A Cartographic Framework for Visualizing Risk

John C. Kostelnick
Department of Geography–Geology / Illinois State University / Normal / IL / USA

Dave McDermott
Haskell Indian Nations University / Lawrence / KS / USA

Rex J. Rowley
Department of Geography–Geology / Illinois State University / Normal / IL / USA

Nathaniel Bunnyfield
Department of Geography / University of Kansas / Lawrence / KS / USA

ABSTRACT

Increased attention to global climate change in recent years has resulted in a wide array of maps and geovisualizations that forecast various scenarios. Since many consequences of climate change are inherently geographic in nature, effective cartographic representations that depict these risks are valuable for planning and mitigation purposes. In particular, sea-level rise resulting from climate change calls attention to the numerous representation issues that warrant consideration for hazard and risk mapping in general, including categorizing and representing risk, selecting an appropriate level of realism, and displaying potential impacts of a hazard on human populations as well as on the natural and built environments. Using examples of potential inundation from sea-level rise at global, regional, and local scales, the authors propose a conceptual framework of key cartographic considerations for maps, Web-based mashups, and geovisualizations that depict risk. The cartographic framework presented here may be extended to other risks of an ambiguous or fuzzy nature and may be used to organize key future research areas for hazard or risk mapping in general.

Keywords: hazards and risks, climate change, sea-level rise, representation, cartographic uncertainty, symbology, realism

RÉSUMÉ

L'attention accrue portée aux changements climatiques mondiaux au cours des dernières années est à l'origine d'un vaste éventail de cartes et de géovisualisations prédisant divers scénarios. Comme beaucoup de conséquences des changements climatiques sont de nature géographique, les représentations cartographiques efficaces qui décrivent ces risques jouent un rôle précieux dans la planification et l'atténuation. En particulier, la montée du niveau de la mer causée par les changements climatiques attire l'attention sur les nombreux problèmes de représentation qui justifient la prise en considération de la cartographie des dangers et des risques en général, y compris la catégorisation et la représentation des risques, la sélection d'un niveau de réalisme approprié et l'affichage des répercussions possibles d'un danger sur les populations humaines, ainsi que sur les environnements naturels et bâtis. Utilisant des exemples d'inondation possible découlant de la montée du niveau de la mer aux échelons mondial, régional et local, les auteurs proposent un cadre conceptuel de facteurs cartographiques clés dont il faut tenir compte dans la création de cartes, des mixages de contenu Web et des géovisualisations qui décrivent le risque. Il est possible d'étendre le cadre cartographique présenté ici à d'autres risques ambigus ou flous et de l'utiliser pour structurer des recherches futures clés pour la cartographie des dangers ou des risques en général.

Mots clés : dangers et risques, changements climatiques, montée du niveau de la mer, représentation, incertitude cartographique, symbologie, réalisme

Introduction and Objectives

Climate change is perhaps one of the most significant environmental challenges confronting the global society. The recent International Polar Year (IPY) has elevated climate change as a major issue that has received significant exposure in the scientific community as well as among the general public. One potential consequence of global

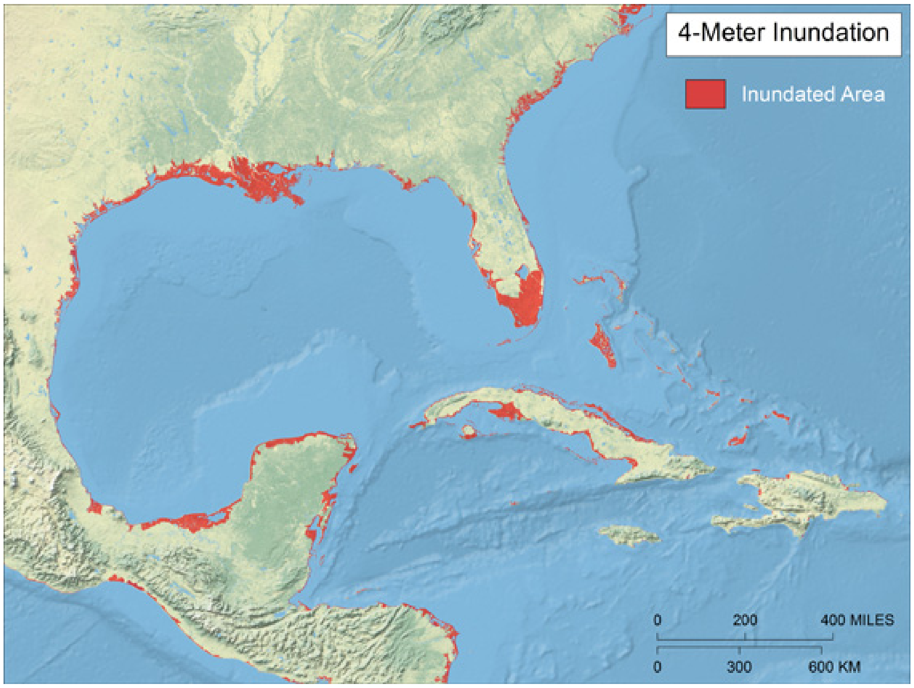

Figure 1. Example of a map that displays a simplistic scenario of sea-level rise to the map user. Source: CReSIS and Natural Earth.

climate change is risk of coastal areas to gradual rise in sea level due to the increased melting of snow and ice pack from the world's temperate glaciers and the major ice sheets, Greenland and Antarctica, as well as thermal expansion of the ocean. According to one estimate, global sea level would rise approximately 80 m if the entirety of the Greenland and Antarctic ice sheets were to melt (USGS 2000). The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2007) report provides an upper-level estimate of 26–59 cm of sea-level rise across the globe over the next century. More recently, climate scientists have estimated that sea level may rise by as much as three times the original IPCC forecasts by the end of this century (Grinsted, Moore, and Jevrejeva 2009). Since approximately 450 million people live in the coastal zone that is within 20 km of the coastline and 20 m or less elevation above sea level (Small and Nicolls 2003), the potential impact of sea-level rise likely would be significant.

Cartographers and geographic information scientists (GIScientists) have provided an important contribution to the issue of global climate change through the production of maps and geovisualizations that depict the predicted consequences of sea-level rise for use by scientists, policymakers, educators, and the general public. Maps of climate change impacts, including sea-level rise, are common in popular media and may be a persuasive means for communicating a science that is subject to much uncertainty (Dietrick and Edsall 2009). The ambiguities inherent in climate change projections are rarely included on maps for the general public, and they often convey an overly simplistic perspective on climate change processes to map users. Given the great influence that such maps and geovisualizations may have for planning, policymaking, education, and a range of other purposes, an important challenge to cartographers is to develop displays that communicate the critical issues associated with hazard and risk events in an effective, yet responsible manner. Despite the abundance of maps and geovisualizations that depict sea-level rise in the popular press and scientific literature, including the recent popularity of the Web to deliver these maps (Monmonier 2008), few studies have documented the range of cartographic issues that warrant consideration for the creation of such displays. Oftentimes a "one map solution" (Monmonier 1991) is presented to map users, with little information provided about the potential limitations and uncertainties inherent in such displays for various tasks (see Figure 1). We contend that many such maps and geovisualizations of sea-level rise often are overly simplistic and do not capture the complexities inherent in the risk for all map users and map use tasks.

The potential limitations and uncertainties of cartographic displays, however, extend far beyond sea-level-rise mapping. The entire subfield of hazard and risk mapping, in fact, is subject to the same dilemma of appealing yet responsible representations. The primary objective of this article is to identify and provide a critical analysis of key cartographic issues that should be considered for maps and geovisualizations that display hazard and risk events such as sea-level rise. To organize our approach, first we propose a general framework that highlights key cartographic issues for natural hazards in general. Next, we demonstrate how the framework may be used for hazard and risk mapping purposes using sea-level rise as an example. We explore a range of topics related to sea-level rise risk specifically, including visualization of potentially inundated areas (PIAs) and representation of potential impacts of inundation. Although the framework and discussion presented here uses sea-level rise as an example, the principles we discuss apply to mapping other natural hazards of an uncertain likelihood. In contrast to more imminent risks with a higher likelihood of inflicting significant damage such as flood, earthquake, or wildfire events, sea-level rise, of course, is a much more gradual event with uncertain consequences given unknowns in climate change projections and future human adaptation measures. In this regard, sea-level rise serves as an ideal example for the framework proposed here given the many uncertainties which have generated much discussion in both the popular press and scientific literature. As such, we propose the framework both as a practical tool for those developing maps, mashups, and other geovisualizations, as well as a broader contribution to future research agendas in the general area of hazard and risk mapping.

Cartographic Representation of Risks and Hazards

Maps and geovisualizations derived from GIS analyses serve several purposes for visualizing data related to hazards and risks during the planning, mitigation, preparedness, response, and recovery stages (Greene 2002). Despite their potential, maps may be misleading and even controversial, such as in cases when they under- or over-predict the geographic extent of a hazard zone (Monmonier 1997). For this reason, effective representations should consider several factors due to the critical role of maps for risk planning and in hazard event situations. Cartographic studies have explored numerous factors related to hazard and risk representation, including specific symbolization considerations for maps used to support activities in domains such as emergency response (Dymon 2003), crisis management (Robinson, Roth, and MacEachren 2010; Roth and others 2011), and humanitarian demining (Kostelnick and others 2008). Bostrom, Anselin, and Farris (2008) provide a broad review of several visualization methods that have been used for communicating risk on maps, yet lament the lack of empirical studies that have evaluated the effectiveness of these graphical techniques on overall risk perception. Citizen concern over industrial wastes has led to research on symbolization of risks associated with toxins and called attention to the challenge of responsibly representing poorly understood relationships such as thresholds of hazardous exposure to different toxins (Scott and Cutter 1997). Other studies have highlighted issues related to the scale of hazard representation. Scale requirements at which map users wish to evaluate risk, for example, may be very different from those at which the data are provided (Zerger 2002). Scale is a particular challenge in the realm of hazard and risk mapping in which data at a geographic scale finer than a county or city are commonly required (Mills 2010).

In addition to highlighting specific cartographic issues for hazard and risk mapping, other researchers have emphasized broader topics related to societal implications of such maps. Cartographic representations of hazards and risks may reflect the values and interests of the cartographer(s) (Koch 2004), which elevates the stakes for the influence that such representations may exert. As such, maps may be used as instruments of political power (Crampton and Krygier 2006). For example, the act of declaring a piece of property to be in a floodplain has immediate consequences for its market value and perceptions of how that property can be used or insured. Similarly, maps of areas that are vulnerable to coastal inundation may be interpreted as statements by the cartographer that such areas are of diminished value. The issue is complicated further when maps are created by Western institutions for areas occupied by indigenous populations – the act of mapping may take on an aura of colonialism (Harley 1992). The growing literature in critical cartography and GIS (e.g., Kwan 2002; Crampton and Krygier 2006; O'Sullivan 2006; Crampton 2010) illustrates how such maps and geovisualizations may be, accidentally or by design, instruments of oppression.

A Framework for Visualizing Risks

Although other studies have examined specific cartographic issues related to hazard and risk mapping, few have examined the topic holistically. Given the growth of hazard and crisis mashups in the web 2.0 era (Liu and Palen 2010), a broader conceptual framework or model is needed to organize many of the cartographic issues inherent in hazard and risk mapping. Based on our experiences developing maps and geovisualizations for sea-level rise (Rowley and others 2007; Li and others 2009), we identify key cartographic issues that warrant consideration for hazard and risk mapping in general, collectively illustrated in Figure 2. The framework organizes key issues and contains elements of a decision tree to provide a practical catalogue of cartographic options for those who develop risk maps and geovisualizations. These key topics were identified through our work over several years, which often involved trial and error as well as feedback from scientists, educators, and the general public, yet should not be considered an exhaustive list of topics for all hazard and risk mapping scenarios. Although we offer potential cartographic approaches here to the issues that we have

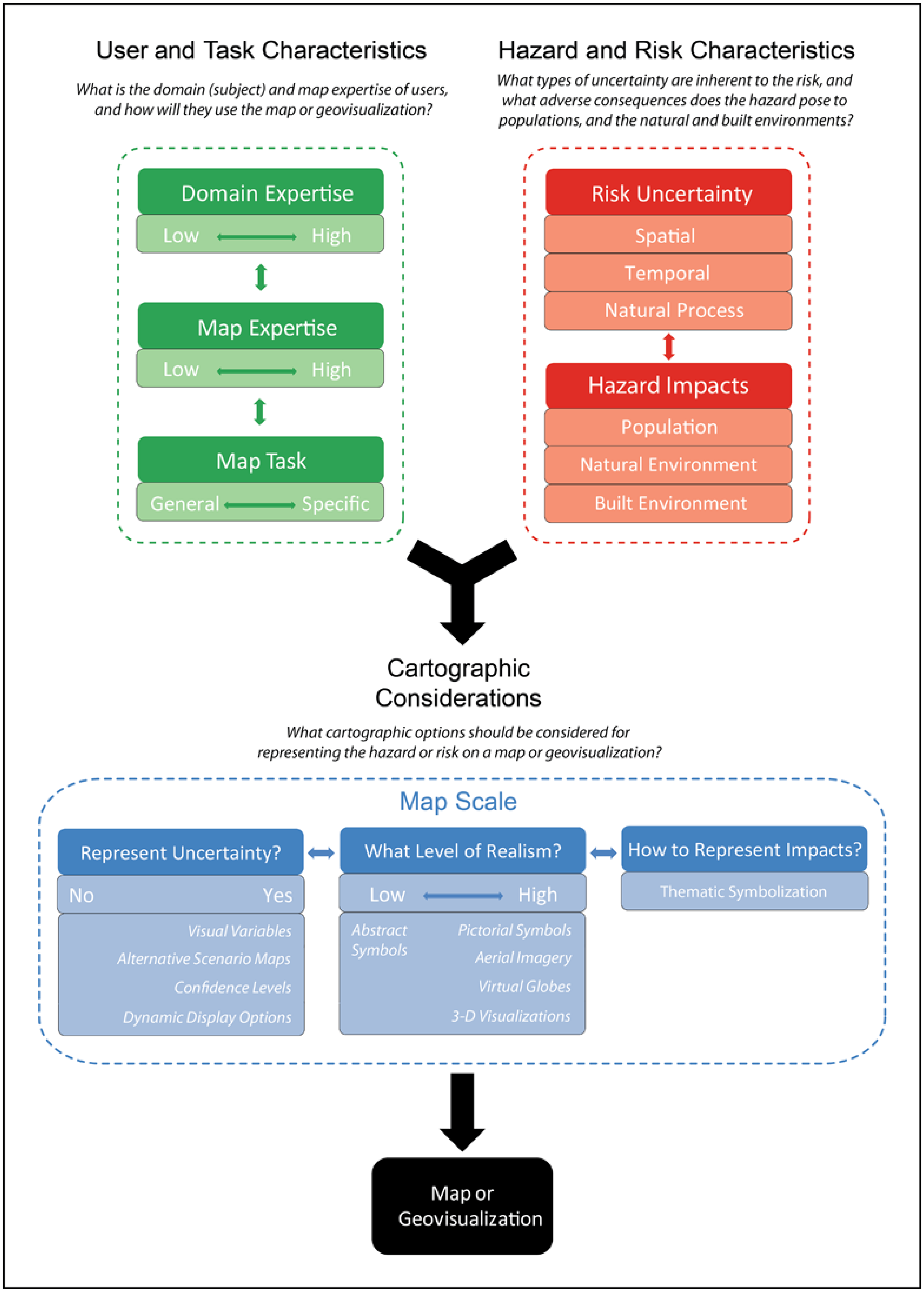

Figure 2. A conceptual framework of considerations for the development of maps and geovisualizations for risks such as sea-level rise.

identified, we also call for more structured testing with users to identify further the specific scenarios under which the potential solutions we present are most appropriate.

OVERVIEW OF THE FRAMEWORK

At the start, we must define the terms *hazard* and *risk* given the inconsistent usage of both terms in the literature (Brooks 2003). For the purposes of the framework proposed here, we adopt the definition of a hazard provided by Cutter (2001, 2): "a threat to people and the things they value." In the context of sea-level rise, hazard encompasses the gradual rise of the ocean and consequential coastal flooding and inland inundation. In contrast, a risk is the probability of a hazard occurring as well as the societal impact of the hazard, defined mathematically by Okrent (1980) as *risk = size of a hazard's impact x probability*. In the context of sea-level rise, risk measures the likelihood that inundation will occur, as well as the total impact that such inundation would incur on society. From a geographic perspective, the spatial extent of a hazard is not necessarily correlated with the level of risk. For example, risk associated with sea-level rise may be low for a coastal area if the probability of inundation is low, if the inundation were to occur in a region of sparse human habitation, or if human mitigation measures may minimize the impact of inundation in populated areas.

Central to the framework proposed here are three primary components that should factor into the development of a risk or hazard map/geovisualization: *cartographic considerations* that are driven by both *user and task characteristics*, and *risk and hazard characteristics* that in turn lead to the application of specific cartographic techniques. First, hazard or risk mapping must consider user and task characteristics, such as the level(s) of domain and map use expertise (ranging from novice to expert for each), as well as the desired task (general vs. specific) for which the map or geovisualization is used (Figure 2, upper left). The probability associated with a risk infers various types of *uncertainty* (categorized generally in the framework here as spatial, temporal, and natural process), which should be characterized further for each unique type of risk (Figure 2, upper right). The occurrence of a hazard, by definition, poses threats to society, which may be conceptualized as "*impacts*" on different variables. Here we propose population and the natural (e.g., flora and fauna) and built (e.g., human infrastructure) environments as key variables that might be impacted by several types of natural hazard events. We should note that we use the term *hazard impacts* as a synonym for *disaster* – the measurable outcomes or consequences of a hazard (e.g., monetary value of damaged property, total number of displaced persons) (Brooks 2003).

Once user and task characteristics and risk characteristics have been inventoried, these guide the specific cartographic considerations and decisions that must be made by the cartographer to represent the risk on a map or geovisualization (Figure 2, bottom). These cartographic considerations should include at least three important factors: representing the risk given the numerous types of uncertainty; representing the potential impacts of the hazard on different variables (e.g., population, real estate, infrastructure); and selecting the appropriate *level of abstraction or "realism"* for depicting the hazard. These factors, in turn, guide specific cartographic design decisions such as appropriate use of the visual variables, selection of thematic symbology, and incorporation of dynamic display methods such as animation or 3D visualization. Collectively, these factors dictate the final representation of the hazard or risk that is chosen for a map or geovisualization (Figure 2, bottom). These considerations are not mutually exclusive and may interact as represented by the multidirectional arrows in the figure; for example, the type and degree of uncertainty for the risk may influence the level of realism chosen for the display. In addition, map scale is represented in the framework as an important consideration inclusive of all the factors described above since hazard impacts are commonly represented at multiple scales (e.g., global, regional, local). We argue that the factors identified in the framework deserve special consideration by cartographers within specific hazard and risk mapping activities, and they offer continued research challenges. In the next section, we examine each of these three components of the framework in more detail, using sea-level rise as a case study for illustration purposes.

User and Task Characteristics

Maps are representations that may be understood at multiple levels, ranging from the perceptual and cognitive processes used by map users for interpreting visual sensory information to the societal meanings that are embedded in maps (MacEachren 1995). The abundance of cognitive and perceptual experiments in cartography to improve map design beginning in the mid-twentieth century underpins the importance of psychological principles in how maps are interpreted by different groups of users (Montello 2002). In the realm of geovisualization, MacEachren and Kraak (2001) identified differences between individuals and groups as a key research challenge. Numerous researchers have heeded this call and cited the importance of specific user characteristics in the design and evaluation of geovisualizations (e.g., Slocum and others 2001; Slocum and others 2003; Robinson and others 2005). Among these user characteristics are different categories of user expertise, including level of domain expertise (Slocum and others 2001).

User characteristics in the context of hazard and risk mapping often dictate the type of task that is performed with the map or geovisualization and whether the map is used for specific measurements or for more general visualization purposes. For example, consider a flood risk map that may be used by an emergency planner to calculate the number and type of critical facilities located within the flood zone. That same flood risk map also may be used by a policymaker to view the general geographic extent of the hypothetical flood within a province or state. The type of task performed with the map must be considered for the selection of data at an appropriate scale, a key challenge in hazard and risk mapping where data sets are often required at a scale finer than a county or city (Mills 2010).

Users of maps and geovisualizations that display risks such as sea-level rise may be quite diverse, ranging from educators to scientists, urban planners to policymakers, and the general public at large. In addition to the range in domain expertise (i.e., knowledge about climate change science and potential impacts on sea-level rise) of these users, map use expertise may also vary considerably. Similarly, risk maps and geovisualizations may be used for multiple tasks. In the context of education, sea-level rise maps and geovisualizations are often used for general purposes, such as displaying general patterns at global or regional scales. An urban planner, however, may wish to use the map for much more specific purposes, such as visualizing potential impacts of inundation on infrastructure in a city. Rosenbaum and Culshaw (2003, 268) emphasize the importance of domain expertise for risk maps displaying geological hazards (earthquakes, landslides, etc.) which often serve a limited purpose for novices since they "assume a significant amount of knowledge of the nature and characteristics of the phenomenon." Anecdotally, we have observed many occasions of map misuse by naïve users who improperly utilize sea-level rise maps, such as the use of geovisualizations developed at a global scale to make local assessments of expected impacts of sea-level rise. Collective understanding of this diversity in user tasks, as well as level of domain and map use expertise, is crucial for ensuring that the map or geovisualization is not used for a purpose that may lead to false or misleading conclusions about the risk. In particular, user characteristics may influence the appropriate level for representation of data uncertainty (or lack thereof).[1]

Risk Characteristics

UNCERTAINTY

All geographic phenomena are subject to various types of uncertainty, either inherent in the phenomenon itself or in the measurement of the data representing it (Couclelis 2003). Categorizations of geographic uncertainty have been proposed in various contexts to describe the ambiguity further. For example, MacEachren (1992) proposed three general categories of uncertainty (attribute, spatial, and temporal) that characterize geographic data. MacEachren et al. (2005) proposed an expanded typology of nine types of uncertainty: accuracy/error, completeness, consistency, credibility, currency, interrelatedness, lineage, precision, and subjectivity. Plewe (2003) characterized uncertainty in historical GIS databases as composed of two primary elements: ambiguity and fuzziness. Pang, Wittenbrink, and Lodha (1997) described three general categories of data uncertainty (statistical, error, and range), although these are not exclusive to geographic data. Uncertainty, they argued, may be introduced from multiple sources, including data measurement, transformation of data, and the visualization process itself.

Approaches for categorizing and handling uncertainty on maps and in GIS analyses have been proposed in many fields of study such as biogeography (Rocchini and others 2011) and landscape evaluation (Canters, DeGenst, and DuFourmont 2002). Uncertainty in geographic data is a particularly important consideration in the contexts of risks, in which the decision-making process may influence the safety and protection of populations, property, and infrastructure. At an extreme level, uncertainty in geographic data may lead to adverse consequences as a result of using the data (Agumya and Hunter 2002). The visual methods used to depict uncertainty in spatial data may significantly impact the decision-making process as well (Hope and Hunter 2007). In their work evaluating software for visualizing the future global water balance, Slocum et al. (2003) report that representation of uncertainty may be discomforting to decision makers, which calls attention to the circumstances under which uncertainty representation is most appropriate. Likewise, level of expertise (such as domain and map use) may significantly influence the assessment of risk for hazards such as flooding when uncertain information is presented on maps (Roth 2009). In a study of online drought maps, Dow, Murphy, and Carbone (2009) report that domain experts without cartographic or GIS experience may not fully comprehend sources of uncertainty, which suggests the importance of map use expertise for understanding uncertainty inherent in risk maps.

Some types of uncertainty may be symbolized quantitatively on maps and geovisualizations (Pang 2001; Slocum and others 2003) while others are subject to the speculative or counterfactual nature of the phenomenon being represented and therefore are not easily represented by standard quantitative methods. Regardless of the type of uncertainty or method of cartographic representation, it is critical that map users comprehend the uncertain nature of the phenomenon and the degree to which this uncertainty should be considered for interpretation of maps and geovisualizations for various tasks.

Sea-level rise is emblematic of many natural hazards; it is subject to inherent uncertainties regarding the magnitude, location, and temporal occurrence of the event when displayed on maps based on data inputs from GIS-based models. For the purposes of the risk framework proposed here, we categorize uncertainty for natural hazards into three primary types: spatial, temporal, and natural process. The typology is similar to MacEachren's (1992) broad categorization, which also includes spatial and temporal uncertainty, yet is specific to the context of risks through consideration of natural process uncertainty. A primary challenge in mapping sea-level rise, and many other natural hazard risks, rests in how to convey these types of uncertainty – spatial, temporal, and natural process – to map users. Ultimately, the effectiveness of any risk map or geovisualization depends on how these categories of uncertainty are represented, since they may not be apparent to novice map users.

Spatial Uncertainty

Spatial uncertainty is the level to which the spatial information used to map or visualize a risk is correctly depicted in the data set. In the context of sea-level rise, spatial uncertainty refers to the level of accuracy and precision of the PIAs displayed on a map or geovisualization as influenced by the scale, accuracy, and precision of the input data (e.g., elevation) used in the analysis. Gridded elevation data in the form of digital elevation models (DEMs) are available at several levels of horizontal and vertical accuracy and precision for use in GIS-based predictive models of sea-level rise (Figure 3). But DEMs are subject to several sources of error, uncertainty, and lack of data precision that may propagate into derivative products (Carter 1992; Fisher and Tate 2006). Specifically, spatial uncertainty for predicting inundated areas is influenced, in part, by two important variables: the horizontal or spatial resolution of the DEM and the vertical accuracy and precision of the elevation values themselves. PIAs derived from coarse elevation data sets may have limited value given that the levels of estimated inundation may fall within the vertical accuracy of the elevation data set (Gesch 2009).

Coarse DEMs have been used for global or continental-scale analyses of sea-level rise (see Weiss and Overpeck 2003; Rowley and others 2007; CEGIS 2009; Li and others 2009), including the Global Land One-Kilometer Base Elevation (GLOBE) elevation data set (Hastings and Dunbar 1998), which provides 30 arc-second horizontal or spatial resolution, and the Shuttle Radar Topography Mission (SRTM) with 3 arc-second spatial resolution for much of the earth. Studies related to these specific data sets have demonstrated how these DEMs may over- or underestimate actual elevation values; SRTM, for example, has been found to overestimate elevation consistently with the error varying by land cover type (Shortridge 2006). For maps and geovisualizations at regional or local scales, higher spatial resolution data sets are more appropriate such as 10m or 30-m DEMs provided by the US Geological Survey (USGS). A limitation in each of these data sets is that elevation units typically are in whole metre integer values, and the elevation data themselves often have variances well in excess of 1 m, which makes prediction of sub-metre levels of inundation unfeasible without using sophisticated interpolation techniques (Li and others 2009). PIAs derived from Light Detection and Ranging (LiDAR) DEMs have the potential to portray sea-level rise with more confidence due to the finer spatial resolution (typically a few metres or less) and more precise vertical accuracy (typically sub-metre). In addition, high-resolution LiDAR DEMs may capture features on the landscape such as levees or drainage canals that may influence inundation and go unnoticed in lower resolution elevation data sets (Poulter and Halpin 2008).

In addition to uncertainty inherent in the horizontal and vertical resolutions, DEMs have other inherent idiosyncrasies that may lead to spatial uncertainty for prediction of inundated areas. For example, missing cell values, striping, and other data artifacts may yield inaccurate results when integrated into sea-level rise inundation models, even for data sets that are presumed to be "best available." LiDAR returns may be influenced by water surfaces and other types of land cover, resulting in flawed elevation data for coastal wetlands where accurate data are needed most acutely (Kinzel and others 2007). In particular, LiDAR returns for elevation are often adversely affected in heavily vegetated areas where canopy closure limits the passage of laser pulses to the ground (Barber and Shortridge 2005). Along with errors related to horizontal and vertical accuracy and precision of the elevation data set, such raw physical errors propagate into spatial uncertainty in risk maps.

To demonstrate the uncertainty that results from sea-level rise as a function of the elevation data set used for estimating potential inundation, here we present results comparing PIAs at four different spatial resolutions (1 km, 90 m, 30 m, and 10 m) for the areas of Cobscook Bay, Maine (Table 1), and Charleston, South Carolina (Table 2). The selected areas were chosen to represent diverse physical landscapes: a forested landscape in an area of high coastal relief (Cobscook Bay) and an urban landscape in an area of low coastal relief (Charleston). PIAs were calculated based only on elevation above mean sea level following the approach described in Li et al. (2009). For the sake of analytical consistency among the three study areas, the calculations were all performed using the same Albers Equal-Area projection and do not reflect the contribution of tides, storm surges, or coastal sediments.

The disparities between the total PIAs for each respective increment of sea-level rise for both locations indicate both the impact of scale (i.e., spatial resolution of the respective DEM) and measurement (i.e., methods used for deriving DEM elevation values). SRTM reliably predicted the smallest inundation areas for each level of inundation. These results are consistent with the findings of Shortridge

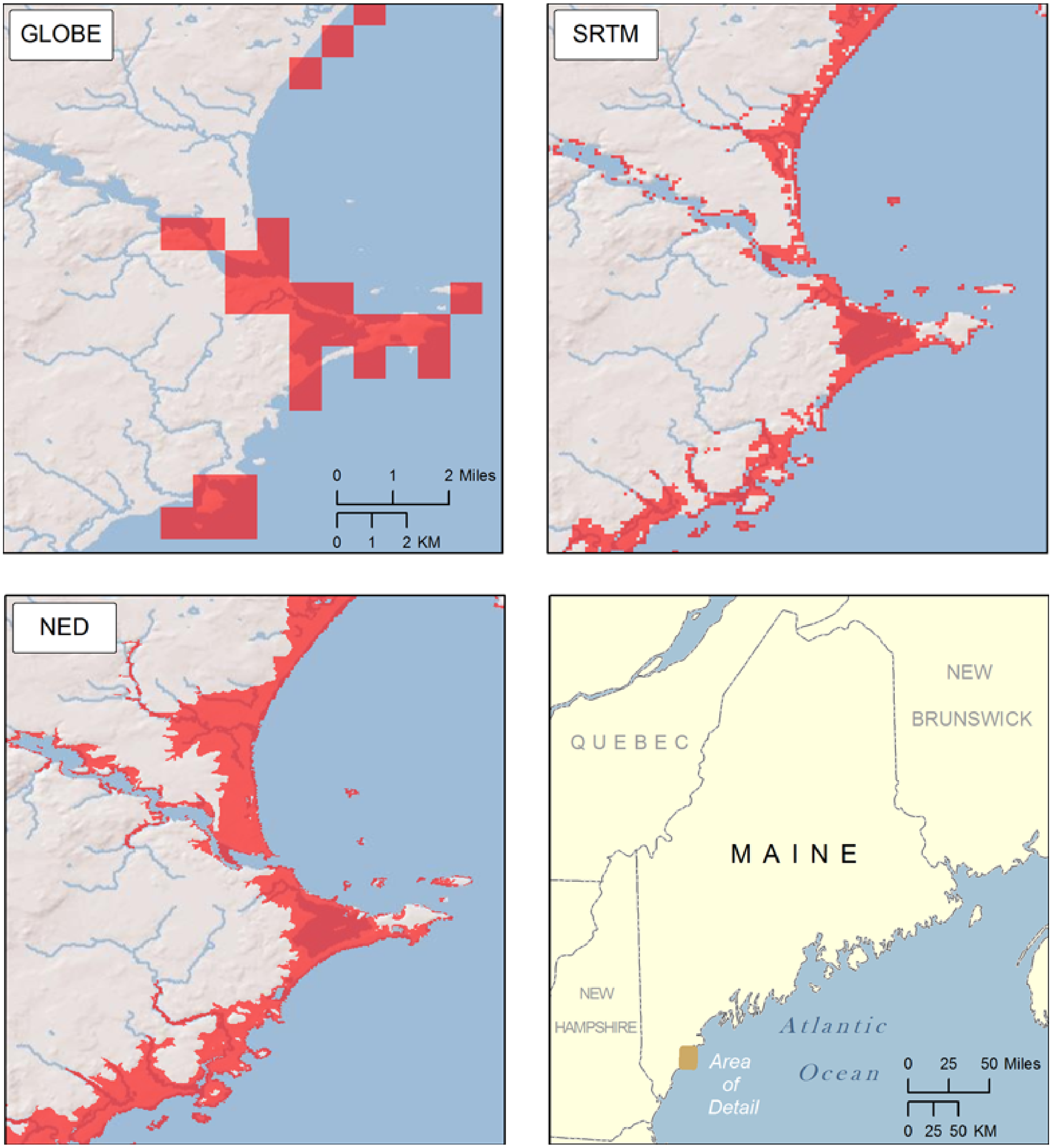

Figure 3. Impacts of varying spatial resolutions of input DEMs on PIAs for 6 m (displayed in dark grey; online, in red) derived from (a) GLOBE (1 km), (b) SRTM (90 m), and (c) NED (30 m). Area is Biddeford Pool, Maine, United States. Basemap Source: Esri World Shaded Relief and Natural Earth.

(2006): generally higher elevation values in the SRTM data set are likely a result of first return signals influenced by forest vegetation and not true bare-ground elevation measurements. The coarse resolution GLOBE data illustrate the abrupt changes in inundation that result from larger raster cells, especially when compared to the smooth changes in inundation produced by the finer resolution NED data sets. Results for the 10-m and 30-m NED DEMs were quite consistent at all inundation increments for both locations despite the differences in spatial resolution. But input elevation data sources sampled to create 10-m and 30-m NED DEMs are often the same (Gesch 2007), thereby accounting for similarities in these results.

Table 1. Comparison of land area inundated at 1–6 m of sea-level rise for DEMs with 1-km, 90-m, 30-m, and 10-m spatial resolution for Cobscook Bay, Maine, United States. Inundation is expressed in km^2 (top) and percentage of the total study area inundated (bottom) for each 1-m increment of sea-level rise.

Inundation Increment (m)		GLOBE (1-km resolution)	SRTM (90-m resolution)	NED (30-m resolution)	NED (10-m resolution)
Greater than 1 and less than or equal to 2	Total area (km^2)	12.8	0.92	3.47	2.56
	% of total area	1.9%	0.2%	0.5%	0.4%
2–3	Total area (km^2)	5.9	1.2	2.8	2.4
	% of total area	0.9%	0.2%	0.4%	0.4%
3–4	Total area (in sq.km)	5.9	1.9	2.7	2.3
	% of total area	0.9%	0.4%	0.4%	0.3%
4–5	Total area (km^2)	5.9	2.1	3.0	2.6
	% of total area	0.9%	0.4%	0.5%	0.4%
5–6	Total area (km^2)	12.9	2.4	3.9	3.9
	% of total area	1.9%	0.4%	0.6%	0.6%

Table 2. Comparison of land area inundated at 1–6 m of sea-level rise for DEMs with 1-km, 90-m, 30-m, and 10-m spatial resolution for Charleston, South Carolina, United States. Inundation is expressed in km^2 (top) and percentage of the total study area inundated (bottom) for each 1-m increment of sea-level rise.

Inundation Increment (m)		GLOBE (1-km resolution)	SRTM (90-m resolution)	NED (30-m resolution)	NED (10-m resolution)
Greater than1 and less than or equal to 2	Total area (km^2)	146.9	39.4	93.4	93.3
	% of total area	13.3%	3.6%	7.6%	7.6%
2–3	Total area (km^2)	128.8	38.8	89.2	87.8
	% of total area	11.7%	3.5%	7.2%	7.1%
3–4	Total area (km^2)	169.0	45.3	77.4	76.1
	% of total area	15.3%	4.1%	6.3%	6.2%
4–5	Total area (km^2)	130.2	52.8	82.9	82.2
	% of total area	11.8%	4.8%	6.7%	6.7%
5–6	Total area (km^2)	82.9	60.9	77.7	77.4
	% of total area	7.5%	5.6%	6.3%	6.3%

Temporal Uncertainty

Many risks are inherently subject to various levels of temporal uncertainty regarding the predicted occurrence and frequency of the risk. Gradual sea-level rise may be anticipated for continents over the course of several centuries, whereas abrupt sea-level changes may be conceptualized for local areas over the course of a day due to tidal cycles. Regardless of the temporal scale, the difficulties of associating a specific time period with each increment of sea-level rise pose challenges for depicting change over time on maps and geovisualizations. The challenge to forecast accurately "X Units" of sea-level rise for "Time Period Y" guarantees a certain level of temporal uncertainty. Such uncertainty is suggested by the IPCC (2007) final report, which predicts a rise in sea level of anywhere between 18 and 59 cm by the year 2100. Temporal uncertainty is further complicated by the fact that sea-level rise rates fluctuate and are not linear, which poses limitations for interpolation of sea-level rise increments between time periods.

Natural Process Uncertainty

Most natural hazards, whether human-caused or purely natural, involve many variables, but most GIS-based models or visualizations of the phenomena often simplify the complexities involved. At its most basic level, modelling sea-level rise is a conceptually simple exercise of querying an elevation data set for all areas whose elevation is less than the

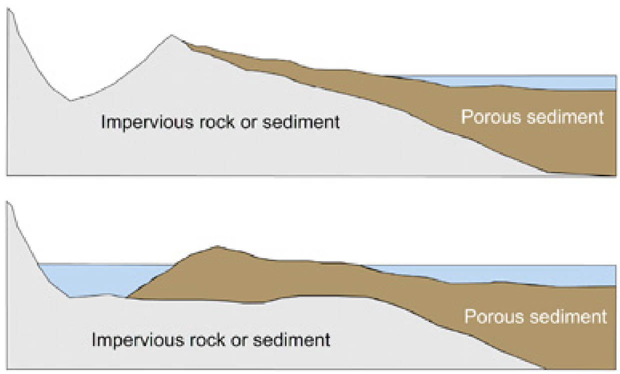

Figure 4. A hypothetical example (displayed as a cross-section) of the role of coastal sediment as a variable influencing natural process uncertainty in predictions of sea-level rise. Note that the basin on the left is not inundated due to the impervious rock or sediment (top), yet the same basin would be inundated in the lower figure if porous sediment were present instead (bottom).

selected amount of sea-level rise. The simplicity of such "bathtub" models, however, fails to consider the geographic complexity of the coastline or environmental variables that influence the process of sea-level rise, thus introducing uncertainty into the resulting PIAs. In addition to elevation, some studies have incorporated water connectivity into sea-level rise models (e.g., Weiss and Overpeck 2003; Rowley and others 2007; Poulter and Halpin 2008; CEGIS 2009; Li and others 2009) to better account for surface flow of water. But the number of adjacent cells (four vs. eight) used to define water connectivity in the analysis may also influence resulting PIAs (Poulter and Halpin 2008).

In reality, sea-level rise is a complex process that may vary considerably at the local level due to numerous other factors such as ocean circulation patterns, tidal regimes, thermal expansion of the ocean, and geologic subsidence and uplift (Szabados 2008). Uncertainty resulting from the complex physical processes of sea-level rise may be reduced, in part, by using models that incorporate additional input factors such as tides and coastal geomorphology. Such models may, for example, consider the characteristics of coastal bedrock and sediment, which will determine whether basins that are not connected to the ocean by surface water will be inundated by means of groundwater passing through porous sediments (Figure 4). More sophisticated models may also account for local tidal variation, which may significantly impact the spatial extent of a PIA since a change at high tide is perhaps a more meaningful indicator of potential destruction to coastal infrastructure than inundation at mean sea level, the vertical datum for most DEMs used in modelling. Weather is another variable that may be included in more complex models, and the likelihood of sea-level rise coinciding with high tides and storm surges will create inland inundation that may be of short duration but destructive nonetheless. The Coastal Vulnerability Index (CVI) from the USGS (Hammer-Close and Theiler 1999) and the Sea Level Affecting Marshes Model (SLAMM) (US Fish and Wildlife Service 2011) represent more advanced modelling efforts that codify the multiple elements of physical geography (e.g., coastal erosion) that contribute to the process of inundation resulting from sea-level rise.

HAZARD IMPACTS

In addition to characterizing the *actual* risk, many hazard and risk mapping activities also call for maps and geovisualizations that consider potential *impacts* of a hazard on populations and the human or natural environments – in other words, the social and biophysical vulnerabilities of a place (Cutter 1996; Cutter, Boruff, and Shirley 2003). Although variables of interest for these hazard impacts (population, infrastructure, critical facilities, etc.) may be similar among natural disasters, geographic location may provide challenges unique to each type. In the context of sea-level rise, assessments of a place's overall vulnerability may be understood to reflect both the exposure to sea-level rise and the extent to which natural and human systems might be harmed by that sea-level rise. The impact is thus a combination of the exposure to inundation and the extent to which human communities have organized themselves and their built environments in ways that are resilient in the face of that exposure. While the concept of resilience comes from ecology (Holling 1973), it can be applied to social systems as well as natural ones. So, for example, a coastal community whose economy is based on lobster harvesting might be more resilient than one whose economy is based on tourism, whose tourist sites might be destroyed or made inaccessible by sea-level rise. Similarly, the coastal built environment can be engineered to be more or less resilient in the face of storm surges through structures sited at safe elevations, buildings constructed to survive inundation, or dikes and levees built in flood-prone areas. At the same time, economically disadvantaged coastal communities may be uniquely vulnerable to both physical and economic harm precisely because they lack the resources necessary to engineer resiliency into their physical infrastructure or their economies (Thomalla and others 2006).

The magnitude of impact that a hazard may have may be evaluated by considering several variables. Here we propose population (which includes socio-demographic characteristics of populations) and the natural (e.g., flora and fauna) and built (e.g., human infrastructure) environments as key variables that might be impacted by several types of hazard events. This three-part classification is consistent with the distinction among risk to "land, communities, and assets" or "land, housing, and population" used by Strauss et al. (2012, 1). The classification could also be expressed as a two-part distinction between the human and non-human world, after Cutter's (1996, 536) aggregation of "place vulnerability" as the sum of "biophysical vulnerability" and "social vulnerability" or Berkes's (2007) distinction between human systems and environment systems as the potential objects of any hazard.

The question of whether a physical or social system is relatively resilient in the face of a risk such as sea-level rise raises additional cartographic challenges. Considerations of vulnerability and resiliency are fundamentally place-based, creating the explicitly cartographic challenge of how to represent resiliency as it varies across space (Turner and others 2003). A key cartographic challenge is to symbolize the nature of the physical hazard, the actual population or type of land use/land cover that may be impacted, and the extent to which those populations or natural systems might respond successfully or unsuccessfully to the change in sea level. While populations may be summed and land areas measured with relative precision, the exact definition of what it means to be vulnerable is a still evolving (Cutter 1996; Brooks 2003). Furthermore, in the case of sea-level rise and other coastal hazards, map scale presents a practical mapping challenge. Standard forms of thematic symbolization for variables such as impacted population in coastal areas can be difficult to view due to location and congestion of symbols, particularly for maps at small scales (e.g., global, continental) (Li and others 2009).

Cartographic Considerations

Once user and task characteristics and risk characteristics have been considered, these may be used to guide specific cartographic decisions for a map or geovisualization (Figure 2, bottom). In the following section, we provide examples of several cartographic strategies that may be used and also provide specific examples that implement these methods using sea-level rise scenarios.

UNCERTAINTY REPRESENTATION

A key cartographic decision related to risk mapping is whether or not to convey uncertainty on a map or geovisualization and, if so, how to display it. Numerous graphic strategies for representing uncertainty have been proposed in different contexts (e.g., Pang, Wittenbrink, and Lodha 1997; Rossum and Lavin 2000; Pang 2001); here we outline several options available to cartographers for symbolizing spatial, temporal, and natural process uncertainty associated with risk (Figure 2, bottom). Uncertainty may be depicted on static displays, in which the visual variables are used to depict data validity, or dynamic displays, where users can explore uncertainty through interactive features (Goodchild, Buttenfield, and Wood 1994). Uncertainty may be implemented in the form of multiple maps, such as a map of actual data values accompanied by another map that displays the level of uncertainty in the data, or as a single map, in which data values and the uncertainty for data values are symbolized on a bivariate map (MacEachren 1992).

The visual variables are commonly used to imply uncertainty in various contexts. For example, DeCola (2002) developed bivariate maps to display predicted incidences of Lyme disease where a blue/red colour ramp was used to display predicted occurrence of Lyme disease and saturation used to depict the confidence in the prediction. Slocum et al. (2003) represented uncertainty with colour for models of future global water balance scenarios. In their approach, each of the three primary colour components of the RGB colour model were used to represent a different contributing variable to the overall model uncertainty. In an experiment of the effectiveness of uncertainty display in urban growth models, Aerts, Clarke, and Keuper (2003) used the visual variable value to indicate model uncertainty ranging on an ordinal scale from "certain" to "uncertain." MacEachren (1992) extended Bertin's (1983) original visual variables to include focus, which may be used to depict uncertainty in one of four ways: crispness, fill clarity, fog, and resolution. An understanding of how these various methods of representing uncertainty in practical situations is necessary to ensure that they are used most effectively. Zuk and Carpendale (2006), for example, analyzed the utility of Bertin's (1983) visual variables as well as design principles proposed by Edward Tufte (2001) and Colin Ware (2004) for representing uncertainty on several types of visualizations, and such studies are particularly relevant for representation of uncertainty in risk mapping.

Alternative scenario maps for a risk prediction on a single map or multiple maps are another approach that cartographers may employ for conveying spatial, temporal, and natural process uncertainty for risks. Such displays provide a means for users to consider several plausible future scenarios. Alternative scenarios may be combined on a single map that utilize the visual variables for symbolization, or they may be displayed as a series of two or more maps displayed for comparison. Monmonier (2006) advocates such "comparison maps" as particularly useful in the context of communicating uncertainty associated with different forecasts. Examples of alternative scenario maps include the "epsilon band" concept described by Hunter and Goodchild (1995) for depiction of error uncertainty in elevation contours and the methods used by Gesch (2009) to depict uncertainty in sea-level rise projections based on DEM vertical accuracy by displaying PIA scenarios both above and below a specified increment of sea-level rise.

Confidence levels derived from statistical methods also may be employed to display uncertainty on risk maps. Integral to such maps is the ability to calculate confidence levels

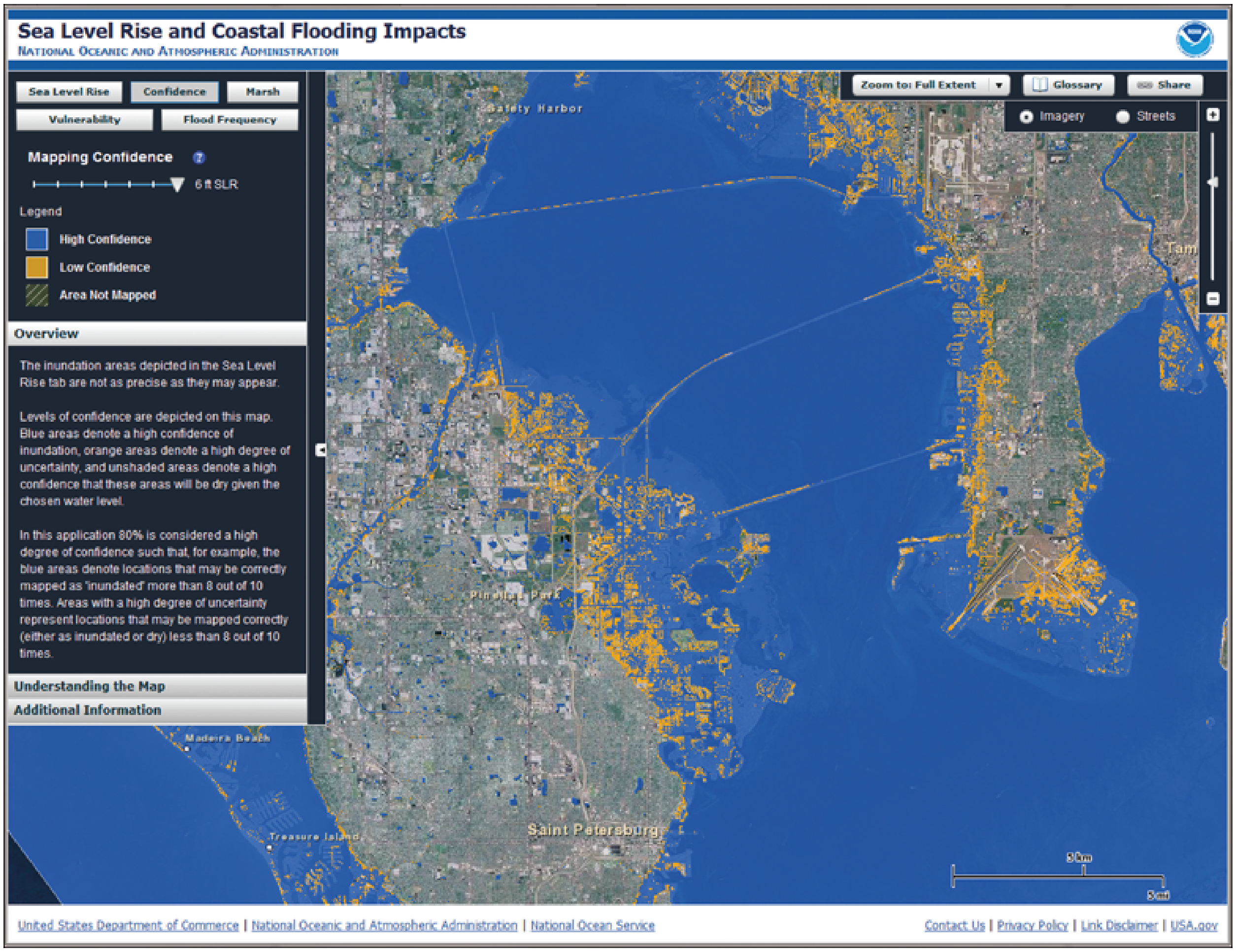

Figure 5. High (defined as 80% or greater confidence level, blue) and low (less than 80%, orange) confidence levels for 6 feet of sea-level rise in the region of Tampa Bay/St. Petersburg, Florida, United States, as displayed in NOAA's Sea Level Rise and Coastal Flooding Impacts Viewer. Source: NOAA Coastal Services Center (Digital Coast), http://csc.noaa.gov/digitalcoast/tools/slrviewer/.

for a predicted risk event, which may include the spatial or temporal extent of the risk, in either a general (e.g., high or low confidence) or specific (e.g., 70% confidence) manner. The NOAA Coastal Services Center's (2012) Sea Level Rise and Coastal Flooding Impacts Viewer, for example, indicates areas of "low confidence" or "high confidence" for predictions of sea-level rise (Figure 5).

Dynamic display options that may be implemented in interactive maps and geovisualizations provide additional techniques for uncertainty representation. Such methods include the use of animation and sonification in dynamic displays (Pang, Wittenbrink, and Lodha 1997) or other features that allow users to explore uncertainty through interactive maps, graphics, and statistics (Goodchild, Buttenfield, and Wood 1994). Dynamic display options may be integrated into many common types of geovisualizations, including Web maps and virtual globes.

EXAMPLES OF SPATIAL UNCERTAINTY REPRESENTATION

Spatial uncertainty related to risk may be displayed along a continuum, ranging from no uncertainty (Figure 6a), to uncertainty implied in a general manner with the visual variables (Figure 6b, herein referred to as the "general view"), to more specific methods that present alternative scenarios (Figure 6c, herein referred to as the "specific view"). Spatial uncertainty is implied, but not quantified, in the general view through the fuzzy nature of PIA edges using the focus variable proposed by MacEachren (1992) to imply a general level of uncertainty (Figure 6b). The use of vignettes such as these is common in coastline mapping (Buckley and Barnes 2004), although here it is extended for inland inundation. The specific view allows map users to see a range of scenarios, such as PIAs +1 and −1 m from a specific inundation level (Figure 6c). Potential inundation at 2 m is displayed at a local scale with the general view in Figure 7 to illustrate how uncertainty may be communicated in the context of urban planning and mitigation activities.

The dynamic display approach for conveying uncertainty may be introduced through zoom display controls in interactive maps, mashups, and geovisualizations that prevent users from zooming in beyond the scale of the input data used to model the risk. A potential danger of providing unlimited zoom capabilities for map users is the chance that the fitness for use of the data may be violated, especially where lower precision inputs are used to draw conclusions for data that require higher precision. For example, in one of our informal demonstrations of a geovisualization created from a global analysis of sea-level rise in 1-m increments with coarse input data sets, one observer attempted to use the zoom in map display controls to estimate the extent of the inundation at a much larger scale, the backyard of a vacation home in a coastal area.

The methods presented here may be implemented for different map uses, map tasks, and scales, yet key questions remain as to when each method is most appropriate. For example, the use of the focus visual variable for the general view may be suitable for general map users who wish to view the extent of predicted inundation from sea-level rise. In such cases, the communication that uncertainty exists may be appropriate, although the quantification of the uncertainty may not be necessary. For more specific map use tasks (such as in the context of decision-making by urban planners), where the amount of uncertainty is important, the alternative scenarios presented by the specific view may be most appropriate. Formal testing with a broader range of users, both domain and map use, in the future will refine these techniques further and provide insight into their overall level of effectiveness. Worth noting is that representation of spatial uncertainty, in either a general or specific context, is uncommon in many sea-level rise maps and geovisualizations, with the maps of Gesch (2009) and the NOAA Coastal Services Center (2012) Sea Level Rise and Coastal Flooding Impacts Viewer (Figure 5) as rare exceptions. Similarly, as Smemoe et al. (2007) have observed, floodplain maps such as those produced by the Federal Emergency Management Agency (FEMA) in the United States typically represent estimated flood zones, such as predicted 100-year flood extents, as a single scenario with no visual display of model uncertainties.

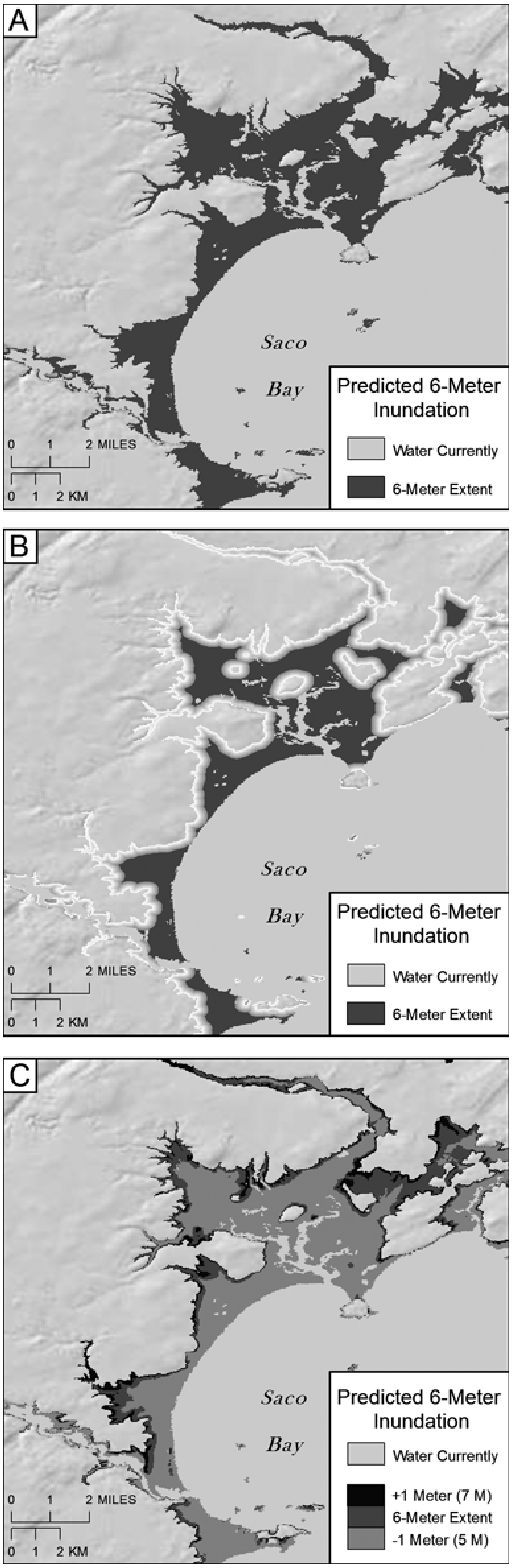

Figure 6. Three representations of predicted inundation from sea-level rise: (a) no spatial uncertainty is conveyed to the map user; (b) a vignette to imply a general level of spatial uncertainty) and (c) a more specific level of uncertainty implied by displaying ± 1 m of inundation for the given increment. Area is Biddeford, Maine, United States. Base map source: Esri World Shaded Relief.

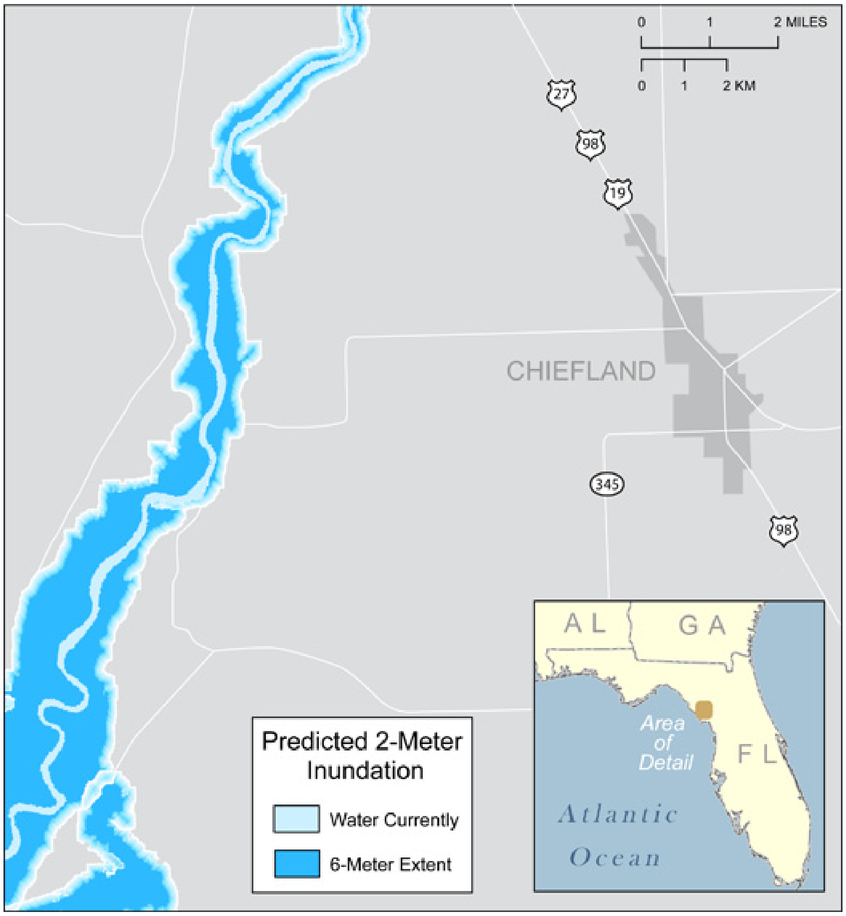

Figure 7. Projected sea-level rise of 2 m near Chiefland, Florida, United States, displayed with the general view of spatial uncertainty. Base map source: Esri, DeLorme, NAVTEQ.

EXAMPLES OF TEMPORAL UNCERTAINTY REPRESENTATION

Although temporal map animations typically display the time increment that corresponds to the map display as the animation cycles, the challenges of associating many risks with a precise time period may require an alternative approach. Rather, the amount of predicted inundation from sea-level rise (which increases with the passage of time) may serve as a better focus, and animation may serve as a dynamic display option to imply temporal uncertainty. Figure 8, for example, is a screenshot from a sea-level rise animation that displays the temporal progression of inundation from 1 to 6 m. Such a focus displays the passage of time indirectly to map users, yet avoids the difficulties of estimating a precise time period for each predicted level of inundation.

In addition to animation, the alternative scenarios approach may be used to convey temporal uncertainty through static snapshot maps or “small multiples” (Tufte 1990) in situations where a time increment(s) can be associated with a risk more precisely. One approach is to convey alternative risk scenarios for an established time period in the future. For example, in the context of sea-level rise, this might entail a series of three maps for the year 2100, each map displaying the low (18 cm), high (59 cm), or midpoint (38 cm) projection of inundation that correspond to predictions by the IPCC (2007). Alternatively, a single map displaying confidence levels or probability of inundation by a specified time period is a related approach to convey temporal uncertainty but assumes that such surfaces can be estimated with a reasonable level of confidence.

EXAMPLES OF NATURAL PROCESS UNCERTAINTY REPRESENTATION

The variables incorporated into GIS models to depict risk greatly impact the resulting cartographic displays used for visualization purposes. Ideally, sea-level rise maps and geovisualizations convey directly to map users the input variables and processes used to derive PIAs and provide alternative scenarios to communicate the uncertainty associated with the process of sea-level rise. The PIAs displayed in Figure 9, for example, are from a map animation that displays predicted sea-level rise based on three factors: elevation, coastal geormorphology, and tidal regimes. LIDAR data were used to derive geographic areas below the specified elevation value – 3 m in this example.

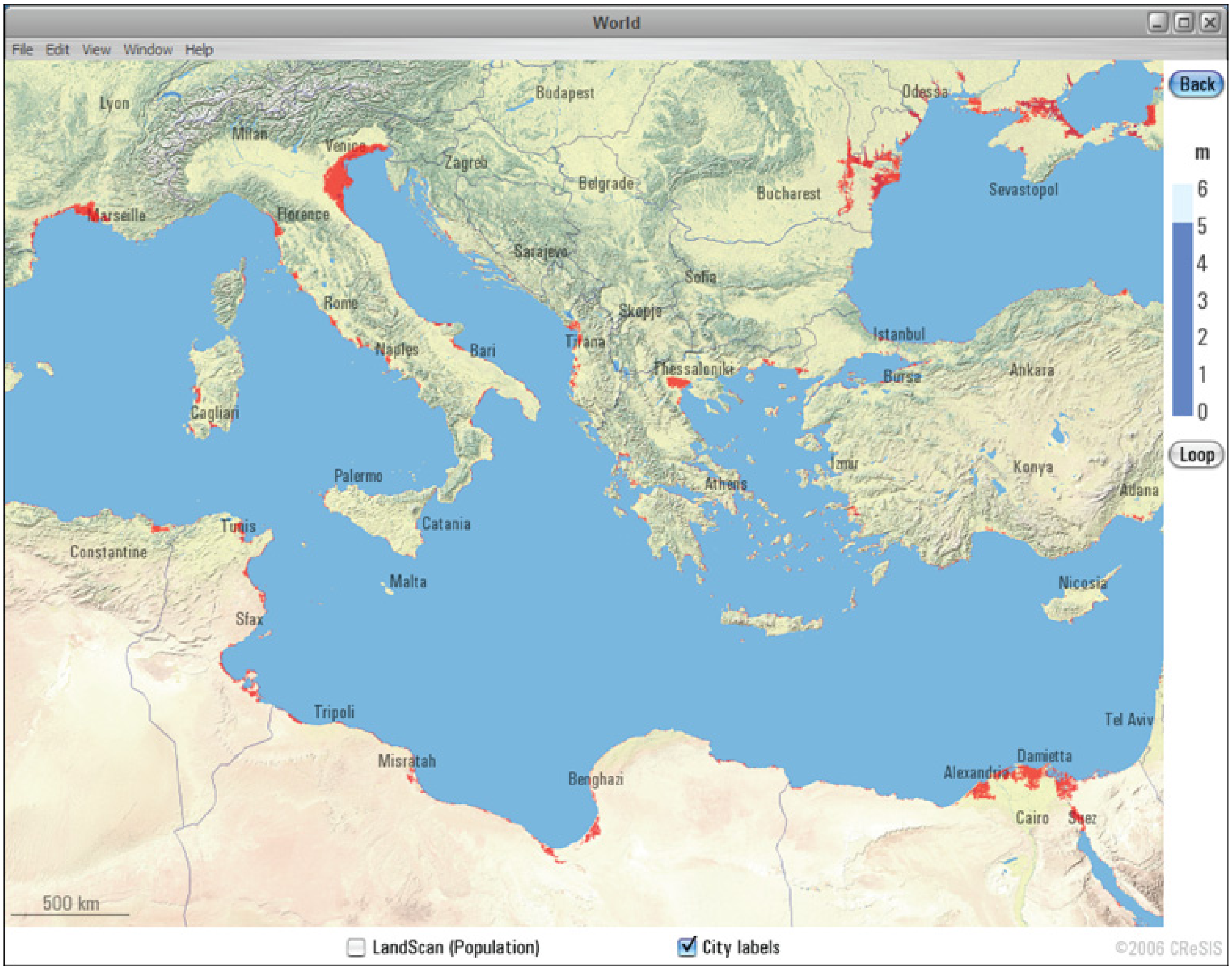

Figure 8. Screenshot from a temporal sea-level rise animation focused on increments of sea-level rise (in black; online, in red) rather than specific time periods.

The model assumes that coastal sediments are highly porous, which allows for inundation in low-lying areas that are not connected to the ocean by surface water. While this assumption is appropriate for the sands of southern Maine illustrated here, it would not be appropriate for the clay soils and igneous bedrock elsewhere on the Maine coastline. To demonstrate the impact of tides on sea-level rise, average daily tidal regimes for the region were incorporated into the model to derive three scenarios (high tide, mean sea level, and low tide) for each increment of inundation, an analytical approach that Strauss and others (2012) have applied at a national scale. The geovisualization illustrates the importance of tides and storm surges in inundation models; areas in light blue that are landward of the predicted mean sea-level extent (medium blue) are still inundated at high tide. By simultaneously depicting the geographic extent of inundation at high tide, mean sea level, and low tide, variation and uncertainty from the process of sea-level rise are conveyed to map users. Sea-level rise maps developed by the Australian national government utilize a similar approach by presenting three sea-level rise scenarios for the year 2100 (low [0.5 m], medium [0.8 m], and high [1.1 m]), each on a separate map series for coastal Australia (Australian Government 2011).

REPRESENTATION OF HAZARD IMPACTS

Visualizing hazard impacts may require creative forms of representation that are tailored to the nature of the hazard (Figure 2, bottom). *Thematic symbology* (e.g., choropleth, graduated/proportional symbol, dot maps), for example, may be used to visualize quantitative data that summarize potential impacts of natural hazards such as populations at risk to a hurricane. But ingenuity may be required to adapt symbology for maps and geovisualizations according to specific characteristics of a hazard. To illustrate, here we describe one approach to the common challenge of representing impacts of sea-level rise: visualizing dense populations that may be impacted by sea-level rise in small coastal areas. Numerous studies have estimated the overall impact of sea-level rise on coastal populations at

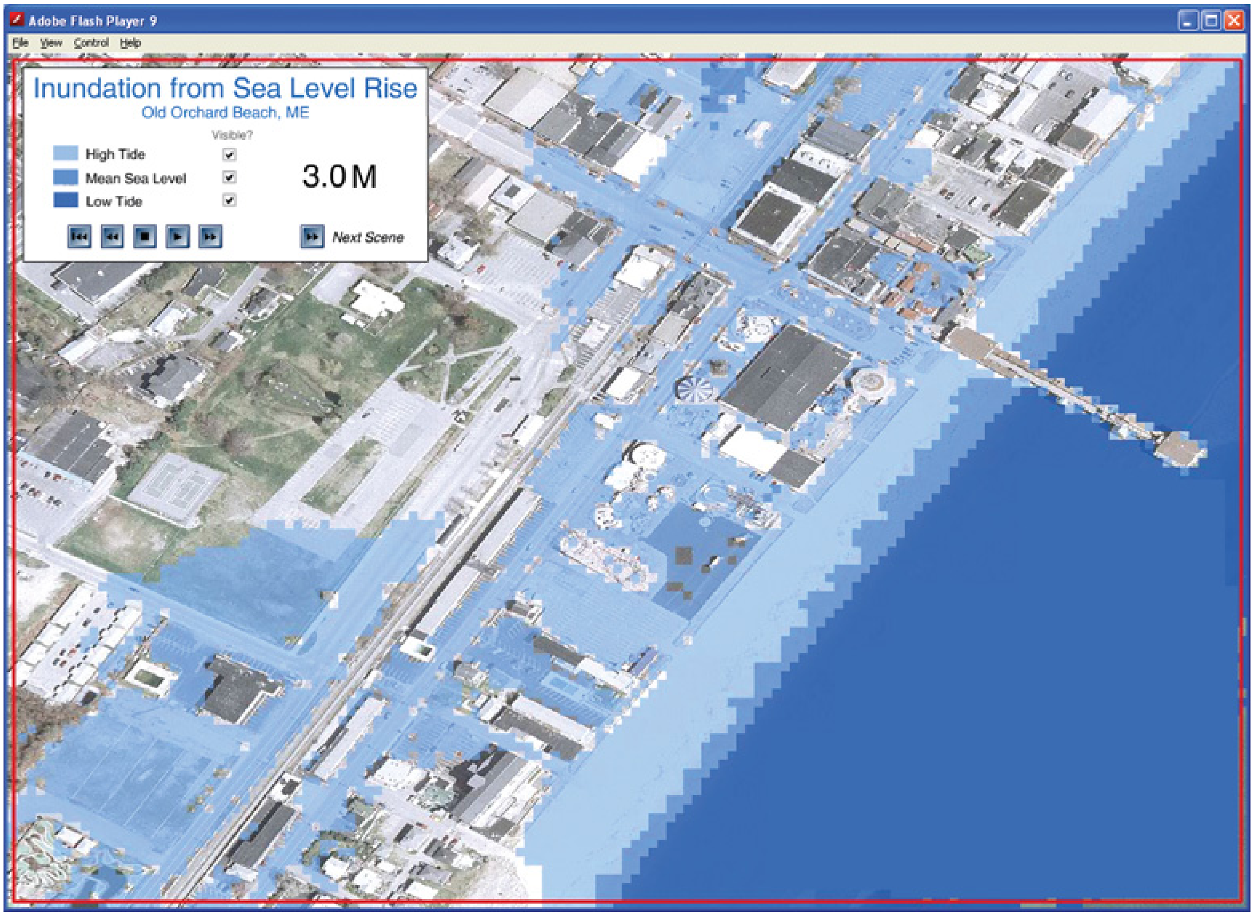

Figure 9. An animation frame displaying predicted inundation at 3 m based on elevation data derived from LiDAR elevation data. The visual variable value is used to show three possible extents of inundation with the less uncertainty the darker the shade of blue: high tide (pale blue), mean sea level (medium blue), and low tide (dark blue). Area is Old Orchard Beach, Maine, United States. Source" Maine Office of GIS.

a global scale and summarized these results in tables or charts by region or country (e.g., Rowley and others 2007; Li and others 2009; Dasgupta and others 2009); however, these studies have stopped short of representing the actual geography of the displaced populations at global or regional scales on maps or geovisualizations. A primary challenge of representing such impacts on population at a global scale involves selecting a form of symbolization that effectively displays the population within the PIAs by balancing symbol placement with congestion of neighbouring symbols. Standard graduated/proportional symbol maps may display the general impact of sea-level rise on populations by enumeration units such as countries (Figure 10) with minimal congestion. Such maps may be useful to display impacts of inundation for general purposes; for example, a policymaker may be interested in viewing general patterns of inundation summarized by country, where the specific impact within the country is not important. But a major disadvantage of graduated/proportional symbol maps is that they may be misleading by not clearly indicating a more precise location within a country where population is impacted by sea-level rise.

An alternative approach is to disaggregate population from country borders to finer geographic units (Figure 11) and select an appropriate level of generalization using aggregation and displacement methods suitable for the map scale. In the method presented here, PIAs first were derived from the GLOBE DEM and then intersected with the gridded Landscan global population database following methods described in Rowley et al. (2007) and Li et al. (2009). Since congestion of symbols in small coastal areas is great for standard dot or graduated/proportional symbol maps, the 30 arc-second Landscan cells were aggregated to a coarser cell size (3° for the global scale of the map in Figure 11) and the total population values summed for each aggregate cell. A graduated symbol was placed in the centroid of each aggregated cell, sized in proportion to the total population of the cell. The approach is similar to the non-contiguous cartograms introduced by Dorling (1993), although graduated symbols in this example are

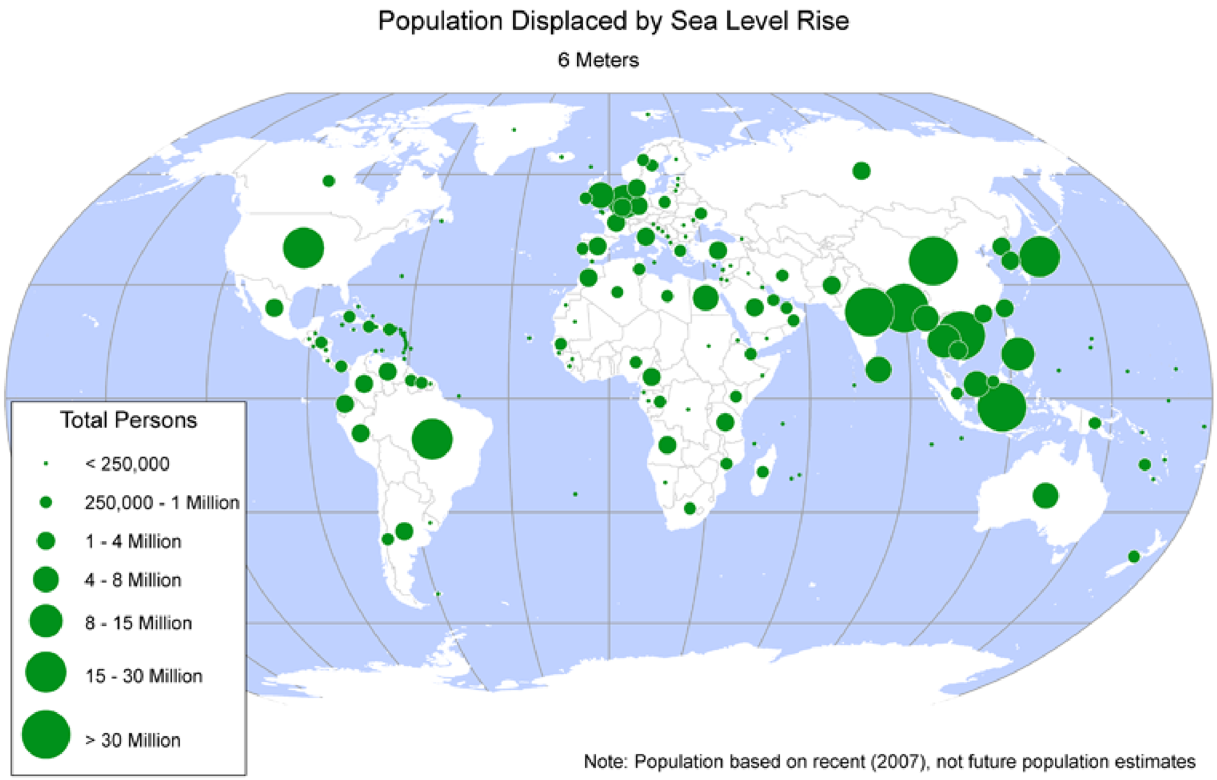

Figure 10. World population impacted by sea-level rise of 6 m displayed as a graduated/proportional symbol map where the circle for each enumeration unit (country in this example) is placed in the centroid of the polygon.

permitted to overlap if the size of the circle is larger than the overall grid cell and therefore are not moved from the centroid of the grid cell. By allowing larger circles to overlap a reasonable amount, circles remain closer to their true geographic position and roughly follow the coastline of the inundated land area. The approach allows for variation to be noticed within individual countries; for example, sea-level rise impacts on populations are much more evident along the Atlantic (East) Coast more than the Pacific (West) Coast in the United States. As the scale of the map changes to a region of the world, a finer grid may be used (Figure 12). The example displayed here is similar to the ScaleMaster concept proposed by Brewer and Buttenfield (2007) to guide changes in symbol design at multiple scales. Ideally, the method would be integrated into an interactive Web mashup environment with tiles at predefined scales, which would allow the resolution of the grid to change automatically as map users zoom in or out on the display. In addition, uncertainty information may be added to the map since spatial uncertainty in the PIAs due to differences in global elevation data quality cascades to the population calculations. Figure 13 is one such approach, where confidence levels for the displaced population calculations are indicated with the visual variable value as proposed by Edwards and Nelson (2001).

LEVEL OF REALISM

Related to the discussion of visualizing risk uncertainty and hazard impacts is the selection of an appropriate *level of realism* to represent geographic data in cartographic form (Figure 2, bottom). For the purposes here, we define *realism* as a measure of how "real" a phenomenon appears on the map or geovisualization in relation to the real-world objects it represents. The term is most commonly used today to refer to the realistic portrayal of objects with photo-rendering or 3D technology. The term *abstraction* has a related usage and has been used commonly in cartography to refer to how closely a map symbol replicates a real-world object – thus we include the term in the discussion here as well. A key cartographic decision in hazard and risk mapping is selecting an appropriate level of realism, which can be envisioned to range along a continuum from low to high. Abstract forms of map symbology, for example, utilize low levels of realism while pictorial symbology, high resolution aerial imagery, virtual globes, and 3D geovisualizations (e.g., 3D rendering software, virtual reality and immersive environments, and stereoscopic displays) provide cartographers with additional options for elevating the level of realism (or lowering the level of abstraction) used for representation of hazards and risks.

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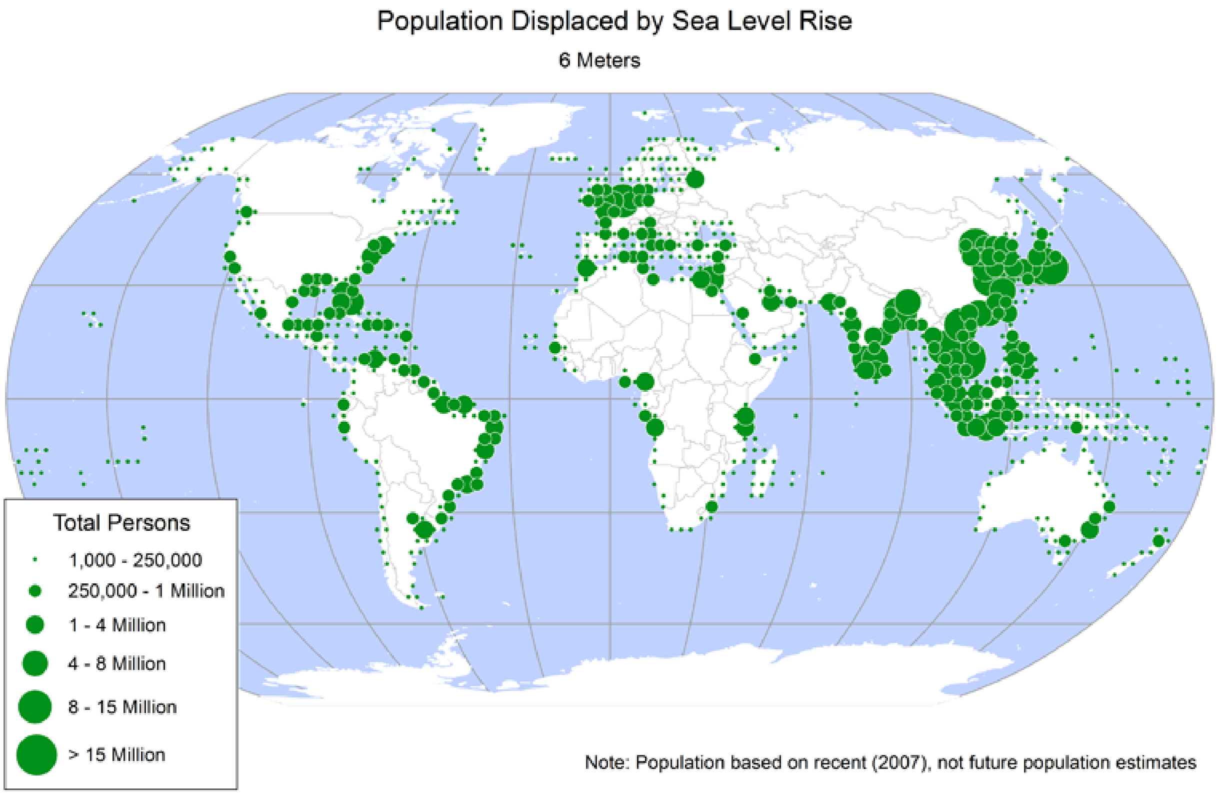

Figure 11. World population impacted by sea-level rise of 6 m displayed as a graduated/proportional symbol map utilizing a modified Dorling cartogram approach. Population grid spacing is three degrees.

An important issue is whether or not realistic geovisualizations enhance user understanding of a risk or if they increase the likelihood that users will misinterpret risk simulations with a higher level of confidence simply due to the method of presentation. There appear to be both pros and cons for realistic geovisualizations. In the context of an actual hazard event, enhanced realism or low level of abstraction may be advantageous to convey to map users an elevated level of danger, such as in the creation of pictorial symbols to convey danger associated with hazards (Kostelnick and others 2008). Sheppard (2005) has argued that realistic landscape visualizations may be beneficial for engaging people's emotions and attachment to place, which may be needed for eliciting behavioural change needed to mitigate future risks such as climate change. Realistic visualizations have an added benefit of engaging users at a higher level due to "wow factors" such as virtual fly-throughs and other interactive features that allow users to customize the display as they explore a place (Sheppard and others 2008; Sheppard and Cizek 2009). But when uncertainties inherent to the risk are not portrayed, there is a danger that a hypothetical risk may be portrayed as overly realistic in a manner that deceptively obscures uncertainties inherent to the underlying risk. At the cognitive and perceptual level, at least one empirical study (Zanola, Fabrikant, and Çöltekin 2009) has found that confidence levels in spatial data quality for map users increases when higher levels of realism are used. Realistic visualizations, of course, may also evoke fear or panic for users and perhaps even dramatize a topic so much as to encourage "over the top" public policy or mitigation measures to confront a risk.

A high level of realism may be achieved on sea-level rise maps through the use of high-resolution aerial or satellite imagery and 3D visualization software to depict the impact of sea-level rise on the built and natural environments (Figure 14). Such maps and geovisualizations have the potential to communicate the severe impacts of sea-level rise in a powerful, evocative manner. As Figure 14c demonstrates, powerful rendering software can produce overly real images that look like photographs of actual inundation but which are, in fact, simulations of purely hypothetical events subject to many sources of uncertainty. Virtual globes are also a useful means for presenting sea-level rise due to the public's general familiarity with such displays and the ease of distributing data sets for viewing on that platform. Likewise, Web-based mashups have become more common recently for crisis mapping purposes (Liu and Palen 2010), yet a limitation of these mashups is that they often combine data sets of varying quality into

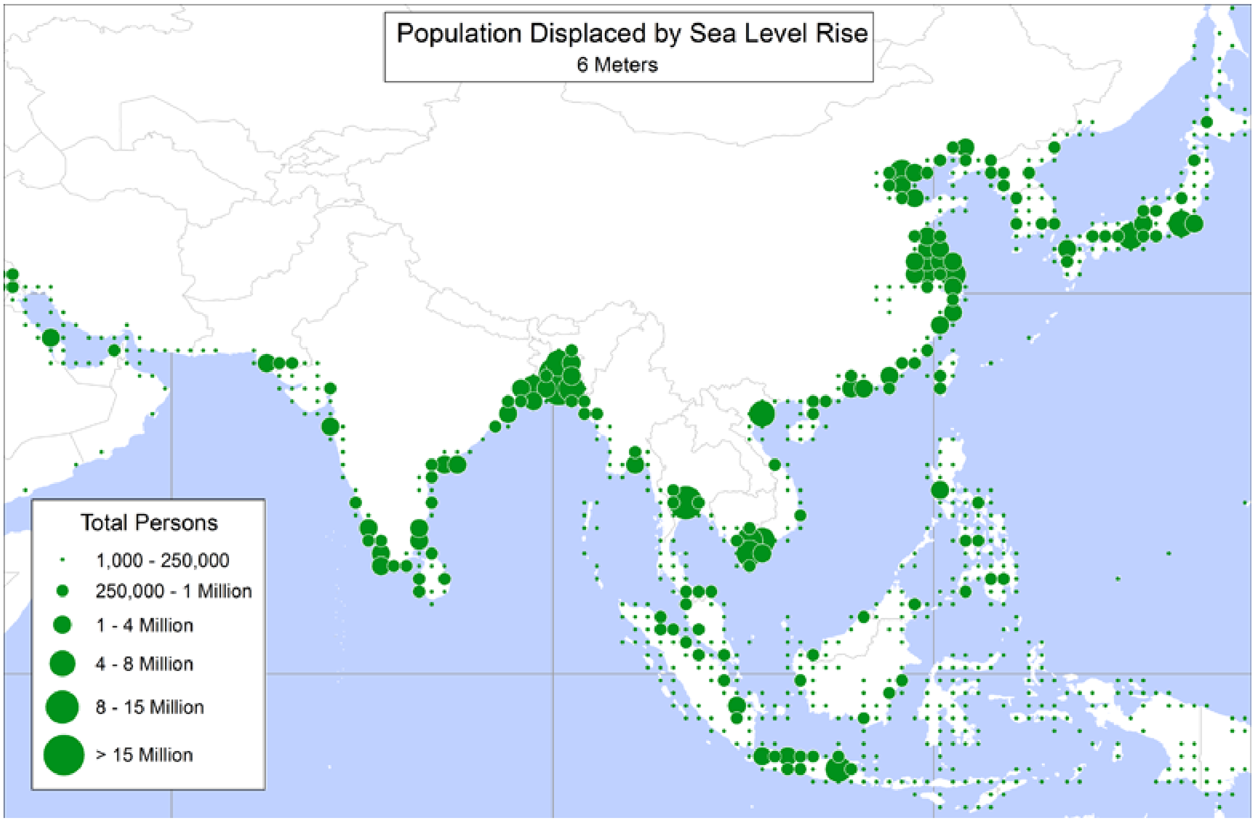

Figure 12. Regional population impacted by sea-level rise of 6 m displayed as a graduated/proportional symbol map utilizing a method similar to a Dorling cartogram. Population grid spacing is one degree.

a single map, such as the accuracy of a high-resolution aerial image displayed underneath the uncertainties of a sea-level rise prediction map. Through informal observations, we have noticed that when sea-level rise inundation is displayed on high-resolution imagery and 3D terrain in virtual globes such as Google Earth, map users tend to be more prone to use these displays for more specific tasks that go well beyond the fitness of the data.

Two key issues related to realism and risk visualizations are yet to be addressed fully. First, user-centred studies of the effects of varying levels of realism are necessary for understanding how users estimate levels of risk from maps and geovisualizations, particularly as the use of Web-based mashups and virtual globes, which commonly integrate high-resolution imagery, become more common in hazard and risk mapping. Second, ethical guidelines, standards, and other best practices based on empirical studies with users are needed to guide visualizations that utilize a high degree of realism (Sheppard 2005). The general set of ethical guidelines for landscape visualization with virtual globes such as Google Earth proposed by Sheppard and Cizek (2009), for example, are a step in this direction that may be expanded further by other GIScientists.

Conclusions and Future Work

Hazard and risk mapping present several challenges that offer a fruitful area for cartographic expertise, innovation, and creativity; however, all too commonly, hazard and risk maps and geovisualizations are prone to a “one size fits all” approach. In this article, we have provided a critical analysis of sea-level rise maps and have outlined a framework of important issues that should be considered for mapping risks related to natural hazards. We staged our framework by arguing that effective hazard and risk mapping should carefully consider user and task characteristics (domain expertise, map use expertise, and map use task) in conjunction with risk characteristics (types of uncertainty and potential impacts of the hazard) as driving forces that influence key cartographic considerations (representing uncertainty, representing potential impacts, and selecting an appropriate level of realism). We applied this framework to mapping PIAs from sea-level rise as an example of how the framework may be used in practical hazard and risk mapping scenarios.

We hope that the framework presented here may serve at least three purposes. First, others mapping risk from various natural hazards may utilize the framework as a

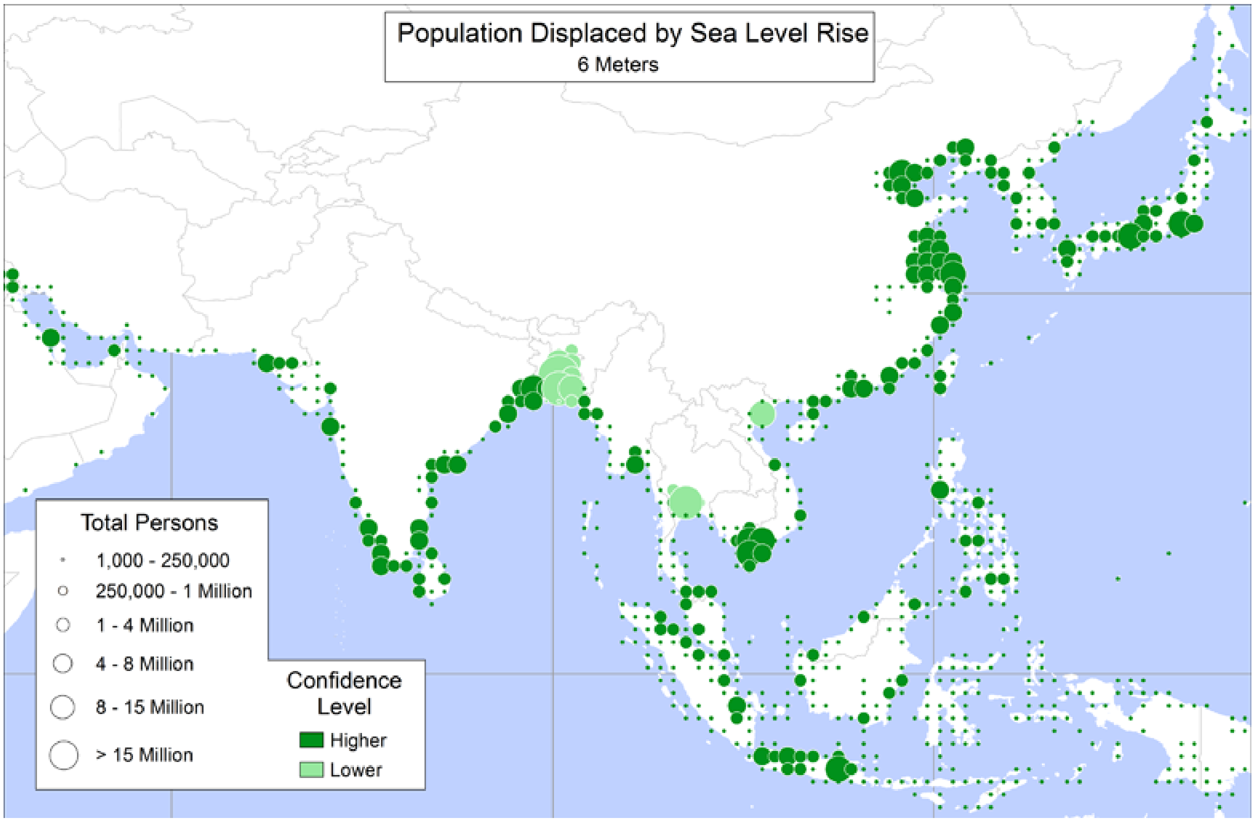

Figure 13. Confidence level (higher or lower) added to the map in Figure 12 for calculations of displaced population at 6 m of sea-level rise. Coastal areas of Bangladesh, Thailand, and Vietnam are classified as "lower" due to striping and other DEM errors in these regions, resulting in errors in PIAs and uncertainties in population calculations. Note that this same approach could also be used to display confidence level of population data quality.

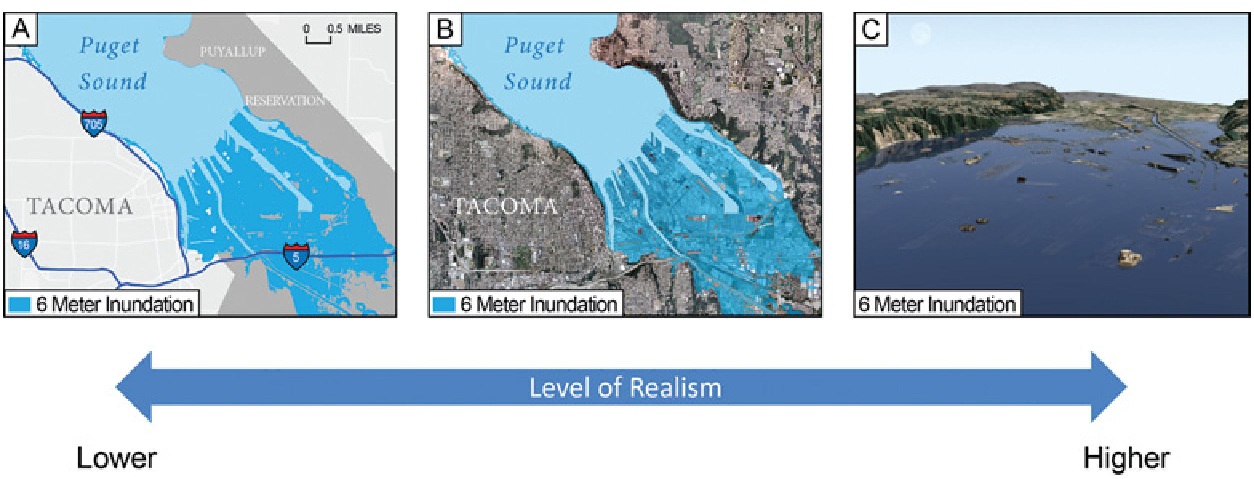

Figure 14. Different levels of realism displayed for predicted sea-level rise inundation for a portion of Puget Sound, Washington, United States: (a) inundation displayed in map form only; (b) inundation displayed on imagery; and (c) a 3D visualization created with Visual Nature Studio (VNS). Note that the orientation for (c) has been modified to a perspective view looking from the northwest to the southeast. Source: Puget Sound Regional Council, NAIP, ESRI, DeLorme, NAVTEQ.

practical guide for identifying and organizing key issues that may be overlooked otherwise. For example, the framework may be used as a decision tree to guide several data handling and design decisions during the development of risk maps and geovisualizations. Second, the framework presented here could serve as a basis for an expert system designed specifically for hazard and risk mapping that could be used to promote best practices. Such an expert system may be similar to those designed for promoting effective usage of colour (Brewer, Hatchard, and Harrower 2003) or text (Sheesley 2007) on maps. Third, the framework exposes several topics in hazard and risk mapping where additional research is needed, particularly empirical, user-centred research studies, to determine the overall effectiveness and appropriateness of various cartographic techniques. As observed by Bostrom, Anselin, and Farris (2008), the cartographic literature is lacking in regard to empirical studies that have examined the impact of various cartographic representations on perception of risk and effects on the decision-making process. Such user studies are particularly important given that sea-level rise maps and geovisualizations may be used in critical decision-making processes for hazard mitigation amidst much uncertainty. Other researchers have called on the importance of cognitive, perceptual, and human factors issues to ensure that symbolization methods are effective for uncertainty representation (e.g., MacEachren 1992; Aerts, Clarke, and Keuper 2003) and in the context of specific hazard domains such as emergency management (e.g., Akella 2009). User-testing of uncertainty representation in geographic data may also include studies conducted in decision-making scenarios as well (Hope and Hunter 2007). We call for a range of such user-centred studies, including those specific to the context of sea-level rise scenarios given the prominence of the issue in the broader discussion on global climate change.

From a broader perspective, sea-level rise calls attention to the delicate line between the need for responsible risk maps and geovisualizations of natural hazards for future planning and mitigation purposes, so as to not dramatize the topic beyond realistic scenarios supported by science. In his book *Disaster Deferred*, geologist Seth Stein (2010) effectively illustrates how changing assumptions and definitions of earthquake hazards over time by the US Geological Survey has resulted in new maps that display a dramatically elevated level of risk (now on par with California) for the New Madrid Fault region in the American Midwest, which have had significant implications for property insurance purposes and building codes in the region. Similar to earthquakes, sea-level rise represents a powerful, high stakes issue where maps may be used in an evocative manner, elevating the topics of informed communication and cartographic ethics to the utmost importance. In this light, we should be mindful of the power of maps and visualizations for significantly influencing risk perception of many types of hazards. Maps may sway public sentiment, persuade policy-makers and legislators, and ultimately influence how we invest limited resources to mitigate risks for protection of lives and property. Maps and visualizations of climate change impacts, therefore, should strike a balance between scenarios that are both dramatic and defensible (Sheppard 2005; Sheppard and others 2008; Shaw and others 2009). We hope that by framing important issues in hazard and risk mapping, cartographers and GIScientists may heed this challenge to develop improved methods supported by empirical studies.

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Author Information

John C. Kostelnick is an associate professor in the Department of Geography-Geology and director of the Institute for Geospatial Analysis and Mapping (GEOMAP) at Illinois State University. E-mail: jkostelnick@ilstu.edu. He holds a PhD in geography from the University of Kansas and formerly served as an instructor at Haskell Indians Nations University. His primary research interests include multiple facets of GIScience, including geovisualization, GIS integration into science and society, Web-mapping, remote sensing, and hazard/risk mapping.

Dave McDermott is a Geography and GIS instructor at Haskell Indian Nations University. E-mail: dtmcdermott@gmail.com. He holds a PhD in geography from the University of Kansas and was formerly affiliated with the Center for Remote Sensing of Ice Sheets, University of Kansas. His interests include cartography, GIS, and the geography of North America.

Rex J. Rowley is an assistant professor in the Department of Geography–Geology, Illinois State University. E-mail: rjrowle@ilstu.edu. He holds a PhD in geography from the University of Kansas and was formerly affiliated with the Center for Remote Sensing of Ice Sheets, University of Kansas. His interests include application of geospatial technologies to human geography questions; place perception and sense of place; and, more generally, the human and cultural geographies of the United States and Japan.

Nathaniel Bunnyfield was formerly a graduate research assistant affiliated with the Center for Remote Sensing of Ice Sheets, University of Kansas. E-mail: natebunnyfield@gmail.com.

Note

1 For example, see MacEachren and others (2005) for a review of the role of uncertainty representation in the context of decision-making.

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