small Island Developing States (SIDS).

6.2 EVALUATION AGAINST THE GEMINI PRINCIPLES

To provide a structured evaluation, the GeoTwin framework is assessed against the Gemini Principles: Purpose, Trust, and Function (Centre for Digital Built Britain, 2018). These principles offer a framework for evaluating a digital twin's value beyond its technical specifications.

6.2.1 Purpose: A Tool Forged by Need

The Gemini Principles state that a digital twin must have a clear purpose that delivers tangible benefits. GeoTwin's purpose was directly shaped by the operational needs identified during fieldwork with stakeholders in Dominica. The interviews revealed a critical gap: the need to translate meteorological data into actionable, visual insights. The statement from the Dominica Meteorological Service official, questioning what would happen *"if we have a certain amount of... 100 millimeters of rainfall"*, highlights the demand for a tool that can answer predictive, scenario-based questions. This is further supported by the stakeholder questionnaire, where 90% of respondents preferred interactive 3D visualizations over static 2D maps (van den Bout & Koeva, 2025). GeoTwin's purpose is therefore a direct response to these needs: to provide a platform for visually exploring "what-if" flood scenarios.

The Gemini Principles

Purpose: Must have clear purpose	**Public good** Must be used to deliver genuine public benefit in perpetuity	**Value creation** Must enable value creation and performance improvement	**Insight** Must provide determinable insight into the built environment
Trust: Must be trustworthy	**Security** Must enable security and be secure itself	**Openness** Must be as open as possible	**Quality** Must be built on data of an appropriate quality
Function: Must function effectively	**Federation** Must be based on a standard connected environment	**Curation** Must have clear ownership, governance and regulation	**Evolution** Must be able to adapt as technology and society evolve

Figure 6.1: Digital Twins Gemini Principle*Source: Centre for Digital Built Britain, 2018.*

6.2.2 Trust: Transparency and Acknowledged Limitations

Trust requires that a digital twin be open and provide data of sufficient quality for its intended use. GeoTwin builds trust through two main pillars: its open-source architecture and a clear acknowledgment of its operational limitations.

The decision to build GeoTwin on an open-source stack aligns with Dominica's existing open spatial data infrastructure and removes the financial and dependency barriers associated with proprietary software. This transparency allows for independent verification and fosters local capacity.

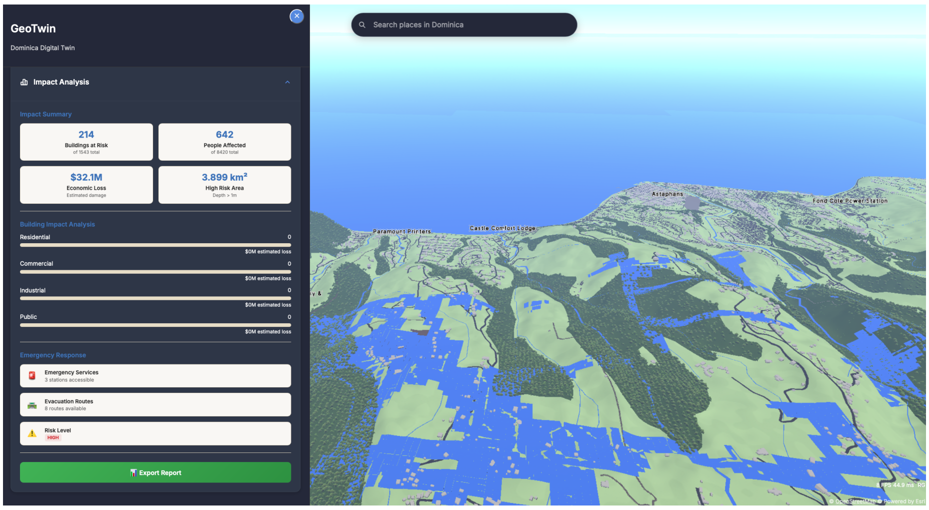
Trust is also maintained by clearly defining the tool's boundaries. The use of the FastFlood API provides the necessary speed for interactive scenarios but involves simplifications compared to more detailed hydrodynamic models (van den Bout et al., 2023). Therefore, GeoTwin is presented as a tool for strategic planning, awareness, and rapid response coordination, not for site-specific engineering design. This clear communication of its intended purpose is essential for building trust with users.

6.2.3 Function: An Integration Platform for Decision Support

A digital twin must function effectively to deliver value. GeoTwin's function is defined by its ability to integrate and visualize diverse datasets within the resource-constrained reality of an SIDS.

As part of the larger ESA project, a key function of the platform is to serve as an integration point for different data sources that are normally shown separately. It successfully combines vector data (building footprints from OSM), raster data (flood depths from FastFlood), and elevation data (DEMs from ESRI) into a single, coherent 3D scene, as shown in Figure 5.12. This integration provides a holistic view that is difficult to achieve with traditional 2D GIS tools.

The platform's functionality is demonstrated through its key features, which were designed based on stakeholder input. Users can select an area, run a flood simulation, and receive building-level impact information and an aggregated impact report (Figure 6.2). Furthermore, the interface also provides on-click building attributes information (Figure 6.3), which can be edited directly on OSM, if the current information is missing or incorrect, as shown in Figure 6.4. These features provide decision-makers with tangible outputs that can be used for planning and communication.



GeoTwin
Dominica Digital Twin

Impact Analysis

Impact Summary

214 Buildings at Risk of 1543 total

642 People Affected of 8420 total

$32.1M Economic Loss Estimated damage

3.899 km² High Risk Area Depth > 1m

Building Impact Analysis

Residential 0 $0M estimated loss

Commercial 0 $0M estimated loss

Industrial 0 $0M estimated loss

Public 0 $0M estimated loss

Emergency Response

Emergency Services 3 stations accessible

Evacuation Routes 8 routes available

Risk Level HIGH

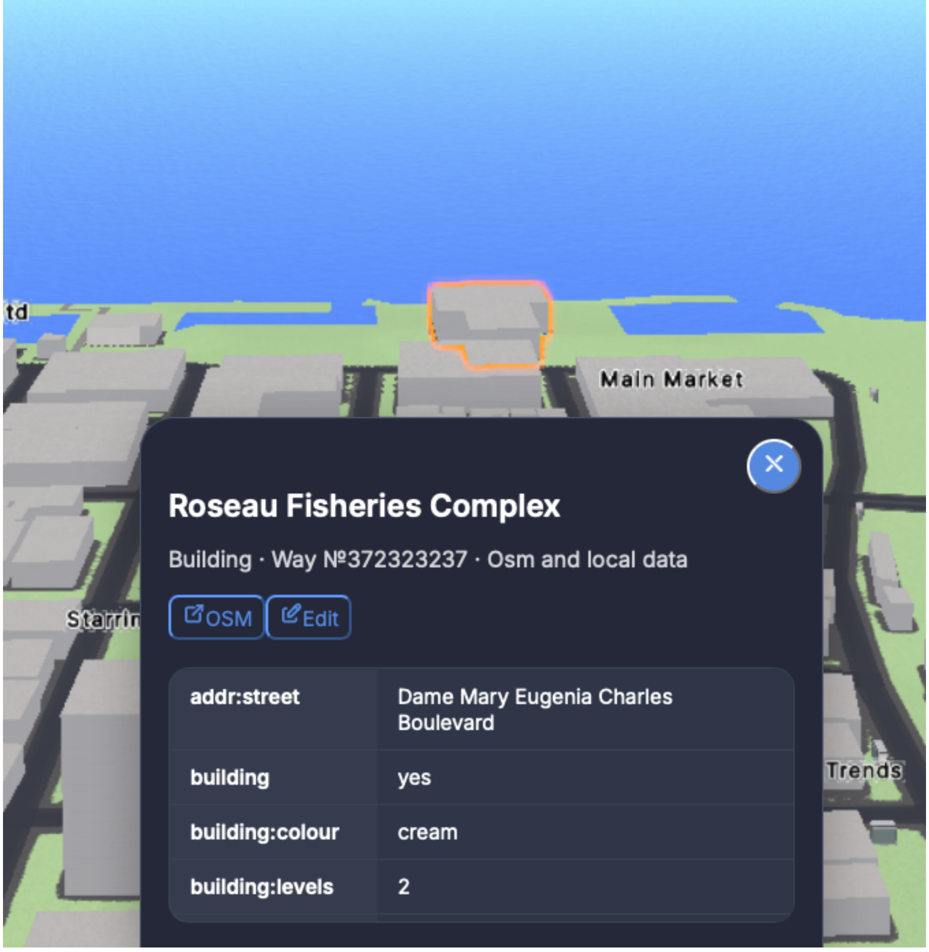
Figure 6.2: The GeoTwin platform interface, showing the 3D visualization of Castle Comfort and surroundings, and the user control panels. (Note: the building impact analysis in the panel is temporarily turned off.)

6.3 FINDINGS AND IMPLICATIONS

The development of GeoTwin provides several findings regarding its potential to assist risk communication workflows and its implications for the use of digital twins in SIDS.

6.3.1 Assisting in Risk Communication

GeoTwin has the potential to assist risk communication from 2D flood visualization to a 3D environment. The current workflow, as described by stakeholders, often ends with a 2D map created post-event. In contrast, GeoTwin offers a web environment where technical and non-technical users can jointly explore parameterized scenarios. This interactivity can foster a more collaborative understanding of risk. The 3D environment makes flood risk more tangible; seeing simulated water against familiar landmarks provides a street-level perspective that can enhance risk perception compared to interpreting 2D maps. This observation aligns with research indicating that 3D



Roseau Fisheries Complex

Building · Way №372323237 · Osm and local data

addr:street	Dame Mary Eugenia Charles Boulevard
building	yes
building:colour	cream
building:levels	2

Figure 6.3: Example of building characterization data available on-click within GeoTwin.

visualizations can improve risk comprehension and engagement (Amirebrahimi et al., 2016).

6.3.2 Accessibility and Transferability

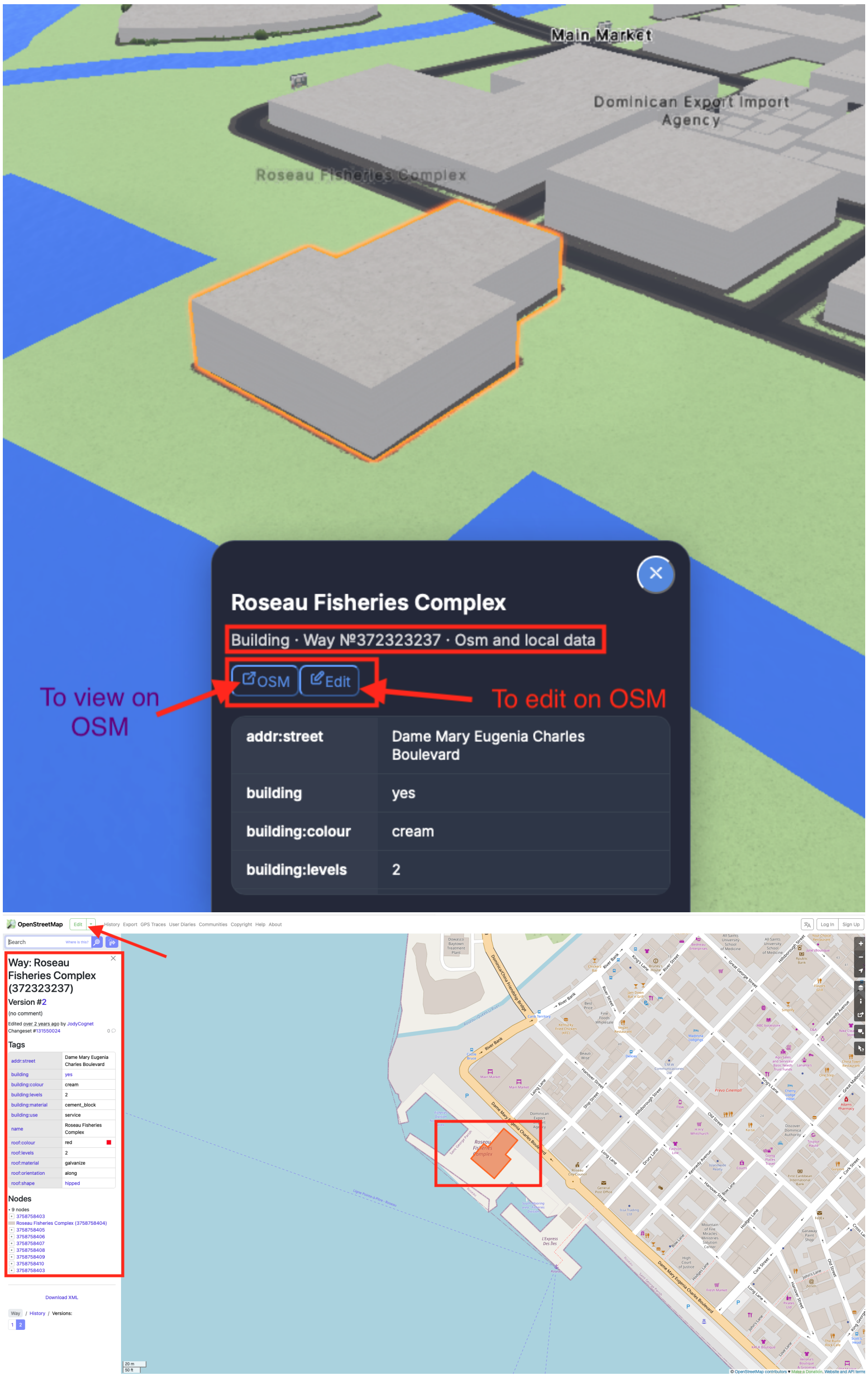
A key finding relates to accessibility. The browser-native, open-source architecture removes some of the financial and technical barriers associated with traditional GIS software. This design democratizes access to advanced visualization tools.

The framework is also designed to be transferable. Setting up GeoTwin for a new area requires a defined series of steps: (i) providing a new vector tile dataset (MBTiles) for the building and context layers. To set this up, stakeholders need to download the latest OSM PBF files, and these can be acquired from places like BBBike [1]. For the users who require dataset from the whole world, these data can be found from places like SNT [2], which are updated daily. After obtaining the datasets, the PBF files can be converted into MBTile format using the planetiler street instance. (ii) defining the new area's bounding box for the FastFlood API. While this current process still

---

[1] https://extract.bbbike.org

[2] https://ftp.snt.utwente.nl/pub/misc/openstreetmap/



Roseau Fisheries Complex

Building · Way №372323237 · Osm and local data

addr:street	Dame Mary Eugenia Charles Boulevard
building	yes
building:colour	cream
building:levels	2

Way: Roseau Fisheries Complex (372323237)

Version #2

(no comment)

Edited over 2 years ago by JodyCognet
Changeset #131550024

Tags

addr:street	Dame Mary Eugenia Charles Boulevard
building	yes
building:colour	cream
building:levels	2
building:material	cement_block
building:use	service
name	Roseau Fisheries Complex
roof:colour	red 🟥
roof:levels	2
roof:material	galvanize
roof:orientation	along
roof:shape	hipped

Nodes

- 9 nodes
  - 3758758403
  - Roseau Fisheries Complex (3758758404)
  - 3758758405
  - 3758758406
  - 3758758407
  - 3758758408
  - 3758758409
  - 3758758410
  - 3758758403

Download XML

Way / History / Versions:
1 2

Figure 6.4: Building information can be *viewed* and *edited* on OSM upon clicking.

requires a certain level of technical expertise to set up, it provides a replicable framework that is significantly more accessible than developing a similar system from scratch. In the future, these steps can be further automated as part of the framework.

6.4 SUMMARY

This research demonstrates the viability of a lightweight, "fit-for-purpose" digital twin model for resource-constrained environments. The findings suggest that a stakeholder-centered approach is critical for ensuring such tools are aligned with the real-world workflows and capacities of their intended users. By doing so, there is potential to foster local ownership and enhance digital self-reliance in disaster risk management.

This chapter has discussed the GeoTwin framework, evaluating it against the Gemini Principles and analyzing its findings. The analysis confirms that the platform is aligned with its intended purpose, builds trust through transparency, and functions effectively in its target environment. The findings highlight the platform's potential to enhance risk communication and data integration by visualizing diverse data sources in a unified 3D scene. By providing an accessible, open-source alternative to proprietary systems, this research offers a replicable model for developing stakeholder-driven digital twins in SIDS and other resource-constrained regions.

Chapter 7

Conclusion

This research identified a critical gap in the flood risk management workflow in Dominica: the difficulty in translating complex hazard data into clear, actionable insights for decision-making. In response, this thesis presents the development and evaluation of GeoTwin, a browser-native 3D digital twin. The work demonstrates a complete, open-source workflow that links rapid flood simulations to an interactive visualization and an integrated impact analysis module, transforming raw hazard data into a usable format for risk communication in Small Island Developing States (SIDS).

The primary scientific achievement of this thesis is the practical implementation of a Digital Risk Twin (DRT), a concept that adapts the digital twin paradigm for the realities of disaster management (Ghaffarian, 2025). GeoTwin functions as a DRT by integrating diverse data sources and prioritizing a human-in-the-loop decision-making process. It is not a fully automated system but a dynamic platform where local experts can explore scenarios and apply their contextual knowledge, a necessity in environments where automated interventions are not feasible (Ghaffarian, 2025; Riaz et al., 2023). The system serves as a bridge, making the outputs of external models like FastFlood visually intuitive and directly usable.

This project's main contribution to flood risk management is the demonstration of a viable, lightweight, and sustainable digital twin model for SIDS. By building a client-side rendering engine, this work challenges the prevailing notion that such tools must be proprietary, costly, and server-heavy. This approach fosters digital self-reliance and local capacity, democratizing access to technology. As part of the collaborative ESA EO4MULTIHAZARDS project, the platform also functions as an integration point, capable of visualizing diverse data on building stock, risk, and economic cost being developed by other researchers, thereby creating a more holistic view of risk [Deliverable D4.1 of ESA funded project EO4MULTIHAZARDS].

While this research successfully developed a functional prototype, the path forward involves maturing GeoTwin into a more comprehensive DRT. Future work should focus on integrating real-time sensor data to enhance early warning capabilities, incorporating socio-economic vulnerability data to move beyond physical exposure analysis, and expanding its functionality to address the multi-hazard landscape of Dominica, including landslides. The ultimate vision is a platform that adapts in near real-time to the evolving nature of a disaster.

In conclusion, this thesis presents a validated methodology for a "fit-for-purpose" digital twin. It proves that by prioritizing purpose, embracing openness, and designing for the user's reality, it is possible to build powerful systems that enhance resilience. GeoTwin provides a robust, open foundation for flood risk communication, offering a clear answer to the need for tools that help us better see, understand, and act upon the risks we face.

Chapter 8

Ethical Considerations

This research was done for academic purposes as part of a Master of Spatial Engineering thesis at the University of Twente, and as a contribution to the European Space Agency (ESA) EO4MULTIHAZARDS project. The main goal is scientific advancement and an open-source tool for disaster risk management in Small Island Developing States (SIDS).

All research activities involving human participants, including the unstructured stakeholder interviews, were conducted according to the ethical guidelines of the University of Twente. The research plan and protocols were approved by the Faculty's ethics committee (Geo-Information Sciences), as documented in application 250254.

Informed consent was obtained from all participants before the interviews started. Participants were made aware that their involvement was voluntary and that they could withdraw at any time without consequence. To ensure confidentiality and prevent any professional or personal conflicts, all interview transcripts and quotes used in this thesis have been anonymized, with stakeholders referred to only by a generic identifier (e.g., S1, S2).

The data collected, including interview recordings and transcripts, is stored on the University of Twente's cloud infrastructure, according to university and GDPR data protection standards. The analysis is at the institutional and community level and does not include personal or household level information. Furthermore, the platform's Level of Detail (LOD) system for building visualization serves as an additional layer of privacy protection. By rendering buildings as simple, untextured blocks at a distance (LOD 1), the system prevents the identification of specific, detailed building features unless a user toggles to LOD 3, so it enhances visual anonymization at city scale.

The flood risk data generated by the GeoTwin platform is for planning, preparedness, and communication purposes only, and not for insurance rates or property valuation.

List of References

Aksa, F. I., Ashar, M., Siswanto, H. W., & Malem, Z. Z. (2025). Immersive virtual reality for improving flood evacuation behaviour and self-efficacy. *Jàmbá-Journal of Disaster Risk Studies*, *17*(1), 1655. https://hdl.handle.net/10520/ejc-jemba_v17_n1_a1655

Ali, A. Y. (2025, August). OSM Building Footprints Vector Tiles Dataset – Dominica, 2025. https://doi.org/10.5281/zenodo.15234667

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2016). A framework for a microscale flood damage assessment and visualization for a building using bim-gis integration. *International Journal of Digital Earth*, *9*(4), 363–386. https://doi.org/10.1080/17538947.2015.1034201

Ariyachandra, M. R. M. F., & Wedawatta, G. (2023). Digital twin smart cities for disaster risk management: A review of evolving concepts. *Sustainability*, *15*(15). https://doi.org/10.3390/su151511910

Ariyachandra, M. M. F., & Wedawatta, G. (2023). Digital twin smart cities for disaster risk management: A review of evolving concepts. *Sustainability*, *15*(15), 11910. https://doi.org/https://doi.org/10.3390/su151511910

Bakhtiari, V., Piadeh, F., Behzadian, K., & Kapelan, Z. (2023). A critical review for the application of cutting-edge digital visualisation technologies for effective urban flood risk management. *Sustainable Cities and Society*, *99*, 104958. https://doi.org/https://doi.org/10.1016/j.scs.2023.104958

Bank, W. (2018). *Dominica – third phase disaster vulnerability reduction project: Environmental assessment and management framework* (tech. rep.). World Bank. http://documents.worldbank.org/curated/en/417621468248649746

Bapon, F. (2020). Risk communication for multi-hazard early warning system. https://shmfakhruddin.net/2020/04/09/sinking-swimming-and-surfing-risk-communications-of-uncertainties-of-the-pandemic/

Barrile, V., Genovese, E., Maesano, C., Calluso, S., & Manti, M. P. (2025). Developing an urban digital twin for environmental and risk assessment: A case study on public lighting and hydrogeological risk. *Future Internet*, *17*(3). https://doi.org/10.3390/fi17030110

Barry, M. (n.d.). Onthegomap/planetiler: Flexible tool to build planet-scale vector tilesets from openstreetmap data fast. https://github.com/onthegomap/planetiler

Bentivoglio, R., Isufi, E., Jonkman, S. N., & Taormina, R. (2022). Deep learning methods for flood mapping: A review of existing applications and future research directions. *Hydrology and Earth System Sciences*, *26*(16), 4345–4378. https://doi.org/10.5194/hess-26-4345-2022

Beven, K. (2012). Down to basics: Runoff processes and the modelling process. In *Rainfall-runoff modelling* (pp. 1–23). John Wiley& Sons, Ltd. https://doi.org/https://doi.org/10.1002/9781119951001.ch1

Beven, K. J. (2012). *Rainfall-runoff modelling: The primer*. John Wiley & Sons. https://doi.org/10.1002/9781119951001

Bilandzic, M., & Venable, J. (2011). Towards participatory action design research: Adapting action research and design science research methods for urban informatics. *The Journal of Community Informatics*, *7*. https://doi.org/10.15353/joci.v7i3.2592

Blair, G. S., Beven, K., Lamb, R., Bassett, R., Cauwenberghs, K., Hankin, B., Dean, G., Hunter, N., Edwards, L., Nundloll, V., Samreen, F., Simm, W., & Towe, R. (2019). Models of everywhere revisited: A technological perspective. *Environmental Modelling& Software*, *122*, 104521. https://doi.org/10.1016/j.envsoft.2019.104521

Bradshaw, C., Sodhi, N., & Brook, B. (2009). Tropical turmoil: A biodiversity tragedy in progress. https://hdl.handle.net/2440/51545

Brunner, G. W., & of Engineers, U. A. C. (2016). Hec-ras, river analysis system hydraulic reference manual. https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%205.0%20Reference%20Manual.pdf

Cashman, A., & Nagdee, M. R. (2017). Impacts of climate change on settlements and infrastructure in the coastal and marine environments of caribbean small island developing states (sids). *Science Review*, *2017*, 155–173. http://ns1.crfm.net/~uwohxjxf/images/11._Settlements_and_Infrastructure_combined.docx.pdf

Centre for Digital Built Britain. (2018). *The gemini principles: Guiding values for the national digital twin and information management framework* (tech. rep.). University of Cambridge. Cambridge, UK. https://www.cdbb.cam.ac.uk/files/gemini_principles.pdf

Cesium. (2012). Cesiumjs [Accessed: 2025-07]. https://cesium.com/platform/cesiumjs/

Cha, E. J., Knutson, T. R., Lee, T.-C., Ying, M., & Nakaegawa, T. (2020). Third assessment on impacts of climate change on tropical cyclones in the typhoon committee region – part ii: Future projections. *Tropical Cyclone Research and Review*, *9*(2), 75–86. https://doi.org/https://doi.org/10.1016/j.tcrr.2020.04.005

Charalabidis, Y., Kontos, G., & Zitianellis, D. (2025). Local digital twins for cities and regions: The way forward. In L. Raes, S. Ruston McAleer, I. Croket, P. Kogut, M. Brynskov, & S. Lefever (Eds.), *Decide better: Open and interoperable local digital twins* (pp. 233–259). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-81451-8_9

Chavez, D. (2023, August). An intro to physically based rendering material workflows and metallic/roughness. https://blog.turbosquid.com/2023/07/27/an-intro-to-physically-based-rendering-material-workflows-and-metallic-roughness/

Chen, C., Luan, D., Zhao, S., Liao, Z., Zhou, Y., Jiang, J., & Pei, Q. (2021). Flood discharge prediction based on remote-sensed spatiotemporal features fusion and graph attention. *Remote Sensing*, *13*(24). https://doi.org/10.3390/rs13245023

Choi, J.-E., & Shin, D. (2022). Parallel architecture of cnn-bidirectional lstms for implied volatility forecast. *Journal of Forecasting*, *41*, 1087–1098. https://doi.org/10.1002/for.2844

Costabile, P., Costanzo, C., De Lorenzo, G., De Santis, R., Penna, N., & Macchione, F. (2021). Terrestrial and airborne laser scanning and 2-d modelling for 3-d flood hazard maps in urban areas: New opportunities and perspectives. *Environmental Modelling& Software*, *135*, 104889. https://doi.org/https://doi.org/10.1016/j.envsoft.2020.104889

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban digital twins for smart cities and citizens: The case study of herrenberg, germany. *Sustainability*, *12*(6), 2307. https://doi.org/10.3390/su12062307

Dharmarathne, G., Waduge, A., Bogahawaththa, M., Rathnayake, U., & Meddage, D. (2024). Adapting cities to the surge: A comprehensive review of climate-induced urban flooding. *Results in Engineering*, 102123. https://doi.org/https://doi.org/10.1016/j.rineng.2024.102123

Dominica Central Statistics Office. (2011). *2011 population and housing census* (tech. rep.). Government of the Commonwealth of Dominica. https://dominicanewsonline.com/news/wp-content/uploads/2020/12/Population_and_Housing_Census_2011-1.pdf

Doocy, S., Daniels, A., Murray, S., & Kirsch, T. D. (2013). The human impact of floods: A historical review of events 1980-2009 and systematic literature review. *PLoS Currents*. https://doi.org/10.1371/currents.dis.f4deb457904936b07c09daa98ee8171a

Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., et al. (2012). Sentinel-2: Esa's optical high-resolution mission for gmes operational services. *Remote sensing of Environment*, *120*, 25–36. https://doi.org/10.1016/j.rse.2011.11.026

ESA. (2017). *Land cover cci product user guide version 2.0* (tech. rep.). European Space Agency. https://www.esa-landcover-cci.org/?q=node/164

European Environment Agency. (2023). Economic losses from weather- and climate-related extremes in europe. https://www.eea.europa.eu/en/analysis/indicators/economic-losses-from-climate-related

Fakhruddin, B., Clark, H., Robinson, L., & Hieber-Girardet, L. (2020). Should i stay or should i go now? why risk communication is the critical component in disaster risk reduction. *Progress in Disaster Science*, *8*, 100139. https://doi.org/https://doi.org/10.1016/j.pdisas.2020.100139

Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster city digital twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management*, *56*, 102049. https://doi.org/https://doi.org/10.1016/j.ijinfomgt.2019.102049

Farsi, M., Daneshkhah, A., Hosseinian-Far, A., & Jahankhani, H. (2019, March). *Digital twin technologies and smart cities*. Springer Nature Switzerland. https://doi.org/10.1007/978-3-030-18732-3

FastFlood.org. (2025). Fastflood high-resolution dem and lidar data for dominica [Accessed: August, 2025]. https://fastflood.org/?view=%5B15.2,15.65,-61.5,-61.2%5D&download_overview=https://pub-44840605c38242f083a8b6864370afd6.r2.dev/overview1.zip

Forcada, N. (2025). Chapter 13 - digital twin for construction industry. In T. A. Nguyen (Ed.), *Digital twin and blockchain for sensor networks in smart cities* (pp. 291–297). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-443-30076-9.00014-5

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020a). Digital twin: Enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/access.2020.2998358

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020b). Digital twin: Enabling technologies, challenges and open research. *IEEE Access*, *8*, 108952–108971. https://doi.org/10.1109/ACCESS.2020.2998358

Ge, C., & Qin, S. (2025). Urban flooding digital twin system framework. *Systems Science & Control Engineering*, *13*(1), 2460432. https://doi.org/10.1080/21642583.2025.2460432

gfz. (n.d.). Wegue-oss/wegue: Template and components for webmapping applications with openlayers and vue.js. https://www.openbuildingmap.org/#gfz_z=15.3157&gfz_e=-61.4214%2C15.3554%2C-61.3598%2C15.3971&gfz_r=0&gfz_l=osm-bg%2Cgfz-obm-occupancy

Ghaffarian, S. (2025). Rethinking digital twin: Introducing digital risk twin for disaster risk management. *npj Natural Hazards*, *2*(1), 79. https://doi.org/https://doi.org/10.1038/s44304-025-00135-x

Government of the Commonwealth of Dominica. (2015). *Rapid damage and impact assessment: Tropical storm erika* (tech. rep.). The World Bank. Washington, D.C. https://www.gfdrr.org/sites/default/files/publication/Commonwealth%20of%20Dominica%20-%20Rapid%20Damage%20and%20Needs%20Assessment%20Final%20Report%20.pdf

Government of the Commonwealth of Dominica. (2017). *Post-disaster needs assessment hurricane maria* (tech. rep.). The World Bank. Washington, D.C. https://www.gfdrr.org/sites/default/files/publication/Dominica_mp_012418_web.pdf

Grieves, M. (2014). Digital twin: Manufacturing excellence through virtual factory replication. *White paper*, *1*(2014), 1–7.

Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. *Transdisciplinary perspectives on complex systems: New findings and approaches*, 85–113.

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile augmented reality for flood visualisation. *Environmental Modelling& Software*, *109*, 380–389. https://doi.org/https://doi.org/10.1016/j.envsoft.2018.05.012

Hengl, T., Mendes de Jesus, J., Heuvelink, G. B., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M. N., Geng, X., Bauer-Marschallinger, B., et al. (2017). Soilgrids250m: Global gridded soil information based on machine learning. *PloS one*, *12*(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

Herman, L., Russnák, J., & Řezník, T. (2017). Flood modelling and visualizations of floods through 3d open data. *IFIP International Conference on Computer Information Systems and Industrial Management*, 139–149. https://doi.org/10.1007/978-3-319-89935-0_12

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al. (2020). The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). Design science in information systems research. *MIS quarterly*, 75–105. https://doi.org/10.2307/25148625

Huffman, G. J., Bolvin, D. T., Braithwaite, D., Hsu, K., Joyce, R., Kidd, C., Nelkin, E. J., Sorooshian, S., Stocker, E. F., Tan, J., et al. (2019). GPM IMERG Final Precipitation L3 1 day 0.1 degree x 0.1 degree V06. https://doi.org/10.5067/GPM/IMERGDF/DAY/06

Huong, H. T. L., & Pathirana, A. (2013). Urbanization and climate change impacts on future urban flooding in can tho city, vietnam. *Hydrology and Earth System Sciences*, *17*(1), 379–394. https://doi.org/10.5194/hess-17-379-2013

IMF, I. M. F. (2021). *Growth at risk from natural disasters*. International Monetary Fund. https://www.imf.org/-/media/Files/Publications/WP/2021/English/wpiea2021234-print-pdf.ashx

Intergovernmental Panel on Climate Change. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Core Writing Team, R. Pachauri, & L. Meyer, Eds.). IPCC. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf

Janizadeh, S., Avand, M., Jaafari, A., Phong, T. V., Bayat, M., Ahmadisharaf, E., Prakash, I., Pham, B. T., & Lee, S. (2019). Prediction success of machine learning methods for flash flood susceptibility mapping in the tafresh watershed, iran. *Sustainability*, *11*(19). https://doi.org/10.3390/su11195426

Kusuma, M. S. B., Kardhana, H., Suryadi, Y., Rohmat, F. I. W., et al. (2022). Hourly discharge prediction using long short-term memory recurrent neural network (lstm-rnn) in the up-per citarum river. *GEOMATE Journal*, *23*(98), 147–154. https://geomatejournal.com/geomate/article/view/3462

La Guardia, M., & Koeva, M. (2023). Towards digital twinning on the web: Heterogeneous 3d data fusion based on open-source structure. *Remote Sensing*, *15*(3). https://doi.org/10.3390/rs15030721

Liu, Y., Zhang, L., Yang, Y., Zhou, L., Ren, L., Wang, F., Liu, R., Pang, Z., & Deen, M. J. (2019). A novel cloud-based framework for the elderly healthcare services using digital twin. *IEEE Access*, *7*, 49088–49101. https://doi.org/10.1109/ACCESS.2019.2909828

Mankowski, R. (2023). City-scale digital twins for flood resilience. https://www.gim-international.com/content/article/city-scale-digital-twins-for-flood-resilience

Mienye, I. D., Swart, T. G., & Obaido, G. (2024). Recurrent neural networks: A comprehensive review of architectures, variants, and applications. *Information*, *15*(9). https://doi.org/10.3390/info15090517

Mosavi, A., Ozturk, P., & Chau, K.-w. (2018). Flood prediction using machine learning models: Literature review. *Water*, *10*(11), 1536. https://doi.org/10.3390/w10111536

(Mr.doob), R. C., & Authors, T. T. (2010). Three.js - javascript 3d library [Accessed: 2025-08]. https://threejs.org/

Nabukulu, C., Jetten, V. G., & Ettema, J. (2024). Implications of tropical cyclone rainfall spatial–temporal variability on flood hazard assessments in the caribbean lesser antilles. *GeoHazards*, *5*(4), 1275–1293. https://doi.org/10.3390/geohazards5040060

Noor, F., Haq, S., Rakib, M., Ahmed, T., Jamal, Z., Siam, Z. S., Hasan, R. T., Adnan, M. S. G., Dewan, A., & Rahman, R. M. (2022). Water level forecasting using spatiotemporal attention-based long short-term memory network. *Water*, *14*(4). https://doi.org/10.3390/w14040612

oascities. (n.d.). Mim8: Local digital twins. https://mims.oascities.org/NzWXOO1Fttw4wtqv1Wys/mim8-local-digital-twins

OpenStreetMap contributors. (2017). Planet dump retrieved from https://planet.osm.org. https://www.openstreetmap.org

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., & van Ypserle, J. P. (2014). *Climate change 2014: Synthesis report. contribution of working groups i, ii and iii to the fifth assessment report of the intergovernmental panel on climate change*. Ipcc. https://www.ipcc.ch/report/ar5/syr/

Panwar, J., V, Wilkinson, E., Noy, I., & Institute, O. D. (2024). *The price of a changing climate: Extreme weather and economic loss and damage in sids*. ODI Global. https://media.odi.org/documents/The_price_of_a_changing_climate.pdf

Park, S., Kim, J., Kim, Y., & Kang, J. (2024). Participatory framework for urban pluvial flood modeling in the digital twin era. *Sustainable Cities and Society*, *108*, 105496. https://doi.org/10.1016/j.scs.2024.105496

Pasch, R. J., Blake, E. S., & Roberts, D. P. (2018). Tropical cyclone impacts in the caribbean. In *Hurricane risk* (pp. 249–285). Springer, Cham. https://doi.org/10.1007/978-3-319-75653-3_9

Petrova-Antonova, D., & Ilieva, S. (2019). Methodological framework for digital transition and performance assessment of smart cities, 1–6. https://doi.org/10.23919/SpliTech.2019.8783170

Pharr, M., Jakob, W., & Humphreys, G. (2004). *Physically based rendering: From theory to implementation*. Morgan Kaufmann. https://doi.org/https://doi.org/10.1016/B978-0-12-553180-1.X5000-5

Rajendran, S. (2024). *Development of digital twin framework for decision support in flood risk management*. ITC,UT. https://essay.utwente.nl/101928/1/Rajendran_MSc_ITC.pdf

Ramos, M.-H., Mathevet, T., Thielen-del Pozo, J., & Pappenberger, F. (2010). Communicating uncertainty in hydro-meteorological forecasts: Mission impossible? *Meteorological Applications*, *17*, 223–235. https://doi.org/10.1002/met.202

Riaz, K., McAfee, M., & Gharbia, S. S. (2023). Management of climate resilience: Exploring the potential of digital twin technology, 3d city modelling, and early warning systems. *Sensors*, *23*(5), 2659. https://doi.org/10.3390/s23052659

Schumann, G., Bates, P. D., Horritt, M. S., Matgen, P., & Pappenberger, F. (2009). Progress in integration of remote sensing–derived flood extent and stage data and hydraulic models. *Reviews of Geophysics*, *47*(4). https://doi.org/10.1029/2008rg000274

Slinger-Friedman, V. (2017). Dominica. *Landscapes and Landforms of the Lesser Antilles*, 153–171.

Stewart, I. (2024). Advancing disaster risk communications. *Earth-Science Reviews*, *249*, 104677. https://doi.org/https://doi.org/10.1016/j.earscirev.2024.104677

Tan, W., Qin, N., Zhang, Y., McGrath, H., Fortin, M., & Li, J. (2024). A rapid high-resolution multi-sensory urban flood mapping framework via dem upscaling. *Remote Sensing of Environment*, *301*, 113956. https://doi.org/https://doi.org/10.1016/j.rse.2023.113956

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics*, *15*(4), 2405–2415. https://doi.org/10.1109/TII.2018.2873186

Teng, J., Jakeman, A., Vaze, J., Croke, B., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling& Software*, *90*, 201–216. https://doi.org/https://doi.org/10.1016/j.envsoft.2017.01.006

Uber Technologies, Inc. (2016). Deck.gl: A webgl-powered framework for visual exploratory data analysis of large datasets [Accessed: 2025-07]. https://deck.gl/

UNISDR. (2017). *National disaster risk assessment words into action guidelines governance system, methodologies, and use of results* (J. Abrahams, K. Berryman, A. Bower, E. Clarke, F. Hamdan, M. Hohl, I. Khan, R. Muirwood, J. Rolfe, N. A. Santamaria, A. Simpson, & M. Woolf, Eds.). UNDRR. https : / / www . unisdr . org / files / 52828 _ nationaldisasterriskassessmentpart1.pdf

USDA, S. (1986). Urban hydrology for small watersheds. *Technical release*, *55*, 2–6.

van den Bout, B., & Koeva, M. (2025). Stakeholder questionnaire survey – dominica, 2024. https://doi.org/10.5281/zenodo.15212825

van den Bout, B., Jetten, V. G., van Westen, C. J., & Lombardo, L. (2023). A breakthrough in fast flood simulation. *Environmental Modelling & Software*, *168*, 105787. https://doi.org/10.1016/j.envsoft.2023.105787

van Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview [Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning]. *Engineering Geology*, *102*(3), 112–131. https://doi.org/https://doi.org/10.1016/j.enggeo.2008.03.010

Wang, Y., Wang, W., Zang, H., & Xu, D. (2023). Is the lstm model better than rnn for flood forecasting tasks? a case study of huayuankou station and loude station in the lower yellow river basin. *Water*, *15*(22). https://doi.org/10.3390/w15223928

Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban digital twin challenges: A systematic review and perspectives for sustainable smart cities. *Sustainable Cities and Society*, *99*, 104862. https://doi.org/https://doi.org/10.1016/j.scs.2023.104862

Westen, C., & Greiving, S. (2017, February). Multi-hazard risk assessment and decision making. IWA Publishing. https://doi.org/10.2166/9781780407135_0031

Yin, W., Hu, Q., Liu, W., Liu, J., He, P., Zhu, D., & Kornejady, A. (2024). Harnessing game engines and digital twins: Advancing flood education, data visualization, and interactive monitoring for enhanced hydrological understanding. *Water*, *16*(17). https://doi.org/10.3390/w16172528

Zhang, Y. (2024, January). *Digital twin: Architectures, networks, and applications*. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-51819-5

Zhao, X., Wang, H., Bai, M., Xu, Y., Dong, S., Rao, H., & Ming, W. (2024). A comprehensive review of methods for hydrological forecasting based on deep learning. *Water*, *16*(10). https://doi.org/10.3390/w16101407

Appendix A

Other figures

A.1 STATEMENT OF AI USAGES

Open-source AI tools like Qwen, LLaMA, DeepSeek, and similar models were used in a limited capacity to support debugging, language, structure, formatting, and editing. No AI was used to generate original content, analyze data, or produce findings. All core research and writing were done independently, and I take full responsibility for the final work. (including this text)

A.2 INTERVIEWED STAKEHOLDERS

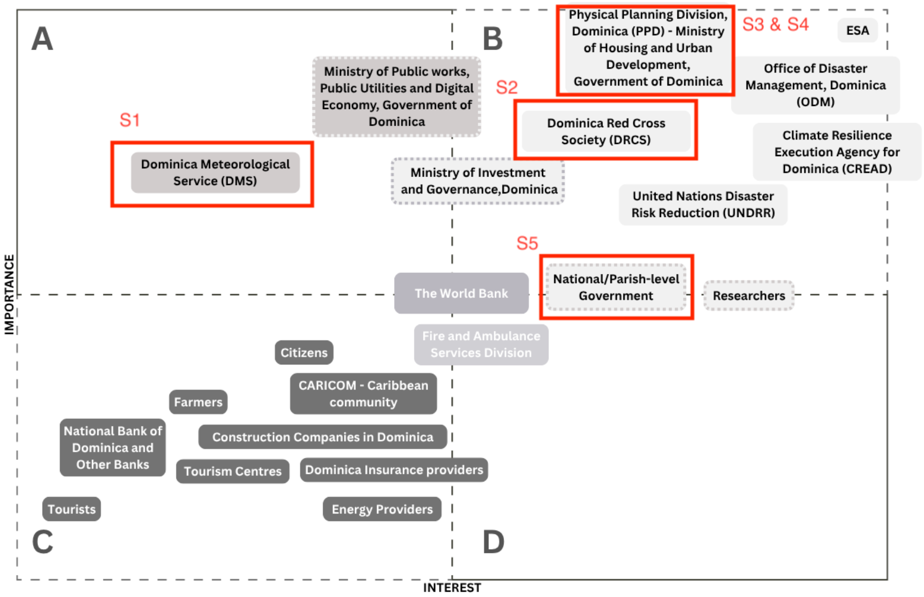


Figure A.1: Interviewed stakeholders highlighted in the stakeholder classification matrix

A.3 BUILDING TYPE DISTRIBUTION PLOTS

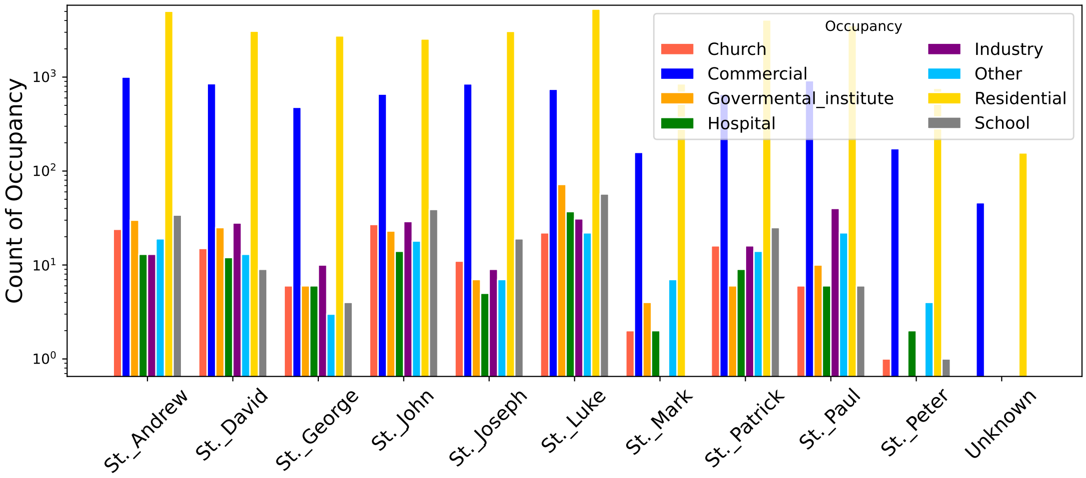


Figure A.2: Building types distribution for each parish, based on occupancy.

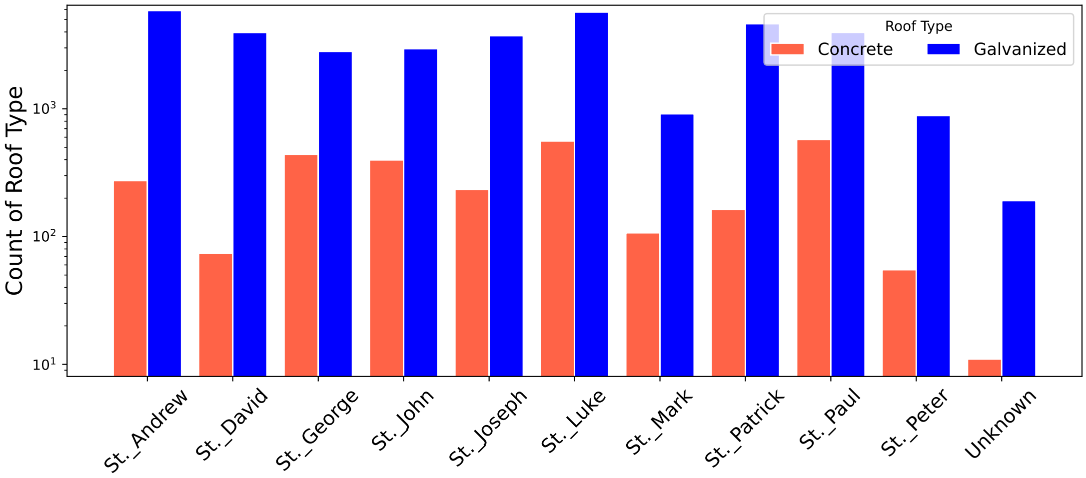


Figure A.3: Building types distribution for each parish, based on roof type.

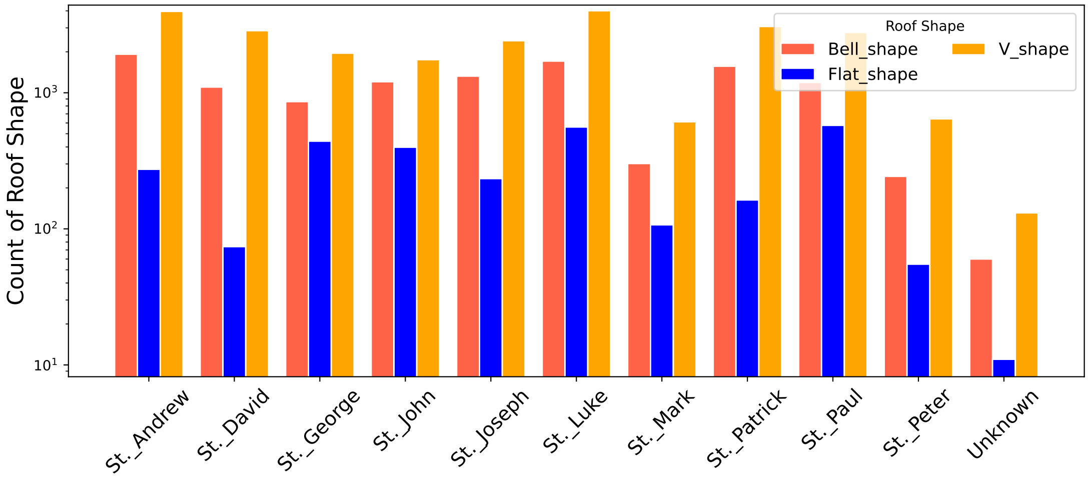


Figure A.4: Building types distribution for each parish, based on roof shape.

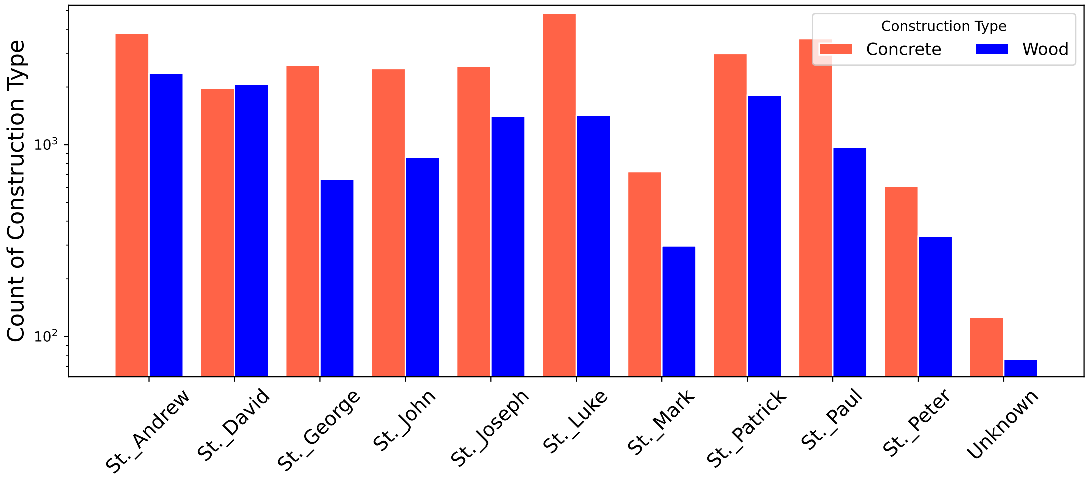


Figure A.5: Building types distribution for each parish, based on construction type.

A.4 TEXTURE MAPS

In the PBR (Physically Based Rendering) workflow, material attributes are defined by **Albedo/Base Color:** The color of the material, affecting light absorption and reflection. **Metallic/Metalness:** Reflectivity, with 0.0 for non-metal and 1.0 for metal; intermediate values can represent materials like satin. **Roughness:** Texture smoothness, where 0.0 is smooth and 1.0 is rough.

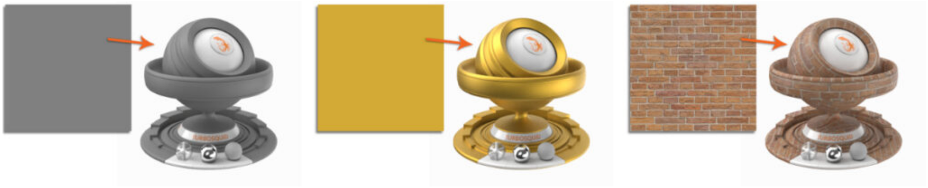


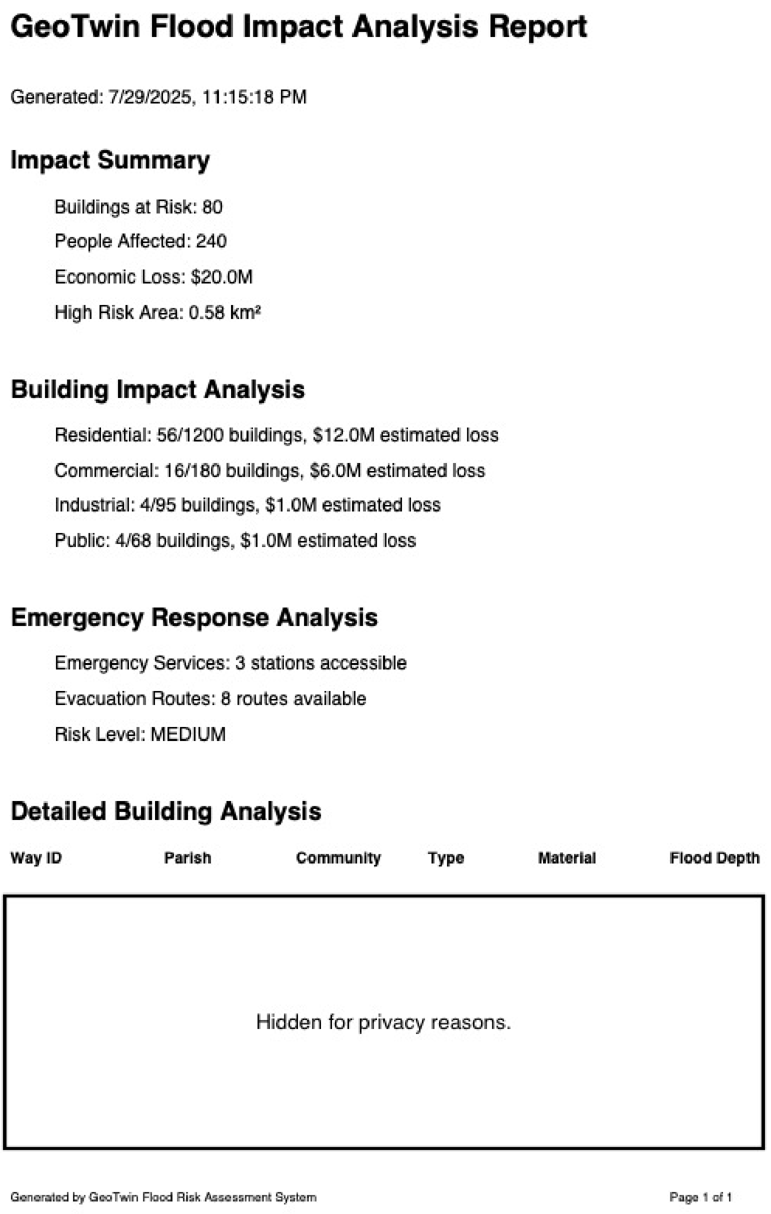
Figure A.6: Albedo or Base Color. In most cases, this is an RGB value or diffuse texture that defines the color of the material. *Source: Chavez, 2023.*

Figure A.7: Metallic or Metalness with a constant base color. The higher the value, the more metal the material's reflective properties are. The PBR workflow will calculate the energy conservation following the laws of physics. In the baked texture map, a metallic of 0 will produce a pure black value, and a metallic of 1 will produce a pure white value. *Source: Chavez, 2023.*

Figure A.8: Roughness on a dielectric material (Metal 0.0). Higher values scatter the reflected light in more directions. In the baked texture map, a roughness of 0 will produce a pure black value, and a roughness of 1 will produce a pure white value. *Source: Chavez, 2023.*

Figure A.9: Roughness on an electrically conductive material (Metal 1.0). The specular highlights in the rougher metals will always follow energy conservation laws. *Source: Chavez, 2023.*

A.5 IMPACT ANALYSIS EXAMPLE REPORT



GeoTwin Flood Impact Analysis Report

Generated: 7/29/2025, 11:15:18 PM

Impact Summary

Buildings at Risk: 80
People Affected: 240
Economic Loss: $20.0M
High Risk Area: 0.58 km²

Building Impact Analysis

Residential: 56/1200 buildings, $12.0M estimated loss
Commercial: 16/180 buildings, $6.0M estimated loss
Industrial: 4/95 buildings, $1.0M estimated loss
Public: 4/68 buildings, $1.0M estimated loss

Emergency Response Analysis

Emergency Services: 3 stations accessible
Evacuation Routes: 8 routes available
Risk Level: MEDIUM

Detailed Building Analysis

Way ID	Parish	Community	Type	Material	Flood Depth

Hidden for privacy reasons.

Generated by GeoTwin Flood Risk Assessment System

Page 1 of 1

Figure A.10: Example impact analysis report generated from GeoTwin.

A.6 INTERFACE FIGURES

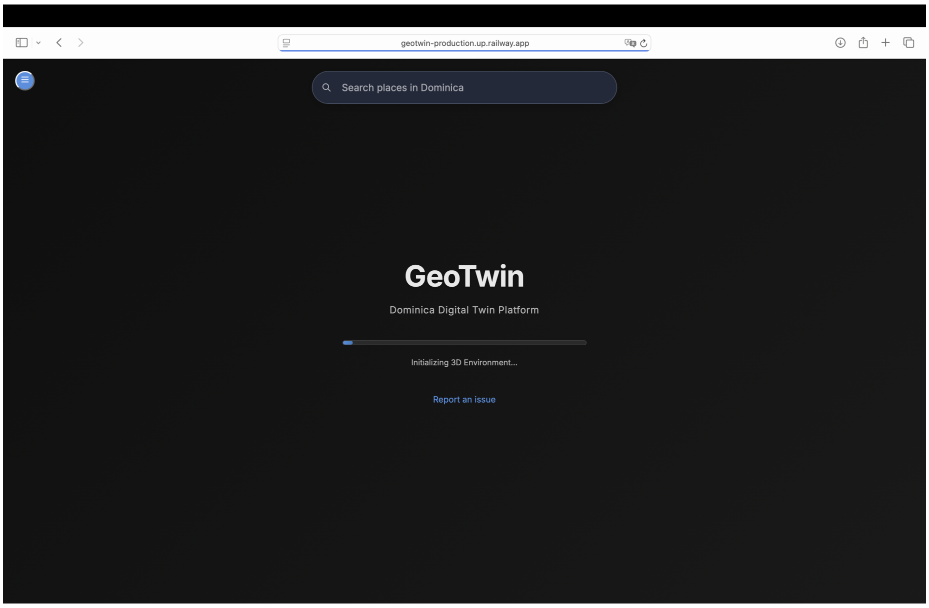


Figure A.11: Start page of the application.

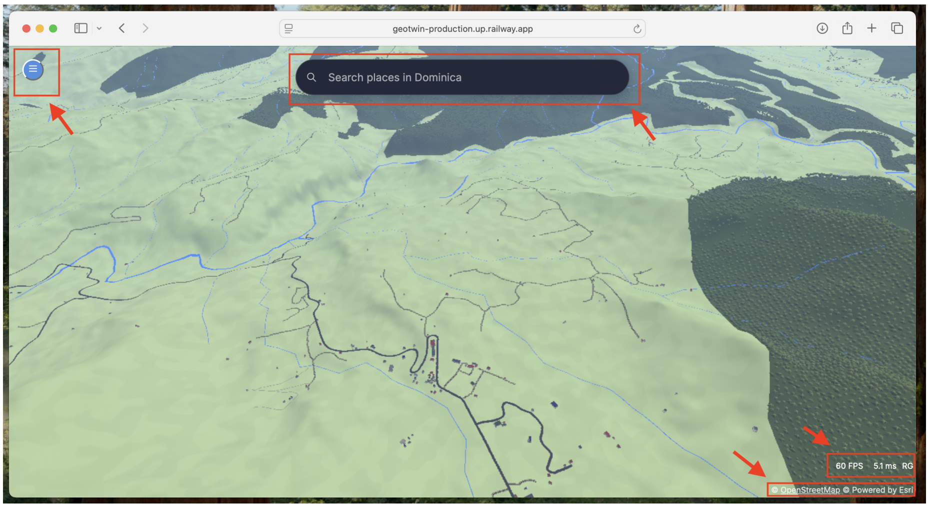


Figure A.12: Main page of the interface, key elements are highlighted.

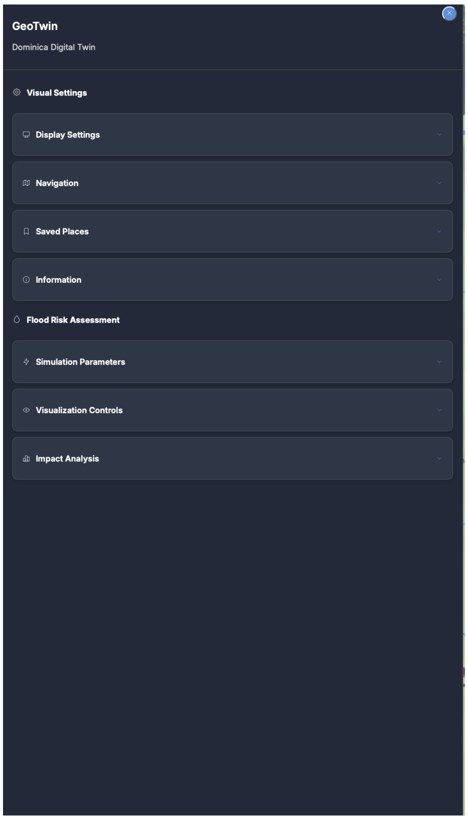
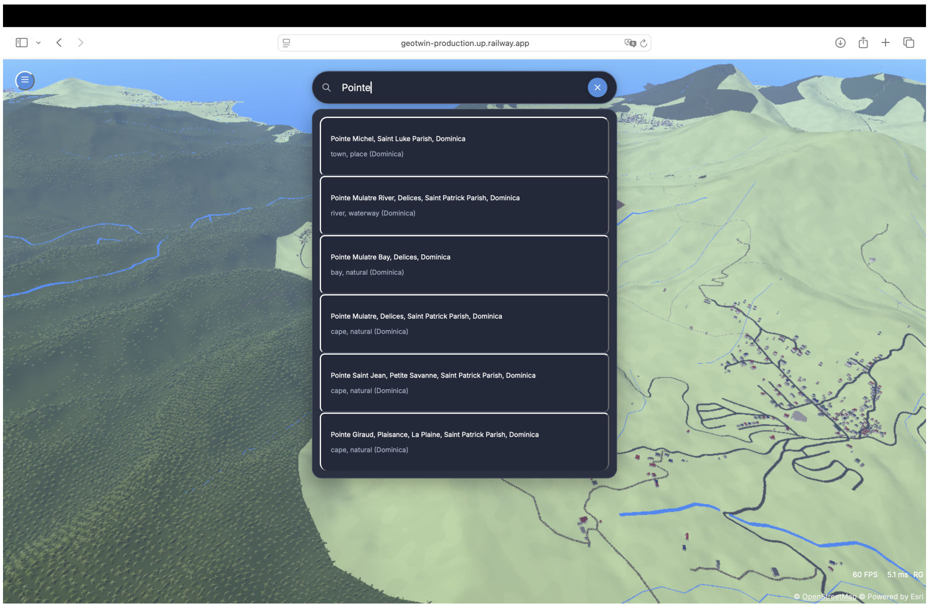


Figure A.13: Panel overview.



Pointe

Pointe Michel, Saint Luke Parish, Dominica
town, place (Dominica)

Pointe Mulatre River, Delices, Saint Patrick Parish, Dominica
river, waterway (Dominica)

Pointe Mulatre Bay, Delices, Dominica
bay, natural (Dominica)

Pointe Mulatre, Delices, Saint Patrick Parish, Dominica
cape, natural (Dominica)

Pointe Saint Jean, Petite Savanne, Saint Patrick Parish, Dominica
cape, natural (Dominica)

Pointe Giraud, Plaisance, La Plaine, Saint Patrick Parish, Dominica
cape, natural (Dominica)

Figure A.14: Searching for location with auto-complete suggestions.

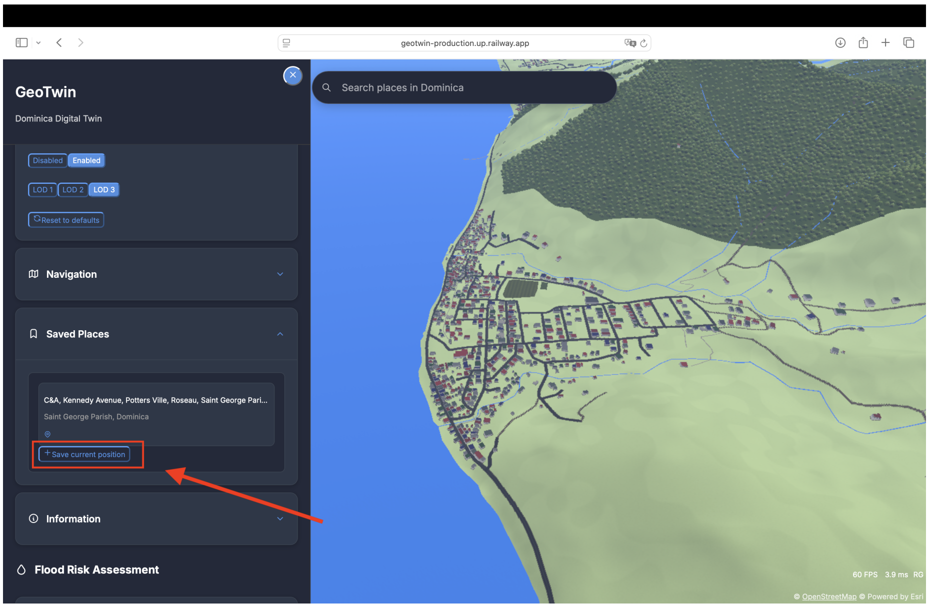


Figure A.15: Saving a location.

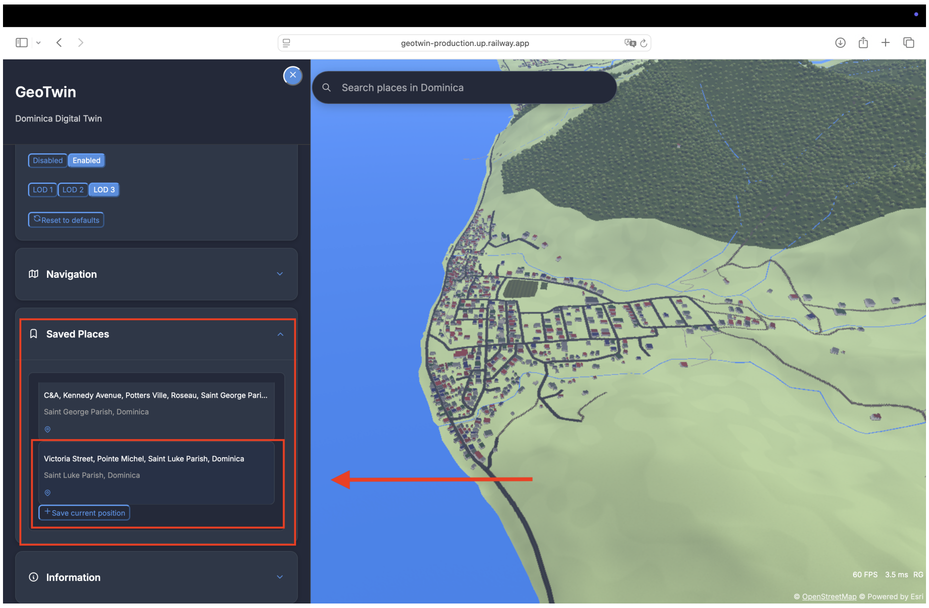
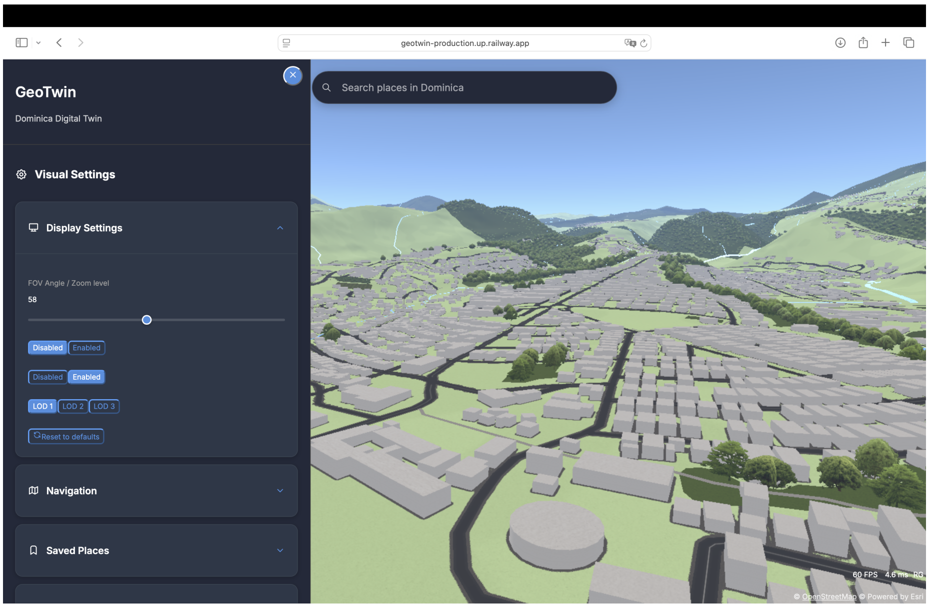


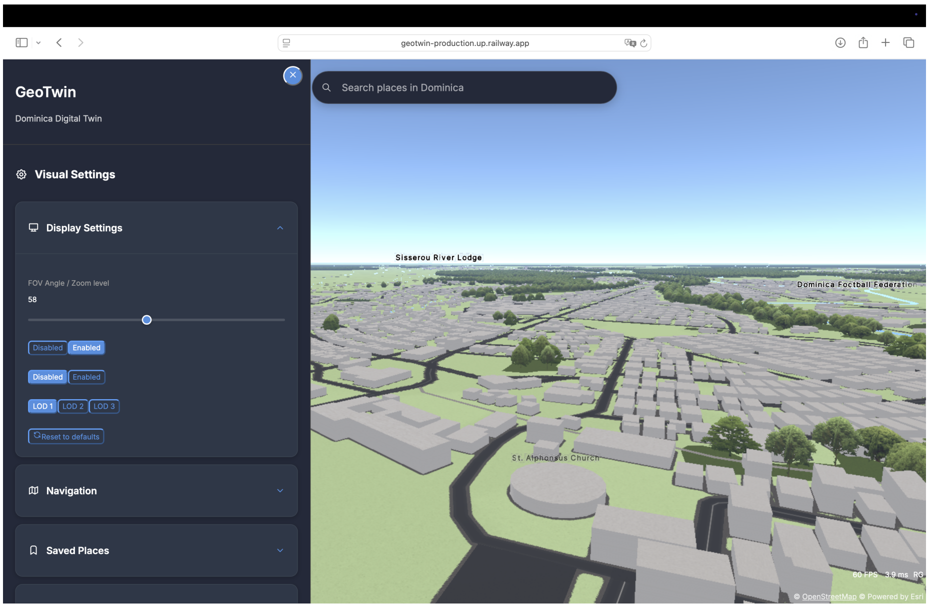
Figure A.16: Current location saved.



FOV Angle / Zoom level
58

Figure A.17: Interface with terrain enabled.

Figure A.18: Interface with terrain disabled.



FOV Angle / Zoom level

58

Figure A.19: Labels of the buildings enabled.

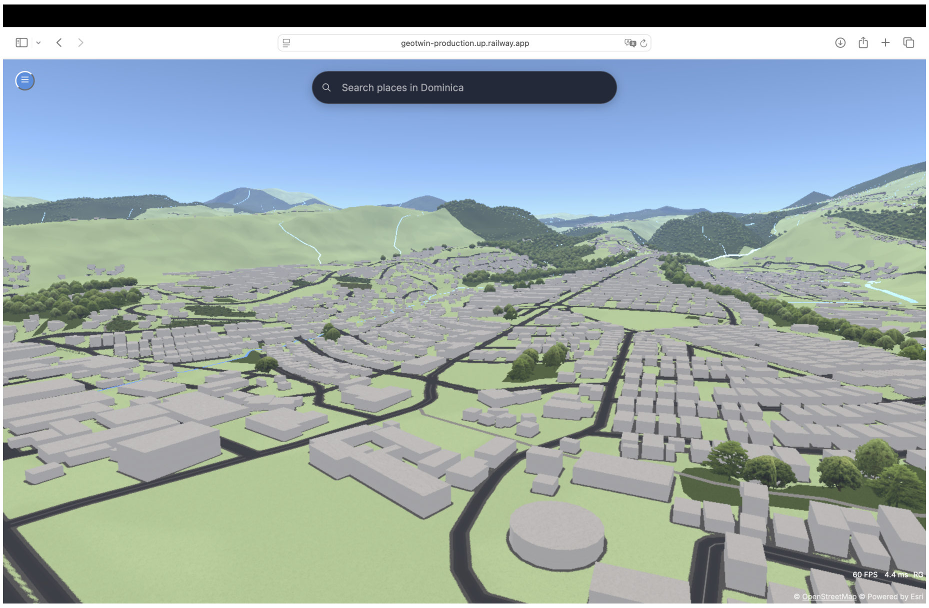


Figure A.20: Labels of the buildings disabled.

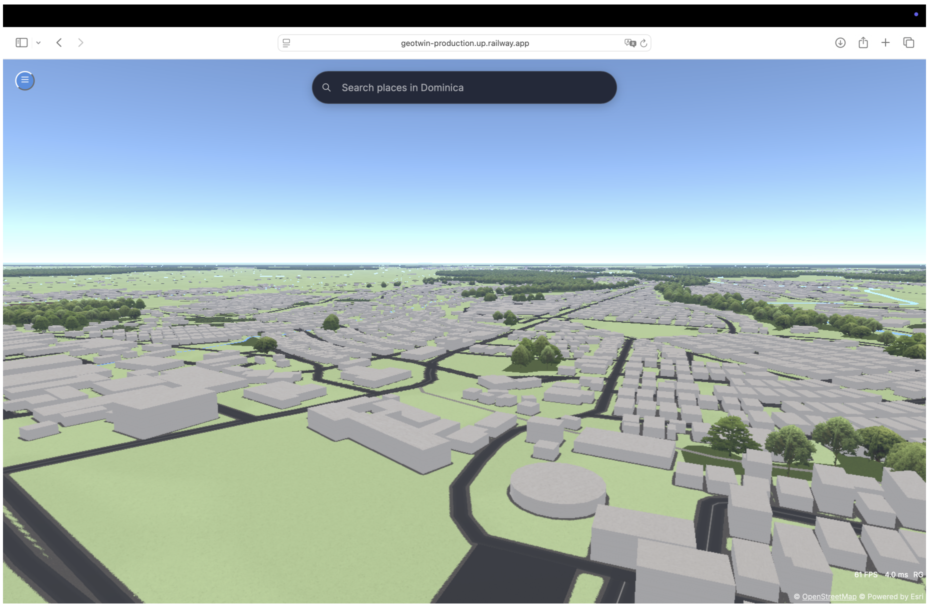
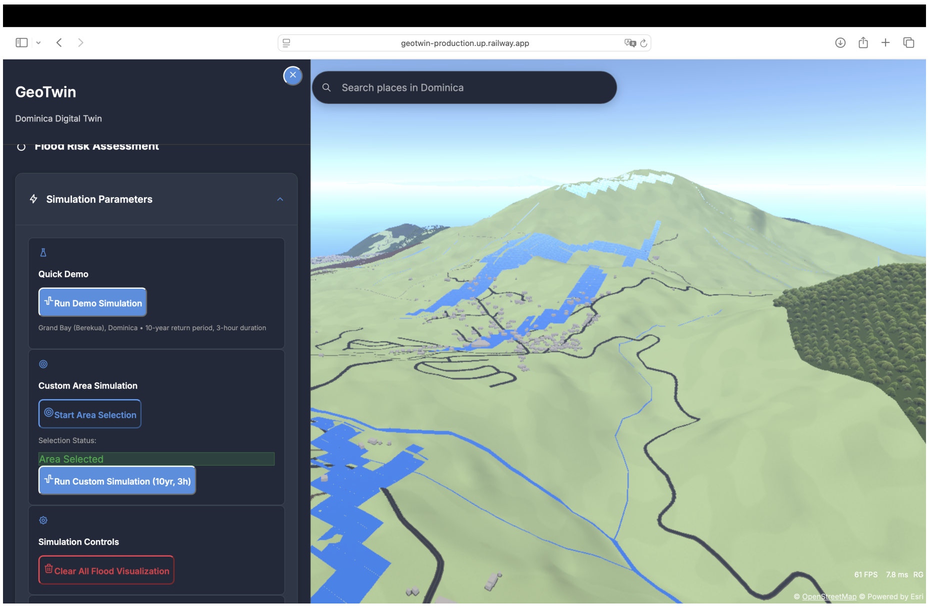


Figure A.21: Labels of the buildings and terrain disabled.



Grand Bay (Berekua), Dominica • 10-year return period, 3-hour duration

Selection Status:
Area Selected

Figure A.22: Flood simulation in selected area.

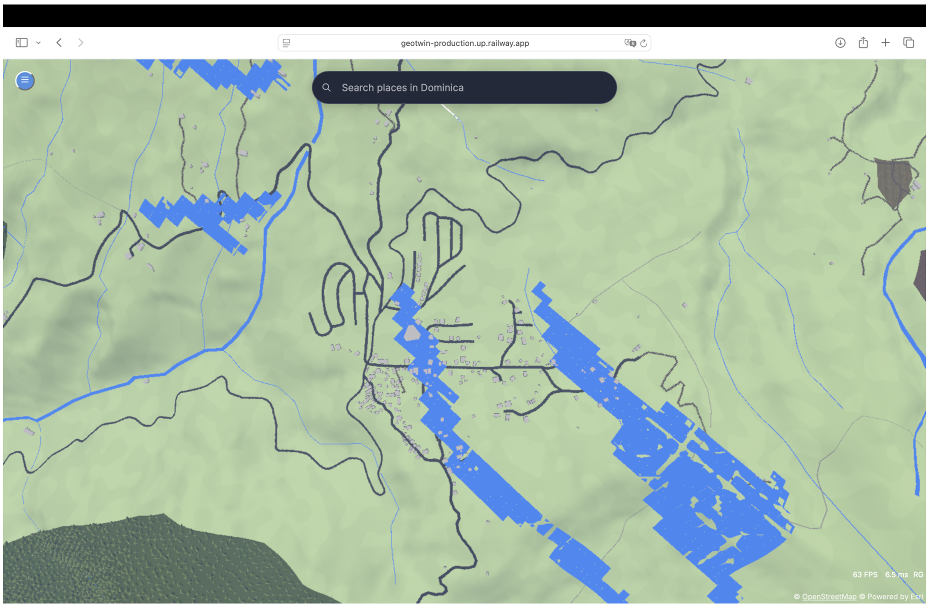
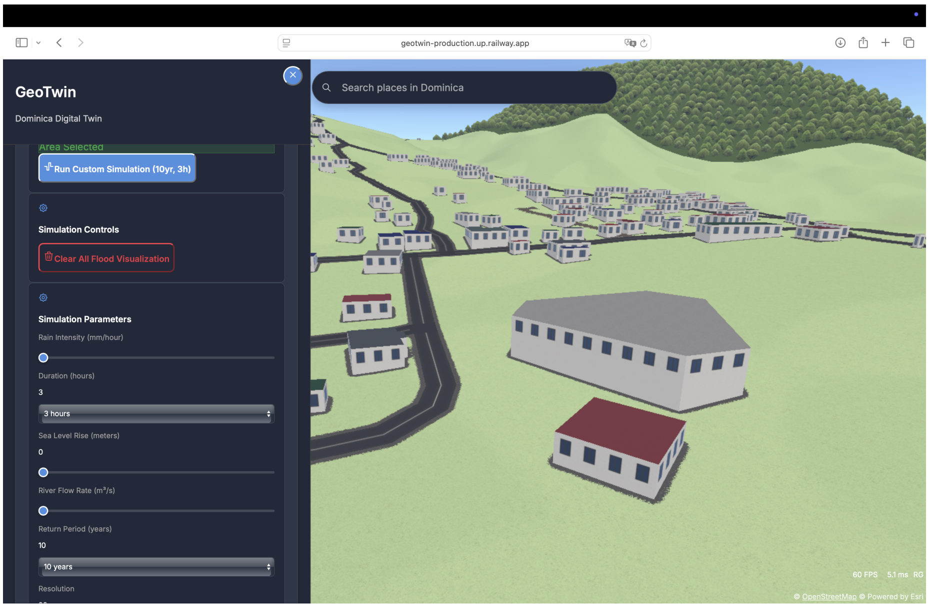


Figure A.23: Flood simulation from a top angle.



Rain Intensity (mm/hour)

Duration (hours)
3
3 hours

Sea Level Rise (meters)
0

River Flow Rate (m³/s)

Return Period (years)
10
10 years

Resolution

Figure A.24: Flood cleared after simulation.

A.7 CODE USED TO GENERATE WORD CLOUD

```
import os
import string
import nltk
from nltk.corpus import stopwords, wordnet
from nltk.stem import WordNetLemmatizer
from collections import Counter
from sklearn.feature_extraction.text import CountVectorizer
from wordcloud import WordCloud
import matplotlib.pyplot as plt
nltk.download(’punkt’)
nltk.download(’wordnet’)
nltk.download(’stopwords’)
nltk.download(’omw-1.4’)

lemmatizer = WordNetLemmatizer()
custom_stopwords = stop_words = list(set(stopwords.words(’english’)).union({
    ’yeah’, ’okay’, ’one’, ’well’, ’um’, ’uh’, ’oh’, ’like’, ’you’, ’know’,
    ’just’, ’get’, ’got’, ’also’, ’really’, ’going’, ’think’, ’say’, ’said’,
    ’gonna’, ’would’, ’could’, ’make’, ’maybe’, ’thing’, ’things’, ’even’,
    ’dont’, ’cant’, ’wanna’, ’im’, ’ive’, ’thats’, ’theres’, ’didnt’, ’doesnt’,
    ’aint’, ’must’, ’needs’, ’want’, ’lets’, ’see’, ’still’, ’sure’, ’right’,
    ’yes’, ’yeah’, ’no’, ’nah’, ’hmm’, ’mean’, ’something’, ’someone’, ’much’,
    ’lot’, ’going’, ’us’, ’people’, ’person’, ’everyone’, ’everything’, ’project’, ’projects’,
    ’work’, ’guys’, ’basically’, ’actually’, ’youre’, ’theyre’, ’stuff’, ’thank’, ’probably’,
    ’using’, ’use’, ’many’, ’sometimes’, ’name’, ’especially’, ’may’, ’two’, ’another’,
    ’example’, ’nice’, ’done’, ’foot’, ’gi’, ’part’, ’person’, ’first’, ’whatever’,
    ’come’, ’take’, ’whithin’, ’thanks’, ’always’, ’around’, ’based’, ’give’,
    ’clearly’, ’ensure’, ’big’, ’good’, ’different’, ’particularly’, ’way’, ’look’,
    ’quite’, ’keep’, ’face’, ’sort’, ’able’, ’amount’, ’youve’, ’term’, ’terms’
}))
preserve_words = {’gis’, ’geotwin’, ’ai’, ’qgis’, ’kobo’, ’dominica’, ’hazard’, ’copernicus’}

def preprocess(text):
    text = text.lower().translate(str.maketrans(’’, ’’, string.punctuation))
    words = text.split()
    tokens = [
        w if w in preserve_words else lemmatizer.lemmatize(w, pos=’n’)
        for w in words
        if w not in custom_stopwords and len(w) > 2
    ]
    return tokens
def extract_bigrams(docs, min_freq=3):
    vectorizer = CountVectorizer(ngram_range=(2, 2), min_df=1, stop_words=custom_stopwords)
    X = vectorizer.fit_transform(docs)
    bigram_counts = zip(vectorizer.get_feature_names_out(), X.toarray().sum(axis=0))
    return {bigram: freq for bigram, freq in bigram_counts if freq >= min_freq}
def generate_wordcloud(freq_dict, title="Word Cloud"):
    wordcloud = WordCloud(width=1000, height=600, background_color=’white’).generate_from_frequencies(freq_dict)
    plt.figure(figsize=(12, 6))
    plt.imshow(wordcloud, interpolation=’bilinear’)
    plt.axis(’off’)
    plt.title(title)
    plt.show()

folder_path = "./interviews"
docs = []
all_tokens = []
for filename in os.listdir(folder_path):
    if filename.endswith(".txt"):
        with open(os.path.join(folder_path, filename), "r", encoding="utf-8") as file:
            raw = file.read()
            tokens = preprocess(raw)
            all_tokens.extend(tokens)
            docs.append(" ".join(tokens))

word_freq = Counter(all_tokens)
bigram_freq = extract_bigrams(docs, min_freq=3)
combined_freq = dict(word_freq)
combined_freq.update(bigram_freq)
generate_wordcloud(combined_freq, title="GeoTwin Word Cloud from Interviews")
```