Interactions among flood predictions, decisions, and outcomes: A synthesis of three cases

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Abstract

To complement other flood mitigation measures, hydrometeorological predictions are often used in decisions leading up to and during floods. Understanding the role played by predictions in flood events can help forecasters provide more useful information, and it can help decision makers use this information more effectively as part of a broader flood loss reduction strategies. This article examines the interactions among predictions, decisions, and flood-related outcomes by analyzing three cases of severe flooding in the U.S.: the Red River basin flood of April 1997 in Grand Forks and Fargo, North Dakota; the Fort Collins, Colorado flood in July 1997; and the Pescadero Creek basin, California flood in February 1998. The floods occurred in different hydrometeorological and societal circumstances, had different types of predictive information available, and had different societal impacts, providing an opportunity to compare and contrast lessons learned. Issues explored include the interplay between the floods and their hydrometeorological and societal context and the roles of predictions and predictive uncertainty in decisions and outcomes.

Subject headings: Floods; Decision making; Weather forecasting; Natural disasters; Emergency services; Dikes; Detention reservoirs; Precipitation

1. Introduction

Floods are one of the most common natural hazards, causing significant damage, loss of life, and other negative impacts in the U.S. and around the world (e.g., Pielke and Downton 2000; Mitchell and Thomas 2001; Jonkman 2005; Douben 2006). To help mitigate flood losses, communities and people at risk can employ a variety of long-term measures. Yet these measures cannot prevent all floods, nor can they eliminate the possibility of loss if flooding occurs. Floodplain regulations and flood control structures, in particular, are designed to protect only up to a certain level of flooding, and structures sometimes fail (Tobin 1995; Burby 2001; ASFPM 2007). Moreover, in some flood-prone areas, structural protection is not available or leaves some at high risk. Thus, despite significant investment in flood mitigation, floods continue to cause deaths and substantial damage and disruption.

To complement other mitigation strategies, predictions of potential flooding are often used in decisions leading up to and during floods. Depending on the processes contributing to the flooding and the hydrometeorological information available, such predictions can be made minutes to months in advance. Predictions are critical for issuing warnings and helping evacuate people at risk. They can also help prevent or reduce flood impacts by aiding decisions about operating flood control structures, releasing water from reservoirs to provide floodwater storage, and augmenting levees or dikes. With sufficient lead time, predictions can also help at-risk residents and communities move property, purchase insurance, allocate flood fighting and response resources, and develop plans that can be implemented if flooding occurs (White 1939; Handmer 2001).

As technology and scientific understanding advance, predictions of floods are improving. At the same time, flood losses appears to be increasing despite mitigation efforts, as more people and property are situated in locations at risk (Changnon and Changnon 1998; Kunkel et al. 1999; Pielke and Downton 2000). Moreover, changes in land use, as well as climate variability and change, may be increasing flood likelihood and severity (Larson and Plasencia 2001; Milly et al.

2002; Trenberth et al. 2003; Groisman et al. 2004, 2005). Together, these factors are making predictions an increasingly important component of strategies to reduce flood losses. Within the broader flood mitigation context, this article seeks to understand the roles flood prediction can and does play in flood-related decisions and outcomes. Such findings can help forecasters provide more useful predictive information, and they can help decision makers incorporate this information more effectively into broader flood loss reduction strategies. The article focuses on the U.S. experience, but aspects of the findings are likely applicable in other countries.

Flood losses result from a complex combination of factors in the natural, built, and human environments, and each flood is unique (Montz and Gruntfest 2002). This complexity and uniqueness can make it challenging to generalize findings across cases. As an intermediate step between in-depth case studies and broader syntheses, this article synthesizes findings across three cases of severe flooding in the U.S.: the Red River basin flood of April-May 1997 in Grand Forks and Fargo, North Dakota; the flood of July 1997 in Fort Collins, Colorado; and the Pescadero Creek basin flood of February 1998 in rural San Mateo County, California. The floods occurred in four communities, but the Grand Forks and Fargo floods are combined in one case since they are closely related and Fargo's experience is used primarily in comparison to that of Grand Forks.

The floods occurred in different regions under different hydrometeorological and societal circumstances with different predictive information available. In the Red River basin case, snowmelt on flat terrain led to riverine and overland flooding in Grand Forks and Fargo, with weeks of advance notice. The Fort Collins case was an urban flood near steep terrain that occurred with little or no warning due to the locally heavy rainfall and insufficient hydrometeorological observations. The Pescadero Creek basin case also evolved quickly in and near steep terrain, but because the storm system causing the rainfall was fairly large and well-observed, several hours of advance notice were available. The floods also varied in the use of predictions and the societal impacts: in Grand Forks and Fort Collins, the impacts were devastating, while in Fargo and Pescadero, flooding and damage occurred, but local officials successfully used predictions to mitigate impacts. Because of these differences, analyzing results across the cases provides an opportunity to compare and contrast lessons learned and synthesize findings.

In this article, the term *prediction* is used to include all types of information that can provide advance notice of a specific potential flood event. Such predictions are generally developed through some combination of precipitation or streamflow observations, extrapolation, inference, hydrometeorological models, and other information. The analysis focuses around decisions that can use such predictive information, shortly prior to and during floods. Some decisions by community residents and others are considered, but the primary emphasis is on decisions by local public officials responsible for fighting and responding to floods (such flood engineers, emergency managers, and emergency responders). This augments existing knowledge on organizational decision makers' actions leading up to disasterous events, which have been less widely studied than individuals' and households' decisions (Sorensen and Mileti 1987).

Because "natural" processes are only one contributor to flood impacts, scientific and technological approaches are, at best, only a small component of reducing flood disasters (e.g., Blaikie et al. 1994). Thus, while the article focuses around flood predictions, it analyzes their role within the broader context in which flooding, flood impacts, and flood mitigation occur. In doing so, it seeks to improve understanding of how predictions best fit into the broad flood mitigation strategies that many flood-hazard researchers and practitioners advocate (e.g., Kusler and Larson 1993; Myers and White 1993; Galloway 1995; Larson and Plasencia 2001).

Section 2 of the article provides an overview of the three cases. Section 3 analyzes how the hydrometeorological and societal context interacted with predictions, decisions, and outcomes in the cases. This discussion illustrates the importance of context in understanding the role of predictions, and it provides a starting point for the remainder of the analysis. Sections 4 and 5 examine in greater depth the use of flood predictions in decisions and the effects of predictive uncertainty and confidence. The final section summarizes key findings and discusses potential implications for flood predictions and their use in decision making.

2. Three cases of flooding

This section describes the three cases of flooding, emphasizing issues important for the analysis. The case analyses are based on a variety of primary and secondary data. For the 1997 Red River basin flood in Grand Forks, oral histories of the flood (Glassheim 1999; Glassheim et al. 2002) provided a major data source, along with federal agency reports (NWS 1998; USACE 1997), journal publications (Pielke 1999; James and Korom 2001a,b), and other documents (Glassheim 1997; Grand Forks Herald 1997; Porter 2001). Information about the 1997 flood in Fargo was obtained from many of the same sources as the Grand Forks flood, along with other documents (Forum 1997; Stensrud 1999). For the 1997 Fort Collins flood, the major data sources were interviews with local officials and a site visit conducted several years after the flood (Downton et al. 2005), first-hand accounts of people's experiences during the flood (Colorado State University 1997; The Coloradoan 2007), journal publications (Grimm 1998; Grigg et al. 1999; Ogden et al. 2000; Weaver 2000; Weaver et al. 2000), and other documents (Doesken and McKee 1998). For the 1998 Pescadero Creek basin flood, the major data sources were interviews with emergency management officials and meteorologists and a site visit conducted several years after the flood (Morss and Ralph 2007), along with documents discussing flooding in the Pescadero Creek area (Pacific Forest Trust 1995; SFBRWQCB 2002; ESA 2004).

For all three cases, readily available data was supplemented by an internet and library search for relevant information in regional and national media, gray literature, and other first-hand accounts of flood experiences. Overall, the Grand Forks and Fort Collins floods are much better documented due to their disasterous impacts. Consequently, this supplementation was especially important for the Fargo and Pescadero events. Much of the analysis is based on a combination of information from multiple sources. Given the type of data used, the goal is not to develop primary analyses of the cases, although the cases themselves raise a variety of interesting issues. Rather, the goal is to synthesize findings from the three cases to examine the role of predictions in flood risk mitigation from a broader perspective.

a. Red River basin – Grand Forks and Fargo, North Dakota – April-May 1997

Grand Forks, North Dakota, is a community of about 50,000 people located on the western banks of Red River of the North. The Red River flows northward along the North Dakota / Minnesota border into Canada. The river's gradual slope and shallow channel, combined with the tendency for south-to-north melt and ice jams downstream, make it prone to flooding (USGS 1997; Bell and Halpert 1998). Prior to 1997, the flood of record in Grand Forks and its sister city across the river (East Grand Forks, Minnesota) was a stage of 15.3 m (50.2 ft) in 1897, and larger floods likely occurred earlier in the 19th century. The most significant flood in the 20th century was in 1979, when the river crested at 14.9 m (48.8 ft) and caused millions of dollars in damage. The 1979 flood prompted a number of flood mitigation projects, including modifying dikes and the storm and sewer systems (Porter 2001; Glassheim et al. 2002). Grand Forks experienced less significant flooding in several subsequent years, including a river stage of 14.0 m (45.8 ft) in 1996. In 1996, a significant flood fight was mobilized, with help from National Weather Service (NWS) predictions of 13.3-13.5 m (43.5-44.5 ft), and was successful at preventing major damage (NWS 1998; Porter 2001).

In the spring of 1997, high seasonal snowfall and an unfavorable spring thaw led to flooding in many parts of the Red River basin. In February 1997, the NWS began warning that flooding along the Red River could exceed 20th century records (Stensrud 1999; Porter 2001). Because of high flood risk, the NWS issued a flood "outlook" for Grand Forks two weeks earlier than usual, in February, predicting a river stage of 14.5 m (47.5 ft) with average melt and no additional precipitation and 14.9 m (49.0 ft) with average melt and average precipitation (NWS 1998; Porter 2001). With help from the state and the U.S. Army Corps of Engineers (USACE), local officials began preparing, starting from detailed plans developed based on previous floods. They planned to construct and raise dikes to protect the community to 15.5 or 15.9 m (51 or 52 ft), allowing about a meter (3 ft) of freeboard over the NWS prediction (Porter 2001; Glassheim et al. 2002). Although some residents began preparing, most seemed relatively unconcerned (Porter 2001). The NWS issued the same outlook, 14.9 m (49.0 ft), again in March and early

April.

By early April, communities to the south began flooding, and a late-season blizzard brought more snow. Officials prepared for flooding with increasing urgency, and many Grand Forks residents joined the flood fight. The community expended much of its effort on primary dikes along the river, while also fighting overland flooding (Porter 2001; Glassheim et al. 2002). On April 14, the Red River reached 13.4 m (44 ft) at Grand Forks, and the NWS issued its first "forecast" for Grand Forks, predicting a river stage of 15.2 m (50 ft). Over the next few days, the river continued rising rapidly, and the NWS gradually increased its stage forecasts (NWS 1998; Porter 2001). Officials and residents began raising dikes further and trying to build new dikes, but the river was rising too quickly, and there was insufficient time, material, resources, and high ground from which to fight (Grand Forks Herald 1997; Porter 2001; Glassheim et al. 2002). Dikes began leaking on April 17 and overtopping on April 18. Despite preventative efforts, the storm sewer system overflowed, transporting floodwater to areas away from the river. A major fire erupted in flooded downtown Grand Forks, and firefighters had difficulty controlling it due to the flooding. A few days later, the river crested at more than 16.5 m (54 ft) — 8 m (26 ft) above flood stage (Porter 2001; Glassheim et al. 2002).

Approximately 16000 homes in Grand Forks (80% of the city) were damaged by flooding, most of them outside the mapped 100-year floodplain (Forum 1997; James and Korom 2001a). In Grand Forks – East Grand Forks, the flood caused an estimated $1 billion or more in damage. Despite months of warning and significant effort raising levees, officials and most residents were not prepared for the severity of the flood. Ninety percent of the Grand Forks population was evacuated, some people with little notice. Some residents left nearly all of their property in their homes, including possessions in their basements; others moved valuables to the second floor and were flooded to the roof (Grand Forks Herald 1997; Glassheim 1999; Glassheim et al. 2002). Despite public encouragement from the Federal Emergency Management Agency (FEMA), Congresspeople, and local officials to purchase flood insurance in 1997, the vast majority of Grand Forks residents did not (Pynn and Leung 1999; Porter 2001).

Some in Grand Forks blamed the disaster on the NWS, for underpredicting the flood crest (Grand Forks Herald 1997; Glassheim 1999; Pielke 1999). While in retrospect unprecedented flooding seems inevitable, substantial snowfall in the upper Midwest does not always lead to severe flooding; the timing of the thaw, which is not known in February or early March, also plays a major role (Voelker 1997; Bell and Halpert 1998; Adolphson et al. 2005). While the NWS communication of predictions played a role in the disaster, the NWS did not cause the flood, and other factors contributed to the flood's impacts (Pielke 1999; Morss and Wahl 2007). One important contributor was local officials' decision (with help from the USACE) to focus on protecting the entire city, without sufficient contingency plans if the flood was more than a meter (a few feet) higher than predicted (James and Korom 2001a; Porter 2001; Glassheim et al. 2002). Given the volume of water, it is unlikely that the flood could have been contained within the primary dikes at Grand Forks. To prevent much of the community from flooding, officials would have had to build secondary dikes that sacrificed some homes, and they were concerned about residents' protests (Glassheim 1999; Pielke 1999; Glassheim et al. 2002). Officials did build secondary dikes, including one that helped protect a western part of the city, but they did not start soon enough to reduce damage in most of the city (Porter 2001; Glassheim et al. 2002).

Fargo, North Dakota is a community of about 90,000 people located approximately 130 km south (upstream) of Grand Forks on the Red River, and it is prone to flooding for similar reasons. In Fargo and its sister city (Moorhead, MN), the flood of record prior to 1997 was 11.9 m (39.1 ft), in 1897, compared to a flood stage of 5.2 m (17 ft). Like Grand Forks, Fargo had experienced several severe floods in the 1960s-1980s, including a crest of 11.4 m (37.3 ft) in 1969, that prompted significant mitigation measures (Stensrud 1999).

In 1997, the same conditions as in Grand Forks led to substantial flood risk in Fargo. The NWS's spring 1997 outlook for Fargo predicted stages of 11.0 m (36.0 ft) and 11.4 m (37.5 ft), respectively, in the no-added-precipitation and average-precipitation scenarios. Officials began preparing for a flood crest of 11.6 m (38 ft), or perhaps as high as 12.2 m (40 ft; Stensrud 1999). Like Grand Forks, Fargo expended significant effort on constructing and raising dikes, with help from the USACE and other agencies (Stensrud 1999).

As in Grand Forks, many residents in Fargo were initially unconcerned but began participating in the flood fight as flooding grew closer. Unlike in Grand Forks, however, the NWS's first "forecast," issued on April 9, raised the predicted flood crest to 12.0 m (39.5 ft). The community began frantically trying to prepare for a higher river crest, while fighting overland flooding. The river crest prediction was lowered to 11.4 m (37.5 ft) on April 10 when a faulty gage reading was discovered, and on April 11-12, the river appeared to be cresting at about that height (Forum 1997; Stensrud 1999; Porter 2001). But then the river began rising again. Officials built secondary dikes, causing some residents on the "wrong" side to protest. They also developed further contingency plans. On April 18, as Grand Forks flooded, the river in Fargo crested at 12.0 m (39.5 ft), very close to the level of the "erroneous" April 9 forecast. Some dikes leaked or failed, and floodwaters entered a few neighborhoods, damaging 86 homes. Most of the community was protected, however, and several of the contingency dikes were not needed (Forum 1997; Stensrud 1999).

Fargo's success in preventing extensive flood damage is attributed by some to good preparation, and by others to luck. According to city officials, it is a combination: "the harder you work, the better your luck gets" (Stensrud, p. 3; also see Pielke 1999). Fargo officials were prepared for different scenarios, and they made difficult, controversial decisions that angered some residents but saved others' homes. Officials also spent substantial time and effort communicating and coordinating with residents, and they had plans in case of higher flooding that they never needed to fully implement (Stensrud 1999). These suggest that preparation, communication, and contingency planning were significant contributors to Fargo's success. Yet Fargo's flood was only 0.6 m (2 ft) higher than predicted in February and 0.1 m (0.4 ft) above the 1897 flood, compared to 1.6 m (5.3 ft) and 1.2 m (4.1 ft), respectively, in Grand Forks. Unlike Grand Forks, Fargo also experienced a plateau in river stage before the eventual peak, which allowed more time to implement contingency plans. It is not known what would have happened in Fargo had the river risen more rapidly or a much higher flood occurred. Perhaps officials' planning would have mitigated substantial losses, or perhaps Fargo would have suffered a flood as devastating as that in Grand Forks.

b. Fort Collins, Colorado – July 1997

Fort Collins, Colorado, is a community of approximately 100,000 people situated on the eastern edge of the Rocky Mountains, where the mountains meet the plains. Spring Creek is one of several streams and irrigation canals running through Fort Collins. The area climate is generally dry, with approximately 38 cm (15 in) annual average precipitation. However, summer thunderstorms are common, and the area has experienced extreme rainfall and significant flooding (Doesken and McKee 1998; Coloradoan 2007). Most notable was the July 1976 Big Thompson flood near Fort Collins, which killed at least 140 people (Gruntfest et al. 1978).

In part because of this flood experience, Fort Collins implemented a variety of structural and non-structural flood mitigation activities in the 1980s and 1990s. Recognizing these activities, in 1996 FEMA gave the Fort Collins a Class 6 rating in the National Flood Insurance Program's Community Rating System (CRS), which was in the top 10 among approximately 1000 participating CRS communities. In the Spring Creek basin, specifically, the City had mitigated flood risk through channelization, culvert and bridge improvements, and removal of people and property (Colorado State University 1997; Grimm 1998, Grigg et al. 1999). Horsetooth Reservoir, constructed in the mid-20th century, also controls runoff in the western portion of the Spring Creek basin.

In late July 1997, an unusually moist air mass led to locally heavy rainfall and flooding in several locations in Colorado (Doesken and McKee 1998; NCDC 1997). On the evening of July 27 and morning of July 28, approximately 23 cm (9 in) of rain fell several km northwest of Fort Collins, causing local flooding. In Fort Collins, 2-10 cm (1-4 in) of rain fell during this period (Doesken and McKee 1998). After a short lull, rainfall re-intensified starting around 5:30PM[†] on July 28, focused on western Fort Collins just below Horsetooth Reservoir. By the time the rain

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[†] All times discussed in this case are local (Mountain Daylight) time.

ended late on July 28, more than 35 cm (14 in) of rain had fallen in western Fort Collins over a 31-hour period, with 25 cm (10 in) between 5:30-11PM (Doesken and McKee 1998; Grigg et al. 1999). Reports of basement flooding began around 6:30PM, with street flooding and other problems beginning shortly thereafter (Weaver 2000; Coloradoan 2007). By around 8:30PM, detention ponds began overtopping, with still more rain to come. The local emergency dispatch center received a large volume of calls, and emergency responders began water rescues. As the situation intensified rapidly, rescue crews and local officials fell behind in assessing and managing the increasingly dangerous flood (Colorado State University 1997; Grigg et al. 1999; Weaver 1999).

In the meantime, along Spring Creek, water collected behind a 6-m (19-ft) railroad embankment designed to hold the 500-year flow, with culverts designed to pass the 100-year flow. As the detention pond filled around 10:30PM, water poured over the embankment and broke through an old culvert that had been plugged during previous mitigation. A train (including a car with chlorine gas) derailed, and a trailer park and other structures on the other side of the embankment were inundated rapidly, leading to gas explosions and fires, several deaths, and a number of hazardous rescues (Colorado State University 1997; Grigg et al. 1999; Weaver 1999; Ogden et al. 2000; Coloradoan 2007). The flood resulted in 5 deaths, all along Spring Creek, as well as 54 people injured, hundreds of people rescued, and hundreds of millions of dollars in damage (Colorado State University 1997; Grigg et al. 1999).

The local NWS office, which in 1997 was about 100 km south of Fort Collins in Denver, had identified the potential for flooding. They issued flood Advisories for the Fort Collins area on July 27, and they issued a Flash Flood Watch for much of north-central Colorado at approximately 5PM on July 28. However, NWS forecasters had a number of thunderstorms in north-central Colorado that evening to monitor and warn for, and the NWS radar significantly underestimated the surface rainfall in Fort Collins (Colorado State University 1997; Doesken and McKee 1998; Ogden et al. 2000). The trailer park close to Spring Creek was outside the designated floodplain, in an area with extensive prior flood mitigation that local officials and firefighters thought would be safe. The railroad embankment and detention pond were dark and unmonitored (Colorado State University 1997). Consequently, forecasters and local officials did not recognize the severe flooding until it was in progress. Most residents were not warned, and although officials and firefighters had begun mobilizing earlier in the day, they were not prepared for the magnitude of the flooding and impacts (Colorado State University 1997; Weaver 1999). Given the rapidly evolving situation and lack of warning, local officials managed the situation by improvising (Colorado State University 1997; Weaver 1999).

c. Pescadero Creek basin – San Mateo County, California – February 1998

San Mateo County, California is located in the San Francisco Peninsula south of San Francisco, west of San Francisco Bay. Most of the county's population and services are in the urban northern and eastern portions of the county. In the southern and western portion of the county, population is relatively sparse. Pescadero Creek and its tributary, Butano Creek, run westward through the Santa Cruz Mountains in rural San Mateo County, draining to the Pacific Ocean. The small town of Pescadero is situated near Pescadero and Butano Creeks, close to the ocean. Loma Mar and several other small communities lie upstream, along steep slopes prone to erosion. Approximately 1500 people reside in the Pescadero Creek basin (Ralph et al. 2003; Scott 2007). Year-round population has grown in recent decades, due to increased road access and increasing population and housing costs in other parts of the county (ESA 2004).

The town of Pescadero experiences flooding multiple days each year, including bridge flooding that blocks access to coastal State Highway 1 to the west. To the east, the primary access routes are narrow, winding roads through the hills, including a road along Pescadero Creek. Passage is difficult for emergency vehicles, and heavy rain occasionally leads to mudslides that wash out roads and bridges. Thus, heavy rain and flooding regularly block major transportation routes in the area, restricting residents' access to medical care and other services. Flooding in the town of Pescadero also restricts access to emergency equipment in the nearby California Department of Forestry fire station.

The chronic flooding in the town of Pescadero is caused by a combination of sedimentation that has significantly reduced Butano Creek’s channel capacity, historical modification of the stream channel and floodplain, old agricultural levees, and other factors (SFBRWQCB 2002; Freeling 2002; SMCRCD 2003; ESA 2004; Gordon 2006). The sedimentation and mudslides are due to high natural erosion rates exacerbated by road building, widespread logging in the early-mid 20th century with minimal erosion control, and other past and current human activities (Pacific Forest Trust 1995; SFBRWQCB 2002; Freeling 2002; SMCRCD 2003; ESA 2004). The watershed is listed as impaired for sediment under the Clean Water Act, and the watershed and marsh provide essential habitat for several threatened and endangered species (SFBRWQCB 2002; SMCRCD 2003; ESA 2004). Thus, environmental concerns limit some options for long-term flood mitigation. The public-private mix of land and road ownership (including various state and county agencies) further complicates planning and implementing long-term mitigation measures, and so chronic flooding continues despite community concern (Freeling 2002; SMCRCD 2003; Gordon 2006).

The winter of 1997-98 coincided with a strong El Niño event, which tends to increase precipitation over California. In February 1998, a series of winter storms generated heavy precipitation, flooding, landslides, and over $550 million damage in California, including $75 million damage in San Mateo county (Ross et al. 1998; Wilson 1998). On February 2-3, approximately 15 cm (6 in) of rain fell in 36 hours in the Pescadero Creek basin, on ground already saturated from rainfall in January (Ralph et al. 2003). Pescadero Creek experienced record flow, and major flooding and mudslides occurred in the area (NWS 1998; Ralph et al. 2003; ESA 2004).

Based on the saturated ground and their past experience, San Mateo County emergency managers knew in early February that further rainfall posed a significant flooding and mudslide risk in several parts of their jurisdiction, including the Pescadero Creek basin. The NWS Weather Forecast Office in Monterey, CA, warned of the approaching storm, and a scientific field experiment (CALJET) obtained data offshore that helped NWS forecasters improve predictions (Ralph et al. 2003; Morss and Ralph 2007). The NWS warnings of heavy precipitation helped convince San Mateo County emergency managers to position emergency teams and dive crews near Pescadero, before flooding and mudslides blocked off transportation into the area. Their decision to begin positioning crews and equipment hours in advance was affected by their trust in the forecasters, based in part on their good relationship with the NWS office. The crews rescued and evacuated 129 people via inflatable boat. One person in Loma Mar died; volunteer firefighters were able to reach him and perform CPR, but more advanced medical care was needed and could not access the area. Some area roads were closed for a few weeks, and residents were without power or phone service for almost six weeks (Scott 2007). Although there was significant damage in the region, emergency managers credit accurate, timely NWS forecasts with saving lives (Ralph et al. 2003; Morss and Ralph 2007).

3. Influence of hydrometeorological and societal context

Each flood was embedded in a larger space- and time-scale hydrometeorological event, and all four communities had previously experienced flooding. This section analyzes how these and other aspects of the hydrometeorological and societal context influenced the predictions available, their interpretation, and their use in decisions in the three cases. The discussion also illustrates the importance of the larger context in understanding any case of flooding, and thus in understanding the role of prediction in flood mitigation.

In the Red River basin, there was significant flood risk across the region in the spring of 1997, followed by widespread flooding. This hydrometeorological context motivated earlier NWS predictions and brought substantial federal and state resources to help Grand Forks and Fargo prepare. This helped both communities use predictions to stage an extensive flood fight, which in Fargo reduced flood damage. However, in Grand Forks, the early NWS prediction contributed to anchoring people's expectations to the 1979 flood (NWS 1998; Pielke 1999). This, along with the substantial flood fighting resources available, contributed to Grand Forks' focus on protecting the entire town from flooding and expectations of minimal damage.

According to one resident: “Much of the failure to prepare as much as we should have for this flood was because we kept believing we would have simply the same situation as in 1979, some seepage, only more of it. So in a sense ’79 actually tricked us” (Glassheim 1999, p. 41).

The hydrometeorological context also meant that Grand Forks and Fargo watched other communities prepare for and experience flooding. In Grand Forks, watching other communities helped raised awareness and concern as the flood approached (Porter 2001; Glassheim et al. 2002). However, it may also have increased some people’s confidence in Grand Forks’ flood fight. One Grand Forks resident recalled: “Inside Sandbag Central we got word that Fargo was losing it and they had water in the streets. We felt for poor Fargo, but we thought well, gee, they’re not as well prepared as we are” (Glassheim et al. 2002, p. 5). Several days later, Fargo built a contingency dike while watching the devastation in Grand Forks, which added “a still greater sense of urgency” (Stensrud 1999, p. 27).

Regarding the societal context, both Grand Forks and Fargo had extensive previous experience with flooding and flood mitigation. This initially helped officials in both communities plan and implement the flood fight (Stensrud 1999, Glassheim et al. 2002). However, in Grand Forks, the NWS outlook was for a crest just above the 1979 flood, and substantial mitigation measures had been implemented since 1979. Grand Forks had successfully fought a flood nearly as high in 1996. The prediction, mitigation, and experience combined in a way that led Grand Forks officials and many residents to believe that the flood fight would without doubt be successful. Thus, in retrospect, Grand Forks’ flood experience affected people’s interpretations and use of the NWS predictions in ways that likely worsened the damage.

Another aspect of the societal context, the community-oriented regional culture[‡], may also have contributed to the disaster in Grand Forks. In both Grand Forks and Fargo, officials had to make difficult decisions about allocation of flood-fighting resources that angered some residents.

[‡] The author thanks Eugene Wahl for this observation.

In Grand Forks, concern about causing conflict or panic appears to have affected officials' decisions about building secondary dikes or warning residents of evacuations (Porter 2001; Glassheim et al. 2002). Some people faced social pressure to not engage in personal mitigation, such as moving belongings or evacuating; they were encouraged to "pull together as a community" and be a "good citizen" (Glassheim 1999, p. 121; see also Glassheim et al. 2002). This reflects a "disaster subculture" in Grand Forks that provides norms for how officials and residents should interpret and respond to flood predictions (Anderson 1965). Afterwards, some Grand Forks residents felt that, in order to maintain community calm, officials had not given them sufficient information to make mitigation and evacuation decisions (Glassheim 1999; Glassheim et al. 2002).

In the Fort Collins case, the hydrometeorological context was important in two ways. First, thunderstorms were occurring across the region on the evening of July 28. With the limited observations available, this meant that forecasters had difficulty predicting which of the many storms might cause extreme rainfall and flooding (Colorado State University 1997; Doesken and McKee 1998). Second, the spatial and temporal characteristics of the rainfall complicated predictions and decisions. In Colorado, the classic flash flood is caused by a few hours of extreme rainfall. Non-riverine flood mitigation in Fort Collins is based on this model (Downton et al. 2005), but in the 1997 flood, Fort Collins experienced significant rainfall in several pulses over more than a day, filling up detention ponds before the final several-hour burst of rain (Colorado State University 1997; Ogden et al. 2000). In addition, much of the area impacted was downstream of the highest rainfall. Early on the evening of July 28, neither forecasters, nor officials, nor residents were aware of the volume of water that had already fallen in the area and what might happen if more rain fell (Colorado State University 1997; Weaver 1999; Coloradoan 2007).

The societal context was also important in the Fort Collins flood. Experience led officials to focus on monitoring certain parts of town, while recent flood mitigation led them to believe that the trailer park near Spring Creek was safe. A culvert plugged during prior mitigation also ended up contributing to the damage and loss of life. However, Horsetooth Reservoir and other flood control structures attenuated flow through Fort Collins. Thus, without prior structural mitigation, the flood could have been significantly worse (Ogden et al. 2000). City officials estimate that previous mitigation (structural and non-structural) saved several million dollars in damage and almost 100 lives in the 1997 flood (Grimm 1998; see also Colorado State University 1997).

In the Pescadero Creek basin flood, California had been preparing for significant rainfall during the winter of 1997-98 due to the strong El Niño. By the end of January, San Mateo County officials knew that the next storm could cause flooding and mudslides. Within this context, the NWS prediction of the approaching storm raised sufficient concern that San Mateo County decided to open its Emergency Operations Center for the first time in 30 years. As expected, the storm caused flooding across the county and the region. Yet officials decided to allocate resources to the rural Pescadero region before flooding began, in part because of the forecasts, and in part because of officials' experience with flooding and mudslides in the Pescadero region. Had officials not had this historical knowledge, more lives may have been lost.

Another role of the hydrometeorological context is providing environmental cues that influence how people interpret and use predictions. In the Red River basin flood, the record-breaking winter snowfall led many to realize the potential for record flooding (Glassheim 1999). However, flooding is highly dependent on the melt, and many Grand Forks and Fargo residents waited for the river to rise and overland flooding to begin before making substantial preparations (Stensrud 1999; Porter 2001). Moreover, even as they saw devastating flooding upstream and the river near the top of the dikes, most Grand Forks residents still did not anticipate how bad flooding might get in their community (Glassheim 1999; Glassheim et al. 2002). In Fort Collins, flooding occurred in areas that did not receive torrential rainfall, hampering officials' and residents' abilities to use perceptions of rainfall to anticipate flooding. It was also difficult for people to perceive the amount of rain that had fallen over the 31-hour period. Environmental cues were also important in the Pescadero Creek basin flood: officials did not evacuate people until flooding began, but knowing the soil was saturated from earlier rainfall helped them use the forecasts to decide to position crews.

Given the societal and historical context, people's conceptions of flooding are often anchored to their experience in past events. This can aid decision making, unless the event evolves substantially differently than expected (Burn 1999). The Fargo and Pescadero Creek basin floods were more severe than other recent floods, but they evolved similarly enough that officials were able to apply their experience to save property and lives, and to adapt to new circumstances as they arose. In contrast, the Grand Forks and Fort Collins floods diverged from experience, and officials had to adjust rapidly, without recent experience to use as a guide (Colorado State University 1997; Glassheim et al. 2002). As one Grand Forks official said, "We've taken [49 ft] before and we knew exactly what to do," but as the predicted crest kept rising, "there was a lot of bewilderment" (Glassheim et al. 2002, p. 17). In Fort Collins, in the trailer park area alone, emergency responders had to handle a water rise of 1.7 m (5 ft) in 3 minutes, 3 trailers on fire, 162 people in imminent danger requiring rescue, a building explosion, and derailment of a train that included a car carrying chlorine gas, with no advance notice. According to a Battalion Chief with the local fire authority, given this situation, emergency responders "pretty much flew by the seat of their pants" (Colorado State University 1997, p. 33; see also Coloradoan 2007).

How experience is interpreted and applied interacts with individuals' risk perceptions and other aspects of the context (Sorensen and Mileti 1987; Burn 1999; Drabek 2000; Parker et al. 2007). For example, in Grand Forks, some anchored their expectations to the most significant recent flood, in 1979, while others recalled the more recent 1996 event (Glassheim 1999; Porter 2001). Some people also seemed to consider the successes of 1979 or the subsequent mitigation more than the damage (Glassheim 1999; Glassheim et al. 2002). In addition, while experience with flooding can raise awareness, repeated experience — especially with floods that cause minimal damage — may increase tolerance of flood risk, reducing concern and thus response to warnings (Gruntfest 1987; Drabek 2000). For example, longer-term residents of Grand Forks were less likely to have purchased flood insurance, even after accounting for mortgage requirements (Pynn and Ljung 1999).

4. Use of flood predictions in decisions and effects on outcomes.

This section examines how predictions of flooding were or could have been used in the cases, within the context discussed in the previous section. First, the cases illustrate the fine line that can exist between a “close call,” a “near-disaster,” and a “disaster,” and the role decisions and predictions can play in the difference. On a community level, the floods in Grand Forks and Fort Collins are generally considered “disasters,” while the Fargo and the Pescadero Creek basin floods are “near-disasters.”[§] In each community, the difference between a near-disaster and a disaster hinged on one or a few critical decisions by officials. In Grand Forks and Fargo, a critical decision was how to plan the flood fight, in terms of effort spent on primary dikes versus secondary dikes and other contingency plans. In the Pescadero Creek basin, a critical decision was positioning search and rescue crews before flooding began. And in Fort Collins, a critical decision would have been to monitor flow along Spring Creek upstream of the detention area or water levels behind the railroad embankment. The cases are not direct contrasts: Grand Forks and Fort Collins officials did make decisions that reduced damage and saved lives. Moreover, the critical decisions are only evident in hindsight, now that the unique dynamics of each event have unfolded. Nevertheless, key outcomes in each flood depended on a small set of decisions.

Key property- and life-saving decisions are often thought of as taking specific protective action immediately prior to or during an event. However, sometimes key decisions can be less evident and occur during earlier planning stages. For example, in Grand Forks, once officials had decided to expend most of their time, effort, and resources on planning and building primary dikes, they were not able to plan and build secondary dikes fast enough when the flood grew

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[§] In all four communities, flooding caused significant impacts for some residents. However, Grand Forks and Fort Collins experienced extensive community-wide impacts, while in Fargo and the Pescadero Creek basin, impacts were more localized and could have been significantly worse.

worse than expected. In the Pescadero case, if officials had not decided to position rescue crews and equipment before the flood began, they would not have been able to reach the area. In other words, the decisions that framed the flood fight and allocated resources for rescue operations turned out to be as important as the actual dike-building and rescues.

The cases also illustrate how a key decision may not always be a specific action, but rather where to focus attention, for gathering information, monitoring a situation, or considering alternate outcomes. In Fort Collins, officials did not consider the detention area filling, and so they did not gather information about flow upstream or monitor the area. In Fargo, as officials watched the flood evolve, they realized that it might be worse than originally expected and were able to develop and implement additional plans.

Predictions are only one of many factors that influence people's flood-preparation and response decisions. Nevertheless, the cases illustrate that when predictions are available, they can play a significant role in key decisions, and thus in outcomes. In Grand Forks, the NWS's prediction of a 14.9-m (49-ft) flood crest was a major factor in officials' decision to focus on protecting the entire town. One Grand Forks official said, "We were fully in control of the situation with a 49-foot crest … We were going to beat 49 feet. There just wasn't a problem" (Glassheim et al. 2002, p. 30). Moreover, the NWS's slow increase in the predicted flood crest for Grand Forks contributed to officials' decisions "to add 'just one more foot' to the emergency levees until it was not possible to reallocate resources effectively to save critical facilities or higher elevation neighborhoods" (NWS 1998, p. 23). According to another Grand Forks official: "You've got to remember that the crest forecasts were still relatively low early in the week before the flood. … The forecasts were just inching up, but we could live with those few more inches, even another half a foot. With those crest forecasts there was no need for evacuation. You have to remember that we didn't plan for failure" (Glassheim et al. 2002, p. 16). It was not until the river rose to 15.8 m (52 ft) and the predictions even higher that Grand Forks officials realized that they needed to drastically change their flood fighting strategy (Glassheim 1999; Porter 2001). By then, for most of the town, it was too late. Perhaps a few more days of advance notice would have allowed time to plan and construct secondary dikes and prevent flooding through the storm sewer system.

Predictions also played a major role in Fargo's key flood-fighting decisions. The February NWS prediction helped officials plan and implement the initial flood fight (Stensrud 1999), and in early April, the "erroneous" 12.0-m (39.5-ft) prediction motivated urgent contingency planning and dike construction. According an official in Fargo's sister city, Moorhead, "That false forecast saved our butts as far as I'm concerned … Thank god we added two more feet to our dikes" (Forum 1997, p. 47). In the Pescadero flood, predictions of the approaching storm were crucial: without them, officials would not have been able to position crews. Specific predictions were not available in the Fort Collins flood. However, better hydrometeorological observations and predictions could have helped officials close flooding roads and warn people downstream of the Spring Creek railroad embankment. This would likely have reduced the substantial automobile damage, large number of water rescues, and loss of life (Colorado State University 1997; Weaver 1999; Weaver et al. 2000). Recognizing the importance of this information for future decisions, Fort Collins officials improved their monitoring and prediction capabilities after the 1997 flood (Weaver et al. 2000).

As discussed in section 3, how a flood evolves compared with people's experience can play an important role in decisions and outcomes. The Grand Forks and Fort Collins floods evolved sufficiently differently from previous events that officials and many residents fell behind in assessing the situation and making protective decisions. Unfortunately, predictions can rarely foresee precisely how an event will unfold, particularly in extreme events in complex systems such as the cases studied here. Thus, one useful function of predictions can be to supplement experiential knowledge with scenarios of alternate possible outcomes. This can reduce surprise, help people prepare for different possibilities, and aid contingency planning (Harrald 2000). In Fargo, such "what if?" exercises appear to have helped the community prepare (Pielke 1999). In Grand Forks and Fort Collins, predictions of alternate flood scenarios could have helped officials and residents take actions that would likely have significantly mitigated losses (James and

Korom 2001a). According to a National Guard Captain involved in the Grand Forks flood: "I think we planned well but we failed to plan for the worst case scenario" (Glassheim et al. 2002, p. 181).

5. Uncertainty and confidence

Flood predictions are unavoidably uncertain, due to uncertainties in hydrometeorology, its interactions with engineering structures and the built environment, and a variety of societal factors. This is true even with the best data and predictive models. On one level, many decision makers are aware of scientific uncertainty, and they have ways of managing it (Morss et al. 2005). One way that people hedge against predictive uncertainty is by engaging in longer-term mitigation. Another way is by supplementing predictive information with environmental cues, as discussed in section 3, or by waiting for experiential confirmation of flooding before taking certain actions. Decision makers can also assume some level of predictive error and develop plans to protect at that level. For example, in March and early April 1997, officials in both Grand Forks and Fargo planned and implemented a flood fight that accounted for nearly a meter (2-3 ft) of possible error in the February NWS outlooks (Schensul 1999; Porter 2001; Glassheim et al. 2002). In Fargo, this "cushion of error" (Porter 2001, p. 29) was sufficient, but in Grand Forks, it was not.

The average error in the NWS outlook for Grand Forks is more than a meter (3 ft); this information, while potentially useful, was neither communicated by forecasters nor understood by decision makers (Pielke 1999). Instead, local officials relied primarily on experience, intuition, and observations of the flood to decide what level to protect to (Glassheim et al. 2002). The record-breaking nature of the 1997 Red River basin flood added further uncertainty to the predictions, beyond the typical event. While knowledge of this additional uncertainty could also have aided decision making, it was not fully recognized even by forecasters (Pielke 1999; Morss and Wahl 2007). More specific information about predictive uncertainty has potential to aid decisions, but only if the information is scientifically sound and decision makers can understand

and use it (NRC 2003, 2006; Morss et al. 2008).

Given predictive uncertainty, decision makers' confidence and trust in those providing predictions — the forecasters — can significantly influence decision making and outcomes. In the Pescadero Creek basin flood, San Mateo officials' confidence in NWS forecasters was a key factor in their decision to position crews early. In Grand Forks, rumors of forecasts from sources other than the NWS appeared at several points during flood preparation, and there was debate in the community over which forecast should be trusted (Porter 2001; Glassheim et al. 2002). While Grand Forks officials recognized that the NWS prediction was uncertain, they still placed substantial faith in it (Glassheim et al. 2002). This led to substantial faith among Grand Forks residents, and it led some to blame the disaster on the NWS (Glassheim 1999).

Despite the role played by predictions and other scientific information, flood mitigation decisions involve a variety of factors in addition to scientific predictions (Morss et al. 2005). In this context, it is not clear what predictive uncertainty means for local officials' decisions in once-in-career events, such as the floods discussed here. Most people have difficulty conceptualizing an extreme flood, especially a flood that would devastate their own home or community. How can or should a local official interpret a prediction that a flood has a certain chance of exceeding a level that would cause personal, professional, and/or community disaster? This highlights the role of those with a broader experience base and flood risk portfolio, such as regional, state, and federal agencies, in helping communities decide how to prepare for floods in the face of predictive uncertainty. In Grand Forks and Fargo, the USACE and National Guard expended substantial resources helping implement the flood fight, but local officials made the primary planning decisions (Stensrud 1999; Porter 2001). According to Porter (2001, p. 34), USACE officials "initially encouraged Grand Forks officials to construct new protective devices" but ended up going along with local officials' plan to enhance existing dikes (Porter 2001, p. 34). In this situation, the USACE appears to have better understood the importance of adopting flood-fighting strategies that accounted for the possibility of a much more severe flood. Local officials best understand the needs of their communities, and local control is important and appropriate, but it can be difficult for local officials to interpret and use predictive uncertainty information given the high stakes involved in an extreme event.

A major contributor to the Grand Forks disaster was officials' and most residents' certainty in the flood fight. Several city officials noted after the flood that "losing wasn't an option; we were going to win" (Porter 2001, p. 53; see also Glassheim et al. 2002). According to one observer: "Everyone, to the person, was sure that that water was not going to come over that dike … They were not going to lose anything … So many people lost so many things because they were not prepared … In some instances they hadn't even moved their possessions up out of the basement, because they just assumed that there would be no water" (Glassheim 1999, p. 37). Many people simply did not consider an unsuccessful fight possible, and they transferred their certainty in the flood fight onto certainty in the NWS forecast. This complete confidence in what turned out to be a largely unsuccessful flood fight is likely the greatest tragedy of the Grand Forks event.

6. Summary and discussion

This article examines the interactions among flood predictions, flood management decisions, and societal outcomes, drawing on analysis of three cases of severe local flooding that involved four U.S. communities. The analysis focuses around the role of predictive information in decisions immediately prior to and during floods, within the broader flood risk management context. In doing so, it adds to existing knowledge about flood hazards, flood warnings systems, and flood mitigation. By synthesizing findings across several cases, the analysis develops findings with potential broader applicability, supported by in-depth case examinations.

The three cases illustrate how each flood is embedded in a hydrometeorological and societal context that affects predictions, their use in decisions, and outcomes. Many floods, including those studied here, occur within a larger space- and time-scale hydrometeorological event. Like most communities where flooding occurs, the communities studied here also had experience with flooding and flood mitigation. This context significantly influenced the predictive information available, people's interpretations of predictions and flood risk, and the protective decisions they made. Experience with flooding —or more accurately, people's interpretations of their experience — played an especially important role: in each case, people's conceptions of potential flooding and their interpretations of predictions were anchored to past events. This application of experiential knowledge can aid decision making and reduce impacts (as in Fargo and the Pescadero Creek basin), unless the event diverges substantially from experience (as in Grand Forks and Fort Collins).

The difference between a "close call" or "near-disaster" and a "disaster" can hinge on one or a few critical decisions, which are often only apparent in hindsight. As the cases illustrate, critical decisions may be how to allocate resources or where to focus attention, for contingency planning or information gathering. Predictive information (or lack thereof) played a key role in critical decisions in all of the cases studied. Decisions based on incorrect expectations and subsequent surprise were major contributors to the loss of life and property in the Fort Collins and Grand Forks floods. Thus, one useful function of predictions can be to supplement experiential knowledge with alternate possible scenarios. As discussed by Burn (1999, p. 3457), flood mitigation "should not be regarded as a linear function of the magnitude of the flood event"; different flood levels may require different types of responses. Predictions that present different possibilities or "worst-case scenarios" can reduce surprise and help decision makers consider the range of responses that might be required, as they did in the Pescadero Creek basin and Fargo floods.

Given the inherent uncertainty in flood predictions, one way to help reduce surprise is by providing predictions that explicitly communicate predictive uncertainty. In part because of cases like the Grand Forks flood, where predictive uncertainty was not communicated but turned out to be key, communicating uncertainty is of growing interest in both hydrology and meteorology (e.g., Georgakakos and Krzysztofowicz 2001; NRC 2003, 2006; Ntelekos et al. 2006; Morss et al. 2008). While communicating uncertainty has potential value, uncertainty information should be scientifically sound and incorporate knowledge of all potential sources of uncertainty. Otherwise, decision makers may still underestimate predictive uncertainty as they did in the Grand Forks flood. Then, an inaccurate or otherwise inadequate prediction can lead to worse outcomes than no prediction at all (White 1939).

People will interpret predictions containing uncertainty information, like all predictions, through the lens of their experience, perspective on flood risk, and trust in forecasters, along with other factors. Many people, particularly practitioners who have experience with scientific information, are aware that scientific information such as flood predictions is imperfect, and they already have mechanisms for dealing with this uncertainty. To be useful, new uncertainty information must augment these pre-existing conceptions of uncertainty and fit into existing decision frameworks. The Grand Forks oral histories (Glassheim 1999; Glassheim et al. 2002) illustrate the difficulty many humans have in conceptualizing disasters and catastrophic losses before they occur. For once-in-a-lifetime events, it is not clear what predictive uncertainty means for a local decision maker who may experience catastrophic personal or community loss. Ultimately, this suggests that the goal of communicating predictive uncertainty should be not simply to provide information, but to improve interpretation of predictive information, decisions, and outcomes.

Most damaging floods in the U.S. occur in managed systems, in which humans have altered the environment to attempt to reduce flood losses. However, flood risk management activities are designed to only protect up to a flooding of a certain level, often the 1% (100-year) flood. Yet larger floods occur, sometimes with damage exacerbated by structural measures. Thus, a significant proportion of U.S. flood losses are caused by floods larger (or less frequent) than the 1% flood (Tobin 1995; Burby 2001). These interactions between longer-term mitigation and flood impacts are illustrated by the 1997 Grand Forks and Ft Collins events. In both communities, structures designed to protect to a certain level were overcome by a larger flood. Officials and residents relied on these structures, knowingly or unknowingly, with disasterous consequences.

Further complicating long-term mitigation, estimating flood risk for infrequent events involves a number of approximations and assumptions that can lead to significant uncertainty about the level of protection or to less protection than intended (Kusler and Larson 1993; Tobin 1995; Gosnold et al. 2000; Burby 2001; Larson and Plasencia 2001; James and Korom 2001a; Downton et al. 2005). Thus, despite extensive flood risk management efforts in the U.S., flood damages remain high. Consequently, many flood researchers and practitioners recommend that the U.S. modify current floodplain management approaches and adopt broader flood mitigation strategies (e.g., Kusler and Larson 1993; Myers and White 1993; Galloway 1995; Larson and Plasencia 2001; ASFPM 2007). Yet improved floodplain management, while important, cannot eliminate all risk of flooding. Residual risk is often poorly understood by local officials and residents, and mechanisms for managing residual risk, such as flood insurance, have not been as successful as intended (Burby 2001; ASFPM 2007). In this context, predictions of flooding are a major tool that communities can use to mitigate against residual risks (Handmer 2001). Predictions can complement other flood risk management strategies by helping officials and residents augment mitigation measures, evacuate people and property at risk, and engage in other protective activities if a damaging flood threatens despite longer-term mitigation. In order to provide such benefits, however, predictions must be available with adequate lead time, sufficiently accurate, well-communicated and understood, and used wisely.

Flood disasters are caused by many factors besides hydrometeorology, and effective warnings of flooding involve much more than predictions (e.g., Blaikie et al. 1994; Gruntfest 1987; Drabek 2000; Handmer 2001). Thus, scientific and technical information are just one small component of addressing flood impacts. Nevertheless, the cases studied here suggest that predictions now play a critical role in decisions and outcomes in some (if not many) floods. Even as floodplain management strategies evolve, many U.S. communities will continue to rely on structural measures for flood protection (Tobin 1995; ASFPM 2007). Further, flood risk is expected to increase with growing population and property in flood-prone areas, and possibly climate variability and change. This suggests that flood predictions and warnings systems will continue to be an important component of managing flood risk, particularly in extreme floods. It is hoped that the findings in this article can benefit communication and use of flood predictions and build knowledge of how flood predictions can best complement and support other flood mitigation strategies.

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