Advancing Tsunami Risk Communication through Geographic Visualization

by

Christopher Dylan Lonergan

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Name: **Christopher Dylan Lonergan**

Degree: **Master of Science**

Title: ***Advancing Tsunami Risk Communication through Geographic Visualization***

Examining Committee: **Chair:** Paul Kingsbury
Associate Professor

Nick Hedley
Senior Supervisor
Associate Professor

John Clague
Supervisor
Professor

Scott Miles
External Examiner
Associate Professor
Environmental Studies
Western Washington University

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Abstract

Advancements in geovizualization research and technologies present new opportunities to develop sophisticated risk communication strategies in at-risk coastal communities. This thesis seeks to improve tsunami risk communication in coastal communities through the development of new empirical methodologies, conceptual frameworks, and visualization prototypes through several key research contributions. The development of a conceptual framework for 3D visibility analysis presents an opportunity to assess the visibility of tsunami evacuation sign placement in Seaside, Oregon. Further geovisual research is established through the development of a mixed reality visualization interface that enables *in situ* visualization and simulation of geographic phenomena. This interface is then applied to the visualization and simulation of tsunami events in Ucluelet, British Columbia. This research provides the groundwork for future usability studies on the effectiveness of mixed reality visualization for risk communication.

Keywords: risk communication; geovisualization; tsunami; visibility analysis; visualscape; mixed reality

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Chapter 1.

Introduction

1.1. Overview

Tsunamis are hazardous events that pose significant risks to coastal communities in seismically active regions. Coastal Northwest Pacific communities might have less than 20 minutes to evacuate to safe ground should a great earthquake occur at the Cascadia Subduction Zone (CSZ) (Clague, Munro & Murty., 2003; Xie, Nistor & Murty, 2012). The devastating 2004 Indian Ocean and 2011 Tōhoku tsunamis emphasize both the risk faced by coastal populations and the necessity for effective preparation.

Risk and hazard are distinct concepts that must be understood to discuss tsunami threats. Hazards are physical processes or events that threaten populations and the built environment, whereas risk refers to the probability and scale of damage and injury that a hazardous event causes (Cutter, 2003). Risk communication is defined “as an interactive information exchange between individuals, groups or institutions, about the nature of risks, risk related opinions, anxieties and coping strategies” (Hagemeier-Klose & Wagner, 2009). Existing approaches to communicate tsunami spatial risk and build community resilience rely on the development and provision of 2D paper maps (Clague et al., 2003; Dengler, 2005; Kurowski, Hedley & Clague, 2011). Additional forms of communication include sirens and physical signage located along evacuation routes (Darienzo, 2003; Ministry of Civil Defence & Emergency Management, 2008).

Goodchild (1988) defines geographic information systems (GIS) as “integrated computer systems for the input, storage, analysis and output of spatially referenced data” (p. 560). The field of geographic information science (GIScience) deals with theoretical concepts and challenges resulting from the development, application, and use of GIS (Goodchild, 1992). Both academic and governmental GIS communities accelerated their research in GIScience following the catastrophic 2004 Indian Ocean tsunami (Kelmelis, Schwartz, Christian, Crawford, & King, 2006). Data collection, security, accuracy, representation, and communication were recognized as serious investments for the safety of at-risk populations.

Geographical visualization, or geovisualization, research has provided a rich body of work that can be leveraged to improve existing methods of risk communication or entirely new approaches. Geovizualization refers to the study of geospatial data analysis through visualization techniques and theory (MacEachren & Kraak, 1997). The field focuses on representation, knowledge construction, interface design, and cognitive usability issues for geospatial visualizations (MacEachren & Kraak, 2001).

In this thesis, I apply geovizualization to coastal communities that are at risk from tsunamis. Specifically, I use visualscapes, defined as spatial representations of visibility, (Llobera, 2003) to determine the visibility of existing tsunami evacuation route signage. Visibility analysis is a rapidly advancing domain, particularly within urban design and architectural research fields. I use mixed reality (MR), defined as a form of spatial interface combining real views of the environment with digital objects and information (Milgram & Kishino, 1994; Tamura, Yamamoto & Katayama, 2001; Hedley, Billinghurst, Postner, May, & Kato, 2002), as a conceptual basis for the development of several new approaches to visualizing both tsunami risk and hazard.

Through this research, I seek to improve risk communication and public safety in coastal communities through the contribution of new empirical methodologies, conceptual frameworks, and visualization delivery mechanisms. Providing vulnerable communities with effective risk communication tools is vital to their ongoing preparedness and safety. By addressing questions concerning the relations among geovisualization design, interface design, and geographic sense-making, I hope to derive improved methodologies and approaches for tsunami risk communication.

1.2. The Research Problem

The relationship between visibility and the perception of tsunami risk has yet to be fully explored. Guidelines on the placement of tsunami evacuations signs exist; but they are limited to colour and size specifications. Given the importance of visibility in navigation and perception (Gibson, 1979), an examination of the visibility of signs from a spatial perspective enables an evaluation of existing communication and could inform future placement of signs.

I employed digital elevation models (DEMs) in this research. DEMs are used in a wide variety of tsunami research applications. In the context of visibility analysis, line-of-sight (LOS) models use their geometry to determine if a spatial location can be seen from an observer's location. The structure of these DEMs typically is topologically 2D (2.5D). Critical challenges are encountered when topologcailly 2D DEMs are used to represent environments that are structurally complex in three dimensions, such as the built urban environment (Bishop, Wherrett, & Miller, 2000; Bishop, 2003). These challenges extend to representations of 3D visibility. 3D visibility analysis has been examined for more than a decade (Bishop, 2003; Conroy & Dalton, 2001; Fisher-Gewirtzman, 2003); however, an effective, all-encompassing conceptual framework of 3D visibility has yet to be developed.

In addition to the above issues, the delivery of spatial information to at-risk audiences presents both a challenge and a research opportunity. Many coastal communities deliver evacuation, risk, and hazard information by individual paper maps. Information conveyed by these visualizations are typically limited to static representations of hazardous zones, evacuation routes, and evacuation destinations (Kurowski et al., 2011). Yet, such maps are only one possible method for delivering spatial information. Given advances in geovisual research, new approaches to tsunami risk communication are possible.

Existing tsunami visualizations are non-situated and range from dynamic to static, although most are static. 'Situatedness' is a term that refers to the connection between on-site research activities and how location influences, action, perception, and understanding (Vannini, 2008). *In situ* and *ex situ* refer to whether or not such an activity is taking place within a defined location. Visualizations and interfaces that leverage differing forms of dimensionality, interactivity, and situatedness might offer considerable potential for new kinds risk communication experiences. The following questions guide this thesis:

1. How can we conceptualize, define, and describe visibility in three dimensions?
2. How might visualscapes aid the assessment and development of tsunami evacuation sign placement?
3. How can mixed-reality, situated geovisualizations better communicate spatial information?
4. How do existing tsunami visualizations communicate spatial information?
5. How does a geovisual perspective inform new kinds of tsunami risk communication?

1.3. Research Objectives

The main goal of this work is to link advanced geovisual research to tsunami risk communication. I have developed several new methodologies and conceptual frameworks to provide new risk communication experiences to stakeholders. The following objectives follow from research questions I posed in the preceding section.

1. Develop of a framework for representing 3D isovists and visibility;
2. Develop and apply visibility analyses to tsunami evacuation sign placement in an at-risk coastal community;
3. Develop a spatial interface that can deliver geographic information *in situ*;
4. Compare and contrast a sample of academic and public tsunami visualizations using a framework consisting of dimensionality, interactivity, and situatedness;
5. Develop new forms of situated tsunami risk communication.

1.4. Thesis Organization

This thesis comprises six chapters. Following the introduction, four main chapters address my research objectives. Each main chapter is written as a stand-alone journal article for publication in a peer-reviewed journal.

Chapter 2 examines how visibility is conceptualized and communicated in spatial research by reviewing relevant isovist and visualscape literature, with a particular emphasis on 3D visibility. The main purpose of this chapter is to develop a framework of isovists based on geometries of visibility and the relationships between the observer and observed. The chapter is grounded with applied examples in the context of urban privacy.

Chapter 3 develops and applies visibility analyses in the context of evacuation signage visibility in Seaside, Oregon. The main purpose of the chapter is to demonstrate the usefulness of visibility research in an applied context. I use standard 2.5D visibility analysis methodologies and a newly developed topologically 3D LOS approach to visibility analysis using raw LiDAR datasets to characterize the Seaside landscape in terms of signage visibility.

Chapter 4 reports on a geospatial, mobile, augmented reality system that can run *in situ* simulations of dynamic spatial phenomena. I review advanced geovisualization technologies and concepts in order to produce a unique mixed reality interface that can perform a variety of 3D visualizations and basic simulations in real space.

The final research chapter connects the mixed reality interface developed in Chapter 5 to the visualization of tsunami risk and hazard. This chapter introduces dimensionality, interactivity, and situatedness (DIS) as geovisual interface constructs and assesses their presence within 129 examples of visual tsunami risk communication in both the academic and public literature. A conceptual cube is developed to aid the comparison. The results reveal differences in the distributions of DIS in the literature. In response to underused combinations of DIS, I also report on three new tsunami risk visualization interfaces.

Chapter 6, the concluding chapter, discusses the significance of the research introduced in the previous chapters and identifies possible future directions in geovisual tsunami research.

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Chapter 2.

Unpacking Isovists: A Framework for 3D Spatial Visibility Analysis[1]

2.1. Abstract

This paper explores the ways in which researchers conceptualize and visualize visibility in spatial research – using isovists and visualscapes. I review how visibility analyses have been used in spatial analysis and visualization. I dissect the geometric conceptualization of isovists, and geometric relationships between isovist origins and targets. From this I develop an expanded typology of isovists based on geometries of visibility and the relationships between observer and observed. This typology differentiates panoptic isovists, constrained isovists, and targeted isovists. I apply these isovist examples to urban privacy and surveillance to ground the new conceptual framework. I conclude with a discussion surrounding future research and conceptual development needed to advance visualscapes and visibility analysis.

2.2. Introduction: Visibility and Viewshed analysis

Visibility analysis, through the use of geographic information systems (GIS), computes and analyzes the visibility of objects and space. The visualscape was introduced in an attempt to unify methodological approaches to visibility analysis within geographic information science (GIScience). This concept is defined by Llobera (2003) as a "spatial representation of any visual property generated by, or associated with, a

[1] A version of this Chapter has been submitted to *Cartography and Geographic Information Science* under the co-authorship of Nick Hedley.

spatial configuration" (p. 30). Visualscapes encompass analytical techniques such as intervisibility, viewsheds, isovists, and visibility graphs.

The most ubiquitous GIS platforms perform viewshed analyses using: i) vector ray tracing; and ii) raster algorithms designed to interpret elevation coordinates attached to a particular set of X and Y coordinates. Various forms of visualscapes can be generated in this manner. For example, intervisibility considers whether one point can be seen from another (Longley, 2011), whereas a viewshed considers the area of surface that is visible from a point location. Viewsheds can be applied to a variety of spatial relationships and phenomena including: determining what is visible from a tourist viewpoint, the visual impact of new constructions, and optimal logging sites for natural vista preservation. Additionally, the viewshed approach can be extended to other line of sight (LOS) spatial relationships such as solar radiation exposure and cellular transmission strength.

The isovist is a popular technique used in a variety of fields to compute visibility. Originally conceptualized by Tandy (1967), the isovist is defined as the volume of space representing the visual field of an observer from a specified origin (Benedikt, 1979). Isovist research has typically used a panoptic approach in the generation of isovists and resultant visualscapes. This chapter considers 'panoptic' to refer to omnidirectional visibility. While omnidirectional visibility is useful for visualizing potential viewing directions of various entities, it often does not reflect real-world observers, each with varying needs and limitations (people, cameras, lookouts).

In the following sections, I review how visibility analyses have been used in spatial analysis and visualization. I dissect the geometrical relationships of isovist origins, facilitating the development of an expanded isovist typology. Included is the differentiation between panoptic isovists, constrained isovists, and targeted isovists. I unpack the geometric conceptualization of isovists in order to develop a more specific typology of isovists based on geometries of visibility and the relationships between observer and observed. Applied examples are used to ground this conceptual framework. I conclude with a discussion surrounding future research and conceptual development needed to advance visualscapes and visibility analysis.

2.3. Previous Research in Visibility Analysis

The visualization of visibility (both objects and environment) has been a topic of research for many decades and spans several distinct fields of research. Broad types of visibility analysis crop up in a wide variety of problem contexts including national security (VanHorn & Mosurinjohn, 2010), healthcare (Alalouch & Aspinall, 2007), and navigation (Delikostidis et al., 2013). Patterns of specialized visibility analyses and the resultant visualscapes can be seen across different research domains. The majority of cutting-edge isovist work, for example, has occurred within archaeology (Paliou, 2011) and urban design (Benedikt 1979; Batty 2001; Fisher-Gewirtzman & Wagner 2003; Turner, Doxa, O'Sullivan & Penn, 2001).

A variety of visibility metrics have been developed in order to analyze and visualize different characteristics of visible space and patterns found within them. These include binary viewsheds (Shultz & Schmitz, 2008; Wilson, Lindsey & Liu, 2008), visual openness (Fisher-Gewirtzman & Wagner, 2003; Wilson et al., 2008), and visual magnitude (Llobera, 2003; VanHorn & Mosurinjohn, 2010; Wilson et al., 2008). These metrics represent distinct quantifiable properties of visibility under differing spatial configurations.

Visibility metric analysis and visualscapes can vary in dimensionality. One of the characteristics of the visualscape, as defined by Llobera (2003), is that they are “essentially three-dimensional [and] they may be explored using any of the standard concepts that apply to 3D surfaces” (p. 31). This suggests that the visualscape embraces a limited form of 3-dimensionality; however, early GIS work was limited by the fundamental structure of 2.5D digital elevation models (DEM) (Bishop, 2003). 2.5D structures only account for one elevation value at each XY coordinate. Overhanging geometry, tunnels, and other bridge-like features are not satisfactorily represented in such an approach (Yang, Putra, & Li, 2007). Pyysalo, Oksanen, and Sarjakoski (2009) review the differences in LoS viewshed analyses applied to truly 3D voxel representations of the environment and 2.5D DEM representations.

For example, while Wilson et al. (2008) converted a 3D LiDAR dataset to a 2.5D elevation model in order to run a visual magnitude assessment, the final visualscapes are presented in 2D. VanHorn and Mosurinjohn's (2010) study on sniper hazards used the extrusion of a 2.5D raster array to represent urban topography. This contrasts with their topologically 3D approach to hazard visualization, which placed a spherical 3D weapon potential dome within their study area. Given our increasing capability to run sophisticated 3D analysis, misrepresentation of analytical processes and results is a real risk.

Isovist research has fully embraced, and responded to, this challenge. In particular, the field of urban design has produced sophisticated prototypes, tools, and metrics, and other conceptual research. Conceptual constructs that utilizing isovists include isovist fields and spatial openness. Other properties such as isovist openness and jaggedness have shown promise as predictors of spatial behaviour and experience (Wiener & Franz, 2005).

Isovist fields are generated by generating isovists at regular intervals within a defined space, then using the results to produce a field representing sum attributes of the generated isovists (Batty, 2001; Benedikt, 1979; Turner et al., 2001). Attributes represented by the fields can include metrics such as isovist area and perimeter. These methods are stated to be applicable in 3D (Turner et al., 2001), but were neither fully developed nor tested until (Teller, 2003).

Fisher-Gewirtzman and Wagner (2003) report on the conceptual development and application of spatial openness. Spatial openness is "the volume of free space measured from all internal observation points," (p. 37) or in other words, isovist volume. In this work, the authors are restricted to 2D isovist area (Turner, 2003); however, recent development demonstrates a successful shift to truly 3D analysis using 3D voxel representations of the environment (Fisher-Gewirtzman, 2012; Fisher-Gewirtzman, Shashkov, & Doystsher, 2013).

2.4. An Expanded Isovist Typology

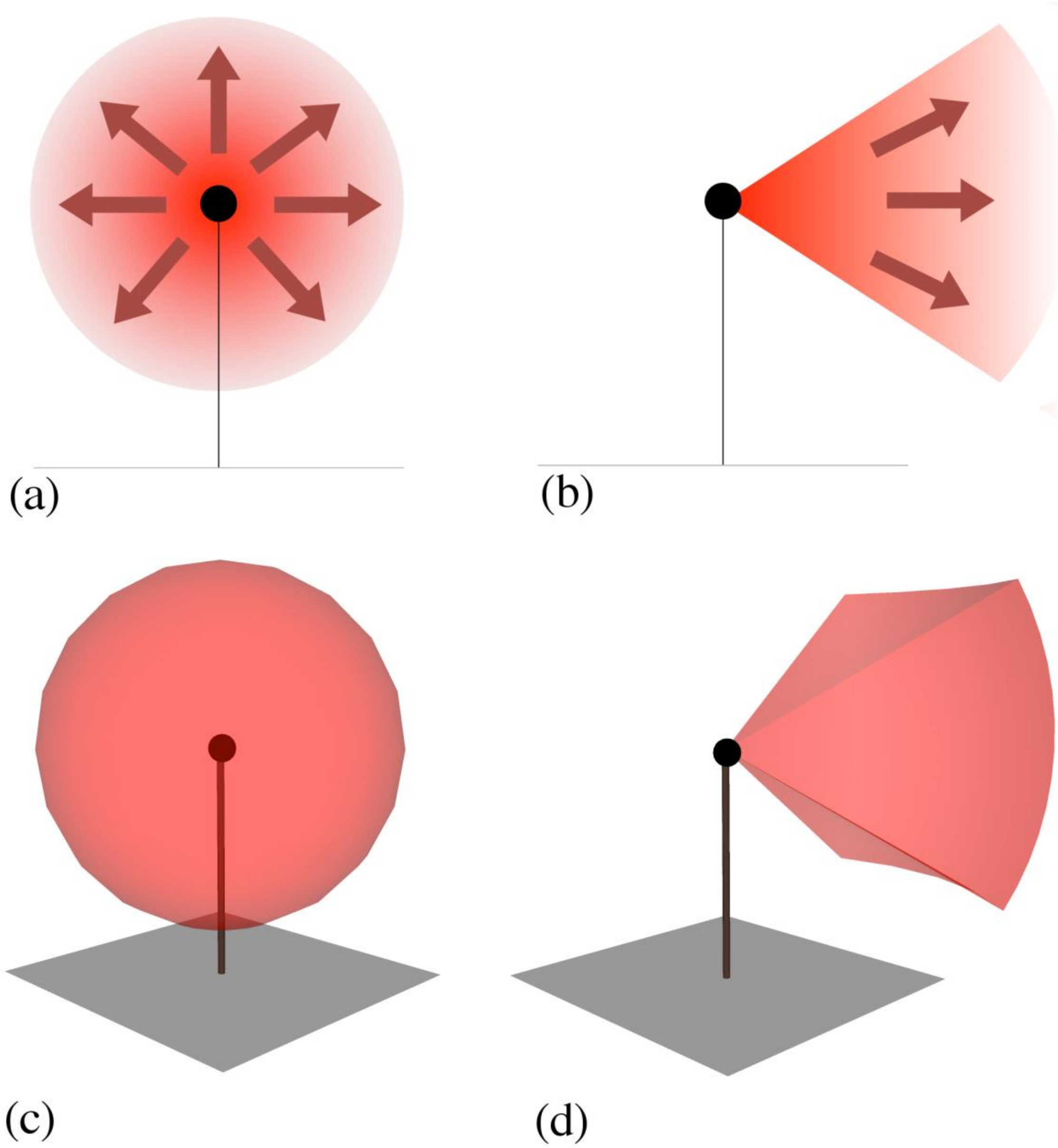
The application of 3D isovists in spatially complex environments necessitates the development of a more robust isovist typology than that which currently exists. I propose a classification framework with which I can specify a typology of isovist attributes: isovist-target relationships, intervisibility, isovist interception, isovist mobility, and scanning versus fixed isovist behaviour. Through this framework, I aim to deliver a conceptual basis with which to compare and evaluate the implications of using one or more isovist-based visibility analyses in different analytical contexts. I ground this typology with existing examples of isovist use in the literature and expand were none yet exist. A richer conceptual framework for isovists enables us to design visibility analyses for unique geometries of specific problem contexts.

2.4.1. Unpacking the Geometry of Panoptic and Constrained Isovists

Most isovist applications employ what I have defined in section 2.2 as panoptic isovists. New research has unlocked the capability to generate and analyse 3D isovists; with these new opportunities comes demand for clearer terminology when both subtle and drastic variations of visibility origin geometry are present. Targeted isovists and constrained isovists are distinguished from the panoptic isovist in this new lexicon. These differentiations must be explicitly acknowledged (and perhaps dealt with).

My conceptualization of the panoptic isovist is derived from Jeremy Bentham's panopticon (Bentham, 1995; Foucault, 1995). Bentham's theoretical prison contains a guard tower that is capable of viewing in all directions at once; likewise, the panoptic isovist is generated from an origin point with an omnidirectional gaze (Figure 2-1a and Figure 2-1b).

Figure 2-1. 2D and 3D Perspective Views of Panoptic and Constrained Isovists



The panoptic isovist (a) and (c) assumes the capability to view in all directions and at all angles from an origin. The constrained isovist (b) and (d) has some form of limited observational capabilities. This may include limited viewing angles and directionality.

Examples of panoptic isovists are very common and are present in both 2.5D and 3D visibility analyses. Fisher-Gewirtzman (2012) consider visibility from all angles without restriction in their topologically 3D approach to assessing spatial openness. Likewise, Wilson et al. (2008) do not restrict the viewing potential of their viewshed origins in their topologically 2.5D examination of visual openness and magnitude for urban pedestrian trails. It must be noted that this is not implicitly a criticism of their approach. Panoptic isovists are extremely useful for assessing the potential viewshed of an observer at a fixed location. That being the case, no human can observe in 360° at once. As such, the use of panoptic isovist necessitates that any result generated reveals potential visibility (however, an exception might be made for two or more observers standing back-to-back, or a complex CCTV set-up). Such an approach reveals what observers could see, not what they will or do see.

There are fewer examples of restricted isovists being applied in the literature. Paliou (2011) incorporates maximum vertical eye rotation limitations in their analysis of Bronze Age mural visibility. The author in this case did not choose to limit the visibility in the horizontal view; as a result, the paper still represents potential visibility. Again, it is important to note that this is not an implicit criticism, but I feel that the relationship between the geometry of the isovist and resultant visibility representations must be made clear. Choices made in how we structure visibility affects what final visualscapes represent.

In response, I introduce the term constrained isovist to describe isovists generated from viewpoints containing limiting characteristics, such as a limited field-of-view or directionality. Its geometry is variable, but can be likened to a searchlight shining a beam onto a landscape (Figure 2-1c and Figure 2-1d). This beam has directionality and breadth, which define how much of the landscape is illuminated. Unlike panoptic isovists, the constrained isovist can be used to represent observational constraints.

The application of constrained isovists may be advantageous in situations where an actor has a constrained or focused gaze. For example, constrained isovists would better represent fixed location CCTV cameras with limited fields of view and static directionality. They may also represent observers who can theoretically view any angle or direction, but can only observe a certain range at any given moment.

2.4.2. Considerations of the Geometry of Isovist Origins

I have discussed the differentiation of panoptic and constrained isovists in response to representational issues identified above; however, I have not (yet) taken issue with the representation of observers as fixed points in 3D space. Motivations for computing visibility vary. Many visibility analyses compute isovists from points, which are used as analogues for the origin of optics of a camera or human viewpoint. I propose that isovist origins can be linear, areal, or volumetric. Considering this potential will at the very least enable a healthy discussion on representing observation and visibility, but may also unlock new approaches to visualizing visibility.

As an example, linear origins might be used to compute visibility from a path. Both Conroy and Dalton (2001) and Koltsova, Tunçer, and Schmitt (2013) deal with path representation by establishing point-origin isovists at regular intervals along a defined route. While this enables sophisticated analysis such as route vision profiles and isovist field generation, they are still representing a non-point feature as a series of points. By representing observers as non-point geometries, I present a distinct representational approach. I discuss the merits and disadvantages of such methods at length in section 2.5.2.

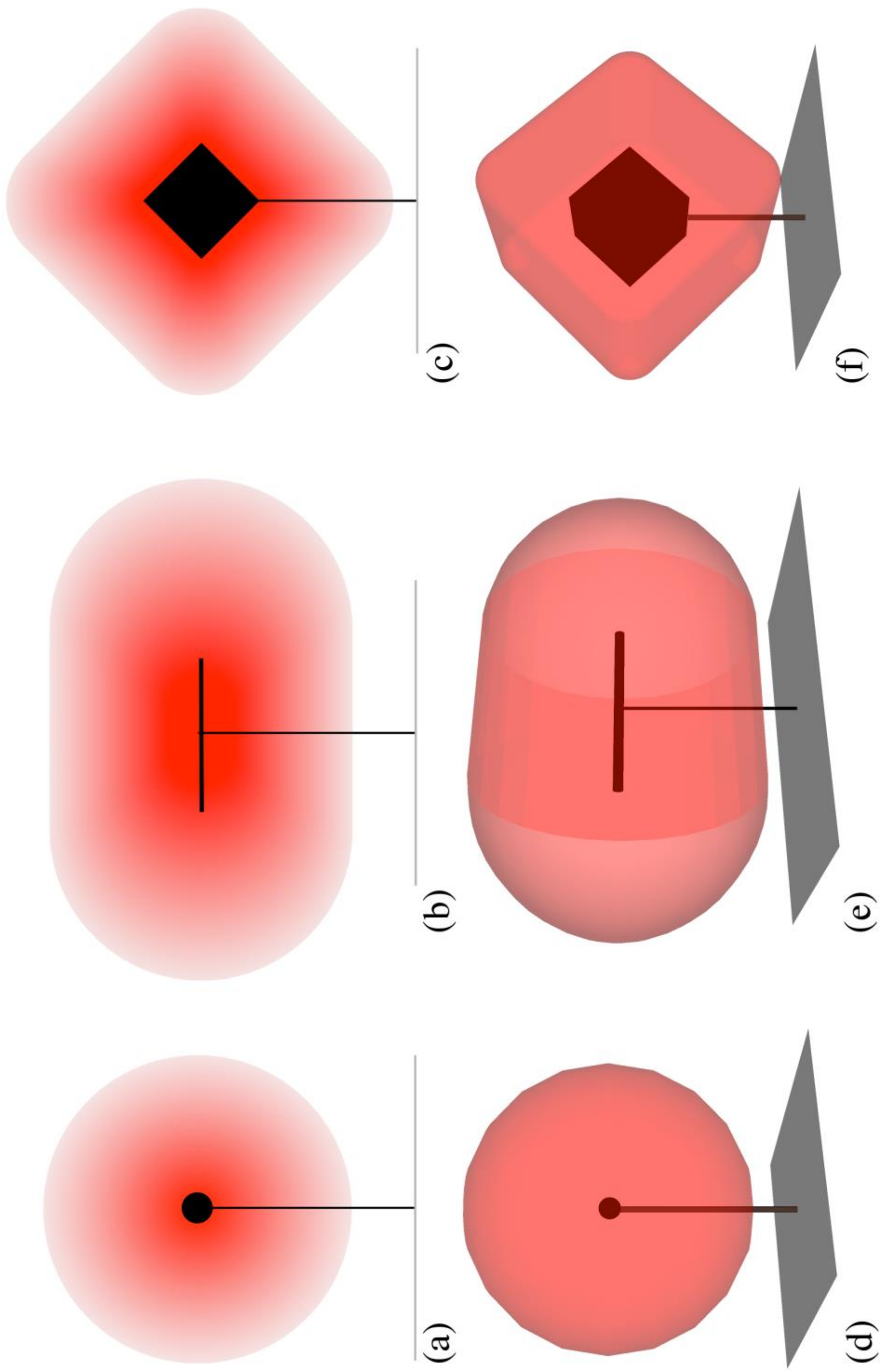
Areal origins may offer another distinct way to represent visibility and observation. If one were to compute the visibility of a proposed development from viewpoints in an existing town square, computing visibility from each mobile individual human origin within the square would be difficult, somewhat arbitrary, and inefficient. Typically, this is dealt with achieved by generating a lattice of point-origin isovists and developing isovist fields from the results. An alternative approach might be to compute the potential visibility from a polygon representing the town square, at an average head height; this polygon would be an areal origin of an isovist analysis. Areal origins might also be applied in a visual impact assessment of billboards for several reasons: A billboard surface is a 2D polygon, is meant to be viewed from many angles, and the audience must perceive the whole surface at once. This is a distinct approach to representing the geometry of observation when compared with the standard lattice-like analysis of multiple point origins.

Figure 2-2 illustrates the geometry resulting from panoptic isovists with point, line, and volumetric origins. This differentiation subsequently helps us understand the origin-target relationships between isovist origins and targets of different geometric combinations (Table 2-1). I propose that by selecting non-point origin geometries, I may represent a conceptually district version of visibility. I discuss these conceptual differences, their advantages, and their disadvantages, and their potential usefulness in section 2.5.2.

Table 2-1. Proposed Targeted Isovist Classifications

Origin Geometry	Target Geometry			
	Point	**Line**	**Area**	**Volume**
Point	Point-to-point	Point-to-line	Point-to-area	Point-to-volume
Line	Line-to-point	Line-to-line	Line-to-area	Line-to-volume
Area	Area-to-point	Area-to-line	Area-to-area	Area-to-volume
Volume	Volume-to-point	Volume-to-line	Volume-to-area	Volume-to-Volume

Figure 2-2. The Variable Origins of Panoptic Isovists



2D illustrations of the side profile of panoptic isovists with point (a), linear (b) and volumetric (c) origins, and their 3D counterparts (d), (e), and (f).

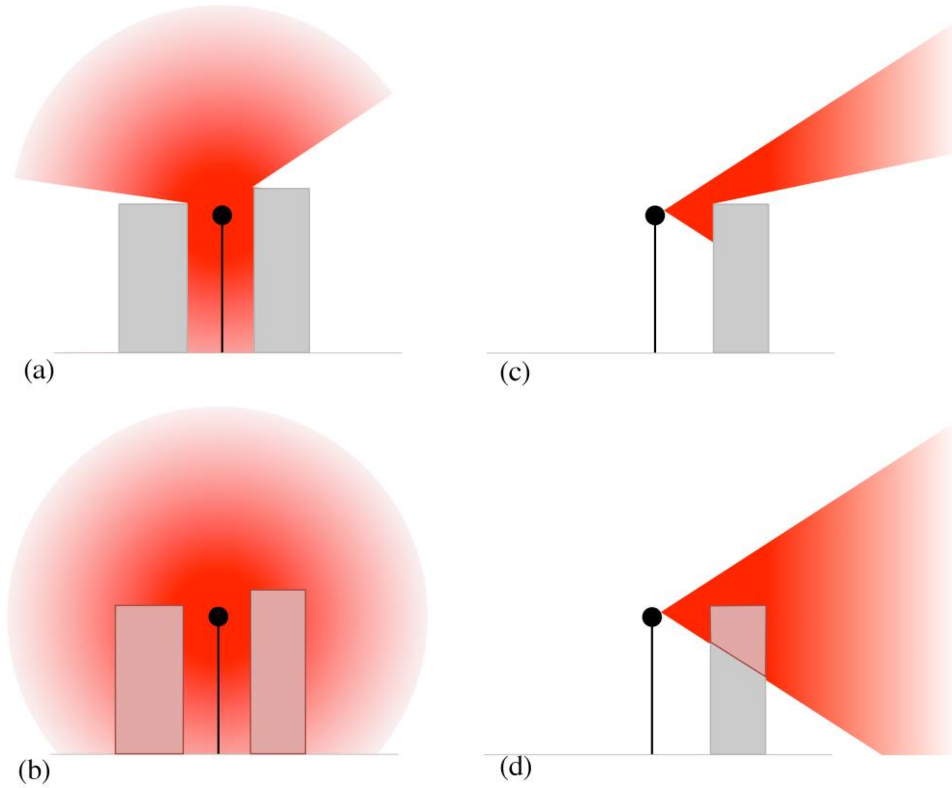
2.4.3. Isovist Interception in Applied Contexts

Panoptic and constrained isovists are each defined by attributes that exist independent of the environment in which they are computed (observer attributes). Additional properties become relevant when isovists are applied in real spaces. Isovist range, as an example, can be considered to be the sensing range of a sensor, or the intended capture range of a system. Distance in the context of isovists has been examined before. Kim and Jung (2014) propose a distance-weighted isovist field, given the importance of proximity across various spatial disciplines. Many research efforts select maximum distances for isovist limitation. For example, Bilsen and Poelman (2009) select a panoptic isovist with a maximum range of 225 m. The representation of observation is thus a sphere with a radius of 225 m. Scenarios in which range is relevant might include the maximum acceptable range of a sensor system or cellular signal propagation.

In certain contexts, uninterrupted isovist geometries (of varying ranges) are appropriate representations of visibility phenomena. For example, an isovist generated by an infrared or X-ray camera may pass through solid objects. A panoptic isovist would remain spherical, no matter how the spatial configuration of the environment is changed. In conjunction with range, sensing wavelength becomes important in determining the final geometry of an isovist in wavelengths that interact with material objects.

Whether panoptic or constrained, an isovist will be intercepted by materials that fall within its field of view and range (Figure 2-3). For example, the cylindrical geometry of Bentham's (1995) panopticon results from the interception of the isovist of surveillance contained within the geometry of the prison building. Understanding these principles and their resultant geometries may help to better understand visibility analyses from a 3D isovist perspective.

Figure 2-3. Spatial Configurations and their Effect on Isovist Geometry

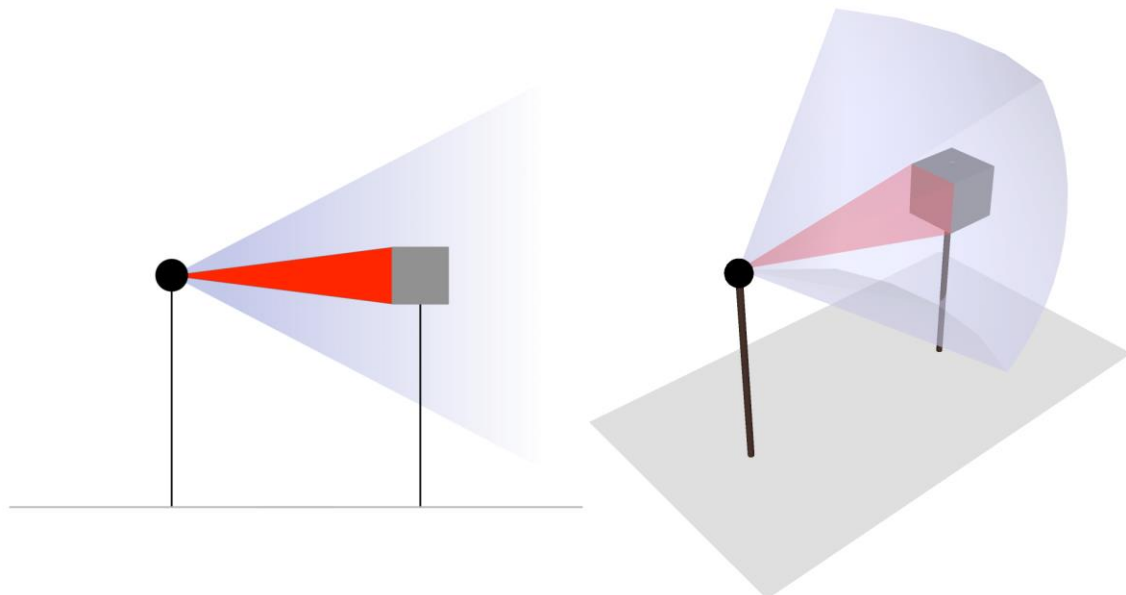


Panoptic (a) and constrained isovists (c) can be interrupted by geometry in certain wavelengths, or remain unimpeded (b) and (d).

2.4.4. Targeted Isovists and Origin-to-Target Isovist Relationships

In addition to differentiating panoptic and constrained isovists, a more specific terminology might be used to describe 3D visibility relationships between observers and what is observed. I propose the term targeted isovist to define a visualscape in which the rendered isovist geometry is limited by a specified target space. The key difference between this and panoptic or constrained isovists is that a targeted isovist does not visualize all that the viewer can see, rather, it reveals only the visible portions of a target space and the gaze path between the observer and target space (Figure 2-4). In other words, targeted isovists are subsets of panoptic and constrained isovists.

Figure 2-4. Targeted Isovists

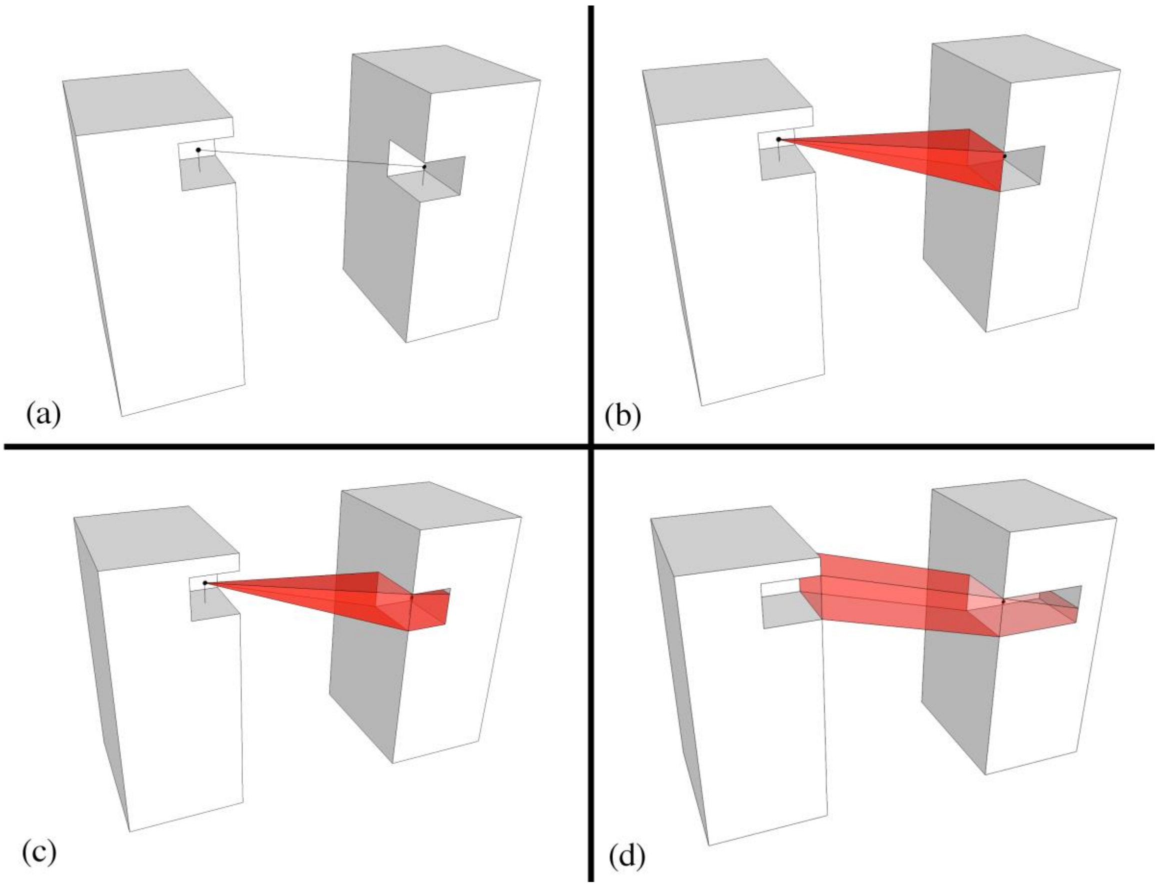


The targeted isovist represents only what is visible of a target area or volume and the gaze path between observer and target. This is a subset of the total viewing capability of the observer, in this case a constrained isovist.

To the best of my knowledge, no one has explicitly considered isovist geometries of this type; however, some research does intersect with my conceptual work. Gal and Doytsher (2013) introduce Visible Pyramids as a component of a mass modeling approach to 3D urban visibility. These geometries are defined by a viewpoint and a rectangular visible surface. These shapes are good representations of what I consider targeted isovists; however, they are restricted to pyramidal shapes, something that actual gaze paths might not obey. Paliou (2011) developed an isovist based analysis that reveals the visible area of murals and wall paintings as percentages. These results are visualized as 2D rasters in which visibility can sometimes be seen to project outwards from the targeted features. If one is to consider the paintings to be origins of visibility, the visualscape representing ‘high-visibility’ sections of space appear to be similar to my targeted isovists conceptualization.

Sub-categories of targeted isovist can be defined using the geometric attributes of both its origin (section 2.4.2 above) and target space. This includes points, lines, areas, and volumes. A preliminary categorization of isovist origin-to-target combinations by geometry can be found in Table 2-1. Figure 2-5 illustrates some examples of origin-to-target geometric pairings.

Figure 2-5. Targeted Isovists and Variable Origin Geometry



A selection of targeted isovists with differing origin-to-target geometries: (a) Point-to-point, (b) Point-to-area, (c) Point-to-volume, (d) Area-to-volume.

This classification might add clarity to real-world visibility contexts. For instance, point-point targeted isovists may be appropriate in determining the best locations for CCTV cameras monitoring a (small) singular object. A continuous line (intervisibility) from the camera to the object must be unbroken in order to maintain security, regardless of the camera's field of view. Point-to-area isovists might describe the visibility of a movie screen from specific seats. Premium seating should be designed so that the entire area of the screen is visible from a viewer's seat. The visibility of anything else (the non-visualized portion of the viewer's total isovist) is irrelevant to the problem at hand. A point-to-volume targeted isovist might define the visibility of the contents of an apartment room from an external viewpoint. The point-to-volume isovist would reveal both the 3D space within the apartment that is visible to the observer, and their gaze path.

We have discussed the possible applications of various point-to-space isovists; however, as discussed in section 2.4.2, observer geometries are not necessarily restricted to a single point in space. This can be illustrated by expanding upon my point-to-volume apartment visibility. The apartment room is likely to be visible from several rooms within the opposite building; as such, calculating the room's visibility from a singular point does not reveal realistic visibility. Instead, a volume-to-volume isovist might be more appropriate. Point observers may choose to shift their location within a certain volume in order to peer into the target space. By representing these potential locations of the observer as a volume, a volume-to-volume isovist geometry is produced. This visualizes what can potentially be seen from possible viewpoints.

These examples of variable origin and target geometry suggest that there are a wide variety of key geometrical and conceptual differences in the application of isovists to problem spaces. The selection of different representative geometries often results in critical differences in what the final visualscapes represent. A detailed lexicon and classification system of targeted isovists might be beneficial in the communication of these differences and might stimulate the development of new forms of visibility analysis.

2.4.5. Dynamic Isovists and Visibility

Many observers are mobile, and are therefore poorly represented by fixed geometries. Early work in dynamic isovists can be seen in Fisher-Gewirtzman, Burt, and Tzamir (2003) where a space-time experience track is visualized as a series of static isovists and a collection of views. The classifications discussed above do not include dynamic attributes such as moving observer locations, changing directionality, and varying viewing angle. This might be engaged by representing mobile point actors as lines, areas, or volumes; however, it forces any resulting visualscapes to represent potential visibility of a mobile observer, rather than the actual visibility of a mobile observer. I address the representation of mobile observers and dynamic isovists without resorting to potential visibility in following sections; however, I first discuss a classification scheme for representing dynamic observers and isovists.

Table 2-2 gives a preliminary taxonomy for dynamic isovists. Mobile observers with changing physical locations can be classified as mobile or immobile. Examples of mobile observers include moving pedestrians and cars, while stationary CCTV cameras are immobile. Isovists may also exhibit scanning behaviour. For example, some security cameras can adjust their orientation, resulting in a greater swath of potential visibility. Finally, an observer may possess zoom and focus capabilities that change. For instance, a zoom lens alters its total field of view as it is adjusted resulting in isovist geometry that changes through time.

Table 2-2. Proposed Dynamic Isovist Classifications

Is the isovist…	**Moving?**	**Scanning?**	**Focusing?**
Yes	Mobile	Scanning	Focusing
No	Immobile	Fixed	Non-focusing

These expanded typologies help us tune visibility analyses to accommodate specific geographic objects, geometries, and spatial relationships. There are many different forms of geometry, mobile actors, and observer-observed relations in the built urban environment. Surveillance and privacy are particularly relevant examples of visibility relationships in urban space. A more sophisticated framework of isovist forms and methods might improve the characterization of these relationships.

2.5. An Analysis of Isovists in Two Case Studies

In the following section, I describe geovisual analysis research I pursued to implement and evaluate selected examples of the isovist and observer-target framework introduced above. Additionally, I seek to conceptualize and implement uncommon isovist geometries (point-to-volume, area-to-area, and volume-to-volume) to enable new forms of visibility analysis.

Two groupings of visualscapes were produced: A 3D targeted isovist privacy analysis of two downtown Vancouver apartment buildings and animated viewsheds along major downtown Vancouver streets. By developing these visualscapes, I evaluate and compare the isovist types, subtypes, geometries, and relationships involved in my conceptual framework designs.

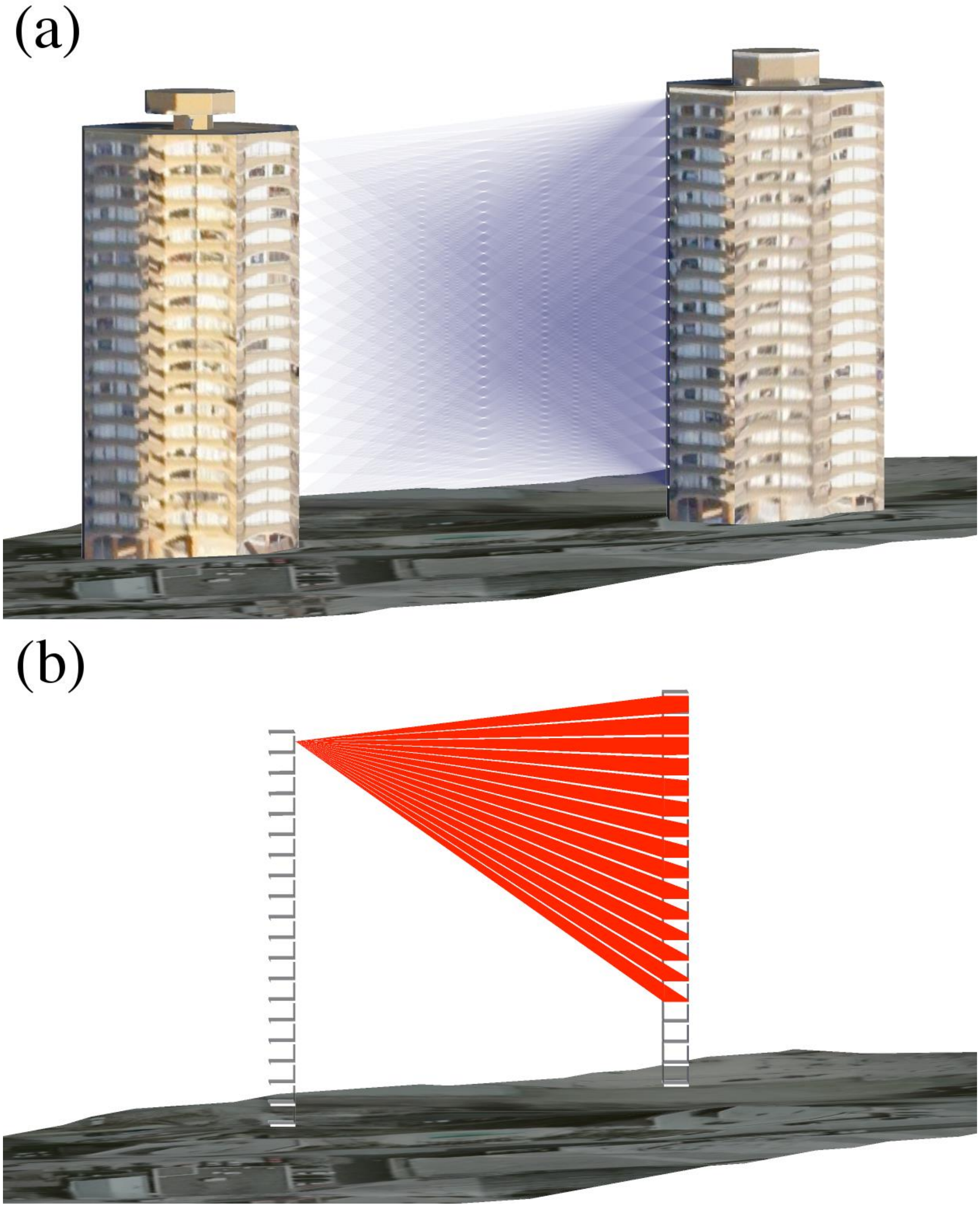
2.5.1. 3D Isovists and Urban Privacy

Using urban privacy as an applied context, I demonstrate the potential applicability of both topologically 3D isovists and expanded isovist typologies in order to overcome limitations that arise from traditional approaches to visibility analysis in urban space. Apartment buildings serve as observational platforms that gaze upon and into cityscapes, but may also obstruct (and be obstructed by) urban geometry. SketchUp 8 was employed to develop the 3D isovists for this project. Although this is changing, contemporary GIS software platforms, such as ArcGIS, do not yet have the capacity to create the necessary geometries and perform the desired analyses in the detail that this approaches requires.

Our research focused upon two Vancouver apartment buildings located at 1616-1666 Pendrell Street. I generated a series of 3D isovists from lines along the faces of each window of each floor. The isovists were generated from horizontal linear origins located 1.5 metres off of the ground at each of the 19 building's floors. This is representative of an observer standing at any point along the window; as such, I represent potential visibility.

Using the conceptual framework of the targeted isovist introduced above, I examined the capability of the isovists to view a volume of space 3 metres deep into the opposing building. Under the targeted isovist classification scheme described in section 2.4.4, these geometries are defined as line-to-volume targeted isovists. Figure 2-6a reveals the entirety of targeted isovists originating from Building A.

Figure 2-6. Targeted Isovists Applied to Two Apartment Buildings



Targeted isovists are projected from the left building (a). Line-to-volume targeted isovists are projected from one building to another (b). The origin of the isovist is a line along the top floor of the left-hand building, while the target volumes are apartments in the right-hand building.

A sample-targeted isovist is shown in Figure 2-6b. The volume represents all that can be seen of a specific target area from a certain viewing location and the observer's view-path. My specified target areas are apartments in Building B. 19 targeted isovists were created per floor for a total of 361 targeted isovists; each one revealing the visibility of a target space within Building B from Building A.

By selecting key isovists for visualization, relative privacy and isovist-origin specific privacy can be revealed. I exposed specific volumes of an apartment and their relative visibility from differing vantage points (the top, middle, and ground floors of Building A). The resulting geometries show visibility from different origins varies throughout the targeted building (Figure 2-7a and Figure 2-7b).

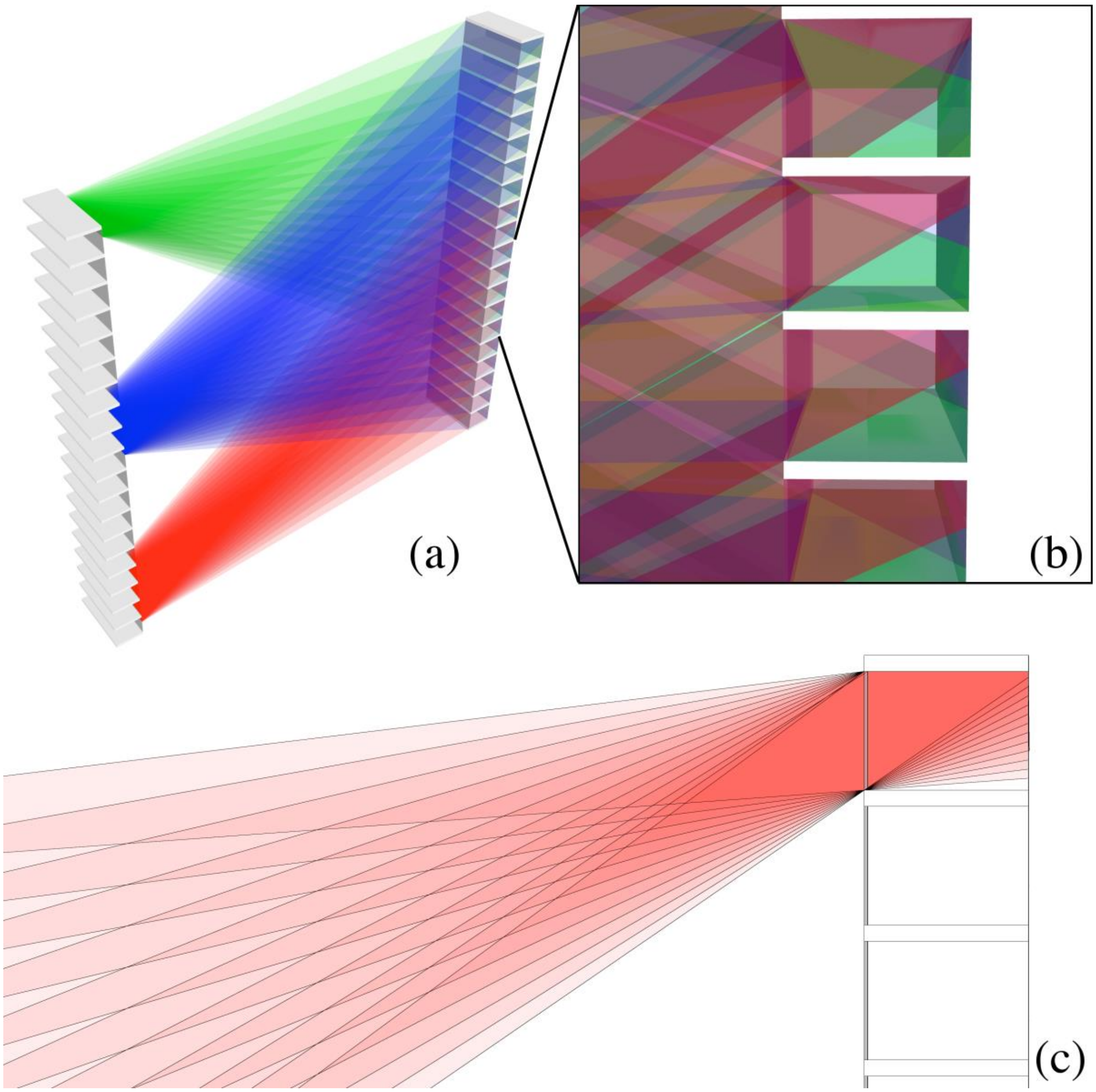
Relative privacy of target spaces can also be demonstrated. A specific apartment was queried and all of the targeted isovists that breach that volume of space were visualized (Figure 2-7c). This can be considered a topologically 3D cumulative visibility analysis. The accumulation of geometry reveals a pattern; spaces close to the window and ceiling are more visible while space is less visible as one moves into the room and approaches the floor.

As a final exercise, I applied a classification scheme to the building floors in order to represent cumulative visibility and privacy from floor-to-floor. A projection all of the targeted isovists was used to classify each building floor. An isovist was counted if it incurred a privacy violation (defined as an isovist encroaching at least 3 metres into an apartment). These incursions were tallied and a symbology was applied to the 3D model of the apartment building (Figure 2-8). The least private floors have 17 privacy incursions, while the most private floors have only 11. The resulting product reveals relative privacy that is not only visualized using the buildings' 3D geometry, but is defined by it.

2.5.2. Dynamic Isovists for Dynamic Observers

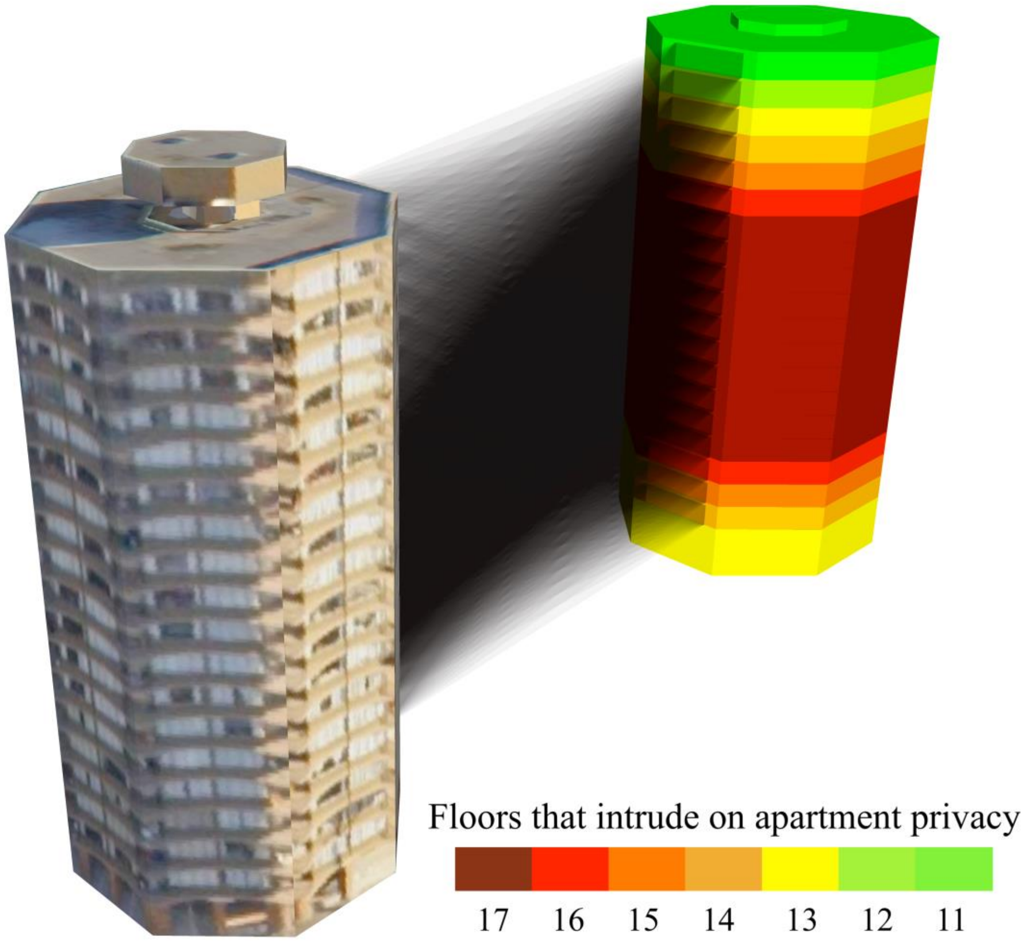
We have previously discussed the use of line-, area-, and volume-to-target isovists to reveal potential visibility from mobile observers; however, this does not capture their moment-to-moment dynamism. Static visualscapes do not offer an adequate solution to this problem. In response, I developed 2D animations revealing the mobile isovists of cars along major Vancouver streets with the goal of illustrating the advantages of dynamic isovists and the necessity of a dynamic isovist classification scheme.

Figure 2-7. Overlaying 3D Isovists to Classify Space



Overlaying multiple targeted isovists (a, b) can reveal the relationship between visibility origins, targets, and spatial configurations. Relative privacy of a specific target volume is revealed by visualizing only the targeted isovists that enter a targeted space (c).

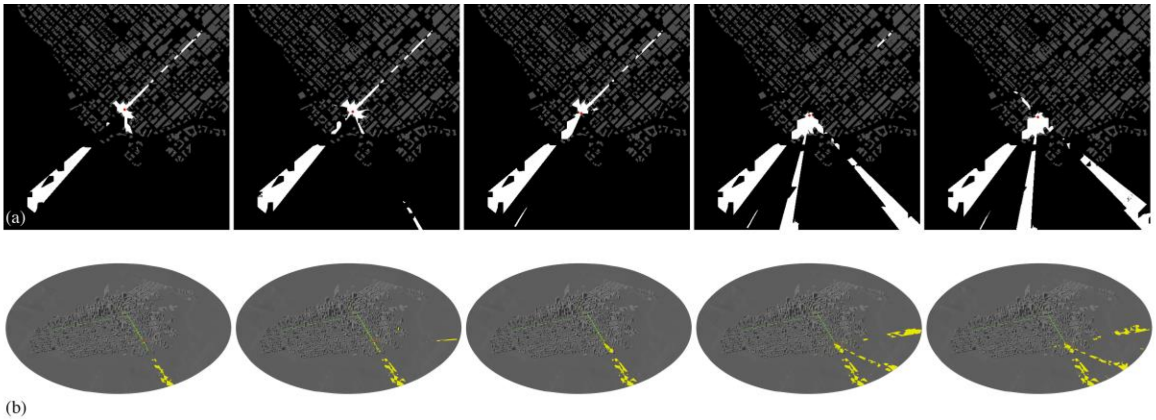
Figure 2-8. Classified Privacy of an Apartment Building by Floor



A simple classification scheme is applied to the apartment building in order to reveal patterns of privacy. This classification both uses topologically 3D geometry and is based in topological 3D analysis.

We generated 2D isovists at equal intervals along streets within the downtown core of Vancouver using a 2D DEM containing building elevation data. A 2D animation was then developed from this analysis. By animating individual frames in the proper temporal order, the mobile viewshed of a dynamic observer can be visualized (Figure 2-9). Draping the isovist onto an extruded DEM resulted in an additional (2.5D) visualization. The isovists used in this analysis can be defined as mobile and scanning isovists given my previously discussed classification schemes.

Figure 2-9. An Animated Viewshed in an Urban Environment



Still frames from a 2D (a) and 3D (b) animation revealing the viewshed of a mobile observer in Vancouver's downtown core.

The animations in both 2D and 2.5D capture the dynamic aspect of urban entities in a manner that static visualscapes do not. As the animations progress through time, the isovists shift accordingly. Differences between the 2D and 2.5D visualizations reveal the limitations and advantages of the respective approaches.

The 2D animation does not adequately represent the complex and vertical topography of a downtown core. It is possible to visualize viewsheds on nearly horizontal surfaces; however, the vertical sides of skyscrapers are nearly impossible to see. Only a few cells are illuminated in a top-down view, while in reality the observer should be able to see the entirety of a building's imposing vertical surfaces.

The 2.5D animation improves the communication of visible vertical surfaces; however, it is not perfect. The viewing angle of the visualization has been changed so that building faces can be observed. Users are now able to determine what portion of a particular building face is visible. Additionally, the scale of visual space dominated by the building faces is fully revealed. Downsides to this approach include the occlusion of buildings and building faces that are hidden behind other geometries; however, this problem is not unique, as all 3D visualizations must deal with this limitation in some fashion.

2.6. Discussion

2.6.1. Conceptualizing Isovists

Isovist theory and isovist analyses have gained considerable momentum in the spatial analytical literatures. In part 2.3 above, I considered the way in which isovists are typically conceptualized in spatial analysis. Definitions of isovists include: "the set of all points visible from a given vantage point in space" (Benedikt, 1979, p. 47); "...the visible space from a vantage point..." (Morello & Ratti, 2009, p. 837); and those by Batty (2001) and Turner et al. (2001). In many cases, the isovists used in analysis are implicitly panoptic, and unconstrained; however, the differentiation of constrained isovists from panoptic isovists is important enough to warrant clear distinction.

While exciting and sophisticated 3D isovist research is present in the field of Urban Design (Batty, 2001; Conroy & Dalton, 2001; Engel & Döllner, 2009; Fisher-Gewirtzman, 2012; Fisher-Gewirtzman & Wagner, 2003; Shach-Pinsly, Fisher-Gewirtzman & Burt, 2011; Turner et al., 2001) 2D isovists dominate contemporary visibility assessments (Bhatia, Chalup & Ostwald, 2012). Often, these constructs are simply referred to as isovists; however, this conflates what is being represented. 2D isovists are subsets of a 3D isovist. Computational restrictions in early years necessitated the use of 2D isovists in lieu of more complex geometries. This restriction has and will likely continue to diminish given advances in computing technologies. While some applications may not require 3D analysis, progress in the conceptualization of 3D versus 2D geographic space and spatial analysis should enable researchers to more specifically qualify the mode and dimensionality of visibility analysis used. I proposed more nuanced specifications of their panoptic versus constrained natures, and their dimensionality.

2.6.2. Isovist Origins and their Influence on Isovist Geometry

In the same way that panoptic isovists have tacitly been the default approach to visibility analysis, the majority of visibility analyses have used point geometry for isovist origins. Leveraging Lynch's (1960) specification of urban geometry, Morello and Ratti

(2009) present and discuss methods to compute isovists for urban features. These isovist analyses were perhaps more focused on the geometry of the urban features rather than the geometry of the isovist origins.

There is nothing wrong with the use of point origin isovists per se. Given the correspondence between a geometrical point and a singular human observer, or the optical origin of a camera system; however, other isovist origin geometries are possible, and may be more suitable to the geometry of analysis in specific contexts. The result of this approach might be isovist fields that are more representative of the real world. Batty's (2001) conceptualization of isovist fields provides us with some of the foundation for this observation, and with some of the fuel with which to expand my conceptualization of isovist origins and their geometries:

> Isovists can be defined for every vantage point constituting an environment, and the spatial union of any particular geometrical property defines a particular isovist field. (Batty, 2001)

While Lynch (1960) and many people since, have differentiated the geometry of urban features, perhaps we need to apply equal attention to the geometry of isovist origins. Vantage points may in fact be vantage lines, areas or voxels. As Batty (2001) points out, an isovist field results from the spatial union of geometrical properties of each particular case. So perhaps I might respectfully extend this definition by suggesting that:

> Isovists can be defined for every combination of origin geometry (the geometry of observation/origin of visibility analysis) and target geometry (i.e. the object/feature of interest); isovist fields resulting from the spatial union of origin and target geometry combinations.

My proposition reveals other challenges. Benedikt (1979) notes that to quantify a whole configuration, more than a single isovist is required. He suggests the way in which we experience a space is related to the interplay of isovists. This leads him to formulate an isovist field of his measurements. Isovist fields are constructs that record "a single isovist property for all locations in a configuration by using contours to plot the way those features vary through space." (Turner et al., 2001, p. 45)

If isovist fields result from the spatial union of multiple isovists from all possible vantage points, then we must consider how we derive isovist fields. Isovist fields in 3D space present a challenge, given that 3D space contains an infinite set of possible vantage points. Peponis, Wineman, Rashid, Hong Kim and Bafna (1997) draw a comparison with the necessity of sampling points to draw isovists with sampling points for contour maps. If we interpolate an isovist field from a set of discrete set of points along a path, across an area, or from within a volumetric space, where should the origins be? Are informed sample locations better than a regular grid of point isovist origins to generate the isovist field?

Extending the principles introduced by Openshaw's (1984) Modifiable Areal Unit Problem (MAUP) one might find themselves dealing with a Point Isovist Origin to Isovist-Field Interpolation Problem (PIOIFIP)! Should a grid of point origins be used to compute a 3D isovist field, at what sampling resolution should this be done? Cumulative visibility based on 3D and 2.5D isovist analyses typically use a grid of regularly spaced points to serve as the origins of the analysis (Suleiman, Joliveau, & Favier, 2011; 2013). Linear, areal, and volumetric isovist origin points can be used to encompass a wider range of possible visibility geometries, while avoiding the pitfalls of arbitrary point origin choice and interpolation; but, this approach does not allow for any form of immediate cumulative visibility analysis. It appears a choice between revealing cumulative visibility through isovist fields at the expense of a MAUP-type challenge, or revealing binary visibility at the expense of cumulative analysis must be made. The analytical potential for non-point origin isovists appears to be limited at this time.

2.6.3. 3D Isovist Analysis

The targeted isovist conceptual framework offers a new perspective on privacy visualization and supports a new typology of isovists that can be expanded and improved through further research. For example, varying definitions of privacy might be incorporated into the analysis, using the following factors: penetration of windows, reflectivity of windows, building shape, distance decay and viewing angles.

A persistent issue with 3D isovist analyses is that ArcGIS, the most common modern GIS platform, is not yet optimised for this type of analysis. GIS-focused platforms such as ArcGIS appear to be trending towards a fully functional GIS with the capability to deal with complex 3D geometry and 3D viewsheds, 3D isovists, and other forms of 3D visualscape. Because of this, SketchUp 8 was used to design the 3D isovist geometries in this research. Critical limitations result from the use of this software: complex geometry and sightline projection is not possible, there is very limited cross-compatibility with common GIS platforms, a lack of GIS symbologies, and limited geo-referencing capabilities. GIS must be developed further to fully support a topologically 3D approach to isovist analysis and generation.

Other environments are typically used when dealing with 3D isovists, especially in the field of Urban Design. Koltsova et al. (2013) present a tool for analyzing visual pollution by billboards that runs in a Grasshopper for Rhinoceros, parametric environment. Fisher-Gewirtzmann's (2012) most advanced work utilizes Microsoft visual studio 2008 and GKUT (Open GL Utility Toolkit) to analyze and visualize 3D isovists. These tools possess the GIS capabilities; however, given the current widespread use of topologically 2D GIS environments, these 3D tools have not been implemented to their full potential.

2.6.4. Computing Animated Isovists along Paths

Computing static isovists for paths has been associated with visibility analyses along street networks; however, it is not representative of dynamic observers such as pedestrians and automobiles. Computing a visibility isovist for a path is certainly possible in 2D or 3D; using a spline as the origin for ray tracing, for example. This static approach would result in an analysis of visibility potential along a path, outside of time. Using the same method to compute visibility for a pedestrian along a path would not match the pedestrian's temporal mobility in space at each spatial coordinate along the path. This suggests a discontinuity between the conceptual/computational construct and the phenomenon for which it has been generated. An adequate representation of visibility for an individual along the path would require a moving isovist origin matching the location and speed of the pedestrian along the path.

The implication of this relationship is an important one. Visibility analyses from paths can create challenging discontinuities between space, time and the phenomena being observed. Being everywhere along a path at once (i.e. ray tracing from a spline) is physically impossible for an individual, but may fit evaluation of a surveillance camera system design.

While a moving isovist may be a better fit for computing visibility for a moving agent, it raises further challenges. An excellent example of this is Google's Street View system. Google's Street View data gathering agents move along paths to generate full coverage of views along road networks; but, the very fact that the data gathering system moves along these paths, and stops to capture each panoramic image group tells us that two important things are going on. First, the imagery - while contiguous in appearance once images are stitched into 360 panoramic images – is in fact a discretization of space. Second, because it takes time to travel from each sampling point to the next, there is a time shift between adjacent samples. Scaled to entire surveys, there is considerable time dilation across geographic space.

These considerations are critical to understanding what isovists do (and do not) capture, and what they therefore do (and do not) represent as samples of geographic space and time. Compelling visualization environments often distract us from these considerations.

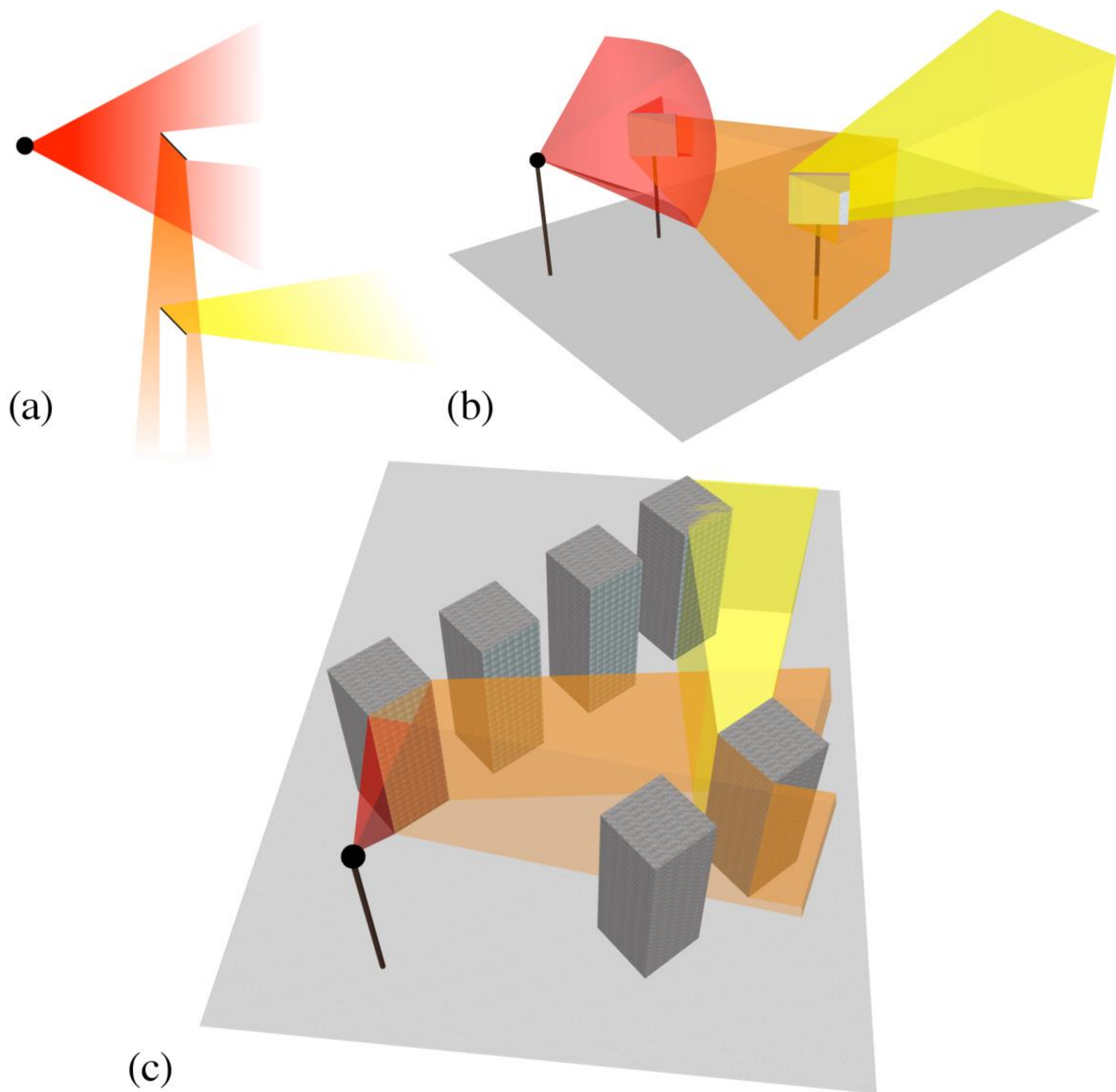
2.6.5. Extending Isovist Types: Second and Third Order Isovists

Further differentiation and classification of the typologies introduced in section 2.4 are both possible and are likely to be useful for visualscape analysis. One such extension is language that can encompass the geometries of isovists formed through reflections and refractions.

Traditional isovist analysis assumes Euclidean LOS; that is, an observer's view path extends linearly from the origin and terminates upon encountering certain materials. In spatial configurations where reflective surfaces are present, observers can gain additional visual information via light reflected off of those surfaces. Features that would normally fall outside of a singular isovist become visible to an observer.

An example of this phenomenon is the use of rear-view mirrors in the operation of vehicles. Drivers rely upon reflective surfaces to extend their gaze to the rear of the vehicle in order to see what is hidden from their front-facing perspective. This visibility can be represented by what I define as secondary and tertiary isovists. These are generated from reflective origins (typically areal or volumetric) that fall within a primary isovist generated from an observer (Figure 2-10).

Figure 2-10. Primary, Secondary, and Tertiary Isovists



Primary, secondary, and tertiary isovists represented in 2D (a) and 3D (b), and along a hypothetical urban street. Secondary and tertiary isovists are generated from reflective origins that fall within another isovist.

The refractive properties of air, water, and other transparent mediums may also serve as generators of secondary and tertiary isovists; however, only in cases where one transparent medium transitions abruptly from one to the other. The bending of light through one continuous medium as a result of refraction or turbulence is beyond this research's scope.

The ability to compute reflection and simulate refraction has been possible for some time in the computer graphics and rendering communities. Those in the architectural realm have perhaps done the most to make these capabilities analytical in solar and urban development impact analyses (Shih & Huang, 2001). There remains, however, a considerable opportunity to link these methods to geospatial visibility analysis techniques, and to the problems they are used for - such as privacy and surveillance analysis. In particular, secondary and tertiary isovists (Figure 2-10) might be used to analyze visual surveillance situations where direct LOS do not exist, but secondary or tertiary LOS do (Figure 2-10c).

2.6.6. The implications of 3D Isovists for Urban Privacy

We introduce the targeted isovist terminology in section 2.4.4 in order to both clarify existing isovist research, and suggest new approaches to 3D visibility analysis. The targeted isovist emphasizes information relevant to the targeted space. This might allow for a wider variety of visibility analyses not possible through panoptic or constrained isovist geometries. New isovist origin geometries might open further developments.

Prior research has engaged with similar concepts; however, my typologies help to strongly link isovist theory and other forms of visualscapes. Bartie, Mills, and Kingham (2008) and Bartie, Reitsma, Kingham, and Mills (2010) developed several methodologies for calculating visibility in urban spatial configurations. Included among these is a LOS-based method for calculating the visible portions of a feature of interest (FOI). The authors differentiate their work from traditional 3D isovist analysis "which quantif[y] the space around the observer", as opposed to their work, where "attention is on how much of a target feature is visible" (Bartie et al., 2010, p. 519). My typology unites these conceptual geometries by considering targeted isovists to be subsets of panoptic or constrained isovists. Any LOS analysis that only considers geometries relevant to a FOI would be contained within the larger geometry of a panoptic or constrained isovist.

2.7. Conclusions and Future Work

In this paper I have reviewed the use of isovists and visualscapes for visibility applications. I explored the potential to enhance the analytical capability of isovists, by expanding the geometric conceptualization of isovists, isovist origins, and visibility targets in three dimensions.

We investigated the geometric permutations of isovists that result from different combinations of isovist origins and targets. I introduced an expanded typology of isovists to formalize this work, and as a framework to accommodate geometric complexity in three-dimensional urban environments. These principles were demonstrated with recent research exploring ways to visualize privacy and surveillance regimes in urban environments. I hope this work informs ongoing visibility research, as geographical analyses become more three dimensional.

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Chapter 3.

A Visibility-based Assessment of Tsunami Evacuation Signs in Seaside, Oregon[2]

3.1. Abstract

Tsunami risk mitigation programs often include iconic evacuation signage to direct locals and visitors to safety during a tsunami event. This paper examines sign placement in Seaside, Oregon from a visibility perspective. It leverages existing visibility analysis methodologies characterize the visibility of the community's evacuation signage and reveals patterns in the viewable landscape. Additionally, I develop a topologically 3D approach to visibility analysis using raw LiDAR datasets. This applied works situates a discussion on existing patterns of visibility, how to improve existing signage placement, 2D and 3D representation of landscape, and the importance of visibility analysis. This work aims to stimulate discussion and development of hazard research that incorporates a visibility perspective.

3.2. Introduction

Communities along the Pacific coasts of Vancouver Island, Washington, and Oregon may have as little as 20 minutes to evacuate to safe ground in the event of a tsunami caused by a great earthquake at the Cascadia Subduction Zone (Clague, Munro & Murty., 2003; Xie, Nistor & Murty, 2012). These communities use maps and signage to communicate risk, potential inundation zones, evacuation routes, and assembly

[2] A version of this Chapter has been submitted to *Natural Hazards* under the co-authorship of Nick Hedley and John Clague.

points. Kurowski, Hedley & Clague (2011) provide an extensive review and comparison of educational tsunami evacuation map designs in Washington and Oregon, and how differences cartographic design may result in different interpretations of risk and evacuation.

While map brochures are a key component of an evacuation plan, tsunami evacuation signage is essential for marking routes in the real world. Choices made in sign design and placement can greatly impact the effectiveness of a community's evacuation plan. Kurowski et al. (2011) note variability in how or whether evacuation signs are mentioned in brochures. On-the-ground signage may provide more immediate guidance than brochures, but it is unclear whether physical signage adequately or effectively communicates the evacuation strategy conveyed in maps. Evacuation maps and tsunami signage perhaps operate as two disparate information systems; research is needed to investigate how they serve and connect citizens to risk awareness.

Blue and white tsunami evacuation signage, which is common in Pacific coastal communities, is typically novel for visitors but a familiar sight for locals. I wonder whether their visibility and effectiveness have been adequately assessed. Do we understand how well signage placement and orientation serve community residents and visitors? How many citizens can see signage from their place of work or residence? How many cannot? How many citizens are served by signage that guides them to safe evacuation sites? How well does existing signage communicate the evacuation schemes derived from geographical information systems, typically presented in evacuation map leaflets?

3.3. Scope and Objectives

As a step towards answering these questions, I studied tsunami evacuation sign placement and visibility in the community of Seaside, Oregon, USA. Here I present a detailed analysis of tsunami evacuation signage visibility aimed at: quantifying the spatial relationships between signage location and orientation, landscape, structures and vegetation; improving sign placement and design logic; and showcasing the implications of spatial data and methods used to perform these analyses. By doing so, I aim to demonstrate how new visibility analysis and analytical visualization methods may mitigate tsunami risks. I discuss the outcomes and their implications for tsunami evacuation planning, and hazards research.

Our work uses and compares high-resolution 2.5D and 3D models of Seaside to reveal patterns of visibility at specific points along evacuation routes and within hazard zones. I show how careful consideration of data resolution and dimensionality may provide new insights into the positioning and potential effectiveness of tsunami evacuation signage. I compare patterns of visibility derived from my analyses with existing evacuation strategies and signage.

3.4. Visibility Analysis

3.4.1. Visibility Analysis: Concepts and Considerations

Visibility analysis has developed in a number of fields, including architecture, urban planning and design, and geographical information science (GIS). Several key concepts have become touchstones of this domain of spatial analysis, including viewsheds and visualscapes.

A viewshed is spatial construct that represents the potential visible area of an observer. Viewsheds are generated from a sequence of lines projected from an observer to a 2D DEM or TIN (Bishop, 2003). A visualscape is a "spatial representation of any visual property generated by, or associated with, a spatial configuration" (Llobera 2003, p. 30). Visualscapes are amenable to viewshed, line-of-sight (LOS), and isovist analyses. These constructs and their derivatives are fundamental to an exploration of how we might apply them productively to an assessment of tsunami signage visibility.

A review of the literature on visibility assessment reveals that orientation or field-of-view limitations are not typically considered in scholarly visualscape analyses. There are, however, examples of relevant research, such as Paliou's (2011) examination of the effects of restricting the vertical visual fields of observers in the context of mural visibility. In the real world, visual occlusion is a critical reality in communities that rely on the position, orientation, and visibility of signage to evacuate residents and tourists during natural hazard emergencies.

3.4.2. Spatial Data Representations of Landscapes and implication for Visibility Analysis

Spatial data are required to perform visibility analysis, regardless of the specific method used. As a result, the resolution, topology, and quality of spatial data that are used have fundamental implications for how well the geometric relationships between signage, topography, buildings, and vegetation can be represented, and therefore how well visibility can be analyzed.

Several researchers have examined the importance of accurate and detailed DEMs in the context of visibility analysis. Maloy and Dean (2001) noted the lack of accuracy in predicted viewsheds and suggested that insufficient data resolution may be to blame. However, the fundamental structure of DEMs and other 2.5D GIS approaches also present significant challenges (Bishop, Wherrett, & Miller, 2000; Bishop, 2003) – raster-based grids are used to represent topography, where each tessellated cell contains one elevation value (Guth, 2009; Murgoitio, 2012). This approach is problematic in structurally complex 3D environments where objects such as bridges, trees, and other overhanging objects would not be adequately represented.

A representational and analytical approach that accounts for view-obstructing geometries in three dimensions is essential for an accurate representation of actual on-the-ground visibility in environments that are structurally complex, including urban and forested environments. The importance of 3D representation of landscape has recently been stressed by the U.S. Geological Survey, with the announcement of the new 3D Elevation Programme (3DEP) (GIM International, 2014; United States Geological Survey, 2014), as part of a larger initiative by the U.S. Government to build resilience to climate change and natural disasters through, among other mechanisms, advanced mapping data and tools (The White House, 2014):

> Current and accurate 3D elevation data is essential to help communities cope with natural hazards and disasters such as floods and landslides, support infrastructure, ensure agricultural success, strengthen

> environmental decision-making and bolster national security. (United States Geological Survey, 2014)

Many examples of 3D visual analysis can be found in the fields of architecture, urban planning, and archaeology (Engel & Döllner, 2009; Delikostidis et al., 2013; Gal & Doytsher, 2013; Koltsova, Tunçer & Schmitt, 2013). However, most of this research relies on the use of uniquely developed software, and none, to my knowledge, deals with visibility in outdoor risk and hazard contexts. Additionally, most approaches utilize 3D models of buildings and other structures rather than raw LiDAR return data. Building models may be effective in certain scenarios, but it is difficult to produce accurate vegetation models given its complexity.

Others have attempted to deal with the vegetation issue by using a 'permeability' approach – designing visibility models that reduce the probability of visibility by a permeability coefficient as the line-of-sight passes through vegetation (Dean, 1997; Llobera, 2007). LiDAR-derived elevation models offer a potential solution to both the limits inherent in data resolution and true 3D representation, and obstruction by vegetation and buildings. While I do not consider permeability in this research, I do use raw LiDAR points to develop a unique approach to 3D visibility analysis.

3.4.3. Applying Visibility Analysis to Evacuation Signage

Although Seaside residents are likely to have been exposed to tsunami awareness programs and probably possess an innate knowledge of their community's layout, non-residents are unlikely to have the same level of spatial knowledge. Instead, these non-experts must rely on hazard and evacuation maps, hazard and evacuation signage, and their own visual assessment of the landscape. These strategies are directly influenced by the visibility of objects and the environment.

More sophisticated tsunami evacuation signage visibility analyses are not limited to new technical methods. They are coupled with theories of environmental perception and situational awareness. Gibson's (1979) ecological theory of perception, for example, is potentially significant in the context of tsunami evacuation. Gibson considered relations between agents and environment joined through sets of affordances. Affordances are relations between an object or environment and agents that afford the opportunity to execute an action. An example is a door handle that affords pulling. Natural vision is another concept that Gibson developed: the tendency for human agents to move in directions that permit additional movement; it is achieved by moving from one visually open space to another. In evacuation terms, visibly open movement pathways might encourage movement in that direction.

Applied to pedestrian behaviour models, Turner and Penn (2002) used an agent-based model that implements rules derived from Gibson's affordance principles. They considered the possibility that movement patterns could be reproduced with "rules based solely on building configuration, without recourse to models involving learned paths, goals, or destinations, or any more detailed social theory framework" (p. 474), while at the same time recognizing that other socioeconomic factors affect movement. Ying, Li and Gao (2009) took a similar approach by applying natural vision in a pedestrian simulation in urban space. Visibility and visibility of signage, therefore, may significantly influence evacuation behavior.

Existing research on tsunami-specific evacuation models does not appear to have made extensive use of visibility in simulations. Congestion and navigation time (Taubenböck et al., 2009) are cornerstones in many agent-based evacuee models, whereas cost-weighted distance methodologies (Freire, Aubrecht & Wegscheider, 2011) are used in others. Path-finding algorithms (Mas, Suppasri, Fumihiko, & Koshimura, 2012) are often used to determine agent navigation. I found one study (Yamabe, Nakano & Tani, 2012) that incorporated informative evacuation signs, but it does not appear that sign orientation, size, and visibility were considered. Ngyuen, Chevaleyre and Zucker (2012) also examined the optimization of evacuation sign placement, but the impact of local topography and its effect on sign visibility were not discussed.

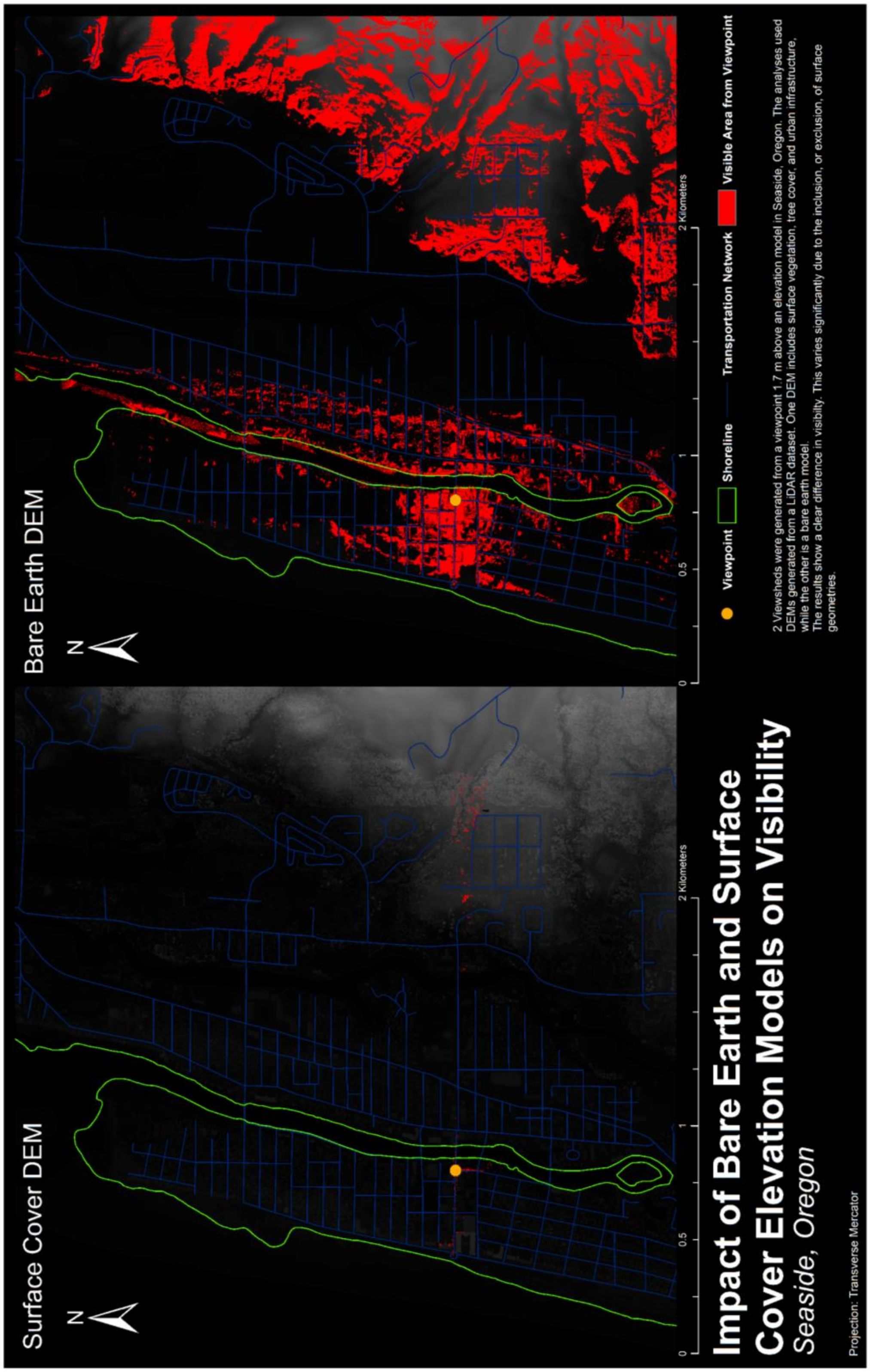
3.5. Methods

Seaside is a low-lying coastal community with a resident population of about 6500 (U.S. Census Bureau, 2013); it hosts a large number of visitors (ca. 40,000) during summer months (Connor, 2005). This community has been the site of a number of tsunami-related studies including geologic studies of prehistoric tsunami deposits (Peterson, Jol, Horning & Cruikshank, 2010), numerical inundation analysis (González et al., 2009), and economic loss modelling (Wiebe & Cox, 2014).

I reviewed guidelines that govern the placement of tsunami evacuation signs in Oregon (Darienzo, 2003). The signs are typically blue, round (although new signs are square and contain the original round design), and 18” (46 cm) and 24” (61 cm) in diameter. Guidelines for sign placement appear to be relatively relaxed – signs must be placed along local government-designated evacuation routes; the iconic wave curl should point towards high ground; and optional arrow signs are recommended for use in tandem with the round design. Placement of evacuation signs, however, appears to be left to the discretion of local governments and road workers. A review of the literature on tsunami evacuation signs did not yield any results on the effectiveness of placement.

Our research examines signage visibility from both topologically 2D and 3D perspectives. In both cases, I acquired 2009 LiDAR data (8.61 points per square meter) for Seaside, which are available online through the Oregon Department of Geology and Mineral Industries. I converted the raw LAZ files to LAS datasets using LAStools for use in ESRI’s ArcGIS. Return data were extracted from these files and converted into two 1-m resolution DEMs. I then created a bare-earth model and a DEM that includes surface cover (including trees, vegetation, and urban infrastructure) for use in topologically 2D analysis. Figure 3-1 shows significant differences in visibility when different representations of landscape are used – in this case, a bare earth model versus one that accounts for surface vegetation and buildings) The unconverted LAS datasets were also used for topologically 3D analysis.

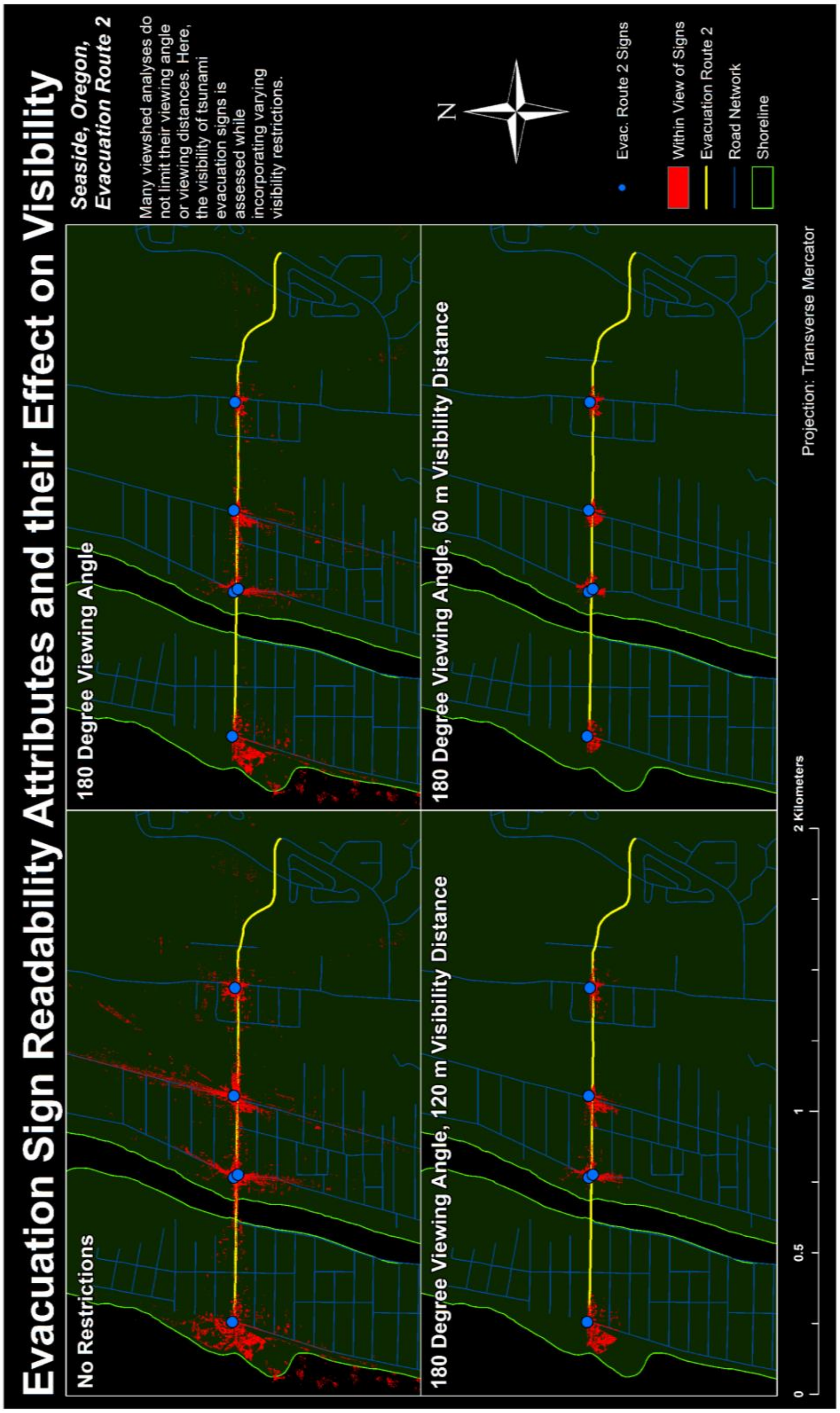
Figure 3-1. The Effect of Surface Geometry on Raster-based Visibility Analysis



I defined evacuation routes using a combination of official evacuation maps, unofficial shapefiles, and Google Street View imagery (September 2013 capture dates). Official maps (Oregon Department of Geology and Mineral Industries, 2013) use black arrows to indicate the general direction in which evacuees should move, rather than defining exact pathways. Exact route data were found online (Duh, 2007), but could not be verified as being up-to-date. Given the lack of both exact and official data, I developed my own GIS datasets by digitizing the locations of signs and routes found in Street View. Official and unofficial maps were used as guidelines, and the road network was acquired from the Oregon Department of Transportation (2012). I identified six evacuation routes and recorded the location, height, and orientation of their evacuation signs.

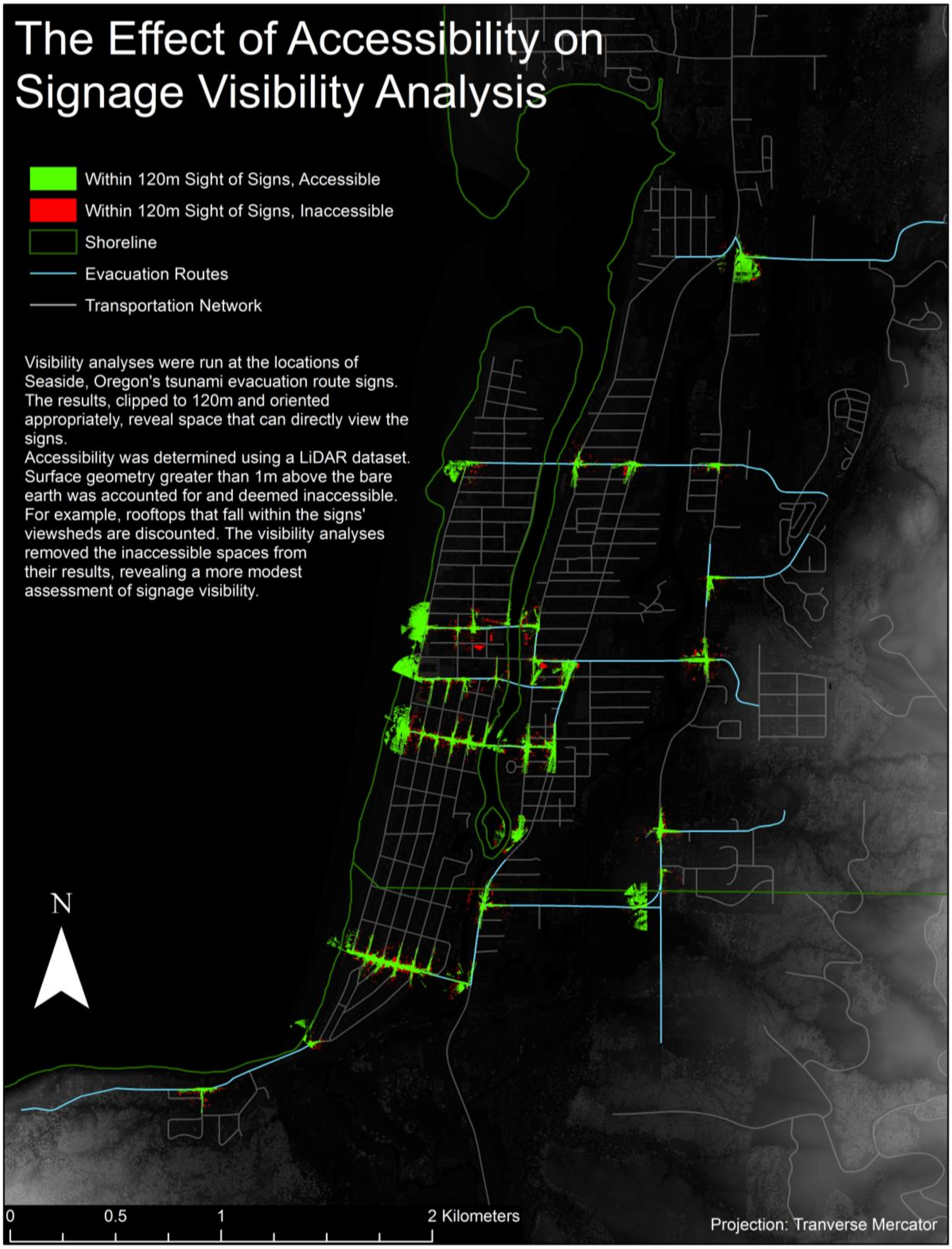
I performed viewshed analyses using the locations of the signs as origins and surface-cover 1-m resolution DEMs. The resulting visualscapes represent space that is visible to the sign; but, more importantly, they reveal space in which an observer can view a sign through the principle of intervisibility. In other words, the visualscapes represent informed space. I applied radius and distance limitations in the analysis to account for the geometry of the evacuation signs. For example, a one-sided sign is not visible from the rear, so a 180° restriction of the visibility analysis restricts visibility from that side (Figure 3-2). The above results included many surfaces that are not ordinarily traversable or relevant during an evacuation. I therefore removed visible surfaces that correspond to non-traversable spaces such as trees, shrubs, and rooftops (Figure 3-3). Visibility distances were set at 60 m and 120 m, in accordance with official recommended values for similarly sized signs in New Zealand (Ministry of Civil Defence & Emergency Management, 2008).

Figure 3-2. Observer Attributes and their Effect on Visibility



Variations in angle and radius of visibility create very different representations of what is considered visible.

Figure 3-3. The Effect of Accessibility on Signage Visibility Analysis



Space that is visible to an evacuation sign is not always relevant to evacuees. Treetops and building roofs should not be considered when highlighting areas that fall within sight of a sign.

I determined visibility to and from evacuation routes from the entire length of the route, rather than assessing visibility from singular points. I split each evacuation route into viewpoints located at 1-m intervals. Viewsheds were then calculated from each viewpoint at a height of 1.7 m, and combined into a single dataset. Each cell contains a count of the viewpoints from which that cell is visible. For example, if a cell has a value of 32, that cell is within the viewshed of 32 viewpoints derived from the original linear geometry. Higher values represent relatively more visible spaces. I repeated this process using the entire Seaside road network, viewpoint intervals of 10 m, and viewpoint heights of 1.5 m to create a cumulative visibility product for the city as a whole.

I developed dynamic viewsheds along the evacuation routes at 1-m intervals and then combined the viewsheds into a time-enabled data layer that shows the potential view of an evacuee at a variety of points in time or space. Whereas cumulative visibility analyses show total visibility from points along a route as a whole, these results display moment-to-moment visibility from singular points. Using the temporal datasets, I plotted route vision profiles (Conroy & Dalton, 2001) of visible space along the evacuation routes based on distance from the route origin.

I applied the above methods using topologically 2D representations of my study area. Using the 3D LiDAR datasets, I developed a methodology based on a topologically 3D approach to visibility analysis. Here, I describe an approach that only requires basic ArcGIS 3D analysis tools and raw LiDAR points.

Using the LAS datasets, I separated ground and surface cover returns in a 120-m diameter LiDAR point cloud subset surrounding an evacuation sign. 3D sightlines were generated between the sign's position and every LiDAR point within the subset. I created a topologically 2D TIN from the ground return points. Fifty-centimetre 3D buffers were then generated around the remaining points, representing trees, shrubs, buildings, and power lines. The final step was to perform a LOS analysis. I checked the 3D sightlines to see if they intersected the TIN bare-earth surface or if they came within 50 cm of a surface cover LiDAR point. Wherever an intersection occurred, the sightline was clipped and the obstruction position noted. The result is a series of 3D lines and LiDAR points that can be seen from the evacuation sign's position.

3.6. Results

3.6.1. Point-origin Viewsheds from Signage Locations

Figure 3-4 illustrates Seaside's evacuation sign coverage at visibility distances of 120 m and 60 m. Further analysis yielded datasets that reveal regions where signs provide essential evacuation communication and where there are gaps in informed space. Fig. 5 indicates the visibility and non-visibility of evacuation signage in the 100-year tsunami inundation zone (Wong, 2006). The results generated with this approach suggest that there are many areas that are not within sight of an evacuation sign.

The type of land cover that is within sight of an evacuation sign provides a sense of who would benefit from particular placements of signage (Figure 3-6). My analysis suggests that existing signs effectively target the most important spaces – they primarily serve more populated areas and the ocean shoreline. The inverse of this analysis, in which I visualize and quantify land cover types that fall outside evacuation sign viewsheds, reveals patterns in the 'uninformed' landscape. Most of the space that is not within sight of evacuation signs is more sparsely populated.

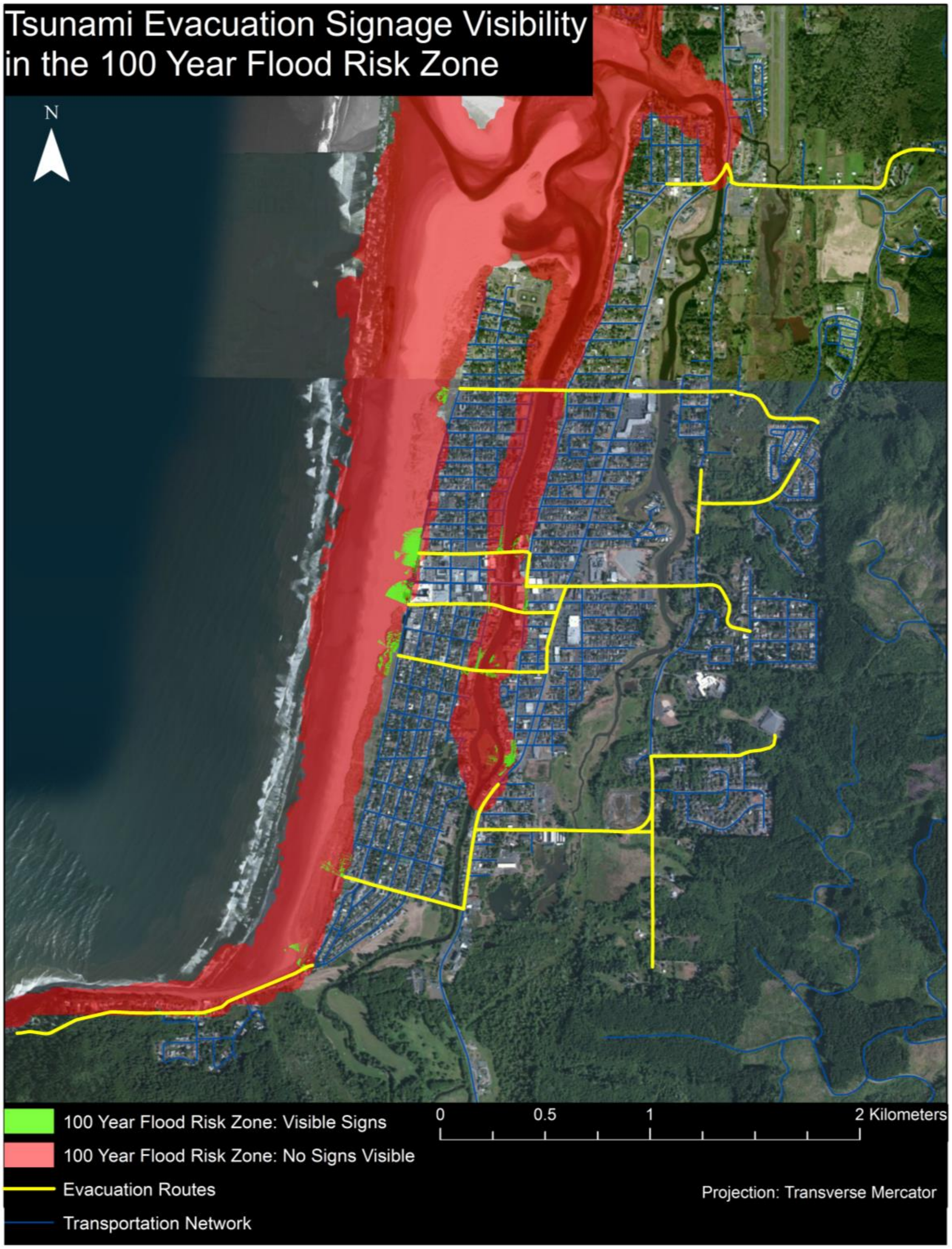
3.6.2. Cumulative Visibility from Roads and Evacuation Routes

Cumulative visibility at the scale of the entire Seaside evacuation network is shown in Figure 3-7. Hilltop tree cover and cliffs in south Seaside are associated with high visibility, whereas clear-cuts and building rooftops have low or no visibility. The most visible point can be viewed from 29% of the city's transportation network, suggesting the existence of potential landmarks for navigation. Cumulative viewshed analysis of the individual evacuation routes reveals regions within the study area that are visible from large sections of the evacuation route (Table 3-1). In particular, analyses of routes 1, 2, and 6 indicate that an evacuee would be able to see at least one landmark from nearly 75% of the routes.

Figure 3-4. Tsunami Evacuation Route Sign Visibility

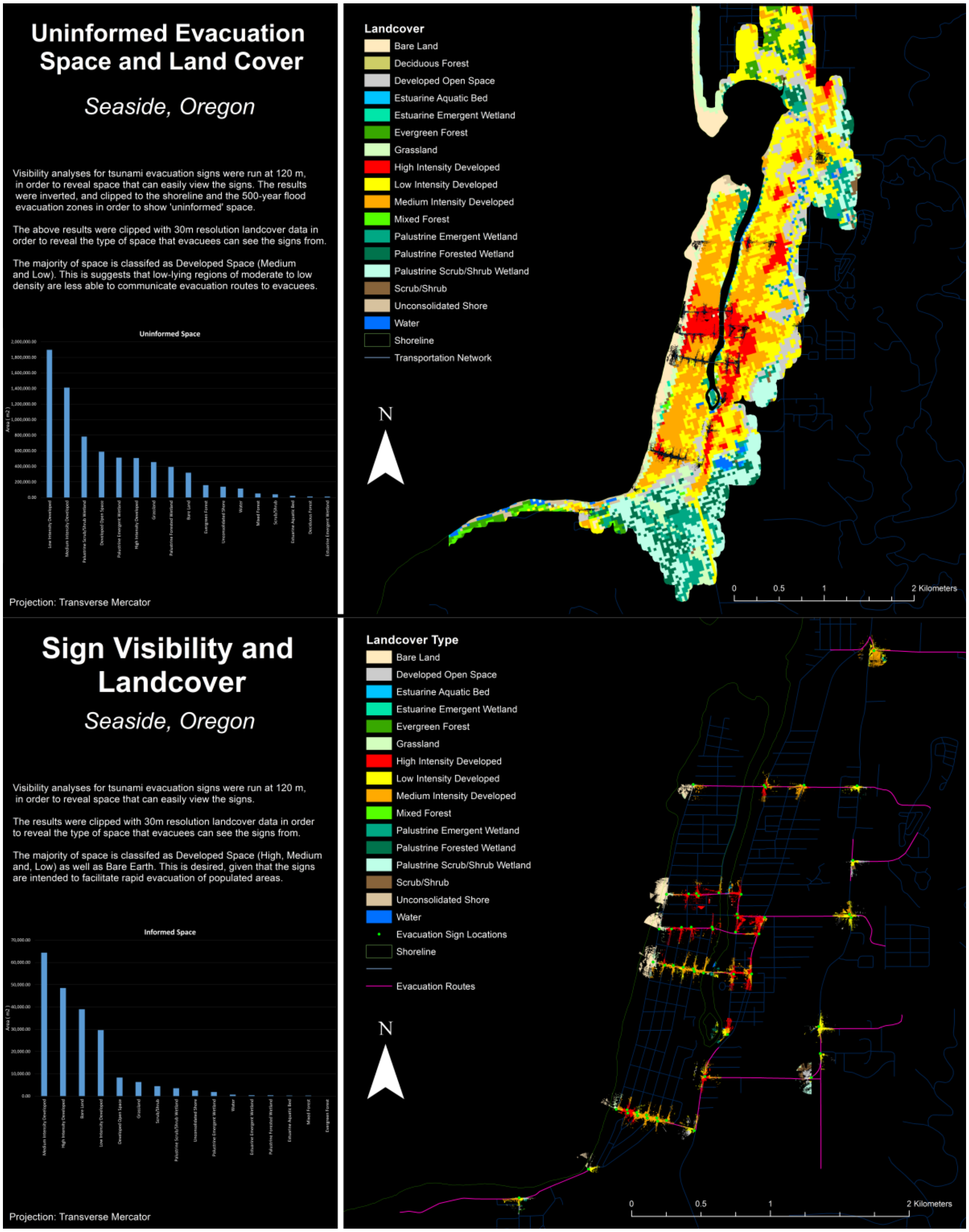
The visibility of signs differs greatly depending on the selected visibility distance.

Figure 3-5. Tsunami Evacuation Signage Visibility in the 100 Year Flood Risk Zone



The most at-risk areas in Seaside have gaps in sign coverage, although much of this space is sparsely populated.

Figure 3-6. Tsunami Sign Visibility and Land Cover



Visibility and other spatial datasets, such as land cover, indicate whether sign placement reaches its intended audience.

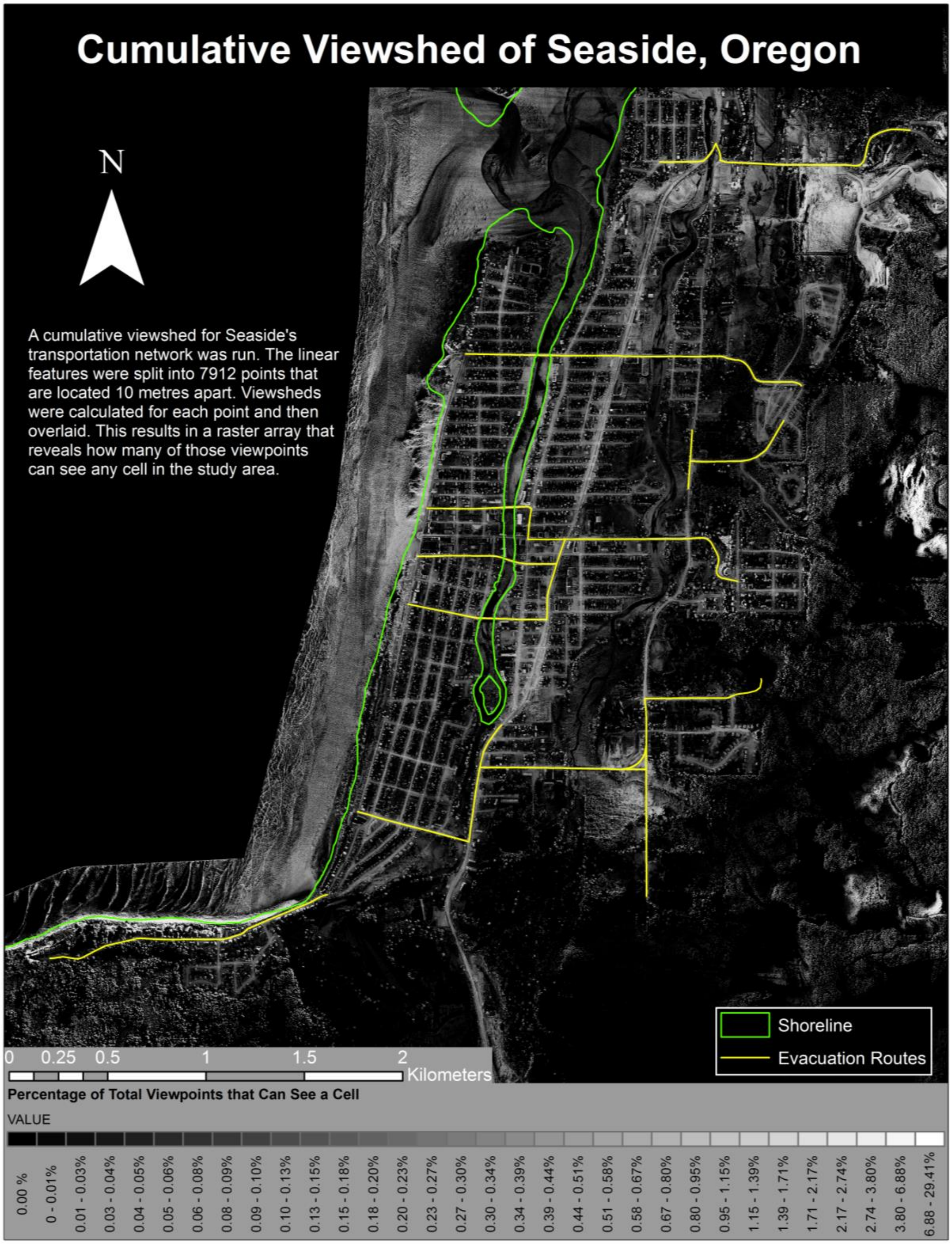
3.6.3. Animated Viewsheds for Evacuation Routes

Figure 3-8 shows key frames derived from the animation of visibility along route 1. The visualization provides moment-to-moment information on mobile observer visibility. I paired a route vision profile for route 1 with information on elevation, hazard zone location, and sign visibility to give a sense of the relationship between visibility and various characteristics of the landscape (Figure 3-9). There are significant differences in visibility profiles along the six routes. Route 3, for example, is comparatively short and does not offer large vistas. In contrast, route 6 begins in a highly viewable open space, but visibility suddenly drops off due to obstructions that limit evacuees' viewsheds.

Table 3-1. Cumulative Viewshed Highly Visible Space Results for Seaside Evacuation Routes

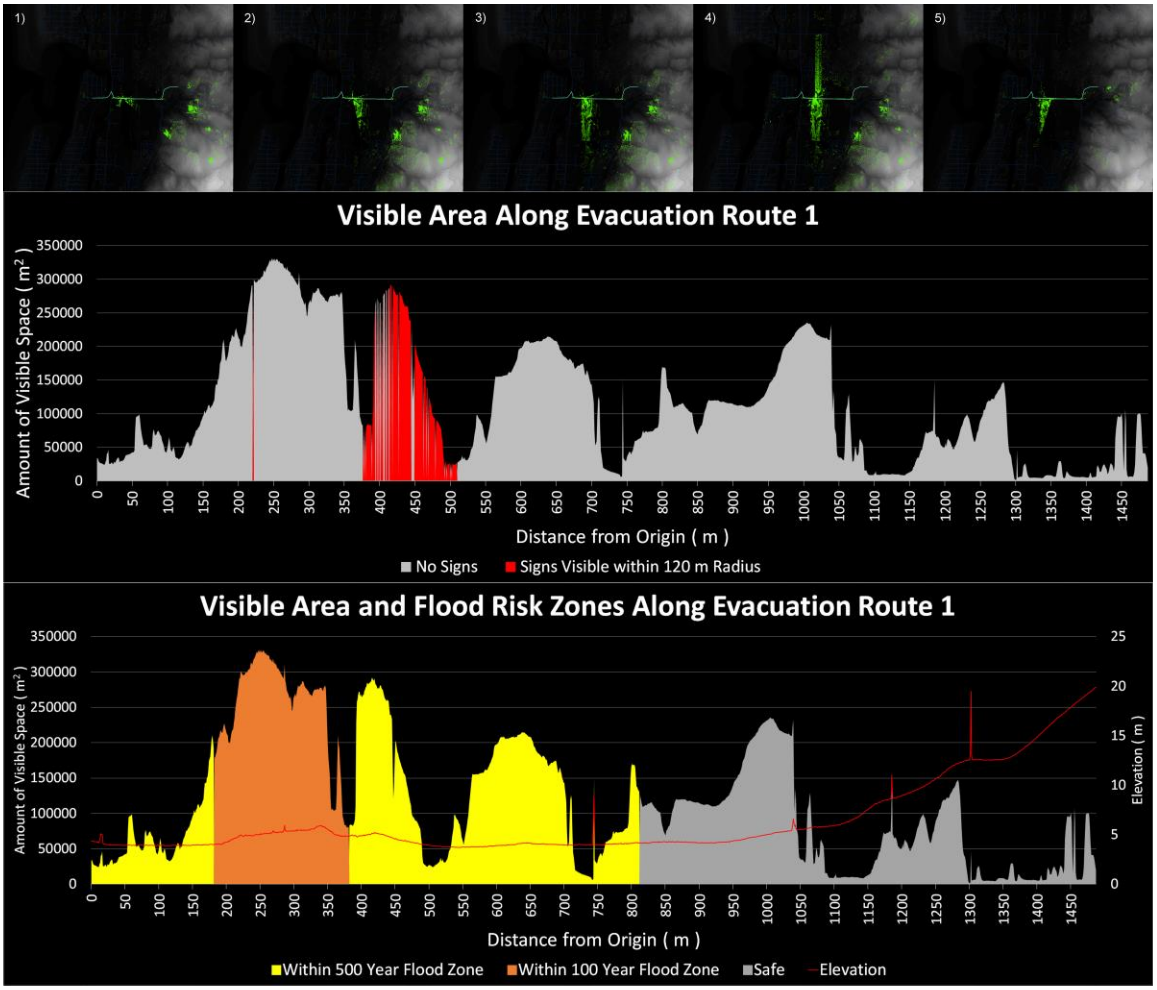
Evacuation route	Percentage of route with view of the most highly visible space
1	72.2%
2	74.5%
3	49.7%
4	67.2%
5	43.7%
6	74.6%

Figure 3-7. Cumulative Viewshed of Seaside, Oregon



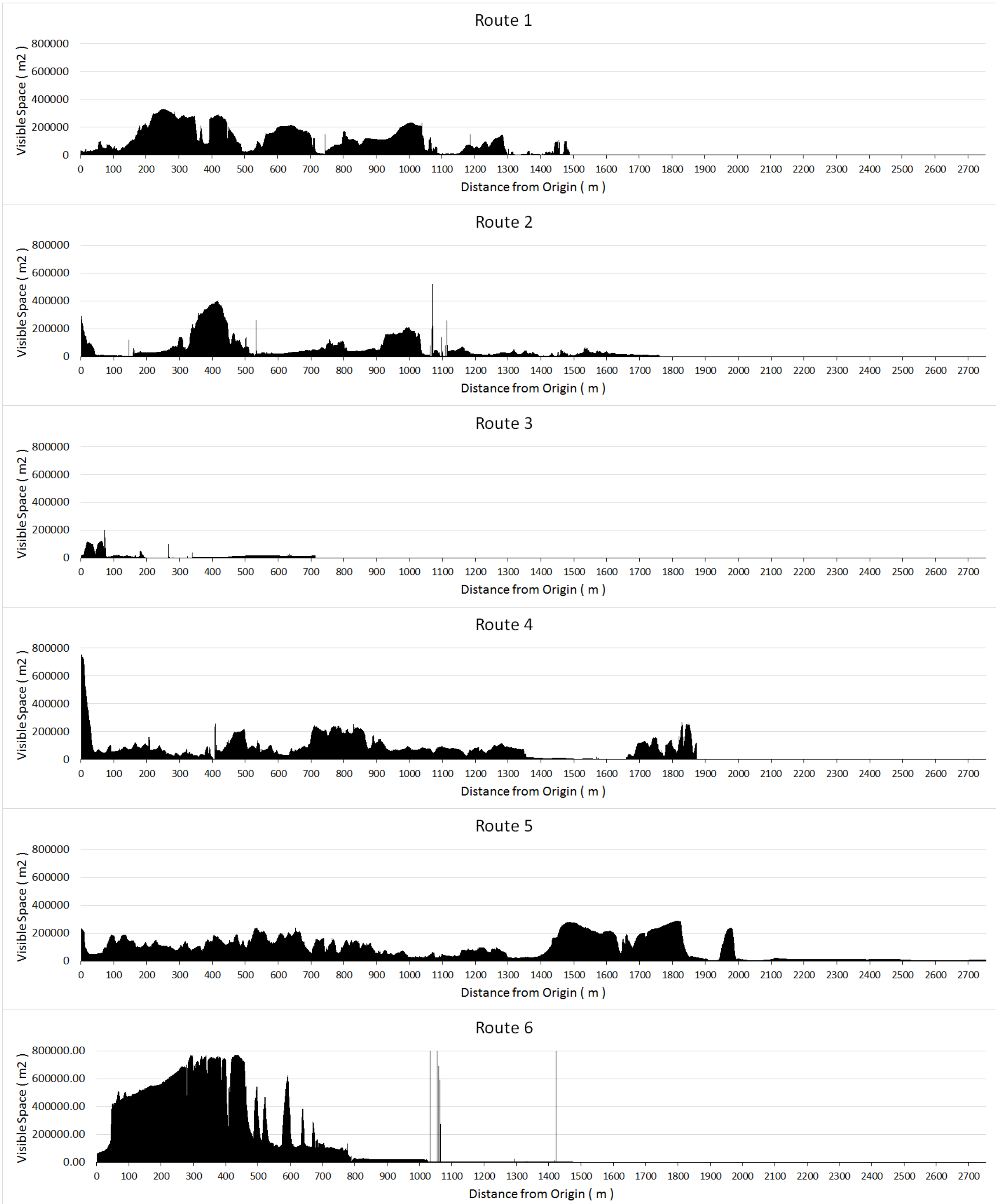
Cumulative viewshed analysis reveals patterns in relative visibility of the landscape. Seaside's roads, cliffs, trees, and tall buildings are comparatively more visible than clear-cuts and backyards.

Figure 3-8.   Animated Viewsheds for Evacuation Routes



Animated viewsheds provide dynamic visualizations that represent a viewshed of a moving evacuee. The data can be visualized, along a temporal or distance-based axis, in the form of route vision profiles.

Figure 3-9. Route Vision Profiles for Evacuation Routes in Seaside, Oregon



Route vision profiles for the six evacuation routes show significant differences in visibility experienced by evacuees as they move along the paths.

3.6.4. Topologically 3D Visibility Analysis

The visualscape results presented above rely on topologically 2D representations of elevation data. My use of 3D LiDAR point clouds demonstrates a topologically 3D approach to hazard signage visibility analysis. Figure 3-10 compares the 2D and 3D approaches. Visibility is represented by uninterrupted lines-of-sight between the origin of the evacuation sign and ground or surface LiDAR points.

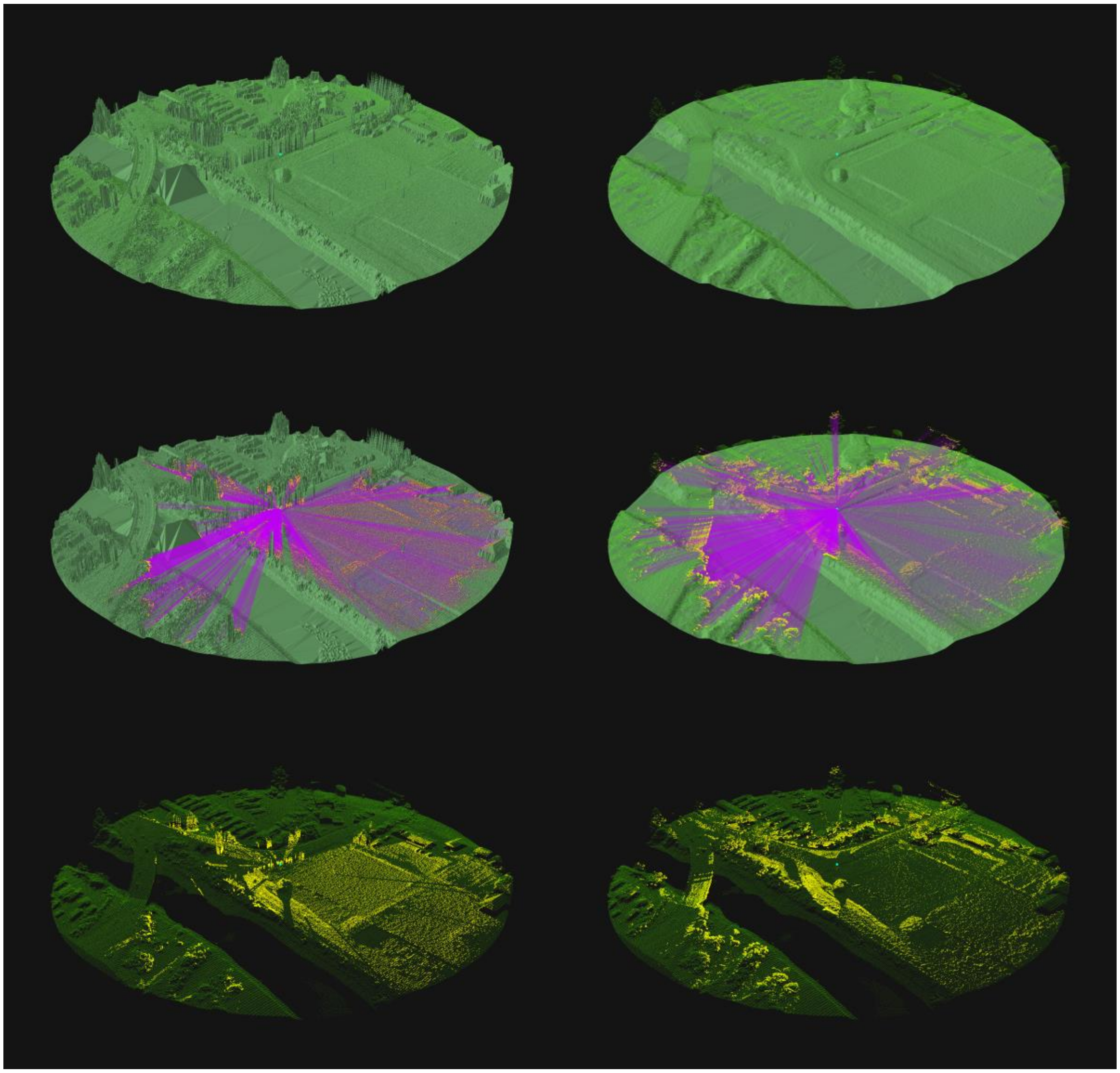
Comparison of the different dimensional approaches highlights the differences between them. Because TINs poorly represent overhanging structures, features such as power lines and bridges are converted into wall-like geometries. This problem is most apparent in the middle of the river where a power line is rendered as an artificial obstruction. In this case, the 2D approach is too conservative; that is, it suggests that the sign is less visible than it truly is. The 3D approach avoids such false obstructions. This can be seen by noting the visibility of the opposing riverbank and bridge-top, which are correctly assessed as visible space in the topologically 3D analysis.

3.7. Discussion

3.7.1. Evaluation of Evacuation Signage

Our assessment of evacuation sign placement suggests that the signs in Seaside are well targeted. That is, the placement of the signs, as well as the evacuation routes, maximizes viewing by the largest number of people in key hazard prone areas. The signs are visible to residents and visitors in densely populated areas and the beachfront (Figure 3-6). Although the placement of existing signs is effective, my results suggest that there is room for improvement. Figure 3-6 also reveals that most space not served within the 500-year tsunami inundation zone is classified as low- and medium-density developed space. The evacuation signs might not be targeted at local residents who have a good spatial understanding of both their community’s risk and evacuation options, but these regions represent significant dark spots for visitors who would likely be unfamiliar with the local transportation network.

Figure 3-10. Topologically 3D Visibility Analysis



2D (left) and 3D (right) representations of landscape can lead to differing LOS results. Raw LiDAR points and the resultant TINs (top), LOS and obstructions (middle), and raw LiDAR points and obstructions (bottom) are shown. A topologically 3D approach does not produce the false obstructions created by the 2D approach, but poses new challenges (see text for details).

Evaluations of individual evacuation routes offer a more detailed view of potential visibility issues and possible solutions. Sign placement on routes appears to be inconsistent. All routes have large stretches of road without any visible signs. Although I did not find any misleading signs, the possibility of missing a sign, and thus a turning point, remains a concern. This issue is compounded by the placement and orientation of many signs. Several signs appear to be placed on the back of stop signs, perhaps as a cost-cutting measure, or are simply one-sided, which reduces by half the potential visibility coverage of the sign.

Route vision profiles (Figure 3-8 and Figure 3-9) offer another metric for evaluating the needs of evacuees. Many evacuation routes are flat and, in some cases (e.g., route 2), terminate at a lower elevation than the origin. Flat routes, in combination with sudden drops in overall visibility and a lack of signage, could cause confusion for an evacuee unfamiliar with the region. These profiles may help to identify problem areas that should be dealt with.

Based on these observations, I suggest some key strategies for improving the existing evacuation communication infrastructure. One strategy is to increase the number of signs along evacuation routes to increase the likelihood that a sign will be viewed. Signs might be placed at every intersection, providing evacuees clear choices when presented with multiple paths. Another strategy is to ensure that all existing signs are double-sided, although cost issues related to increased signage could be problematic. Additionally, there is evidence that a large and sudden increase in safety measures could alarm tourists (Rittichainuwat, 2013), thus there may be opposition from businesses and residents who do not want to frighten potential visitors in a tourism-based community.

Our visibility-based assessment leads us to some observations about Seaside's tsunami evacuation signage and cumulative visibility in the community. Landmark-based processes are one class of navigational techniques humans use to orient and direct themselves (Montello, 2006). Highly visible landmarks can be seen from many of the designated routes in Seaside (Table 3-1). Cumulative visibility visualscapes enable users to identify these highly visible locations – valuable information that may be used in the design of routes, sign placement, or evacuation plan communication. For example, a sign might provide exact directions and also communicate to viewers that they should head towards a specific landmark, such as a mountain, that is visible from most of the route. Navigation and visibility of landmarks have been examined in urban contexts (Delikostidis et al., 2013); an extension of this methodology could be important in natural hazards research.

3.7.2. Comparisons with Previous Work

Visualscape analysis is a valuable new tool in the design and assessment of evacuation routes and signage. Previous researchers have explored evacuation sign visibility (Jeon, Kim, Hong & Augenbroe, 2011; Ouellette, 1993; Wong & Lo, 2007), but they have mainly focused on interior evacuations for fires or earthquakes. Visibility issues dealt with in these scenarios (smoke and darkness from fire and power loss) are fundamentally different from those that would be experienced during a tsunami evacuation (poorly placed signage or vegetation). There is a large body of research on the placement, design, and visibility of road signs (Jacobs, Johnston & Cole, 1975; Johnannson & Backlund, 1970), but the focus of that research is mainly visibility to drivers travelling at high speeds, whereas tsunami evacuation signs are primarily aimed at pedestrians. Koltsova et al. (2013) present an interesting tool for analyzing visual pollution by billboards, but it runs in a parametric environment (Grasshopper for Rhinoceros), not a GIS. It is not clear whether such a tool could be implemented at a community scale or whether vegetation and LiDAR data could be easily integrated. Nevertheless, this research might provide a valuable methodology if adapted to tsunami evacuation.

3.7.3. Limitations of Topologically 3D Visibility Analysis and Spatial Representation

I have presented a topologically 3D method for analyzing sign visibility that takes into account overhanging structures and geometry, unlike TIN or raster surface-based approaches. Topologically 3D visibility analyses are not completely new (Engel & Döllner, 2009; Delikostidis et al., 2013; Gal & Doytsher, 2013; Koltsova et al., 2013), but my use of LiDAR points and GIS software appears to be unique. While the ability to assess visibility in true 3D is advantageous, it has limitations. LiDAR data resolution, data-gathering methods, and representational issues remain significant challenges.

LiDAR data resolution has a strong effect on the quality and value of any visibility analysis. Because my analysis is rooted in the creation and visualization of line-of-sight between an origin and raw LiDAR points, the quantity and accuracy of the LiDAR data points affect the outcome. If there are too few points, not enough lines-of-sight will be generated to provide a sense of overall visibility. Although my reliance on LiDAR returns might be considered a weakness, the fact that LiDAR does not interpolate a surface bolsters my confidence in the outcome. If the LiDAR returns are of sufficient number and resolution, they will produce a more accurate 3D representation of a space than TIN or raster-based approaches.

Methods used to gather LiDAR data bear on the issue of insufficient data resolution. The LiDAR data used in this study were collected from aircraft; consequently returns from flat roofs are more closely spaced (typically more than 1 point per 50 cm) than those from sloping surfaces (e.g., there are few or no returns from building walls). A dearth of wall-defining returns means that a wall will not be accounted for in the visibility analysis. This is less of an issue with a TIN-based approach, because wall geometry is interpolated between the roof and the ground. Terrestrial LiDAR may offer a solution to both the low-wall and resolution issues, because such systems can gather higher resolution datasets at angles that are more relevant to ground-level visibility analysis.

Our approach checks to see if other LiDAR points obstruct a LOS from an origin to a LiDAR point. I used 3D buffers to check if a LOS passes near (within 50 cm) of a LiDAR point, because it is unlikely that any line will exactly intersect a LiDAR point. Essentially, I am representing 3D surface geometries as buffered, opaque, bubble-like features. This representational approach enables representation and analysis of overhanging obstructions, something that is not possible with topologically 2D surfaces. It is, however, an abstraction of the real world. I chose a buffer size that is slightly larger than the average LiDAR density of 8.61 points per square meter. Buffer size has a significant effect on the result, thus its choice requires careful consideration.

3D buffers represent real-world structures with different degrees of accuracy in a visibility analysis. Trees and shrubs are particularly well represented by opaque 3D buffers, given that the return point may be located within a dense tangle of vegetation. Walls and building roofs are not represented as well, because a LiDAR point must be on a flat, well-defined surface that is not surrounded by buffering geometry. A more nuanced approach to topologically 3D visibility analysis may be needed. By leveraging the advantages of my 3D LOS analysis with existing methods for creating bare-earth models and extracting simple building structures, I might develop a more robust methodology.

3.8. Conclusion

In this paper, I have introduced a visibility-oriented approach to the assessment of tsunami evacuation communication. Specifically, I investigated the visibility of signage marking evacuation routes and destinations; the influence of position and orientation of signage on visibility; and the relationship between landscape, building, and vegetation morphology on signage visibility. Using this approach, I found deficiencies in visibility that provide guidance for improving evacuation signage placement design, evacuation sign design, and their spatial relationship to citizens, community infrastructure, and the topographic context of individual coastal communities.

This research focuses on tsunami evacuation, but there is opportunity to apply similar visibility analyses to other problem spaces, such as those affected by volcanic eruptions and hurricanes. By working exclusively in a GIS for most of my analyses, I was able to integrate existing geographical datasets and perform interesting socio-economic analyses. While the fields of urban design and architecture already utilize powerful 3D visibility analytical approaches, the use of non-GIS software limits their potential for further analysis.

Visibility is important in evacuation scenarios, particularly in rapid, time-sensitive events such as tsunami inundations. It is my hope that by connecting existing visibility research to tsunami risk assessments, I have demonstrated the value of visualscapes towards hazard planning, communication, and mitigation.

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Chapter 4.

Flexible Mixed Reality and Situated Simulation as Emerging Forms of Geovisualization[3]

4.1. Abstract

This paper reports on applied research that has resulted in a geospatial mobile augmented reality system that can run *in situ* simulations of dynamic spatial phenomena. In this paper I summarize previous work that has led to a critical convergence of enabling technologies, and identify new forms of geovisualization that they facilitate. I introduce situated simulation as a new form of augmented situated geovisual analysis, using two versions of a prototype called A Touch of Rain. This system allows users to run augmented precipitation simulations in real space, where virtual rain falls onto, and interacts with real landscapes and buildings. This results in an ability to perform augmented geovisual analysis. I describe how this method enables new opportunities to link geospatial data, models and everyday spaces. I discuss implications and opportunities for geographical information science.

4.2. Introduction

Mixed reality (MR) is a field of interface research that holds considerable potential for geographic visualization (Hedley, Postner, Billinghurst & May, 2001; Hedley, Billinghurst, Postner, May & Kato, 2002). In this paper, I describe the application of 3D geovisualization, and mixed reality spatial interfaces to urban drainage and watershed

[3] A version of this Chapter has been accepted in *Cartographica* under the co-authorship of Nick Hedley. Reprinted with permission from University of Toronto Press (www.utpjournals.com).
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dynamics. In doing so, I aim to reveal the potential for *in situ* visualizations of complex and dynamic geographic phenomena to foster new forms of geographic knowledge-building.

MR refers to visualizations and interfaces that combine elements of virtual environments (VE) with the real world. Milgram and Kishino (1994) introduced the 'Virtuality Continuum,' which covers an array of spatial interface types, ranging from entirely virtual environments to the non-augmented real world. Within this framework, MR occupies the middle ground between fully virtual (virtuality) and fully real (reality) spaces. Mixed realities can be composed of different proportions of real and virtual content; these are classified by the MR subtypes of augmented reality (AR) and augmented virtuality (AV). AR interfaces provide views of real world environments augmented by superimposed digital information (Azuma, 1997), whereas, AV environments are predominantly virtual and enhanced by information from the real world (Tamura, Yamamoto & Katayama, 2001).

Mobile augmented reality (MAR) is a variant of AR that enables augmented views of real environments through mobile devices. Hedley (2008) highlights the key benefit of MAR interfaces when compared to non-mobile AR; MAR interfaces possess the ability to reify hidden or abstract geographic phenomena in a variety of real spaces. In other words, spatial information and relationships that are typically hidden from the human eye (such as watershed surface flow) can be made visible *in situ* through the use of MAR. This concept is defined as real-time reification (RTR).

The objective of this paper is to describe work I have done to develop and demonstrate the potential of geospatial mobile augmented reality for situated simulation and geovisual analytics. I present research that leverages mobile technology, MR, and tangible user interfaces (TUI) for the RTR of dynamic geographic phenomena. Several interfaces were developed that allow interactive visualization of watershed and urban drainage dynamics. By allowing users to view geographic information *in situ* and manipulate it using TUIs, I aim to encourage geographic visualizations that are more closely linked to real space.

4.3. Previous Work

This research has resulted from trends in the fields of mobile geographic devices, and spatial mixed reality applications. Geographers have been interested in the emerging mobile information technologies and devices, which have increasingly enabled information use, data gathering, and database access *in situ*. These technologies have improved to the point that real-time visualization of geographic data and objects is possible on lightweight, mobile platforms such as smartphones and tablets. In the following sections, I comment on selected exemplars of these trends. Interest in MR interfaces for geographic applications has been increasing as a result of research by a small number of geographic researchers. The following sections expand on these trends.

4.3.1. Mobile Devices for Geographic Visualization

Mobile devices and *in situ* geographic learning experiences are concepts that have been discussed in earnest since lightweight, wireless, and inexpensive computing technologies have become ubiquitous. In 'Manifesto on Mobile Computing in Geographic Education,' Armstrong and Bennett (2005) suggest four key technologies that might support the future of mobile geographic education: GPS; GIS software; wireless communication; and compact computing devices. Since publication of this paper, additional enabling technologies have developed to be far more than mobile digital devices with which to make conventional content portable. Instead, contemporary mobile devices, sensors, and software can be leveraged for *in situ* geographic visualizations using new modes of spatial interaction. Internal sensors, cameras, and digital compasses on mobile devices unlock the ability to develop orientation-aware applications, while touchscreen TUIs provide new ways to control and explore data *in situ*.

Tablet computing devices such as Apple's iPad and Microsoft's Surface offer examples of devices built around interactive surface concepts. These devices are essentially lightweight, mobile interactive surfaces that can be location-aware, and connected to vast information networks. They typically contain a GPS sensor, accelerometer, compass, video camera, and a display. Together, these hardware elements provide the architecture necessary for creating location-aware MR interfaces.

Mobile computing devices, such as tablets, have become more sophisticated in subsequent years. These location-aware devices facilitate entirely new ways to query and interact with geographic spaces, and new forms of geographic educational experience that result from: collaborative geographic information transactions; tangible user interfaces (TUIs) such as multi-touch devices. Collaborative learning has been found to be facilitated by the use of tablet computers when compared to netbook-type computers. This is a result of both the use of more complex and natural gestures (TUIs) (Alvarez, Brown & Nussbaum, 2011), and their allowance for a higher degree of interaction between digital information and the physical world (Mobility and MR) (Chipman, Fails, Druin & Guha, 2011).

4.3.2. Mixed Reality in Applied Geographic Contexts

MR has been examined in several geographic contexts including: collaborative topographic visualization (Hedley et al., 2001; 2002); navigation (Dünser, Billinghurst, Wen, Lehtinen & Nurminen, 2012; Tsai et al., 2012; Tsai & Yau, 2013), post-disaster damage assessments (Kamat & El-Tawil, 2007), and revealing hidden phenomena (Schall et al., 2009). Many of these MR applications are 'single-use' in that they possess limited applicability beyond their original functions (Billinghurst & Dünser, 2012). MR interfaces have also been investigated in geographic education contexts. Shelton and Hedley's (2002; 2004) work focused on tangible AR interfaces as educational tools, finding two factors supporting AR's use as a spatial interface for geographic education. Firstly, a user retains proprioception within the interface; that is, the user's perceptual frames of reference remain continuous when viewing data and the physical world. Secondly, the user's bodily movements and gestures directly influence the visual feedback of the display itself. Desktop metaphors and clunky mouse and keyboard interfaces are not present in certain AR interfaces allowing a more direct learning experience.

4.3.3. Real-Time Reification for Geographic Education

One of the strengths of VEs is their capacity to reify spatial phenomena that are abstract, inaccessible or invisible in the physical world. This has been achieved in several geographic problem spaces including ocean circulation (Windschitl, Winn & Hedley, 2001; Winn, Windschitl, Fruland & Lee, 2002) and planetary science using tangible AR (TAR) (Shelton & Hedley, 2004). These examples do not reify their respective phenomena *in situ*; the applications display visualizations in spaces that are removed from the location of the subject matter.

Hedley's work on RTR demonstrates that "we can leverage existing reifications of abstract geographic phenomena in conventional geovisualization, [to] bring them into real geographic spaces." (Hedley, 2008, p. 11) In other words, I can make the unperceivable, perceivable *in situ*. RTR differs from basic reification in that spatial phenomena are revealed in an appropriate spatial context. This is demonstrated though a prototype MR device that visualizes a digital elevation model (DEM) overlaid on a live view of Mount Seymour Provincial Park, BC. The DEM is made visible in the appropriate location relative to the physical topography. Early work to explore reification of buried pipes and cables has begun (Schall et al., 2009). Researchers developed a MR device that reveals the location of hidden infrastructure belowground while observing the ground surface. To date, MR based reification is predominantly applied to static visualizations of inert spatial objects. The application of augmented reality to reify dynamic visualizations and simulations of spatial phenomena is a more challenging enterprise that fewer researchers have pursued.

Recent efforts have begun to develop more complex *in situ* visualizations of geographic phenomena. Hedley and Lonergan (2012) have demonstrated early augmented simulation prototypes, while Veas, Grasset, Ferencik, Grünewald and Schmalstieg (2013) demonstrate an interface that allows live updates of environmental sensor readings to be seen in an AR display. Additionally, simulations of flooding can be run offsite and then returned to the onsite display for *in situ* visualization. Such an approach characterizes the latest advancements of MR visualization techniques; however, further development of dynamic visualizations and simulations *in situ* are still possible.

4.3.4. Tangible User Interfaces in Geographic Visualization

A TUI is defined as an interface that allows users to interact with non-physical information though physical means (Ishii, 2008; Ishii & Ullmer, 1997); such interfaces may foster strong collaborative learning experiences (Jordà, Julià & Gallardo, 2010). TUIs have been applied to geographic visualizations in the past; much of this research focuses on providing tangible, graspable objects for manipulation (Cheok, Yang, Ying, Billinghurst & Kato, 2002; Ishii & Ullmer, 1997; Ullmer & Ishii, 2000). In such cases, complex systems of cameras, objects, projectors, and surfaces must be present in order for object-based TUIs to function correctly (Underkoffler, Ullmer & Ishii, 1999). Mobile versions of these large multi-part TUIs are simply not possible; as such, my research focuses on compact interactive surfaces on tablet computers (touch-screens) so as to reduce the size and amount of technology necessary for tangible interaction.

Our research applies interactive surface TUIs (touch-screens) to MR geovisualizations in order to produce a tangible MR interface system that combines both display and interface. This allows users to explore and manipulate data by touching visual representations of the information *in situ*.

4.3.5. Linking Mobile Devices, MR, RTR, and TUIs for Contemporary Geovisualization

The preceding sections provided brief summaries of trends in mobile device use, mixed reality, reification and tangible user interfaces. I believe that there are powerful ways to combine these devices, their location-awareness, and ability to link geographic spaces with abstract data spaces using meaningful geovisualizations. In the following sections of this paper, I unpack these capabilities, and describe recent research I have conducted to demonstrate the potential of MR and TUI for RTR of geographic phenomena *in situ*. I focused this exploration through the lens of precipitation simulation and interception by topography, overland flow, and urban drainage simulation. By creating a location-aware MR interface experienced through a touch-screen tablet computer, I aim to produce a highly situated interface for a variety of geographic applications. This interface allows us to evaluate the augmented reification of hidden and abstract phenomena *in situ*.

4.4. Methodology

I describe here a prototype geovisualization interface that leverages mobile, TUI, and MR technologies towards the RTR of dynamic geographic phenomena. My prototype can be applied to a variety of information visualization contexts; however, I focus on the visualization and communication of watershed and urban drainage phenomena. The following section describes the essential hardware and software components for my prototype interface.

4.4.1. Interface Device

Our prototype was developed for Apple's iPad technology. This device is a tablet computer that possesses all of the necessary hardware components for a TUI- and MR-capable application. The unit is lightweight and thus easily portable in a variety of terrains; this is essential for geographical fieldwork that may take researchers far from controlled environments. Device ruggedness is often inversely related to portability. Device ruggedness takes on renewed significance as my work connects visualizations (previously developed in indoor academic spaces) to outdoor geographic space. Industry has already responded through the retail of casings that protect from simple shock damage, all the way to complete immersion in water.

Location Awareness

GPS capability is a necessity for mobile devices in geographical contexts (Armstrong & Bennett, 2005). MR interfaces require location information so that they may render information based on the user's location on the Earth's surface. If this information is inaccurate, the information will no longer align with, or correspond to the user's surroundings – potentially neutralizing the benefits of *in situ* visualization. This is particularly critical for RTR, as an accurate visualization of hidden or abstract data must be synced to the users position at all times for a 'live' view of the data.

MR requires more detailed information regarding the direction and orientation of the user's relationship with the display. GPS technology provides a user with their position on the Earth's surface. Despite its usefulness for certain applications (2D mapping, navigation, transects), it does not provide enough spatial information for accurate representation of orientation and direction within a MR interface. Additional components are necessary (Table 4-1), all of which must be present at the same location as the user, camera, and display in order to create a comprehensible interface.

Table 4-1. Essential Components of a Mobile Mixed Reality Spatial Interface

Technology	Use in a MR Interface
GPS	Reveals device's location on Earth's Surface.
Accelerometer or Gyroscope	Reveals device's orientation relative to gravity's pull.
Compass	Reveals device's orientation relative to magnetic north
Camera	Provides device with a video stream upon which to render data
Display	Provides user with a live feed of the device's view (Camera) with superimposed information (Calculated from GPS, Accelerometer/Gyroscope, and Compass)

Display System

Many AR systems superimpose visual data onto a live view of the world, either through a projection onto a transparent surface (optical see-through) or by rendering data onto a video feed (video see-though). My research focuses on the latter. Display systems typically fall within three categories: head-mounted displays (HMD), handheld displays or projection-based displays (Schmalstieg & Reitmayr, 2007). My display system may be categorized as 'handheld display' and has two components: a camera and a display.

Similar to the location-awareness components of an MR-capable device, appropriate positioning of display system components is critical to maintaining a comprehensible visualization. Ideally, the camera would face away from the direction the display projects creating the illusion of a transparent surface. Ensuring that the location-aware and display system components are all present on one mobile device can produce a MR 'window' that views real, digital, and mixed realities (see Figure 4-1).

A Mobile TUI

The final technological component required by my prototype is a touch-screen. Given the complexity of multi-part TUIs, and the difficulty handling multiple objects in the field, I have focused on treating the display of a tablet device as an interactive surface rather than implementing another form of TUI. The iPad is capable of supporting multiple touch inputs (multi-touch) at the same time. This opens up the capability to have multi-finger gestures and even multiple users using the same device. By incorporating the touch-screen onto the display of my MR 'window,' users may not only view, but also interact with objects in MR using a variety of gestures.

4.4.2. Geovisualization Interfaces for Mixed Reality

Our research aimed to produce a MR interface capable of revealing watershed and urban drainage dynamics in the real world. As such, I required geographic datasets of terrain and urban spaces. Additionally, a physics engine capable of calculating and visualizing surface flow in real-time was crucial. Furthermore, the software had to be lightweight as mobile devices have comparatively less computational capacity than desktop machines. Appropriate workspaces for both creating MR visualizations and supporting their use were needed.

Geovisualization Development

Depending on the geographic application of a MR interface, the geovisualization development workflow can vary significantly. The requirements of a watershed and urban drainage simulation included a DEM of my study area and the 3D geometry of any urban structures were needed in order to create the sandbox in which the simulation would be run. A bare-earth DEM of the Vancouver North Shore Mountains was imported into my geovisualization interface. For smaller scale urban drainage visualizations, DEM data were combined with local scale urban geometry (such as in Vieux-Quebec, where I did not have access to detailed building models) using tools that included Trimble's SketchUp program. All of these products were exported to the COLLADA format for use in the interface development workspace.

Interface Development

A programming language and software development kit capable of supporting 3D visualizations, physics, location-awareness, video feeds, and touch-screen interfaces in the iOS environment was necessary. No GIS software exists (to my knowledge) that is capable of all of the above. Instead, I selected a 3D game engine, ShiVa 3D, as the platform of my choice. The engine is capable of all of the above with limited support of geographic datasets. Scripts were written in the Lua programming language.

A VE was rendered using the DEM and 3D geometry of the study areas. By accessing the tablet device's locational data, the application is aware of the device's position and orientation in real space, information that is used to locate and orient a virtual camera at the corresponding location within the VE. As the device is moved in the physical world, the virtual camera adjusts accordingly. The result is a device that uses real-world positioning and orientation to view a corresponding VE. By allowing the user to activate the device's camera, a live-feed of the real world can be rendered in the VE; thus, mixing realities.

The final component that was integrated into the MR interface was the touch-screen. Code was developed that applied ray casting to the VE; when the user touches the display surface, objects in the VE can be manipulated. By performing this task with an active video feed, users may manipulate virtual objects within a MR environment.

4.5. Visualizations

Our research produced two categories of prototype geovisualization interfaces. The RTR of drainage and water flow using real spaces was achieved using the prototype devices described in section 4.4. The first geovisualization interface is a regional-scale watershed simulation. The second is a local scale urban drainage simulation. The difference in scale serves to highlight a variety of considerations and issues that become apparent when developing MR visualizations for real spaces and differing scales.

4.5.1. A Touch of Rain: Vancouver

A Touch of Rain: Vancouver (TOR: Vancouver) consists of a 3D DEM of Vancouver's North Shore Mountains, several rain generators, and a lightweight physics simulator. This prototype has been designed to give users a real-time rain and watershed simulator that displays virtual water flow on real surfaces. Its goal is to allow the user to perform sandbox-like experiments *in situ*. For example, the user can query and test informal hypotheses; where would water flow, if it rained here?

TOR: Vancouver initially presents a top-down 2D view of the region. Here, users may place rain sources on the map. This prototype implements a simplified model of rain fall using ShiVa 3D's built-in particle simulator, where: particles representing rainfall have mass; particles fall subject to gravity; particles are intercepted by topographic and urban geometries (which operate as impermeable surfaces); and flow to lower elevations based on mass, gravity and friction coefficients assigned to topographic and urban geometry.

Our geovisualization interface demonstrates the potential of connecting 3D physics-based spatial simulations to field environments, and to show a new workflow through which domain experts might implement situated geovisual simulations in geographic space.

Our flexible mixed reality approach enables users to seamlessly transition between 2D map views, first-person situated virtual environments, or augmented reality views. Leveraging the location-awareness of the interface, the user may examine the flow of water using the device as window into a VE. Adjusting the direction and orientation of the physical device, the virtual camera pans about the VE. By activating the device's camera, the user may view the flow of virtual water on top of a live view of the real world. This functionality shifts the interface's classification on the virtuality continuum towards AR (see Figure 4-1).

Figure 4-1. Mixed Reality for Geovisualization

Using mobile devices as situated mobile augmented reality ‘lenses’ (top) through which to view geographic space. (bottom) Augmented geovisualization view through device.

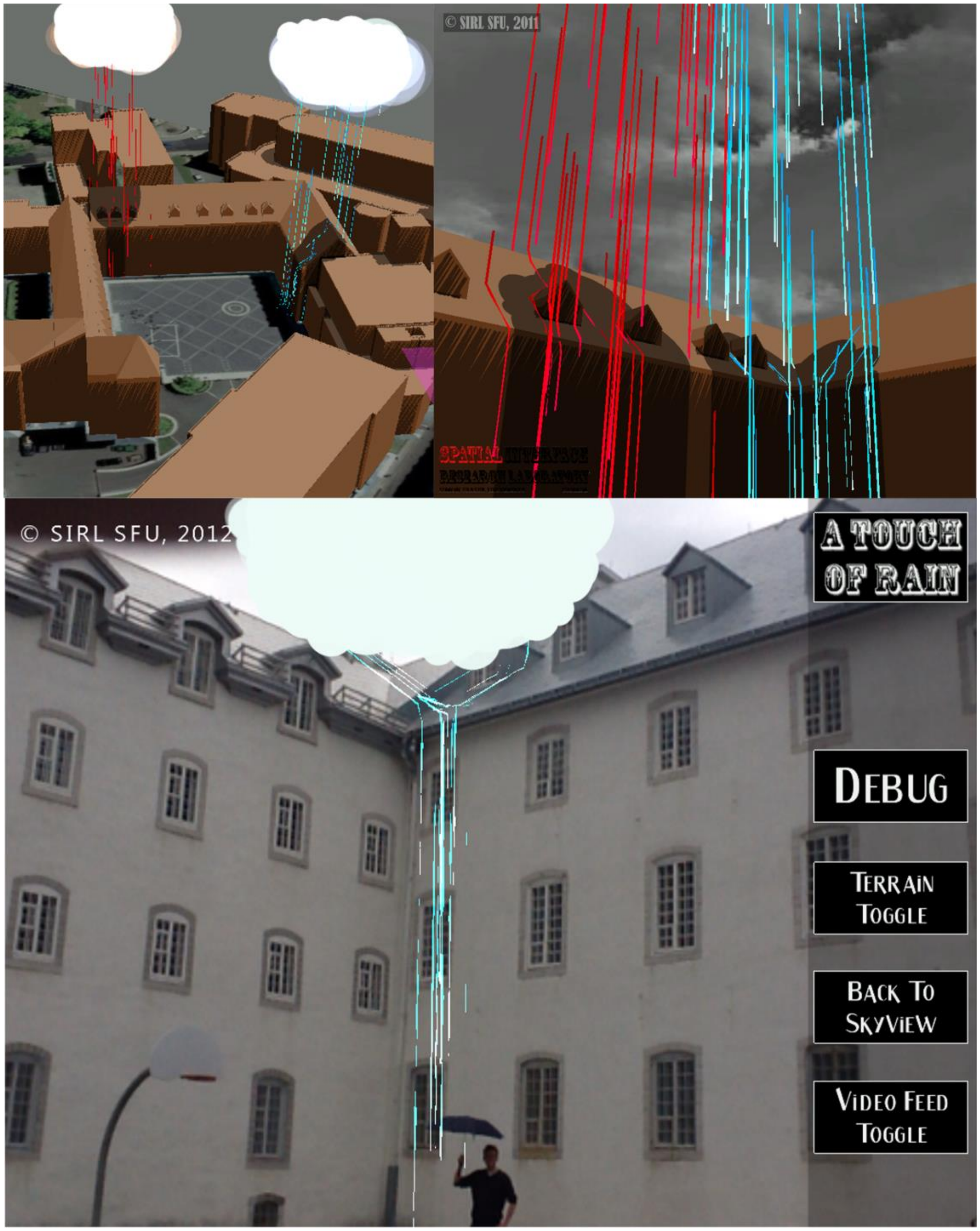
The implementation of multiple particle generators unlocks additional experimentation and collaborative opportunities. By colour-coding the water particles originating from different sources, users may compare the flow path from different origins (see Figure 4-2). Additionally, leveraging the multi-touch capability of the interface, generators of differing colours may be assigned to multiple users. By introducing game-like mechanics, the interface may be able to guide the users through various competitive or collaborative scenarios. For example, multiple users may be encouraged to move their water source to fill a watershed basin quicker than their opponent.

4.5.2. A Touch of Rain: Vieux-Québec

The second prototype developed is titled ‘A Touch of Rain: Vieux-Québec’ (TOR: Québec). While it shares many of the same mechanics as TOR: Vancouver, the scale of the study area and VE differ significantly. TOR: Québec uses 3D models of the courtyard of Petit Séminaire de Québec and various other locations within the region as a VE in which local-scale water drainage is modeled. Urban water flow is visualized and made interactive in the same manner as TOR: Vancouver, but within a much smaller study area (see Figure 4-2).

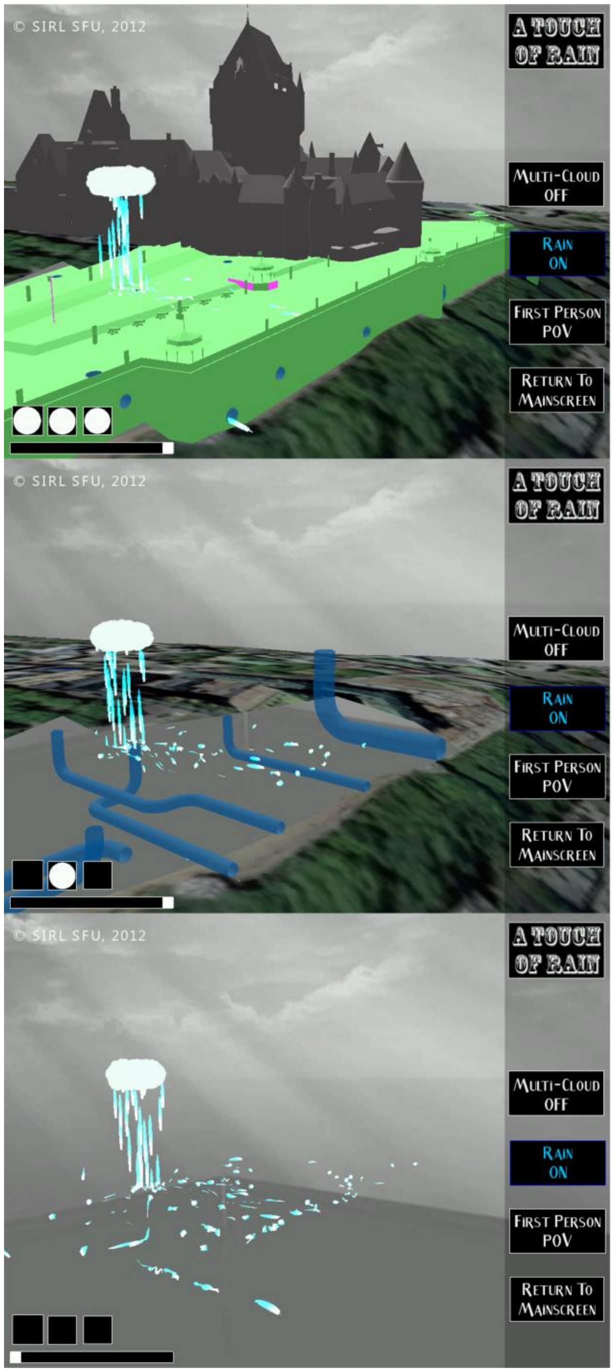
The complex geometries of urban spaces provide an opportunity for experimentation with visibility and transparency of real-world and virtual objects in MR. In a Vieux-Québec prototype, the user is given the option to toggle the visibility of certain virtual objects. This was made possible by implementing a segmentable 3D spatial geometry, allowing buildings and portions of the terrain to be removed so that underground geometry, such as sewer pipes, can be seen (see Figure 4-3).

Figure 4-2. Mixed Reality Geovisualization in Urban Space



Touch of rain urban precipitation simulation in VE (top left). Close up of color-coded rain simulations for multi-user and analytical differentiation (top right). Using the mobile augmented reality (MAR) version of TOR *in situ*, resulting in interaction of virtual raindrops with real urban structures (bottom).

Figure 4-3. Segmentable 3D Spatial Object Geometry



'Segmentable 3D spatial object geometry' – enables users to remove surface building geometry (top) and terrain elements, to reveal underlying hidden structural features, such as pipes (middle). Users can also make all scene elements invisible to isolate visualizations of flow simulation pathways (bottom) that use 3D topology.

4.6. Discussion

This paper aims to introduce a vision for future situated geovisualization, geovisual analysis and situated simulation. I have intentionally reported the capabilities of a new type of geovisualization interface I have developed – in order to introduce this method and its capabilities, and discuss associated concepts and implementation considerations. In doing so, I may identify new opportunities for situated spatial analysis. I will report usability research in subsequent manuscripts.

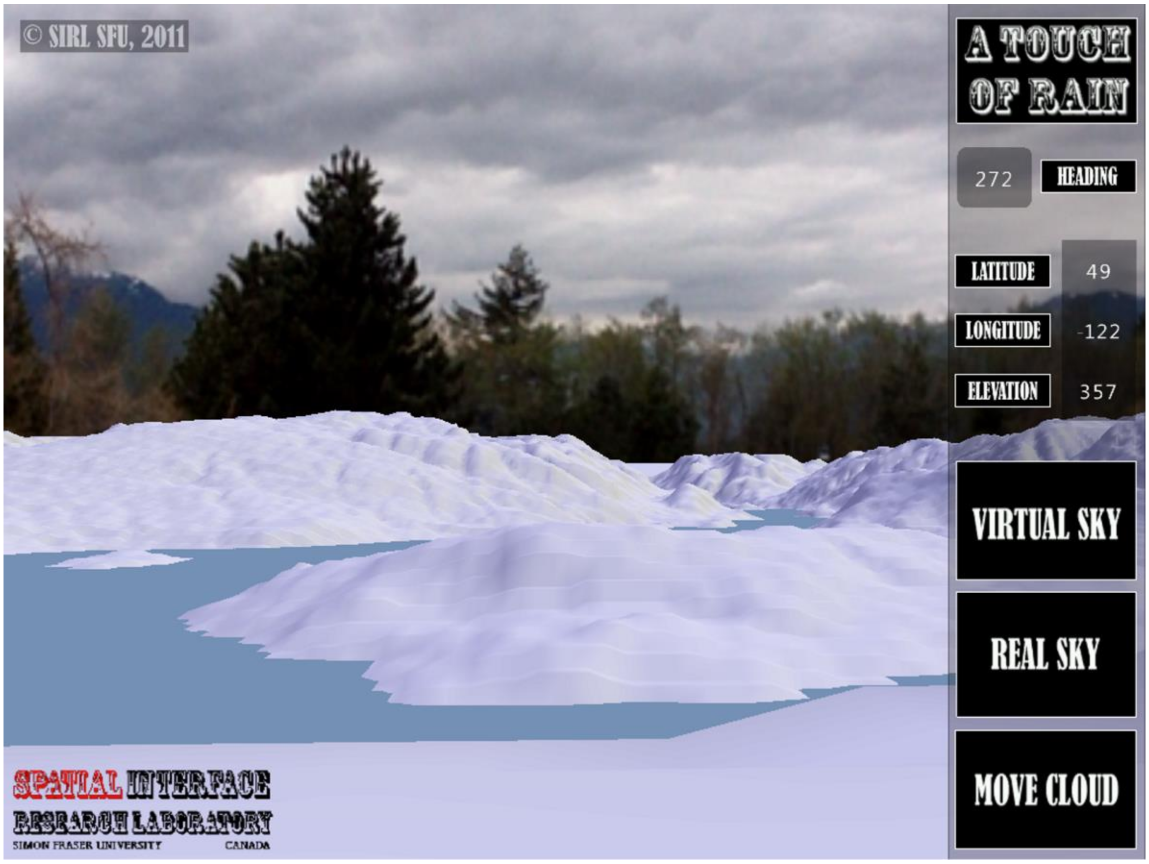
I discuss both observations derived from development and potential directions for further research in the following section. Informal field-testing amongst the authors and colleagues took place at various stages of the development cycle.

4.6.1. Visualization Limitations

A common concern within MR visualization and interface development is digital occlusion. Occlusion refers to when a digital object within a MR display is superimposed on top of a real object that should be behind it. If the visualization is rendered in such a way that objects are occluded incorrectly, the visualization becomes nonsensical; distant digital objects may appear in front of nearby real-world geometry. This can lead to misconceptions of the phenomena being displayed, motion sickness, and eyestrain as our visual expectations are undermined (Fuhrmann, Hesina, Faure & Gervautz, 1999).

In the context of my research, occlusion issues present a challenge due to my interface's ability to be used in the field. Detailed DEMs and models of test environments are costly, limited to bare-earth models, or non-existent. This means that many objects or local topographical details can be occluded by superimposed imagery. Trees proved to be problematic, given that my DEMs for the large-scale watershed simulation did not include surface details. In some cases, nearby trees where occluded by distant models of mountains and surface flow (see Figure 4-4). Similarly, the local scale urban drainage analysis showed rain flowing down the backside of a building, despite my inability to see that face from my test position.

Figure 4-4. Occlusion Issues in Mixed Reality



Several solutions to occlusion issues have been proposed; however, the realities of using MR in unprepared and uncontrolled environments may be undermined unless augmentation design has carefully considered interposition and perceptual cogency.

MR research has identified a number of solutions (Maidi, Ababsa & Mallem, 2010; Tian, Guan & Wang, 2010) to this issue; however, many rely upon controlled environments, fiducial markers, or detailed knowledge of the environments geometry. This is not always possible to achieve for MR applications set in large-scale and uncontrolled environments. A clear, cost-effective, resolution for MR occlusion in such contexts remains elusive.

In addition to realistic occlusions, a real-time 1-to-1 relationship between the real world and virtual components of the MR interface display is required for coherent visualizations. This relationship is maintained by registration of the interface's position in the real world, and can be achieved through fiducial markers, natural feature tracking, GPS, or a combination of technologies (Xu, Prince, Cheok, Qiu, & Kumar, 2003). As discussed previously, my work employs GPS, compass bearings, and accelerometers to register the position of the interface in real-space so that this relationship is maintained.

Despite the recent proliferation of location-awareness technologies, inherent inaccuracies, environmental interference, and service disruptions inhibit accurate registration. Immersion breaks down if the virtual components of MR visualizations become out of sync with their real-world counterparts, causing confusion and even motion sickness. This was observed during testing when GPS signals were weak (underground and beside large buildings) and when the interface device was moved too rapidly for the GPS and accelerometer to keep up. This was less of an issue for regional-scale visualizations, as registration errors of greater than 100 meters were needed to noticeably impact the visual output. The GPS component of the iPad device was generally accurate to within 30 meters.

In contrast to the regional-scale interface, local-scale AR is much more sensitive to variations and inaccuracies in the GPS, compass, and accelerometer technology. This is because registration errors on the order of centimeters could affect the visual output. As such, it was necessary to include a 'tuning' capability in the interface. Through the use of menus and sliders, manual adjustments can be made to the orientation and position of the virtual camera within the VE. By doing this, I have achieved a new way to 'tune augmented reality 'virtual lens' visualizations to geographic space. This spatial MAR 'tuning' ability helps overcome a number of the spatial positioning limitations of current visual MAR applications using GPS and accelerometer hardware.

4.6.2. Flexible Mixed-Reality

Transitions between various degrees of mixed-reality using window metaphors have already been examined through the lens of mobile computing (Cheok et al., 2002). Through an AR capable headset, users were able to view a VE through a digital window projected onto their AR gear. Tablet-based interfaces differ in that the VE 'window' is a singular device, thus it is possible to view a VE without additional gear. This attribute gives advantage in terms of mobility and portability; however, some of the seamless VE-

AR transitional capability is lost. For example, the work of Cheok et al. allowed for the virtual window to rapidly fill the user's field-of-view; this creates the illusion of falling through a portal, something that is not possible with a singular tablet-based device.

Instead, my interface deals with MR transitions in a slightly different manner. Users are able to toggle the visibility of various portions of the VE as well as the video feed from the real world. This results in a visualization that varies in position along the virtuality continuum depending on the visibility of virtual and real imagery on the display. It is unlikely that one form of MR is suitable for all applications; a 'flexible reality' interface may enable rapid development of appropriate visualizations.

4.6.3. Real-time Reification of Geographic Phenomena

I presented a watershed sandbox that allows users to interact with virtual objects *in situ*. Most applications of MR in geographic contexts have been virtual annotation of the real world. This can be either 2D or 3D annotation. For example, some work has focused on revealing hidden 3D geometry through AR (Schall et al., 2009). These approaches combine geo-located 3D geometry with a location-aware display to reveal hidden objects or annotations.

Our goal was to examine a different conceptual approach, in which a physics-capable VE underpins a MR interface, instead of static geometries or annotations. By creating a situated VE 'alternate-reality' I enable users to interactively explore the relationship between precipitation, watershed topography, and surface flow in real space. Instead of showing the user information, RTR and MR interfaces enable users to interact and change information in real spaces.

The purpose of this research is to conceptualize and demonstrate a potential evolutionary path for *in situ* geovisualization. Watersheds and surface flow are not the only geographic phenomena that could be loaded into such an interface. Slope stability, soil types, and weather simulation are just a few examples of hidden or abstract geographic phenomena that could be examined, visualized, and interacted with in a RTR MR interface. This class of interface can be applied in many geographical contexts; however, the question remains, should it be?

4.6.4. Should Situated Mixed Reality be used?

How, why, and whether or not users would actually derive benefit from such an approach present clear 'next steps' emanating from this research. The fact that data and information can be visualized and interacted with in 3D and MR, does not necessarily demonstrate that they should be. In the past decade, mixed reality interfaces have become more popular. However, I must be careful not to mistake novel interfaces for enhanced perception of visualizations. A balanced approach in determining whether or not phenomena should be visualized in MR systems is needed.

Our inroad into the development of MR interfaces for geovisualization is rooted in empirical evidence which suggests that the spatial characteristics of MR interfaces may deliver a meaningful way for spatial researchers to view, interact with, and understand inherently 3D spatial phenomena (Shelton & Hedley, 2002; 2004). MR for underground infrastructure visualization has also received positive feedback from expert users (Schall et al., 2009). It is my intention that this research serves as a platform by which further assessments of MR interfaces can be researched, including, but not limited to, secondary school geography students, urban planners, and geography field researchers.

It is important to remember that not all types of MR interface necessarily improve spatial perception and understanding. For example, MR systems do not automatically improve navigation and any noted benefits or limitations vary with gender or socio-economic attributes (Dünser, Billinghurst, Wen, Lehtinen & Nurminen, 2012). Selective application and assessment of *in situ* MR interfaces is needed given the large range of potential geographic applications and audiences.

The capability of *in situ* MR interfaces to visualize abstract or invisible phenomena suggests that potential applications of this technology should consider the visibility of the subject material. Additionally, the complexity, scale, and volumetric depth of a geographic phenomenon will influence the difficulty of delivering and performance of MR geovisualization systems. Two examples of complex phenomena that may be difficult to communicate with traditional 2D visualizations are ocean currents and underground geomorphic processes. 3D representation and visualization may provide meaningful inroads to comprehension of complex spatial phenomena. Being able to view such visualizations in 3D using (M)AR may enhance perception. (Re)connecting analytical virtual representations of dimensionally complex spatial phenomena to their real-world source take this process one step further, enabling us to reveal normally scientific analyses and interpretations in geographic space. Note that not all geographic phenomena may benefit from visualization in 3D, or using a MR interface. 2D maps may be more appropriate.

The suitability of situated MR interfaces is likely to be dependent on several interacting variables. User based testing in order to determine those properties is a potential direction for future MR research. Other research provides examples of how this may be determined.

MR interface usage has been assessed through a variety of frameworks that have roots in Human-Computer Interaction (HCI) and Spatial Cognition research (Dünser et al., 2012; Shelton & Hedley 2004; Shelton & Hedley 2002). HCI offers methodologies for examining interface use (Tobón, 2005; Preece et al., 1994), while the field of spatial cognition (Montello, 2009) offers opportunities to examine how the MR interface affect mental models and perception of geographic phenomena. The field of visual analytics (VA) (Andrienko et al., 2010; Thomas & Cook, 2005) has developed several novel approaches to interface analysis through eye-tracking (Çöltekin, Heil, Garlandini, & Fabrikant, 2009) that may be suitable for determining linkages between phenomenon attributes and their suitability for various forms of visualization. Empirical evaluation will be considered in future reporting, as the current paper aims to demonstrate the potential of hybrid mobile geovisualization interfaces for linking geographic and abstract data spaces.

4.7. Conclusions

This paper reports on applied research that has resulted in an ability to perform *in situ* simulations of dynamic spatial phenomena using geospatial mobile augmented reality. In this paper I summarize previous works that have led a significant period of convergence in geovisualization and spatial interface research. Combinations of 3D virtual simulations, location-aware mobile devices, tangible interfaces and, critically, spatial interface design, can deliver meaningful situated mobile augmented reality geovisualizations. I introduced situated simulation as a new form of augmented situated geovisual analysis that these systems can now provide. A Touch of Rain demonstrates this potential, allowing users to run augmented precipitation simulations in real space, resulting in an ability to enable 3D interaction between virtual (rain) simulation and real landscapes and building geometry. This ability further introduces a new category of geovisualization: augmented geovisual analysis. While these geovisualization experiences are new and perhaps novel, this method provides researchers with new opportunities to (re)connect geospatial data, models and analyses to everyday spaces. By doing so, I may close the gap between abstract spatial analyses and society, enabling greater dissemination of scientific understanding across stakeholder networks.

Finally, this research highlights emerging opportunities for the geovisualization, geomatics and GIScience research communities. There is much existing intellectual capital that may be brought to bear on the future development of this emerging subfield. These include interactive geovisualization, spatial cognition, empirical usability work in geovisualization, data optimization and integration, and the design of augmented geographic space. I hope that this research will encourage technological innovation, stimulate methodological development, and new conceptualizations of the relationship between geographic space and existing virtual geographic information spaces.

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Chapter 5.

Navigating the Future of Tsunami Risk Communication: Using Dimensionality, Interactivity, and Situatedness to Interface with Society[4]

5.1. Abstract

2D paper maps are well-established tsunami risk communication tools in coastal communities. Advances in GIS, geovisualization and spatial interface technologies, suggest new opportunities to deliver tsunami risk communication using 3D, interactive and situated risk visualization. This paper introduces a set of geovisual interface constructs – dimensionality-interactivity-situatedness (DIS) – and evaluates their presence, absence and distribution in 129 examples of existing academic and public visual tsunami risk communication. The resulting analyses reveal structural differences in the distributions of DIS found in each of academic and public risk communication literatures, and opportunities for interactive location-aware risk communication. The second half of this paper reports on three new tsunami risk visualization interfaces informed by, and developed to demonstrate how I might explore new undeveloped risk communication territory revealed by the DIS cube analysis. I discuss the design, rationale, and implications of: EvacMap, ARRO3D, and Tsunamulator. These risk visualization interfaces deliver location-aware, user-centered risk maps, as well as virtual risk maps and tsunami simulations that can be viewed while standing *in situ* in coastal environments. This work is a first step intended to help the risk communication community systematically engage an emerging territory of interactive and location-aware 3D visualizations. It aims to facilitate and encourage progress toward developing a new

[4] A version of this Chapter has been submitted to *Natural Hazards* under the co-authorship of Nick Hedley.

strand of interactive, situated geovisual risk communication research, by establishing these guiding constructs, their relationship to existing works, and how they may inform the design of future systems and usability research.

5.2. Introduction

Effective public risk communication is integral to improving tsunami preparedness; an informed citizenry must understand spatial risk and be able to take appropriate action during these time-sensitive events. Such preparation is of particular importance along seismically active and vulnerable coastlines of the Pacific Ocean basin. Recent research on public tsunami risk perception indicates a high reliance on official emergency communications and inaccurate perceptions of personal risk (Couling, 2014). Public tsunami risk communication relies heavily on 2D paper maps and safety brochures for the visualization of hazard zones (Clague, Munro & Murty, 2003), maps and signage at trailheads, and signage along roads. Given the prevalence of visualizations as risk communication tools, audience, intent, and design must be considered carefully. Effective academic visualization does not necessarily make for effective public risk communication.

Tsunamis are structurally three-dimensional (3D), temporally dynamic, and difficult to predict (Geist, Bilek, Arcas & Titov, 2006). They might vary in propagation, speed, and arrival angle; factors that are further complicated by the variability of intercepting coastal topography. Tsunami scientists strive to capture these multivariate complexities using computational models and simulations. Visualization, geovisualization, and (geo)visual analysis are used at various stages of the spatial scientific process, to view raw data and models; look for structure, patterns, and relationships; observe and compare simulated scenarios; make sense of unknowns (Andrienko et al., 2010; MacEachren & Kraak, 2001; Thomas & Cook, 2005). Visualizations intended for public use are derived from these steps. Translating academic research into representative yet comprehensible visualizations for public is challenging and there is potential to inadvertently modify results. Public and academic visualizations serve significantly different needs and expectations of their respective user-bases.

This research effort has four objectives: 1) review examples from the academic and public risk communication literatures; 2) identify the constructs of dimensionality, interactivity, and situatedness as properties of emerging geovisual interfaces; 3) reveal the structural distribution of these attributes in academic and public risk communication, as a result of classifying 129 visualizations using these constructs; and 4) demonstrate how these constructs enable the design of new forms of risk communication interface to connect abstract analysis with real space.

Emphasizing disaster prevention through an approach that integrates natural hazard science and people-oriented research has been a recent trend (Haque, Dominey-Howes, Karanci, Papadopoulos & Yalciner, 2006; Paton, 2000; 2003). This paper introduces a 'spatial interface' approach to tsunami visualizations, in which I demonstrate new ways to communicate tsunami information through interface technology and design. I review and classify a sample of existing tsunami visualization work, introducing a conceptual cube of visualization affordances as a way to illustrate existing trends in tsunami risk communication. I reveal how they operate as interfaces to communicate science-based risk analyses to stakeholders and citizens in geographic space. From this review exercise, I derive a set of interface factors that are leveraged to design and develop a new generation of tsunami risk visualization interfaces. To demonstrate this potential, I report on new geovisualization research in which I have used these principles to develop new tsunami risk visualization interfaces: EvacMap, ARRO3D, and Tsunamulator. Reviewing existing literature using new constructs, and demonstrating how they might inform the design of new methods, are necessary steps in developing a new strand of risk communication research. This in turn forms a logical foundation for future usability research.

5.3. Trends in Tsunami Visualization

In the past (and still to some degree) there was perhaps a tacit assumption that once a map is produced, it would work 'as designed by the cartographer' once deployed and read, be it on a wall, in the hands of pedestrians, or other settings. Numerous scholars have unpacked the 'secret lives' of maps, how they are appropriated, used and interpreted in a multitude of ways never intended nor anticipated by the cartographic author (Wood & Fels, 1986). Kurowski, Hedley and Clague (2011) demonstrated how closer scrutiny of the content of 2D tsunami maps varied, and suggested how this limits an ability to represent tsunami hazards, and how they (from a cartographic standpoint) differentially communicate risk. How readers interact with visualizations (be they 2D paper maps, web interfaces or 3D environments) influences their perception of the geometry of geographic space, spatial relationships between real features and abstract analyses, such as tsunami risk. In this section, I summarize trends in tsunami visualization so that we may begin to understand how tsunami risk perception may be affected by visualization design choices. I provide a summary of the geographic and organizational scales at which public tsunami risk communication maps are currently being produced.

5.3.1. Public Tsunami Risk Visualization

Public-oriented tsunami risk and hazard visualizations appear to fall within three broad categories, each of which corresponds with differing map scales and organizations responsible for map production. The first category is large-scale national and international tsunami hazard visualizations. Federal organizations such as the West Coast/Alaska Tsunami Warning Center and the Pacific Warning Center provide up-to-date forecasts and warnings on their websites through simple 2D mapping services. These large-scale visualizations are designed to provide regional warnings, rather than communicating localized topography and hazard zones (Pacific Warning Center, 2014). Light interactivity, such as panning, zooming, and map layers, can be integrated into the map interface (West Coast/Alaska Tsunami Warning Center, 2014).

The second broad category of public-oriented tsunami visualization consists of local hazard maps produced by smaller organizations, such as municipal governments or contractors. These maps are for public use; however, their intended audiences are local stakeholders such as residents, tourists, local business, and local government. The majority of visualizations produced in this category are static 2D maps that are often available digitally or in the form of paper pamphlets (City of Port Alberni, 2007; CRD Environmental Services, 2006; District of Port Hardy, 2014; District of Tofino, 2006; Wellington Region Emergency Management Office, 2011).

The Washington and Oregon state governments demonstrate a final class of public tsunami risk visualization. The governments have made efforts to standardize tsunami visualizations across the region, rather than leaving risk communication to the discretion of the communities. Two series of tsunami evacuation maps of both States' coastlines have been produced and standardized for coastal communities (Oregon Department of Geology and Mineral Industries, 2012; Washington State Department of Natural Resources, 2012). These maps are static, 2D, and accessible via the Internet or as paper pamphlets *in situ*.

Tsunami risk-focused organizations typically place priority on signage and educational map pamphlets for public awareness (Dengler, 2005; González et al., 2005; Kurowski et al., 2011). The importance of geospatial information and visual representations of risk and hazard are recognized by a variety of fields (Cutter, 2003; Dransch, Rotzoll & Poser, 2010). Despite the importance of visual communication, universal standardization of tsunami maps in safety brochures along contiguous hazard zones, such as the Cascadia Subduction Zone (CSZ), remains a work in progress (Kurowski et al., 2011). But, as indicated in the preceding paragraph, the states of Oregon and Washington have worked hard to standardize the content and visualization of tsunami hazard maps in recent years. While such an issue may seem innocuous at first, inadequate (or mis-informative) visualizations can undermine tsunami risk awareness, disaster preparation, and response times (Schafer, Carroll, Haynes & Abrams, 2008).

Many communities have settled on 'one map per community' with which to communicate risk Single maps are often created to impart a single, clear message to citizens: where is the flood risk, safety, and how does one move to safety? As such, it is critical that these maps translate the expertise of science accurately and effectively into public awareness (Kurowski et al., 2011). The one-map-per-community model is perhaps at odds with the nature of tsunamis, and what we do (and do not) know about their probability and behaviour. A single, static map of inundation or risk zones is a very limited representation of a dynamic, multivariate phenomenon that can manifest in many different ways (see section 4.4.1 further discussion on interactivity).

An important consideration is that typically paper tsunami risk maps do not link the user to their specific location on the map, and therefore, their relationship to risk in geographic space. Users bear the cognitive burden of identifying their location in space, identifying the equivalent location on the map, and then identifying the spatial relationships between user location, risk, evacuation and safety.

To the best of my knowledge, most contemporary public tsunami risk communication visualizations do not allow for a high degree of user interaction. This may be the result of the limited capacity for coastal municipalities to produce and support such visualizations. It may also be a result of perceived liabilities associated with a tsunami communication tool that enables more open-ended interpretation, rather than a single message. However, there are some examples of interactive risk mapping tools. Kurowski et al. (2011) reviewed the Northwest Association of Networked Ocean Observing Systems (NANOOS) web-mapping tool (NANOOS, 2014). This web mapping service allows users to search, pan, and zoom while visualizing static representations of inundation risk along the Oregon coast. So, while most spatial tsunami risk is typically communicated to the public through non-interactive paper maps, there are some exciting advances occurring within the field.

5.3.2. Academic Tsunami Risk Visualization

The visualization of tsunamis and their associated risks and hazards in academic contexts merits distinction from public risk communication. Tsunami risk and hazard visualization within the academic community is more varied and advanced than what is typically seen in the public realm. I comment on tsunami visualization trends within the academic community so as to contrast what is being visually communicated within the research community, and what makes it to at-risk stakeholders.

Academic researchers as a visualization audience have different needs and goals than the public when considering the design of tsunami risk and hazard maps. There is a requirement to illustrate research model mechanics and stages of development, unlike public maps which require simple and clear messaging. Additionally, varying degrees of scientific knowledge and interpretive skills are assumed depending on where publication venue. Furthermore, the peer-review structure, in which research is legitimized, can be quite restrictive. Typically journals require static, 2D, black and white figures. Variations of this format can incur extra cost. This limitation is changing, as journals and other forums offer opportunities to link readers to online content, including animations, 3D models, and even complete research tools, yet it is still present. Effective academic visualizations do not always make for effective public communication. Misinterpretations are a very real risk.

A recent example of misinterpretation is a tsunami propagation map produced by the National Oceanic and Atmospheric Administration (NOAA) that was construed by some members of the public as representing radiation propagation (NOAA, 2012). While there are no apparent cartographic design errors, public perception of its intended message was inaccurate. Flood risk management is a similar domain that deals with communicating science to responders and the public. There is an extensive research background highlighting the challenges in communicating concepts such as model uncertainty, accuracy, and ownership to emergency managers and the public (Faulkner, Parker, Green & Beven, 2007; McCarthy, Tunstall, Parker, Faulkner & Howe, 2007). Uncertainty and the complexities of fluid simulation present challenges to visualization in flood risk communication; parallels may be drawn with the challenges faced by tsunami visualization.

Tsunami visualizations (as opposed to analytical aspects of research) developed within the field of natural hazards can are typically static representations. Static visualizations include choropleth maps where spatial risk is indicated using colour-coded zones (Eckert, Jelinek, Zeug & Krausmann, 2012; Grezio, Gasparini, Marzocchi, Patera & Tinti, 2012; Strunz et al., 2011), 2D static maps indicating colour-coded sea surface elevation changes (Borrero, Sieh, Chlieh & Synolakis, 2006; Ribeiro, Silva & Leitao, 2011), or at different time intervals (Xie, Nistor & Murty, 2012).

Dynamic tsunami visualizations are less common; much of the research is focused towards animated maps revealing tsunami wave propagation at regional and global scales (Sevre, Yuen & Liu, 2008; Synolakis & Bernard, 2006; Zhang et al., 2008).

Despite the dynamism of these visualizations, authors are still limited to presenting static frames of animations.

Dynamic geovisualizations can be powerful tools for communication. It is important to note that there are significant differences between dynamic visualizations as representations of dynamic phenomena, versus interfaces that provide ways to dynamically view visualizations; regardless of whether they are static or dynamic characterizations of the phenomenon. This is an important consideration at a time when tsunami risk communication is exploring opportunities for new forms of public communication and engagement.

Examples of this include Basic and Nuantawee's (2004) flooding interface that allows the user to query and visualize maximum flood level, address, time until maximum inundation, and safety precautions. The dynamic properties of the phenomenon itself (speed and direction of flow over time) are not the priority of this information tool. More recent examples, such as the research of Tate, Burton, Berry, Emrich and Cutter (2011) in the Integrated Hazards Mapping Tool, involve a more complex combination of dynamic representation and interactivity. Increasingly sophisticated representations of tsunamis (dimensionality, dynamism) and emerging interactive visual information tools provide risk communication specialists with new ways to deliver public risk information. I might maximize these efforts with a more developed framework with which to guide the use of dynamism and interactivity for effective visual risk communication.

The majority of tsunami visualization within the research community is conducted in 2D (Borrero et al., 2006; Eckert et al., 2012; Grezio et al., 2012; Ribeiro et al., 2011; Strunz et al., 2011; Titov et al., 2011). Again, this observation is about the manner in which it is communicated, not the analytical work that was achieved. Comparatively fewer cases have focused on 3D visualization. Exceptions include Zhang et al. (2008) who developed an interface that places images of tsunami propagation in Google Earth (a 3D Globe visualization program); however, these visualizations appear to be 2D images of propagation wrapped around a 3D globe as such it may be misleading to call this a truly 3D visualization. Sevre et al. (2008) developed a series of 3D visualizations representing tsunamis as exaggerated deformations of a mesh. Again, it may be misleading to call these truly 3D visualizations since mesh deformations can be conceptualized as 2D planes with height values as an attribute of a specific coordinate on the plane.

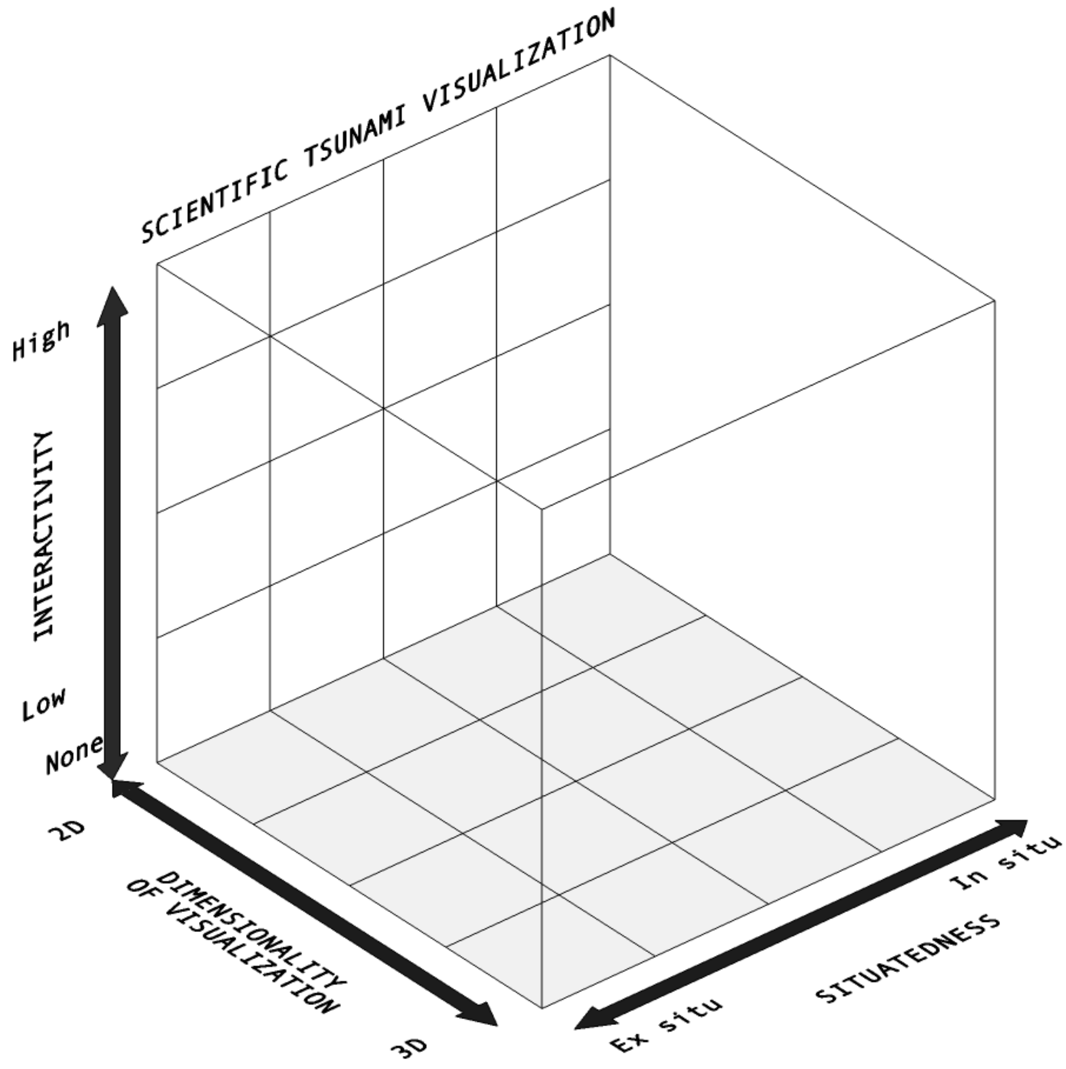
The above 3D visualizations are regional and global in scale. Local-scale 3D tsunami visualizations are uncommon in both research, and public communication. Basic and Nuantawee's (2004) local-scale lake flooding visualization research offers an example from a similar problem space; however, their work focuses on final maximum flood heights rather than the dynamic onset of the flood. Perhaps local-3D visualization has been avoided because of perceived difficulties in communicating inundation chronologies, pathways, and water dynamics. Communicating such phenomena is particularly difficult if one is limited to static 2D visualizations, as is often the case in both the research community and the public sphere.

5.4. Using *DIS Cube Space* to Reveal the Structure and Distribution of Existing Public Tsunami Communication

Our summary of trends in tsunami visualization in part 2, above, was based on a sample of 14 academic tsunami visualization and 115 public tsunami risk communication examples. I actively searched for examples of interactive tsunami visualization systems for public education. My review was focused through the lenses of dimensionality (2D or 3D), interactivity, and situatedness. These constructs allow us to derive a composite dimensionality-interactivity-situatedness (DIS) cube space with which to broadly classify the tsunami visualizations sampled (introduced in Figure 5-1, below).

As spatial analytical visualization methods have progressed, it has become possible to create new forms of interactive and three-dimensional visualizations, using a variety of immersive devices. It is for these reasons that I have developed the DIS cube space. This conceptualization uses a cube construct similar to MacEachren and Kraak's (1997) cubic conceptualization of map use; a conceptual space that enables classification of patterns in goals of map use by identifying a map's position within the cube. My DIS cube space is a construct I can use as a ‘lens’ to review a sample of existing hazards and risk communication visualization in the literature, in order to better understand the frequency and distribution of these methods in each of the academic and public risk communication communities. I define and discuss dimensionality, interactivity, and situatedness in the following section.

Figure 5-1. Dimensionality –Interactivity-Situatedness (DIS) Cube Space



A conceptual construct with which to classify current types of public tsunami visualizations.

5.4.1. Defining Terms Used in the *DIS* Constructs

The dimensionality I emphasize in my DIS cube review of existing visualization literature refers to the dimensionality of the visualization. I am primarily concerned with the manner in which data are visualized at the conclusion of analysis. Has a flat paper map been produced, or a 3D animation? Of course, I cannot dismiss the importance of considering data and analytical models. Their quality and value hinges on how well the analytical spatial visualization is matched to available data for specific phenomena - this has been at the core of rigorous geographical information science for some time. It is also critical to remember that 3D visualizations may be compelling, but they are not necessarily better than 2D visualizations of phenomena.

In the same way, interactive visualizations are not necessarily better or worse than static visualizations. They are simply different approaches to presenting analytical visualization outputs through user control, visual, auditory and other feedback. If designed well, different mixtures of these ingredients can result in engaging information experiences that may lead to enhanced factual and conceptual understanding of complex spatial phenomena (Shelton & Hedley, 2002; 2004). There is risk of audiences failing to receive the intended risk communication message due to only seeing part of the whole visualization ‘experience.’

Sevre et al. (2008) identified the benefits of allowing real-time querying and response for the analysis of tsunami hazards as a basis for future studies. However, I have found almost no examples in the literature that unpack the significance and potential of interactivity for tsunami risk communication and its analysis.

Geovisualization researchers have long argued that interactivity may enable more informative exploration and comprehension of spatial data and messaging in thematic maps (Andrienko & Andrienko, 1999; Kraak, 1998). The fields of visual analytics (VA) (Thomas and Cook, 2005) and geovisual analytics (GeoVA) (Andrienko et al., 2007; Keim et al., 2008) have since emerged to establish principles of interactive visual analysis as a powerful approach to the analysis and communication of complex spatial phenomena.

In the context of tsunami risk communication, single static map products (such as paper risk maps or their digital PDF versions) present examples of low interactivity visualizations. Most present a single message about one or more variables to express individual or composite risk in geographic space, as the user cannot change the display. The NANOOS (2014) web mapping application discussed in section 5.3.1 offers an example of an interactive visualization. The interactivity axis of the DIS cube aims to capture the range of possible ranges from low to high, and refers to how responsive the visualization is to user inputs.

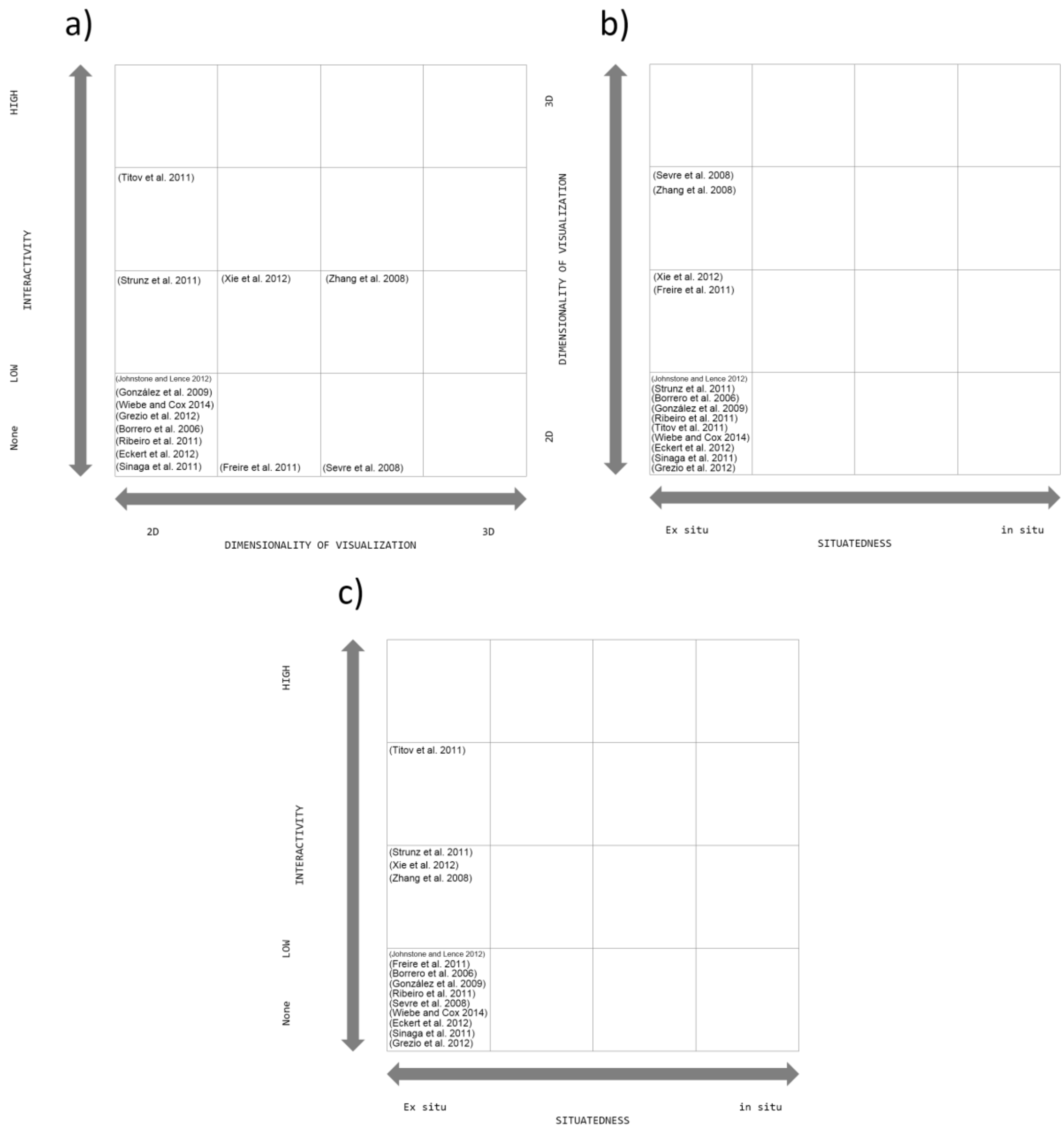
Development of effective risk communication takes local social, institutional contexts into account (Dengler, 2005; González, Titov, Mofjeld, Venturato & Newman, 2001; González et al., 2005). 'Situatedness' is a term that has been in use by social scientists for some time. The term refers to the interplay between physically on-site research activities and the way local contexts and influences shape such activities, perceptions, and understandings (Vannini, 2008). Cognitive researchers have defined 'social situatedness' as the interplay between agent, situation and context (Rohlfing, Rehm & Goecke, 2003). Situatedness has also been of great interest to the human-computer interaction (HCI) research community. Suchman's (1987) ethnomethodology acknowledged the significance of interplay between being *in situ*, activity, and technology – ideas that can constructively inform our development of situated risk communication.

Incorporating the social, spatial and technological dimensions of situatedness in contemporary visual risk communication design is essential to effective transmission of expert science into society, and to connect abstract risk to real landscapes. This is particularly true in an era of spatially enabled mobile devices, and in a problem domain that has so much to do with situated information and situational awareness. For example, risk in safety map brochures is often presented as static zones of risk. Connecting these zones of risk to a user in the field might facilitate compression of personal risk and their possible responses. I raise this point, in order to consider to what degree existing risk communication materials, visualizations, and risk information interfaces and information activity are used *in situ* or *ex situ*, whether they can be used *in situ*, versus whether they have been designed for use *in situ*.

5.4.2. Using *DIS Cube Space* to Categorize Trends in Tsunami Visualization

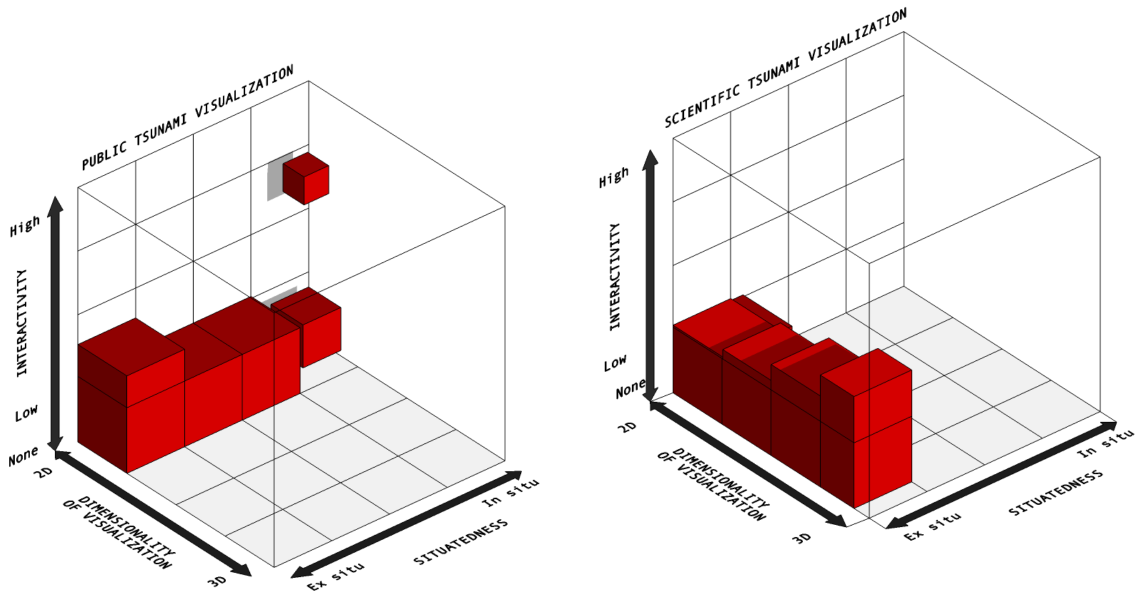
Locating existing tsunami visualization in the DIS cube space enables us to gain a sense of how tsunami risk is being transmitted to society, in terms of whether they use 2D versus 3D visualizations, their degree of interactivity, and their degree of situatedness. By doing so, I can show the distribution of existing visualizations; comment on current and emerging trends within these spaces; identify forms of visualization that have not been used; aim to explain reasons for these structural distributions; and identify opportunities (and rationales) for new forms of risk communication. Figure 5-2 below illustrates the positioning of 14 academic articles and their visualizations reviewed and placed within the DIS cube space.

Figure 5-2. Academic Tsunami Visualizations within DIS Cube Space



The positioning of 14 academic articles along the three axes pairs of the DIS cube space: a) interactivity and dimensionality, b) dimensionality and situatedness, and c) interactivity and situatedness.

Figure 5-3. Academic and Public Tsunami Visualization in DIS Cube Space



Dimensionality-interactivity-situatedness (DIS) cube spaces summarizing current types of tsunami visualizations in; public risk communication (L); and the academic community (R).

Figure 5-3 above shows that academic and public communication communities' tsunami visualizations occupy distinctly different regions of the DIS cube space. The most significant messages I can derive from this distribution are:

1. The majority of current public tsunami risk communications are 2D visualization products, whereas academic tsunami visualization spans 2D and 3D visualization methods.

The differential in visualization dimensionality is, understandably, a function of the objectives and tools in science versus public communication. In the academic community, accurate characterizations of tsunamis' morphology and behaviour are priorities, requiring sophisticated 3D modelling. By contrast, public communication of these hazards and risks is largely delivered in 2D form. This can be for several reasons. From an operational standpoint, municipalities and emergency management teams generally want clear messages to mitigate risk and coordinate evacuation. This need has in part led to a common one-static-map-per-community. 2D static maps have an almost impossible task to represent and communicate unpredictable, rapid-onset, volumetric, and dynamic phenomena, such as tsunamis. While 2D static maps may provide singular, fixed messages for operational needs, they may be at odds with communicating the spatial and temporal complexity of risk, inundation, and evacuation. If we were to communicate these events in 3D, we might be able to: convey their structural complexity, and behaviour during inundation, rather than just demarcating the high water mark; convey multiple possible scenarios, thus accommodating the considerable uncertainty surrounding their case-by-case manifestation.

2. The majority of public tsunami risk visualizations are static 2D maps with no or low interactivity, whereas there is some interactivity in the academic community (mainly associated with the platforms used, rather than with intentional interactive information experiences in mind).

Interactivity in 2D visualizations occurs mainly in 2D GIS or web applications. The visualization component of a 2D paper map itself is not interactive (one cannot change displayed information content). Such interactivity is only possible in GIS and web applications found within the sample. Analytical GIS tools are typically interactive in their ability to modify combinations of spatial data layers for changing the visualization or analysis. Interactive web applications are far less standardised (some are very GIS-like, while others are not). Despite these trends, there is an emerging interest in delivering interactive, and situated content in the public tsunami communication domain such as the NANOOS (2014) application.

3. Situatedness in public tsunami visualizations spans whole ex-situ-to-in-situ spectrum, whereas most academic tsunami visualization still occurs almost entirely *ex situ.*

Many academic tsunami visualization tools are used within research institutions and government offices of various types. Examples of public tsunami risk communication methods include 2D paper maps and pamphlets, 2D map posters, and 2D signboards. A 2D (paper) map, for example, might be put on a wall in an office, mounted on a public signboard in a park, or folded and taken into the field. So, while the map may be useable in the field (as a portable visualization), was it designed for use in the field, or for situated risk communication? Similarly, 2D digital maps online may not be specifically designed for in-situ use. They could be used on a mobile phone with Internet capability, and viewed *in situ*, but the interface design may not accommodate unpredictable challenges found in field studies.

The dimensionality-interactivity-situatedness (DIS) cube analyses help us perceive the structure of existing academic and public tsunami risk communication, and how they occupy different combinations of dimensional representation, interactivity and situatedness. Revealing these differences are important for at least three reasons:

First: tsunami hazards are complex, volumetric, and dynamic. Their visualization through static, 2D visual documents is a limited representation of these characteristics. This is common practice in public risk communication due to clear messaging and simplicity in operational emergency management. But, is there opportunity retain this clarity while presenting more accurate (dynamically and dimensionally) visualizations of the phenomena? Can we deliver public risk communication that provide more sophisticated representation through 3D visualizations?

Second: tsunamis expose coastal environments to risk differentially as a result of many factors that govern their propagation, velocity, angle of arrival, and local topography. They are highly variable in space and time, creating considerable uncertainty about how they will behave. Enabling citizens to explore and understand these many possible scenarios is both a challenge and an opportunity for communicating risk. Providing citizens with interactive tools with which to specify starting conditions may be a way to communicate broad implications of broad starting conditions. While balancing level-of-specificity and representation may be a considerable challenge, there is an opportunity to build new forms of resilience in citizens through ‘hypothetical scenario’ knowledge gained through interactive cause-and-effect visualization experiences.

Third: tsunamis occur in real geographic spaces, not synthetic computer environments or scientific reports. An opportunity exists for the risk communication community to develop new ways to improve the connection between abstract science and physical space through the use of emerging new data formats, devices, visualization methods, and situated information experiences. While these might be used to enhance existing forms of tsunami science visualization and public communication maps, there is an opportunity to create entirely new forms of risk communication. For example, the use of topologically 3D data and 3D visualization might improve transmission of tsunami accuracy to citizens, while careful use of interactivity might enable citizens to view and explore dependencies and outcomes in evacuation scenarios. Developing tools to deliver improved tsunami representations and interactive inundation scenarios *in situ* may enable us to (re) connect science to geographic spaces.

Existing academic visualizations and public communication maps have resulted from cartographic convention, institutional norms, and available technology. Yet, they are only some of the possible ways we might communicate tsunami risk. My DIS cube analysis shows that there are areas of dimensionality, interactivity and situatedness that have not yet been explored in one or both academic and public tsunami communication domains. Developments in spatial interface research reveal new opportunities to develop visual information systems that deliver public tsunami visualizations that are 3D, temporal, interactive, and situated. Spatial interface research is an emerging field, combining the concepts, theory, methods, and technology of geovisualization, GIScience, HCI and VA. I discuss how a spatial interface approach allows us to respond to these opportunities in the following section.

5.5. Considering Tsunami Visualization from a Geovisual Interface Perspective

Geovisualization is a research field integrating visual, statistical, and computational methods to support knowledge creation from geographically-referenced data and information (MacEachren et al., 2004). More recently, the field of GeoVA has emerged, combining spatial analysis, geovisualization, user interfaces, and spatial cognition (Andrienko et al., 2007). These fields combine an understanding of (spatial) visualization design and human visual perception of visual information through the use of interactive visual interfaces (Andrienko et al., 2010; Keim et al., 2008; MacEachren & Kraak, 2001; Thomas & Cook, 2005). A geovisualization and geovisual analytics approach allows us to combine dynamic and interactive visualizations to elucidate critical spatial and temporal features in tsunami inundation.

I believe several key technologies and interface research developments have strong potential to link abstract science to geographic space and to enhance risk communication: tangible user interfaces (TUI), mixed reality (MR) and mobile augmented reality (MAR). TUI and MR technologies offer opportunity to improve interface experiences through the improvement of visualization interactivity and situatedness, respectively, two largely undeveloped axes of the DIS cube.

5.5.1. New Opportunities for Tsunami Visualization Interfaces

TUIs might be an elegant way to enable broad stakeholder audiences to engage tsunami risk communication on popular computing devices. These forms of interface allow for the manipulation of non-physical data by physical means, often through physical touch and gestures (Ishii, 2008; Ishii & Ullmer, 1997). The increasing use and decreasing cost of mobile devices affords an opportunity to improve application interactivity through a relatively new form of human-computer interaction. The most popular approach to public TUI design is the use of interactive surfaces; architectural surfaces that have been transformed into an interface between physical and virtual spaces (Ishii & Ullmer, 1997). The screens of mobile devices serve as these surfaces, allowing for gesture and touch-based interaction. Touch-based interaction design has been used in only one identified example (NANOOS, 2014) and is limited to view control.

Geovisualizations employing TUIs have been developed for a variety of geographic applications. ‘Urp’, an urban planning interface developed at MIT (Underkoffler and Ishii 1999), allows for physical models to be placed on a surface while a camera and projector determine the orientation of the models and project relevant geospatial data onto the scene. Like ‘Urp’, many cutting-edge applications of TUIs focus upon the use of physical objects and spaces in order to bridge virtual and real spaces (Cheok, Yang, Ying, Billinghurst & Kato, 2002; Hedley, Billinghurst, Postner, May & Kato, 2002; Ishii & Ullmer, 1997; Ullmer & Ishii, 2000); however, while applicable in controlled settings, such TUIs might prove cumbersome in uncontrolled spaces. For example, non-expert users exploring the relationship between local topography and tsunami hazard would not wish to interact with multi-component workbenches and projectors in challenging terrain. As such, my applied work focuses on mobile devices controlled with simple touch based-gestures to deliver augmented views and simulations of risk in coastal environments, as a way to link geovisual analyses to real-world environments.

5.5.2. Situated Geovisual Communication Interfaces for Risk and Situational Awareness

Given the spatial nature of tsunami risk and hazard, situated tsunami visualizations could offer better methods of communicating risk to coastal populations. My work seeks to take risk communication in an altogether new direction through the use and application of MR and AR tools that enable users to draw upon natural hazards analyses – to enable two new forms of situatedness: situated geovisual analytics and situated simulation.

MR is defined as a class of interface that combine views of real spaces with content from virtual environments (VE) (Milgram & Kishino, 1994; Tamura, Yamamoto & Katayama, 2001). Milgram and Kishino (1994) define the 'virtuality continuum,' which is a range of possible combinations of (user interface) information experiences between those in real space and those in entirely virtual spaces. Augmented reality (AR) is a subset of MR and is defined as a spatial interface that allows for the user to see the real world while digital objects, annotations, and other forms of data are superimposed onto their view (Azuma, 1997). AR can be found towards the real-world end of the virtuality continuum.

MR has been previously used to communicate spatial and geographical concepts and phenomena (Hedley et al., 2002; Lonergan & Hedley, 2014; Shelton & Hedley, 2002); however, the majority of this type of work falls within the immersive VE portion of the virtuality continuum (Shelton & Hedley, 2004). Examples that may apply to the tsunami problem space include: revealing hidden phenomena (Schall et al., 2009), navigation (Dünser, Billinghurst, Wen, Lehtinen & Nurminen, 2012; Tsai et al., 2012; Tsai & Yau, 2013), and post-disaster damage assessments (Kamat & El-Tawil, 2007), Many of these tools are single-use prototypes with limited application outside of their original problem space (Billinghurst & Dünser, 2012).

Several attributes make MR a viable research topic for geographic risk communication. The removal of desktop metaphors that may stand between the geovisualization and the user allows them to experience geovisualizations without having that experience diluted by the barrier of a computer screen, mouse, and keyboard interface (Shelton & Hedley, 2004). The authors also suggest two properties of AR interfaces that may benefit geographic visualization. First, the user retains proprioception within an MR interface; that is, the user's sense of self remains continuous. Second, the user's skeletomuscular motions and adjustments are directly tied to the interface. Movement of the interface device by the user results in a 1-to-1 adjustment of visuals on the display itself; closely linking the user to their virtual spaces.

These enabling technologies offer considerable potential for new kinds risk communication experiences. In response, this research introduces several prototypes that target unexplored regions of the DIS cube analysis. Lonergan and Hedley (2014) have recently introduced flexible mixed reality - a cross-platform 3D geovisualization interface architecture that links analytical visualization with real spaces. This system is leveraged to deliver situated tsunami simulation and risk visualization in the following section.

5.6. Applied Work: Implementing Interactive Situated 3D Tsunami Visualization Interfaces

In this section, I report on three visualization prototypes developed to explore the usage of 3D geovisualization, interactivity, and situatedness (Table 5-1) in tsunami risk and hazard communication. The DIS cube approach revealed unoccupied spaces of the cube – which represent forms of interaction, situatedness, and dimensionality that have not be used by either the public or academic visualization community. The prototypes were designed to explore and demonstrate risk communication interfaces in these new territories might be able to deliver.

Table 5-1. Tsunami Risk Communication Prototypes and *DIS* Classification

	2D (paper map)	EvacMap	ARRO3D	Tsunamulator
2D	X	X		
3D			X	X
Interactive		X		X
Situated	Can be	X	X	X
Mobile AR			X	X

Ucluelet, British Columbia, served as the study area for the developed geovisualizations. The interfaces were developed using 3D game development software (ShiVa 3D). The interface prototypes were authored to a mobile tablet computer (Apple iPad) as stand-alone applications in order to take advantage of location-awareness capabilities. The titles of the interface prototypes are: EvacMap; ARRO 3D; and Tsunamulator.

5.6.1. EvacMap

EvacMap is a location-aware iPad-based interface that allows users to interactively browse between different evacuation maps of Ucluelet (evacuation by distance, time, and transportation type). The purpose of EvacMap is to enable citizen users to customize risk and accessibility maps based on their mode and speed of movement, and their geographic location. Users select their mode of travel (walk, run, bicycle, car), and relative speed (fixed speed ranges within transportation type). Selection of these variables, combined with the device's GPS technology enables the user to quickly produce evacuation and accessibility maps based on specific parameters and physical location.

This prototype was designed with the limitations of existing static maps in mind. Evacuees are highly variable in their speed and origin during tsunami events. Running, walking, and vehicle speed may be different enough to alter recommended routes to safety and ultimate destinations. Paper maps cannot be altered once printed, so great care is taken to ensure they are usable for a variety of people. By allowing users to select their mode of travel customized evacuation maps can be provided based upon personal circumstance.

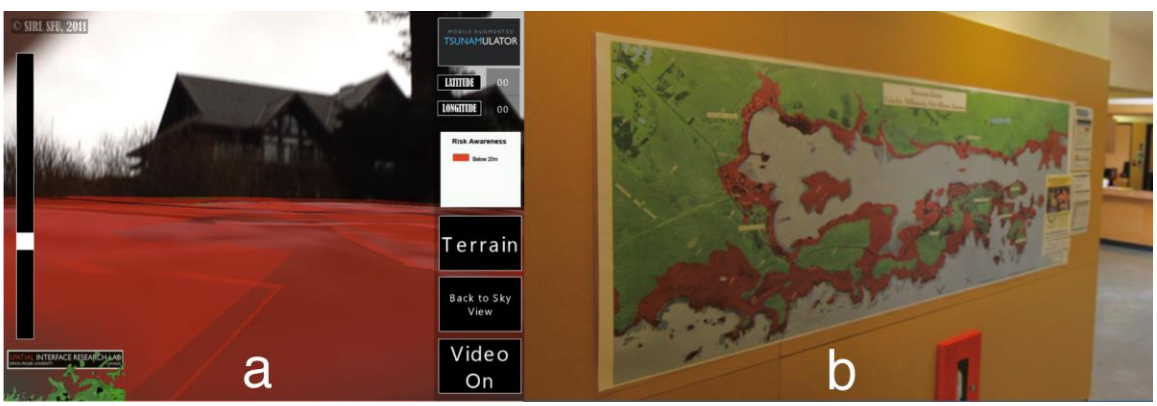
EvacMap is positioned within the DIS framework as a highly interactive and moderately situated interface. It shares a similar conceptual positioning with the NANOOS mobile tsunami application (NANOOS, 2014). Both represent uncommon forays into situated and interactive tsunami risk communication design; however, they remain clearly 2D and do not offer situated experiences beyond noting the user's current location.

5.6.2. ARRO3D

Augmented Reality Risk Overlay 3D (ARRO3D) is a prototype interface that links abstract risk maps to real space by enabling risk maps to be placed into the real world. This linkage is achieved through the use of MR, traditional risk analysis, and a coastal topographical model. A 20-meter inundation map was draped on top of a 3D VE of Ucluelet. The interface is MR-enabled; that is, the scene is viewable from a first-person perspective that integrates a live view of the real world. By adjusting the angle and orientation of the visualization device, users can see if they are standing within the 20 m inundation zone (Figure 5-4).

The MR component of this interface places this prototype further along the situatedness axis of the DIS cube than previous location-aware tsunami visualizations. This is because the visual output of the interface depends upon two highly-situated inputs: user location and visual input of the camera device. The combination of these factors with the digital risk overlay links the abstract geographical risk with everyday space.

Figure 5-4. The ARRO3D Risk Interface



The ARRO3D interface overlays digital risk information onto a live view of the landscape, indicating elevations that are below 20 m. (b) Existing red (risk) and green (safe) zoning map in a community centre.

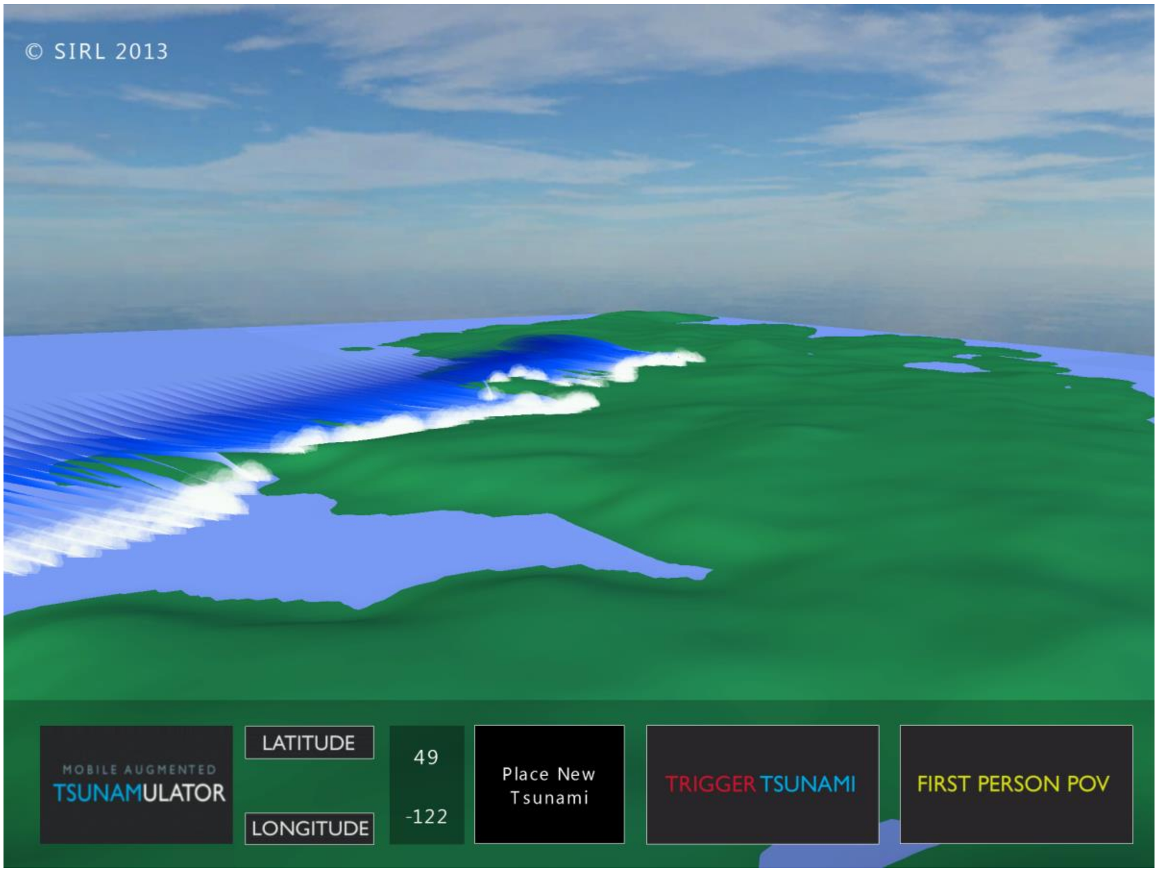
As seen in Figure 5-4, traditional forms of risk communication in local communities can be presented in ways that are disconnected from the landscape they portray. A map on a wall requires mental rotation and translation if a reader is to locate objects represented in real space. ARRO3D is designed with this challenge in mind. By allowing users to view representations of abstract risk in real space, I may avoid a potential misinterpretation of data.

5.6.3. Tsunamulator

The ‘Tsunamulator’ interface is the most advanced example of my new geovisualization interfaces. It combines dimensionality, interactivity and situatedness in one tool, to deliver a new way to link virtual simulations to geographic space for tsunami (risk) visualization. This system seeks to provide a dynamic visualization through which educators might demonstrate basic tsunami principles such as sudden onset and how local topography can alter run-up. While the simulation presented here is simplistic, it serves as a demonstration of how simulations with varying degrees of complexity and rigour might be visualized *in situ*.

This system is composed of a particle-based tsunami simulator and a VE of Ucluelet. The first interface modality provides a top-down view through which the user defines a tsunami origin point and direction of flow using a multi-touch TUI. Once the origin is determined, the interface switches to a perspective 3D simulation-viewing mode. The camera perspective is then unlocked to allow full control over the viewing angle and orientation by means of touch-based gestures.

Figure 5-5. The Tsunamulator Interface



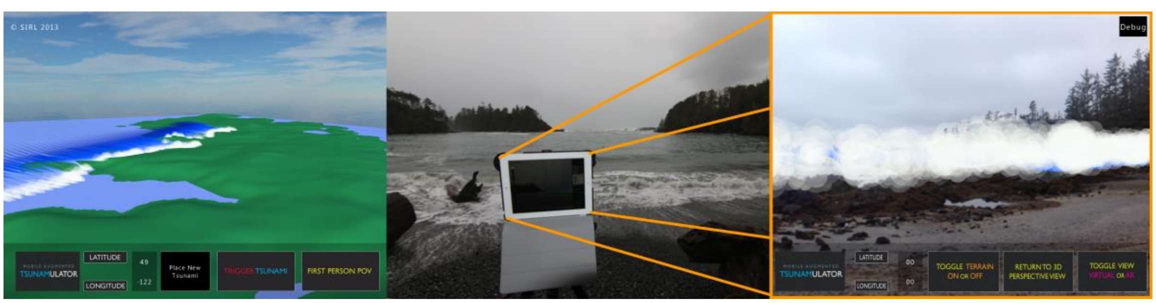
In the Tsunamulator interface, particles simulate the sudden onset of a tsunami from a 3D perspective view of a virtual Ucluelet shoreline.

The visualization itself generates particles along the linear tsunami origin. These move through the 3D environment along the user-defined vector by means of ShiVa 3D's physics engine (Figure 5-5). The particles behave as rough approximations of water breaking along the shoreline when they collide with the solid topographical geometry. While these particle simulations are certainly less accurate when compared to flow analyses generated by dedicated software, the rougher approximations are not without benefits. This lightweight flow approximation approach enables rapid visualization of inundation events on low-power mobile devices. While I acknowledge that this particle simulation is not as sophisticated as models used in scientific fluid simulation, this prototype demonstrates the potential of mobile devices to deliver simulations *in situ* as a way to connect science to geographic space. Porting results from more robust models of tsunami simulations into this environment is the next logical step.

From the 3D perspective-viewing mode, the user is given the option to switch to a ‘first-person VE’ viewing mode. This mode allows users to examine the VE from a first-person perspective – resulting from their physical location (coordinates) and manipulation of the mobile device (orientation; panning). I call this mode a situated portable virtual world – where a location-aware mobile device can be used as a portable lens through which to look into a scientific virtual simulation ‘parallel universe’ from the equivalent coordinate in real and virtual spaces.

The final – and most radical – visualization mode that Tsunamulator delivers is situated augmented reality visualization. In the previously introduced ‘situated VE mode’, the user looks through a device into a parallel virtual environment from a coordinate in the real world. By contrast, in the situated augmented reality mode, the user is able to look at everyday space through a mobile device used as a lens, and see virtual simulations run over the real landscape, with virtual particle simulations interacting with the geometry of the coastal environment. Figure 5-6 below, shows how through this new interface design, I can link abstract virtual simulations to real geographic spaces.

Figure 5-6. Linking Situated Simulation with Real Geographic Space



Tsunamulator delivers the capability to link virtual 3D simulations with real geographic space, using situated and mobile augmented reality. (L) The virtual environment version of Ucluelet, BC; (middle) a location-aware tablet running Tsunamulator; (R) user view when looking at real world view through a mobile device - an inundation simulation arriving on a local Ucluelet beach.

Individually, each prototype explores visual interface techniques to leverage dimensionality, interactivity and situatedness in one or more ways. Together, these tsunami visualization interface prototypes make new inroads into as-yet uninhabited space within the ‘DIS cube’. While perhaps novel in appearance, their purpose is serious: to find meaningful new ways to link tsunami science, simulations, visualization, users and real space. Tsunamulator is the most sophisticated outcome of this development research. It provides a fundamentally new way to link abstract scientific models, 3D virtual environments to visualize them, situated virtual environments to view them aligned with real-world coordinates (situated VE mode), and mixed/augmented reality situated simulations in geographic space.

5.7. Discussion

The primary objective of this paper is to help advance the field of tsunami risk communication. I reviewed select academic and public tsunami risk communication examples and classified them using the DIS cube space. This revealed differences in the structure of tsunami science versus public communication realms – in terms of the dimensionality (2D versus 3D) of visualizations, the level of interactivity of these visualizations, and the degree of situatedness they were designed to deliver. These differences suggest that conventional forms of tsunami science and public risk visualizations: do not commonly transmit the volumetric, dynamic characteristics of tsunamis in public risk communication (perhaps for good reason); are not typically interactive (therefore limited in their ability to communicate scenario variability); each reside in distinctly different parts of the situatedness spectrum (tsunami science typically *ex situ*, public communication being a mixture of *ex situ* and *in situ*, but often not designing maps for *in situ* use).

The structural differences I have illuminated suggest two main issues. First, as tsunami science is transmitted through existing forms of public visual risk communication, these complex phenomena are transformed into less sophisticated representations –simplifying variability and behaviour over time into static aggregate snapshots as 2D inundation footprints. The reasons for the simplifications are, in many cases, understandable, for reasons of message clarity, ease of emergency management, and limitation of liability. Still, I wonder whether oversimplification of tsunamis in current forms of visual risk communication reduces our ability to mitigate public risk. This is true from a cartographic design standpoint (Kurowski et al., 2011). But I believe that an emerging range of interactive, 3D, and situated interface methods might be harnessed to deliver significantly more informative risk visualizations.

This leads to a second significant outcome of my DIS cube analysis. Through this analysis I realized that existing visualization methods (in both academic and public communication communities) are not using all of the 2D-3D dimensionality, interactivity, and situatedness that numerous current and emerging interface technologies enable. This fact suggests that transmission of tsunami science to society might be significantly improved if we were able to: preserve the dimensional sophistication of scientific models as they are imparted to the public; use interactive visualization to reduce public uncertainty surrounding tsunami scenario variability (allow citizens to browse and explore collections of science-based hypothetical scenarios to mitigate risk through experiential education); transform on-the-ground public risk awareness by delivering new forms of situated tsunami risk visualization – allowing citizens to see our best science linked to their everyday geographic surroundings.

EvacMap explored ways in which we might make conventional 2D maps more situated, using location-awareness technology. This might be as simple as 'you are here' in existing 2D risk maps, and seeing your location change over time. This 'light' situatedness might also be used to trigger localized evacuation accessibility maps pre-computed for locations across a region – enabling citizens not only to view their location within aggregate risk zones, but to also view evacuation analyses (how far am I in time/distance from safety?) computed for their specific location.

It is through MR interfaces that I feel that situatedness may be maximized; ARRO3D and Tsunamulator offer two samples of how MR might be applied to improving the communication of abstract science. Traditional geospatial MR applications are mainly limited to digital annotation or static 3D geometries (Billinghurst & Dünser, 2012). ARRO3D follows this trend by overlaying 2D risk information in real space. 2D risk zones are the standard format for communicating risk to the public; do we gain anything by bringing this information into real, 3D space? Tsunamulator represents a more complex approach to risk visualization in real space. By bringing a dynamic tsunami simulation into the real world, I am actively connecting previously separate abstract risk (developed through tsunami science), to the coastal geographic spaces at risk (populated by citizens). While further research incorporating empirical user testing will evaluate their impact on risk awareness, I believe that MR interfaces (that combine virtual environments and real spaces, as per Milgram's (1994) continuum), have the potential to deliver our best tsunami risk analyses to citizens in everyday spaces.

5.8. Conclusions and Future Work

2D maps are the most common form of public tsunami risk communication, and have been used for a considerable amount of time. As many new spatial data types, visualization techniques and interface technologies emerge, I believe that there are as-yet-untapped ways to enhance transmission of our best tsunami science to society – through new forms of public risk communication interfaces.

I propose that, if we approach tsunami visualization from an interface perspective, a map is only one kind of interface through tsunamis can be visualized and communicated. This paper reviewed and compared the ways tsunami science versus public risk communication has visualized these phenomena. This revealed clear differences in the way these two communities currently use 2D versus 3D representation, interaction, and situatedness in tsunami visualization. Currently, the public is highly reliant on official communication (Couling, 2014); as such, information transmission needs to be effective. Contemporary and emerging geovisualization methods and interface technologies might have the potential to maximize the communication of tsunami science to society by facilitating interactive sense-making (allowing citizens to explore 'what if' scenarios) and by (re)connecting science-based visualization to everyday spaces, using location-awareness of mobile devices, and MR experiences.

This tool has been designed and implemented using a modular workflow. This results in an interoperable ability to combine different mixtures of spatial data, visualization assets, and mobile devices. While it is true I have used some devices that may be expensive in developing nations, my modular workflow is designed to adapt to circumstances involving limited data, connectivity, and other devices. My long-term plan is to develop research collaborations in coastal communities of all kinds to explore and build resilience using these tools.

My review of existing tsunami visualization, using the DIS framework, reveals as yet untapped forms tsunami risk communication interfaces, whose properties might enhance transmission of science to society. My applied work demonstrated how new forms of 2D and 3D, interactive and situated tsunami visualizations might improve alignment between tsunami science and the communication of risk to society.

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Chapter 6.

Conclusions

6.1. Summary

My primary research goal was to apply advanced geovisual methods to tsunami risk analysis, visualization, and communication. To accomplish this goal, I used: geographical information science (the science of representing, analyzing, and visualizing geographic phenomena using spatial data); geovisualization and geovisual analytics; spatial interface research; and risk communication.

This thesis comprises four discrete, but related pieces of research that connect advanced geovisual research to tsunami risk and hazard communication. The outcomes of this research include: a new conceptual framework for representing and analyzing visibility 3D spaces; a new geovisual analytical framework for tsunami evacuation signage visibility; a new set of geovisual analytical tools using mixed and augmented reality; demonstration of a set of new geovisual analyses in geographic space – in particular, situated simulation; demonstration of a collection of geovisual analytical spatial interfaces adapted to tsunami risk communication and visualization.

Chapter 2 presents a typology of isovists that account for geometrical attributes of visibility and the relationships between the observer and the observed. I defined and presented several classes of isovist: panoptic isovists, constrained isovists, and targeted isovists. Additional classification schemes were developed to characterize the geometries and attributes of observers and targets. I recognized and demonstrated point, linear, areal, and volumetric observers and targets. Finally, I categorized dynamic attributes of observers. These conceptual frameworks provide new opportunities for 3D geovisual analysis and development.

Chapter 3 is an assessment of tsunami evacuation signage placement in Seaside, Oregon. The main objective was to apply the previous chapter's conceptualization of visibility to demonstrate the value of visualscapes as hazard communication and research tools. I ran topologically 2D and 3D visibility analyses to determine the visibility of the community's evacuation signs placed along the 6 designated routes. The influence of observer geometries was given particular attention in order to capture the visibility of single-sided signs placed with orientations. The visualscapes produced by this approach revealed patterns of visibility and their relationships to other spatial characteristics such as land cover, population density, and elevation.

Chapter 4 develops a mixed reality (MR) and situated approach to geovisualization. I created of an interface that can run *in situ* simulations and visualizations of geographic processes. The main objective of this research was to demonstrate how advancements in geovisual interface technology can be leveraged for highly situated experiences.

Chapter 5 applies the technology developed in Chapter 4 to tsunami risk communication by identifying and reviewing trends within the literature on tsunami risk and hazard communication. I reviewed 129 examples of visualizations from a dimensionality, interactivity, and situatedness (DIS) perspective. These three attributes were conceptualized as axes in a cube to aid in visualizing differences across the literature. Based on the patterns identified, I developed three new risk communication interfaces: EvacMap, ARRO3D, and Tsunamulator. The interfaces apply MR and location-aware technologies to provide highly situated experiences.

6.2. Research Contributions

My research contributes to the fields of geography, GIScience, geovisualization, and natural hazards by taking a multi-pronged approach to connecting geovisual research, concepts, and technology to tsunami hazard communication. The conceptual framework for 3D visibility and the DIS cube introduced in Chapters 2 and 4 contribute to geovizualization and geohazard literature, while the work presented in Chapters 3 and 5 applies geovisual tools in a tsunami risk communication context. Tsunami risk communication has typically been restricted to 2D paper brochures (Kurowski, Hedley & Clague, 2011); this research explores more dynamic, interactive, and situated approaches to tsunami visualization.

Chapters 2 and 3 apply existing 3D visibility research in urban planning and design to natural hazards. A geovisual perspective led to the creation of descriptive language and classification schemes for 3D visibility, which, in turn, led to the development of the visibility- and visualscape-based approach to tsunami evacuation sign assessment presented in Chapter 3. This research contributes to the literature by connecting geovisual perspectives to existing 3D visibility research, and then to an applied geohazards problem.

Chapters 4 and 5 advance geovisual design research in MR interfaces, which previously have been identified as promising technologies for geographic visualization (Hedley, Postner, Billinghurst & May, 2001; Hedley, Billinghurst, Postner, May & Kato, 2002). I design a situated simulation interface in Chapter 4 and apply it in Chapter 5 to develop tsunami risk visualization designs that have not yet been fully explored. The literature suggestes that static, 2D images and maps are the standard products for visualizing tsunami risk. I contribute to this body of literature by introducing mixed reality to risk communication.

6.3. Future Directions

This research lays the groundwork for a variety of geovisualization research opportunities. The conceptual framework for 3D isovists developed in Chapter 2 offers opportunities for further research on the variable relationships between observers and the observed, visibility, and how they are represented. In this chapter, the concepts of reflection, refraction, and how they might be represented as secondary or tertiary isovists were introduced.

Likewise, the applied visibility research presented in Chapter 3 might be advanced with continued research. I introduced truly topologically 3D visibility analysis for hazards communication; however, rapid advances in technology, particularly in the fields of urban planning and design, offer opportunities to perform more sophisticated analyses. Additionally, only tsunami evacuation signage was considered during this analysis. Research on the visibility of other infrastructure, other evacuees, or weather or light limitations might prove valuable. The methods introduced in Chapter 3 could also be applied in other settings, such as other potential disaster settings, or in privacy research.

Flexible MR, a concept introduced in Chapter 4 and applied to tsunami research in Chapter 5, was shown to be possible using current geovisualization technologies. Exactly how such an approach might benefit, or impair, risk communication, however, has yet to be empirically examined. Research has shown that MR does not necessarily improve communication (Dünser et al., 2012). Empirical evidence could be gathered on the effectiveness of MR for risk communication by assessing the effectiveness of the interface prototypes developed in Chapter 5. This research would advance the field of geovisualization.

In closing, this thesis presents research that contributes to geovisualization, natural hazards, and GIScience through theoretical development and technological work. The new forms of geovisual information design and analysis described in each chapter of this thesis illuminate and demonstrate opportunities to apply geovisualization science to applied hazards research, risk analysis, and risk communication. Individually and in combination, these works aim to inform the natural hazards, risk communication and geovisual analysis communities as they pursue future research in tsunami visualization and communication.

6.4. References

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