Applied Geography 50 (2014) 1–14

Contents lists available at ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

Deterministic and probabilistic flood modeling for contemporary and future coastal and inland precipitation inundation

Courtney M. Thompson, Tim G. Frazier*

Department of Geography, University of Idaho, P.O. Box 443021, Moscow, ID 83844-3021, USA

Keywords:
Probabilistic
Deterministic
Sea-level rise
Vulnerability
Coastal hazards

ABSTRACT

While hazard mitigation lowers hazard impacts, communities cannot mitigate all possible risks. Targeting mitigation allows agencies with limited resources to mitigate areas within a community where hazard impacts are highest. To target these areas effectively, better hazard modeling is needed to provide more accurate hazard extents to pinpoint mitigation and conduct more complete vulnerability assessments. Deterministic models are useful for developing mitigation policies based on their hazard identification and exposure outputs in vulnerability analyses, but are limited because they do not calculate risk. Probabilistic models provide more information about the range of risk allowing decision makers to target mitigation and land-use management focuses toward areas of higher risk. Deterministic models used in conjunction with probabilistic models can also be used to perform all three levels of vulnerability assessment and produce more complete hazard modeling extents, which is something not traditionally done. To explore the need for the use of probabilistic models in conjunction with deterministic modeling, research presented here creates a theoretical framework for a stochastic storm surge model using deterministic hazard extents that depict coastal hazard inundation, using Sarasota County, Florida as a case study. The deterministic hazard extents are created for use in multiscalar vulnerability assessments that simulate storm surge, inland precipitation and sea-level rise (SLR) to depict holistic coastal hazard inundation. The deterministic extents also provide higher-resolution hazard identification that can aid local decision makers targeting high-risk areas, not all exposed areas.

Introduction

Development often occurs in areas that are exposed to natural hazards, which leads to increased vulnerability and the potential for loss (Adger, 2006; Cutter, 2003; Frazier, Wood, Yarnal, & Bauer, 2010; Turner et al., 2003; White & University of Chicago, 1945). Coastal communities in particular are vulnerable to a variety of natural hazards including hurricanes, tropical storms, flooding, and climate change-related hazards influenced by sea-level rise (SLR) (Frazier et al., 2010; Frazier, Walker, Kumari, & Thompson, 2013; H. John Heinz III Center for Science, Economics, and the Environment, 2000; Tate & Frazier, 2013; Wisner, 2004; Wu, Yarnal, & Fisher, 2002). In spite of available tools such as economic incentives and legislation, it is difficult to guide or relocate development out of the hazard zone. These tools are often only marginally effective for new development and virtually ineffective for existing development due to competing interests in many communities (e.g. natural resources, tourism, amenities, etc.). The general trend of continuing development in vulnerable areas will also create increased future exposure to both contemporary hazards that may be enhanced by climate change (Frazier et al., 2010). This is especially true in coastal communities where there is an intense pressure to allow development to occur along the coast regardless of known impacts from future hazards such as SLR. For these reasons, hazard mitigation is essential to lowering the impacts of hazards on human populations and property and to helping speed the recovery process. As such, more research is needed to develop enhanced modeling techniques that can better estimate hazard behavior and impacts. Thus, this research seeks to develop new and enhance existing models to assist stakeholders in targeting hazard mitigation to areas they deem more critical. This research also seeks to enhance vulnerability and resilience assessments through the use of probabilistic physical exposure modeling. Often, the lack of probabilistic modeling results in less sophisticated hazard modeling techniques, which may result in targeting scarce mitigation resources to areas where hazard exposure may be lower.

* Corresponding author. Tel.: +1 208 885 6238; fax: +1 208 885 2855.
E-mail addresses: thom7660@vandals.uidaho.edu (C.M. Thompson), tfrazier@uidaho.edu (T.G. Frazier).

http://dx.doi.org/10.1016/j.apgeog.2014.01.013
0143-6228/

Vulnerability/resilience assessments and hazard modeling

Conducting vulnerability assessments has been a major focus of hazards research for the last 50 years, and yet these assessments often do not result in lowered societal losses or shortened recovery times. While hazard mitigation lowers hazard impacts, it is not possible to mitigate everywhere within the community when there are large numbers of societal assets within the hazard zone. Limitations in the availability of existing federal pre-disaster mitigation and adaptation funding results in more of the financial burden for these activities being placed on state and local governments (Frazier, Thompson, Dezzani, & Butsick, 2013). Targeting mitigation allows agencies with limited resources to mitigate areas within a community where hazards impacts are highest (Frazier, Walker, et al., 2013). In order to determine where hazard exposure or risk is the highest, communities often conduct vulnerability assessments to measure their vulnerability to hazards, where vulnerability is a function of exposure, sensitivity, and adaptive capacity (Turner et al., 2003). Vulnerability assessments are traditionally conducted at the county level, resulting in assessments that generalize local vulnerability and are less effective for community level hazard mitigation. Recent research by Frazier, Thompson, and Dezzani (2013) developed a spatially explicit, sub-county vulnerability model called Spatially Explicit Resilience-Vulnerability (SERV) that demonstrates the importance of conducting vulnerability assessments that rely on more accurate local hazard models.

Vulnerability assessments ascertain vulnerability through three levels of evaluation: hazard identification, vulnerability analysis, and risk analysis. Hazard identification illustrates where hazards are likely to occur within a study region, thus determining where they might intersect with societal assets. Vulnerability analyses determine which factors cause populations to experience increased vulnerability to hazards. Risk analysis calculates probabilities of a hazard occurring and probable levels of damage or injuries that could occur in specific areas (Burby, 1998). Risk analyses also illustrate varying probability of occurrence for coastal hazards across a given scale (Krzysztofowicz, 2001), and provide a greater understanding of where the risk of a hazard may be greater (Burby, 1998; Krzysztofowicz, 2001).

In order to conduct the hazard analysis portion of vulnerability assessments, physical hazard modeling is typically conducted to delineate the extent of specific hazards. Due to uncertainty in hazard behavior, however, it is not possible to delineate the exact extent of a disaster event prior to occurrence. Instead, physical hazard modeling is utilized to simulate where hazards might occur given a certain scenario, along with the risks associated with that hazard. There are two main categories of hazard models used in vulnerability assessments: deterministic and probabilistic. Deterministic models have fixed outputs regarding the possible extent of the hazard, whereas probabilistic models provide a probabilistic distribution of a hazard extent and illustrate areas of a community that might be more adversely impacted (Chen & Yu, 2007; Krzysztofowicz, 2001; Skidmore, 2002; Vogel, 1999).

Vulnerability assessments traditionally only utilize deterministic models when conducting hazard analysis (Cutter, Mitchell, & Scott, 1997; Cutter, Mitchell, & Scott, 2000; Frazier et al., 2010; Kleinosky, Yarnal, & Fisher, 2007; Wood, Soulard, Geographic Analysis and Monitoring Program (Geological Survey), Washington (State), & Geological Survey (U.S.), 2008; Wu et al., 2002). Deterministic models assume that hazard extents are a result of a direct causal relationship between the terrain and the geophysical hazard process, and do not take randomness into account (Haneberg, 2000). If the same inputs in the model are used, the model will produce the same results (Haneberg, 2000). This makes them useful for developing hazard extents that delineate hazard exposure given certain scenario inputs (Di Baldassarre, Schumann, Bates, Freer, & Beven, 2010; Frazier et al., 2010; Glahn, Taylor, Kurkowski, & Shaffer, 2009). Model outputs are used in conjunction with geographic information systems (GIS) to create hazard layers that depict exposure for vulnerability assessments (Cutter et al., 2000; Frazier et al., 2010; Kleinosky et al., 2007; Wood, Hawaii Pacific Disaster Center, & Geological Survey (U.S.), 2007; Wu et al., 2002). Several deterministic GIS-compatible models have been created to delineate the extents of many coastal hazards, such as storm surge, tsunami wave run-up and inundation, flood inundation, and the potential effects of SLR (Glahn et al., 2009; Frazier et al., 2010; Mercado, 1994; Stamey, Wang, & Koterba, 2007; Zerger & Wealands, 2004; Zhang, Xiao, & Shen, 2008). The extents are overlayed with socioeconomic data to determine a community's level of exposure and sensitivity to specific hazards (Cutter et al., 2000; Frazier et al., 2010; Wood et al., 2008; Wu et al., 2002). This type of overlay analysis quantifies differing social and infrastructure sensitivity, which provides information about which specific areas have higher sensitivity and identifies factors that influence increased sensitivity (Frazier et al., 2010; Wu et al., 2002).

Deterministic models are useful for developing mitigation policies based on vulnerability analyses outputs, but are limited in application because they do not reflect a range of scenarios and only illustrate hazard identification and exposure (Haneberg, 2000). This limitation is not true of probabilistic models because they use a range of values to determine probabilities, which change over multiple model runs (Krzysztofowicz, 2001). Therefore, probabilistic models with the same inputs may produce different results (Haneberg, 2000; Krzysztofowicz, 2001). Deterministic models may also alter risk perception because they only delineate a flood extent, but do not illustrate variable inundation risk (Paton, Smith, Daly, & Johnston, 2008). This delineation provides people with a false sense of security that they are either in or out of a hazard zone, which may not necessarily be true due to uncertainties in hazard models.

Probabilistic models provide more information about which areas have higher hazard risk and which areas are lower risk but are still susceptible to hazard impacts. This information could be used to guide mitigation focuses toward higher risk areas, rather than all exposed areas. Frazier, Thompson, and Dezzani (2013) demonstrated in their case study that vulnerability varies across a county with most mitigation strategies currently targeting exposed areas and not necessarily areas where vulnerability is highest. Hazard models, both deterministic and probabilistic, only depict a line of physical damage; they do not depict cascading impacts (such as loss of overall economic activity within the community) caused by the hazard event. People also develop their risk perception based on social trust in managing authorities (e.g. emergency managers and planners) when they lack personal knowledge of the hazards themselves (Siegrist & Cvetkovich, 2000). Therefore, better hazard modeling can help planners better mitigate and manage decisions on which societal assets need to be fortified or prioritized in the mitigation and recovery process, which can increase social trust in managing authorities.

Several probabilistic models have been used in hazards literature to develop risk mapping for a variety of hazards, such as fires, landslides, tsunamis, rainfall, and seismic risk (Akkaya & Yücemen, 2002; Apel, Thieken, Merz, & Blöschl, 2006; Dickson et al., 2006; Glahn et al., 2009; Jang, Yeh, Fu, Huang, & Yu, 2012). However, few probabilistic coastal hazard models exist and are limited in respect to the hazard behaviors they model. These models can also be computationally expensive and parameterization is often difficult to compute for forces that are not fully predictable. In addition, existing probabilistic coastal hazard modeling studies often only