Exploring the Concept of a Digital Twin Smart City for Disaster Emergency Preparedness Planning in Nova Scotia, Canada

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ABSTRACT

Cities worldwide are grappling with complex challenges, including rapid urbanization, crowd control, ageing infrastructure, and the necessity for efficient emergency response. These issues are exacerbated by climate change and the increasing risk of natural disasters, compelling innovative solutions for sustainable urban development. The emergence of the Smart City concept has provided a transformative approach to addressing these challenges through advanced technologies to enhance quality of life, urban resilience, and sustainability. Digital Twins (DTs) have emerged as a game-changing tool among these technologies. A DT is a virtual representation of a physical city that mirrors its systems, processes, and operations in real-time. This paper conceptualizes DTs for disaster-resilient smart cities, including descriptive, diagnostic, predictive, prescriptive, and autonomous according to their maturity level. This exploratory paper contributes to the emergency management literature by enhancing the understanding of how different DT maturity levels can be deployed in disaster contexts, especially for flood hazards in Novascotia.

Keywords

Digital twins, Smart cities, natural disasters, emergency preparedness

INTRODUCTION

Urban areas worldwide are facing significant challenges due to rapid urbanization and population growth. By 2050, nearly 70% of the global population is expected to live in cities, straining infrastructure and public services. This urban crowding leads to traffic congestion and inadequate waste management, diminishing living standards. Concurrently, the increasing frequency of extreme weather events reveals the vulnerabilities of traditional urban systems Global risk report 2025 indicates that over 70% of urban infrastructure is outdated or ill-equipped for modern demands (WEF, 2025). Innovative solutions are urgently needed to address these challenges, prompting the development of smart cities empowered by advanced technology.

The Emergency Events Database (EM-DAT), launched by the Centre for Research on the Epidemiology of Disasters (CRED) in 1988 with support from the WHO and Belgian Government, provides an overview of disasters worldwide. It records data on 26,000 disasters from 1900 to the present, classified into six groups: geophysical, hydrological, meteorological, climatological, biological, and extra-terrestrial (see **Figure 1**). Furthermore, it is also noted that floods are the most common natural disaster occurring. (**Figure 2**)

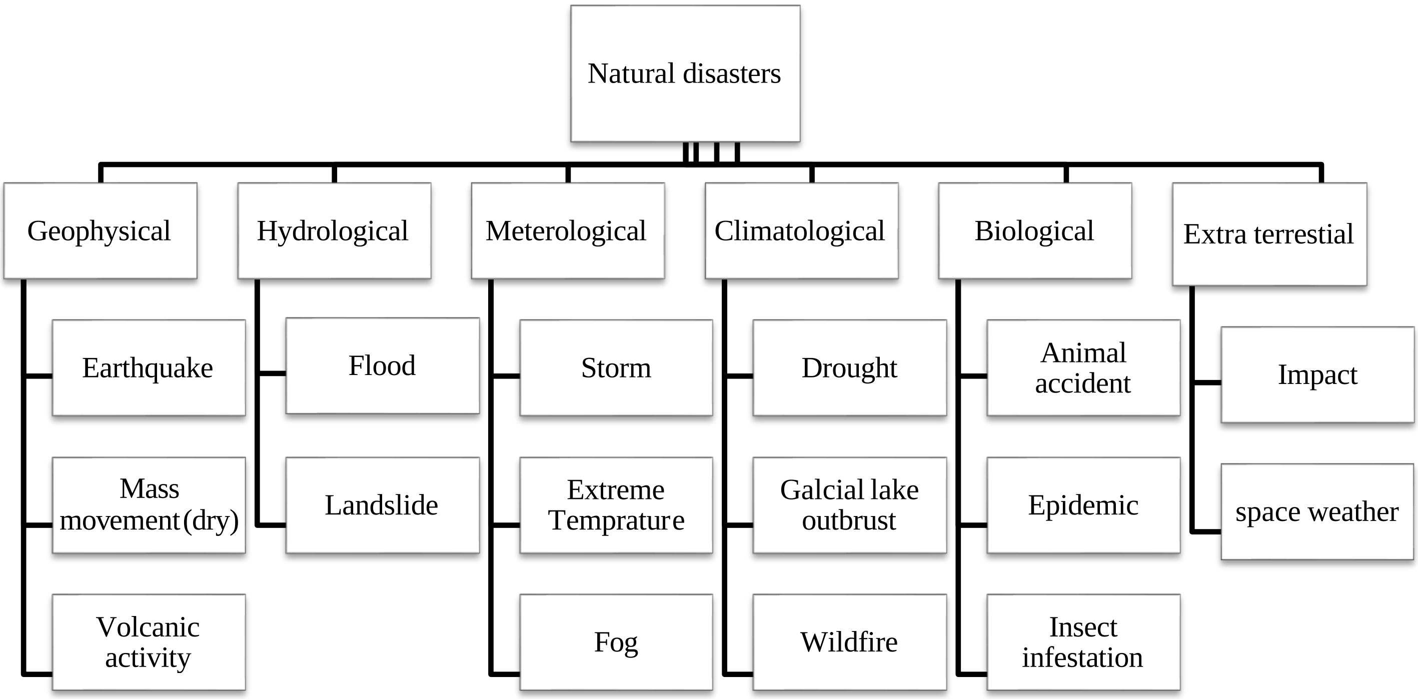

Figure 1: Classification of significant disasters according to the Peril Classification and Hazard Glossary, based on the Emergency Event Database

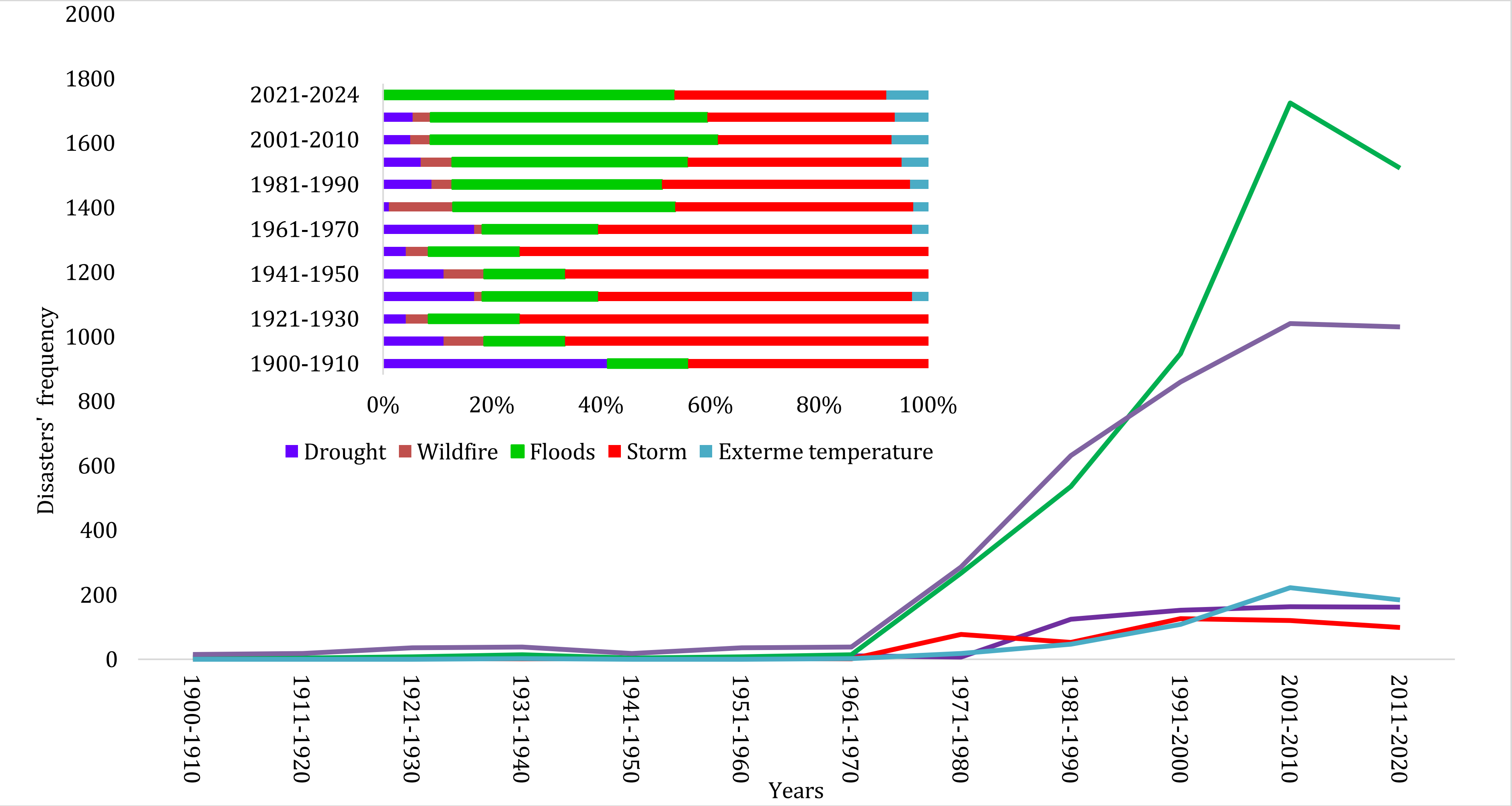

Figure 2: Timelines of significant disasters worldwide, based on the Emergency Event Database (EM-DAT)

(Source: Delforge et al., 2025)

An analysis of major disasters in Canada from 2000 to 2025 identifies floods, storms, wildfires, and extreme weather events as significant occurrences. Floods (33 incidents) are the most frequent, followed by storms (27), wildfires (15), and extreme weather (5). Epidemics have the lowest occurrence, with just 2 cases. This indicates that hydrological and meteorological disasters are more common than climatological and biological ones in Canada.

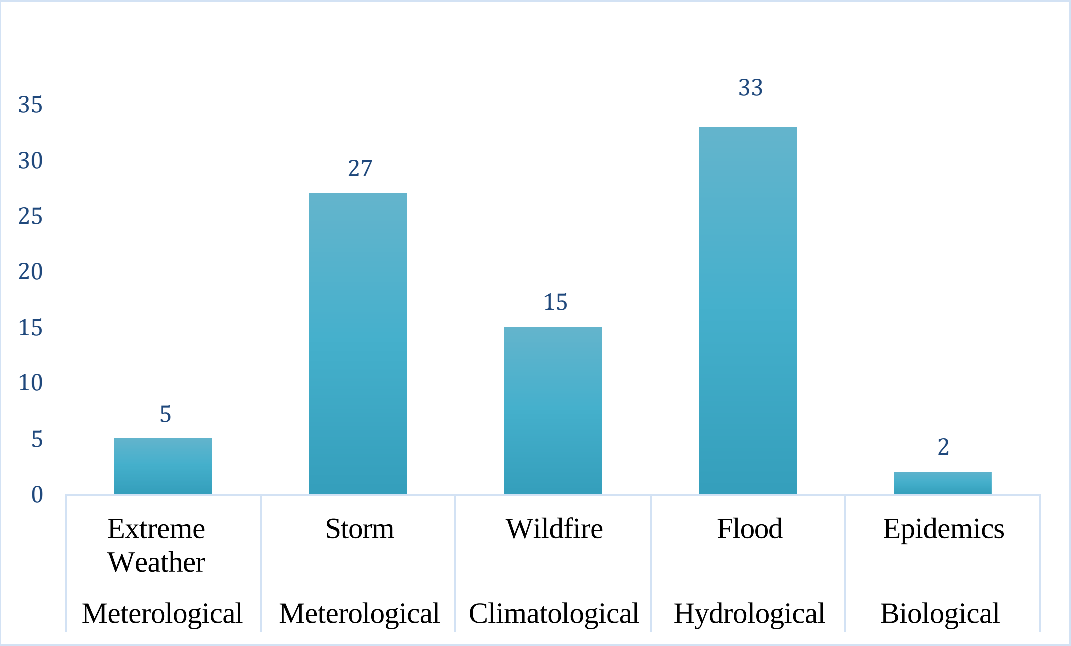

Figure 3: Natural disasters events in Canada from 2000 to 2025 based on EM-DAT database

The rise in natural disasters has highlighted weaknesses in traditional urban infrastructures, underscoring the need for Smart Cities (SC). These events have exposed deficiencies in emergency response and resource allocation (Ford & Wolf, 2020; Deren, et al., 2021). This paper examines how varying levels of DT maturity enhance flood disaster management across all phases—before, during, and after disasters. Despite existing research on Smart Cities and disaster management, there is a lack of studies focused on Digital Twins and their role in flood resilience. We propose a conceptual framework illustrating how DT can be utilized for risk assessment, real-time monitoring, and recovery planning throughout the disaster cycle.

The authors have chosen Nova Scotia, located on the eastern seaboard of Canada, which has been vulnerable to recurrent flood events and faces some of the highest sea level rise in Canada under current climate change projections. Since 1900, several flood events have occurred, resulting in significant economic losses. It is also evident that the frequency of flooding events in specific places in Nova Scotia has increased since 1999 at a very fast pace (Figure 4). Nevertheless, it has also caused substantial fatalities and mass evacuations. As climate change intensifies extreme weather patterns, the urgency to adopt advanced technologies for disaster risk reduction has become increasingly evident. A comprehensive, data-driven, proactive approach that can clearly understand flood behaviours predict future risks and optimize resource allocation during flood events to effectively tackle flood risks to keep pace with the dynamic nature of flooding events is required. This paper's motivation is rooted in the need for innovative, data-driven solutions to address flood risk in a province prone to coastal and inland flooding. Introducing DT could help with short-term disaster response and long-term flood prevention strategies. Through these contributions, the paper not only furthers the academic understanding of DT but also provides a reference guide illustrating how advanced DTs can predict cascading impacts, optimize emergency operations, and improve urban resilience.

Place	Event duration /years	FEDERAL DFAA PAYMENTS (CAD)	PROVINCIAL DFAA PAYMENTS (CAD)
Nova Scotia, Prince Edward Island and Newfoundland	5/2016	30350000	no information
New Brunswick and Nova Scotia	1/1935	5000000	no information
Yarmouth and Halifax NS	39/2010	No information	no information
Meat Cove NS	1/2010	3135000	no information
Bridgewater NS	2/2005	510004	937900
Oxford and Truro NS	1/2003	21065353	4420595
Sydney NS	9/2000	449218	1389625
Maritime Provinces	1/1999	1834365	3077940
Truro NS	4/2003	no information	no information
Nova Scotia	3/1935	no information	no information
Nova Scotia	16/1971	no information	no information
Nova Scotia	6/1980	no information	no information

Figure 4 Flood event information and economic loss in Nova Scotia, DFAA =Disaster Financial Assistance Arrangement (Source: Canadian Disaster Dataset, 2025)

BACKGROUND

Broad overview of smart city (SC) concept

The demand for the SC concept has emerged from the early 2000s. The United Nations Office for Disaster Risk Reduction further emphasized that urban areas—home to over 55% of the global population—are increasingly exposed to climate-induced hazards such as floods, cyclones, wildfires, and extreme heat. This has driven the transition towards Smart City frameworks, integrating Internet of Things (IoT), Artificial Intelligence (AI), big data analytics, and cloud and DT technology to enhance disaster prediction, preparedness, and recovery (Lagap & Ghaffarian, 2024). By leveraging real-time data, automated response systems, and resilient infrastructure, SC can anticipate, mitigate, and adapt to disasters more effectively, ensuring minimal disruption and safeguarding urban populations.

The concept of a SC) has undergone significant transformation over the past few decades. IBM first introduced the term in 2010 (Shao and Min, 2025), initially emphasizing integrating advanced technologies to enhance urban infrastructure and services. Early definitions of Smart Cities were mainly technology-driven, emphasizing digital innovations, automation, and connectivity to enhance city functions (Peldon et al., 2024). From this technological standpoint, SCs have been pioneering urban research and development, attracting considerable scholarly attention toward implementing cutting-edge solutions such as the AI and IoT. These advancements have facilitated the development of intelligent transportation systems, smart grids, digital governance, and efficient waste management solutions, significantly improving urban efficiency and sustainability.

However, SC evolution has transcended the mere adoption of technology as an end in itself. Scholars and urban planners now recognize that technology must serve a broader purpose—contributing to cities' sustainable development (SD) (Ahvenniemi et al., 2017; Keshavarzi et al., 2021). This paradigm shift has moved SCs beyond their traditional focus on digital transformation to embrace people-centric development, ensuring that technology enhances the quality of life, inclusivity, environmental resilience, and long-term sustainability (Schiavo & Magalhães, 2022).

One of the most transformative technologies enabling this shift toward sustainability and disaster resilience is DT technology. A DT is a virtual replica of a real-world city, continuously updated with real-time data from sensors, satellites, and urban monitoring systems. By integrating AI, big data, IoT, and cloud computing, DTs provide an interactive, data-driven simulation of urban environments, allowing city planners and policymakers to visualize, analyze, and predict urban dynamics with unprecedented accuracy.

DT Overview

DT technology has emerged as a transformative solution to tackle urban challenges within this framework. DTs, which replicate physical cities in virtual environments, empower city planners to simulate, monitor, and optimize urban systems in real-time, providing practical solutions to issues like crowd management, infrastructure maintenance, and disaster preparedness. Fan et al. (2021) recently discussed the concept called disaster city DT. They discussed how the DT dynamic and bidirectional capability can help to tackle and solve the disasters situation more efficiently and proactively. DTs play a crucial role in enhancing urban resilience against natural disasters and climate-related threats. By simulating extreme weather events such as hurricanes, floods, and heatwaves, DTs allow cities to assess vulnerabilities, develop real-time emergency response strategies, and optimize evacuation routes. This proactive approach strengthens disaster preparedness, minimizes infrastructure damage, and safeguards communities from potential catastrophes.

DT is sometimes misunderstood with simulation. However, Halúsková (2023) indicates that while simulations are a fundamental part of DT, the scope, functionality, and purpose of DT extend far beyond those of traditional simulations, see Table 1.

Table 1: Comparison of DT and simulations, based on Bronislava (2023)

Feature	*DT*	*Simulation*
Data Flow	Bi-directional, real-time updates	One-way, static
Integration	Deeply integrated with the physical system	Independent of physical systems
Scope	Multiple processes simultaneously	Single process
Adaptability	Real-time, adaptive decision making	Fixed, pre-defined parameters
Purpose	Monitor, predict, optimize	Experiment, analyze
Insights	Continuous, real-time and predictive	Static and Scenario-based

DT technology evolves across different maturity levels, with increasing capabilities and integration as it advances (Fan et al., 2021; Kim et al., 2021). The following five maturity levels have been cited in the literature (Kim et al., 2021, Madina et al., 2021). In certain instances, different terminologies have been employed by various authors and industry experts to describe maturity levels. Despite these variations in nomenclature, the fundamental essence of the definitions remains consistent across the literature. Recognizing this, the author has provided both terminologies to ensure clarity and comprehensiveness, thereby facilitating a more inclusive understanding of the subject matter.

1. **Descriptive level / Standalone**

   At this stage, the DT is a static digital replica of the city, offering basic visualization and historical data insights. It is utilized for documentation and understanding past scenarios, such as mapping disaster-prone areas or recording infrastructure damage from previous events.

2. **Diagnostic Level / Monitoring**

   In this level, a DT offers real-time monitoring and analytical capabilities. It assimilates IoT sensors, GIS systems, and various data sources to oversee urban infrastructure and identify anomalies. For instance, during a flood, sensors can monitor water levels and furnish immediate insights to avert further damage.

3. **Predictive Level**

   At this stage, DT leverage advanced analytics, including Ml and AI, to forecast potential disaster scenarios. Real-time data plays a crucial role in enhancing predictive capabilities by continuously updating the models with live inputs from sensors, satellites, and other monitoring systems. By integrating real-time environmental and infrastructural data, DT can simulate events such as earthquakes, hurricanes, or urban fires with greater accuracy. This enables city planners to identify vulnerabilities, assess risks dynamically, and develop proactive mitigation strategies before a disaster occurs, ultimately enhancing urban resilience and disaster preparedness,

4. **Prescriptive Level**

   This advanced level allows the DT to recommend and implement preventive measures. It incorporates decision-support systems to suggest optimal evacuation routes, reinforce infrastructure, or deploy emergency services during ongoing crises.

5. **Autonomous Level**

   The final stage of maturity entails autonomous operations, where a DT independently manages urban systems during disasters. For example, it can reroute traffic, allocate resources, or shut down utilities in real-time with minimal human intervention.

DT leverage advanced analytics, including MLand AI, to forecast potential disaster scenarios. Real-time data plays a crucial role in enhancing predictive capabilities by continuously updating the models with live inputs from sensors, satellites, and other monitoring systems. By integrating real-time environmental and infrastructural data, DT can more accurately simulate events such as earthquakes, hurricanes, or urban fires. This enables city planners to identify vulnerabilities, assess risks dynamically, and develop proactive mitigation strategies before a disaster occurs, ultimately enhancing urban resilience and disaster preparedness.

METHODS

The author's methodology begins by identifying key terms within the titles and abstracts of relevant papers to categorize various forms of DT technology. These terms include 'mapping' for descriptive DT, 'monitoring' for diagnostic DT, 'predictive,' 'simulation,' and 'modelling' for predictive DT, and 'management,' 'allocation,' and 'planning' for prescriptive DT. In addition, terms such as 'automatic,' 'automation,' and 'human intervention' are associated with autonomous DTs. This initial step is followed by a visualization that illustrates the varying maturity levels of DT technology and highlights corresponding examples of its application in disaster management, providing researchers with a foundational understanding of DT's evolving role in disaster scenarios (see Figure 5). Building on this framework, the authors focus specifically on floods, given their prominence as one of Nova Scotia's most frequent and impactful disasters globally. The authors then propose an implementation methodology and digital framework tailored to flood mitigation measures, the use of DT in disaster response, and capacity building for real-time applications during emergencies. Special emphasis is placed on using DT for managing the most common disasters in Canada, with a particular focus on NS.

This work-in-progress paper provides future work that outlines a comprehensive framework for emergency planning in NS. This framework will employ a mixed-methods approach to gather stakeholder input and opinions. This approach aims to assess the current state of emergency planning and explore methodologies to address flood-related emergencies. Additionally, it will assess the future potential of DT technology in enhancing disaster preparedness and response.

DT CONCEPTUAL FRAMEWORK OF FLOOD DISASTERS

Maturity Levels of Digital Twin Technology and Corresponding Disaster Examples

The authors highlight the application of various DT maturity across different disaster scenarios, providing concrete examples to enhance understanding and clarity regarding the functionality. Figure showcases how DTs evolve in complexity and capabilities, from basic simulations to advanced decision-making tools, illustrating their increasing effectiveness in disaster management.

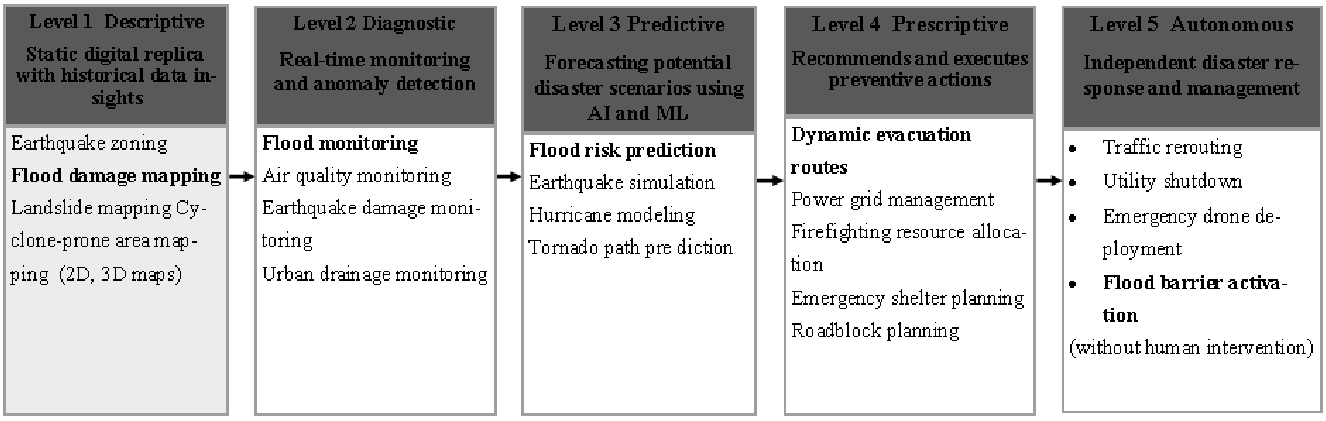

Figure 5: Maturity levels of DTs for emergency response for disasters

(Source: Dal Zilio, et al., 2023; Lumbantobing, et al., 2024; Puspasari, et al., 2023; Topping et al., 2021; Wang et al., 2022; Yalcin et al., 2007; Yu et al., 2023**)**

Digital Twin in Flood context

Due to the world's fast urbanisation, more people are congregating in cities, which has increased the number of impermeable surfaces including buildings, parking lots, and roadways. Because these surfaces prevent water from penetrating, runoff increases, and the likelihood of floods increases. To predict water levels in urban drainage infrastructure during floods and assess the efficacy of non-structural measures, flood forecasting and early warning systems can utilize any physical features of the urban water infrastructure as well as data gathered from multiple sources, including hydrology and weather. This provides important information for decisions regarding flood impact mitigation (Piadeh et al., 2022). When paired with physically based or data-driven models, flood visualisation technologies are useful instruments that can greatly shed light on the possible effects of flooding and the mitigation techniques needed to lessen those effects. Flood visualisation is the practice of using several technologies to create visual representations of flood phenomena, Digital flood maps were created with the advent of geographic information systems (GIS), which made it possible to store and analyse flood data in a digital format (Ma et al., 2020).

The authors conducted a retrospective analysis of flood events using a structured checklist, assessing human fatalities, evacuation statistics, and spatial rainfall distribution (1900-2020) through Geographic Information Systems (GIS) (Fig 6). These assessments served as a foundation for conceptualizing a DT-based flood management framework tailored to the region's hydrological and demographic characteristics. The implementation of DT technology in Nova Scotia would enable the creation of a dynamic, real-time digital replica of the physical environment. This virtual model would integrate real-time meteorological, hydrological, and geospatial data, thereby enhancing situational awareness and enabling data-driven decision-making across all disaster phases—pre-disaster preparedness, real-time response during disaster events, and post-disaster recovery.

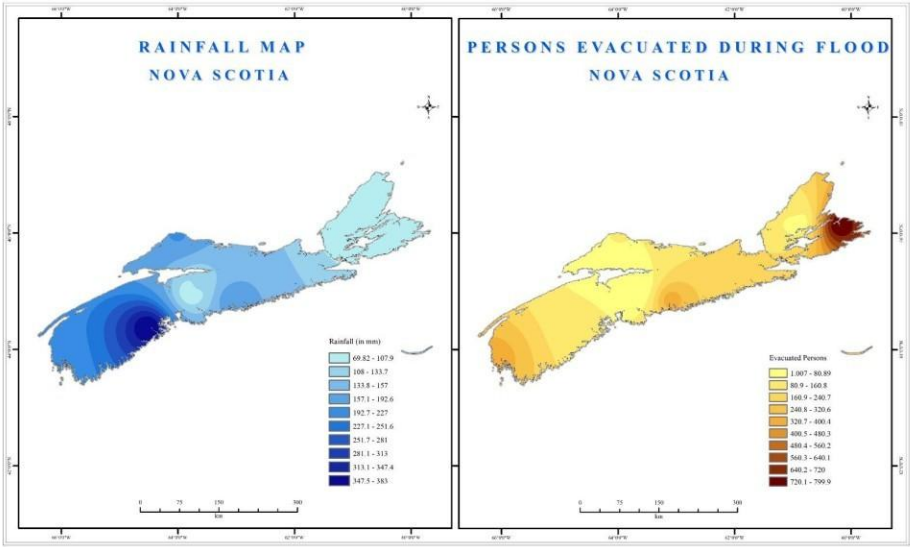

Figure 6. Rainfall map and persons evacuated during flood in Nova scotia (1900-2020)

Implementing Digital Twins (DT) can significantly improve flood risk management by accurately simulating flood behavior. This allows authorities to identify high-risk areas and deploy targeted protections ahead of rising water levels. Real-time data integration facilitates dynamic flood monitoring, enabling faster evacuations and reducing the risk of loss of life. DTs enhance public safety by improving response times, fostering inter-agency collaboration, and providing accessible risk information. In Nova Scotia, the adoption of DT technology could revolutionize flood management, potentially reducing future fatalities, economic losses, and disruptions, while positioning the region as a leader in resilient urban flood management amid growing climate threats.

Web-based flood mapping tools have improved access to flood data, but often present information in a two-dimensional format (Carver, 2019). Recently, the integration of technologies like digital twinning (DT), augmented reality (AR), and virtual reality (VR) has enhanced flood risk management by offering more engaging and intuitive visualizations (Guo et al., 2021; Puertas et al., 2020). These technologies allow stakeholders to utilize realistic simulations of potential flood effects, leading to better flood control strategies . DT, in particular, enables the creation of virtual models of real-world systems, allowing stakeholders to test and simulate flood control methods before implementing them (Ramu et al., 2022).

DT usage in Early Warning systems such as evacuation plans can be made via employing developed protocols and methods. However, the planned evacuation system is frequently difficult to execute because of a number of issues, including the early warning system not working, the situation changing quickly, making it difficult to coordinate and direct the evacuation, making decisions "on the fly," an increase in traffic accidents or unanticipated conditions, the inability to issue "pre-event" evacuation orders, and other issues. In crisis management, DT technology is essential, particularly when developing evacuation plans. This technique could identify flood evacuation routes, simulate urban flood inundation, and serve as a flood warning system. Furthermore, DT technology has been created as a building fire evacuation tool (Piadeh et al., 2022, Manocha et al., 2023). A study by Ghaith et al., 2022 presented a thorough framework that integrates data collection technologies, infrastructure analysis, demographic data, hydraulic and hydrological modelling, and real-time system behaviours to create DT cities that are at risk of flooding. DTs allow for accurate and real-time flood scenario simulation, optimising evacuation routes and strategies. They do this by simulating different flood scenarios based on historical and current environmental data, predicting areas prone to flooding, and optimising evacuation plans to minimise economic and human losses. They also integrate hydrological data to design infrastructure that is flood-resilient, simulate flood dynamics, and optimize response strategies to ensure safe and timely evacuation (Shaharuddin et al., 2022, Astarita et al., 2024, Cheng et al., 2023, Yu & He, 2022).

Implementational Methodology of Digital Twin for Flood measures

A DT based SC must be created in order to simulate how cities might actually operate in the event of a natural hazard as a result of climate change (El-Dakhakhni, 2021). The smart city infrastructure systems (such as buildings, the power grid, the storm, water, wastewater, and transit networks), their intra-dependencies, their interdependencies, and the hazards that affect each system are all represented by a DT, which is a real-time, continuously updated (by sensors) virtual replica of the systems that are integrated into a single platform (Ivanov et al., 2020). To enable a real-time reaction, the method of creating comprehensive disasters resilient digital twin city (DRDTC) must be continuously improved. Different frameworks for the creation of DRDTC based on sensors, the IoT, ML, and satellite and LiDAR data have recently been offered by various fields of study (Li et al., 2022; Papyshev & Yarime, 2021; Austin et al., 2020). The foundation of DRDTC should be represented by hydrologic and hydraulic models for flood risk forecasting in order to characterize hazard characteristics. Hydrologic and hydraulic model construction, calibration, and testing are extremely unpredictable and time-consuming procedures that usually come with a hefty computational cost for simulation. The uncertainty associated with the model structure, inputs, and parameters still limits the model estimates, even after the hydrologic-hydraulic model has been calibrated (Ghaith et al., 2021).

A quick and accurate assessment of the flood hazard features is essential for DRDTC to deliver timely early warnings so that backup measures can be implemented to reduce catastrophic outcomes. Recently, machine learning approaches have been widely employed to supplement or replace physics-based hydrologic and hydraulic models because of the growing amount of rainfall data acquired (e.g., from weather stations, satellites, Lidar, and the Internet of Things). For instance, using data from previous days, artificial neural networks have been utilized to improve hydrologic models' capacity to forecast flow rates in the days ahead (Ghaith et al., 2020, N Marasingha, 2021). Therefore, this paper discusses the development of a Implementation Methodology of the Digital twin Technology (DTT) in flood measures combined with the maturity levels of DT and use cases among the different phases of a disaster.

A city digital twin is a platform that operates in real time and may be used to model how a city might behave in the event of an emergency (such as a danger realization) while considering the interdependencies among its various infrastructure components. Any direct and indirect consequences can be seen on the digital twin of the city. As a result, decision makers can 1) alter the system (by sending maintenance teams, for example) to lower the risk at any time, and 2) model possible hazards on the city digital twin to find areas that are at risk, evaluate possible projects, and create plans for readiness to prevent disastrous events. In order to observe the new effect, the action made can always be connected to the city digital twin using the translator.

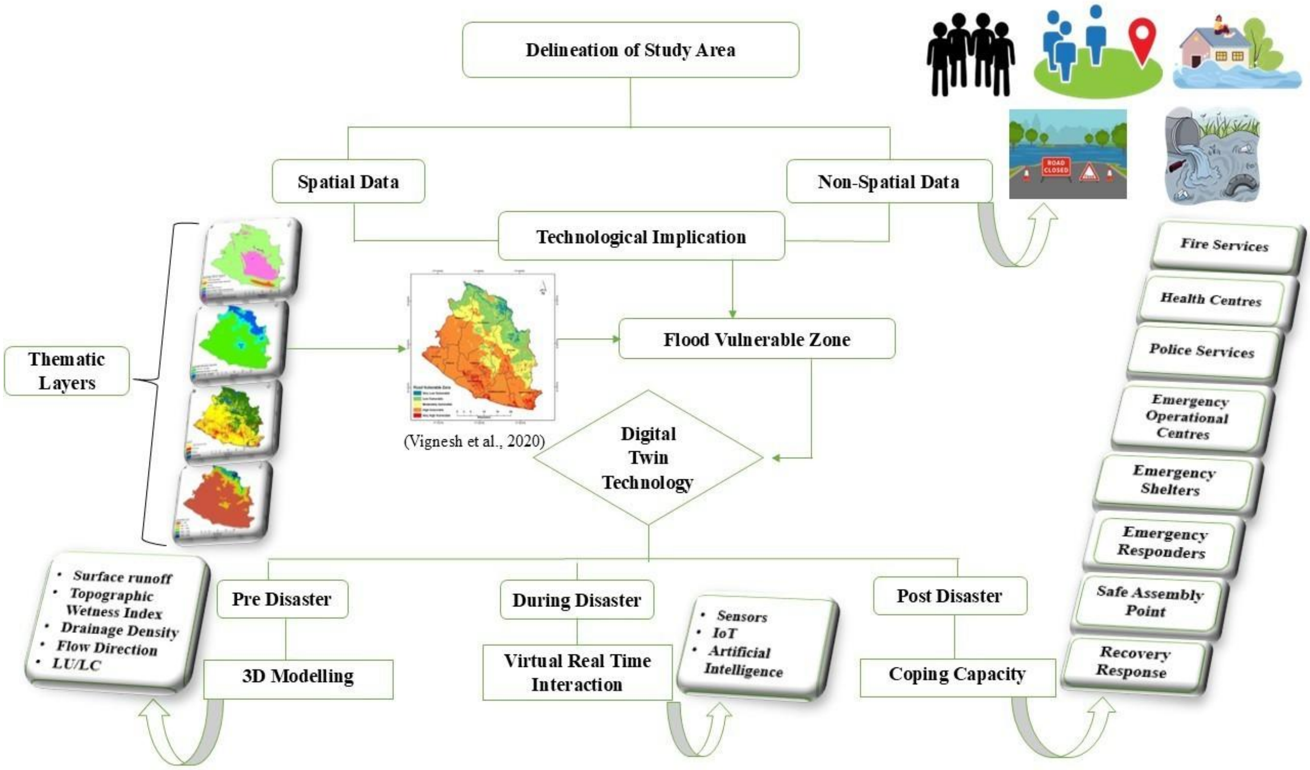

Figure 7. Implementational methodology of DT for Flood measures

DT in Mitigation & Capacity building

Natural hazards are inevitable events that cannot be halted by any means but minimizing the impacts & building measures accordingly will greatly reduce all kinds of losses. The idea of DTs has become a game-changing instrument in the ever-changing fields of urban planning and disaster intervention, especially in the context of smart cities (Huda et al., 2024). They offer a thorough grasp of urban infrastructure, encompassing structures, utilities, transit systems, and environmental factors. combining information from multiple sources, including social media feeds, satellite photography, sensors, and IoT devices. DTs help emergency responders and municipal planners better prepare for, prevent, and handle calamities (Yu et al., 2023).

As depicted in Figure 7, the DT can be utilized in the pre-disaster phase to identify the flood-vulnerable zone using a number of thematic layers, including drainage density, flow direction, surface runoff models, and land use and land cover. These layers are essentially utilized in conjunction with dynamic 3D modelling, which will improve the identification of sensitive zones and the neglect of structural and non-structural measures. Building embankments, clearing encroachments, improving stormwater drainage systems, and implementing other robust strategies are structural measures that lead to hazard resistance.

As discussed in Figure 5. In the Descriptive/Standalone stage, the DT serves as a static digital replica of the city, offering basic visualization and historical data insights. This phase primarily focuses on documentation and understanding past scenarios. For instance, technology can map disaster-prone areas or record infrastructure damage from previous flood events. These insights lay the foundation for more advanced applications of DTT, guiding long-term disaster risk reduction strategies. A significant aspect of using DT in mitigation is the identification of systemic risks for prevention. DTT creates comprehensive models of urban systems, allowing stakeholders to detect interconnected vulnerabilities within the infrastructure. By simulating different disaster scenarios, authorities can pinpoint critical weak points in the system, such as outdated drainage networks or areas with high population density and implement targeted mitigation measures. Additionally, technology aids in identifying vulnerabilities for prevention. By integrating geospatial data, socio-economic information, and infrastructure blueprints, DT models provide a detailed understanding of areas at higher risk. This enables disaster managers to prioritize resource allocation and develop tailored intervention plans to protect the most vulnerable populations. DTT also aids in training personnel through flood simulations, offering hands-on experience in a controlled environment. Regular drills using the DT model improve response team readiness and efficiency (El-

Dakhakhni, 2021, Razavi et al., 2024).

Real time DT usage during emergencies

During disasters, DT facilitates situational awareness and real-time monitoring. They give decision-makers a comprehensive picture of the issue as it is developing by continuously updating real-time data feeds, empowering them to make wise decisions in quickly changing situations (Zhong et al., 2023). For instance, DT can track the movement of people and assets, monitor fire progress, and evaluate air quality during a wildfire outbreak, enabling authorities to promptly issue warnings and direct resources where they are most needed (Zhong et al., 2023).

In the disaster response phase, DTs necessitate two-way dynamic situational awareness and services between emergency service providers, regional staff, and decision-makers. This entails combining the physical and intangible elements that surround them in a way that is intuitive, timely, and interactive. Examples of these include regional geography, probable flood locations, road flood convergence patterns, dynamic weather changes, mobility, and personnel-related situations, among others. By doing this, regional staff will better comprehend their circumstances and make wise decisions by avoiding inaccurate assessments of local trends, vehicle and personnel conditions, and road conditions. Additionally, it will allow emergency service providers and decision-makers to quickly update regional conditions, allowing for more precise resource allocation and decision-making (Ge & Qin, 2025).

Post-disaster components of DT

DT facilitates post-disaster recovery and reconstruction efforts by enabling accurate damage assessment and resource allocation. By comparing pre-event and post-event data, city planners can prioritize restoration efforts, streamline rebuilding processes, and ensure that critical infrastructure is restored in a resilient and sustainable manner. The technology simplifies identifying safe resources such as health centers, emergency shelters, and creating safe assembly points through real-time dynamic modelling. It also supports the coordination of police services and provides assistance with aerial sensors and environmental sensors (Ford & Wolf, 2020). Real-world applications include the use of DT in flood-affected cities to map out damaged roads and prioritize their restoration based on traffic flow data. In areas where hospitals are impacted, digital twins can model alternative routes and temporary health facility locations. They also help in monitoring water contamination levels using environmental sensors, guiding clean water distribution. In collaboration with aerial sensors, digital twins can provide real-time imagery for search and rescue operations, helping emergency responders navigate debris and blocked pathways efficiently. These capabilities enhance decision-making processes and expedite the recovery phase (Ariyachandra & Wedawatta, 2023).

In respect to the Predictive & Autonomous maturity levels of DT in Figure 4. DT can be employed with advanced analytics, including ML and GenAI, to predict potential disaster scenarios. It can simulate events such as earthquakes, hurricanes, or urban fires, allowing city planners to identify vulnerabilities and formulate mitigation strategies prior to the occurrence of a disaster. The final stage of maturity entails autonomous operations, where DT independently manages urban systems during disasters. For example, it can reroute traffic, allocate resources, or shut down utilities in real-time without human intervention.

LIMITATIONS & CHALLENGES IN IMPLEMENTING DT IN DRR

The potential of DT technology for improving flood disaster preparedness in urban areas is significant, yet its practical implementation faces numerous challenges across technological, infrastructural, institutional, and ethical domains (Fuller et al., 2020). A primary barrier is the lack of data standardization, which hinders the integration of data from various sources like meteorological inputs and sensor networks, impacting the system's accuracy. Additionally, traditional municipal IT environments often lack the required computational capacity and connectivity, especially in less urbanized areas (TwinView, 2024).

DT systems also process sensitive data, raising privacy and cybersecurity concerns due to insufficient security frameworks (Ankitha V P, 2024). Complicating matters, the integration of diverse systems without a universal modeling standard can lead to inconsistencies, undermining the reliability of the DT (Pankratova & Chernyakova, 2024). Furthermore, the financial investment necessary for DT deployment, including ongoing operational costs, can be substantial (Fu et al., 2022).

Effective DT implementation requires careful planning and collaboration among municipal authorities, IT providers, urban planners, and communities. Establishing coordinated governance mechanisms is crucial for optimal integration across sectors. To fully leverage DTs for urban flood management, it is essential to address limitations in technological maturity, system interoperability, cybersecurity, and institutional readiness through phased implementation and stakeholder engagement.

CONCLUSION AND FUTURE RESEARCH

This work-in-progress paper presents the initial implementation methodology for using Digital Twin (DT) technology in flood disaster management, based on a secondary database. The methodology focuses on integrating DT into the flood management system, aiming to simulate real-time data and predict flooding events, their potential impact, and corresponding responses. The secondary database provides valuable historical and real-time data, offering an early stage understanding of how DT can be applied to flood management.

The future direction of this research will involve developing a more comprehensive framework for flood disaster planning in Nova Scotia. This framework will be built using a mixed-methods approach, combining both qualitative and quantitative research methods. It will include extensive stakeholder engagement, gathering input and feedback from local authorities, emergency planners, community members, and environmental experts. By collecting diverse opinions and insights, this research aims to assess the current state of emergency planning for floods, identifying gaps and areas for improvement in the existing protocols. Moreover, how integrating DT into the region's flood planning processes will foster a more resilient, adaptive, and data-driven approach to disaster management, ensuring that Nova Scotia is better equipped to face future natural disasters.

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