Mixed Reality Interfaces in Flood Risk Management

by

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B.A. (Geography), Simon Fraser University, 2018

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

in the
Department of Geography
Faculty of Environment

SIMON FRASER UNIVERSITY
Summer 2020

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Abstract

Visualizations play a key role in analysing, understanding, and communicating risks of flooding and possible mitigation options. In particular, 3D visualizations are becoming increasingly prominent for risk communication. At the same time, there is a growing ecosystem of mixed reality interfaces that have potential to transform our interaction with 3D data and visualizations. This thesis outlines the potential of these tools and develops a set of mixed reality flood visualization prototypes that utilize capabilities of the state-of-the-art HoloLens 2 mixed reality system. By leveraging the representational and interactive capabilities provided by hand and eye-tracking, 3D displays, spatial mapping of user environment and positional tracking, these tools provide distinct and compelling experiences of 3D flood visualizations. To illuminate the potential of these tools to support meaningful practice, this thesis reflects on the user experience, hardware performance and usability of MR visualizations.

Keywords: mixed reality, augmented reality, flood, 3D geovisualization, flood risk management

Acknowledgements

I would like to thank my supervisor, Dr. Nick Hedley for his endless support and guidance throughout the work on this thesis. His interest, enthusiasm and dedication to create relevant tools that push the envelope of what is “normal” in GIScience have stimulated this work. I would also like to thank Dr. Daniel Henstra for his informed and informative perspectives that helped to improve this thesis.

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List of Acronyms

AR	Augmented Reality
FRM	Flood Risk Management
GIS	Geographic Information Systems
VR	Virtual Reality
MR	Mixed Reality
UI	User Interface

Chapter 1. Introduction

1.1. Overview

With growing concerns over flooding worldwide due to rising sea levels and changing precipitation regimes, it is increasingly important to understand and communicate inundation risks. Visualizations serve a critical role in connecting planners, decision makers, residents and businesses to information about potential impacts of flooding and possible mitigation strategies (Henstra, Minano, & Thistlethwaite, 2019; Jacquinod & Bonaccorsi, 2019). Over the last decade, there has been a significant growth in 3D visualizations of flooding impacts. These visualizations seek to move beyond traditional maps and provide a compelling and contextually rich representation of flooding impacts that can be understood by a broad set of stakeholders (Lai, Chang, Chan, Kang, & Tan, 2011; Macchione, Costabile, Costanzo, & De Santis, 2019). While most visualizations are still viewed on flat 2D screens, there is a groundswell in emerging interfaces for interaction with 3D representations and data. Ranging from completely virtual realities to the tools that seek to augment real environments with digital content, these mediums can alter our perceptual experiences of geographic data. By changing how we view, manipulate and query data in 3D, these technologies have significant potential to change (and potentially improve) our interaction with rigorous, data-driven 3D environments – as mediators of our understanding of environmental phenomena. As these tools become increasingly feasible to use, the cost of devices decreases, and the complexity of development is reduced, we need to investigate their potential to improve spatial data practice, in order to be ready to engineer the systems and science of future spatial information tools.

1.2. Scope of this work

This work seeks to understand how the state-of-the-art MR systems can contribute meaningfully to the practice of flood risk management in a municipal context. Through interviews with planners working in flood risk management in City of Vancouver and observation of their meetings, I focused this work on a specific type of MR visualization of flooding risks. Much work in this domain focuses on communicating the risks to the public, leveraging the compelling and immersive nature of emerging interfaces. However, my interaction with planners suggested that, given the state of local adaptation, developing tools for internal FRM practice was more appropriate. This work therefore focused on using the state-of-the-art MR visualization platform to develop visualizations based on existing municipal data and information. Beyond presenting workflows to develop such tools, this work unpacks the perceptual outcomes, hardware performance, limitations, usability, and significance of these platforms for planners working in flood risk management.

1.3. Research questions

1. Can geographic representations of data be preserved when displayed across conventional and emerging display mediums? Can they be enhanced by implementation in emerging 3D visualization interfaces?

   Can the conventional and emerging platforms inter-operate based on the same data formats?

   Is representational fidelity of flood risk maintained, lost or gained, as we move from conventional to emerging 3D visualization platforms? What are the strategies to address *deficiencies* in platforms?

2. Do conventional versus emerging data visualization platforms result in different task performance outcomes?

   Do they support identical task performance? Do they impede or reduce task performance? How usable are the emerging display and interaction technologies?

3. Do conventional versus emerging data visualization platforms result in different perceptual outcomes for users (i.e. flood risk awareness)?

   Do they support identical situational/analytical risk perception? Do they impede or reduce perceptual completeness, granularity? Do they improve/increase perceptual completeness, granularity?

4. Do emerging platforms change the capabilities available for flood risk management?

   Is there evidence that the affordances of game engines and interface technologies can enhance flood risk management and communication? (i.e. opportunities for modifications in outreach and analytical strategies)

1.4. Research Objectives

The objectives of this research are to:

- Determine the state of, and trends in use of, (3D) geovisual methods and platforms used in flood risk communication and analysis.
- Assess and develop a review of existing approaches to visualization of flood-risk related information in urban landscapes.
- Identify advances, challenges and opportunities in effective representation and communication of flood risk.
- Determine how well conventional GIS data, information and hydrological models translate into emerging interactive 3-D platforms.
- Demonstrate the capability of emerging platforms to deliver meaningful information experiences in support of risk perception, risk communication, FRG and FRM.
- Assess the reception of models by experts (Planners/Emergency Managers); how the tools can be integrated as part of the day-to-day workflows; to what degree they influence or modify FRM workflow, risk perception and awareness, and consensus building, compared to traditional (i.e. 2D maps of flooding scenarios) risk communication.

1.5. Thesis Organization

This thesis contains four chapters. The two chapters presented after this introduction were prepared as stand-alone articles for publication in peer-reviewed journals. Combined, these papers introduce the use of 3D visualizations in flood risk management, present workflows to integrate 3D visualizations and emerging interfaces, and reflect on the state-of-the art of mixed reality tools for FRM practice.

Chapter 2 presents an overview of the use of 3D visualizations in analysis and communication of flooding risks, discusses the potential of emerging mixed reality interfaces to contribute to FRM practice, and presents a workflow to integrate GIS data and other flood-related information with 3D game engine environments, where mixed reality tools can be developed. By examining the multi-faceted use of 3D visualizations in flood risk analysis and communication, this paper highlights the advances in representing flooding in emerging 3D environments and speculates on the potential uses of augmented and virtual reality interfaces in flood risk management.

Chapter 3 is focused on a practical development of mixed reality visualizations based on municipal flood-related data and information. Through a development of prototypes that enable users to explore contextually rich representations of flooding impacts and a set of potential adaptation scenarios, this work illuminates the growing feasibility of developing relevant, compelling and usable mixed reality tools. Through a focused analysis of hardware performance, user experience, and usability, this work reflects on the implications of available devices for flood risk management and planning practice overall.

The last chapter provides a summary, discusses the significance of research and development presented in Chapters 2 and 3 for spatial data practice and discusses future directions for development and use of mixed reality visualizations in flood risk management.

1.6. References

Henstra, D., Minano, A., & Thistlethwaite, J. (2019). Communicating disaster risk? An evaluation of the availability and quality of flood maps. *Natural Hazards and Earth System Sciences*, *19*(1), 313–323.

Jacquinod, F., & Bonaccorsi, J. (2019). Studying Social Uses of 3D Geovisualizations: Lessons Learned from Action-Research Projects in the Field of Flood Mitigation Planning. *ISPRS International Journal of Geo-Information*, *8*(2), 84.

Lai, J.-S., Chang, W.-Y., Chan, Y.-C., Kang, S.-C., & Tan, Y.-C. (2011). Development of a 3D virtual environment for improving public participation: Case study–The Yuansantze Flood Diversion Works Project. *Advanced Engineering Informatics*, *25*(2), 208–223.

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.

Chapter 2. 3D geovisualization interfaces as flood risk management platforms: capability, potential and implications for practice

2.1. Abstract

Recent advances in technology and workflows related to 3D geovisualization present numerous opportunities for development and evaluation of the usefulness of these tools for analysis and communication of environmental risks. This paper explores how cartographic tools and practices currently used for understanding and managing flood risks could be improved through the use of emerging 3D visualization approaches. The topological and dimensional realism enabled by these platforms have the potential to both improve the quality of representation and analysis, as well as reduce the knowledge barriers impeding understanding of flood risk by non-expert audiences in risk communication. Furthermore, emerging mixed-reality interfaces offer multiple advantages over desktops for interaction with 3D content. The significant recent growth in both interface and visualization domains represents an opportunity for researchers and practitioners to evaluate the contributions of these approaches to real-world planning and risk management. In this study, we overview the recent trends in the realm of flood risk visualization and the contributions mixed reality can have for the field. We then present a pragmatic workflow that enables integration of rigorous geospatial data related to flooding into a 3D visualization environment, to illustrate how various interface platforms can be easily integrated and evaluated.

2.2. Introduction

Increasing global sea level, growing risks of fluvial flooding and intense development across the world make understanding and managing inundation risks an integral part of urban development. Most metropolitan areas across Canada are at-risk from one or more types of flooding (Henstra, Minano, et al., 2019). Flooding is the most costly natural disaster in the country, and the magnitude and frequency of such events is projected to increase in coming decades (Dottori et al., 2018; Vitousek et al., 2017)

Amidst growing costs of providing disaster assistance, the responsibility for managing flooding is increasingly being shifted towards at-risk residents and businesses (Henstra & Thistlethwaite, 2017). However, a recent survey illustrates that half of people living in designated floodplains in Canada express no concern at all related to flooding risk and expect the risks to decrease in coming decades (Henstra, Thistlethwaite, Brown, & Scott, 2019). This concerning state of risk perception among exposed populations is combined with equally concerning state of knowledge availability about flooding risks, where most communities across Canada have outdated maps that are not suitable for public communication (Henstra, Minano, et al., 2019). This context presents opportunities to explore the potential of various recently emerging visualization approaches to enhance analysis and communication of environmental risks.

Typically, flooding risks have been understood and managed through flood extent maps generated from databases and geographical information systems (GIS), illustrating likely extent of flooding of a certain probability, as well as critical infrastructure and the population exposed (Henstra, Minano, et al., 2019). However, GIS tools and 2D maps are only a part of the rich ecosystem of spatial analytics and risk communication. Recent innovations in technology, software and algorithms, methods developed in industry and research are beginning to transform traditional cartographic visualizations into the next generation of 3D geovisualizations that are operationalized by the capabilities of 3D data, cloud computing, artificial intelligence (AI), and emerging interfaces, such as augmented and virtual reality (AR/VR) (De Santis, Macchione, Costabile, & Costanzo, 2019; Narain, 2018; Rao, Qiao, Ren, Wang, & Du, 2017). A number of geographic researchers also identified this potential, and over the years, have steadily built up a corpus of research exploring and developing new frontiers in 3D spatial modelling and visualization technologies and methods applied to grounded spatial problems, using a mixture of emerging technologies (Haynes, Hehl-Lange, & Lange, 2018; Lochhead & Hedley, 2019; Macchione et al., 2019; Schroth, Pond, & Sheppard, 2015). Production of spatially rigorous 3D visualizations has been streamlined significantly over the last decade. They are beginning to demonstrate operational value to sectors of industry and research that face daily challenges to visualize and perceive complex spatial information (such as morphometric change detection in geotechnical industries). While the foundational empirical work of spatial information scientists such as Shelton and Hedley (2002) established hard evidence supporting the perceptual and cognitive significance of being able to view and physically interact with 3D spatial data in proprioceptively powerful everyday environments, these studies were conducted before the current generation of more polished mixed reality interfaces existed. Recent advances in mixed reality interfaces are starting to enable research focused on usability, usefulness and impact of such approaches, rather than a focus on overcoming limitations imposed by idiosyncratic technologies (e.g. display resolution, tracking, processing speeds) (Ens et al., 2019). We are very much in a moment of transition, where we can combine the cumulative experience of evolving visualization platforms and technologies with the experience and evidence of long-term spatial interface research. This growing interest and increasing technological maturity suggest an approaching opportunity to integrate these methods to support meaningful practice. This prospect prompts us to reflect on the recent developments in the field as well as to provide a straightforward visualization workflow that enables researchers and practitioners to evaluate the emerging interface platforms.

2.3. Objectives and Methods

The main objectives of this paper are to provide an overview of recent trends in the realm of 3D geovisualization of flooding risks and mixed reality interfaces and propose a perspective and a framework to inform meaningful integration of emerging interface platforms into practice. To this end, we consider how emerging modelling environments – and the visual analytical capabilities they embody – can contribute and change practice of interaction, understanding and managing flooding risks, by connecting a wide range of citizen and planner stakeholders to an understanding of potential inundation scenarios. We then provide a practical guide to integrating GIS data into emerging visualization platforms to help researchers and practitioners explore these new technologies in meaningful everyday flood risk work. We conclude with some constructive critical reflection and identify relevant research directions we believe need to be addressed by the multi-disciplinary visualization community, as emerging technologies are encountered and assessed for their potential to support meaningful planning practice.

2.4. Visualizations in management and communication of flooding risks

2.4.1. Flood maps

Traditional means of analysis and visual communication of flooding hazards consist of aerial maps of a locale with likely flood extent of a particular likelihood (1-in-100, 200 or 500 years flood) and/or imagery of historical events (Henstra, Minano, et al., 2019). In planning, flood maps are an essential part of the process of risk analysis, land use, emergency management, and climate adaptation as well as communication of the likely inundation zone to the various impacted stakeholders (Henstra, Minano, et al., 2019) . This representation of the flooding hazard is commensurate with the dimensionality of typical hydrological modelling approaches, which represent flooding as a one- or two-dimensional phenomena (Teng et al., 2017). Nevertheless, existing flood maps have significant limitations in their analytical and outreach potential. The abstraction of maps adds significant burden on the viewer to connect color hues on an aerial view to a dynamic inundation phenomenon in situ, which can complicate their understanding by non-expert audiences (Macchione et al., 2019). The topologically two-dimensional representation limits the understanding of flooding as a volumetric phenomenon that has differential impacts on buildings depending on their elevation and structure (De Santis et al., 2019). Furthermore, in the Canadian context, maps are largely outdated and are not designed for public risk communication (Henstra, Minano, et al., 2019). Given the current state of floodplain maps in Canada and a need to provide new visual tools for understanding and managing risks across scales, it is relevant to investigate how emerging approaches for visualizing flooding risks may improve and/or supplement the existing tools available for FRM.

2.4.2. **Emerging Visualizations**

The use of 3D visualizations for flood risk communication has increased significantly over the last decade, owing to advancements in data processing, visualization, and interactive platforms; and in response to increasing recognition and uptake of the analytical and engagement potential of such visual tools. Within the flood risk management domain, 3D visualizations have potential to improve analysis of risks through dimensionally accurate representation of urban landscapes, infrastructure, and flood impacts, as well as to improve understanding of flooding hazards by non-expert audiences. The addition of a vertical dimension allows a (dimensionally) realistic representation of urban environment and flooding impact, resulting in a more vivid and salient representation of risk (Dransch, Rotzoll, & Poser, 2010; Lai et al., 2011). By leveraging the familiarity of people with real landscapes, such visualizations provide a significant volume of hydrological and contextual information to the viewers (Macchione et al., 2019). This can be useful in the analysis of impacts and potential mitigation options as the volumetric representation can simultaneously represent overlapping structures that would be hard to visualize in a 2D environment.

For instance, the intersections of various policies (e.g. setbacks, proposed retreat areas), urban structures, underground infrastructure, and flood depth are hard to represent over the same area in a 2D GIS, and would require use of multiple transparent layers that impose a burden on the viewer to locate various color-coded layers along the vertical dimension. By introducing visual depth cues, parallax and a familiar representation of the landscape, 3D visualizations can assist in developing richer mental models of environmental phenomena and related social context (e.g. populations, policies, infrastructure). Many existing 3D visualization platforms do not yet support sophisticated analytical operations available in traditional GIS environments. Nevertheless, the 3D topology and accurate representation of volumetric complexity of the urban landscape can be invaluable in identifying multi-faceted impacts of flooding.

As opposed to conventional maps, a volumetric urban model has the potential to bridge the understanding gap between professionals interpreting the outputs of hydrological models with planners, decision-makers and the general public (Lai et al., 2011). The reduced abstraction and higher visual realism of urban environment and flooding phenomena in 3D visualizations has been found effective in relating flood risk information to non-expert audiences (Al-Kodmany, 2002; Fenech, Chen, Clark, & Hedley, 2017; Jacquinod & Bonaccorsi, 2019; Lai et al., 2011). This can be particularly useful in communities where floods did not occur for a long time, which results in underestimation of risks and a failure to imagine the impacts. Models similar to ones developed by Macchione et al. (2019) and De Santis et al. (2019) have potential to allow informed discussion of mitigation and adaptation options by a wider set of stakeholders due to the volumetrically and visually realistic representation of referenced urban landscape under a flooding scenario. Nevertheless, similarly to maps, 3D visualizations will likely find a number of additional applications beyond specific needs to communicate flooding risks. Jacquinod & Bonaccorsi (2019) demonstrated that in a real-world setting visualization intended to simply relate hazard information became a focal point in negotiating adaptation approaches and decision-making. The 3D visualizations thus can impact the process of identifying and mitigating risks through reducing the knowledge capital required to relate flood risk information to the real landscapes.

In the recent past, 3D geovisualizations developed for risk analysis and communication relied on bespoke software/hardware solutions (Burch, Sheppard, Shaw, & Flanders, 2010; Lai et al., 2011; Paar, 2006). Currently, integration of the spatial information into common 3D modelling environments used by game designers and animators are becoming increasingly popular (Fenech et al., 2017; Macchione et al., 2019; Schroth et al., 2015). This trend of increasing interplay between professional GIS packages (e.g. ESRI's ArcGIS, QGIS) and game-building software (e.g. Unity, Unreal Engine, Blender) is apparent both in aforementioned research and in the commercial domain (e.g. LaShell, 2019). The interoperability enabled by utilizing game-engine domains enables significant streamlining of the visualization development process (e.g. Reyes & Chen, 2017) and increased visual fidelity of the urban landscapes they aim to represent (De Santis et al., 2019; Macchione et al., 2019). We still lack firm evidence that richly elucidates the relationship between 'realistic representations' of urban landscapes and the resultant cognitive load of users (Juřík, Herman, Kubíček, Stachoň, & Šašinka, 2016). It might be the case that in a manner similar to maps, viewers prefer more complex and/or visually appealing representations, which may in fact be detrimental to their actual performance in tasks (Fabrikant & Lobben, 2009; Hegarty, 2011). The demonstrated potential of these platforms and declining costs of producing rigorous spatial 3D visualization present opportunities to explore their impact on analysis of flood management policies and communication of risks to a wider set of stakeholders.

2.4.3. **Transformative potential of emerging interfaces**

A notable limitation of many studies utilizing 3D visualizations to date has been reliance on flat screen display of such models. By displaying 3D virtual environments on a flat screen, we eliminate binocular and proprioceptive depth cues, and restrict interaction to metaphor-based transduction using keyboard and mouse. By contrast, the affordances provided by emerging mixed reality interfaces can address many of the challenges inherent in interaction and display of 3D data through natural interaction and binocular presentation of 3D content (Roupé, Bosch-Sijtsema, & Johansson, 2014; Shelton & Hedley, 2002). Several researchers have proposed that alternative interfaces may provide a better information transfer and interaction with digital models of physical phenomena (Lin, Chen, & Lu, 2013; Orland, Budthimedhee, & Uusitalo, 2001; Slocum et al., 2001). Shelton & Hedley's (2002; 2004) empirical studies in geographic interface research demonstrated how visuo-motor feedback and proprioception in augmented reality interfaces improved perceptual and task performance on geographic spatial problem-solving tasks using 3D visualizations. This work underscored the potential of emerging mixed reality interface technologies, but also the critical need for empirical evidence to back up claims made about novel visualization tools. However, lack of substantive technological development in commercially available mixed reality systems over the following decade limited the number of studies conducted (Ens et al., 2019).

The recent growth of head-mounted computer interfaces for gaming and 3D work (e.g. virtual reality: Oculus Rift, HTC Vive; augmented reality: Microsoft Hololens, Magic Leap) is beginning to streamline and simplify much of the technological complexity in visualization development characteristic of earlier bespoke platforms (e.g. CAVE) – something discussed by Hedley and colleagues (2001; 2002) as they introduced the significance of collaborative augmented reality for geographic visualization. Researchers and planners can leverage this developed infrastructure to provide immersive and natural interaction with virtual landscapes at significantly lower costs.

While some attempts have been made in leveraging these affordances, the number of prototypes aimed at supporting FRM is low to date. We speculate that recent growth in the number of available devices and decreasing time and money costs of development are not yet reflected in the peer-reviewed visualization applications, while abundant in the commercial realm (ESRI Events, 2019; LaShell, 2019; Narain, 2018). Sections below will outline each of the emerging display and interaction mediums, their implications for urban planning in general, and for flood risk management in particular.

2.4.4. **Augmented Reality**

In augmented reality interfaces, digital representations of spatial information are anchored to the real world in 3 dimensions and they are interactive in real time (Azuma, 1997). The combination of visualizations with real spaces provides several promising applications within the realm of flood risk management. Examples of such visualizations range from analytical applications, where the virtual models of a city are visualized on a table-top, to ones focused on communication of hazards, where smartphones are used to visualize hypothetical flood levels in-situ (Gill & Lange, 2015; Haynes et al., 2018; Lonergan & Hedley, 2014; Tomkins, Hehl-Lange, S, Lange, 2019).

By situating digital flooding models in the context of everyday spaces and providing natural interaction metaphors (e.g. using gestures and manipulating model like an object) we could enable better understanding of the flooding phenomena, through a combination of visual and proprioceptive feedback (Shelton & Hedley, 2002). Improved understanding of information through augmented reality interfaces may increase the potential to connect a broad set of stakeholders to the issue, and possibly to stimulate action by highlighting impacts of flooding to the everyday spaces of viewers (Haynes & Lange, 2016). Furthermore, augmented-reality based platforms have identified potential to improve collaboration, since they allow users to perceive non-verbal cues of collaborators (e.g. ability to see collaborators gaze, posture etc.) (Billinghurst, Belcher, Gupta, & Kiyokawa, 2003; Ens et al., 2019; Rekimoto, 1996).

Some practical issues in the AR visualization realm persist, like managing the occlusion of virtual content by real structures and appropriate lighting/shadows for virtual objects (Billinghurst, Clark, & Lee, 2015; Haynes et al., 2018). However, a number of recent advances in computer vision algorithms, as well as general interest in the application of artificial intelligence and combination of semantic and geometric understanding of the environment by devices, could overcome these challenges in the coming decade (Arth, Pirchheim, Ventura, Schmalstieg, & Lepetit, 2015; Rohmer, Büschel, Dachselt, & Grosch, 2014; Steptoe, Julier, & Steed, 2014). The combination of the growing capabilities of visualization platforms to represent spatial data rigorously and the increasing number of devices available creates a number of possible research venues. These include, for example, studying the effectiveness of collaboration mediated through mixed reality table-top visualizations as opposed to maps and projector screens, as well as in-situ visualization of flood impacts and potential place-specific perceptions of residents with potential for affective response (Lieske, Wade, & Roness, 2014).

2.4.5. **Virtual Reality**

Immersive virtual environments provide a compelling set of interaction metaphors and dimensionality, which could alter the practice of analysis and communication of natural hazard risks. The increased immersion and practically infinite virtual real estate can allow seamless transformation across scale, and more affective understanding of the phenomena, due to the realistic representation and possibility of communication of human-scale (i.e. egocentric) impacts. Such an approach could address the risk perception paradox and improve preparedness, by overcoming the psychological distance and temporal discounting of environmental hazards by presenting an imminent, visually-compelling representation of individual risk in a specific place (Hruby, Ressl, & de la Borbolla del Valle, 2018; Wachinger, Renn, Begg, & Kuhlicke, 2013).

Benefits of VR interfaces to deliver compelling experiences of natural hazards or future environmental conditions have been theorized for a while (Havenith, Cerfontaine, & Mreyen, 2017; Sheppard, 2005). However, to date, even the visualizations aimed to deliver realistic representation of flooding hazards and immersive content have not utilized virtual reality displays. Recent works integrating hydrological information into virtual environments are still presenting highly realistic virtual representation of the world in 3D on a flat screen (e.g. De Santis, Macchione, Costabile, & Costanzo, 2018; Macchione et al., 2019). The most thorough spatial application leveraging the power of virtual environments has been described in a study by Helbig et al. (2014). The immersive capabilities of virtual reality display allowed a unique analytical experience, where more heterogeneous atmospheric data could be displayed simultaneously across dimensions without visual abstraction or clutter. As summarized by the authors: “unique capability provided by interactive 3D visualization is the possibility to directly dive into the evolution of meteorological processes" (Helbig et al., 2014, p.3778). By allowing dynamic representations in which large amounts of heterogeneous data can be toggled on and off, the virtual environment provided a distinct interaction between meteorological data and the analyst, where the capacity of the visual system to process information is combined with intuitive representation of weather phenomena, thus allowing a deeper engagement and understanding of the physical processes affecting weather and climate in a particular area. The nature of flooding phenomena and the data currently available in cities could allow similarly powerful analyses of potential flooding scenarios, mitigation approaches and coordination of responses.

2.5. Porting rigorous spatial 3D visualizations to Mixed Reality

Several accessible workflows exist to generate 3D visualizations of flood and inundation phenomena. However, in order to allow viewing and interaction with 3D visualizations of GIS data, this transformation into three dimensions must be more than visual – we must create inherently 3D geometric representations of spatial features and relationships. Another key consideration is that, while it is quite easy to produce '3D' models of objects by using 3D authoring tools (such as Blender, Maya, or SketchUp), they cannot preserve or support the kind of spatial, geodetic or topological rigor that is critical to spatial analytical work. The workflows to produce spatially rigorous, topologically three-dimensional, and compatible visualizations enable interoperability of a GIS data with mixed reality 3D user interface platforms.

Below, I describe an example of one such workflow: a straightforward approach that enables rigorous transformation of conventional spatial data into a 3D visualization environment that enables interoperability with multiple mixed reality interface platforms.

This solution requires a use of proprietary middleware CityEngine, but the advantages of this approach are numerous: preserve geographic scale and georeferencing of the data, both vector and raster data types can be integrated, and no coding or idiosyncratic knowledge is required. While others (e.g. Macchione et al., 2019) provided an open-source solution, the 3D environment introduced in their workflow (Blender) is not integrated well with mixed reality interface platforms. As discussed above (sec. 3.3), many perceptual and interaction benefits of using 3D representations are not realized if the visualization is restricted to a flat screen.

Our main goal in this process is to convert conventional GIS formats to spatially rigorous 3D models, so that they can be imported into a game engine, where visualization and integration of mixed reality interfaces can be performed. A summary of the workflow discussed below is provided in Fig.1, with example outputs in Fig.2. Production of 3D visualization begins in a conventional GIS environment (e.g. ArcGIS or QGIS) with spatial layers relevant to flood hazard visualization: raster: digital elevation, flood depths, orthophoto; vector: building footprints, adaptation infrastructure (proposed dikes). The only manipulation required in the context of FRM is to use a raster calculator to overlay (add) flood depths to the digital elevation model. This allows a creation of a modified flood depths layer, where the water elevations are respective to a datum, rather than DEM values in the particular location, which is necessary for later 3D model building in CityEngine. Once the relevant layers are available, they can be clipped to a study area and exported in GeoTIFF format for raster layers and shapefile for vector data. Now, the raster layers can be imported as "Terrain" in CityEngine, and vector data (building polygons, lines for dike infrastructure) can be imported in the native format. Within CityEngine, vector data can be modified to an appropriate 3D geometry according to the attribute data (e.g. extruded height of buildings, height/width of a proposed dike). In this study, we focus on a simple approach that results in LOD 1 building models, which correspond to extruded polygon footprints of the buildings (Open Geospatial Consortium, 2012). However, much more detailed building models can be created within

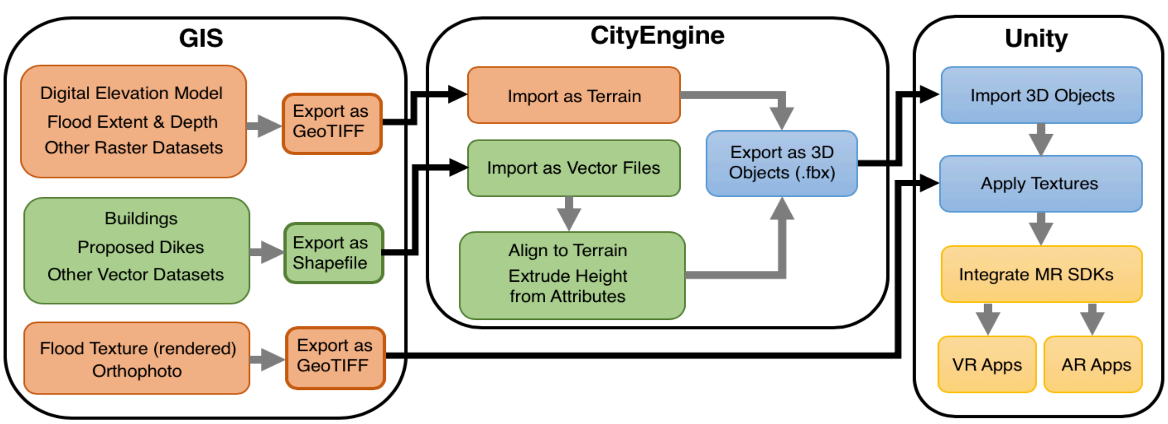

Figure 2-1 – GIS to 3D models workflow

This flowchart provides an overview of conversion of GIS data through middleware into 3D representations that can be used in Unity visualization environment.

CityEngine, which is outside of the scope of this paper. Once the 3D geometry is created according to the attributes of vector features, they can be aligned to the terrain (digital elevation) layer. The result is a 3D model of the area that can be exported in common 3D data formats, such as .fbx or .obj. These data can be moved to most commonly game engines commonly used in visualization (Blender, Unreal, Unity). Once the 3D objects are imported into the visualization platform, orthophoto can be applied as a texture to the Digital Elevation Model, and the rendered flood depth color-codes can be applied to the floodplain 3D object.

In this research I focus on using Unity because it allows fairly easy integration of multiple mixed reality interface platforms. Mobile augmented reality applications can be created using Vuforia SDK (e.g. (Haynes et al., 2018; PTC, 2020; Rydvanskiy & Hedley, 2019). Head-mounted augmented reality visualizations can be created using the most common AR displays, including Magic Leap's Lumin SDK, and HoloLens's MRTK (Magic Leap, 2020; Microsoft, 2019d). The virtual reality platforms are well-integrated within Unity as well, with OpenVR API allowing development for HMD-based VR (Valve Software, 2020),

This workflow, then, illustrates the capabilities/opportunities to transform conventional GIS data into 3D interface-ready assets. In doing so, this research demonstrates a straightforward pathway for existing flood risk information specialists to turn their own data and visualizations into 3D interactive visualizations using a freely available mixed reality platform. This simple act opens up an exciting set of opportunities for applied work, but more importantly, the opportunity for the field as a whole to collectively discuss, design, and develop 3D mixed reality-supported flood risk visualization practices, that may support pressing flood risk assessment, interpretation, communication, and governance challenges.

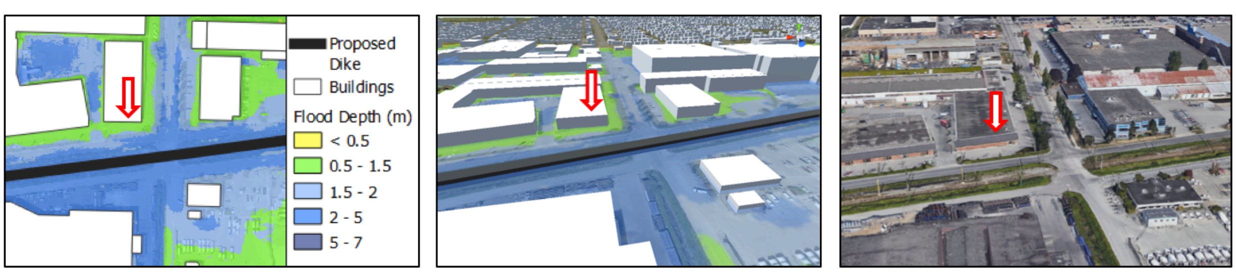

Figure 2-2 – FRM Representations in different visualization tools

Various representations of the same area across 1) Conventional flood map; 2) 3D visualization – colors for flood depths are preserved from existing municipal maps; 3) Google Earth.

2.6. Discussion and Future Research Directions

A persistent challenge in visualization research has been technologically-driven development, as the implicit excitement about 3D, fast-changing software and devices make empirical assessments and theory-driven research difficult (Bleisch, 2012; Çöltekin, Bleisch, Andrienko, & Dykes, 2017; Orland et al., 2001). For instance, how do we construct an empirical basis for understanding various representations and display interfaces, where the growing capabilities and number of devices available yearly outpace the relatively slow progress in collection, publication and application of empirical data on their usability and usefulness? How rigorous visualization research should develop in such context is unclear, given the increasing public interest as well as capital investments into commercial applications (e.g. LaShell, 2019). Given the deployment of 3D visualizations in planning realms, without sufficient evidence on their efficacy and or efficiency, the application of such tools can be seen as a fad, and could ultimately hinder long-term productive development of extended visualization capabilities. Similar observations were made almost two decades ago within the field by Orland et al. (2001), yet the subsequent research efforts produced little empirical evidence on the use of 3D visualizations or virtual environments in general for planning practice.

Nevertheless, the explosive growth and reduction in prices of head-mounted displays and input capture (e.g. eye tracking, voice recognition) over the last couple of years can simplify collection of rigorous data on usability/usefulness of a particular tool. The methodology provided in this research can help both researchers and practitioners to develop spatially rigorous 3D visualizations that can be integrated with mixed reality interface platforms. Production of 3D data assets does not in itself require use of a 3D interface. However, to truly realize the potential and value of 3D data representations of 3D phenomena and structures, they must be viewed - better yet, experienced, manipulated, interacted with – in three dimensions. Without 3D interfaces, it is challenging to experience the data perceptually in three dimensions (viewing 3D assets via 2D display implicitly imposes some degree of cognitive or transformational burden on users).

It is also important to interrogate emerging platforms (such as game engines) and discuss some limitations. A notable limitation of the proposed approach is the reliance on Cartesian model of space within game-engines. Integration of geodetic models and careful management of transformations driven by data projections is necessary for visualizations of more expansive areas, where distortions introduced by projections become relevant for accuracy of shapes, measurements of distance, and so on. The switch of the focus from addressing technical limitations of interface devices and displays to their ability to support routine work and communication provides promising directions for future research. From Human-Computer Interaction studies that assess user performance with different interface permutations to the qualitative studies on meaningful and effective integration of such systems in planning practice, the possibilities for research in an evolving cartographic and GIScience landscape, are immense. We must also seriously consider ethical issues in the development of visualizations, especially given the demonstrated potential of realistic visualization to elicit affective response (Bohman, Neset, Opach, & Rød, 2015; Lieske et al., 2014; Schroth et al., 2015). Such concerns are ever-present part of visualization research (e.g. Sheppard, 1989), but recent achievements in production of computer graphics allow creation of highly visually realistic hydrological and urban landscape models, which are not grounded in rigorous data (Teng et al., 2017).

2.7. Conclusion

The problematic state of flood risk mapping and communication in Canada raises at least two distinct needs: to upgrade the extent and quality of data on flood risk and to identify and develop new modes of engaging with existing and new data that support and connect expert flood risk analysis, planners, and stakeholders. Exploring opportunities for developing next-generation tools of analysis and dissemination of risk information is a response to this latter challenge. Some of the limitations of paper and digital maps are addressed in the emerging visualizations and literature on urban flood risk communication. The ability of visualizations to present natural hazards as imminent and observable within a familiar landscape could address the issues of temporal, psychological and geographical distance-based discounting of natural hazards, which continuously leads to increasing exposure and lack of appropriate risk management response. Furthermore, the mixed reality interfaces bring an opportunity to unlock natural interaction and representation of 3D visualizations, which could augment practice of flood risk analysis beyond conventional flat maps. While there is ample excitement about the ability to represent data in realistic-looking 3D models, we still lack firm evidence on when such representations are superior (or inferior) to flood risk maps. The methodology for creation of mixed-reality base visualization provided herein seeks to address technical and knowledge barriers that exist in production of 3D visualizations. Emerging visualization interfaces provide compelling options to improve interaction with and display of data to ultimately change the ability of users to arrive at insights relevant to the management of flood risks and engage a broader set of stakeholders. Given the growing research and commercial interest in improved spatial displays, it is necessary to engage methodological and ethical questions for productive integration of technologies to the routine processes of flood risk management. It is my hope that a straight-forward approach of integrating spatial data in mixed reality interface platforms can help future researchers to address these challenges.

2.8. References

Al-Kodmany, K. (2002). Visualization tools and methods in community planning: from freehand sketches to virtual reality. *Journal of Planning Literature*, *17*(2), 189–211.

Arth, C., Pirchheim, C., Ventura, J., Schmalstieg, D., & Lepetit, V. (2015). Instant outdoor localization and SLAM initialization from 2.5 D maps. *IEEE Trans. Vis. Comput. Graph.*, *21*(11), 1309–1318.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355–385.

Billinghurst, M., Belcher, D., Gupta, A., & Kiyokawa, K. (2003). Communication Behaviors in Colocated Collaborative AR Interfaces. *International Journal of Human–Computer Interaction*, *16*(3), 395–423. https://doi.org/10.1207/S15327590IJHC1603_2

Billinghurst, M., Clark, A., & Lee, G. (2015). A survey of augmented reality. *Foundations and Trends® in Human–Computer Interaction*, *8*(2–3), 73–272.

Bleisch, S. (2012). 3-D Geovisualization-Definition and Structures for the Assessment of Usefulness. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 129–134.

Bohman, A., Neset, T.-S., Opach, T., & Rød, J. K. (2015). Decision support for adaptive action–assessing the potential of geographic visualization. *Journal of Environmental Planning and Management*, *58*(12), 2193–2211.

Burch, S., Sheppard, S., Shaw, A., & Flanders, D. (2010). Planning for climate change in a flood-prone community: municipal barriers to policy action and the use of visualizations as decision-support tools. *Journal of Flood Risk Management*, *3*(2), 126–139.

Çöltekin, A., Bleisch, S., Andrienko, G., & Dykes, J. (2017). Persistent challenges in geovisualization–a community perspective. *International Journal of Cartography*, *3*(sup1), 115–139.

De Santis, R., Macchione, F., Costabile, P., & Costanzo, C. (2018). A comparative analysis of 3-D representations of urban flood map in virtual environments for hazard communication purposes. In *E3S Web of Conferences* (Vol. 40, p. 6037). EDP Sciences.

De Santis, R., Macchione, F., Costabile, P., & Costanzo, C. (2019). Visual Risk Communication of Urban Flooding in 3D Environments Based on Terrestrial Laser Scanning. In G. Mannina (Ed.), *New Trends in Urban Drainage Modelling. UDM 2018. Green Energy and Technology* (pp. 783–787). Cham: Springer International Publishing.

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., … Feyen, L. (2018). Increased human and economic losses from river flooding with anthropogenic warming. *Nature Climate Change*, *8*(9), 781–786. https://doi.org/10.1038/s41558-018-0257-z

Dransch, D., Rotzoll, H., & Poser, K. (2010). The contribution of maps to the challenges of risk communication to the public. *International Journal of Digital Earth*, *3*(3), 292–311.

Ens, B., Lanir, J., Tang, A., Bateman, S., Lee, G., Piumsomboon, T., & Billinghurst, M. (2019). Revisiting collaboration through mixed reality: The evolution of groupware. *International Journal of Human-Computer Studies*.

ESRI Events. (2019). *High-End 3D Visualization with CityEngine, Unity and Unreal*. Retrieved from https://youtu.be/qdo2WSm_5UU

Fabrikant, S. I., & Lobben, A. (2009). Introduction: Cognitive Issues in Geographic Information Visualization. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *44*(3), 139–143. https://doi.org/10.3138/carto.44.3.139

Fenech, A., Chen, A., Clark, A., & Hedley, N. (2017). Building an adaptation tool for visualizing the coastal impacts of climate change on Prince Edward Island, Canada. In *Climate change adaptation in North America* (pp. 225–238). Springer.

Gill, L., & Lange, E. (2015). Getting virtual 3D landscapes out of the lab. *Computers, Environment and Urban Systems*, *54*, 356–362.

Havenith, H.-B., Cerfontaine, P., & Mreyen, A.-S. (2017). How virtual reality can help visualise and assess geohazards. *International Journal of Digital Earth*, 1–17.

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile Augmented Reality for Flood Visualisation. *Environmental Modelling & Software*, *109*, 380–389.

Haynes, P., & Lange, E. (2016). In-situ flood visualisation using mobile AR. In *2016 IEEE Symposium on 3D User Interfaces (3DUI)* (pp. 243–244). IEEE.

Hedley, N. (2001). Collaborative AR for geographic visualization. In *Proceedings of the Second International Symposium on Mixed Reality* (pp. 11–18). Yokohama, Japan.

Hedley, N., Billinghurst, M., Postner, L., May, R., & Kato, H. (2002). Explorations in the use of augmented reality for geographic visualization. *Presence: Teleoperators & Virtual Environments*, *11*(2), 119–133.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science*, *3*(3), 446–474.

Helbig, C., Bauer, H.-S., Rink, K., Wulfmeyer, V., Frank, M., & Kolditz, O. (2014). Concept and workflow for 3D visualization of atmospheric data in a virtual reality environment for analytical approaches. *Environmental Earth Sciences*, *72*(10), 3767–3780.

Henstra, D., Minano, A., & Thistlethwaite, J. (2019). Communicating disaster risk? An evaluation of the availability and quality of flood maps. *Natural Hazards and Earth System Sciences*, *19*(1), 313–323.

Henstra, D., & Thistlethwaite, J. (2017). *Climate change, floods, and municipal risk sharing in Canada*. Institute on Municipal Finance and Governance.

Henstra, D., Thistlethwaite, J., Brown, C., & Scott, D. (2019). Flood risk management and shared responsibility: Exploring Canadian public attitudes and expectations. *Journal of Flood Risk Management*, *12*(1), e12346.

Hruby, F., Ressl, R., & de la Borbolla del Valle, G. (2018). Geovisualization with immersive virtual environments in theory and practice. *International Journal of Digital Earth*, 1–14.

Jacquinod, F., & Bonaccorsi, J. (2019). Studying Social Uses of 3D Geovisualizations: Lessons Learned from Action-Research Projects in the Field of Flood Mitigation Planning. *ISPRS International Journal of Geo-Information*, *8*(2), 84.

Juřík, V., Herman, L., Kubíček, P., Stachoň, Z., & Šašinka, Č. (2016). Cognitive aspects of collaboration in 3d virtual environments. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *41*, 663.

Lai, J.-S., Chang, W.-Y., Chan, Y.-C., Kang, S.-C., & Tan, Y.-C. (2011). Development of a 3D virtual environment for improving public participation: Case study–The Yuansantze Flood Diversion Works Project. *Advanced Engineering Informatics*, *25*(2), 208–223.

LaShell, D. (2019). NextTech: Seeing Buildings before They're Born. Retrieved June 12, 2019, from https://www.esri.com/about/newsroom/publications/wherenext/gis-bim-and-3d-in-aec/

Lieske, D. J., Wade, T., & Roness, L. A. (2014). Climate change awareness and strategies for communicating the risk of coastal flooding: a Canadian Maritime case example. *Estuarine, Coastal and Shelf Science*, *140*, 83–94.

Lin, H., Chen, M., & Lu, G. (2013). Virtual geographic environment: a workspace for computer-aided geographic experiments. *Annals of the Association of American Geographers*, *103*(3), 465–482.

Lochhead, I., & Hedley, N. (2019). Mixed reality emergency management: bringing virtual evacuation simulations into real-world built environments. *International Journal of Digital Earth*, *12*(2), 190–208.

Lonergan, C., & Hedley, N. (2014). Flexible mixed reality and situated simulation as emerging forms of geovisualization. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *49*(3), 175–187.

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.

Magic Leap. (2020). Developer Portal. Retrieved October 2, 2020, from https://developer.magicleap.com/home

Microsoft. (2019). Getting started with MRTK v2. Retrieved October 2, 2020, from https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-getting-started

Narain, A. (2018). The global GIS and Spatial Analytics market to touch US$88.3 Billion by 2020. Retrieved August 6, 2019, from https://www.geospatialworld.net/blogs/gis-and-spatial-analytics-market/

Open Geospatial Consortium. (2012). City Geography Markup Language (CityGML) Encoding Standard.

Orland, B., Budthimedhee, K., & Uusitalo, J. (2001). Considering virtual worlds as representations of landscape realities and as tools for landscape planning. *Landscape and Urban Planning*, *54*(1–4), 139–148. https://doi.org/10.1016/S0169-2046(01)00132-3

Paar, P. (2006). Landscape visualizations: Applications and requirements of 3D visualization software for environmental planning. *Computers, Environment and Urban Systems*, *30*(6), 815–839.

PTC. (2020). Vuforia Engine 8.6. Retrieved October 2, 2020, from https://developer.vuforia.com/downloads/sdk

Rao, J., Qiao, Y., Ren, F., Wang, J., & Du, Q. (2017). A mobile outdoor augmented reality method combining deep learning object detection and spatial relationships for geovisualization. *Sensors*, *17*(9), 1951.

Rekimoto, J. (1996). Transvision: A hand-held augmented reality system for collaborative design. In *Proceeding of Virtual Systems and Multimedia* (Vol. 96, pp. 18–20).

Reyes, M. E. P., & Chen, S.-C. (2017). A 3D virtual environment for storm surge flooding animation. In *2017 IEEE third international conference on multimedia big data (BigMM)* (pp. 244–245). IEEE.

Rohmer, K., Büschel, W., Dachselt, R., & Grosch, T. (2014). Interactive near-field illumination for photorealistic augmented reality on mobile devices. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 29–38). IEEE.

Roupé, M., Bosch-Sijtsema, P., & Johansson, M. (2014). Interactive navigation interface for virtual reality using the human body. *Computers, Environment and Urban Systems*, *43*, 42–50.

Rydvanskiy, R., & Hedley, N. (2019). EMERGING VISUALIZATION INTERFACES AND THEIR IMPLICATIONS FOR FLOOD RISK PERCEPTION AND MANAGEMENT. In *CityVis Workshop IEEE Vis 2019* (pp. 26–28). Vancouver.

Schroth, O., Pond, E., & Sheppard, S. (2015). Evaluating presentation formats of local climate change in community planning with regard to process and outcomes. *Landscape and Urban Planning*, *142*, 147–158.

Shelton, B. E., & Hedley, N. (2002). Using augmented reality for teaching earth-sun relationships to undergraduate geography students. In *The First IEEE International Workshop Agumented Reality Toolkit,* (pp. 8-pp). IEEE.

Shelton, B. E., & Hedley, N. (2004). Exploring a cognitive basis for learning spatial relationships with augmented reality. *Technology, Instruction, Cognition and Learning*, *1*(4), 323.

Sheppard, S. (1989). *Visual simulation: a user's guide for architects, engineers, and planners*.

Sheppard, S. (2005). Landscape visualisation and climate change: the potential for influencing perceptions and behaviour. *Environmental Science & Policy*, *8*(6), 637–654.

Slocum, T. A., Blok, C., Jiang, B., Koussoulakou, A., Montello, D. R., Fuhrmann, S., & Hedley, N. R. (2001). Cognitive and usability issues in geovisualization. *Cartography and Geographic Information Science*, *28*(1), 61–75.

Steptoe, W., Julier, S., & Steed, A. (2014). Presence and discernability in conventional and non-photorealistic immersive augmented reality. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 213–218). IEEE.

Teng, J., Jakeman, A. J., Vaze, J., Croke, B. F. W., Dutta, D., & Kim, S. (2017). Flood inundation modelling: A review of methods, recent advances and uncertainty analysis. *Environmental Modelling & Software*, *90*, 201–216.

Tomkins, Hehl-Lange, S, Lange, E. (2019). Tracking Visual Engagement in Mixed Reality: A Framework for Analysing Interaction with Digital Models. *Journal of Digital Landscape Architecture*, (4), 160–167.

Valve Software. (2020). OpenVR API.

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., & Storlazzi, C. D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Scientific Reports*, *7*(1), 1399. https://doi.org/10.1038/s41598-017-01362-7

Wachinger, G., Renn, O., Begg, C., & Kuhlicke, C. (2013). The risk perception paradox—implications for governance and communication of natural hazards. *Risk Analysis*, *33*(6), 1049–1065.

Chapter 3. Mixed reality flood visualizations: development, reflections, and implications for practice

3.1. Abstract

Interest in and use of 3D visualizations for analysis and communication of flooding risks has been increasing. At the same time, an ecosystem of 3D user interfaces has also been emerging. Together, they offer exciting potential opportunities for flood visualization. In order to understand how to turn potential into real value we need to develop better understandings of technical workflows, capabilities of the resulting systems, their usability, and implications for practice. Starting with existing geospatial datasets, I develop single user and collaborative visualization prototypes that leverage capabilities of the state-of-the art HoloLens 2 mixed reality system. By using the 3D displays, positional tracking, spatial mapping, and hand- and eye-tracking, I seek to unpack the capabilities of these tools for meaningful spatial data practice. I reflect on the user experience, hardware performance and usability of these tools and discuss the implications of these technologies for flood risk management, and broader spatial planning practice.

3.2. Introduction

With a changing climate and growing sea levels, coastal and riverine flooding is a growing concern across the world. With projected increases in the magnitude and frequency of flooding, understanding the risks and developing policies to address them is an integral part of urban planning. Visualizations play a crucial role in understanding and disseminating information from flood simulations and scenario modeling for planners, as well as negotiating adaptation pathways among exposed stakeholders (Henstra, Minano, et al., 2019; Jacquinod & Bonaccorsi, 2019; Voinov et al., 2016). Given the institutional nature of flood risk management, most developed visualizations attempt to fit into the existing planning/risk management infrastructure. This integration makes the flood visualization domain particularly interesting, as the developed tools can be analyzed within the applied context of spatial analysis of risk and its communication to stakeholders.

Over the last decade 3D visualizations of flood impacts have been increasingly prominent in scholarly literature (Fenech et al., 2017; Jacquinod & Bonaccorsi, 2019; Macchione et al., 2019). These are mostly produced for risk communication purposes, often with an assumption that perspective 3D views of the landscape are easier to interpret for non-experts (Lai et al., 2011). Although many developed tools are compelling, we still lack empirical studies to turn novelty and claims of improved understanding of data into demonstrable value for users. This trend has certainly been influenced by increased generation and use of 3D data (e.g. LiDAR, Structure-from-Motion, BIM) where the vertical characterization of space is more complex (Amirebrahimi, Rajabifard, Mendis, & Ngo, 2016; De Santis et al., 2019). This has, in turn, increased both the need and demand for software that can adequately represent topology in three dimensions and provide interactive and querying capabilities. However, now most of the viewing of and interaction with 3D content is mediated through 2D displays and WIMP (Window, Icon, Menu, Pointer) interfaces. This is significant, because it eliminates binocular depth cues, the potentially invaluable opportunity to view/manipulate and experience inherently 3D data in three dimensions and restricts interaction to keyboard and mouse inputs.

Concurrently, researchers are investigating ways to leverage emerging 3D interfaces to improve interaction with, and perceptual experiences of, 3D data. Within the FRM domain in particular, mobile augmented reality tools have been developed to visualize flood impacts in-situ and immersive virtual environments have been created to visualize potential futures for coastal adaptation (Haynes et al., 2018; Lonergan & Hedley, 2015; Newell, Canessa, & Sharma, 2017). This growth in research interest has mirrored the development of a new generation of mixed reality (MR) interfaces that have potential to alter, and potentially improve, our interaction with and understanding of complex 3D data. When discussing mixed reality tools, I largely follow the definition of an augmented reality system offered by Azuma (1997), which suggested the system combines virtual and real content, is registered in three-dimensional space, and is interactive in real time. The term MR is used here instead of AR for two reasons: AR systems often focus on augmenting the real landscapes with virtual content, while our application is more environmentally agnostic (thus further along the virtuality continuum of Milgram & Kishino (1994). Secondly, the term MR has been used widely by researchers and developers to describe HMD-based systems for AR/MR (e.g. Kim et al. (2019); Wang, Wu, Chen, & Chen (2018).

MR geographic visualization has been developing as a distinct domain over the last three decades, but we are now at the pivotal point, where such tools are becoming usable enough to be introduced into routine work (Billinghurst et al., 2015; Ens et al., 2019; Hedley, 2001; Hedley et al., 2002). In this medium, real world views can be augmented with spatially registered three-dimensional content (Azuma, 1997). With advances in display technology, processing power, cloud computing, computer vision, hand and eye tracking, registration and occlusion management, these tools provide numerous opportunities for development of alternative data interfaces. This moment presents a unique opportunity for researchers and practitioners to evaluate their application in spatial data practice.

While this trend is sparked by the availability of new devices, the interest in emerging interfaces is not about the specific hardware or software. The mixtures of content and narrative are mediated through user interfaces, displays, and input/output channels to deliver unique perceptual experiences of spatial data for the user. Each of the components making up an interface between the underlying data and user have the ability to influence understanding of the phenomena, whether in terms of topology of risk (e.g. flood extents and depths), or the associated narrative (e.g. risk perception, willingness to act) (Lieske et al., 2014). The preceding introduction and commentary reveal that interfaces are far from just novel display devices or interaction systems. They are multifaceted perceptual and experiential relationships between humans and phenomena, mediated by the data that represent them, the visualizations that attempt to convey them, and the interfaces that mediate this exploration. Mixed reality interfaces, in particular, are a promising tool to improve user interaction with three-dimensional spatial data due to the combination of visual, sensory-motor, and proprioceptive feedback in the interaction with virtual objects in real spaces (Shelton & Hedley, 2002, 2004). Proprioception refers to the person's awareness of their own body in space/environment, which is preserved when using MR tools (Shelton & Hedley, 2004). This multi-sensory nature of the interface may improve the comprehension and interaction with complex 3D data. With hand tracking we can develop interfaces that leverage a user's knowledge about interaction with real objects to manipulate virtual content, potentially simplifying interaction with complex 3D content (compared to a WIMP interface).

Furthermore, mixed reality interfaces offer distinct and significant features for applied spatial data practice, especially when it comes to collaborative tasks in a shared environment. In particular, the legacy spaces in which most routine work happens will require dedicated open spaces to leverage completely virtual environments (VR), while we might get most of the benefits of virtual environments in MR systems (e.g. immersion, binocular 3D, natural user interfaces), with a more flexible integration into work spaces. MR tools preserve the ability to see and interact with other people and the surrounding environment, and to interact with non-MR tools (e.g. paper maps, sketches) without the need to exit the interface. Numerous researchers have recognized this potential over the years (Billinghurst, Weghorst, & Furness, 1997; Ens et al., 2019; Grasset, Lamb, & Billinghurst, 2005; Nilsson, Johansson, & Jönsson, 2009; Shelton & Hedley, 2004). Much of the research in the past has focused on overcoming technical hurdles in implementing MR systems. While current MR devices are not yet ubiquitous, much of the development infrastructure needed to create usable visualizations exists. This presents exciting opportunities for researchers to develop and evaluate emerging platforms for their ability to deliver meaningful and useful interaction with rigorous spatial data. Furthermore, much conceptual work is needed to understand the role of various components of the MR interface (data, display, interaction, visualization approaches) in mediating understanding of data and associated phenomena by user.

This paper sits at the intersection of evolving modes of flood risk analysis and communication, and emerging interface technology. Its objective is to report on an applied mixed reality FRM visualization system and then unpack the interplay between interface capabilities, informational experiences grounded in FRM practice, and contemporary workspaces. The sections that follow describe the workflows through which I explored the feasibility of developing MR flood risk visualization tools; the resulting visualization interfaces; critical reflection and review of these systems from the perspectives of their performance, usability and potential as operational tools; and their potential to integrate with current and future spaces of FRM practice. In the first of these sections, I report on the design and development of a set of prototypes to demonstrate the possibilities of single-user and collaborative MR flood visualizations. Using the case study of flood risk management along the shore of the Fraser River in Vancouver, I develop 3D visualizations of the area, associated impacts and potential mitigation infrastructure. By integrating this visualization into the state-of-the-art mixed reality system HoloLens 2, I aim to understand the usability of such tools and highlight how the distinct aspects of the interface alter the perceptual outcomes of 3D visualization. Informed by this experience, I present a discussion of the potential concerns for integration of MR visualizations into practice. Ultimately, this effort seeks to assess MR tools for potential to improve interaction, understanding and communication of flood risks through visualization by planners, decision-makers, and stakeholders.

3.3. Methodology

This section describes the development methodology for the mixed reality flood visualization tools. The workflow consists of data preparation in GIS, conversion of data into 3D objects in CityEngine, integration of mixed reality capabilities and development of the user interface in Unity, based on Mixed Reality Toolkit (Microsoft, 2020). This development workflow mirrors other attempts at 3D geovisualization using HoloLens, with some changes in the software used (Wang et al., 2018; Wang, Wu, He, & Chen, 2019). A high level summary of the process is presented in Figure 2 below, with details expanded in the following sections. The development process was guided by our experience interacting with local planners and observing their policy meetings. I aimed to create visualizations that would reflect (i.e. be useful) current data and flood risk management practices and policies developed by the City of Vancouver.

3.3.1. Study Area

The choice of the study area for this project was guided by existing adaptation efforts at City of Vancouver for the shore of the Fraser River (Figure 1). This area is currently being assessed for development of appropriate adaptation measures, and numerous resources exist to develop contextually rich visualizations of flood impacts in the area (City of Vancouver, 2014, 2018). Located on the south of the City, the Fraser river shore consists mostly of industrial land use, with some critical urban infrastructure located in the area. Given the fact that most of the shore area is vulnerable at current water levels, timely adaptation is an increasingly pressing concern. The extensive mapping and proposed adaptation policies available for this area made them relevant for developing contextually rich visualizations.

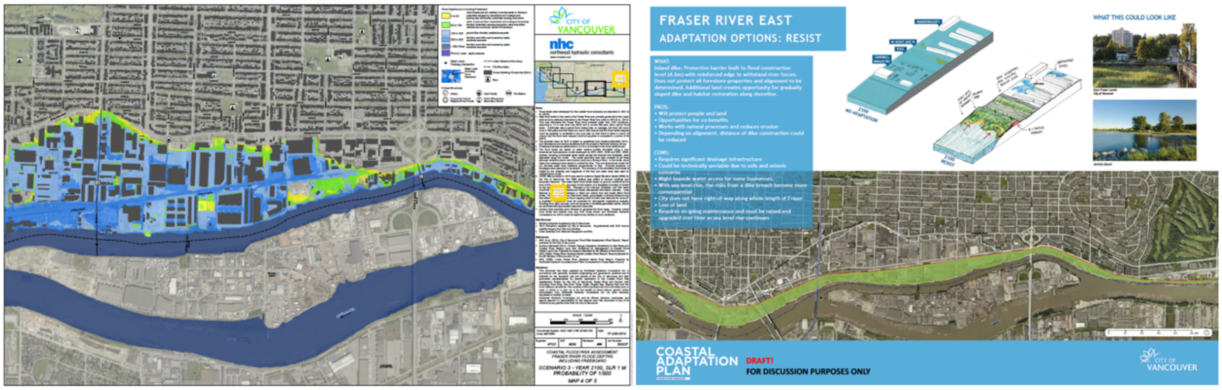

Figure 3-1 – City of Vancouver documents related to FRM

The documents published by City of Vancouver provided guidance to the design of visualization, as well as the text and conceptual drawings used in the User Interface. On the left, is a flood impact map, and the right document is an excerpt from Coastal Adaptation plan describing various adaptation scenarios for the Fraser shore area.

3.3.2. **GIS data to 3D models**

To develop the visualizations, various layers were used,including the digital elevation model (DEM), orthophoto, flood depths, building footprints, and river setbacks. Other layers (e.g., protection infrastructure) were digitized based on existing adaptation proposals developed by the City (City of Vancouver, 2018). All layers were projected to UTM10N in QGIS and clipped to the appropriate extent. To develop a 3D representation of flood depths, the flood depth layer was overlaid with DEM to derive DEM-adjusted flood depth, where the height of water was calculated as flood depth + current elevation (i.e. flood elevation is now relative to absolute elevation, not referencing the DEM elevation). Once the layers were prepared and clipped to an appropriate extent (discussed below), raster layers were exported in GeoTIFF format, and vector layers as shapefiles. These layers were then imported into CityEngine software, with DEM and DEM-adjusted flood depths as terrain layers, and buildings, dikes, and setbacks as vector layers. DEM was textured with orthophoto at 0.2m resolution, and flood depth was textured identically to existing flood maps published by the City. To derive 3D geometry from vector layers, base heights were adjusted to the DEM and building layers' attribute height information was used to extrude buildings. The proposed dikes do not contain specific information on their dimensions, so they were represented as 4-m wide and 6-m high splines, colored in red. The setback lines were visualized as 2 m wide 10 m high splines, colored in white. The 3D geometry generated in CityEngine was exported in Filmbox (.fbx) format, which can be imported across 3D modelling/game engine software, including Unity, which was used to integrate mixed reality capabilities (Esri, 2016).

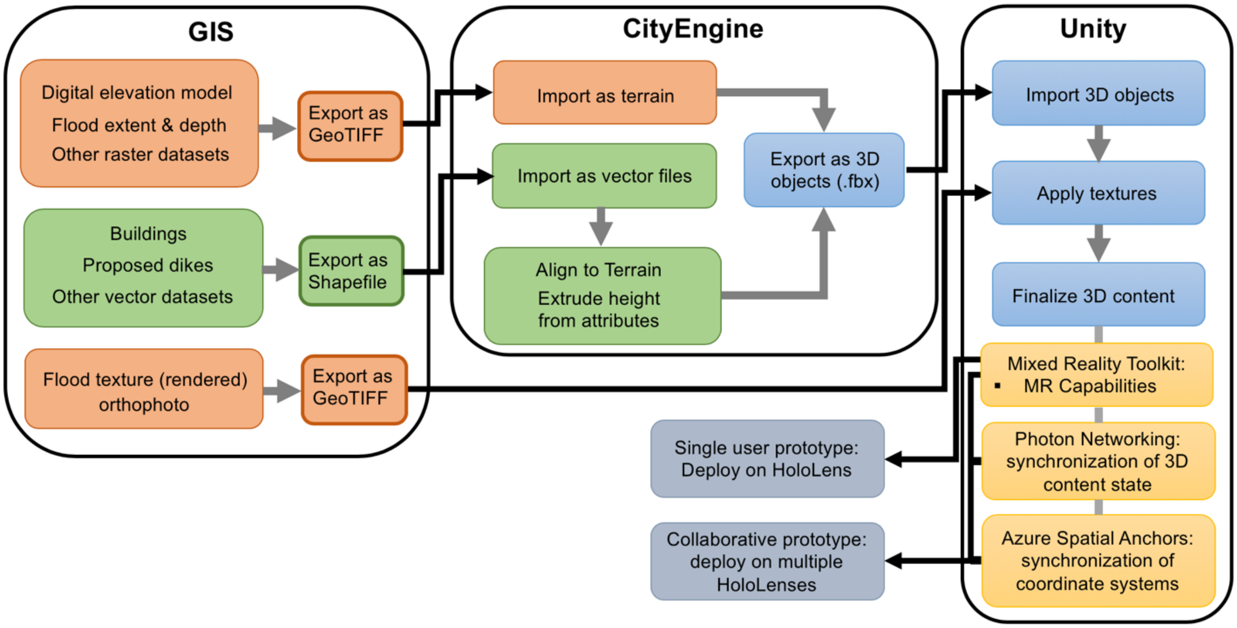

Figure 3-2 – GIS to MR workflow

This flowchart presents an overview of the development workflow from conventional GIS data that is exported in appropriate format and converted to 3D geometry in CityEngine, created 3D model can then be imported into Unity and integrated with various Mixed Reality Toolkit components to create single and shared user applications deployed on HoloLens 2.

3.3.3. **Integration with Mixed Reality Toolkit**

To develop mixed reality visualization based on the created 3D models, I used the mixed reality toolkit (MRTK), which is a platform built to integrate mixed reality capabilities in existing applications (Microsoft, 2019d). It is developed by Microsoft and is an underlying infrastructure used to develop most applications for the HoloLens platform. The HoloLens 2 device is a head-mounted computer system that has stereoscopic displays, 6 Degrees-of-Freedom positional tracking of the user, spatial mapping and occlusion management of environment, eye-tracking, and articulated hand tracking (Microsoft, 2019e). Using the MRTK infrastructure, we can also use synchronized coordinate systems across multiple devices (through Azure Anchors), and develop multi-user applications (through Photon Unity Networking) (Microsoft, 2019a, 2019b). Documentation describing the development process exhaustively is openly available on the Microsoft website.

We used MRTK version 2.3, using Unity 2019.2 and 2019.3 for collaborative, and single user applications respectively. The different versions of Unity were used since some features are only available in the newer version (e.g. eye-tracking), and collaborative capabilities are only available in the older version. I do not present all the minute changes done in Unity to integrate MRTK, since the ongoing changes to the toolkit and changing software versions will make our development guide outdated by the time of publication. Rather, I discuss higher-level content and user interface (UI) design decisions made throughout the development process. For instance, the entire Fraser shore is approximately 10 km, and given the resolution of DEM at 0.5 m and flood depths at 1 m, visualizing the entire shore would be unfeasible given the processing limitations of the device used. Throughout testing and development, it was determined that a clipped area of the shore about 300x300 m resulted in smooth performance (stable at 55-60fps). A final extent ended up being 347 by 391 meters, at 1 m resolution for floodplain and digital elevation model. Larger areas would hinder rendering performance on our devices. This can be addressed through the use of remote rendering, whether in the cloud or on a local machine, but was not used in this case since it limits the capabilities of the device in the current version of MRTK. In particular, articulated hand tracking and eye tracking did not work in our tests, and understanding the capabilities, use and shortcomings of these aspects of the interface was deemed more important than visualizing larger areas with off-device rendering.

3.3.4. **Development of the user interface**

Although mixed reality research has been going on for several decades, it is only relatively recently that robust, high-performance, consumer-grade MR systems have become available (e.g. HoloLens, Magic Leap). Hence, there are few guidelines for the development of appropriate user interfaces for MR applications. Some suggestions for the design of user interface for MR systems have been made in literature, and others are suggested by Microsoft in its design guidelines (Dey, Billinghurst, Lindeman, & Swan, 2018; Dünser & Billinghurst, 2011; Microsoft, 2019c; Stevens & Hanschka, 2014; Vi, da Silva, & Maurer, 2019). The guidelines presented by Vi et al. (2019) seemed particularly relevant, as they were written with last generation head-mounted augmented reality devices (e.g. HoloLens), while many of previous studies concerned themselves with handheld augmented reality visualizations (e.g. Santos et al., 2015). It is important to emphasize that UI design decisions were based on the above literature and our development experience. Development of usable and useful MR user interfaces for spatial data requires much research to understand what aspects of the design contribute to ease of use and provide a compelling user experience. Our goal was to develop an invisible/natural interface, to allow users to remain focused on the task and content at hand, rather than be distracted by novel technology. To this end, I utilized HoloLens's hand- and eye-tracking capabilities, as well as use the spatial map of the environment for occlusion management and content placement.

The goals for the user interface were fourfold: (1) provide interactive capabilities to visualize the four alternative shore adaptation scenarios developed by City of Vancouver on-the-fly, (2) provide inter-connected contextual information to the user based on the state of the 3D model, (3) integrate virtual content into the physical space of the user, and (4) use the available features of the device (hand and eye-tracking) where it seemed to add value to the user experience.

Content layout

The layout of the UI was guided by the desire to utilize virtual space to effectively display contextual information related to FRM. Visualization integrated existing conceptual drawings created by urban planners to illustrate potential layout of the physical space under a specific adaptation scenario. The associated description of potential adaptation scenarios is displayed on the text panel above the 3D content, with a legend for flood depth information (Figure 3). To contextualize the visualized shore, a scale bar and a directional arrow were added to the visualized section of the Fraser shore. The 2D content elements (drawings, text, legend) are placed on 3D slates, which are a thin 3D cube. Once the user launches the application, 3D content appears at a distance of about 1.25 m in front of the user, with the text panel and conceptual drawings panel appearing at user's eye level. This was a compromise between a desire to enable near interaction and reducing vergence-accommodation conflict, caused by proximity of virtual content to user's eyes. The 3D visualization of the Fraser shore flood risks is slightly below the eye-level of the user. The default location of content is informed by ergonomics of head-mounted displays, where putting content more than 15 degrees below the eye level introduces neck strain (Microsoft, 2019c). Furthermore, to reduce unnecessary motion, all of the content fits into the field of view of HoloLens 2.

Interaction

Hand tracking is used across the application for manipulation of 3D content (movement, rotation, scaling), as well as changing the state of content through a virtual menu. The capabilities of MR systems to track the hands and recognize gestures can be used to integrate interaction metaphors for virtual content (e.g., grabbing an object) that leverage the user's knowledge of interacting with real objects. Articulated hand tracking allows the user to manipulate virtual objects at a close distance using their hand (pinch to grab) and at a distance with a virtual ray coming out of the user's index finger. This allows a user to interact with a single hand to move content, and two hands for scaling and rotation. These interactive capabilities were added to all virtual objects in the scene. Given the nature of the content (text, drawings, geographic landscape), rotation was restricted for all information objects to keep them aligned vertically to the orientation of the user and environment.

For the 3D visualization, I added a wireframe bounding box, which provides information on total extents of visualization, and provides a metaphor for interaction with the visualization (virtual box). For the 3D slates holding the 2D content, a capability to align rotation of the slates to the physical walls was added, leveraging the spatial mapping and solvers (surface magnetism) capabilities of the MRTK (Microsoft, 2019f). This capability is enabled once a user grabs the object (slate), with ray cast from the user's index finger detecting a wall and aligning the slate to it. The slate's rotation is updated every 0.6 seconds during the interaction, with the spatial map of the environment being updated every second. By default, this value is set to 0.1 seconds, but the interaction was jittery at this update rate. The spatial mapping capabilities and solvers allow a flexible integration of virtual content across real world environments in which the MR tools can be used. To further the ability of application to quickly adapt to new environments, the hierarchy of objects was designed with 2D slates being children of the main 3D visualization of the shore. This allows a user to just move the model of the shore, and the rest of the user interface follows. However, this can introduce problems from the usability standpoint too, for instance, if the slates are already aligned to the wall, and the user rotates the 3D model, slates will rotate as well, requiring re-alignment.

The hand tracking also allows users to press virtual menu buttons using their index finger, which has a virtual collider. Control of the state of the displayed scenarios is realized through a virtual menu, where users can interact with buttons using their index finger at a close distance, and through a “pinch” gesture at a distance. While it did not seem detrimental to usability to enable user to scale, rotate, and move content freely, for the 3D model of the landscape, rotation is locked to a single axis (i.e. visualization orientation is always aligned to the floor) Figure 3. Audio feedback is provided throughout the application every time the user clicks a button or interacts with visualization contents.

We did not explore interactive capabilities of eye-tracking, apart from a subtle use of gaze detection to show appropriate interaction hints when a user looks on an interactable object. Another use of eye-tracking, which is integrated by default in MRTK, is a highlighting pointer added to a surface that is hit by the articulated eye-gaze (i.e. not just a ray pointing out of the center of the user’s head) highlights content. For instance, when a user looks at a button it becomes highlighted with a slight glow; when a user looks at either of the clipping planes (described in the next paragraph) a text hint appears prompting the user to move it.

Querying data

To investigate the possibilities of querying the topology with mixed reality tools, I utilized MRTK capabilities to clip through 3D content using a 2D plane. A transparent 2D cut plane with outline (handles) was used and a simple grid with 50 m cells was applied to the surface to provide scale reference when looking at the cross-section of 3D geometry. By default, the 2D clipping plane is orthogonal to the displayed direction of 3D content, allowing users to define east and west boundaries of the 3D visualization.

Guidance

Within the single user application, I also integrated some guidance in case the application is used by a novice user. By default, once the application is launched, the text panel describes the visualized section of the Fraser shore, as well as describing the 2D panels, and basics of interaction. Virtual animations (part of MRTK) that show an outline of hand were integrated with text prompts to explain how to move the clipping planes, open the menu, and disable guidance. The 3 animations are shown sequentially, delayed by 5, 10, 15 seconds since the last detection of the user's hand. If user's hand is not present, animations are shown by default.

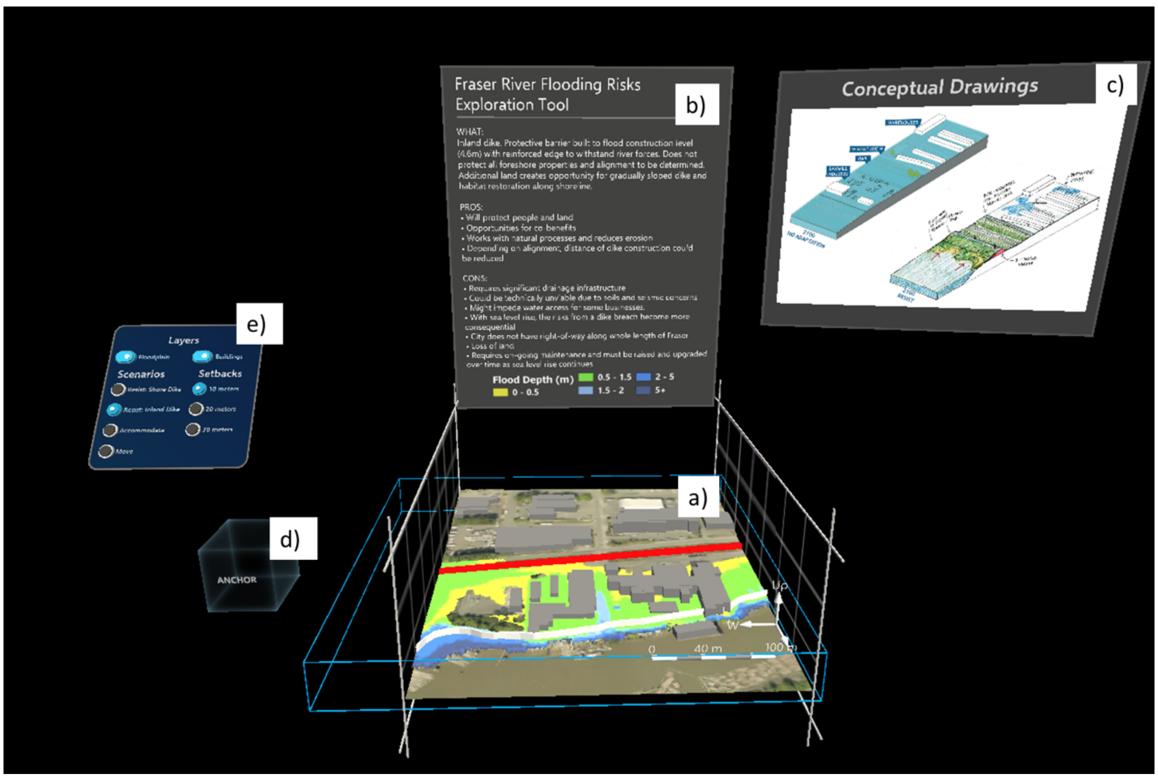

Figure 3-3 – User Interface of shared MR flood visualization prototype

This screenshot captures the developed UI of the visualization in a shared application, with an inland dike adaptation scenario selected: a) 3D content, with 2 clipping planes, scale bar and directional arrows; b) text panel providing vis. and scenario description; c) conceptual drawings related to a scenario; d) Anchor object used to synchronize position; e) content menu.

3.3.5. **Development of collaborative visualization**

To develop the collaborative tools for mixed reality applications it is required resolve three aspects: synchronization of content, position of content in the local coordinate system, and positioning of the coordinate systems across devices. To synchronize the local position of content in the scene I used basic Photon Unity

Networking setup (described in MRTK documentation) (Microsoft, 2019b). To enable synchronization of content state/interaction I used remote procedure calls, which enabled us to synchronize the state of scripts/objects across two users. To co-locate virtual objects in a shared environment I used the Azure Anchor infrastructure (Microsoft, 2019a). All of the content of the visualization is attached to a virtual cube, which is used as an anchor. When a user moves the cube and creates an anchor using a button, and then shares it to the network, another user can retrieve this anchor and co-locate it in space based on the similarities of spatial maps of the environment scanned by two HoloLens devices. This infrastructure is visualized in Figure 4 below. Both systems rely on local wi-fi network to update state of the content across two devices.

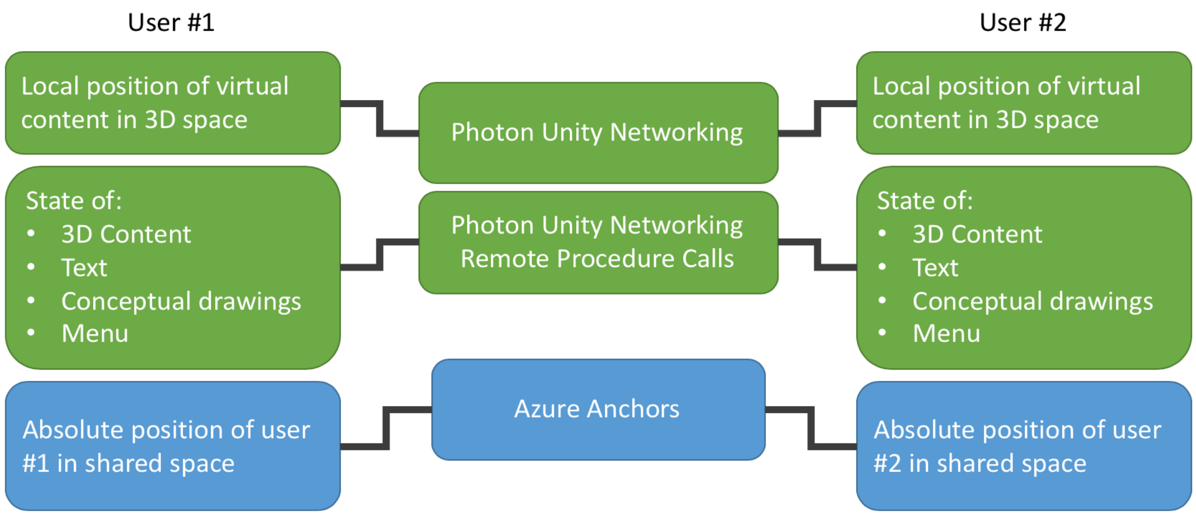

Figure 3-4 – Shared MR prototype networking

This chart illustrates how the various components of the shared experience are synchronized across two users, with Photon Unity Networking and Remote Procedural calls connecting the content state across two users, and Azure anchors providing the common coordinate system for to users.

3.4. Results

Based on the workflow presented above, I developed two visualization prototypes for single user and collaborative MR visualization of flooding and associated adaptation scenarios. In the sections that follow, the user experience, reflections on hardware performance and usability are presented. Through unpacking the developed prototypes through multiple lenses, this work highlights the state-of-the art capabilities of MR as realized within our prototypes.

3.4.1. **Developed applications**

As mentioned above, a single user version was developed to demonstrate the capabilities of current MR devices, while also developing a collaborative prototype, with minor changes. Two versions were created as some functionality of the single user application could not be realized (given our development resources) in a shared version. Specifically, content scaling was disabled, as well as the hand-bound content menu, which was moved into the environment. This can also be considered advantageous to the user experience, as the state of menu is displayed next to the 3D model for both users. Below, a discussion of the user experience and capabilities of developed visualizations is presented.

When a user launches the application, the digital content (3D visualization, text panel, conceptual drawings) is presented in front of the user. The text panel describing the visualization presents a brief description of the visualization, interaction and the legend for the floodplain depth layer. Within the single user application, gesture guidance is provided to the user upon the start of the application, describing how to move content (pinch and hold), bring up the menu (bring palm up) and toggle the guidance off with a switch on the text panel (pinch/air tap). The 3D visualization itself can be moved and scaled freely in space and persist in a specific real-world location. The text and conceptual drawing panels provide contextual information related to the presented flood visualization, as well as serve relevant information when a user chooses a specific adaptation scenario. By selecting one of the four adaptation scenarios, relevant changes to 3D content appear (e.g. display a shore dike), the textual information is switched to describe pros and cons of a specific adaptation approach, and the conceptual drawings illustrate artistic sketches of the future shore layout. This ability to dynamically explore the spatial and policy implications of a particular adaptation approach mirror the role of maps and other 3D visualization tools designed to understand and communicate risks and relevant mitigation policies (Henstra, Minano, et al., 2019; Jacquinod & Bonaccorsi, 2019; Lieske et al., 2014). Another aspect of FRM in City of Vancouver is the development of setback policies to preserve shore areas for potential adaptation infrastructure. The 3D splines representing setbacks from the shore are available to a user in the menu, and the conflicts between the proposed policy and existing buildings can be seen.

Since the environment is mapped by the devices using the array of sensors, occlusion management is done on the fly in a given environment. This map of the environment is also used to align the virtual slates with text and drawings to the real-world walls. In case the alignment to walls does not make sense in a given environment (or the space is poorly mapped), two-handed manipulation rotating the slate can override it. This flexibility of content scaling, movement and alignment enables integration of visualization across a range of environments, from a single user desk to a room-scale visualization.

Two movable clipping planes placed orthogonally to the content present the user with a simple tool to define extents and query 3D geometry of visualization along the clipping plane axis (i.e. transect). The resulting “slice” of the landscape is similar to the cross-section of shore displayed in the conceptual drawings panel. This capability was designed to provide a simple solution to query the 3D geometry of shore, while also providing visual correspondence to “slices” of the shore in conceptual drawings.

The shared application provides the capabilities of mixed reality visualization in a co-located, synchronous, interactive collaborative setting. In terms of actual user experience, the only difference from a single user application is the need to move the anchor (virtual cube to which the content is attached) to a position with sufficiently complex real-world geometry (i.e. not just mid-air, e.g. on a table corner). By moving the cube, the user can use virtual buttons to start azure session, create anchor, and share it to the network. At this point, the anchor cube is locked in space and cannot be moved. The second user then starts an azure session on their device and gets the shared network anchor. At this point the position of the anchor cube is identical for both users and the virtual coordinate systems of co-located users are synchronized, meaning the virtual content appears at the same real-world location. Once both users establish a common coordinate system, the 3D content position, rotation, scale (fixed), and scenario state are all synchronized in real time across users, allowing users to see and share visual information from their own perspective and position. This MR application setup preserves most of the rich context available to co-located collaborators: an ability to see and interact with the surrounding workspace, to talk and to see a peer’s body language and gestures (Ens et al., 2019). This setup was tested with two users, but it is scalable for more users.

3.4.2. **Hardware performance**

In this section, I reflect on the device performance in processing, robustness of spatial mapping, and hand and eye-tracking.

Processing across single and shared user versions were practically identical, given much of processing power is spent on loading 3D visualization. Notably, Figure 5 illustrates that the application utilizes almost 100% of single core GPU capacity of the device, with frame rates beingly fairly stable in the range of 50-60 frames per second. Since I attempted to optimize content to utilize as much of local processing as possible, this demonstrates the limits of current state-of-the art devices. Created 3D visualizations are slightly above the recommended limit of 100 thousand polygons for the device, with the final model being at ~106k polygons. It is important to note that local device limitations should not restrict applications to simple 3D content, low resolution or small aerial footprint. With remote rendering on a machine within a local network (Remote Rendering) or with cloud rendering (Azure Remote Rendering), HoloLens-based tools can fit tens of millions of polygons, which is especially relevant for large/complex spatial datasets.

Mixed reality displays on HoloLens 2 have a fairly limited field of view, which is a limitation inherent to all current head-mounted mixed/augmented reality devices, meaning that much of the peripheral view is not augmented, which does affect immersion and limits the “virtual real estate” that can be used without a need for user to move their head. Another notable limitation of this device is brightness of current displays: the device becomes practically unusable in bright (e.g. lit by direct sunlight) environments.

Spatial mapping was satisfactory for our goals of occlusion management, digital content persistence and alignment of virtual slates to walls. The default update rate of spatial mesh of the environment is 3.5 seconds in MRTK. Update rate was increased to once per second, which resulted in better performance of the above-mentioned features, without apparent performance penalty. There is still room for improvement, especially in environments with complex geometry/shadows. Nevertheless, the spatial mapping of environment and stability of digital content in real space is robust in a well-lit environment and is especially impressive given the lack of any external sensors/fiducial markers.

Hand tracking performance on HoloLens 2 is difficult to capture without a reference to other tracking setups. In our experience, the tracking is not on an "appliance level" of usability. After initial adaptation to the idiosyncrasies of hand tracking (e.g. hand needs to be a certain distance away) and interaction (i.e., gestures and buttons need to be pressed much further than you would expect based on visual feedback), the accuracy of tracking is satisfactory/usable, but still has substantial room for improvement.

Despite the limited use of eye-tracking, it is important to acknowledge almost uncanny accuracy of this capability of HoloLens. The tracking is practically flawless, and this is especially exciting for potential approaches to evaluate user interfaces in mixed reality based on rich articulated eye-tracking data, beyond a simple gaze from a center of the camera/head of the user.

The performance of shared application in synchronizing coordinate systems and content state across two devices was satisfactory, with little (<100 ms) lag. The establishment of the anchor to share the coordinate system requires a sufficiently

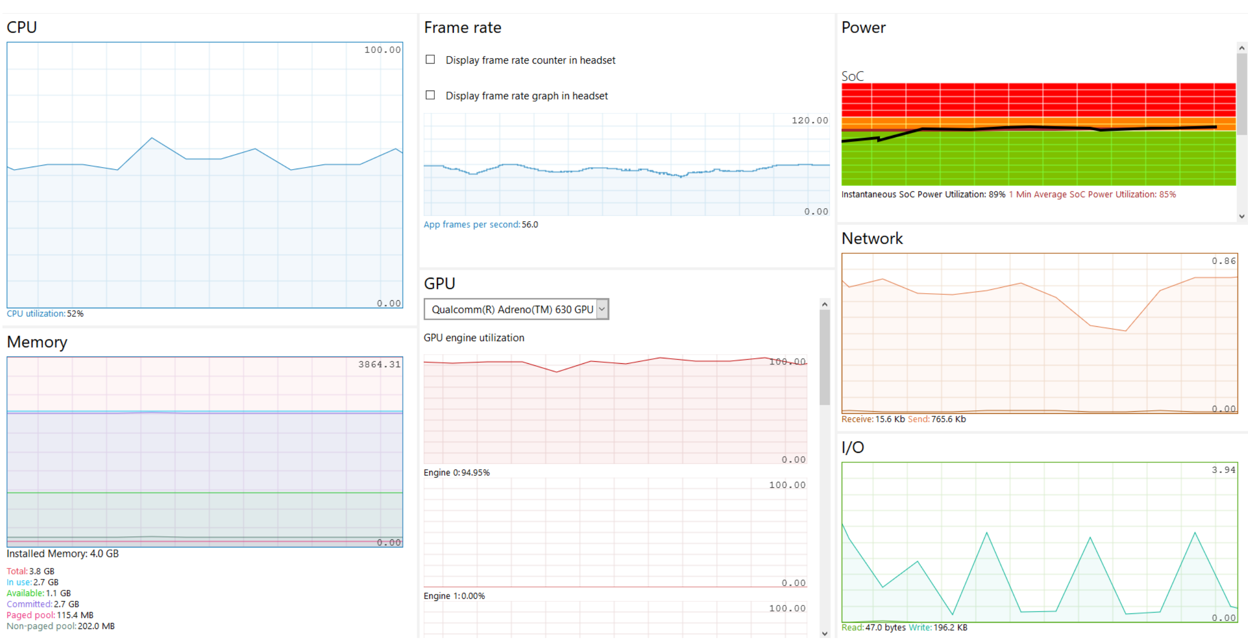

Figure 3-5 – Hardware utilization of MR visualization prototypes on HoloLens 2

Screenshot of a live hardware usage of shared MR visualization. As you can see, the usage of CPU is at 50-60%, and GPU load fluctuates at almost 100%, with framerates fluctuating between 50-60 fps, which is sufficient for smooth application performance.

complex scanned environment. If the anchor is placed on a fairly uniform surface (empty table) or in mid-air, the resulting coordinate synchronization is inaccurate and can be off by 50+ cm. Since both content and coordinate synchronization rely on networked services, local wi-fi overload, poor signal and low speed might impact the delay across two users.

3.4.3. **Usability**

To understand and unpack the usability of developed MR visualization tools, I used Vi et al.'s (2019) framework of 11 MR user interface heuristics. This set of design guidelines has been developed with capabilities of head-mounted systems in mind and provides a useful framework to discuss the user interface design decisions made.

1. Organize the spatial environment to maximize efficiency

The ability of MR interfaces to map the physical environment of a user enables integration of virtual content and physical space. By placing virtual objects on real surfaces (the truest form of AR, according to Azuma (1997)), we leverage human capacity for spatial reasoning and a sense of their own body in space, through strong proprioceptive cues, to interpret virtual content. This is accomplished by occluding virtual content by real surfaces, as well as aligning information panels to physical walls. This set of capabilities makes the application adaptable to complex office environments. I actively tried the MR applications in several spaces to see how they performed visually, spatially and cogently in (and with) different spaces. We tested both shared and single user versions in office, formal conference, and informal co-working spaces (Fig. 5). The on-the-fly spatial sensing/mapping of the device supported impressive agility and flexibility in adapting to different environments. Furthermore, the robustness of spatial awareness capabilities allowed movement of content from one space (meeting room) to another (open office area) without a loss of tracking or synchronicity of content placement in a shared version.

For instance, a user can place a Fraser shore visualization on a table, and information panels on a wall (e.g. Fig. 5, bottom-left). By leveraging the real environment of the user the visualization leverages a set of visual and proprioceptive cues that help understand the scale of virtual object and their relative positions (Shelton & Hedley, 2004). From the user experience perspective, it might be easier to automatically “snap” content to detected surfaces, which is possible through the use of semantic understanding of environment by device (“scene understanding”) but was not realized here due to technical complexity.

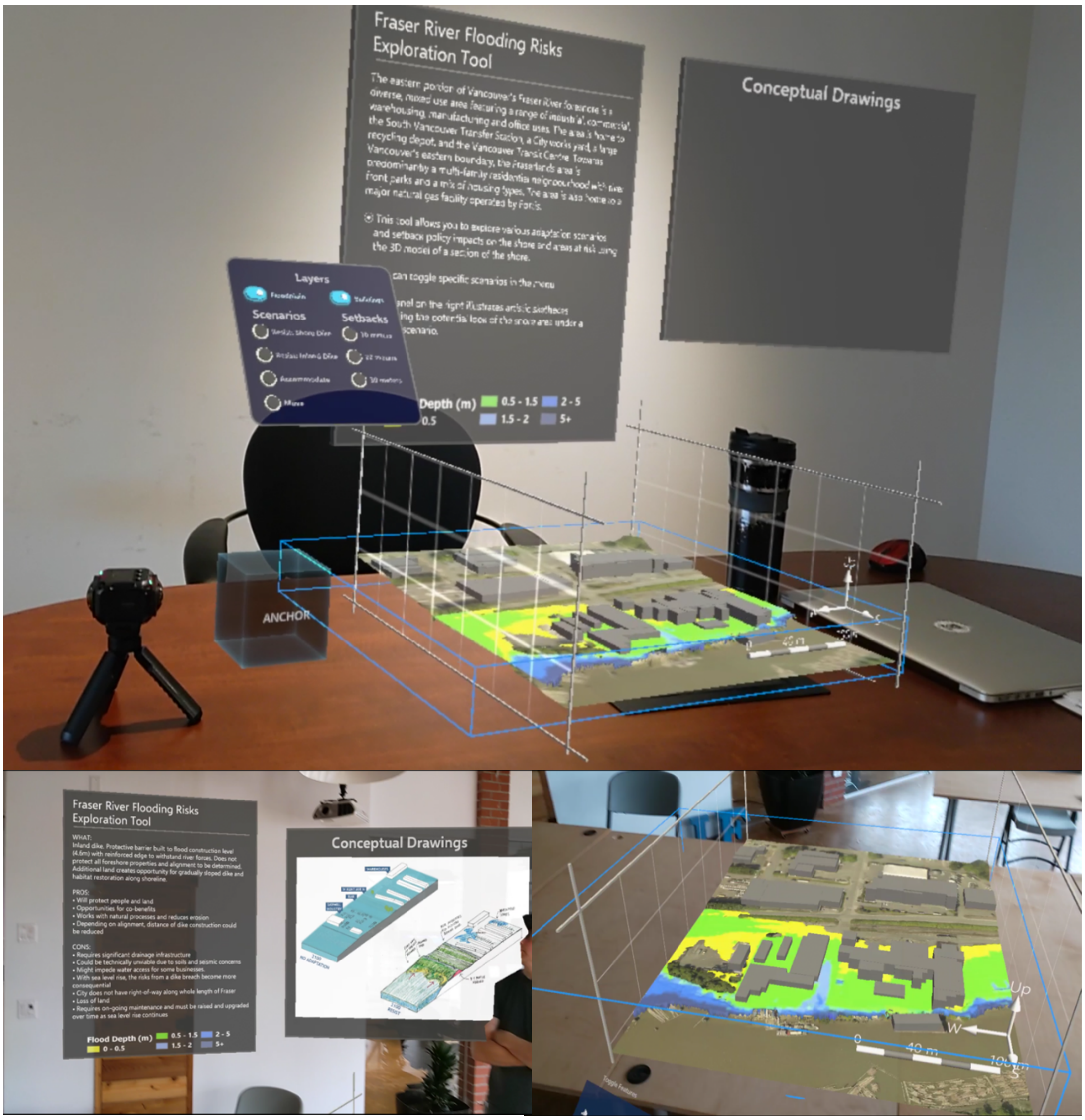

Figure 3-6 – Layout of User Interface in use

(Top) Shared version of MR prototype in a conference room environment. Displayed is a default layout of content on launch, that can be further adapted to the environment. (Bottom) Single user MR visualization adapted to the shared workspace environment. The 3D visualization (Right) is placed on a table and information panels (left) are aligned to a nearby wall. You can also notice dynamic occlusion of a person standing in front of the conceptual drawings panel.

2. **Create flexible interactions and environments**

We sought to leverage hand tracking capabilities of HoloLens to provide intuitive/natural interaction with virtual objects, mimicking real objects. Beyond the ability to manipulate content directly with hands, users can use a virtual ray to grab distant objects. The ability to move, scale and rotate content as desired by a user makes the visualization adaptable to a given environment.

3. **Prioritize user's comfort & 5. Design around hardware capabilities and limitations**

Content placement was guided by the desire to make interaction and viewing comfortable for the user, without intruding into personal space or requiring excess movements, which is realized through the ability to interact with content at a distance. Furthermore, content placement at approximately 1.25m in front of the user by default requires the user to move their hands within the view of device cameras for hand tracking. To accommodate the limited field of view of MR displays on HoloLens, content was placed compactly so as to minimize user's need for neck movement during the use. Processing limitations of the device were addressed by optimizing spatial extents of Fraser shore visualization.

4. **Keep it simple: do not overwhelm the user**

To keep the user focused on the flood impacts, adaptation and associated policy implications, the UI design is minimal and includes only features directly relevant to the displayed content. There is also a clear correspondence in the results of interaction, where a user's choice of scenario reflects a simultaneous change in relevant conceptual drawing, text and 3D content.

5. **Use cues to help users throughout their experience & 8. Build upon real world knowledge**

Once the user launches the application, the first thing appearing in the field of view is the text panel describing visualization contents and interaction. Within the single user version, users are also presented with gesture guide animations for opening the content menu, moving content and distant clicking (air tap) to disable guidance. The subtle use of eye-tracking to show text prompts and highlights at user's gaze position also seek to guide the user through interaction.

7. Create a compelling XR experience

This set of MR visualization prototypes seeks to leverage the existing information related to flood visualization to provide a complete understanding of flooding phenomena. I used most of the information related to shore adaptation of the area available within the visualization, and leveraged the capacities of MR interface (as discussed throughout) to provide an engaging, simple to use tool to interact with spatial data. While prototypes developed are certainly compelling to experience and use, I anticipate that spatial data users will expect to be able to use much larger geographic datasets, based on their GIS experience. This can be accomplished with off-device rendering. There are other aspects of MR interface that can especially highlight the potential of interactive MR environments for data exploration, particularly data with more complex characterization of 3D space and dynamic content (e.g. animated output of a flood simulation).

9. Provide feedback and consistency

When users interact with content, they get the visual, audio and proprioceptive feedback based on their interactions. For instance, when a user chooses a particular scenario in the menu, the associated radial button changes color, a clicking sound is played and the content is changed. We sought to provide users with a feedback on how the device sees their hand/hand gestures, thus we kept the visualization of hand mesh observed by device on, so that a user sees what the device sees (Figure 6). The interaction across different content is consistent, with single handed interaction moving the content, and two-handed manipulation used for scaling and rotating (and moving) virtual objects.

10. Allow users to feel in control of the experience

The displayed content is inert when a user launches the app (apart from hand guidance, which is animated, but fixed in space). This means that content changes state or moves only due to explicit interaction by the user. While good in theory, in practice, some general hand movements were recognized as gestures by the device, leading to unexpected movement of content. This is not a persistent feature of hand tracking, but rather a noticeable “accidental” limitation when using application for prolonged time.

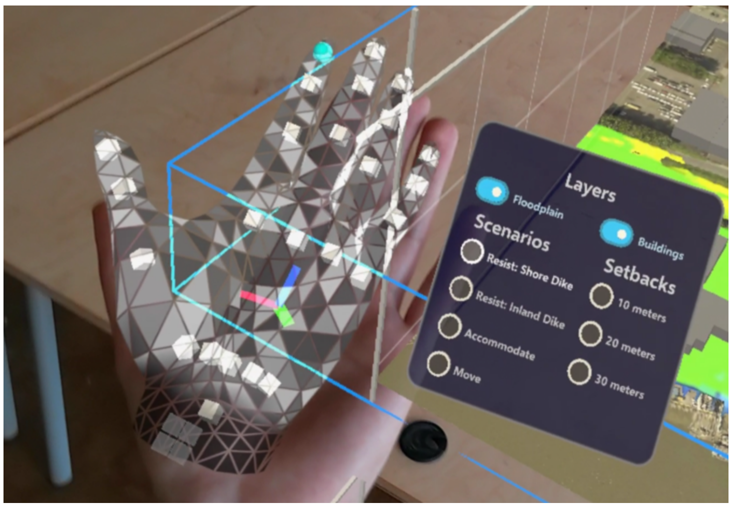

Figure 3-7 – Hand mesh and menu of single user MR visualizations in use

Screenshot of a single user application in use, with the content menu activated by bringing up the palm. You can see the hand mesh visualization, providing visual feedback to the user. Note: the significant displacement /difference between virtual and real hand only appears on captured videos/screenshots.

11. Allow for trial and error

The only error that critically affected the experience and required a restart of the application was accidental movement of content behind a physical object/surface/wall. Due to the nature of MR interfaces and management of occlusion, content can sometimes be practically “lost” behind a wall (i.e. user cannot see or interact with it). This movement of content behind walls is likely fixable through the addition of colliders to walls and virtual objects, but resulted in unexpected behavior (virtual content bouncing off and flying around the room). I wanted to implement the ability to restart the visualization to default position, but restarting a scene with MRTK components in Unity is not straight-forward (see Provencher, 2019) and was not implemented due to practical time constraints.

3.5. Discussion

This section offers critical reflection and review of these systems from the perspectives of their performance and potential as operational tools, and their potential to integrate with current and future FRM and planning practice; and finally, theorization of their significance as data interfaces.

Devices that can deliver usable 3D visualizations with natural user interfaces have appeared only recently and, while there is much room for improvement, they provide distinct and compelling experiences of interacting with 3D data (Billinghurst et al., 2015). Growth of dedicated development frameworks and communities significantly reduces the complexity of development of MR experiences. While contemporary systems have limitations, we are at a critical juncture where the MR systems are becoming usable enough to focus on the applied problems. With decreasing barriers and streamlined integration of geospatial data into MR interfaces, these tools can become a meaningful addition to the planner's toolkit to investigate topologies of impacts, explore datasets across scales and understand the interplay between inundation scenario and proposed adaptation policies.

With the capabilities of HoloLens 2, we can develop flexible collaborative flood visualizations that can be used within real offices without a need for dedicated spaces (as needed for VR), or specialized knowledge for interaction. This work demonstrates the practical workflow and seeks to highlight the significant infrastructure available to build powerful MR tools without significant development experience. The developed prototypes only demonstrate a particular case of ex-situ, and in case of the shared version, co-located synchronous MR. Many researchers are also investigating in-situ visualizations of flood impacts using MR/AR (Haynes et al., 2018; Lonergan & Hedley, 2015). This range of applications highlights the significant potential these tools can have for analyzing and responding to flooding risks, as well as provide compelling environments to provide on-site information to broader set of stakeholders (e.g. decision-makers, businesses, residents, etc.). At the same time, there is massive potential in how MR visualization can transform the flood scenario visualizations done ex-situ to understand the impacts and adaptation based on the available data.

The visualization development process outlined here was guided by datasets available for flood risk management in the local context. Within developed tools (and underlying datasets), the third dimension is only used to display elevation information at a location (ground elevation, flood depth, building height), without much vertical complexity in data. However, to realize the potential of 3D displays and natural user interfaces, we need an integration of data with more complex 3D characterizations of space. With increasing use of truly 3D data, such as LiDAR, 3D models derived from structure-from-motion, and BIM (Building Information Management) to characterize urban landscape and structures, the added value of MR visualizations and interaction over a WIMP interface will likely be more significant. This can result in a more rich analytical experience, as well as improve practical accuracy of understanding of potential impacts of flooding (e.g. Amirebrahimi et al., 2016; De Santis et al., 2019).

To integrate the tools meaningfully into planning generally, and flood risk management in particular, we need much more empirical work to understand what aspects of mixed reality interfaces provide value for the user. The current moment presents numerous research opportunities to investigate these tools for spatial data practice as they become widely available and used across numerous industries. However, it is not clear how to investigate tools developed for complex tasks and goals, such as exploring and supporting policy discussion. Simple usability metrics and task completion times typically used to compare interfaces do not capture the perceptual outcomes, and the potential of MR tools to engage broader set of users in exploring geospatial data (i.e. without the complexities of a desktop GIS).

3.6. Conclusion

This research aimed to integrate existing datasets related to shore adaptation to flooding risks in the state-of-the-art mixed reality interface system. I presented the workflow used to integrate rigorous geospatial data into single user and collaborative MR interfaces. The developed prototypes demonstrate the capabilities of the contemporary MR interfaces to deliver 3D visualization, hand-based interaction, and integration with surrounding environment while being stable and usable in real-world settings. These platforms provide compelling tools to explore spatial data and have a distinct potential to be integrated into actual practice due to their flexibility and potential benefits arising from the distinct perceptual experiences of data in MR. Our work was guided by a desire to develop visualizations that reflect actual flood risk management practice, while focusing on designing a simple and effective user interface, while being mindful of device limitations. Recent developments in enabling interface technologies present exciting critical opportunities for researchers and practitioners to experiment and explore their data in MR environments. Through this work I sought to demonstrate the potential of the state-of-the-art interfaces to mediate interaction with spatial data in an applied context of flood risk management. It is our hope that the technical workflows reported, and conceptual perspectives offered will be useful to support the work of other colleagues in this emerging field. Ultimately, emerging interfaces need to be evaluated for their utility and relevance by practitioners on the ground, and this will help to understand the perceptual and cognitive implications of working interactively with data in 3D MR environments.

3.7. References:

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2016). A BIM-GIS integration method in support of the assessment and 3D visualisation of flood damage to a building. *Journal of Spatial Science*, *61*(2), 317–350.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators & Virtual Environments*, *6*(4), 355–385.

Billinghurst, M., Clark, A., & Lee, G. (2015). A survey of augmented reality. *Foundations and Trends® in Human–Computer Interaction*, *8*(2–3), 73–272.

Billinghurst, M., Weghorst, S., & Furness, T. (1997). Wearable computers for three dimensional CSCW. In *Digest of Papers. First International Symposium on Wearable Computers* (pp. 39–46). IEEE.

City of Vancouver. (2014). *Fraser River maps*. Retrieved from https://vancouver.ca/files/cov/coastal-flood-risk-assessment-scenario-3-maps-fraser-river.pdf

City of Vancouver. (2018). *Coastal Adaptation Plan - Fraser River East current conditions*. Retrieved from https://vancouver.ca/green-vancouver/fraser-river.aspx

De Santis, R., Macchione, F., Costabile, P., & Costanzo, C. (2019). Visual Risk Communication of Urban Flooding in 3D Environments Based on Terrestrial Laser Scanning. In G. Mannina (Ed.), *New Trends in Urban Drainage Modelling. UDM 2018. Green Energy and Technology* (pp. 783–787). Cham: Springer International Publishing.

Dey, A., Billinghurst, M., Lindeman, R. W., & Swan, J. (2018). A systematic review of 10 Years of Augmented Reality usability studies: 2005 to 2014. *Frontiers in Robotics and AI*, *5*, 37.

Dünser, A., & Billinghurst, M. (2011). Evaluating augmented reality systems. In *Handbook of augmented reality* (pp. 289–307). Springer.

Ens, B., Lanir, J., Tang, A., Bateman, S., Lee, G., Piumsomboon, T., & Billinghurst, M. (2019). Revisiting collaboration through mixed reality: The evolution of groupware. *International Journal of Human-Computer Studies*.

Esri. (2016). How To: Export textured models from CityEngine into Unity. Retrieved from https://support.esri.com/en/technical-article/000012449

Fenech, A., Chen, A., Clark, A., & Hedley, N. (2017). Building an adaptation tool for visualizing the coastal impacts of climate change on Prince Edward Island, Canada. In *Climate change adaptation in North America* (pp. 225–238). Springer.

Grasset, R., Lamb, P., & Billinghurst, M. (2005). Evaluation of mixed-space collaboration. In *Fourth IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR'05)* (pp. 90–99). IEEE.

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile Augmented Reality for Flood Visualisation. *Environmental Modelling & Software*, *109*, 380–389.

Hedley, N. (2001). Collaborative AR for geographic visualization. In *Proceedings of the Second International Symposium on Mixed Reality* (pp. 11–18). Yokohama, Japan.

Hedley, N., Billinghurst, M., Postner, L., May, R., & Kato, H. (2002). Explorations in the use of augmented reality for geographic visualization. *Presence: Teleoperators & Virtual Environments*, *11*(2), 119–133.

Henstra, D., Minano, A., & Thistlethwaite, J. (2019). Communicating disaster risk? An evaluation of the availability and quality of flood maps. *Natural Hazards and Earth System Sciences*, *19*(1), 313–323.

Jacquinod, F., & Bonaccorsi, J. (2019). Studying Social Uses of 3D Geovisualizations: Lessons Learned from Action-Research Projects in the Field of Flood Mitigation Planning. *ISPRS International Journal of Geo-Information*, *8*(2), 84.

Kim, S., Lee, G., Huang, W., Kim, H., Woo, W., & Billinghurst, M. (2019). Evaluating the Combination of Visual Communication Cues for HMD-based Mixed Reality

Remote Collaboration. *Conference on Human Factors in Computing Systems - Proceedings*, 1–13. https://doi.org/10.1145/3290605.3300403

Lai, J.-S., Chang, W.-Y., Chan, Y.-C., Kang, S.-C., & Tan, Y.-C. (2011). Development of a 3D virtual environment for improving public participation: Case study–The Yuansantze Flood Diversion Works Project. *Advanced Engineering Informatics*, *25*(2), 208–223.

Lieske, D. J., Wade, T., & Roness, L. A. (2014). Climate change awareness and strategies for communicating the risk of coastal flooding: a Canadian Maritime case example. *Estuarine, Coastal and Shelf Science*, *140*, 83–94.

Lonergan, C., & Hedley, N. (2015). Navigating the future of tsunami risk communication: using dimensionality, interactivity and situatedness to interface with society. *Natural Hazards*, *78*(1), 179–201. https://doi.org/10.1007/s11069-015-1709-7

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.

Microsoft. (2019a). 1. Getting started with Azure Spatial Anchors. Retrieved from https://docs.microsoft.com/en-us/windows/mixed-reality/mrlearning-asa-ch1

Microsoft. (2019b). 1. Setting up Photon Unity Networking. Retrieved from https://docs.microsoft.com/en-us/windows/mixed-reality/mrlearning-sharing(photon)-ch1

Microsoft. (2019c). Comfort. Retrieved June 10, 2020, from https://docs.microsoft.com/en-us/windows/mixed-reality/comfort

Microsoft. (2019d). Getting started with MRTK v2. Retrieved October 2, 2020, from https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-getting-started

Microsoft. (2019e). HoloLens 2. Retrieved June 10, 2020, from https://www.microsoft.com/en-us/hololens/hardware

Microsoft. (2019f). Surface Magnetism. Retrieved June 10, 2020, from https://docs.microsoft.com/en-us/windows/mixed-reality/surface-magnetism

Microsoft. (2020). What is the Mixed Reality Toolkit. Retrieved June 10, 2020, from https://microsoft.github.io/MixedRealityToolkit-Unity/version/releases/2.3.0/README.html

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321–1329.

Newell, R., Canessa, R., & Sharma, T. (2017). Visualizing our options for coastal places: exploring realistic immersive geovisualizations as tools for inclusive approaches to coastal planning and management. *Frontiers in Marine Science*, *4*, 290.

Nilsson, S., Johansson, B. J. E., & Jönsson, A. (2009). A co-located collaborative augmented reality application. In *Proceedings of the 8th International Conference on Virtual Reality Continuum and its Applications in Industry* (pp. 179–184). ACM.

Provencher, E. (2019). The MRTK does not support being unloaded and destroyed #4530. Retrieved June 10, 2020, from https://github.com/microsoft/MixedRealityToolkit-Unity/issues/4530

Santos, M. E. C., Polvi, J., Taketomi, T., Yamamoto, G., Sandor, C., & Kato, H. (2015). Toward standard usability questionnaires for handheld augmented reality. *IEEE Computer Graphics and Applications*, *35*(5), 66–75.

Shelton, B. E., & Hedley, N. (2002). Using augmented reality for teaching earth-sun relationships to undergraduate geography students. In *The First IEEE International Workshop Agumented Reality Toolkit,* (pp. 8-pp). IEEE.

Shelton, B. E., & Hedley, N. (2004). Exploring a cognitive basis for learning spatial relationships with augmented reality. *Technology, Instruction, Cognition and Learning*, *1*(4), 323.

Stevens, M. R., & Hanschka, S. (2014). Municipal flood hazard mapping: the case of British Columbia, Canada. *Natural Hazards*, *73*(2), 907–932.

Vi, S., da Silva, T. S., & Maurer, F. (2019). User Experience Guidelines for Designing HMD Extended Reality Applications. In *IFIP Conference on Human-Computer Interaction* (pp. 319–341). Springer.

Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., … Ramu, P. (2016). Modelling with stakeholders–next generation. *Environmental Modelling & Software*, *77*, 196–220.

Wang, W., Wu, X., Chen, G., & Chen, Z. (2018). Holo3DGIS: leveraging Microsoft HoloLens in 3D geographic information. *ISPRS International Journal of Geo-Information*, *7*(2), 60.

Wang, W., Wu, X., He, A., & Chen, Z. (2019). Modelling and Visualizing Holographic 3D Geographical Scenes with Timely Data Based on the HoloLens. *ISPRS International Journal of Geo-Information*, *8*(12), 539.

Chapter 4. Conclusions

4.1. Summary

My objective with this research was to investigate the intersection of emerging interfaces and contemporary flood risk management practice. Developed visualization prototypes demonstrated the capabilities of the state-of-the-art mixed reality systems to deliver data-driven visualizations of flood risks. Starting with a conventional GIS and data, this work demonstrated how to build 3D geovisualizations, integrate them with 3D game engines, and develop mixed reality user interfaces that can flexibly integrate with real workspaces.

This thesis contains two papers that sought to interrogate the potential of emerging interfaces and deliver relevant, usable mixed reality flood visualization tools. By analyzing the work of colleagues in this domain and guided by my experience of interaction with local planners, this development employed the cutting-edge tools to demonstrate the possibilities, limitations and potential applications of MR tools to change geospatial data practice. This thesis presented a significant development effort that moves beyond a simple integration of data into a novel interface. By studying the capabilities of MR devices and their limitations, I developed prototypes that provide a complete user interface that allowed the user to interact, query spatial data, and collaborate with colleagues in shared mixed reality spaces. By evaluating developed prototypes through multiple lenses, this work sought to further development of MR visualizations for applied practice.

Chapter 2 provided an overview of a range of mixed reality environments that can be used in flood analysis and communication based on 3D visualizations. This review aimed to provide readers with an overview of an evolving landscape of 3D visualization work, the visualization methods being used, and the emergence of 3D interfaces as mediums through which they may be experienced. A workflow was presented to integrate geospatial data formats into a 3D game engine, where virtual, augmented and mixed reality interfaces can be developed, was reported, with the aim of inclusively supporting the FRM visualization community and illuminating emerging AR/MR workflows. This work provided a useful lens on the broader set of emerging interfaces available for planners. Most researchers in the FRM domain using emerging interfaces have focused on the use of augmented reality tools to visualize the impacts of urban flooding in-situ. While these tools can be compelling for communication of changes to the in-situ landscape, the potential of ex-situ exploration of data through 3D user interfaces needs to be explored further as well. Given the abilities of mixed reality tools to visualize potential future landscapes (e.g. altered by climate change) at a high level of detail while leveraging rigorous spatial data, we can develop information interfaces that can help planners, decision-makers, and other stakeholders to understand the morphology of landscape and implications of spatial policy without visiting the site (e.g. mitigating flooding through a construction of inland dike).

Whereas Chapter 2 illuminated the use of 3D visualizations and potential of emerging interfaces, Chapter 3 presented a deeper analysis of the development of mixed reality visualizations, unpacked their capabilities and evaluated their significance for practice. This paper provided a practical workflow to build single user and collaborative mixed reality flood visualizations, that use current FRM data from a municipal partner. By leveraging the extensive mixed reality infrastructure available, I showed that compelling and usable tools can be developed without a specialized computer science, human-computer interaction, or game development background. The paper was considerably more than a detailed description of technology and workflow. It certainly aimed to report an end-to-end design, rationale, workflow, capabilities and performance of the system, but also unpacked the conceptual, theoretical basis for these choices, and theorization of the anticipated outcomes of the tool in use. This second half of the thesis had originally been designed to include an empirical study of these devices physically in use in the everyday working environment of our partners at the City of Vancouver. The COVID-19 pandemic forced all in-person empirical research to be postponed or cancelled by SFU and other institutions, while our partners (CoV) remain in remote working mode. This indefinite postponement required us to find a way to pivot this important work in a way that ensured constructive, productive outputs for the project it is part of.

4.2. Research contributions

The research presented in this thesis makes contributions to the fields of geographic information science, flood visualization, flood risk management and mixed reality data visualization. This work represents some of the first attempts to develop MR visualizations for applied geospatial practice. Furthermore, this work moves beyond a technical presentation of workflows, and theorizes about how components of MR interface impact perceptual and cognitive outcomes for the user.

Chapter 2 provided a foundational overview on the use of mixed reality interfaces in flood visualization, and their potential applications. By providing a workflow that transforms all datasets relevant to FRM to 3D models, I provided a bridge for rigorous spatial datasets and emerging interfaces. The resulting workflow demonstrates the conversion of conventional data formats into 3D models that can be used for visualization, with representational fidelity of landscape and flood risks preserved. This workflow can be adapted to visualize other environmental phenomena that are conventionally understood through GIS and maps. I hope that this particular chapter highlights the emerging trends in visualization development and emerging interfaces and illuminates the need to understand a relationship between changing environmental phenomena, the ways in which data visualizations characterize them and interfaces through which we experience them.

Chapter 3 makes the most significant contribution, as it provided practical workflows that can be followed to develop single user and interactive mixed reality tools, provided a theoretical basis to understand the capabilities, perceptual and cognitive implications of MR for geospatial practice. Much work in this domain focuses on improving understanding of flood impacts by the public (e.g. Fenech et al., 2017; Haynes et al., 2018; Lonergan & Hedley, 2016; Macchione et al., 2019). However, with emerging MR systems that have impressive ability to adapt virtual content into workspaces, it is important to highlight the possibilities of ex-situ application of MR visualizations. Given the collaborative nature of understanding flood risks and developing adaptation policies, the shared, mixed reality environments developed here demonstrate the feasibility of building and integrating such tools into practice. This is especially important in the domain of FRM, where complex topology and geometry of landscape needs to be accounted for in decisions on potential adaptation/mitigation.

With decreasing costs, greater ubiquity of devices, and increasing capabilities, MR is on the cusp of being integrated into practice. Technologies like HoloLens can be considered a state-of-the art mixed reality wearable computer. Their capabilities usher in an altogether new level of potential for integrating data-driven information experiences in everyday environments. For this reason, it is important to develop the intellectual basis to support meaningful development of future user interfaces to interact with spatial data in 3D. This work presented multiple perspectives on developed MR flood visualization prototypes to inform future development, implementation, evaluation and theory of 3D interface use in urban planning and flood risk management. The gesture-based interaction and room-anchored stereo 3D visualization mean that these tools have potential to enable planners to collaboratively view and experience each other's data in co-located information experiences in everyday workspaces. The significance of this is the ability for planners to build robust, shared mental models of environmental risks, risk reduction options and spatial policy based on a collaborative experience of 3D visualizations.

4.3. Future Research

This research represents one of the few attempts to visualize flooding risks in mixed reality environments, and leverages the multi-sensory, spatially integrated data experiences to alter user's perception of data. As such, I only examined at a small subset of potential applications and features of MR visualizations, and purposely used existing municipal datasets to characterize flooding risks and urban environment. With the growth in 3D data collection and use, more complex representations of urban landscapes, including 3D models derived from LiDAR, BIM, Structure-from-Motion can be integrated into 3D MR user interface. This can improve the understanding of impacts, as well as improve the damage estimation from floods (Amirebrahimi et al., 2016; De Santis et al., 2019). The capabilities of digital content can be leveraged further to visualize dynamic outputs of flood simulations instead of showing a maximum floodplain extent under a given scenario. Furthermore, this work focused on the use of vertical space for the visualization of physical features in the landscape. However, for purposes of risk management and policy development, the third dimension can be used to visualize other relevant information, such as the presence/fraction of vulnerable populations in the area, or potential monetary impact of flooding on an area.

Some aspects of streamlining the workflow certainly need to be investigated further, as the multiple steps required to move GIS data into the MR interface can be a barrier to spontaneous, experimental exploration of data. Furthermore, throughout this work I focused on leveraging local processing power of the HoloLens 2 device. However, to support many geographic applications, where datasets can easily exceed millions of polygons, cloud-based rendering (remote rendering) is required for satisfactory performance.

To have a chance to be integrated into practice, the MR visualization environments need to be assessed by practitioners working in the FRM domain to understand whether the visualizations reflect the needs of the end user, and whether the aspects of MR interface actually enhance their practice. As noted above, this is not easy or straight-forward, as the simple metrics such as task completion times, accuracy and usability questionnaires do not capture the perceptual experience, cognitive outcomes, or the quality of interpersonal communication when interacting in a shared MR environment, instead of looking at a screen with a colleague.

As mixed reality devices and workflows become more ubiquitous and accessible, it is important to not only collect empirical evidence, but also tgo theorize and unpack the perceptual and cognitive experience of the user interacting with 3D data in such a distinct medium (as opposed to using a mouse, keyboard and 2D screen). Understanding the appropriate representations of data, user interface design and interaction are pivotal to meaningful integration of mixed reality visualizations into applied spatial data practice.

4.4. References

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2016). A BIM-GIS integration method in support of the assessment and 3D visualisation of flood damage to a building. *Journal of Spatial Science*, *61*(2), 317–350.

De Santis, R., Macchione, F., Costabile, P., & Costanzo, C. (2019). Visual Risk Communication of Urban Flooding in 3D Environments Based on Terrestrial Laser Scanning. In G. Mannina (Ed.), *New Trends in Urban Drainage Modelling. UDM 2018. Green Energy and Technology* (pp. 783–787). Cham: Springer International Publishing.

Fenech, A., Chen, A., Clark, A., & Hedley, N. (2017). Building an adaptation tool for visualizing the coastal impacts of climate change on Prince Edward Island, Canada. In *Climate change adaptation in North America* (pp. 225–238). Springer.

Haynes, P., Hehl-Lange, S., & Lange, E. (2018). Mobile Augmented Reality for Flood Visualisation. *Environmental Modelling & Software*, *109*, 380–389.

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.

Lonergan, C., & Hedley, N. (2015). Navigating the future of tsunami risk communication: using dimensionality, interactivity and situatedness to interface with society. *Natural Hazards*, *78*(1), 179–201. https://doi.org/10.1007/s11069-015-1709-7