DEVELOPMENT OF DIGITAL TWIN FRAMEWORK FOR DECISION SUPPORT IN FLOOD RISK MANAGEMENT

SRUTHIE RAJENDRAN
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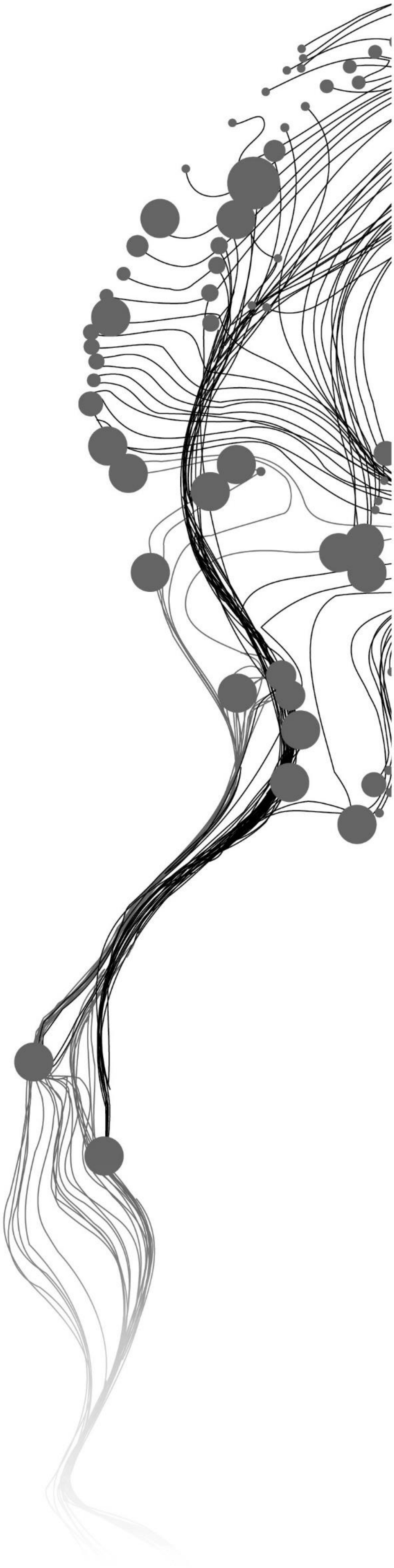
SUPERVISORS:
Dr. M.N. Koeva (Mila)
Dr. B. van den Bout (Bastian)



DEVELOPMENT OF DIGITAL TWIN FRAMEWORK FOR DECISION SUPPORT IN FLOOD RISK MANAGEMENT

SRUTHIE RAJENDRAN
Enschede, The Netherlands, July 2024

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 Spatial Engineering

SUPERVISORS:
Dr. M.N. Koeva (Mila)
Dr. B. van den Bout (Bastian)

THESIS ASSESSMENT BOARD:
Prof. Dr. M. Kuffer (Monika) (Chair)
Dr. P. Nourian March (Pirouz) (External Examiner)

ABSTRACT

Flooding is one of the most destructive and frequently occurring disasters in cities around the world. This study attempts to develop a fully operational digital twin architecture for aiding in the decision-making process of stakeholders for flood hazard management. Digital twin technology offers a solution by allowing for the testing of policies or mitigative measures before real-world implementation, thus saving resources and time while empowering policymakers to make data-based decisions. For the design and development of the DT Architecture, a survey was conducted, and 34 responses were recorded. The primary purpose of the survey was to capture the stakeholders' expectations in a decision support tool for flooding applications. Incorporating the insights gathered from the survey and extensive literature review on Digital Twin technology, Flood modelling and Web development, the development process of the DT framework was envisioned. For creating a DT with flood simulation and analysis capabilities, the web development approach was carried out to bring together the digital 3D representation of physical assets and a web-based flood simulation tool, *Fastflood App*. The application uses datasets from Open Street Maps for building data, Digital Elevation Model (DEM) and other open-source basemap providers for basemap data. Programming languages such as HTML, CSS, JavaScript, and Python were employed, where web libraries including Cesium JS, Leaflet JS, Three JS, etc were utilised for development. Additionally, the application allows the stakeholders to identify flood prone buildings, enabling them to make informed decisions for real-world applications.

The research specifically intended to create the tool as an open-source project. This was accomplished by using all open-source web libraries, techniques, and datasets, guaranteeing transparency, and paving the way for future community collaboration. The potential applications of the developed approach may include planning and testing mitigation strategies, delineating regions vulnerable to flooding, emergency response and evacuation planning, planning development of new residential areas, risk communication, spreading awareness and more.

Keywords: Digital Twin, Flood modelling, Web development, Decision-support, Open source.

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LIST OF ABBREVIATIONS

1D	One Dimension
2D	Two Dimensions
3D	Three Dimensions
AI	Artificial Intelligence
API	Application Programming Interface
AR	Augmented Reality
CDBB	Centre for Digital Built Britain
CHARIM	Caribbean Handbook on Risk Information Management
COG	Cloud Optimised Geotiffs
CREAD	Climate Resilience Execution Agency for Dominica
CSS	Cascading Style Sheets
DEM	Digital Elevation Model
DMS	Dominica Meteorological Service
DSM	Digital Surface Model
DT	Digital Twin
DTM	Digital Terrain Model
ESA	European Space Agency
FBX	FilmBox
GDP	Gross Domestic Product
GIS	Geographic Information Systems
GLB	GL Binary Format
GLTF	GL Transmission Format
GUI	Graphical User Interface
HTML	Hyper Text Markup Language
JS	JavaScript
JSON	JavaScript Object Notation
LOD	Level of Details
MR	Mixed Reality
NDT	National Digital Twin
ODM	Office of Disaster Management, Dominica
OSM	Open Street Maps
PLY	Polygon File Format
PPD	Physical Planning Division, Dominica
QGIS	Quantum GIS Software

SDG	Sustainable Development Goals
SHP	Shapefile Format
SIDS	Small Island Developing State
TIN	Triangulated Irregular Network
UAV	Unmanned Aerial Vehicle
UN	United Nations
UNDRR	United Nations Disaster Risk Reduction
UT	University of Twente
UTM	Universal Transverse Mercator
VR	Virtual Reality
WFS	Web Feature Service
WGS84	World Geodetic System 1984
WMS	Web Map Service

1. INTRODUCTION

1.1. Societal problem

Global warming leading to climate change is the greatest challenge the world has been dealing with, in recent decades (Pachauri et al., 2007; Rajak, 2021; Sivaramanan, 2015). One of the main reasons for the increase in the temperature of the earth is the emission of greenhouse gases, and the higher emissions can be attributed to anthropogenic activities such as burning fossil fuels for energy, deforestation, mining, agriculture, and transportation (Kabir et al., 2023; Shivanna, 2022). The adverse effects of climate change are not only affecting humankind but also affect all other living beings. Some of the detrimental effects of climate change include higher health risks, frequent and intense rainfalls followed by droughts, forest fires, flooding, glacier melting contributing to sea-level rise, etc (United Nations, 2022). Among all the disasters that could be brought on by climate change, flooding is one of the most frequently encountered and extravagant in terms of both economic and physical losses (Amirebrahimi et al., 2016; Oulahen, 2021).

In recent times, the occurrence of flooding has become more prevalent as a result of an increase in the frequency of high-intensity precipitation events caused by altered weather patterns (Clarke et al., 2022; Morante-Carballo et al., 2022). According to Kundzewicz et al. (2014), the reason for flooding is not always constant in every other area, and it varies depending on the local conditions and factors contributing to flooding in a specific area. Prolonged high-intensity precipitations can cause river flooding, while the melting of glaciers could lead to flooding in places of upper latitudes. Similarly, flooding in cities can be due to rapid urbanization, reduction of green spaces, rise in impermeable surfaces and blockage of water channels (Kundzewicz et al., 2014). Therefore, flooding is caused by a variety of elements, including variations in precipitation events as well as urbanization, and deforestation. Urban areas and cities are particularly becoming vulnerable to flooding, specifically flash flooding, and other phenomena, including air pollution, urban heat islands, typhoons, etc (Gao et al., 2022). Water stagnates due to urbanization's detrimental effect on natural water discharge pathways and capacity overruns in drainage systems (Seemuangngam & Lin, 2024). Additionally, during high-intensity rainfall events in urban environments, absorption is less since infiltration rates are often lower than incident precipitation rates due to impermeable surfaces (Feng et al., 2021). Not only are floods more common in urban areas, but they also cause large damages because of the higher human population density in these areas and increased financial losses from infrastructure damage (López-Martínez, 2023). Everyday lives of individuals are severely interrupted as a result of damaged infrastructure, waterlogging, the spread of water-borne diseases, power outages, and reduced mobility, among other factors, resulting in significant financial losses sustained by individuals as a result of such catastrophes (Mobini et al., 2022).

To lower the risk of flooding in cities, thereby essentially enhancing urban resilience, urban planning and design must be significantly strengthened. Urban flood resilience simply refers to the ability of the cities or urban areas to cope with the changing climate scenarios and their drastic effects. Given the frequency with which floods occur in cities around the world, the need for cities to be highly climate-resilient, specifically flood-resilient, has never been more pronounced. It is also recognised by the UN in the Sendai framework that reducing disaster damage to infrastructure is very critical (UNDRR, n.d.). Urban flood resilience, or urban adaptation to climate change, achieved by means of emphasis on urban planning and design, has been the focus over the past decade (Gao et al., 2022). Authorities and researchers worldwide, ranging from international organizations to local authorities, are planning and implementing various measures aimed at enhancing the resilience of cities. For instance, according to Fu et al. (2023), Sponge City - a green and blue infrastructure solution which, when integrated with existing grey infrastructure, may be an effective strategy for reducing flood risk. A sponge city typically includes more green and blue infrastructure, such as wetlands, green gardens, parks, rain gardens, pervious pavement, and urban green roofs, which increase absorption while decreasing runoff and flooding (Rau, 2022). According to different studies, green spaces in the city can be used as flood storage because green spaces increase infiltration, leading to enhanced underground storage (Alexander et al., 2019; Irvine et al., 2023). Azari & Tabesh (2022) then suggests that enhancing or optimizing the city's stormwater drainage infrastructure could increase the city's resilience to flooding. In conclusion, numerous researchers, city authorities, engineers, stakeholders, and decision-makers have developed, designed, and implemented a variety of creative and successful interventions to make the city adaptable to climate change and the disasters it may cause. Deciding on disaster management won't be easy, though, because many people's lives, their financial well-being and the development of the city are in jeopardy. In order to make an informed decision and make plans accordingly, decision-makers must thoroughly understand what the present scenario is and what will happen in the event of a flood disaster. Therefore, for a better understanding, concepts such as flood modelling for simulating historical and future flooding scenarios, followed by digital twin technology for informed decision making, are to be explored to overcome the societal problem of climate change and other factors-induced disasters, including flooding.

Flood modelling

In general, flooding can be caused due to a variety of factors, including extreme precipitation, increased runoff due to impermeable surfaces, lack of green spaces, river overflows, blocked channels, dam breakage, etc. For this reason, understanding how and why flooding happens is very critical for making informed decisions in emergency planning, mitigation strategies development and designing future risk reduction strategies. Flood modelling, in simple terms, can be defined as the method to understand the characteristics of a flood, such as flood depth, flood extent, etc, by simulating a flood event that has happened or is likely to happen. According to Morante-Carballo et al. (2022), there has not been much research and developments on flood modelling up until two decades ago. During the last couple of decades, the number of publications on 1D and 2D flood modelling increased significantly, and the research worldwide included methods such as hydraulic modelling, hydrodynamic modelling, GIS, remote sensing, and urban flooding (Morante-Carballo et al., 2022). Although a large number of 1D, 2D hydraulic and hydrodynamic models have been developed to assess and analyse the flood conditions, there have been limitations associated with them.

According to the author, 1D flood models are not suitable when overflow situations exist, which is likely the case in most real-world situations. Another drawback of 1D flood modelling is that it often just provides flood depth and inundation maps, which makes it difficult to analyse the situation. On the other hand, different flood parameters, such as flood velocity, flood length, time to flood, and others, are provided through 2D flood modelling. These outputs become more usable when coupled with remote sensing and GIS data that facilitates further visualisation, analysis, and planning, specifically for stakeholders like urban planners, local government authorities, etc (Ahmad et al., 2022). Even though 2D modelling is a more effective method for modelling floods, it still has some drawbacks, such as higher computational power, time, and expense requirements.

Recently, a flood simulation tool called "FastFlood App" [1] has been developed by Bout (2021). It is a tool that is more rapid in computation and more accurate than most of the traditional flood modelling tools. Furthermore, this web-based application provides the possibility to download, visualise, and process global or regional datasets, including the Digital elevation model, Land cover, infiltration, precipitation forecast and OSM buildings/roads on the fly, which are required for the flood model. The aforementioned drawbacks of conventional 2D flood modelling techniques are addressed by the Fastflood flood modelling application, which produces flood simulation results that are up to 97% accurate while requiring very little processing time and power (Bout et al., 2023).

However, because urban areas are densely populated, the accuracy and resolution of the current 2D modelling outputs are not always sufficient for enhanced decision-making. Only high-resolution flood modelling outputs, including high vertical resolution, would truly aid in determining the impacts (Guo et al., 2021; Qi et al., 2021). The vertical information corresponding to flood depth maps is one of the outputs of the current 2D flood modelling. Nevertheless, the flood depth maps alone cannot provide the opportunity for collaborative analysis with any additional assets or infrastructure that could enhance decision-making in the region, usable for end-users, including urban planners, asset owners, asset managers and local government authorities. This encourages the investigation of the third dimension in flood simulation results and the incorporation of other three-dimensional elements at risk to support end users' decision-making across a variety of fields.

Digital twin technology

Digital twin technology has its roots in the manufacturing, production, and industrial domains, among various other sectors. In general terms, a digital twin is an interactive, real-time, engaging digital representation of a physical object, scene, or environment that offers 3D visualization while also offering real-time simulation capabilities. Since no single digital twin can provide information that may be used for all purposes, a digital twin is to be customized for every other application (Ye et al., 2022). The author also believes that digital twins and 3D models are frequently used without distinction despite the fact that they are not precisely the exact same thing. While digital twins are more multifaceted, created with real-time information, and enable users to engage and interact with the twin, 3D models do not provide the real-time integration between the model and the physical world that digital twins do. Digital twin technology, over the decades, has developed its applicability in various fields, including biomedical, aerospace, automobile, transportation, geospatial, smart cities, utilities and more (Caprari et al., 2022; Pedersen et al., 2021; Ye et al., 2022). After years of research, a common definition of a digital twin of a city is still lacking for the purposes of city-level digital twin applications. Some researchers try to define a digital twin as a dynamic digital replica of the actual city that enables information to move back and forth between the virtual and physical worlds (Caprari et al., 2022; *Digital Twin Geohub*, 2023; Ferré-Bigorra et al., 2022; Riaz et al., 2023; Ye et al., 2022).

Digital twins can be used to make informed decisions and send notifications before events occur for the majority of urban applications, including traffic, public security, and others. It specifically aids in planning

[1] https://fastflood.org/

since it provides a setting for the testing and trial of novel city-wide initiatives. To avoid security and ethical concerns, the respective stakeholders must responsibly make use of the technology to promote the welfare of the city and its residents (Tzachor et al., 2022). Digital twin technology poses multiple opportunities for providing solutions to diverse real-world issues, by providing the ability to interact with, immerse in 3D, simulate scenarios, and perform analysis.

1.2. State-of-the-art

Although digital twin technology has been around for a while, minimal research has been done on developing easy, workable solutions for disaster management applications. There aren't many developed applications, and the ones that are limited to being sold commercially. According to Ford & Wolf (2020), research on utilising digital twins and its functional aspects for disaster management applications are becoming increasingly relevant and meaningful. It is because, as the physical presence of decision-makers is not feasible during disasters to assess the ground condition, a virtual replication of the physical environment (DTs) is more relevant for decision-making during a disaster occurrence than other applications. Furthermore, when planning to implement infrastructure upgrades or new flood risk reduction measures, it is always beneficial to try and simulate the effects of these plans before actually implementing them in the real world. As a result, only effective mitigation methods or tactics will be implemented, minimizing the waste of money and effort. For example, Ghaith et al. (2022) employ recent technologies such as sensors, the Internet of Things, and infrastructure modelling to create a city digital twin for simulating and identifying susceptible areas in the event of a disaster. Also, Teeuw et al. (2023) have utilised digital twin technology along with the concept of computational fluid dynamics analysis for developing hurricane preparedness maps, which can further be utilised by planners or other stakeholders to make informed decisions. Overall, the digital twin enhances the understanding of the stakeholders about the complex real-world issues, enables them to test and try out new interventions, and presents the interconnections of the different infrastructures and many other opportunities which are critical in flood risk reduction. Despite the potential of digital twin technology for its applicability in flood risk management, little of it is explored. Some of the previous work combining all the 3-D modelling, digital twin and flood modelling techniques are presented separately in the format of a table in Appendix II.

1.3. Research Gap

The possibility of cascading or coupled catastrophes occurring is particularly high in coastal cities due to their higher population densities, increased vulnerability to natural disasters, and higher likelihood of these factors (Riaz et al., 2023). Dominica, being surrounded by the ocean, is specifically prone and more vulnerable to disasters, including storms and hence, the need for planning is crucial. The importance of establishing mitigation and recovery methods ahead of time is especially important for small island developing states, since recovering from disasters is a long and challenging journey (Barclay et al., 2019). Limited studies have utilised current advancements in technologies for the study of disaster management in Dominica, and no digital twin-based fully functional open-source tools are available for flood simulations. Thus, the study attempts to create a digital twin of Dominica's infrastructure, including buildings, followed by studying how the area responds to different flooding instances using a flood simulation tool, "Fastflood App" [2]. As a result, the goal is to assist decision-makers primarily, as well as asset owners and residents, in efficiently preparing for future flooding situations.

[2] https://fastflood.org/

1.4. Objectives

Based on the motivation presented in the previous section, the overall objective for this study is

"To develop a digital twin framework that assists in the decision-making process for flood risk reduction and mitigation planning".

Sub-objectives and Research Questions

1. To understand the stakeholders' requirements and review the open-source methods available for developing digital twins for flood risk reduction and mitigation planning.
   i. What are the requirements of users in a 3D decision support tool for flood risk management?
   ii. What are the current open-source techniques for creating digital twins of cities that can be employed in disaster management applications?
   iii. What are the input datasets needed to create a digital twin tailored for flood risk management?

2. To develop a web-based digital twin framework tailored for flood risk management applications.
   i. What are the prerequisite data preparation steps needed to create a digital twin?
   ii. How to integrate the available multiple datasets and build a digital twin of the study area?
   iii. How is the existing fast flood model integrated with the 3D visualization of elements-at-risk on the web?

3. To assess the developed digital twin for decision-making in flood risk management.
   i. How does the proposed Digital Twin framework for flood risk management perform, and align with the Gemini Principles in enhancing the decision-making process of stakeholders?
   ii. What could be the future advancements in the tool?

1.5. Research Matrix

The information in table 1 below, illustrates what datasets are processed and how it is handled for each research question under the sub-objectives, as well as the results.

	Sub-objectives	*Research Questions*	*Required Data*	*Method*	*Results*
1	To understand the stakeholders' requirements and review the open-source methods available for	1.1. What are the requirements of users in a 3D decision support tool for flood risk management?	Questionnaire	Survey using Questionnaire	Completed survey results. Observations from the survey outputs.
		1.2. What are the current open-source techniques for creating	Previous research work.	Literature review.	List of current open-source techniques for

	developing digital twins for flood risk reduction and mitigation planning.	digital twins of cities that can be employed in disaster management applications?			creating digital twin.
		1.3. What are the input datasets needed to create a digital twin tailored for flood risk management?	Previous research work.	Literature review.	List of input datasets required for developing DT for disaster management applications.
2	To develop a web-based digital twin framework tailored for flood risk management applications.	2.1. What are the prerequisite data preparation steps needed to create a digital twin?	Previous research work.	Literature review.	List of data preparation steps, methods prior to DT development. Textured 3D Model of Coulibistrie generated from UAV imagery.
		2.2. How to integrate the available multiple datasets and build a digital twin of the study area?	Input datasets (refer table 2).	Integrate multiple datasets and create a digital twin.	Digital twin of Roseau, Dominica tailored for the purpose of this study.
		2.3. How is the existing fast flood model integrated with the 3D visualization of elements-at-risk?	Developed Digital twin and Fastflood app.	Integrate them to form a wxeb-based tool.	Web based Digital twin of study area with flood simulation capability.
3	To assess the developed digital twin for decision-making in flood risk management	3.1. How does the proposed Digital Twin framework for flood risk management perform, and align with the Gemini Principles in enhancing the decision-making process of stakeholders?	Results of this research study.	Analysis.	Discussion on assessment of the efficiency of the tools against the set of principles.

	3.2. What could be the future advancements in the tool?	Previous research work, Results of this research study.	Analysis.	List of future recommendations/improvements.

Table 1 Research Matrix

1.6. Conceptual Diagram

A conceptual framework typically maps the concepts that are implemented as variables in a given study and indicates the relationship between the variables, resulting in a better comprehension of the research's focus concerns and the way they work (Leshem & Trafford, 2007). In this section, the topics of this study's emphasis, their relationships and the wickedness of the research problem are presented through the use of the conceptual framework. A problem's wickedness is typically assessed by considering the level of knowledge needed to solve it and the degree of agreement amongst potential stakeholders.

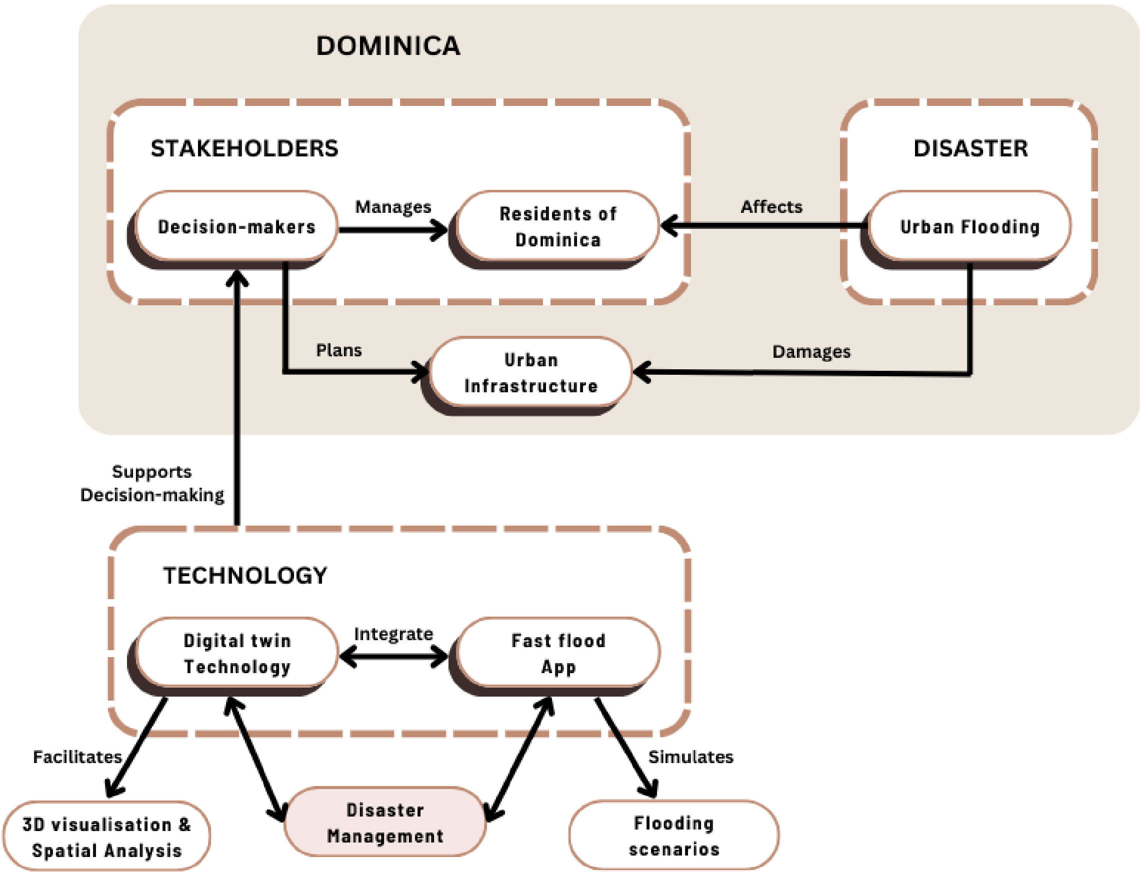


Figure 1 Conceptual framework.

Decision-makers in the study area have not yet thoroughly examined the use of third dimensions in flood simulation and visualization, a lack of knowledge that this work aims to address. By using a 3D decision support tool, this study aims to provide stakeholders with a thorough understanding of the effects of flooding, thereby increasing the probability that the city's flood resilience will be strengthened. The resultant tool's visualisation feature will also lessen stakeholder disagreements by raising their awareness and understanding of the issue when new disaster management policies are implemented. Consequently, the study proceeded with the goal of analysing and decreasing the research problem's wickedness.

Considering that the study addresses the decision-making process in flood risk management, the conceptual framework firstly involves both the stakeholders who make the decision and those for whom the decision is made, followed by the disaster bubble, which includes floods, and finally, the domain of technology. There are two key themes within the technology bubble that will be the technological emphasis of this study extensively: digital twin technology and flood modelling software, "Fastflood App".

1.7. Stakeholder analysis

This section addresses the dimension of stakeholders via a systematically carried out stakeholder analysis. Firstly, people who have a "stake" in the project's design, implementation, and results are commonly referred to as stakeholders. Alternatively, "stakeholders of a project" can also refer to the people who will be affected or have an influence on the development and implementation of the project (Bryson, 2004; Freeman & McVea, 2005; Reed et al., 2009). Identifying and classifying the stakeholders of the project is essential to better address the social impacts of the project, i.e. the design and development of a decision-support tool. Various levels of stakeholder involvement are applied depending on the nature of stakeholders and how they are related to the project. Firstly, the relevant stakeholders are identified and then categorised based on their nature. The following sections address stakeholder identification and classification.

1.7.1. Stakeholder identification and classification

In the section, the relevant stakeholders are identified and presented with the help of a stakeholder interest table. The stakeholder interest table provides an overview of identified relevant stakeholders, how they are relevant to the project, and what their interests are. In the stakeholder interest table, the stakeholders are identified by analysing the project documents, literature review, previous research outputs and field visit observations.

The identified stakeholders can then be classified based on various classification criteria (Fig. 2). The classification criteria provided by (Mitchell et al., 1997) seem to be the most prominent ones used to classify stakeholders based on power, legitimacy, and urgency. However, in this research, the focus is on developing a tool/technique to build the capacity of the specific stakeholders to improve resilience. For this type of research, a broader approach of classifying stakeholders as primary and secondary, as given by (Clarkson, 1995; Freeman & McVea, 2005), is seen as suitable (Jepsen & Eskerod, 2009). Primary stakeholders are the intended beneficiaries of the project while secondary stakeholders are all the other stakeholders in relevance to the project. The stakeholder interest table is presented in Appendix I, including the categorisation of primary, secondary, and external stakeholders.

Table I. Stakeholder classification typologies

Authors	Classification/criteria used
Goodpaster (1991)	The strategic and the moral stakeholder
Savage *et al.* (1991)	Stakeholder's potential powers to threaten or cooperate with the organization
Clarkson (1995)	The primary (with formal relationships) and the secondary (without formal relationships)
Mitchell *et al.* (1997)	Power, legitimacy and urgency
Rowley (1997)	Network density and the centrality of the organization focus
Scholes and Clutterbuck (1998)	Power of influence, impact on the organization and affinity with organizational objectives
Kamann (2007)	Power and the level of interest
Fassin (2009)	Classical stakeholders, stakewatchers, stakekeepers

Figure 2 Literature addressing stakeholder classification criteria (Mainardes et al., 2012).

1.7.2. Stakeholder classification matrix

Generally, a stakeholder classification matrix can be prepared for understanding the relation between various attributes of stakeholders, including interest, importance, influence (or Power) and interaction. In this study, a stakeholders' classification matrix is created to visualise the interest of stakeholders in the project in comparison with the importance of their interests. This stakeholder classification matrix is constructed based on the information from the stakeholder interest table (refer Appendix I). The classification matrix is presented in Figure 3.

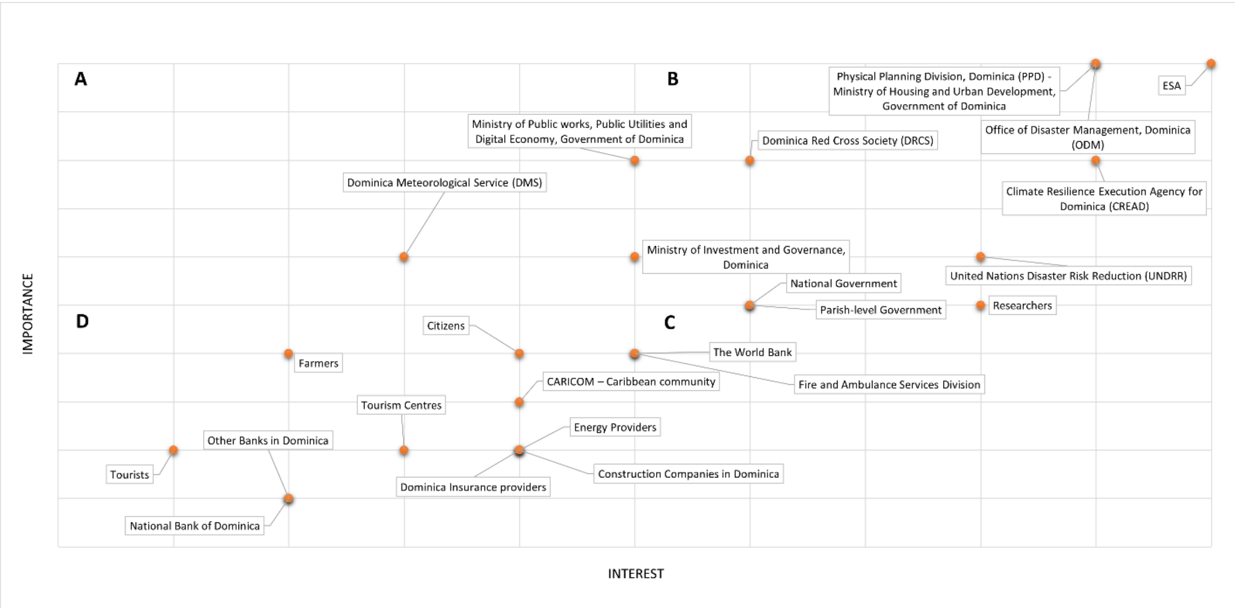


Figure 3 Stakeholder Classification Matrix

The Matix is divided into four Quadrants based on the combination of values of interest of stakeholders in the objectives of the project against the importance of their interests in the development of the project. Quadrant B represents the higher values of interest and importance while Quadrant D defines the stakeholders with low interests and low importance in the project. Quadrant A refers to the stakeholders with high importance however they have relatively less interest in the objectives or outcomes of the project. Quadrant C presents the stakeholders those are highly interested in the design, development, and outcomes of the project however, their importance in the project is relatively less. By reviewing the matrix, it was obvious that the majority of the primary stakeholders considered vital in the research have aligned interests in the study's goals. Some of the primary stakeholders including physical planning division and office of disaster management in Dominica expressed their interests in a visualisation tool during the field campaign of this study.

1.8. Thesis Structure

The research document consists of 7 chapters. Chapter 1: Introduction entails the problem statement, research gap, objectives, the research matrix, conceptual diagram and stakeholder analysis. The research matrix encompasses a matrix of Sub-objectives, research questions, datasets, methods, and results obtained. Chapter 2: Study area and Datasets, includes the description of the study area and datasets used for the research followed by the ethical considerations. Chapter 3: Research design and methods, presents the overall methodology followed by the detailed description of the methods employed in the research. Chapter 4: Results presents the direct outcomes of the methods mentioned in the previous chapter. Chapter 5: Discussion includes assessment of the results followed by research implications, limitations, uncertainties and future advancements. Chapter 6: Conclusion answers the research questions and discusses the concluding impression of the author on the study.

2. STUDY AREA AND DATASETS

2.1. Study area

Dominica is a small island country located on the Caribbean Sea. It is one of the 39 Small Island developing states (SIDS) recognised by the United Nations (United Nations, 2024). Dominica has boundaries defined to the north by the French islands of Guadeloupe and Marie-Galante, and to the south by Martinique. Dominica covers an area of 750 square kilometres and has a population of approximately 72,000 people (Commonwealth, 2022). Figure 4 displays the selected study areas: a) Roseau, capital of Dominica, b) Coulibistrie, for this research project.

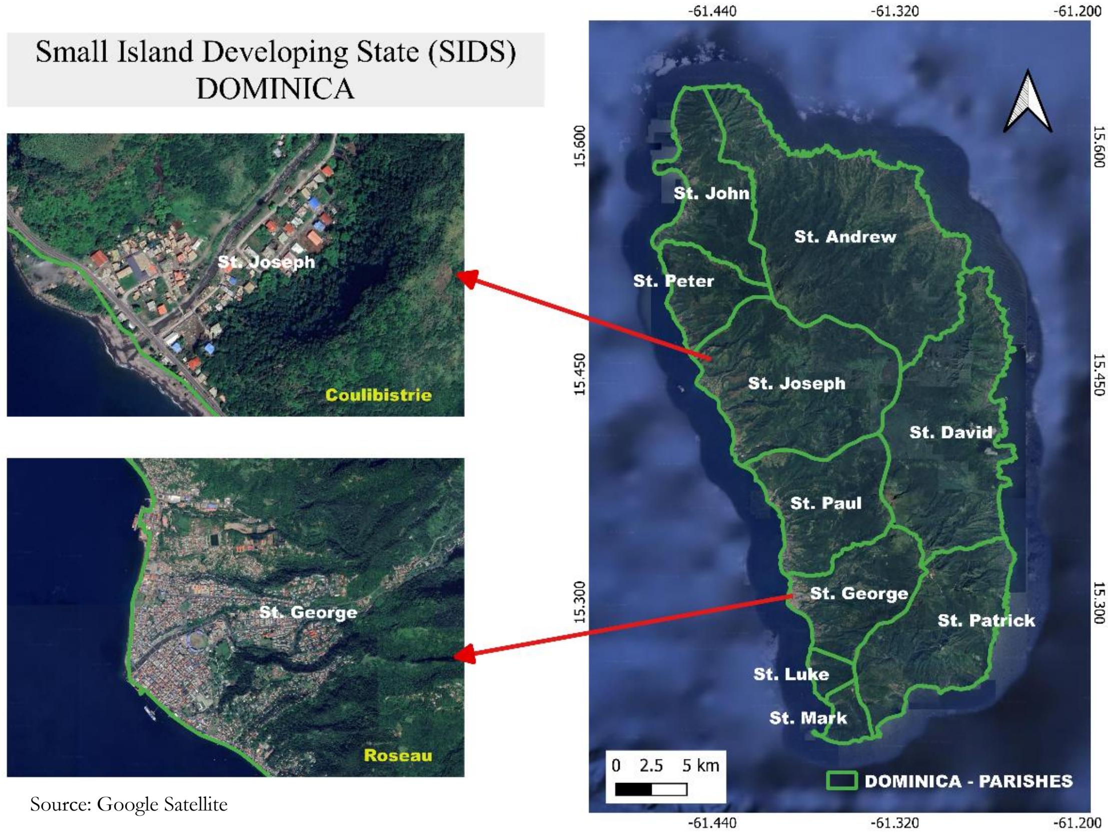


Figure 4 Study area

The capital city of the country is Roseau, which falls on 15.18° N latitude and 61.23° W longitude (Barclay et al., 2019). Roseau's geographic location, which includes numerous river tributaries flowing through the city and then into the sea, offers better possibilities for visualisation and analysis in the context of flooding. Additionally, Roseau has been the primary site of human settlement since colonial times, providing an opportunity for this study to have an impact by understanding flood risk as a more general objective (Barclay et al., 2019). As of 2020 Population density dataset (Figure 5), the city of Roseau has the highest population density. Thus, Roseau could be a suitable location for this pilot study on digital twin development for flooding application. The second study area is Coulibistrie, falling within the administrative boundary of Saint Joseph Parish. It falls on 15.4604° N latitude and 61.4516° W longitude. This small coastal village island of Dominica also serves as an ideal location to understand the interaction of flood water with the settlements.

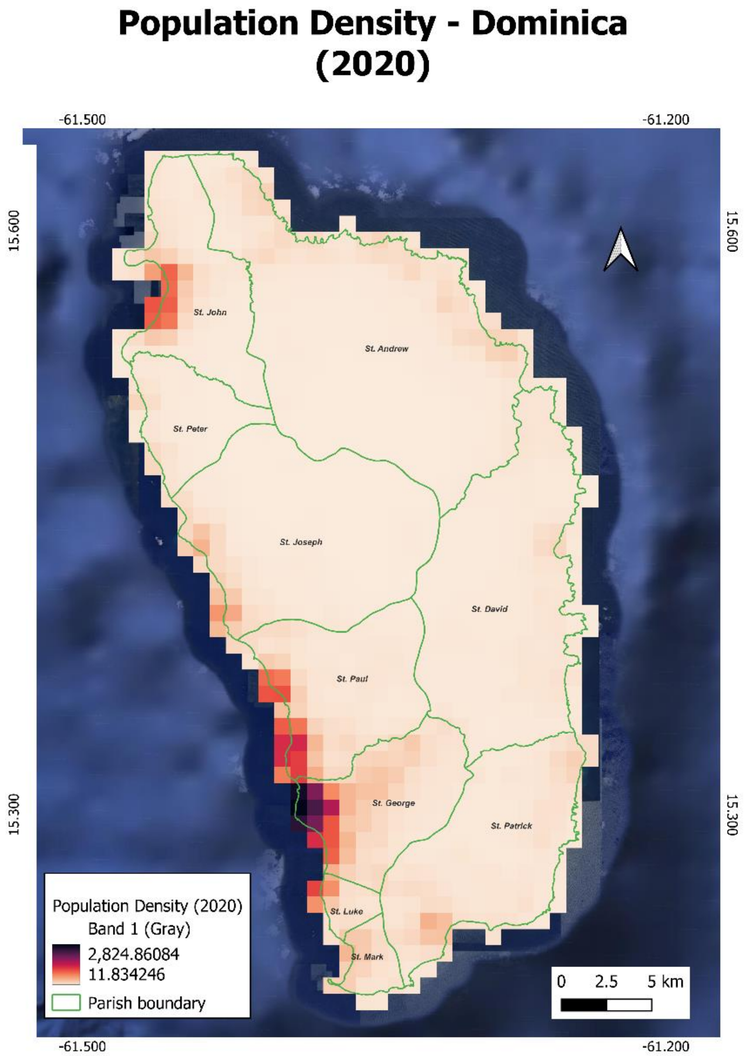


Figure 5 Population density, 2020 (Humanitarian Data Exchange, 2020)

2.2. Datasets

In this section, the list of primary datasets and derived datasets are mentioned. The table 2 entails the list of primary and derived datasets with their name, file format and licensing information. A detailed list of datasets is attached in Appendix III.

Dataset	*Format*	*Source/License*	*Description*	*Availability*
Digital Surface Model (DSM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital surface model	Available
Digital Elevation Model (DEM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital elevation model	Available
Digital Elevation Model (DEM) LiDAR Generated	Tiff (.tif)	ITC, University of Twente	LiDAR captured Digital Elevation Model	Available
Precipitation datasets	CSV	ITC, University of Twente	Text file of two columns:	Available

			precipitation values and time entries.	
Buildings	Shapefile (.shp)	Open Street maps	Vector file of buildings	Available
Aerial Imagery	Tiff (.tif)	(*OpenAerialMap*, n.d.)	Raster file of Roseau (2018)	Available
	Tiff (.tif)	(*OpenAerialMap*, n.d.)	Raster file of Coulibistrie (2017)	Available
Population Density	Tiff (.tif)	(Humanitarian Data Exchange, 2020)	Raster file of Population density values of Dominica	Available
National and Sub national boundaries of Dominica	Shapefile (.shp)	(Humanitarian Data Exchange, 2019)	Shapefile of boundaries	Available
UAV Imagery	Tiff (.tif)	ITC, University of Twente	Images captured using UAV of the Study area (Feb 2024)	Available
Stakeholder requirements	Text file (.csv/.xlsx)	ITC, University of Twente	Survey results	Collected

Table 2 List of Datasets

The Digital surface model (DSM) is available for the coastal areas of Dominica. The dataset covers the coastal line of the entire island. The resolution of the dataset is 0.5 m x 0.5m. The Digital elevation model is available for the entire island of Dominica. It has a spatial resolution of 10m x 10m. Another Digital Elevation model dataset obtained through LiDAR sensor has a resolution of 5 x 5 meters. Utilising a higher resolution DEM, increases the output resolution of flood output as well. The buildings dataset is provided by Open Street Maps (OSM) (OpenStreetMap, 2024). The Open Aerial Map website allows individuals to download aerial imagery of Roseau and Coulibistrie. Global medic uploads the data there as part of the RescUAV Program. The aerial imagery of Roseau and Coulibistrie was acquired in 2018 and 2017, respectively, with resolutions of 5 and 3 cm (*OpenAerialMap*, n.d.). The population density and administrative boundaries of Dominica datasets are acquired from the Humanitarian data exchange platform (Humanitarian Data Exchange, 2019, 2020).

During the fieldwork done earlier this year, by Feb 2024, UAV imagery was collected. This UAV imagery was used to further generate 3D models for further processing. The datasets were collected during the fieldwork carried out by the colleagues of ITC. The 3D models were derived from UAV imagery using photogrammetric techniques employed by the software Pix4D. The image Coordinate System is WGS 84 (EGM 96 Geoid0), but the Output Coordinate System of 3D model is WGS 84 / UTM zone 20N (EGM 96 Geoid).

During the early stages of the study, the questionnaire prepared to understand the user requirements, was presented to collect stakeholder input. This generated dataset was further analysed and utilised for the design and development of the digital twin.

2.3. Software and tools

The software, web packages and tools employed for this research include:

- **Fastflood App:** Flood modelling web application to be integrated with 3D model and precipitation forecast data to create a Digital twin framework for flood management applications.
- **QGIS:** GIS data processing, analysis, and layout creation.
- **Blender:** 3D modelling software to import, process, animate, analyze, and export 3D models, add textures, and visualize realistic 3D models.
- **Web libraries:** Cesium JS, Three.js, Geotiff.js, Georaster-for-leaflet.js, Leaflet.js, etc.

2.4. Ethical Considerations

The Ethical consideration for this research includes the data collected through the stakeholder engagement activity, i.e., a survey using a questionnaire. The ITC Geo Ethics committee of University of Twente performed the ethics assessment using the ethics questionnaire available on the website. Ethical approval was obtained for the research from the committee, and the guidelines provided by them were followed during the research. The research data was also encrypted using UT recommended encrypting software. No personal or any information leading to identification of any individual is included in the publishing documents. Any personal information of the stakeholders collected will be destroyed by the end of this research.

2.5. Summary

This chapter entails a detailed description of the study area chosen for this research. The study area discussed includes Roseau, the capital city of Dominica and Coulibistrie, a coastal island in Saint Joseph Parish of Dominica. This chapter also presents the datasets utilised for the research with their resolution, licensing, and other information. Additional datasets for the research are mentioned in the table attached in the Appendix III. Next, the software employed during the research, along with a brief description of its purpose, is presented. Finally, the ethical considerations and measures followed are elaborated.

3. RESEARCH DESIGN AND METHODS

In this chapter, the overall research methodology framework is presented, followed by a detailed explanation of individual methods and/or techniques employed in the methodology.

The overall methodology framework is presented followed by a description of each phase of the methodology employed to obtain the results for this study. The overall methodology is given in the Figure 6.

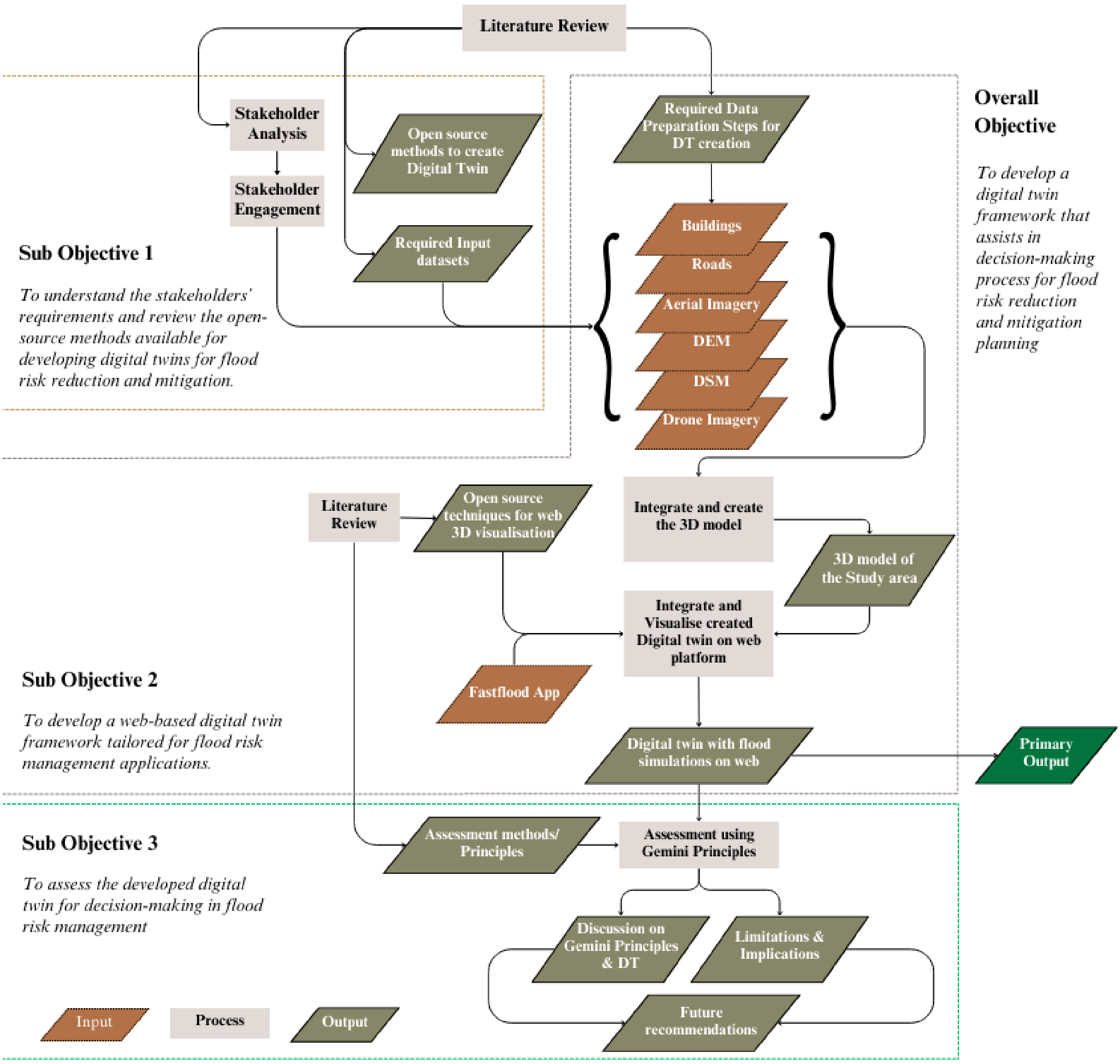


Figure 6 Overall Methodology

The overall methodology can be divided into three broad phases. The initial phase of the research methodology includes identifying datasets and existing methods to develop a city digital twin for flood management applications. During this phase, the stakeholder engagement activity is also performed to gather user requirements on a decision support tool for flood hazard management. Secondly, literature review on identifying open-source techniques to develop DT specifically on web for flood application was explained, followed by the data preparation steps. This is followed by the final phase, which includes the actual development of city digital twin for flood management by employing local and global datasets. This developed model was intended to function smoothly in integration with the flood model, i.e. Fastflood App, to create a fully operational digital twin for flood hazard management.

3.1. Stakeholder Engagement

3.1.1. Survey

During the first phase of the project, a stakeholder engagement activity was conducted to collect the stakeholder input on their requirements, needs or expectations on a decision support tool for flood risk reduction and mitigation planning. The activity involved conducting surveys with the help of a well-curated questionnaire developed using Microsoft Forms. The questions were iteratively designed and modified to better capture the interests of the stakeholders. The questionnaire focused on the Fastflood App, its features and what functionalities could potentially be appended to the tool so that the app serves as an efficient and essential decision-support tool for flood hazard management. The questionnaire addresses the type of stakeholders participating in the survey, their relation to the decision support tools and their expectations of such a tool in terms of the visualisation, processing, and analytics aspects of the application.

The table below (Table 3) elaborates on the categories of questions in the questionnaire, their data type, optional status, remarks, and number of answers (single/multiple).

	Questions	*Data type*	*Required/ Optional*	*Single/ Multiple*	*Description*
Participant	Role/Occupation	String	Required	Single	Occupation of Survey participant
Participant and Decision Support tool	How often the participant interacts with the tool?	Rating	Required	Single	1-5
Technical Aspects of the tool	What types of features of interest to visualise?	String	Required	Multiple	Roads, Buildings, etc
	Level of interactivity within the tool?	String	Required	Single	Basic/Advanced
	LOD of the 3D Model?	String	Required	Single	Level of Detail
	Necessary features within the tool?	String	Required	Multiple	Important features in a decision support tool
	Additional datasets to explore?	String	Required	Multiple	-
Applications	Potential applications?	String	Required	Multiple	Applicability of this tool.
	How useful is this tool?	Rating	Required	Single	Level of usefulness
Stakeholders' involvement	How much should the stakeholders be involved in decision making?	Rating	Required	Single	Low, Medium, High
Communication	Is it necessary to communicate risk through this tool? If yes, how often?	Boolean If yes, String	Required	Single	Yes/No
Data Privacy	How important does data privacy matter?	Rating	Required	Single	1-5

Extra	Additional Comments	String	Optional	Single/ Multiple	-
	Graphical Representations for visualising flood variables?	String	Required	Multiple	This question was added only in a later version
	Effective communication techniques for flood risk	String	Required	Multiple	This question was only included in the earlier version

Table 3 Survey Questions

The survey was conducted at four different events to collect responses. The first event was a project meeting where experts from planning, disaster management and geospatial fields participated. A total of 16 responses were recorded during the event. The second event at which the survey was conducted was a class seminar at ITC, thus, the participants were majorly master program students of 3D modelling and urban planning. Some of these students also have work experience as decision-makers or policymakers. A count of 13 responses were collected during this instance. During the third time, the survey was conducted in a class of students majoring in floods and hazards, where four responses were collected. The final point of time, when the response was recorded, was during the fieldwork of colleagues in Dominica. A single response was recorded during this field work. The final version of the questionnaire that was used for collecting the responses is attached in the Appendix IV.

3.1.2. Stakeholder Interview

During this field campaign, some of the stakeholders did not record their input in the form however, their opinions and interests were collected by colleagues in the way of interviews. These stakeholders include the Office of Disaster Management, Dominica (ODM), the Physical Planning Division of Dominica (PPD), the Ministry of Public Works - Public Utilities and Digital Economy - Government of Dominica, Dominica Red Cross Society (DRCS) and the Climate Resilience Execution Agency for Dominica (CREAD). The aforementioned stakeholders were interviewed by other colleagues involved in the overall research, of which this particular research is a part, and those stakeholders' views were gathered (Bout et al., 2024).

3.2. Methods Identification and Datasets Preparation

3.2.1. Literature Review

In addition to the literature review performed in the initial sections, literature that are very similar in construction to this study are filtered from various sources for identifying the current technological advancements in the field. Firstly, to explore and comprehend the available techniques to prepare the datasets and develop an open-source framework for the Digital Twin, literature review was conducted. The literature review was conducted with the help of databases including Google Scholar, IEEE Xplore, Research Gate, Springer Link, etc. The majorly used keywords include 'Digital Twin', 'Flood', '3D visualisation/visualization', 'web', etc. The fundamental purpose of this literature review was to get a comprehensive understanding of the research that has been happening in the field and to identify the techniques and datasets required. Additionally, from the literature, a historical event of significance in both the contexts of Dominica and Flooding was to be identified for flood simulation. This was further used to test and iteratively optimise the development. This step in the methodology is vital as it acts as input for further steps in the entire research.

Since this is a development and explorative study, literature review is considered to be essential for acquisition of diverse information. The extensive list of stakeholders in the study area i.e., Dominica was also identified from the literature and insights from prior projects. The next section discusses the preparation of datasets identified and necessary for the development.

3.2.2. Dataset Preparation

This section primarily addresses the steps carried out to prepare the datasets necessary for further integration and visualisation on the digital platforms. To begin, the existing Fastflood App[3], a web application accepts input parameters such as elevation, landcover, infiltration, rainfall, and other variables to create rapid flood simulations. The application provides facilities to auto-download input parameters for the simulation by using global datasets available. Precipitation data can also be auto downloaded or included manually to predict the flood conditions in an area. The tool allows to download precipitation forecast data, which allows for near real time monitoring of flood conditions in the area. This simulation feature generates the flood water height as a raster array output. In the existing stable version of the app, this raster array is converted as a Georaster layer using *the georaster-layer-for-leaflet JavaScript* library and is visualised as a raster overlay over a 2D web map. Figure 7 below shows an example of a simulation output visualised on the Fastflood App in 2D. The figure displays the output flood height values of a 100-year return period event in Roseau city of Dominica.

Figure 7 Simulation output in 2D visualisation (Fastflood App: https://fastflood.org/)

This data can further be utilised for visualisation on the third dimension. The further steps of integration and development on the web platform are explained in detail in the following section.

[3] https://fastflood.org/

Textured 3D Representation

Next, for exploring high fidelity third dimension visualisation on the integrated DT framework, certain data preparation steps were carried out. First, the UAV imagery of the study area, Coulibistrie was processed using Pix4D. This UAV imagery was collected during the field work of ITC member in Dominica in Feb 2024. The Pix4D software is a photogrammetry software employed for UAV mapping (Pix4D, 2024). The software leverages photogrammetric techniques to generate a point cloud dataset or 3D data models for further use. A 3D model of Coulibistrie as of Feb 2024 is generated using UAV imagery and Pix4D. The note, "*The 3D Textured Mesh file is not georeferenced. It has coordinates on a local coordinate system centred around the project*", generated along with the results from Pix4D software. The 3D model can be exported in different file formats namely fbx, obj, ply, and dxf. The outputs are then integrated into the DT framework.

3.3. Development of Digital twin framework

The development of digital twin framework for flood risk management using geospatial datasets, web development techniques and flood model: *Fastflood App*[4] is addressed in this section.

The method employs open-source packages and techniques to utilise open-source global datasets to create a digital twin capable of simulating multiple flood scenarios and visualising those scenario outputs in a third dimension. This technique uses a wireframe design as its graphical representation of the 3D elements. It is purely LOD1 when looking at the DT from a Level of Details perspective. As identified from the survey earlier, from the stakeholder perspective for this context of the problem i.e., flood hazard management, the LOD1 already sufficiently satisfies the preliminary needs of the stakeholder. However, this research further explores the LOD2 of 3D modelling of the study area through photogrammetric techniques and open-source software, including Blender, in a later section.

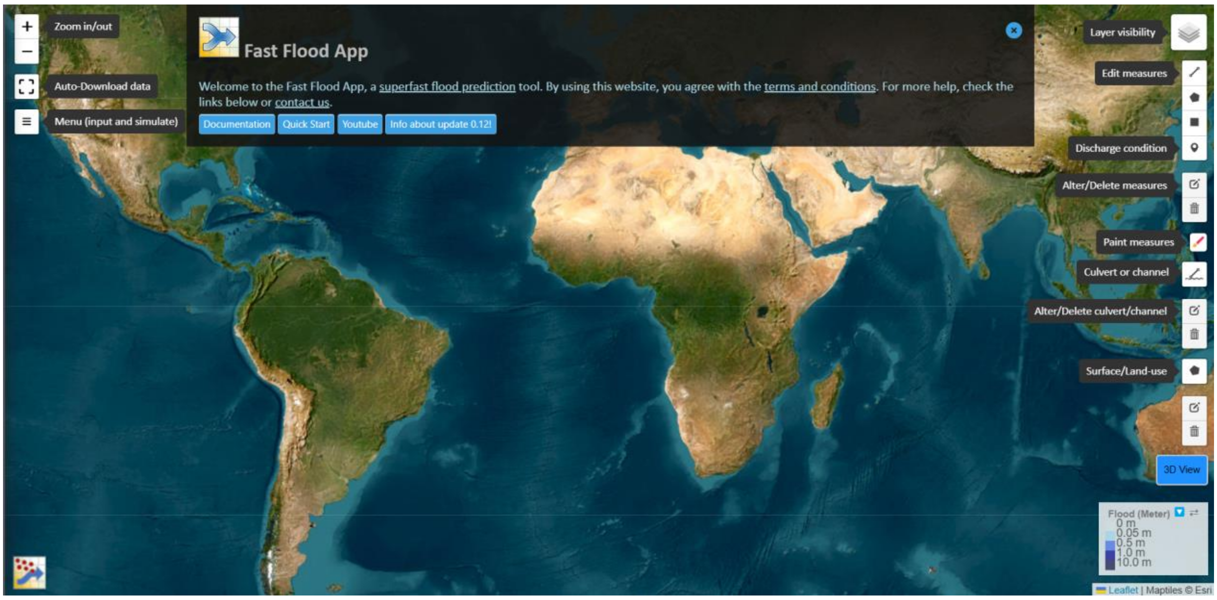


Figure 8 Fastflood App with new button: 3D View

[4] https://fastflood.org/

This section starts from the existing flood simulation tool, primarily based on web. Using the Cesium JS package, a three-dimensional perspective to analyse the simulation results was added. The Cesium JS package files among other packages are imported into the Fastflood App[5] development environment i.e., Github repository (https://github.com/FastFlood/FastFloodApp). A new tool named *3D* View, was added on the right-side panel of the homepage.

The '3D View' button on-click, switches from 2D Map view into a 3D Globe view. When clicked, this tool initialises a Cesium Globe Viewer, and the Open Street maps (OSM) building datasets are added to the viewer to visualise the buildings in 3D at LOD1 (Level of Detail). The user can visualise the water height values as a raster overlay over the Cesium Globe. Figure 9 depicts the detailed development workflow of web development performed.

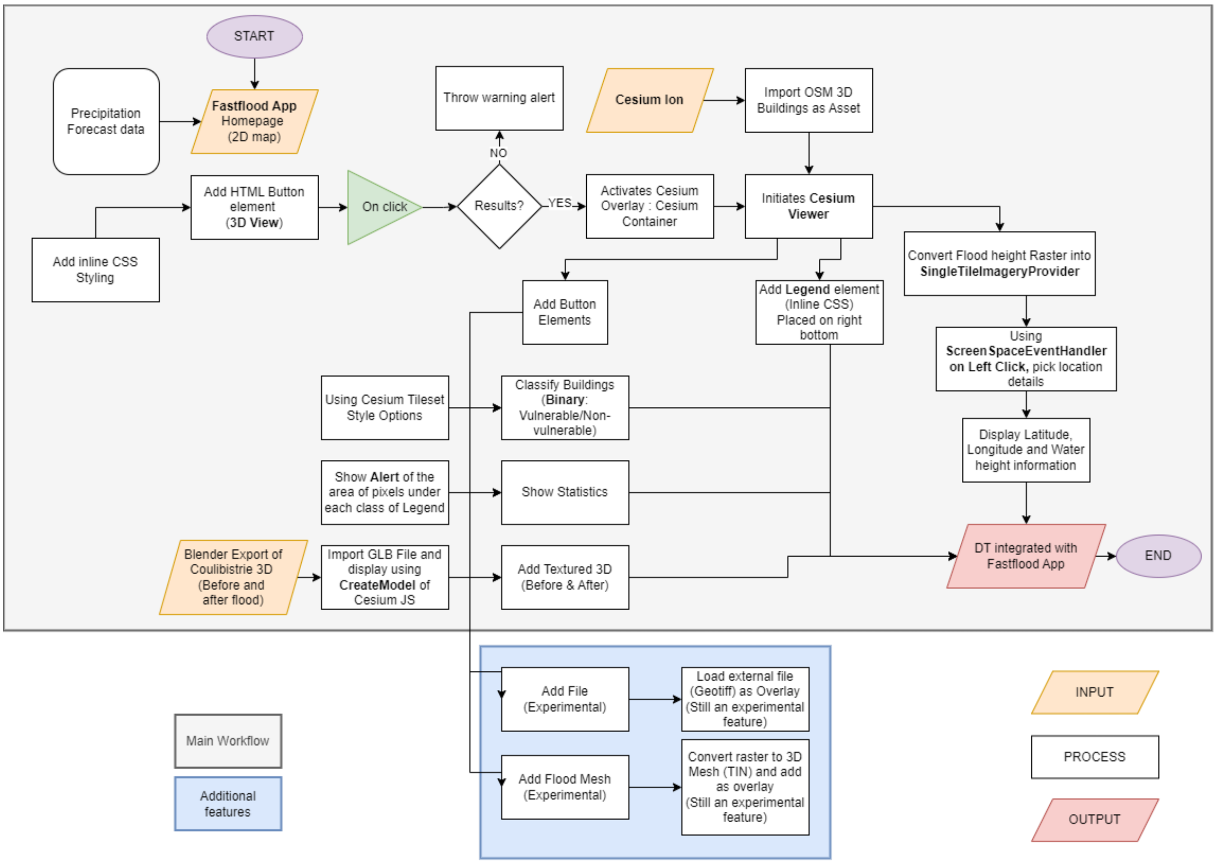


Figure 9 Workflow - Development of Digital twin on Web

As mentioned above, the required Javascript packages such as Cesium JS, Leaflet JS, GLTF Loader JS, Tippy JS and more along with CSS modules are included into the development environment. The detailed workflow elaborates on the methods and libraries utilised to achieve the desired output. The new '3D View' button HTML element is added to shift the view to Cesium Globe. Subsequently, the viewer is opened. The Cesium viewer has a button element on the top right corner, '2D View'. This shifts the user's view back to the original homepage in 2D, i.e., 'Cesium Container' to 'Map container'.

[5] https://fastflood.org/

When the 3D View option on screen is clicked without having simulation results, the app would throw an alert. If results exist, the flood height would be added onto the Cesium Viewer and zooms to the location of the results. The legend for the flood variable was added to the bottom right corner of the container. The legend scale in both viewers is matched to enhance the interpretability and comprehensiveness of the users. Furthermore, the 'ScreenSpaceEventHandler' is employed to pick the specific location's information on water height, latitude and longitude and display it when 'Left-clicked'.

Five different button elements are appended as child to the parent 'Cesium Container'. Three of them are fully functional while two are 'experimental'. As the name suggests, the 'experimental' features are explored during the study. Three functional buttons include 'Show Statistics', 'Classify Buildings', and 'Add Textured 3D'. The first button displays the total area covered under each legend class. Thus, it displays the statistical information as an alert. Second, 'Classify Buildings' classifies the buildings as vulnerable and non-vulnerable. The algorithm employed behind is the simple logic of 'If water height of a pixel > 1 m {Buildings within (Buffer of 0.001 around the pixel)} = Vulnerable else {non-vulnerable}'. The vulnerable buildings are shaded in red. The third option, 'Add Textured 3D' shows two high-fidelity, static 3D scenes of the Coulibistrie study area. In order to communicate to the stakeholders if this could be of additional value to them, before and after flooding 3D scenes of the area are given. This paves the way for future investigations.

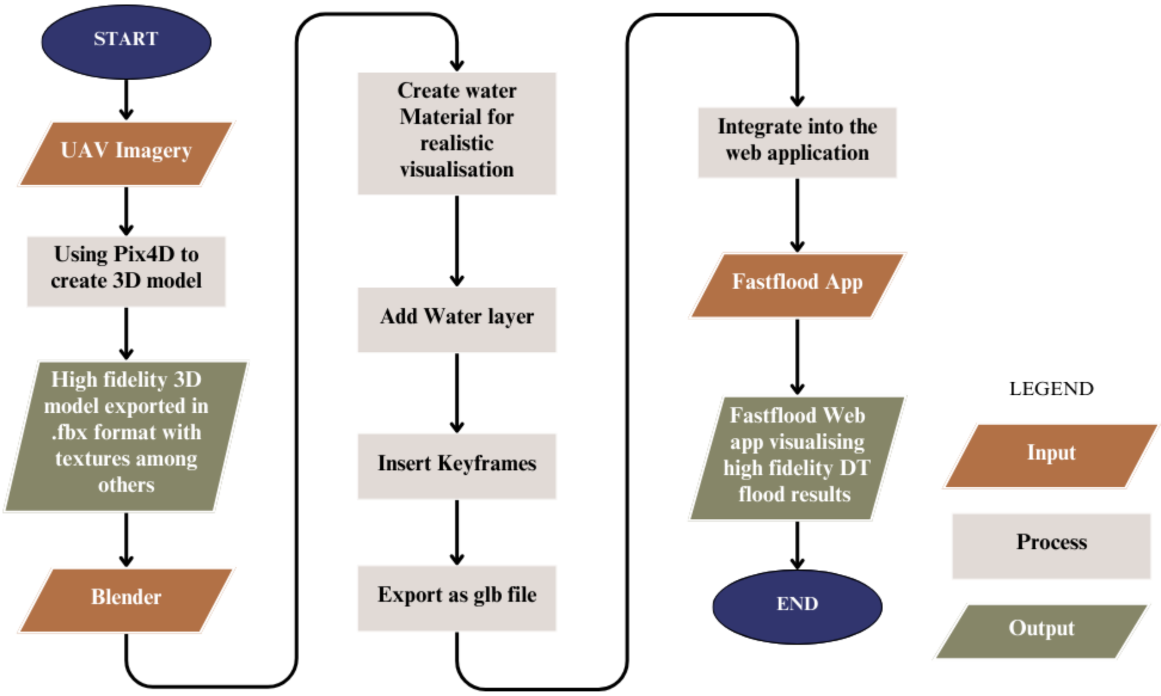


Figure 10 Workflow - Preparing High fidelity 3D Scenes of before and after flooding in Coulibistrie

Prior to attaching the static scenes, some manipulation on Blender needs to be done to the 3D models generated from the captured UAV Imagery. Figure 10 presents the workflow followed in Blender to generate the static scenes.

Among other file exports of 3D Model from Pix4D, fbx file format of 3D model is imported into Blender for further processing. Fbx file format is the comparatively suitable 3D file format among the others for storing and importing 3D assets along with their textures, painting, and animation information (Autodesk, 2024). Blender application is an open-source 3D modelling software used for processing and manipulating 3D assets along with animating simulation scenarios and more (Blender, 2024a).

The visualisation, which was created using the high-fidelity 3D model and the Blender[6] tool, depicts an animation of a pre and post increase in water level across the research region i.e., Coulibistrie. This can be accomplished by designing a realistic water material in the material editor. The water plane and Mesh could be modelled together so that the interaction depicts the pre and post water heights in case of a flooding event.

Finally, the two experimental buttons include Add file and Add flood Mesh. The Add file button was intended to allow the users to overlay external Geotiff datasets to perform an extensive analysis by combining multiple datasets. However, at the time of this document, the feature only allowed specific Geotiff files with custom-defined coordinate systems. Therefore, the feature was explored solely for experimentation and is not a component of the fully functional digital twin workflow. This was explored to see the interaction between different datasets if possible. Secondly, the 'Add flood Mesh' button involves add a 3D Mesh of the water height values obtained through the simulation. For this purpose, the JavaScript libraries including Three JS, Turf JS were included in the development environment and the feature was attempted. However, many challenges were faced specifically with the computational power and time. This, nevertheless, could be a potential research direction for future as this is a novel approach that not many researchers have attempted in the past.

3.3.1. Additional

Furthermore, as a continuation to the LOD2 3D Model derived from UAV Imagery and photogrammetric techniques, some animations with detailed 3D model and fluid object was explored. The Water plane with realistic water material was then placed such that it intersects with the 3D mesh (Coulbistrie) and the water level rises 0.5 m for every timestep. This method allows for the steady rise in water level over an area to be demonstrated in order to understand the ground situation during a flood event before it occurs.

Additionally, for the next type of visualisation, after importing the 3D Model of Study Area - Coulibistrie into Blender, it can then be manipulated by adding textures, adding new features for creating water simulations. Over the 3D mesh dataset of Coulibistrie, two cube items were added. To design fluid simulations using physics settings in Blender, there has to be three primary type of assets. Our study area 3D mesh acts as the *effector*, while a new cube to be added acts as a *domain* and another cube acts as an *inflow* object. Under the *fluid* option of Physics tab, the option for setting the objects as Domain, flow or effector has to be turned on. There are options to modify the viscosity of the fluid, acceleration of the fluid in x, y or z axis and more. These can be manipulated according to the specific needs of the user or the study area. The animation can then be baked by defining a certain desired time frame. The baked animation can then be visualised, modified, optimised, and exported with ideal settings and format.

[6] https://www.blender.org/

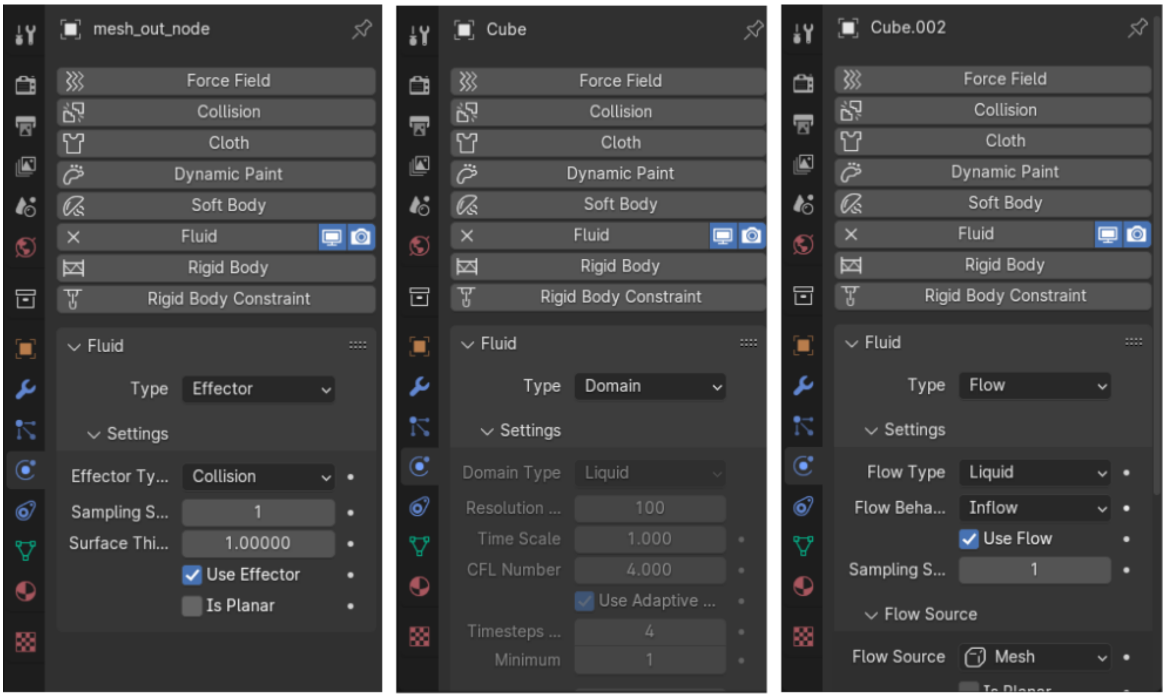


Figure 11 Physics settings in Blender

Following the methodology explained here with Blender, these fancy animations may not be used for presenting real simulations in a continuous and automatic way, however, could be developed for a certain significant historical scenarios and presented to primary stakeholders such as city planners, emergency planners, etc or to the general public to create awareness, expand knowledge and provide training.

Some animations created may be uploaded to any possible cloud platform and the link could potentially be distributed if stakeholders are interested in such modelling techniques.

3.4. Assessment

The developed tool may be assessed based on its performance in terms of computational power, computational time, browser compatibility, hardware requirements, etc. Individual new features developed as part of this research are analysed for its functioning, dynamic or static nature, benefits, and limitations. Additionally, the Digital twin was evaluated based on the Gemini Principles put forth by the Centre for Digital Built Britain. The Gemini Principles are majorly categorised under three sections: Purpose, Trust and Function.

3.5. Summary

This chapter elaborates the research methods and techniques employed to achieve the objectives of the study. Firstly, an overall research methodology flowchart is presented followed by detailed description of each step. The stakeholder engagement section discusses the preparation of questionnaire for conducting surveys. Next, how the identification of open-source techniques and datasets for DT development was performed, using Literature review followed by the preparation of datasets is discussed. The next section elaborates on the development of a digital twin framework employing a combination of global and local datasets, in which several Java Script libraries and methodologies are used within the Fastflood app that generate three-dimensional visualisations of flood variables as well as other elements-at-risk, such as buildings. After this, the purpose of the features/buttons added to this Viewer for analysing the results are elaborated in detail. Three fully operational features followed by two experimental yet significant were elaborated.

Post this section, two different ways of flood water visualisation using Blender and textured 3D model is elaborated. First, a realistic water material is synthesized and applied to a 3D water plane, followed by keyframe animation and baking. The second method of visualization leverages water runoff simulation across the 3D scene of Coulibistrie. Although this is an extra section, it is documented to highlight the fact that highly intricate DT is feasible for flood simulations but not for real-time simulations. In the following results chapter, a test scenario is simulated using Fastflood App for analysing the integrated 3D DT for flood applications. The Algorithms of the flood model and the source code for the webpage development for smooth functioning of the application are published and maintained on the GitHub repositories of LISEM open and Fastflood App respectively. The code generated by the author for the beta version of the tool add-on (DT integration) is published separately on a new GitHub Repository (https://github.com/Sruthie-36/3D_FastfloodApp).

4. RESULTS

4.1. Stakeholder Engagement

4.1.1. Survey

This section highlights the survey results and the key observations obtained from analysing the responses. Refer to Appendix V for the graphical representation of the results obtained from the survey. The stakeholder engagement activity altogether received 34 responses. Almost half of the participants were students of urban planning and flood studies, followed by researchers, scientists, and those in the teaching field. The results imply that the frequency of using decision support tools for city planning and disaster risk management was neither too high nor too low; there were evenly distributed values in terms of usage frequency.

Predominantly, the participants voted to visualise the roads, buildings, water bodies and bridges in a 3D decision support tool, and some wished to visualise green spaces, culverts, drainage systems, industrial areas, and vegetation types. Even though the tool's advanced interaction received more responses, basic interaction was nearly equally preferred, and some felt that it was important to highlight how different users' demands may be based on the circumstances.

The stakeholder responses confirmed the argument presented in the earlier sections that for the application of flood risk management, wire-frame representation would serve the purpose, and there is no need for textured realistic representation. However, both representation approaches are attempted in this study to explore and understand the scope of each. As the primary functionality of the tool, flood simulation capabilities received more preference, followed by multiple scenarios simulation, 3D visualisation and exposure analysis. Technical requirements such as integration with external GIS systems and datasets were moderately perceived as significant by the participants. Risk communication was also deemed as a significant functionality to be had in a decision support tool, with the frequency of alerts recommended only when necessary.

Local stakeholder involvement in crafting flood risk management policies was regarded as moderate to extremely necessary, requiring direct participation in decision-making processes. The most significant applications anticipated by survey participants for this tool are urban growth and planning, future flood risk reduction planning, community participation and education, emergency response planning, and infrastructure maintenance, in decreasing order of priority. On a scale of 1 to 5, the tool's perceived usefulness in decision-making is rated at 3.59. The rating implies that the development of a digital twin to aid in decision-making would be recognized as a noteworthy contribution to the scientific community and society. Finally, despite the potential benefits of the tool, participants view data privacy and security as one of the primary concerns. Therefore, this study and researchers performing similar nature of studies should prioritize addressing these issues.

Category	*Stakeholders' Requirements*
3D Assets / Datasets	Buildings, Water level
Level of Detail of 3D Model	Wireframe representation

	Additionally, Textured representation was explored for a pilot study area.
Necessary functionalities	Flood simulation capabilities; 3D simulation
Stakeholder participation	Moderate (providing input & feedback)
Data privacy	High

Table 4 Stakeholders' requirements that were included during the development phase.

Considering and interpreting all of the survey data, the study concentrated on the outcomes that might be attained in the time frame of this particular investigation; the remaining outcomes were suggested to be attained in the future. The aspects of the investigation and the observations incorporated in the design of the tool are mentioned in the table above.

4.1.2. Stakeholder interview

This section documents the observations of the colleagues on the stakeholders during the field visit on Feb 2024 in Dominica (Bout et al., 2024). The observations and opinions of stakeholders collected, that are more relevant to this research are only documented in this section. The Office of Disaster Management (ODM) believes Fastflood App would be greatly useful for them as they currently do not possess or use any visualization tools. The ODM states the reason for not having a visualization tool was lack of time and labour. They also expressed interest in the risk changes and pre-built models that are easy to visualise.

The physical planning division of Dominica (PPD) uses CHARIM for hazard assessment for communities. They expressed their interest in Fastflood App when it was presented to them and how beneficial it could be. Also, a website called *Dominode*, funded by the World Bank, containing the datasets about Dominica was expected to be stable by June 2024. Additionally, they were welcoming to training the personnel not necessarily in person. Online versions of the applications and cloud services were preferred as they believed there were more advantages to uploading maps online than negatives. In conclusion, they were predominantly responding to the events rather than taking precautionary measures and being prepared for disastrous occurrences.

Next, the Public Works Department of Dominica focuses more on roads and their classification without much focus on buildings. It is also critical to mention that they did not prefer 3D visualisation as they were worried about the limitation of graphics and hardware requirements. They rely majorly on local datasets including hazard maps for current projects on roads. Analogous to PPD, they also seem to lack preparation to disasters while responding to the best of their ability.

The Red Cross Society in Dominica utilises Google Maps, and other data to map out the hazards. They focus on disaster preparedness and response and for that, the tools including Fastflood app would be highly valued. As much as they would value a tool like Fastflood, it is also critical for them to ensure the reliability of information on Fastflood.

Finally, the Climate Resilience Execution Agency for Dominica (CREAD) perceives the Fastflood App to be very useful and relevant to the nature of their work. Forecasts customised for local conditions and serving local users would be appreciated. Pre-built models and their information on how much precipitation would affect a certain community would be very useful to CREAD. Using of maps for hazard perception and further analysis is extensively followed and is majorly preferred.

Overall, stakeholders expressed a preference for a tool with a visualization component, pre-built to minimize computational time, power, and human resources to maintain/operate. They desired specific simulations and recommendations tailored to local regions, such as watershed, parish, and district levels. Additionally, they favoured a cloud-based or online tool that can also quantify and validate results to ensure reliability.

4.2. Methods Identification and Datasets Preparation

4.2.1. Literature Review

This section documents the results of the literature review conducted to identify the prevalent open-source techniques or methods to create a digital twin framework for applications in the domain of flood hazards. The articles that utilise open-source techniques partially or completely to develop a Flood digital twin framework along with association to web development are filtered. The literature that deemed relevant to the study or provided inspiration to the study was plotted in a matrix of literature. Appendix II depicts the literature review matrix with columns: name of the article, methods employed & datasets used, Study area, and Year of publication.

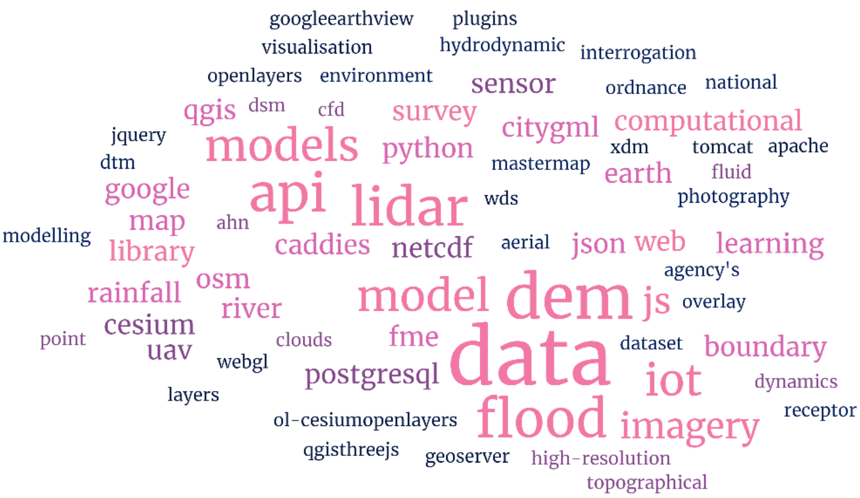


Figure 12 Word cloud of Methods and datasets identified from Literature.

Based on the literature review and online research on the study area, Dominica and the hazards that it had faced over the years, Hurricane Maria is chosen for test simulation. The once-in-a-lifetime disaster, Hurricane Maria, imposed a lot of damage on human lives, properties, livestock, vegetation and more. The tiny island of Dominica faced heavy damage during the event and is still recovering from the terrible hazardous event (NPR, 2023). In September 2017, Hurricane Maria hit the eastern Caribbean Island of Dominica and the devastations it had caused is greater than any other storms that had hit the island earlier.

The figure 13 below shows the origin and movement of the storm during the week starting from September 16th of 2017. This scenario would be more suitable to simulate and analyse how the third dimension of water in visualisation adds to the analysis.

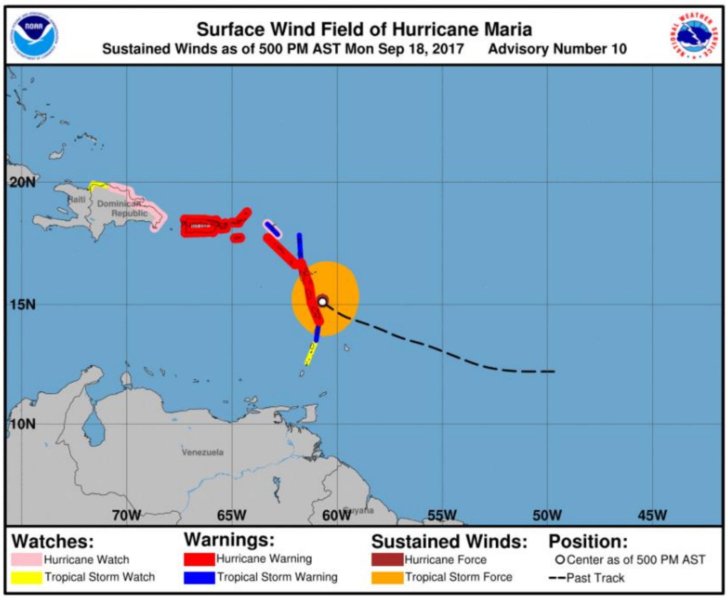


Figure 13 Hurricane Maria - Wind Movement

Through this, the impact of 3D visualisation on stakeholders' perceptions of hazard can be examined. The simulation is performed using Fastflood App with the combination of local and global datasets for the Hurricane Maria conditions. The following section addresses the Fastflood App settings used for the simulation.

4.2.2. Datasets Preparation

To be used as input for the 3D Visualization on the viewer, the Fastflood App simulation of Hurricane Maria was conducted.

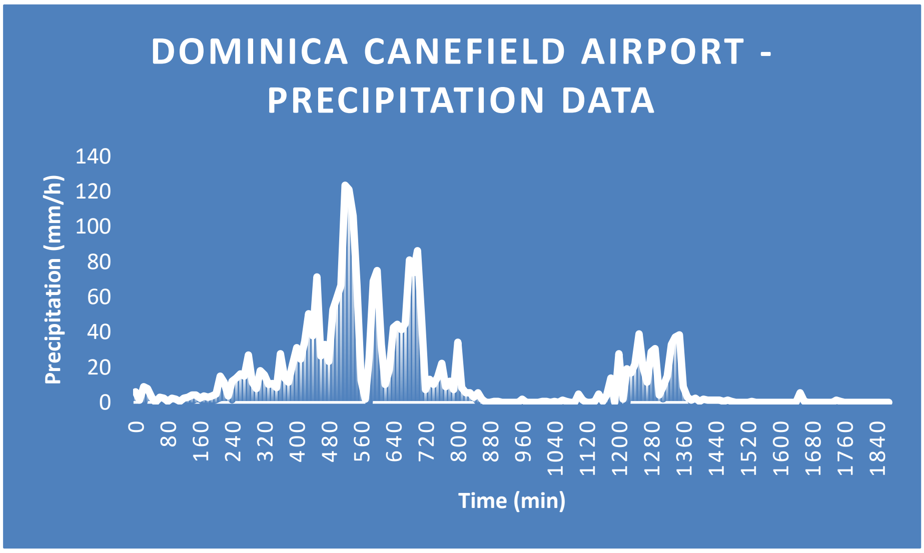


Figure 14 Precipitation dataset: Dominica Canefield Airport

The input parameters for the simulation mainly include the LiDAR (Light Detection and Ranging) Datasets with a spatial resolution of 5-meters x 5-meters. The Precipitation datasets were obtained from the only possible 'active' station during the disastrous hurricane Maria, the Canefield Airport station in Dominica (Fig. 14). The dataset includes precipitation values against time data (in minutes). The precipitation values are in mm/h units. Using these inputs, the Fastflood App simulation is performed to generate simulation output. Figure 15 shows the output of Fastflood App for the historical Hurricane Maria scenario.

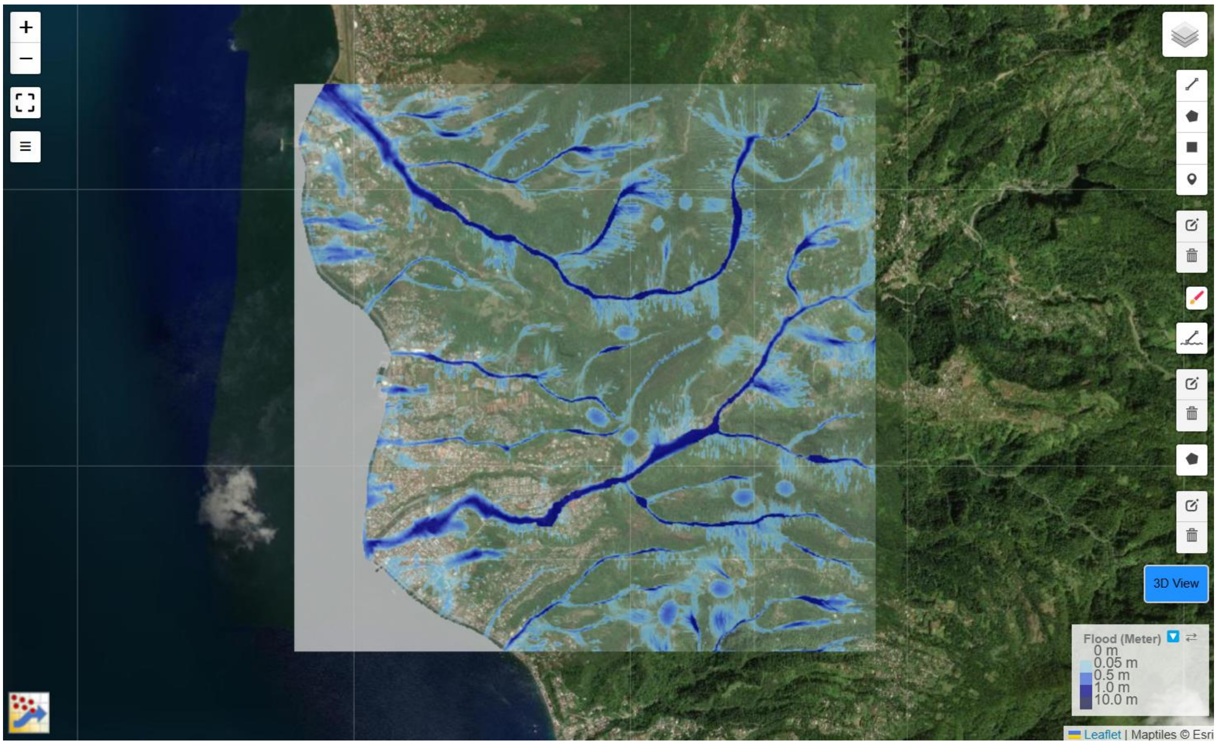
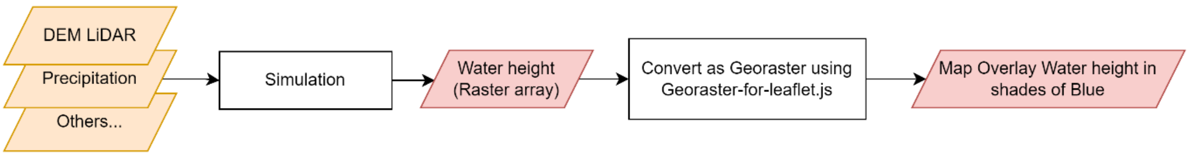


Figure 15 Fastflood App Simulation Results in 2D (Hurricane Maria)

The graphics below quickly shows the workflow of how the output of simulation is added onto the 2D viewer using leaflet JS.



This raster array of flood height values can further be processed to be visualised in 3D with the help of web JS packages including Cesium JS, Three JS, Leaflet JS, turf JS, etc. The next section on development of digital twin framework continues the further development steps.

Textured 3D Representation

A new three-dimensional (3D) model of Coulibistrie, a tiny village in Dominica, is created using Pix4D software, photogrammetric techniques, and UAV imagery datasets. Figure 16 represents the textured 3D model generated using UAV imagery. This may then further be manipulated for analysis and visualisation.

Figure 16 Texture 3D Model generated from UAV imagery

4.3. Development of Digital twin framework

This section presents the results of the development of digital twin generated by integrating 3D physical assets with Fastflood App: Flood modelling web application. The Fastflood App[7], a web based dynamic application is a private GitHub repository (https://github.com/FastFlood/FastFloodApp) where the programming languages utilised for the development are C++, Javascript, HTML, CSS, and Python. To this, using the Cesium Js library among other JS libraries, Core JavaScript functions, DOM (Document Object Model) methods, HTML and CSS options, this development of 3D visualisation is presented. The detailed development process is explained in the methodology section.

[7] https://fastflood.org/

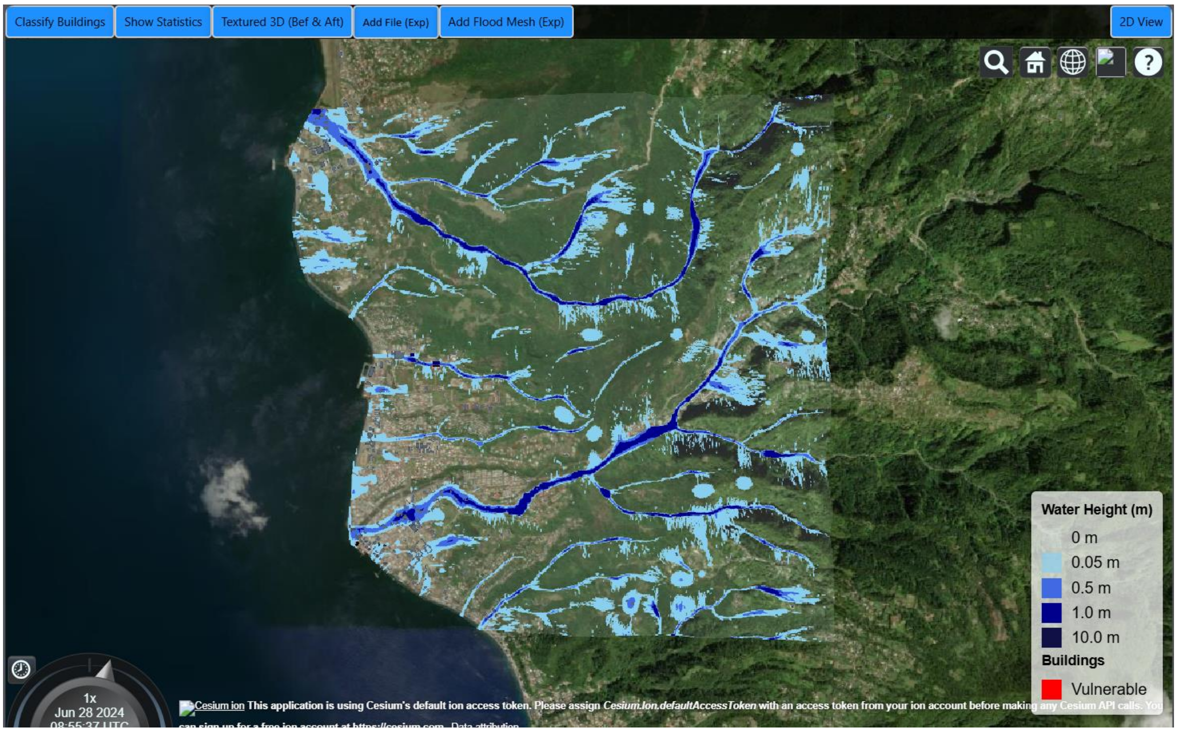


Figure 17 Cesium Viewer with Flood results

The test scenario used, Hurricane Maria, has flood simulation outputs visualised as given in Figure 15 in the previous section. The '3D View' button when clicked initiated the 3D view. If there are no flood simulation results, it is designed to throw a warning. When result exists, it initialises a viewer with 3D world Terrain. The world terrain has multiple basemap layers to toggle from. Over the Cesium globe, the water height values are overlayed in the shades of blue. The shades of blue are matched with the 2D visualisation on the map for better user experience and user comprehension. The viewer further zooms into the location where the water height raster is added (Fig. 17).

For navigating around the viewer, the Scroll up and down zooms in and out. While holding the *ctrl* button, left click and move around to visualise the 3D content from the side view instead of top view. Move around the area with left click and ctrl buttons.

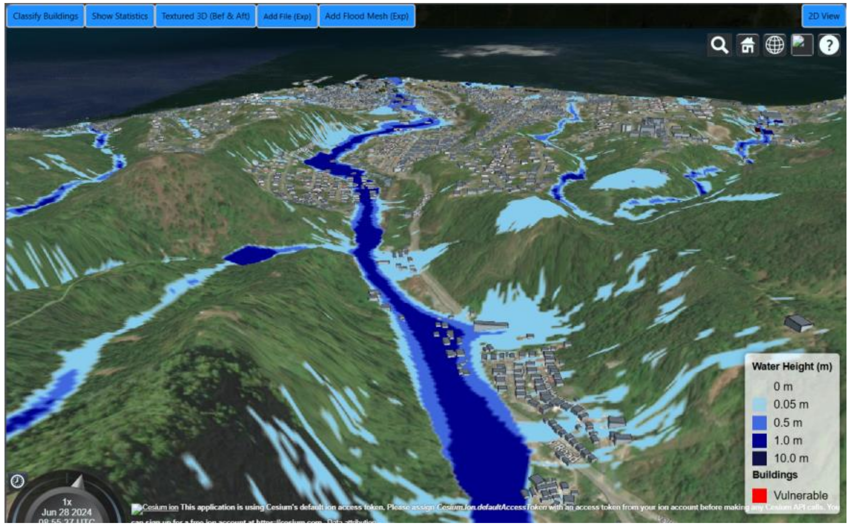
Figure 18 Functionality displaying Water depth value at each pixel

The values of water depth can be viewed when left-clicked over a pixel. This was handled by *screenspaceeventhandler*. It displays the latitude, longitude, and water depth value of the pixel in a pop-up div element over the cesium viewer. As mentioned before, there is an option on the top-right corner of the screen stating '2D View' to switch the visualisation to 2D. Users can switch back and forth between 2D and 3D by clicking *2D View* and *3D View* iteratively.

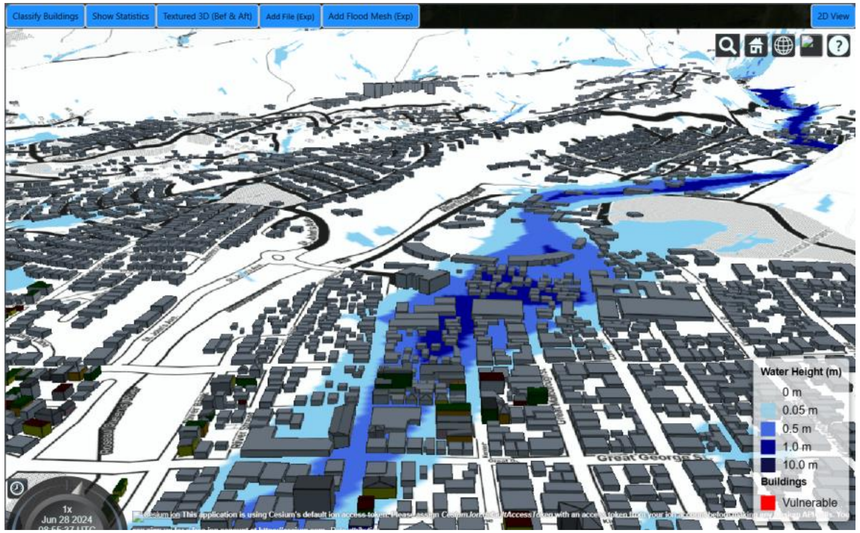
Figure 18 presents the functionality to display the pixel details: when a location is left-clicked using the mouse, the pixel value, latitude and longitude at the cursor location is displayed on the screen adjacent to the cursor.

Figure 19 with sub figures: a, b, c, d, depict the visualisation of water height in the realistic 3D terrain from different angles and by using different basemaps. The variation in shades of blue depicts the differences in water height. The intense the blue is the higher the values of water height are. The legend element also explains the colour and their related attributes.

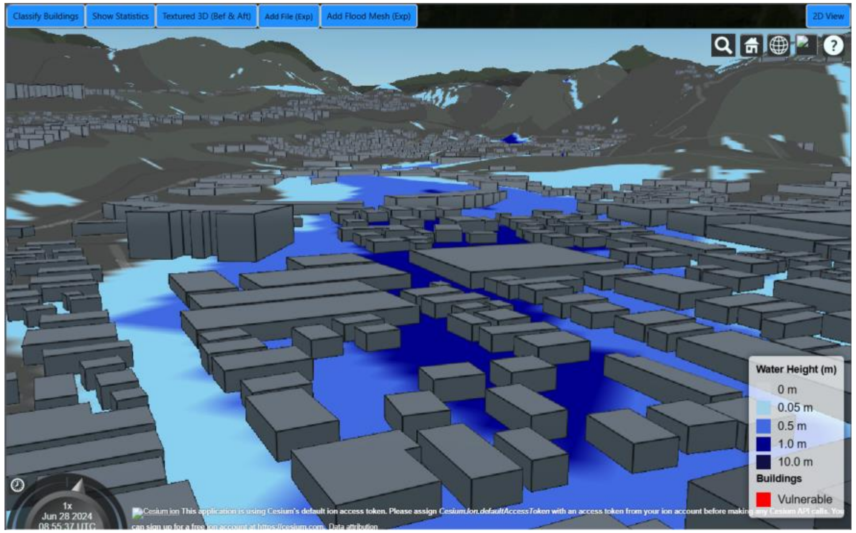
a)



b)



c)



d)

Figure 19 Visualisation of water height variable in 3D Viewer from different angles

On the 3D Viewer, the button *Show Statistics*, displays the total area of the individual categories of flood height. Figure 20 shows the total area of flood height under different levels obtained for the Hurricane Maria scenario for instance. The values of total area covered against specific water height include:

More than 1 m: 0.406475 km², more than 0.5 m: 0.568475 km², more than 0.05 m: 3.015075 km², more than 0: 16.9049 km² (Refer Figure 20).

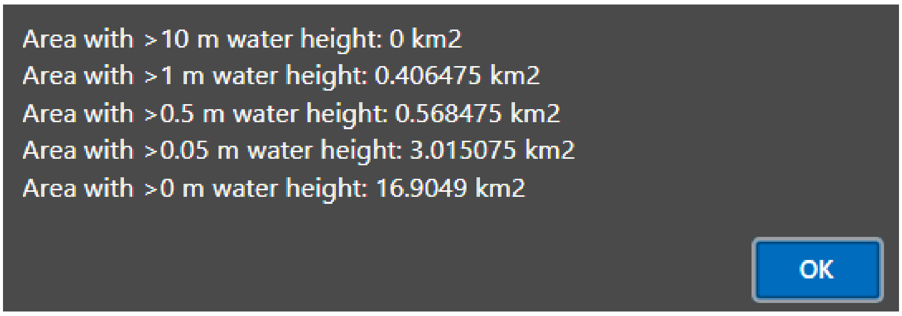


Figure 20 Snapshot of Statistics generated from the tool

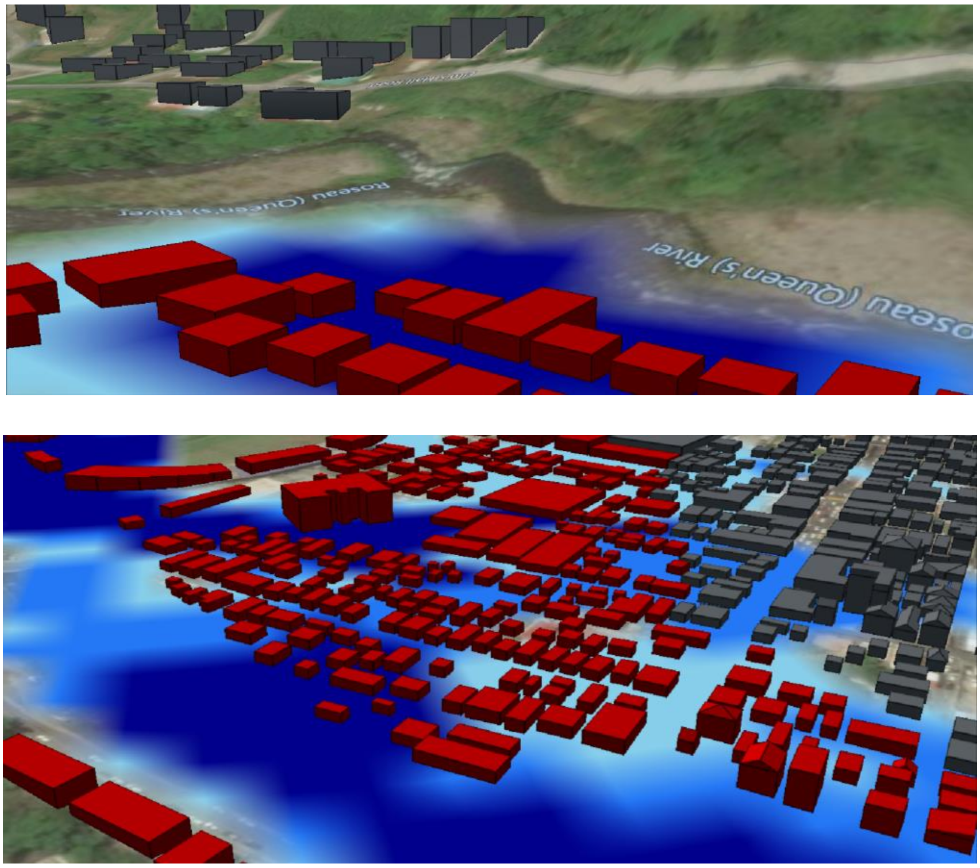
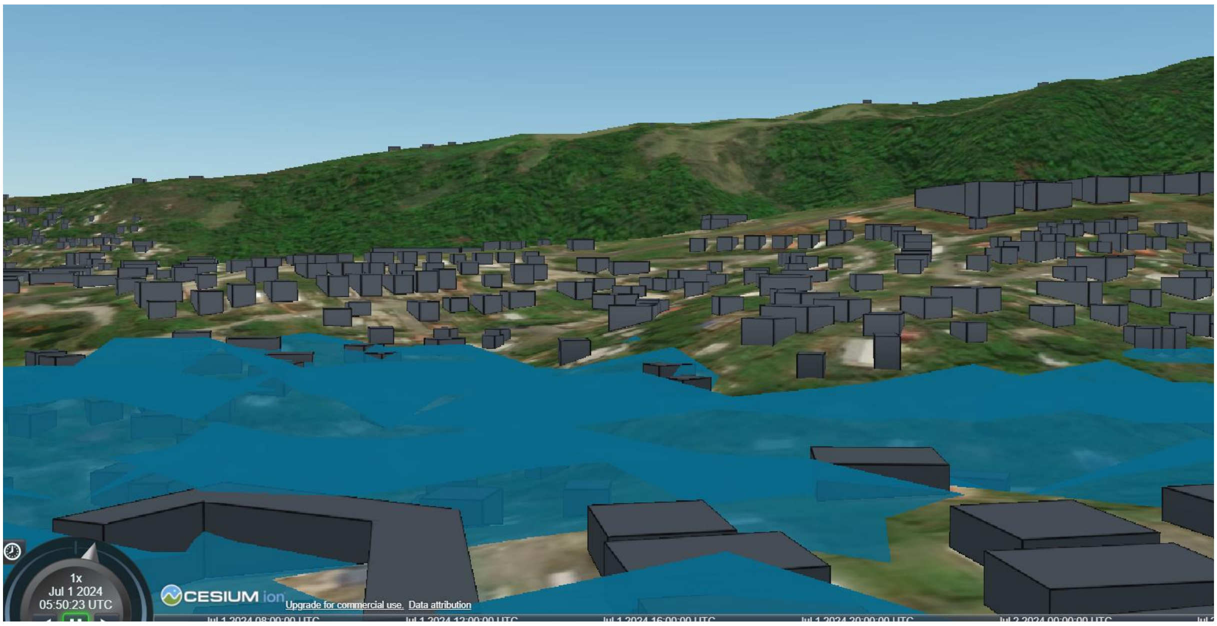


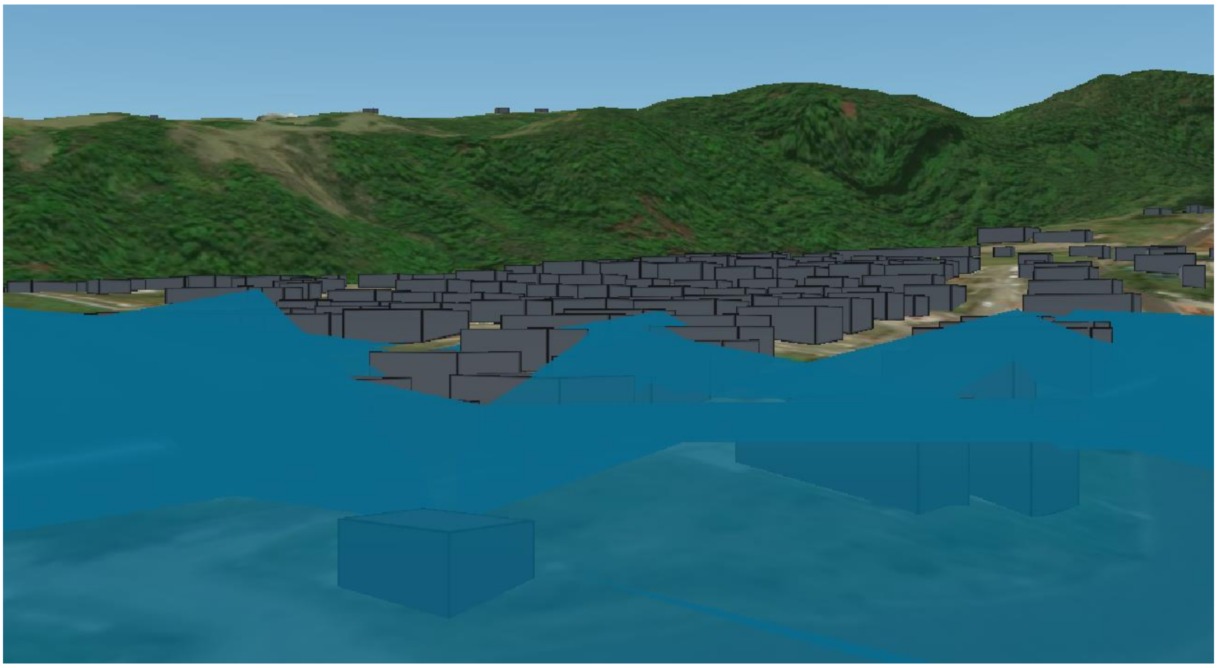
Figure 21 Snapshots of the 3D Viewer with water height values and classified buildings (a & b)

Next, the button 'Classify Buildings' on-click, classifies the buildings those fall within a buffer size of 0.001 of the pixels, whose water height values were above 1 m as Red. Post classification, the users can also recognise the colour of the buildings by matching with the legend entry for easier identification. Figure 21 presents the snapshots of the buildings classified based on the water height values.

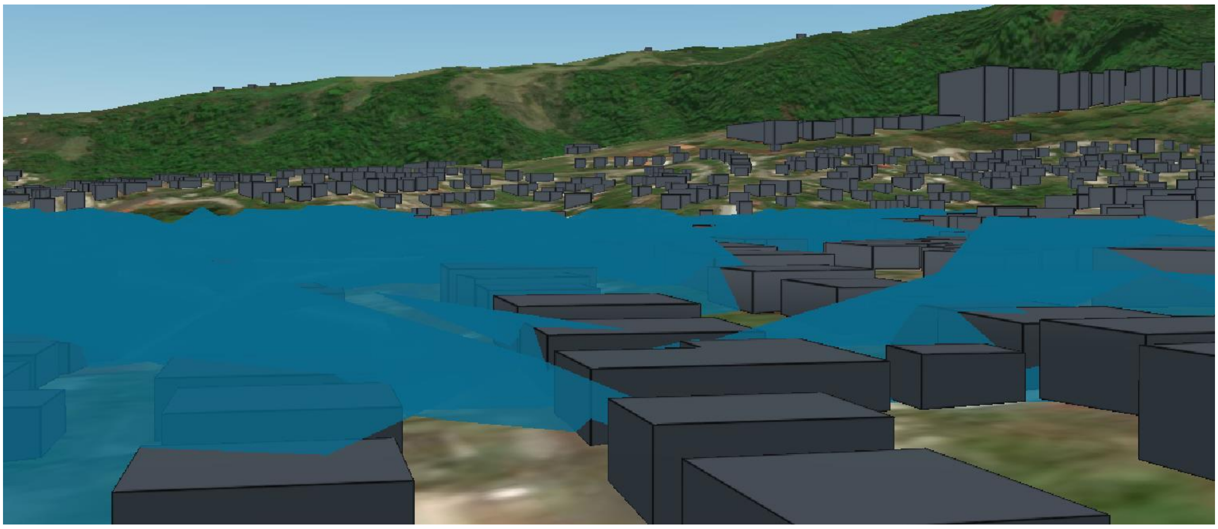
The experimental feature of 'Add Flood (mesh)' adds a 3D mesh dataset of flood height values over the Cesium viewer. This visualises the water in 3D along with the three-dimensional terrain and buildings. Figure 22 a, b, c depicts the water height values visualised in 3D by the use of a TIN approach. In Figure 22 b, the tool allows for a clear view of the buildings beneath the water mesh, providing a comprehensive understanding of whether the assets are being flooded and to what vertical extent.



a)



b)



c)

Figure 22 Flood Water height in 3D (3D TIN Mesh of water height)

A sample 3D mesh with randomized water height values was added to test and visualize the 3D water mesh and its interaction with other 3D assets, such as buildings (Fig. 22). Unfortunately, this is not a feature that is available for real-time simulation results as the conversion of the raster array into 3D Mesh dataset is not available yet within the tool architecture. The figure 23 below shows the workflow of how this was performed technically.

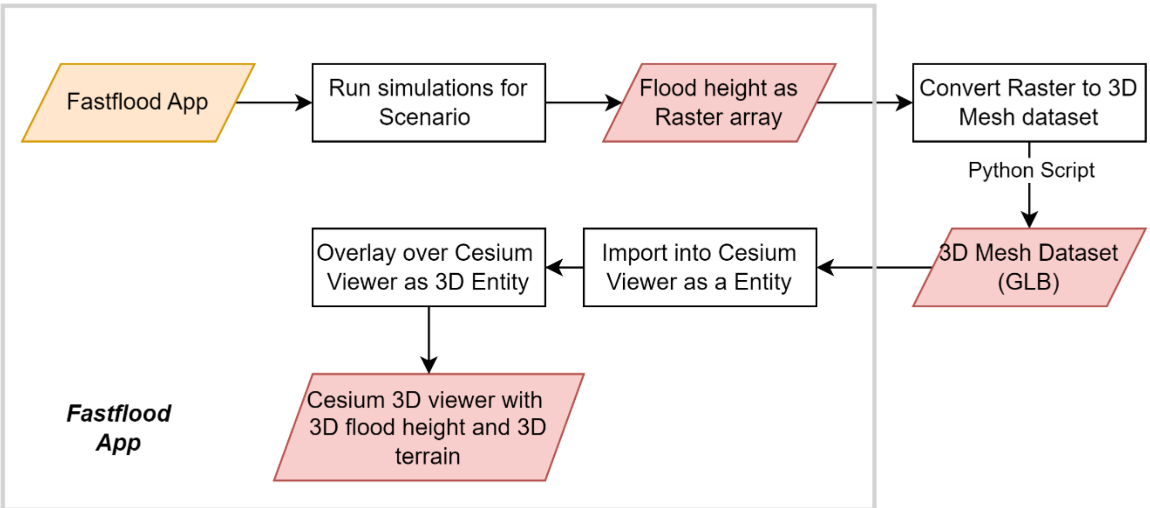


Figure 23 Workflow for 3D Mesh Visualisation of Flood height

The next button 'Add Textured 3D', at the moment does not show real-time flood simulation results. It just presents the static Textured 3D scenes before and after flood scenarios of the area, Coulibistrie. This was manipulated and modelled on Blender software where realistic water material was designed and developed. Figure 24 presents the visualisation when the *Add textured 3D* button is clicked.

Figure 24 Snapshot of 3D Viewer showing: 1) Textured 3D Coulibistrie (After flood)

2) Textured 3D Coulibistrie (Before flood)

3) Coulibistrie - OSM Buildings on 3D Terrain

The users may be able to zoom in, zoom out and fly around to inspect the model, analyse, and present interpretations on the scenario. The detailed 3D model provides more structural information on the buildings enabling the users to get a perspective of how flooding might look like in a real scenario.

Using the UAV images collected for the area of Coulibistrie during the field work of ITC in February 2024, a 3D model of Coulibistrie was constructed using Pix4D software. The output 3D model along with its textures was exported as a FBX file, to be compatible with most of the open source and proprietary 3D modelling software. For creating the static meshes, the 3D model was imported into the Blender viewport. Over the 3D mesh, a new 3D cube is added to fit the mesh within it. The texturing of the cube for creating a realistic 3D visualisation is performed using the material editor. A new material is created by a combination of parameters which involves Surface and volume texture (Fig. 26). For the surface texturing, a mix shader of glass BSDF and transparent BSDF are used. *"The Glass BSDF is used to add a Glass-like shader mixing refraction and reflection at grazing angles"* (Blender, 2024b). *"The Transparent BSDF is used to add transparency without refraction, passing straight through the surface, as if there were no geometry there"* (Blender, 2024c). For designing the glass texture, noise texture via Bump feature is added to create the wave effect for the realistic water representation. The detailed material construction is presented in the figure 25 below.

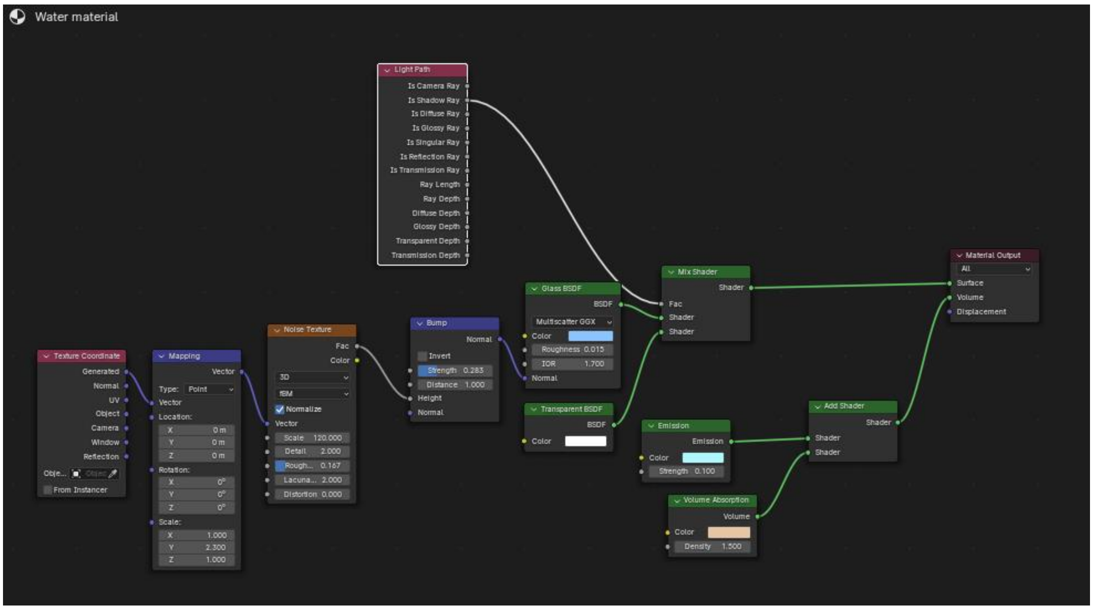


Figure 25 Material Editor in Blender (Water Material blueprint)

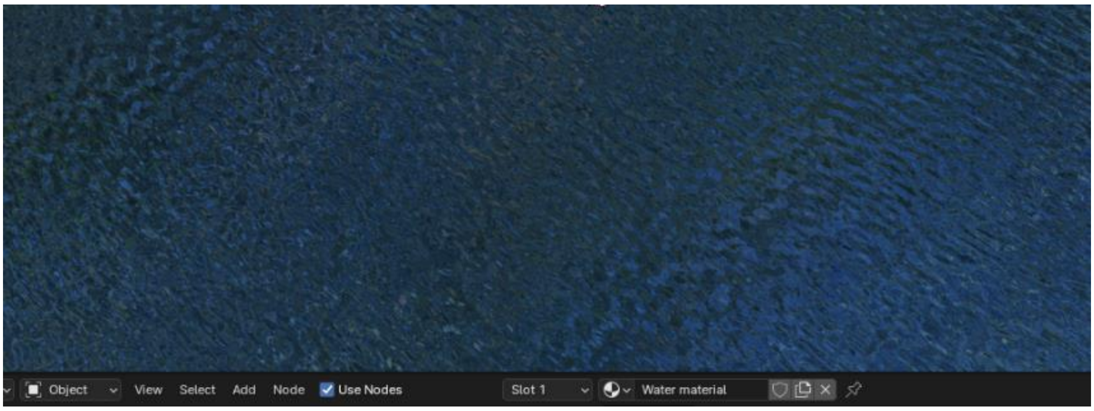


Figure 26 Water Material

Figure 27 A realistic textured 3D flooding Scene in Coulibistrie (Output from Blender)

Figure 26 represents the output realistic water material obtained as a result of material development using material editor. Figure 27 shows a scene of Coulibistrie when flooded using the water material created. After preparation of the water material, it is applied to the water plane. Instead of just having two static models, an animation can be baked and exported. This animation video can also be made accessible to users to get a perspective on realistic visualisation and if it is widely preferred, this could be a potential future direction of research. This can be achieved with the help of python package, BPY (Blender python). However, a back-end server to handle the different functions of programming languages such as JS, Python, C++, etc and their interoperability has to be considered and set up. This arrangement could potentially be explored in future as the time was limited in this research.

4.3.1. Additional

Extending this, a new type of visualization including evenly rising water level across the study area scene was created. Different key frames are inserted based on the water level. In this way, the final animation will depict how the scene would be when the water levels are gradually increasing. Every frame has a variation of 0.5 m in water height. The variations in the scene can be observed using the figures attached below:

Water height – 0 m

Water height – 0.5 m


Water height – 1 m


Water height – 1.5 m


Water height – 2 m


Water height – 2.5 m


Water height – 3 m


Water height – 3.5 m

Figure 28 Flood visualisation using realistic water material (Coulibistrie, Dominica)

The link to the animated video: https://youtu.be/48hJbLXgfP0

Finally, for the next type of visualisation, after importing the 3D Model of Study Area - Coulibistrie into Blender, it can then be manipulated by adding textures, adding new features for creating water simulations.

This file was imported into the Blender as a 3D mesh object, followed by creation of two cube objects. These cubes are modified to match the desired dimensions, position and orientation for further modelling and simulation. As mentioned in the methodology section, the objects' properties of physics are adjusted in such a way that the water simulation is created.

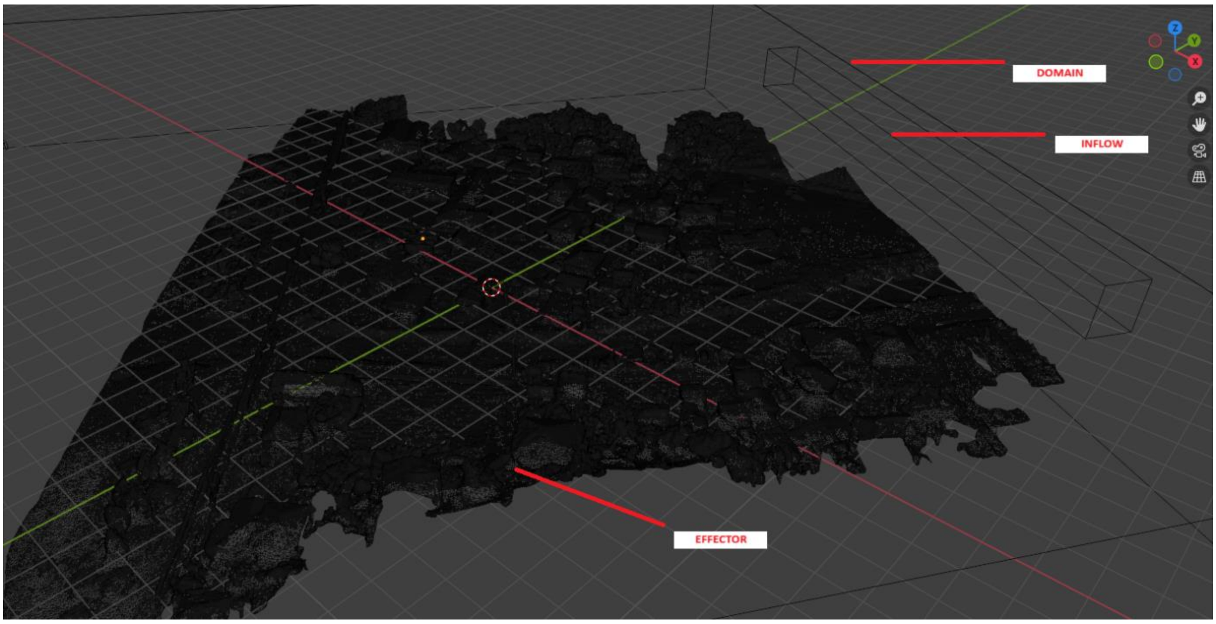


Figure 29 3D Modelling - Types of 3D assets

Following this, by adjusting the inflow settings including the viscosity, acceleration in three dimensions, the settings are baked. After it is baked, the animation can be visualised to understand how the scene interacts with the fluid. This increases the perception of flood interaction with the real-world assets in the stakeholders and/or local communities. This visualisation depicts the responsiveness of the 3D scene to the flood water by arrival time. The pros, cons, and applications of this type of visualisation is discussed in detail in the following chapter.

Figure 30 High-fidelity Flooding simulation in Coulibistrie, Dominica

The link to the animated video: https://youtu.be/ypZCOYI6Jz4

4.4. Assessment

This section outlines the discussion on the hardware or software requirements for using the tool, as well as the tool's computational power and time efficiencies.

The flood simulation and its 3D rendering using the tool are not computationally intensive. The task is completed within a few seconds and does not consume significant system memory. Secondly, the human resources or training required are minimal, as the GUI of the Fastflood App is straightforward, leading to reduced training time. There are possibilities to store and load pre-configured input parameters for simulations, enabling even non-technical users to easily run simulations and benefit from the results. The application was tested on popular browsers including Microsoft Edge, and Google Chrome and it works perfectly well. This makes the tool desirable, as stakeholders explicitly mentioned during interviews the need for a tool with minimal computational power and time requirements, as well as low human resource demands.

However, some beta versions of the features investigated in this research, such as 'identifying vulnerable buildings to flooding', are computationally demanding. It is because it classifies buildings pixel by pixel. The way around this was to pre-compute the pixel values and classify the buildings in one go, but this did not work as expected. As a result, the previous strategy was retained. This will need to be resolved in the future.

The Show Statistics feature displays the total area covered under each category based on Legend. This could further be extended to present the results visually using a graph representation for a comprehensive understanding by visual interpretation.

The flood height mesh and textured 3D visualisation are only accessible for the test cases used for static visualization to reflect the technological feasibility investigated in this study. This is not yet fully operational within the tool for real-time visualisations of simulation results as a kind of dynamic and computational representation; instead, this technique employs a Python script to convert the raster to triangulated irregular network. This presents the opportunity for further development on this novel approach to flood variable visualization within the digital twin framework. There has been no prior research that uses a 3D TIN technique to visualise floods that may interact with 3D assets and provide important insights by analysing the interactions between flood height and buildings in both horizontal and vertical directions.

4.5. Summary

In this chapter, the results obtained by employing the overall research methodology described in Chapter 3 is presented. The results are outlined in the same order and under same sections as that of the methodology chapter.

Firstly, the observations from the stakeholder engagement activity including survey results and interviews excerpts are presented. The requirements identified from the stakeholder engagement activity that were incorporated into the tool are listed. This is followed by the section, where a comprehensive literature review was conducted to understand and identify the suitable open-source methods and datasets that could potentially be adopted into the study. The process of preparing the datasets is also described in this section. Next, the section which contains the direct outcomes of the digital twin framework is provided. In this, all of the new features developed within the tool, how to use it and how is it useful for the end users are all given. This includes all the visualisation outputs. Finally, the assessment section which contains some of the critical reflection on all the developed features within the tool are all mentioned. Furthermore, the assessment of the development based on the Gemini Principles are then presented in the following chapter V.

5. DISCUSSION

The main goal of the research is to develop a Digital twin framework for flood simulations in Dominica. Additionally, this study explores different techniques to enhance visualisation in addition to developing a Digital twin framework integrated with Fastflood App, as visualisation plays a significant role in decision-making processes (Eberhard, 2021). The Digital Twin framework developed in this study aims to assist in the decision-making process of the stakeholders on flood risk management. This chapter examines the potential of the Digital Twin generated in this study from different aspects using the Gemini Principles. Furthermore, the prospective benefits, negative aspects, and implications of the DT are discussed. Consequently, this chapter covers the study's limitations, uncertainty, and future research directions of the study.

5.1. Analysis using Gemini Principles

The developed Digital Twin for flood management in this research may be studied and analysed by using different standards. In 2018, the Centre for Digital Built Britain published a set of principles called Gemini Principles to guide the development of the National Digital Twin. According to the CDBB, the definition of Digital Twin is, "*a realistic digital representation of assets, processes or systems in the built or natural environment*" (Bolton et al., 2018). The CDBB proposes that an NDT should be looked into from the aspects of its usefulness, function, and trustworthiness. Figure 29 below shows the framework that was suggested.

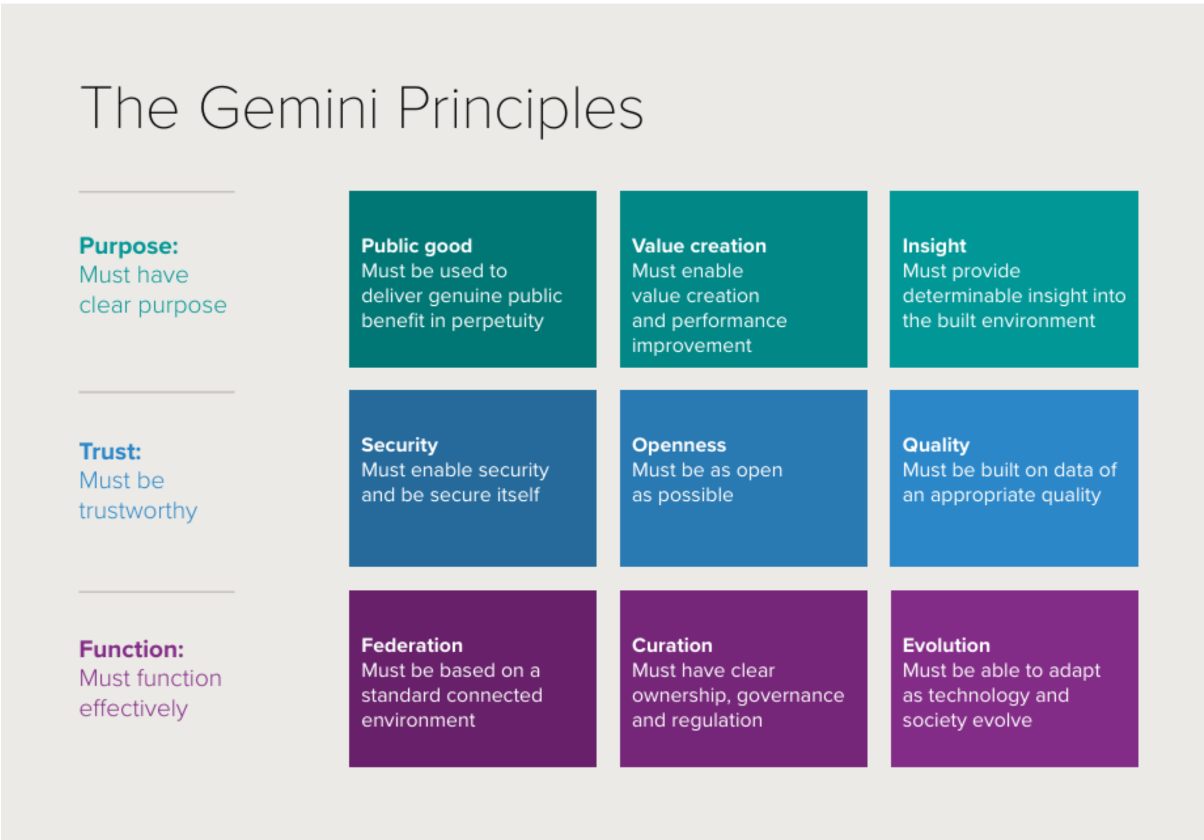


Figure 31 Gemini Principles by CDBB (Bolton et al., 2018)

Based on the principles suggested, the developed digital twin is assessed to understand how it fits within the framework. Firstly, the purpose is explored, followed by trust and its function.

5.1.1. Purpose

The primary purpose of the resultant Digital Twin is to deliver insights on flooding events and their impact on society, to the primary stakeholders. Dominica has always been highly vulnerable to natural hazards including hurricanes, landslides, flooding and more. Such a Small Island Developing State (SIDS) faced terrible damages due to the hurricanes, leading to loss of more than 200 percent of the country's GDP (Government of the Commonwealth of Dominica, 2017). Although there have been worse experiences with natural hazards in the past, the Department of Planning and Disaster Management still uses the static maps and satellite or aerial imagery for analysis and decision-making. With Dominica taking a decision to be the world's first Climate Resilient Country, it is essential that the country owns a decision-support tool that enables them to be proactive when it comes to hazards such as flooding. Recently, Dominica has come in possession of their own digital platform to share and consume geospatial data among others. Following this, a fully operational flood simulation tool with additional capabilities, including enhanced visualization in 3D, serves as a necessary technological development for the Country, as it increases the knowledge and perception of flood risk. This tools inform the impacts of a certain flooding event before it even happens and by this, one of the primary stakeholders, the Physical planning division get to investigate and invest on the physical assets at vulnerable places over others. This leads to a structured and risk data-based approach to mitigation planning and preparedness. Overall, this tool will benefit the stakeholders and the society by facilitating informed decision-making.

Unlike approximately identifying specific flood-prone regions based on static hazard maps and then implementing mitigation measures, the digital twin enables the stakeholders such as city planners to make informed decisions about where to implement new plans, thereby proactively strengthening preparedness. Such a tool is employed not only for the future, but also in the present. When a storm strikes, emergency planners are unable to be on the ground to deal with hazards such as flooding. So, simulating a hazard event from a secure location and planning an emergency response is vital.

This digital twin primarily can be used for generating critical insights about a flooding event, encompassing vulnerable areas in a city, blocked roads, and buildings surrounded by higher water levels. These insights can further be processed alongside other datasets for planning mitigative measures or evacuation plans in case of emergencies.

5.1.2. Trust

The trust aspect of a Digital Twin is highly significant because any well-developed multi-functionality application could go unused if it is not trusted as reliable by the users for the intended benefit. The trust function of this Digital twin can be discussed in terms of three central elements: Security, openness, and Quality. The security in the developed digital twin framework is very limited. There are no explicit elements in the design of the tool on the web to ensure security. Although, there is an authentication element to recognise the user, login is not always required for simple modelling. The Security enhancement for the tool must be considered a future direction for the study.

The tool was designed to be transparent about its development and features, promoting the Digital Twin (DT) for extended use and encouraging collaboration among various stakeholders. The globally adopted datasets within the tool's framework are free from inappropriate information, ensuring user confidence.

Details about the datasets, including their completeness and inaccuracies, are transparently discussed in this and the global datasets release documents. Users may even decide to manually include datasets if the available online options do not meet the accuracy or completeness standards.

The quality of the developed Digital Twin framework is dynamic and user-controlled. Users can enhance the framework by providing higher-quality input datasets, either through global auto-downloads or manual uploads. Although the program uses global datasets such as OpenStreetMap (OSM), which may contain missing data or small errors in feature placement in some areas, users can enhance the overall output quality by using better datasets thanks to the tool's flexibility.

5.1.3. Function

The web-based application is always accessible to the public as an open-source tool for flood simulations. The Digital Twin (DT) can manage data across various spatial scales. However, enabling 3D visualization may reduce the performance of the app in general, when rendering large datasets, as 3D requires significant graphics processing. This study also investigated a feature that allows one to import and overlay several raster data classes with flood outcomes over a 3D viewer. This makes room for overlay or comparative analysis, the deduction of patterns, a theory that one increases while the other decreases in a given area, and so forth.

The development of the digital twin involves considerations of data ownership and tool management. Currently, the Fastflood App, developed at the University of Twente, is owned by members of the ITC faculty at UTwente. The datasets integrated into the tool are owned by their respective data providers, who bear responsibility for their accuracy and maintenance.

The Fastflood App is on a continuous journey of adaptation and transformation, integrating new techniques and datasets. The app is committed to exploring and improving the quality of datasets used, contributing to the principles of open science. As an ongoing development, the app welcomes the incorporation of local datasets, which can significantly enhance the resolution of its outputs. This tool was designed to predict floods in two dimensions, but it now includes three dimensions as well as forecasting data to improve its capabilities and make it a near real-time data simulation source. This tool is designed to be sustainable, continuously evolving by incorporating better data and techniques while ensuring sustainability.

5.2. Implications

The research output may be used to simulate historical flood scenarios and by this, it enables the stakeholders to understand where and how the flood event affects the city. By understanding the highly vulnerable areas, there can be guidance to change of land use or relocation of residents to prevent the casualties in case of an emergency. When a disaster is predicted, it can be quickly simulated in a couple of seconds to anticipate its effects on locations and prepare response teams. This includes planning emergency shelters, evacuation and other measures. The land use in the most vulnerable regions can be changed to address the situation more effectively. For instance, the population near the river's banks may be moved and the channel's width may be widened to accommodate more water. This will cause a flood event, such as a river overflow, to occur later than it would have otherwise.

Urban planners who are planning prospective developments in the area may find this tool helpful as it helps identify high-risk areas that should be avoided due to flooding, vacant spaces that are safe for new construction, and locations that don't obstruct natural drainage systems. This facilitates the decision-making process of urban planners and local officials, for all types of advancement in the city region, including new infrastructure systems in addition to just buildings, such as water, gas, and electrical infrastructure. This can be critical since flooding may have an impact on the infrastructure supporting subterranean electricity and endanger public safety. Transportation might be crucial for the public to get to safe places in case of sudden calamities. Identification of routes that are void of water logging could be performed by visual interpretations of the 3D depiction of the results.

Following the catastrophic Hurricane Maria, Dominica's prime minister stated before the UN general assembly that Dominica would grow into the world's first climate-resilient nation. The establishment of measures to support the formulation of climate adaptation and resilience strategies is essential as Dominica moves toward being a climate-resilient nation. Additionally, one of CARICOM's strategic goals for climate adaptation involves using innovative approaches to tackle climate changes, for instance, using digital twin technology for addressing flood hazards in this research. The technology can be employed in the construction industry to choose the materials for building construction or reconstruction based on maximum water levels predicted for the area. By this, the utmost resilience is ensured for the buildings during actual disasters.

Since this tool is designed to be open source, it can be utilised by stakeholders, researchers, and students to get acquainted with the information platform and develop solutions based on the primary results of this application. The results can be used in conjunction with other datasets to deduce solutions: identifying suitable locations for green space development to increase water permeability, where to plan water storage facilities to reduce runoff, identify existing channels to clear any obstructions or create new pathways by widening the rivers or natural waterways.

Awareness creation about flood risk: Improve residents' awareness and perceptions of flood risk and the destruction that certain catastrophes can inflict by visualizing the flood scenario well ahead of time. Raising awareness can result in improved mitigation strategy implementation, a rise in local community readiness, and a decrease in the number of fatalities. Stakeholders, specifically local residents, tend to respond and participate better in an activity when their understanding towards the cause is better perceived. By means of its enhanced 3D visualization, this program gives the residents the ability to watch and comprehend the state of emergency that is about to unfold well in advance of it actually happening.

Furthermore, this can be employed to train emergency responders on how and where to respond to in case of hazardous events. Allocating resources to the right location at the right time matters in the context of disasters, thus the significance. Insurance companies may benefit from this tool by deciding their claim and premium conditions by foreseeing the damages that could potentially happen.

5.3. Limitations and uncertainties

At the start of the research, a survey was conducted to understand the requirements and expectations of the stakeholders in a decision support tool for flood management applications. Around half of the participants are students, who may not have sufficient real-world experience in the relevant field. This draws into uncertainty the confidence of the survey results for adopting the results as those of the stakeholders.

The primary uncertainty of the digital twin using global datasets could be the incompleteness in the global datasets including open street maps data for the building assets. If the global elevation datasets such as SRTM with 20 m resolution are utilised as input for simulation of the flood model, then there is an approximation inflicted in the output values of flood variables. Additionally, the low resolution of infiltration, land cover and other parameters may contribute to a compromise in the precision of the output values. The precipitation values, if entered as a single intensity value for a specific duration, certainly projects a larger approximation of the varying precipitation intensity values and over time. Thus, global datasets with coarse resolution might result in coarse output results.

The computational power and time taken to calculate exposure using the current algorithm might be time-consuming depending on the size of the bounds of flood simulation. This is because the algorithm uses a pixel-wise approach for calculating. Further refinement needs to be done to reduce the computational power and time by optimising the logic employed in calculating and identifying the vulnerable buildings. The overconsumption of processing power and time for calculating the exposure output might not be an issue if the simulation is run for smaller areas. However, this is not an optimal solution as the water runoff for a specific area in the real world is generally dependent on the surrounding areas as well.

Similarly, when exploring the novel TIN approach for flood visualisation on the web, it is crucial to consider the high processing power and graphics it requires to render the visualisation. Additionally, a back-end server with a Python setup is required to convert the output to a 3D mesh, as performing this conversion in JavaScript is considered challenging. There are optimization algorithms available that can convert raster data to TIN mesh on the fly and render it within seconds. Thus, by overcoming these obstacles, this proposed approach has the potential to elevate flood visualization to a higher level, significantly increasing stakeholders' understanding and perception of flood risk.

5.4. Future research directions

Considering the study's findings, several possibilities for future investigation appear. These opportunities not only seek to enhance understanding of the subject, but also to overcome existing limitations and explore new applications. By delving into these directions, researchers may advance the field and contribute to continued innovation. The potential future directions involve:

1. Integration of automatic generation of 3D mesh by setting up back-end server utilising Python for vertical analysis of water interaction with 3D assets. Extend the static representation of flood available now to a dynamic computation representation of flood results (as a mesh) within the DT framework.

2. Enable appending and visualisation of various datasets over the flood variable outputs to enhance geospatial analysis in the context of flood risk management to provide data driven decisions.

3. The tool might incorporate more up-to-date and complete datasets on assets, such as buildings and other critical infrastructure.

4. Examining ways to generate maps or provide output at different simulation time stamps to demonstrate to stakeholders and users how the gradually increasing water levels, interacts with the surroundings might be a fascinating direction.

5. The tool uses forecast information to conduct simulations, and by combining resident data, it may generate alerts for potentially at-risk households.

5.5. Summary

All real-world objects possess 3D characteristics. Therefore, assessing flood risk with a 3D depiction aligns closely with reality, highlighting vulnerabilities and other critical aspects of the area. The fundamental aim of the study is to curate a framework for city-scale Digital Twin to assist in decision-making process of flood preparedness and mitigation planning. Since visualisations have a way of conveying information to humans, this approach emphasises a focus on visualisation to enhance the perception of stakeholders on hazards, namely flood risk. Since there is more at stake in this area of application, the visualisations should not be deceptive. Unreliable data concerning flooding, disasters, emergency preparation, etc., should be avoided and handled with extreme caution because multiple lives are potentially at risk. The transferability and reproducibility are crucial glasses to look through when it comes to developing open-source approaches for decision-making tools, contributing to open science when it comes to developing open-source approaches for decision-making tools, contributing to open science or modern research on providing solutions in general. Since the proposed system combines and brings together global information for building footprint, landcover, precipitation forecast, etc., with open-source approaches, it can be implemented for any part of the world. A similar application could be replicated without complications by using a similar architecture that included Java Script, HTML, CSS, a flood modelling technique, and the integration of global remote sensing, GIS, and real-time precipitation datasets.

In this chapter, the integrated digital twin approach proposed in this study was discussed using the Gemini Principles, namely, Purpose, Trust, and Function. These different aspects of the Digital Twin were considered to be guiding principles for establishing a National Digital Twin by the Centre for Digital Built Britain. Although some of the elements of the Function principle, such as federation and curation, were very specific to developing a National Digital Twin, others were adopted to analyse this study's DT.

Furthermore, the implications of the proposed approach in different domains of use were presented briefly. Following this, under the Limitations and uncertainties section, a critical reflection on the drawbacks of the tool was given. In an ideal case scenario, when and if a similar approach with any underlying flood modelling software is followed to create this Digital Twin at the national level for public use, there needs to be critical ethical considerations therefore a determined board of members, including members from government, domain experts, and stakeholders is to be formed for the smooth and secure operation of the technology for the greater benefit. This is an extension of the Federation principle of Gemini principles.

The final result of this research delivers strategic partners and policymakers a better understanding of the situation through data-driven perception of risk. In nations like Dominica, where policy implementation mostly depends on public collaboration with authorities, this enables data-driven decision-making, opening doors for expanding public awareness of flood risk and individual household disaster preparedness strategies.

6. CONCLUSION

Dominica is an island country in the Caribbean region that is highly susceptible to natural disasters such as Hurricanes, Floods, Landslides and more. Every few years, one of these catastrophic hurricanes strikes this nation, causing up to a 200% loss in GDP. Having faced a devastating hurricane Maria in 2017, Dominica chose to become completely climate resilient in the near future. As a progression towards climate resilience, this tool intends to build capacity by enhancing their knowledge and assist in decision making through the use of a decision support tool. The primary aim of the study is to develop a digital twin framework that assists in the decision-making process for flood risk reduction and mitigation planning. To achieve this, specific research questions were framed and those are answered below.

What are the requirements of users in a 3D decision support tool for flood risk management?
As mentioned in section 3.1.1, a stakeholder survey was conducted with the use of a well-curated questionnaire. 34 responses in total were captured and the observations from the results are analysed and elaborated in section 4.1.1. Additionally, the interview responses from Stakeholders obtained earlier this year were included. Out of the different questions to identify requirements of stakeholders, five requirements involving datasets included, preferred Level of Detail of 3D Model, necessary functionalities, choice of stakeholder participation, and data privacy importance are included in the further development.

What are the current open-source techniques for creating digital twins of cities that can be employed in disaster management applications?
Based on the literature review conducted on scholarly articles in the fields of DT and flood management, the potential open-source techniques for creating DT to be employed for disaster management applications were identified. Although there are different open-source platforms to bring together the datasets to create an integrated DT along with simulation capabilities. Our choice of underlying flood modelling application, *Fastflood App* limits the options to those techniques that can be incorporated into web for achieving a resultant fully operational DT system. Web libraries such as Cesium JS, Three JS and Turf JS were identified to be useful for handling 3D assets on web, followed by databases including Cesium Ion storage, Geo Server, etc. Since DT's real-world, real-time simulations are computational representations, they require a functional framework of continuous integration & continuous delivery (CI/CD). This restricts the choices to those that are compliant with conventions for web development.

What are the input datasets needed to create a digital twin tailored for flood risk management?
The input datasets utilised in this study to develop a decision support tool for flood risk management encompasses the building asset dataset from OSM, Digital Elevation Model (DEM) generated from LiDAR dataset, UAV Imagery, Precipitation Dataset, and other global datasets auto downloaded from Fastflood App for flood simulations. Section 2.2 highlights the details of all the datasets consumed in the study.

What are the prerequisite data preparation steps needed to create a digital twin?
Some of the pre-requisite data preparation steps carried out to develop a digital twin were identifying the suitable scenario for test case simulation. Hurricane Maria was chosen to be the test case simulation for generating results for consequent development. The methods followed for performing this, and the results obtained are explained in sections 3.2 and 4.2, respectively. Additionally, for exploring textured 3D visualisation, the generation of 3D model from UAV imagery using Pix4D is performed.

How to integrate the available multiple datasets and build a digital twin of the study area?
Since the development of DT was implemented on the existing web based Fastflood App[8], any datasets to be included had to be imported into the web. Either the public datasets published as a Web Map Service (WMS) or Web Feature Service (WFS) can be added into the platform using Java Script functions or can be uploaded to an online storage server such as Geoserver, Cesium ion assets, etc. In this study, Cesium Ion asset storage is preferred as the rest of the development for DT framework highly involves Cesium JS. For textured 3D visualisation, an open-source 3D software called Blender is employed to combine different datasets. Section 4.3 elaborates on the procedure followed to perform the integration within this research context.

How is the existing fast flood model integrated with the 3D visualization of elements-at-risk?
As mentioned, Fastflood App is a web-based application hosted from GitHub repository, thus limiting the integration options to web-based techniques. Primarily, the programming languages such as Java Script, HTML and CSS are utilised for the development. Java Script libraries namely Cesium JS, Three JS, Leaflet JS, etc are predominantly used for the development. The asset datasets are imported as entities into Cesium Viewer if Vector datasets (as JSON), 3D models (as GLB), or as SingleTileImageryProvider, terrain for raster datasets and so on. Section 4.3 discusses the functions and logic implemented for the integration in detail.

How does the proposed Digital Twin framework for flood risk management perform and, align with the Gemini Principles in enhancing the decision-making process of stakeholders?
Aligning with the Gemini Principles, makes the developed approach more impactful as that would mean the trustworthiness, functionality, and purposeful nature of the DT. Nevertheless, from assessing the proposed approach, the utilised datasets may be replaced with reliable and precise datasets.

What could be the future advancements in the tool?

Moving forward, the probable future directions as a continuation of the study are presented in section 5.4. These include those goals that were intended to be attained but didn't happen, as well as approaches that may benefit stakeholders further in providing better solutions against flooding.

6.1. Scientific contributions

Based on the end products developed through this study, the following scientific contributions could be:

1. Proposes a novel approach of employing Triangulated irregular Network (TIN) as a way of visualisation to enhance the understanding of interactions between the flood water and the other real-world assets.

2. The research contributes to increasing the knowledge of the stakeholders in Dominica by providing a sustainable tool for decision support in the flood risk management domain. This is attributed to SDG goal 11: '*Make cities and human settlements inclusive, safe, resilient and sustainable*'.

3. The code for the decision-support tool addressed in this research (as an add-on to the Fastflood App, which is a separate private GitHub repository) is publicly available on GitHub, enabling researchers to

[8] https://fastflood.org/

collaborate. This contribution promotes open science by encouraging transparency and community interaction.

Highlights

- **Code published on GitHub Repository:** https://github.com/Sruthie-36/3D_FastfloodApp
- **Flood Simulation Animation videos on YouTube:** https://youtu.be/48hJbLXgfP0 , https://youtu.be/ypZCOYI6Jz4
- **Presentation:** Rajendran, S., Koeva, M.N., Van den Bout, B., 2024. Development of Digital twin framework for flood risk reduction and mitigation planning. 3rd 4TU/14UAS Research Day on "Digitalization of the Built Environment" in Delft.
- **Book of Extended abstracts:** Rajendran, S., Koeva, M.N., Van den Bout, B., 2024. Development of Digital twin framework for flood risk reduction and mitigation planning. 3rd 4TU/14UAS Research Day on "Digitalization of the Built Environment" in Delft (Submitted for publishing).
- **Scientific Article:** Rajendran, S., Koeva, M.N., Van den Bout, B., Development of Digital twin framework for flood risk reduction and mitigation planning (In preparation).

LIST OF REFERENCES

Ahmad, I., Wang, X., Waseem, M., Zaman, M., Aziz, F., Khan, R. Z. N., & Ashraf, M. (2022). Flood Management, Characterization and Vulnerability Analysis Using an Integrated RS-GIS and 2D Hydrodynamic Modelling Approach: The Case of Deg Nullah, Pakistan. *Remote Sensing 2022, Vol. 14, Page 2138*, *14*(9), 2138. https://doi.org/10.3390/RS14092138

Alexander, K., Hettiarachchi, S., Ou, Y., & Sharma, A. (2019). Can integrated green spaces and storage facilities absorb the increased risk of flooding due to climate change in developed urban environments? *Journal of Hydrology*, *579*, 124201. https://doi.org/10.1016/J.JHYDROL.2019.124201

Allen, T. R., Katragadda, S., Chen, Y.-H., Terry, B., Baptist, J., Yetkin, O., Tahvildari, N., Han, S., Steiner, B., McLeod, G., Dangendor, S., Sun, Q., & Richter, H. (2023). *A Digital Twin to Link Flood Models, Sensors, and Earth Observations for Coastal Resilience in Hampton Roads, Virginia, U.S.A*. 1388–1391. https://doi.org/10.1109/igarss52108.2023.10283168

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. In *Sustainability (Switzerland)* (Vol. 15, Issue 15). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/su151511910

Autodesk. (2024). *FBX | Adaptable File Formats for 3D Animation Software | Autodesk*. https://www.autodesk.com/products/fbx/overview

Azari, B., & Tabesh, M. (2022). Urban storm water drainage system optimization using a sustainability index and LID/BMPs. *Sustainable Cities and Society*, *76*, 103500. https://doi.org/10.1016/J.SCS.2021.103500

Barclay, J., Wilkinson, E., White, C. S., Shelton, C., Forster, J., Few, R., Lorenzoni, I., Woolhouse, G., Jowitt, C., Stone, H., & Honychurch, L. (2019). Historical Trajectories of Disaster Risk in Dominica. *International Journal of Disaster Risk Science*, *10*(2), 149–165. https://doi.org/10.1007/s13753-019-0215-z

Blender. (2024a). *Features — blender.org*. https://www.blender.org/features/

Blender. (2024b). *Glass BSDF - Blender 4.1 Manual*. https://docs.blender.org/manual/en/latest/render/shader_nodes/shader/glass.html

Blender. (2024c). *Transparent BSDF - Blender 4.1 Manual*. https://docs.blender.org/manual/en/latest/render/shader_nodes/shader/transparent.html

Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., Harradence, F., Keaney, E., Kemp, A., Luck, A., Pawsey, N., Saville, S., Schooling, J., Sharp, M., Smith, T., Tennison, J., Whyte, J., Wilson, A., & Makri, C. (2018). *Gemini Principles*. https://doi.org/10.17863/CAM.32260

Bout, B. van den. (2021). *Fast Flood App*. https://fastflood.org/

Bout, B. van den, 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

Bout, B. van den, Roon, K. van, & Das, S. (2024). *Stakeholder Interview during field work in Dominica*.

Bryson, J. M. (2004). What to do when Stakeholders matter. *Public Management Review*, *6*(1), 21–53. https://doi.org/10.1080/14719030410001675722

Caprari, G., Castelli, G., Montuori, M., Camardelli, M., & Malvezzi, R. (2022). Digital Twin for Urban Planning in the Green Deal Era: A State of the Art and Future Perspectives. *Sustainability 2022, Vol. 14, Page 6263*, *14*(10), 6263. https://doi.org/10.3390/SU14106263

Chen, A. S., Khoury, M., Vamvakeridou-Lyroudia, L., Stewart, D., Wood, M., Savic, D. A., & Djordjevic, S. (2018). 3D visualisation tool for improving the resilience to urban and coastal flooding in Torbay, UK. *Procedia Engineering*, *212*, 809–815. https://doi.org/10.1016/J.PROENG.2018.01.104

Clarke, B., Otto, F., Stuart-Smith, R., & Harrington, L. (2022). Extreme weather impacts of climate change: an attribution perspective. *Environmental Research: Climate*, *1*(1), 012001. https://doi.org/10.1088/2752-5295/AC6E7D

Commonwealth. (2022). *Dominica | Commonwealth*. https://thecommonwealth.org/our-member-countries/dominica

Digital Twin Geohub. (2023). https://www.utwente.nl/en/digital-society/research/digitalisation/digital-twin-geohub/

Eberhard, K. (2021). The effects of visualization on judgment and decision-making: a systematic literature review. *Management Review Quarterly 2021 73:1*, *73*(1), 167–214. https://doi.org/10.1007/S11301-021-00235-8

Evans, S. Y., Todd, M., Baines, I., Hunt, T., & Morrison, G. (2014). Communicating flood risk through three-dimensional visualization. *Proceedings of the Institution of Civil Engineers: Civil Engineering*, *167*(5), 48–55. https://doi.org/10.1680/CIEN.13.00020/ASSET/IMAGES/SMALL/CIEN-167-5-048-F10.GIF

Feng, B., Zhang, Y., & Bourke, R. (2021). Urbanization impacts on flood risks based on urban growth data and coupled flood models. *Natural Hazards*, *106*(1), 613–627. https://doi.org/10.1007/S11069-020-04480-0/TABLES/3

Ferré-Bigorra, J., Casals, M., & Gangolells, M. (2022). The adoption of urban digital twins. *Cities*, *131*. https://doi.org/10.1016/j.cities.2022.103905

Ford, D. N., & Wolf, C. M. (2020). Smart Cities with Digital Twin Systems for Disaster Management. *Journal of Management in Engineering*, *36*(4). https://doi.org/10.1061/(asce)me.1943-5479.0000779

Freeman, R. E. E., & McVea, J. (2005). A Stakeholder Approach to Strategic Management. *SSRN Electronic Journal*. https://doi.org/10.2139/SSRN.263511

Fu, G., Zhang, C., Hall, J. W., David Butler, |, Slavikova, L., Wright, N., & Jepson, W. (2023). Are sponge cities the solution to China's growing urban flooding problems? *Wiley Interdisciplinary Reviews: Water*, *10*(1), e1613. https://doi.org/10.1002/WAT2.1613

Gao, M., Wang, Z., & Yang, H. (2022). Review of Urban Flood Resilience: Insights from Scientometric and Systematic Analysis. *International Journal of Environmental Research and Public Health 2022, Vol. 19, Page 8837*, *19*(14), 8837. https://doi.org/10.3390/IJERPH19148837

Ghaith, M., Yosri, A., & El-Dakhakhni, W. (2021). *Digital Twin: A City-Scale Flood Imitation Framework*. https://www.researchgate.net/publication/352055849

Ghaith, M., Yosri, A., & El-Dakhakhni, W. (2022). Digital Twin: A City-Scale Flood Imitation Framework. *Lecture Notes in Civil Engineering*, *250*, 577–588. https://doi.org/10.1007/978-981-19-1065-4_48/FIGURES/8

Gibson, M. J., Chen, A. S., Khoury, M., Vamvakeridou-Lyroudia, L. S., Stewart, D., Wood, M., Savić, D. A., & Djordjević, S. (2020). Case study of the cascading effects on critical infrastructure in Torbay coastal/pluvial flooding with climate change and 3D visualisation. *Journal of Hydroinformatics*, *22*(1), 77–92. https://doi.org/10.2166/HYDRO.2019.032

Government of the Commonwealth of Dominica. (2017). *Post-Disaster Needs Assessment Hurricane Maria A Report by the Government of the Commonwealth of Dominica*.

Guo, K., Guan, M., & Yu, D. (2021). Urban surface water flood modelling-a comprehensive review of current models and future challenges. *Hydrology and Earth System Sciences*, *25*(5), 2843–2860. https://doi.org/10.5194/HESS-25-2843-2021

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile Augmented Reality for Flood Visualisation. *Environmental Modelling & Software*, *109*, 380–389. https://doi.org/10.1016/J.ENVSOFT.2018.05.012

Herman, L., Russnák, J., & Řezník, T. (2017). Flood modelling and visualizations of floods through 3D open data. *IFIP Advances in Information and Communication Technology*, *507*, 139–149. https://doi.org/10.1007/978-3-319-89935-0_12/FIGURES/3

Humanitarian Data Exchange. (2019). *Dominica - Subnational Administrative Boundaries - Humanitarian Data Exchange*. https://data.humdata.org/dataset/cod-ab-dma

Humanitarian Data Exchange. (2020). *Dominica - Population Density - Humanitarian Data Exchange*. https://data.humdata.org/dataset/worldpop-population-density-for-dominica

Irvine, K. N., Suwanarit, A., Likitswat, F., Srilertchaipanij, H., Sahavacharin, A., Wongwatcharapaiboon, J., Boonkam, P., Ingegno, M., & Janpathompong, S. (2023). Nature-based solutions to enhance urban flood resiliency: case study of a Thailand Smart District. *Sustainable Water Resources Management*, *9*(1), 1–23. https://doi.org/10.1007/S40899-023-00821-6/FIGURES/13

Jepsen, A. L., & Eskerod, P. (2009). Stakeholder analysis in projects: Challenges in using current guidelines in the real world. *International Journal of Project Management*, *27*(4), 335–343. https://doi.org/10.1016/J.IJPROMAN.2008.04.002

Joy, J., Kanga, S., & Kumar SINGH, S. (2020). *3D GIS-RETROSPECTIVE FLOOD VISUALISATION*. http://acta.fih.upt.ro/

Kabir, M., Habiba, U. E., Khan, W., Shah, A., Rahim, S., Rios-Escalante, P. R. D. los, Farooqi, Z. U. R., & Ali, L. (2023). Climate change due to increasing concentration of carbon dioxide and its impacts on environment in 21st century; a mini review. *Journal of King Saud University - Science*, *35*(5), 102693. https://doi.org/10.1016/J.JKSUS.2023.102693

Kehl, C., & de Haan, G. (2013). Interactive simulation and visualisation of realistic flooding scenarios. *Lecture Notes in Geoinformation and Cartography*, *0*, 79–93. https://doi.org/10.1007/978-3-642-33218-0_7/FIGURES/10

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Https://Doi.Org/10.1080/02626667.2013.857411*, *59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411

Leshem, S., & Trafford, V. (2007). Overlooking the conceptual framework. *Innovations in Education and Teaching International*, *44*(1), 93–105. https://doi.org/10.1080/14703290601081407

López-Martínez, F. (2023). Are Floods Becoming a More Expensive Hazard? A Damages Review of the Southeastern Spanish Coast (1996–2016). *Land 2023, Vol. 12, Page 1035*, *12*(5), 1035. https://doi.org/10.3390/LAND12051035

Macchione, F., Costabile, P., Costanzo, C., & De Santis, R. (2019). Moving to 3-D flood hazard maps for enhancing risk communication. *Environmental Modelling & Software*, *111*, 510–522. https://doi.org/10.1016/J.ENVSOFT.2018.11.005

Mainardes, E. W., Alves, H., & Raposo, M. (2012). A model for stakeholder classification and stakeholder relationships. *Management Decision*, *50*(10), 1861–1879. https://doi.org/10.1108/00251741211279648/FULL/PDF

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a Theory of Stakeholder Identification and Salience: Defining the Principle of Who and What Really Counts. *The Academy of Management Review*, *22*(4), 853. https://doi.org/10.2307/259247

Mobini, S., Pirzamanbein, B., Berndtsson, R., & Larsson, R. (2022). Urban flood damage claim analyses for improved flood damage assessment. *International Journal of Disaster Risk Reduction*, *77*, 103099. https://doi.org/10.1016/J.IJDRR.2022.103099

Morante-Carballo, F., Montalván-Burbano, N., Arias-Hidalgo, M., Domínguez-Granda, L., Apolo-Masache, B., & Carrión-Mero, P. (2022). Flood Models: An Exploratory Analysis and Research Trends. *Water 2022, Vol. 14, Page 2488*, *14*(16), 2488. https://doi.org/10.3390/W14162488

NPR. (2023). *Hurricane Maria decimated Dominica as rebuilding moves slowly : NPR*. https://www.npr.org/2023/06/14/1180477017/dominica-recovers-hurricane-maria-2017

OpenAerialMap. (n.d.). Retrieved June 9, 2024, from https://openaerialmap.org/

OpenStreetMap. (2024). *OpenStreetMap*. https://www.openstreetmap.org/#map=7/52.154/5.295

Oulahen, G. (2021). Flood hazards, environmental rewards, and the social reproduction of risk. *Geoforum*, *119*, 43–51. https://doi.org/10.1016/J.GEOFORUM.2020.12.021

Pachauri, R. K., Reisinger, A., Bernstein, L., Intergovernmental Panel on Climate Change. Core Writing Team, & Intergovernmental Panel on Climate Change. (2007). *Climate change 2007 : synthesis report*.

Pedersen, A. N., Borup, M., Brink-Kjær, A., Christiansen, L. E., & Mikkelsen, P. S. (2021). Living and Prototyping Digital Twins for Urban Water Systems: Towards Multi-Purpose Value Creation Using Models and Sensors. *Water 2021, Vol. 13, Page 592*, *13*(5), 592. https://doi.org/10.3390/W13050592

Pix4D. (2024). *Professional photogrammetry and drone mapping software | Pix4D*. https://www.pix4d.com/

Qi, W., Ma, C., Xu, H., Chen, Z., Zhao, K., & Han, H. (2021). A review on applications of urban flood models in flood mitigation strategies. *Natural Hazards 2021 108:1*, *108*(1), 31–62. https://doi.org/10.1007/S11069-021-04715-8

Rajak, J. (2021). A Preliminary Review on Impact of Climate change and our Environment with Reference to Global Warming. *International Journal of Environmental Sciences*, *10*(1), 11–14. www.crdeepjournal.org

Rau, S. (2022). *Sponge Cities: Integrating Green and Gray Infrastructure to Build Climate Change Resilience in the People's Republic of China (ADB Brief 222)*. https://doi.org/10.22617/BRF220416-2

Reed, M. S., Graves, A., Dandy, N., Posthumus, H., Hubacek, K., Morris, J., Prell, C., Quinn, C. H., & Stringer, L. C. (2009). Who's in and why? A typology of stakeholder analysis methods for natural resource management. *Journal of Environmental Management*, *90*(5), 1933–1949. https://doi.org/10.1016/J.JENVMAN.2009.01.001

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 2023, Vol. 23, Page 2659*, *23*(5), 2659. https://doi.org/10.3390/S23052659

Seemuangngam, A., & Lin, H.-L. (2024). The impact of urbanization on urban flood risk of Nakhon Ratchasima, Thailand. *Applied Geography*, *162*, 103152. https://doi.org/10.1016/J.APGEOG.2023.103152

Shivanna, K. R. (2022). *Climate change and its impact on biodiversity and human welfare*. *88*, 160–171. https://doi.org/10.1007/s43538-022-00073-6

Singh, H., & Garg, R. D. (2016). Web 3D GIS Application for Flood Simulation and Querying Through Open Source Technology. *Journal of the Indian Society of Remote Sensing*, *44*(4), 485–494. https://doi.org/10.1007/S12524-015-0498-5/TABLES/3

Sivaramanan, S. (2015). *Global Warming and Climate change, causes, impacts and mitigation*. https://doi.org/10.13140/RG.2.1.4889.7128

Tarpanelli, A., Bonaccorsi, B., Sinagra, M., Domeneghetti, A., Brocca, L., & Barbetta, S. (2023). Flooding in the Digital Twin Earth: The Case Study of the Enza River Levee Breach in December 2017. *Water (Switzerland)*, *15*(9). https://doi.org/10.3390/w15091644

Teeuw, R., Cannata, M., Argyriou, A. V., & Lieberman, O. (2023). Geoinformatics for Caribbean hurricane risk management and improved community resilience. *2023 Joint Urban Remote Sensing Event, JURSE 2023*. https://doi.org/10.1109/JURSE57346.2023.10144191

Tsujimoto, R., Fukuda, T., & Yabuki, N. (2024). Server-enabled mixed reality for flood risk communication: On-site visualization with digital twins and multi-client support. *Environmental Modelling and Software*, *177*. https://doi.org/10.1016/j.envsoft.2024.106054

Turner, R., & Sun, Q. chayn. (n.d.). *Advancing Flood Resilience: A Responsive Digital Twin Framework for Real-Time City-Scale Flood Modelling and Disaster Event Monitoring*. https://ssrn.com/abstract=4643740

Tzachor, A., Sabri, S., Richards, C. E., Rajabifard, A., & Acuto, M. (2022). Potential and limitations of digital twins to achieve the Sustainable Development Goals. *Nature Sustainability 2022 5:10*, *5*(10), 822–829. https://doi.org/10.1038/s41893-022-00923-7

UNDRR. (n.d.). *What is the Sendai Framework for Disaster Risk Reduction?* Retrieved November 19, 2023, from https://www.undrr.org/implementing-sendai-framework/what-sendai-framework

United Nations. (2022). *Causes and Effects of Climate Change*. United Nations. https://www.un.org/en/climatechange/science/causes-effects-climate-change

United Nations. (2024). *List of SIDS | Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States*. https://www.un.org/ohrlls/content/list-sids

Van Ackere, S., Glas, H., Beullens, J., Deruyter, G., De Wulf, A., & De Maeyer, P. (2016). Development of a 3D dynamic flood WEB GIS visualisation tool. *International Journal of Safety and Security Engineering*, *6*(3), 560–569. https://doi.org/10.2495/SAFE-V6-N3-560-569

Wang, Q. (2022). Concept of digital twin construction scheme for flood storage space in mid-lower Yangtze River. *Metaverse*, *3*(2), 12. https://doi.org/10.54517/met.v3i2.2125

Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., Ham, Y., & Cai, Z. (2022). Developing Human-Centered Urban Digital Twins for Community Infrastructure Resilience: A Research Agenda. *Journal of Planning Literature*. https://doi.org/10.1177/08854122221137861/ASSET/IMAGES/LARGE/10.1177_08854122221137861-FIG1.JPEG

APPENDICES

In line with the 'Use of AI in Education at the University of Twente' guidelines:

During the preparation of this work the author used ChatGPT in order to assist in code-writing for web development. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the work.

Appendix I - Stakeholder Interest Table

Stakeholders	How are they involved?	Interests	Potential project impact	Relative priority of interests
Primary Stakeholders				
Office of Disaster Management, Dominica (ODM)	Government Division focusing on Disaster Management	• Having flood simulation/geodata visualisation tools for disaster management. • Preparedness for disasters. • Understand disaster risk changes in the area. • Plan/develop efficient climate adaptation plans and disaster management plans. • Extend support during response and recovery phases.	+	1
Physical Planning Division, Dominica (PPD) - Ministry of Housing and Urban Development, Government of Dominica	Government Division focusing on physical planning in Dominica.	• Having flood simulation/geodata visualisation tools for disaster management. • Open-source tools are preferred as funding is a limitation. • Prefers cloud/online tools. Prefers to publish maps online. • Better techniques to plan and develop climate resilient urban community.	+	1
Ministry of Public works, Public Utilities and Digital Economy, Government of Dominica	Ministry of the National government working on public works, public utilities, and digital economy.	• Having tools to classify and index roads preferably than the rest. • Prefer 2D over 3D due to graphics requirements. • Climate resilience models.	+	1
Dominica Red Cross Society (DRCS)	An NGO/humanitarian organisation in the area with a focus of Disaster risk reduction.	• Involved in disaster preparedness and response. • Pre-developed model of Fastflood for entire island. • Having flood simulation/geodata visualisation tools for disaster	+/?	1

		management. • Building codes. • Hazard maps with demographic and risk information.		
Climate Resilience Execution Agency for Dominica (CREAD)	A statutory government agency to build climate resilience in Dominica.	• Having flood simulation/geodata visualisation tools for disaster management. • Interested in knowing information on precipitation levels that affects certain regions/community. • Flood warning and flood alert systems. • Information on landslides, rockfalls and sea surge. • Capacity building. • Hazard, risk maps.	+/?	1
European Space Agency (ESA)	E04Multihazards project	• Digital twinning / 3D visualisation of disaster including floods.	+	1
Dominica Meteorological Service (DMS)	Monitors and forecasts Weather conditions in the area.	• Awareness to the public. • Preparedness in disaster management cycle. • Weather forecasting. • Weather warning/alerts.	?	2
Secondary Stakeholders				
Citizens	Reside in the area.	• Avoid fatality. • Avoid damages to property, cattle, automobile, or life.	+	3
Tourism Centres	Responsible for managing tourism within the country.	• Make profit. • Attract more tourists to the area. • Ensure safety to tourists	?/-	3
Tourists	Tourism - Important source of income in the area.	• Require environment safety in terms of being resilient to climatic catastrophes.	+/?	3
Farmers	Agriculture - Important source of income in the area.	• Avoid damages to crops. • In case of disasters, need compensation for damages to fields and crops.	?	4
Dominica Insurance providers	Plays a significant role in the recovery of the area post a disaster event.	• Make profit. • More resilient structures –> Less damages in turn leading to less compensation.	+/?	5
National Bank of Dominica	Funding in the area.	• Make profit. • More transactions. • More loan requests/repeated investments for recovery.	-	5
Other Banks in Dominica	Funding in the area.	• Make profit. • More transactions. • More loan requests/repeated investments for recovery.	-	5
Energy Providers	Disruption of energy supply in case of	• Avoid damages to Energy infrastructure in case of	+/?	3

	Disaster event.	disasters. • Build/maintain climate resilient energy infrastructure.		
Construction Companies in Dominica	They participate in prevention, preparedness, and recovery phases of disaster management cycle in the area.	• Make profit. • More construction works for steady income.	-/?	4
Ministry of Investment and Governance, Dominica	Approves funding for new investments and policies for climate adaptation and climate resilience.	• Meaningful investments for growth of the country.	+	4
Fire and Ambulance Services Division	Provide emergency services in case of a disaster/crisis.	• Suitable urban development for rescue operations during a catastrophe. • Better preparedness for evacuation schemes.	+	3
External Stakeholders				
Researchers	Working on similar studies.	• Better solutions for all four stages of disaster management cycle. • Reproducible, sustainable, and transferrable solutions for disaster management.	+	1
United Nations Disaster Risk Reduction (UNDRR)	Provides guidelines to the countries on disaster risk reduction.	• Reduce disaster risk in the developing countries including Dominica by making them adaptive to climate change. • Strengthening knowledge and capacity building.	+/?	3
National Government	Developed the Dominica's Climate resilience and recovery plan (CRRP). Decided and working on to become climate resilient as a nation.	• Becoming the first Climate resilient nation.	+/?	3
Parish-level Government	Involved in building climate resilience in the area.	• Contributing to becoming the first Climate resilient nation.	+/?	3
CARICOM – Caribbean community	Community of nations including Dominica focusing on integration and growth.	• Better integration among the Caricom member nations and growth of the nations.	?	5
The World Bank	They work towards making the countries resilient and sustainable in development.	• Disaster Vulnerability Reduction Project (DVRP)	+/?	4

Table 5 Stakeholder Interest Table

Appendix II – Literature Review Table

Article	Datasets/Methods used	Study Area	Year	Reference
Interactive Simulation and Visualisation of Realistic Flooding Scenarios	LiDAR data, AHN-2 point clouds, High-resolution imagery, Computational fluid dynamics (CFD) models	Delft, The Netherlands	2013	(Kehl & de Haan, 2013)
Communicating flood risk through three-dimensional visualisation	Topographical data (Lidar data such as DSM & DTM, aerial photography and Ordnance Survey MasterMap data), and interrogation of the Environment Agency's national receptor dataset, Hydrodynamic modelling, Overlay layers	Exeter, UK	2013	(Evans et al., 2014)
Development of a 3d dynamic flood web GIS visualisation tool	Ol3-CesiumOpenlayers web library, OpenLayers3 map	Not specific	2016	(Van Ackere et al., 2016)
Web 3D GIS Application for Flood Simulation and Querying Through Open-Source Technology	Apache Tomcat, WebGL, X3DM, jQuery, W3DS, Geoserver, CityGML	Sample dataset	2016	(Singh & Garg, 2016)
3D visualisation tool for improving the resilience to urban and coastal flooding in Torbay, UK	The flood model CADDIES 2D, 3D visualisation plugins, qgis2threejs and GoogleEarthView in QGIS	Torbay, UK	2018	(Chen et al., 2018)
Mobile Augmented Reality for Flood Visualisation	JVM + JDK API libraries & tools + OpenGL ES, Vutoria SDK, JSON, HTTP connection, REST API → AR application	Doncaster, UK	2018	(Haynes et al., 2018)
Flood Modelling and Visualizations of Floods Through 3D Open Data	Open-source DEM datasets, Open-source Software, Open-source 3D rendering	Prague, Czech Republic	2018	(Herman et al., 2017)
Moving to 3-D flood hazard maps for enhancing risk communication	Google Earth 3D, Lidar Survey, Python, Numerical computational models, Blender	Cosenza	2019	(Macchione et al., 2019)

3D GIS – Retrospective Flood Visualisation	-SRTM DEM, Panchayat boundary, OSM River & building footprint polygon and flood inundated area as raster layer -AutoCAD, Sketchup, Lumion, Camtasia,	Kerala, India	2020	(Joy et al., 2020)
Case study of the cascading effects on critical infrastructure in Torbay coastal/pluvial flooding with climate change and 3D visualisation	caFloodPro , Flood models (Overstopping conditions): Caddies Model, Amazon Model, Google Earth Pro, Unity 3D game engine	Torbay, UK	2020	(Gibson et al., 2020)
Digital twin: a city-scale flood imitation framework	Hec-Ras, DEM, Flow record, Manning coefficient, OSM, Satellite imagery.	Calgary, Canada	2021	(Ghaith et al., 2021)
Concept of digital twin construction scheme for flood storage space in mid-lower Yangtze River	Machine Learning, Deep learning, Cloud computing, Historical flood data, real-time rainfall data, Landuse, Risk assessment, Feedback, Decision interaction, Boundary condition, System inheritance, Spatiotemporal situation map, etc.	Yangtze River, China	2022	(Wang, 2022)
Towards a national digital twin for flood resilience in New Zealand	BG-FLOOD, NIWA, FME, RiskScape, Bathymetry, LiDAR, WFS, RDBMS, Geofabrics python library, Opentopography, NETCDF, DEM, Cesium JS, API,	Kaiapoi, New Zealand	2022	(Wilson et al., n.d.)
A Digital Twin to Link Flood Models, Sensors, and Earth Observations for Coastal Resilience in Hampton Roads, Virginia, U.S.A	LiDAR DEM, IoT Sensor Data, Public STACs, Landsat, NetCDF, COG, UAV, Landcover, IoT sensors, PostgreSQL	Virginia, U.S. A	2023	(Allen et al., 2023)
Flooding in the Digital Twin Earth: The Case Study of the Enza River Levee Breach in December 2017	2D hydraulic models, SAR, Sentinel2 Imagery, NDWI	Enza river, Italy	2023	(Tarpanelli et al., 2023)

Advancing Flood Resilience: A Responsive Digital Twin Framework for Real-Time City-Scale Flood Modelling and Disaster Event Monitoring	IoT Sensor Data, DEM, River height, Rainfall, Buildings, QGIS, FME, POSTGRESQL, POSTGIS, Cesium JS, Turf JS, RDT web app, RRL API, CityGML, JSON, HTML, CSS, Javascript	Melbourne, Australia	2023	(Turner & Sun, n.d.)
Digital Twin Smart Cities for Disaster Risk Management: A Review of Evolving Concepts	UAV, Mobile crowd sourcing, IoT, AI, CNN, Geo-Parsing	Not specific	2023	(Ariyachandra & Wedawatta, 2023)
Server-enabled mixed reality for flood risk communication: On-site visualization with digital twins and multi-client support	API, MR, Flood model, CPU, Memory, OS	Not specific	2024	(Tsujimoto et al., 2024)

Table 6 Literature Review Table

Appendix III – List of available datasets

Dataset	Format	Source/License	Description	Availability
Digital twin development				
Digital Surface Model (DSM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital surface model	Available
Digital Elevation Model (DEM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital elevation model	Available
Buildings	Shapefile (.shp)	Open Street maps	Vector file of buildings	Available
Road network	Shapefile (.shp)	ITC, University of Twente	Vector file of Roads	Available
River network	Shapefile (.shp)	ITC, University of Twente	Vector file of river network	Available
Bridges	Shapefile (.shp)	Dominica - Engineering Department	Vector file of Bridge locations	Available
Digital Surface Model (DSM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital surface model	Available
Digital Elevation Model (DEM)	Tiff (.tif)	ITC, University of Twente	Raster file of Digital elevation model	Available
Buildings	Shapefile (.shp)	Open Street maps	Vector file of buildings	Available
Aerial Imagery	Tiff (.tif)	(*OpenAerialMap*, n.d.)	Raster file of Roseau (2018)	Available
	Tiff (.tif)	(*OpenAerialMap*, n.d.)	Raster file of Coulibistrie (2017)	Available
Population Density	Tiff (.tif)	(Humanitarian Data Exchange, 2020)	Raster file of Population density values of Dominica	Available

UAV Imagery	Tiff (.tif)	ITC, University of Twente	UAV Images of Study area	Available
		Flood Simulation		
Elevation, Land cover, Infiltration, Rainfall	Raster	Auto-download through Fastflood app from various data sources	Raster files from data sources including SRTM (Elevation), Sentinel – 2 (Land cover), ECWMF (Rainfall forecast), Soilgrids.org (Soil data to calculate Infiltration)	Existing provision to download through website of Fastflood
Historical precipitation records	Text file	UT - ITC – Previous projects	During Hurricane Maria and tropical storm Erica	Available
		Additional Data		
Geological and Hydrogeologica l data	Raster	PARATUS project	-	Available
UAV data	Raster	Previous projects	Available only for certain regions of interest	Available
Disaster databases including Flood hazard maps	Raster and vector formats	UT - ITC	Detailed inventory for hurricane Maria, and tropical storm Erika	Available

Table 7 List of available datasets

Appendix IV – Questionnaire : Stakeholder Engagement survey

Stakeholder Interview - 3D Flood simulation tool

This questionnaire is crafted to understand the requirements and needs of the stakeholders, ensuring that the to-be-developed tool supports their analytical and decision-making processes in flood risk management. It broadly addresses familiarity of users with similar tools, desired functionalities, and related aspects.

Disclaimer:
Any personal details collected in this survey will not be disclosed/published anywhere.

* Required

This section addresses questions regarding future developments/integrations on this tool.

This is the landing page of the existing "Fastflood App" (https://fastflood.org/). Further developments and integrations are to be made on this existing tool.

1

What is your role in the company/organisation of employment? *

- ○ Disaster Management Authorities
- ○ Consultants/Project Managers (GIS/Disaster/Urban related)
- ○ Urban/City Planners
- ○ Meteorologists/Hydrologists
- ○ Teaching
- ○ Student
- ○ Other

2

How often do you interact with decision support tools related to city planning and disaster risk management? *

☆ ☆ ☆ ☆ ☆

3

What specific information or data would be critical for you to visualize in a 3D city model during flood simulations? *

(Select as many as relevant and suggest other features if any)

- ☐ Roads
- ☐ Bridges
- ☐ Buildings
- ☐ Rivers
- ☐ Green spaces
- ☐ Culverts
- ☐ Other

4

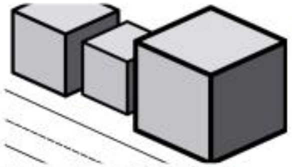
What level of interactivity would you prefer in navigating the 3D city model? *

- ○ Basic navigation (zooming, panning, etc)

- ○ Advanced interaction (simultaneous multiple scenarios/layout interaction, manipulating features, etc)
- ○ Other

5

What level of detail is required in a 3D city model for flood simulation application? *



- ○ Wire-frame representation (Consisting of transparent points, lines, curves, polygons)

- ○ Textured realistic representation (Detailed building information including facades, windows, etc. | Image based photo-realistic visualisation)
- ○ Other

6

In which scenarios do you foresee using this decision support tool? *
(Select as many as relevant and suggest other features if any)

- ☐ Future flood risk reduction planning
- ☐ Flood extent mapping
- ☐ Emergency response planning
- ☐ Flood forecasting
- ☐ Urban development and planning
- ☐ Community engagement and education
- ☐ Infrastructure maintenance
- ☐ Other

7

What do you think are the necessary functionalities in such a tool? *
(Select as many as relevant and suggest other features if any)

- ☐ 3D visualization
- ☐ Flood simulation capabilities
- ☐ Customization of simulation input parameters
- ☐ Multiple scenario simulation and visualization (Climate change scenarios)
- ☐ Exposure analysis
- ☐ Forecasting flood events
- ☐ Integration with external data
- ☐ Integration with external GIS systems
- ☐ Exporting capabilities such as Maps/Layout
- ☐ Other

8

What level of involvement do you think is appropriate for local stakeholders (e.g. Residents) in shaping flood risk management policies and strategies? *

- ◯ High (Direct participation in decision-making)
- ◯ Moderate (Only providing input and feedback)
- ◯ Low (Just receiving information without active participation)

9

Would you find it valuable to explore the incorporation of risk communication features for stakeholders in the future?

If yes, how often should residents receive updates on flood conditions in their area? *

- ◯ YES - Daily
- ◯ YES - Weekly
- ◯ YES - Monthly
- ◯ YES - Only when needed (Emergency/Risky conditions)
- ◯ NO
- ◯ Other

10

Considering different visualization methods for flood-related information, which graphical representations do you think would be most effective? *

- ☐ Probability Distribution Charts
- ☐ Conventional 2D Maps
- ☐ Heatmaps
- ☐ Immersive 3D Maps
- ☐ Other

11

In your opinion, how useful will this tool be in decision-making of flood risk management? *

☆ ☆ ☆ ☆ ☆

12

What additional datasets or elements do you think could be more interesting to explore and integrate in this tool?

(Select those that you think could be useful. If you have additional answers, enter in the 'other' option) *

- ☐ Population/Demographics data
- ☐ Climate change projection data
- ☐ Critical infrastructure information
- ☐ High resolution Satellite Imagery
- ☐ Cadastral data
- ☐ IoT/Mobile sensor data
- ☐ Transportation network
- ☐ Historical data
- ☐ Other

13

What level of importance do you place on data privacy and security, especially when dealing with sensitive information related to city infrastructure and risk? *

☆ ☆ ☆ ☆ ☆

14

Any additional comments or suggestions are most welcome!

Participant Details

If you consent to participate in a similar questionnaire at the end of the development process to provide feedback, kindly provide your name and email address . It would support the project's evaluation phase and ensure effective use of stakeholder input.

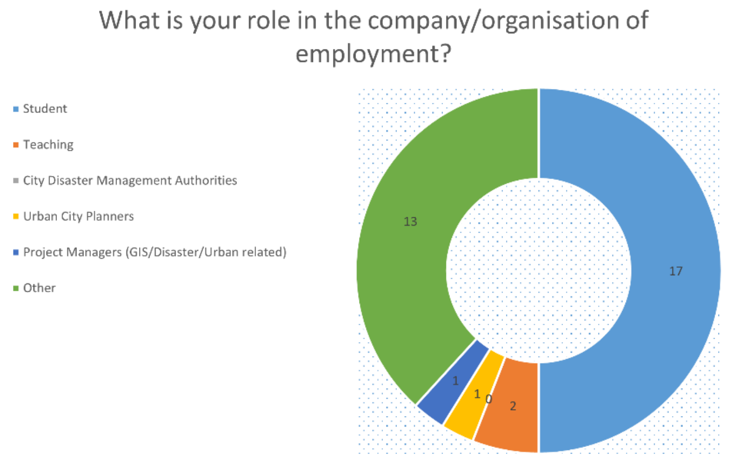
15

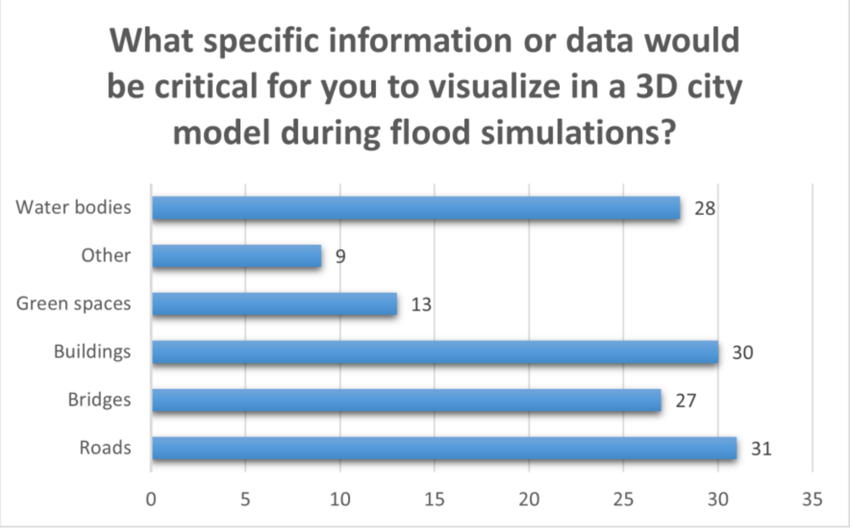
Name (Optional)

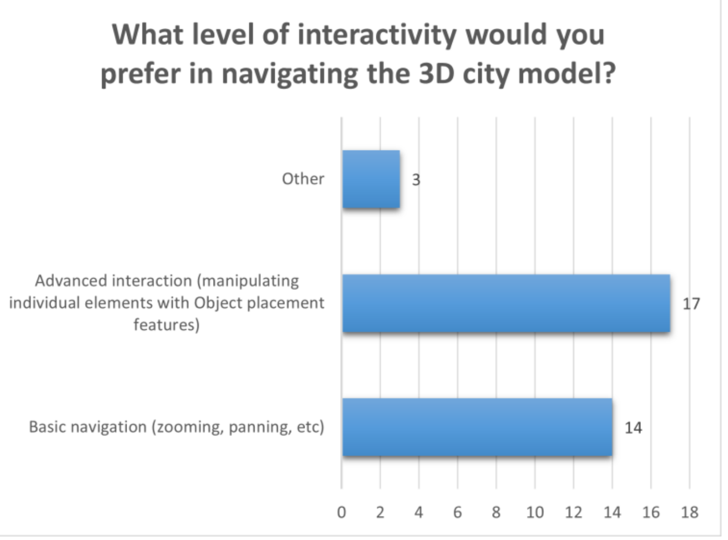
16

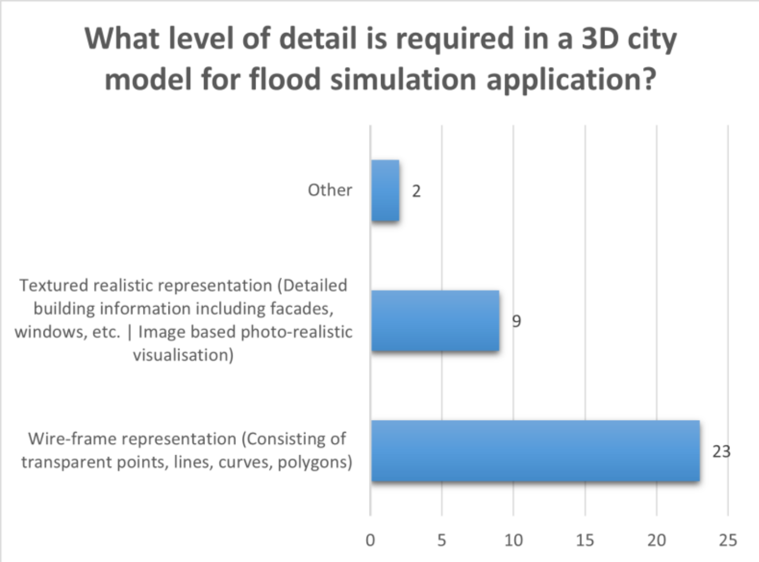
Work email address (Optional)

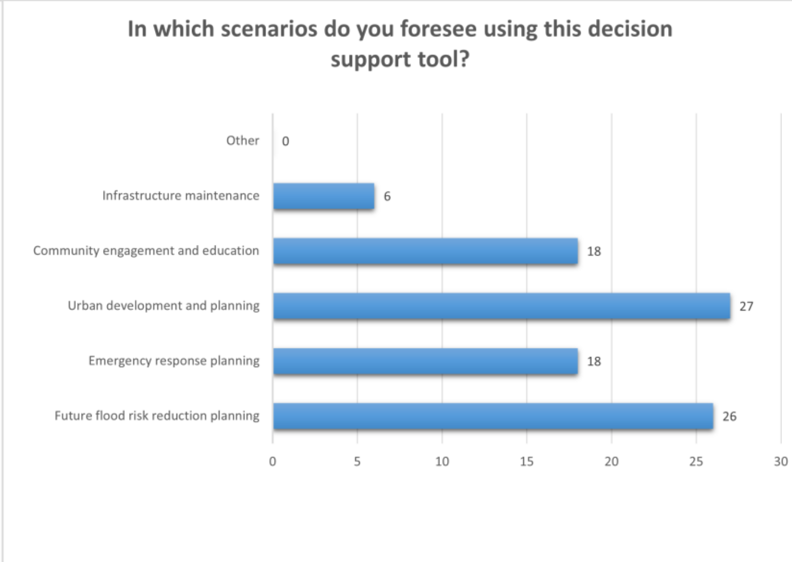
Appendix V – Stakeholder Survey Results

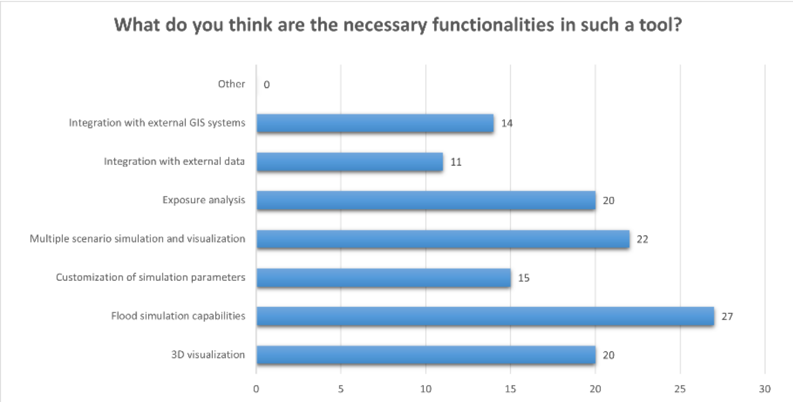




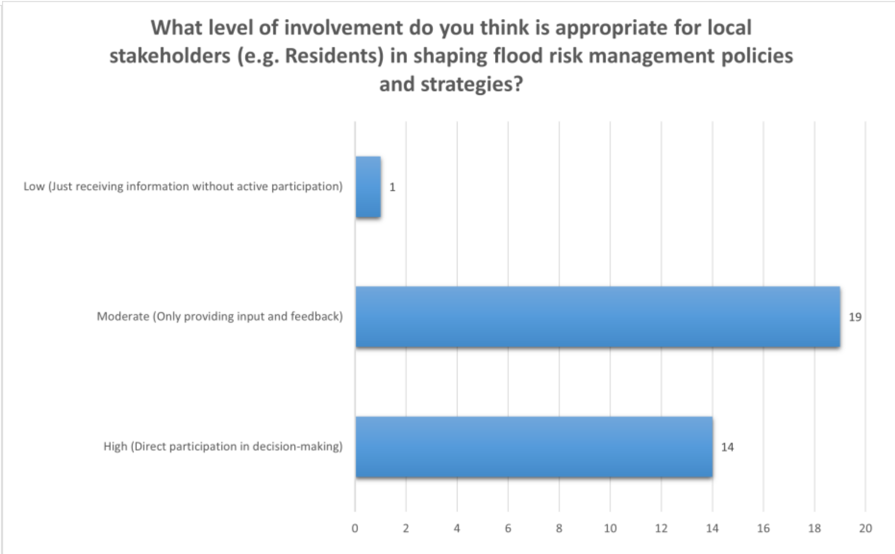


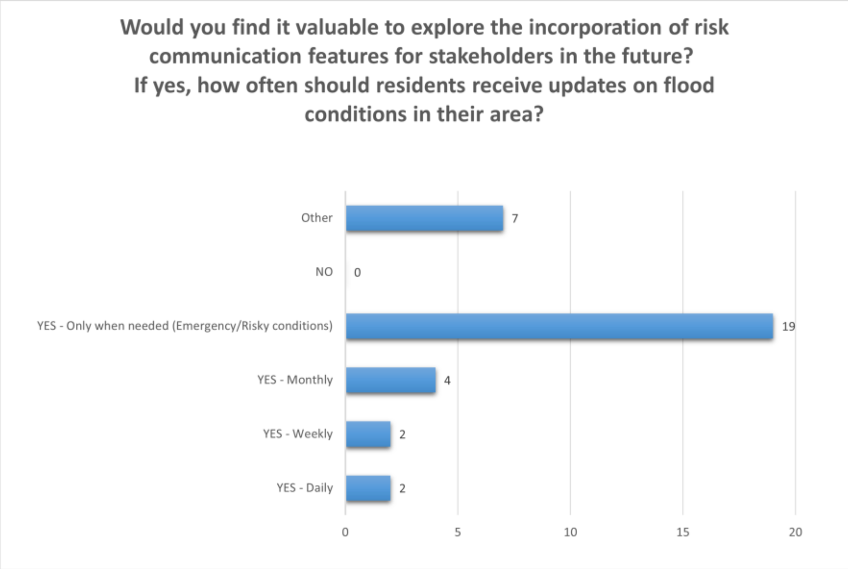


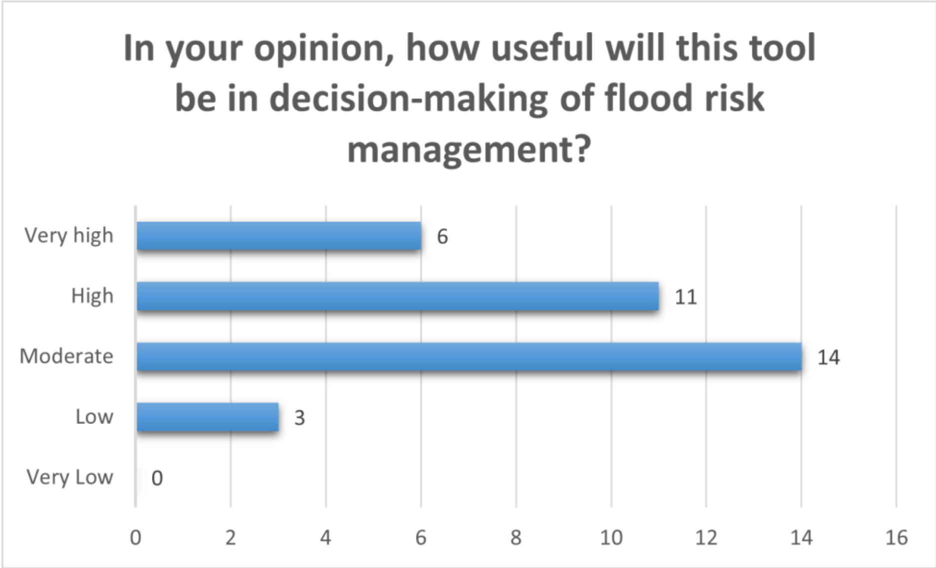


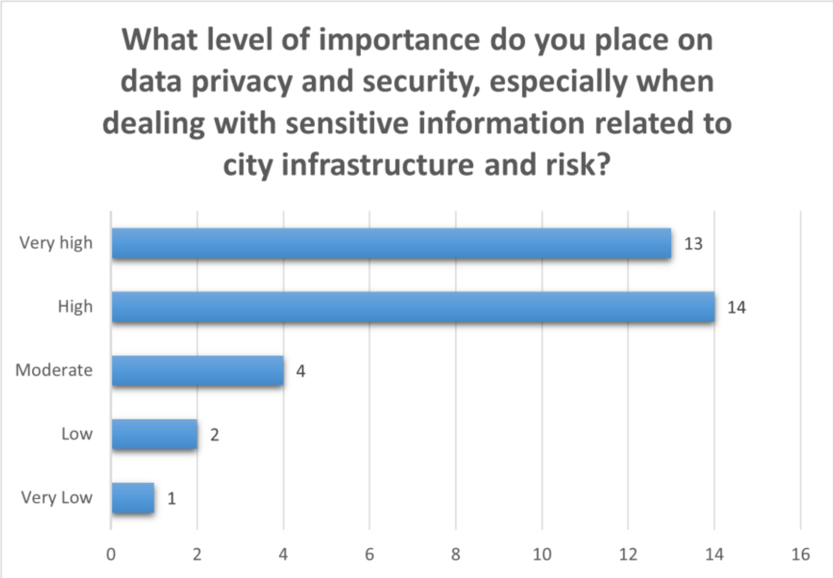


EXTRA	
Risk communication to Stakeholders	14
Forecasting flood events	2
Exporting capabilities such as Maps/Layout	4




Would you find it valuable to explore the incorporation of risk communication features for stakeholders in the future?
If yes, how often should residents receive updates on flood conditions in their area?
Other
7
NO
0
YES - Only when needed (Emergency/Risky conditions)
19
YES - Monthly
4
YES - Weekly
2
YES - Daily
2
0
5
10
15
20


In your opinion, how useful will this tool be in decision-making of flood risk management?
Very high
6
High
11
Moderate
14
Low
3
Very Low
0
0
2
4
6
8
10
12
14
16


What level of importance do you place on data privacy and security, especially when dealing with sensitive information related to city infrastructure and risk?
Very high
13
High
14
Moderate
4
Low
2
Very Low
1
0
2
4
6
8
10
12
14
16