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Integrated Risk Assessment for the Natomas Basin (CA)

Analysis of Loss of Life and Emergency Management for Floods

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Abstract: This article assesses the risk to life for the Natomas Basin, a low-lying, rapidly urbanizing region in the Sacramento-San Joaquin Delta in California. Using an empirical method, the loss of life is determined for a flood (high water), seismic, and sunny-day levee breach scenario. The analysis indicated that more than 1000 fatalities may occur in the flood scenario and that there is a high flood risk compared to similar systems (such as dams and flood-prone areas in the Netherlands). Findings show that risk to life highly depends on evacuation effectiveness. The evacuation and emergency management system (EEM) was further analyzed through interviews with regional emergency managers and training exercise evaluation reports. Using an analytic framework, critical factors that affect EEM performance and reliability were identified. Results indicate a need to assess EEM performance to improve preparedness and reduce the risk to life. Findings from the investigation contribute to more integrated risk analyses of both the technical and management components for engineered systems.

CE Database Subject Headings: floods; fatalities; emergency services; evacuation; risk management; deltas; levee failures

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Introduction and Background

Flood events lead to widespread damage and loss of life on a global scale. Low-lying areas with substandard levees in deltas and coastal areas are especially susceptible to large-scale flooding. Relatively recent catastrophic flood events in the United States include the flooding of New Orleans due to Hurricane Katrina and the consequent levee failures in 2005 and the flooding of the Mississippi River in 2011. One region in the United States that has a significant flood risk level is the Sacramento–San Joaquin Delta in California (Hanak et al., 2011).

A large-scale risk assessment concluded that there are significant regional flood risks due to levee failures caused by earthquakes, high river discharges, or geotechnical failures (URS, 2009).

Many protected areas in the Delta (islands) have relatively small populations and a predominantly agricultural function (Suddeth et al., 2010). However, parts of the Delta are characterized by high population densities in low-lying, flood prone areas, e.g. Sacramento and Stockton areas. One important consequence of large-scale flood events is loss of life. The Delta Risk Management Study (DRMS) assessed risks to life for flooding in the Delta (URS, 2009b), but did not specifically analyze the risks for major urban areas, including large parts of Sacramento County. The modeling approach adopted in the DRMS study followed the principles of the Lifesim model for estimating the loss of life (Aboelata et. al, 2002).

Alternative methods for loss of life estimation have been developed that were directly calibrated based on empirical data from recent disasters such as Hurricane Katrina and other historical flood events (Jonkman et al., 2009).

This article demonstrates how the risks to life can be estimated for densely populated areas in the Delta using recently developed methods. The Natomas Basin in northern Sacramento and Sutter Counties was selected as the case study area. The results of our analysis are presented in the form of ranges to account for the variations and uncertainties in conditions (e.g. flood levels, evacuation effectiveness) that affect the loss of life.

Another aim of the article is to demonstrate how Human and Organizational Factors (HOF) can be included in risk assessment and management. A key premise of our research shows that these factors strongly interact with the technical factors and variables (RESIN, 2008). In particular, HOF influence the effectiveness of the Evacuation and Emergency Management System which significantly affects the risk to life. In these ways, the findings from our investigation contribute to more integrated analyses of risks in highly engineered systems.

The road map for this article is as follows. The second section introduces the Natomas flood management and emergency management systems. The methods and results of risk-to-life estimates are presented in the third section. The fourth section

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analyzes the evacuation and emergency management system for the region. Concluding remarks are presented in the final section.

The Natomas Basin System

In order to evaluate the risk to life in the Natomas Basin, the Levee System and Evacuation & Emergency Management Systems have been characterized. Following Gwynne et al. (1999) and Bea et al. (2002), a framework of three main components provides a structure for the analysis.

Environment and Hazards

The Natomas Basin is a low-lying area of approximately 222 km^2 that is protected by levees against flooding. It is located at the confluence of the Sacramento and American Rivers, which form the western and southern boundaries (NA, 1995). As shown in Figure 1, the region is bounded by three canals, the Natomas East Main Drainage Canal (NEMDC), Pleasant Grove Creek Canal (PGCC), and the Natomas Cross Canal (NCC). The area is relatively flat with an elevation ranging from approximately 3m to 12m above sea-level and lies entirely within the 100-year floodplain of the rivers and local drainage systems (NA, 1995). Regional hazards to the levee system include floods, earthquakes, and sunny-day events (see the section "types of levee failures" for details). These hazards in Natomas are significant because the grade surface elevation of the land adjacent to the levee is lower than the water surface of the American and Sacramento Rivers.

Physical Components

The Natomas Basin is encircled by an estimated 69 km ring of levees. During the growing season, water is pumped from the Sacramento River into the internal canal systems for agricultural uses. The NCC diverts run-off from large watersheds in West Placer and Southern Sutter Counties around the Natomas Basin and into the Sacramento River. Two weirs and two

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bypasses at strategic locations along the Sacramento River were constructed as release points to reduce the pressure on the levees and convey the floodwaters safely past urban areas to the San Francisco Bay (RD, 2010).

Since the levee system's original construction for early 20th century agriculture, the region has experienced a rapid rural-urban transformation. Although today 40% of the basin is urbanized (USACE and SAFCA, 2010), minor efforts have been directed towards improving the levee system. Approximately 100,000 people live in the Natomas Basin (USCB, 2010) with the highest densities concentrated in the southern portion of the basin. Two of the nation's primary highways, namely Interstate 5 and Highway 80, also intersect in this southern section (Fig. 1). The Sacramento International Airport, a major regional transportation hub with 150 departures per day and 8.5 million passengers per year, is also located in the region. The accessibility of the Natomas Basin combined with its proximity to the state capital directly across the American River has contributed to its rapid urbanization and population growth (NA, 1995).

Natomas has other critical facilities including 15 public school campuses and 43 care facilities for vulnerable populations (children, the disabled, and seniors) (USACE and SAFCA, 2010). These can be resources in the event of an emergency, but require more management attention as will be discussed later in this article.

Operators, Procedures, & Organizations

The US Army Corps of Engineers (USACE) is the Federal agency responsible for major flood control projects from their design to construction to operations and maintenance oversight. During a declared disaster, the USACE also leads the emergency flood-fighting response (RD, 2010). On a regional level, the Sacramento Flood Control Agency (SAFCA) coordinates an effort to finance, construct, and maintain facilities to ensure a reasonable and prudent level of flood protection for a developed and urbanizing area.

Currently, SAFCA and the USACE are partner agencies in the Natomas Levee Improvement Program (NLIP). The project's objective is to restore the 100-year flood protection level as quickly as possible and achieve a 200-year flood protection level overtime (PB, 2011). To expedite the construction, SAFCA manages the improvements along the Sacramento River Levee and NCC while the USACE leads the construction of the PGCC, NEMDC, and American River Levee (SAFCA, 2010).

If flood defenses fail, the evacuation and emergency management system will have to mobilize the capabilities of the local, regional, state, and national emergency managers, depending on the developing scenario. In the event of a high river

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stage, the Flood Operations Center (FOC) staffed by the California Department of Water Resources (DWR) and the National Weather Service (NWS) will take added action. Its weather monitoring and forecasting systems will disseminate reports. Meanwhile, the local reclamation districts will patrol vulnerable segments of the levees in search of failure signs such as boils, cracks, and erosion of the levee crest. The Sacramento Office of Emergency Services (SACOES) is responsible for strategic management of the entire system. As the disaster scales up, the SACOES will establish an Emergency Operations Center (EOC). The response structure is to follow the Standardized Emergency Management (SEMS) and National Incident Command System (NIMS) protocols. Recently, the Sacramento-San Joaquin Flood Response Group has developed the Delta Multi-Agency Coordination System (MACS) to promote and prioritize integrated, regional emergency management and response operations (FRG, 2011). The effectiveness of the response depends on the awareness and cooperation of the public. The emergency management structure and effectiveness will be described more in detail in the "analysis of the Evacuation and Emergency Management System" section.

The components of the described systems characterization are linked by interfaces. . Some interfaces can be weak links that fail under high stress and time pressure situations. For example, the public's awareness of the environmental hazard is critical if they are to respond quickly and comply with EEM procedures.

Risk to life due to flooding for the Natomas Basin

The risk to life for a levee breach scenario in the Natomas Basin is analyzed in this section. The subsections outline the general approach, estimate the loss of life, and discuss the regional risk level.

Approach for loss of life estimation

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General

The loss of life due to flooding is affected by the number of people that are present in the flooded area, the flood conditions, and the extent to which these flood conditions result in loss of life. The factors are represented in Equation (1) (Jonkman et al., 2009) and this is used for analyses in this article:

$$N = F_D(h)(1 - F_E)N_{PAR}(h) \qquad \textbf{(Eq. 1)}$$

where N=number of fatalities; F_D=mortality fraction [-]; F_E=Fraction of the population that evacuates to a safe location [-]; N_{PAR}=number of people at risk in the area affected by flooding; h=flood conditions such as flood depth and flow velocity.

Since flood risk depends on uncertain conditions, including water level and evacuation fraction, this study focuses on bandwidths for the elements in Equation (1). As an implication, the estimates of consequences and risk levels are presented as ranges.

The following sections outline the different elements of Equation (1) including the various types of potential flood conditions in the region, the method used to estimate mortality, and information on the population and evacuation effectiveness.

Types of Levee Failures

In general, three types of levee failures can occur in the Delta: (high-water) flood, sunny-day, and seismic failures (URS, 2009).

Flood failures, may result from high-waters caused by heavy winter and spring rains that persist over a period of at least three weeks. These conditions approximate a one in one hundred year storm event (Porter et. al 2011). In this scenario, high water flows along the Sacramento and American Rivers put pressure on the levees until they are overtopped or breach. The levee system around the Natomas Basin was designed to withstand a water level for a 100 year return period. However after Hurricane Katrina, the SAFCA Natomas Levee Evaluation Study (CSP, 2008) concluded that considerable improvements were needed to meet the USACE's revised 100-year flood protection criteria. The Natomas levee system was decertified in 2006 (CSP, 2008). Currently, the Natomas Basin Levee Improvement Program is underway to address the deficiencies (CSP, 2008). The target completion date to reinstate the 100-year flood protection level is 2014 (SAFCA, 2010). Meanwhile, the USACE is also laying the groundwork to achieve the 200-year flood protection level (CSP, 2008). Based on this information

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and interviews with local experts, it is estimated that the levees provide protection for storms with return periods in the range between 75 and 100 years.

Sunny-day failures, such as levee instability and seepage, are "no-notice events" that occur during non-flood flow periods. To date, no separate failure probability has been determined for this failure mode in the Natomas Basin.

Although no active faults run through the Natomas Basin, numerous earthquakes of magnitude 5.0 or greater have occurred on regional faults, primarily within the San Andreas Fault System (USACE, 2010). In context of the broader Delta system, the San Andreas, Calaveras, and Hayward faults are located within 26 km of the Delta. Seismologists estimate that by 2050 an earthquake will almost certainly strike the region (Flynn, 2007). Such "no-notice" events can cause liquefaction and geotechnical failure of levees resulting in an earthquake-induced flood. This threat is somewhat unique because it can trigger multiple breach sites and wider breaches than a flood or sunny-day failure (URS/JBA, 2007). The probability of failure of the levees depends on the magnitude, proximity to the epicenter, and the water level at the time of the seismic event. Based on this information and estimates for similar areas (URS, 2009c) it is estimated that the return period of this seismic scenario for the basin is on the order of 1000 years.

Table 1 gives an overview of the three scenarios and their ranges of return periods. The river water level for the flood scenario is considered the 100-year flood river stage (MBK Engineers, 2008).Geotechnical sunny-day failures and seismic failures could occur at any water level, for the purposes of this analysis a conservative scenario of +6m river stage, corresponding to the average annual maximum, is reported.

Estimation of mortality

Mortality is defined as the number of fatalities divided by the number of people exposed to flooding in that area. Since the flood conditions, vulnerability of the population, and existing infrastructure affect the mortality, the rate is complex to predict accurately. Various approaches have been developed for a loss of life estimation (see e.g. Jonkman et al., 2008; URS, 2009b; Aboelata et al., 2002). Analyses of historical events show that mortality is correlated with certain flood conditions, such as water depth and flow velocity. Based on an analysis of the loss of life after Hurricane Katrina, relationships were developed for areas of New Orleans affected by levee breaches (Jonkman, 2009). These relationships are applied to estimate the mortality in the Natomas Basin.

Figure 2 shows the empirical relationship between mortality and water depth for New Orleans after Hurricane Katrina (R^2=0.42, so there is still considerable uncertainty associated with this prediction model). Equation (2) describes this function:

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$$F_D(h) = \Phi_N\left(\frac{\ln(h)-\mu}{\sigma}\right) \qquad \textbf{(Eq. 2)}$$

where Φ_N=cumulative normal distribution; h=water depth [m]; μ=average of the normal distribution μ=5.2m; σ =standard deviation of the normal distribution σ=2.0m.

Differences between the observations and trend-line are due to additional environmental and physical factors that are challenging to quantify within the model parameters (Fig. 2). These factors introduce uncertainty in the model that should not be overlooked.

Based on observed mortality near breaches in New Orleans, an additional criterion has been defined to account for the loss of life in high-velocity flood zones, i.e. mostly near breaches. When the combination of flood depth (d [m]) and flow velocity (v [m/s]) is larger than dv=5m^2/s, the mortality rate will be approximately F_D=0.05.

Despite differences with the expected conditions during a levee breach in the Natomas Basin (e.g. water temperature), comparisons with other historical levee breach events show that the empirical relationships for New Orleans can also be applied to predict the loss of life for other levee breach flood events (Jonkman et al., 2009).

The application of the above modeling framework to the Natomas Basin flood scenario has required a number of assumptions. Similar to the methods developed by USACE (2011), a relatively simple screening-level approach has been chosen to allow the analysis of loss of life for various scenarios characterized by different water levels, evacuation effectiveness values, and breach conditions. In this way, the approach seeks to take into account the inherent and modeling uncertainties in these parameters. This approach differs from other methods for evacuation and life loss estimation (e.g. Dawson et al., 2011; Johnstone et al., 2005; Simonovic and Ahmad, 2005) that require detailed input data on local conditions and infrastructures to analyze a single scenario.

To analyze the flood characteristics, a simplified approach has been adopted. In the three scenarios it is expected that after breaching the water level in the Natomas Basin will equilibrate with the water level in the river. The local flood depth is thus determined by the river water level and the local elevation. This basin storage approach yields a simplified but realistic analysis that forms a foundation for a more detailed hydrodynamic simulation.

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Additional assumptions have been formulated to account for local effects of breaches. The flood and sunny-day failures are considered single breaches, whereas a seismic failure scenario is characterized by a large number of breaches. Based on hydrodynamic calculations for typical delta conditions (URS, 2009b) it is assumed that the breach zone for a single breach (where dv>5m^2 /s) forms a half circle around the breach location with a radius of 330m.

The single breach occurs in the Sacramento River East levee in close proximity to the Sacramento International Airport (indicated in Fig. 4). The selected location has been identified by the USACE and Sacramento City and County as one of the five most vulnerable sections of levee and it is approximately located halfway between the Northern and Southern system boundaries.

For the seismic scenario it has been conservatively assumed that continuous breaches occur in all the levee sections bordering urban areas. This is the case in the southern part of the Natomas Basin. It is noted that it can be useful for land use planning and zoning purposes to evaluate the breach zone as a strip with specific risk characteristics.

Natomas population and evacuation fractions

For our purposes, the Natomas Basin is sub-divided into 22 tracts defined by the US Census Bureau and the population for each tract is determined from the 2010 Census. The assessed region has a total of about 100,000 individuals (USCB, 2010). The population of each tract is assumed to be evenly distributed across the tract. Additionally, the elevation of each tract is assumed to be constant and equivalent to the average elevation within that tract. Ranges of different evacuation fractions (F_E) have been assumed for each scenario and these have been included in Table 1. Since no specific information was available regarding differences in evacuation effectiveness at various locations in the Natomas Basin, constant evacuation fractions have been assumed for all tracts within the system.

Due to non-compliance to warnings, a full evacuation (100%) will never be achieved (Jonkman, 2007). For the flood scenario an evacuation fraction between 50% and 90% is assumed, which is consistent with the 80% evacuation effectiveness from DRMS (URS, 2009b). A similar evacuation fraction was observed in New Orleans prior to Hurricane Katrina (Wolshon et al., 2006).

Sunny-day and seismic failures are typically characterized by unexpected levee breaches. It is therefore expected that the evacuation fraction will be low, and a range of 0% to 20% has been adopted.

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Results: loss of life estimates

The method introduced earlier has been used to generate loss of life estimates for the scenarios. Figure 3 shows the results for the flood scenario with a range of evacuation fractions (50% - 90%) and three values of water levels that represent the expected return period of the event including a bandwidth (11.6m ±1m). Due to the relatively high water levels during flood conditions, a large part of the Natomas Basin is expected to be flooded. The loss of life for this scenario could range from a few hundred fatalities for a 90% evacuation fraction to more than a thousand for an evacuation fraction of 50%. Figure 4 illustrates the spatial distribution of fatalities for one flood scenario. Results indicate that most fatalities occur in the areas with lower elevation in the densely populated western and southern parts of the basin.

The results for the sunny day failure (single breach) and seismic scenarios (continuous breach) are shown in Figure 5. The expected water levels (6m ±1m) for these scenarios will lead to flooding of a limited part of the Natomas Basin. It is noted that the loss of life results for the seismic scenario only include fatalities due to the flood effects induced by the earthquake. The loss of life increases rapidly with the water level and depends on the occurrence of breaches near densely populated areas. Assuming a continuous instead of a single breach leads to a significant increase in the loss of life, due to high population densities near the levees in the southern part of the basin.

The sensitivity of the loss of life to different water levels and evacuation fractions is shown in Figure 6 for the continuous breach case. The resulting water level after breaching will mainly depend on the local elevation (Fig. 1). Overall the loss of life could range from few to no fatalities for a single breach with water levels lower than the yearly maxima (about 6m) to hundreds of fatalities for multiple breaches with higher water levels. Furthermore, loss of life could increase significantly if a seismic failure coincides with a high water level event.

The results provide further insight in the ranges of loss of life for the Natomas Basin. This area was not included in previous risk estimates for the Delta (URS, 2009b; URS, 2009c). The general modeling approach highlights the sensitivity to conditions such as the water level, evacuation effectiveness and numbers of breaches. Further research can be done to assess the flood conditions in the area more accurately by means of two dimensional hydrodynamic models, and to gain further insight in evacuation effectiveness by means of transportation models. Since the loss of life model was based on observations from New Orleans, there is also a need to modify specific parameters to capture conditions specific to the Natomas Basin. For example, the minimum water temperature in the Sacramento River is 9°C compared to more than 25°C in the flooded areas in New Orleans (Pardue et al., 2005). Individuals can only survive 2-5 hours in the colder river water (Hayward, 1983).

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This could lead to even higher losses of life and poses significant challenges for rescue operations. Other differences between Natomas and New Orleans could exist in variables such as housing type and the public's disaster awareness.

Risk assessment and discussion

In order to assess the risk level associated with flooding of the Natomas Basin, ranges of return periods and consequences were plotted in a so-called FN curve and compared with other related systems (Fig. 7). This curve shows the probability of an event with a certain number N or more fatalities. The risks for the Natomas Basin are represented for the flood and seismic scenarios. Since the return period is not available for the sunny-day failure, this scenario has not been included, but the results presented earlier in this paper indicate that the loss of life is smaller compared to the other two scenarios.

The F-N relationships associated with other related systems have been added to this figure. These include dams in the US (Prof. G. Baecher, personal communication), a major flood prone area in the Netherlands (Jonkman et al., 2009) as well as a line delineating a historically acceptable risk level at which various structures perform (Whitman, 1981; Lambo and Pepperell, 1982). In addition, flood risk estimates for the Delta (URS, 2009) are shown, but these exclude the Natomas Basin. These estimates have been displayed in the FN curve by means of shapes to account for uncertainties in the probability and life loss estimates. The risk estimates for South Holland and the Sacramento delta are based on similar factors as included in the loss of life estimates in this study, but they were originally reported as FN lines. The typical uncertainties in probability and consequence estimates have been taken into account to display these estimates by means of shapes.

From this figure it becomes clear that the risks to life for the Natomas Basin particularly related to the flood scenario are:

a) significantly higher than those for the other systems displayed;
b) are expected to contribute significantly to the overall risks in the Delta; and
c) are located in the unacceptable zone (Figure 7) when compared with the general risk acceptance criterion.

These projected outcomes form a basis for further discussion on the acceptance of risk in this region as well as the need and effects of risk reduction strategies. Preventive measures should lead to a vertical downward shift of the risks in this diagram. Measures such as improved evacuation and elevation of homes could lead to a reduction of consequences.

The consequences for these low-lying, densely populated areas ranging from hundreds to more than a thousand fatalities are comparable to similar areas in the Netherlands. However, whereas California and the US have protection levels of 1/100 to 1/200 per year, the Netherlands has adopted protection of levels of 1/1000 to 1/10,000 per year (Jonkman et al., 2008). It is

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noted that when the somewhat higher protection level of 1/200 per year is implemented in the Natomas Basin, the risks to life will remain high, given the current levels of population and evacuation effectiveness.

It is expected that other low-lying and densely populated areas in the Delta, such as the Sacramento Pocket region and areas near Stockton, will have relatively high risk levels that would be of serious concern (URS, 2009b).

Future changes such as levee subsidence, increasing frequencies of flood events due to climate change, and especially urban development in the area could lead to an increased risk to life.

Ultimately, the definition of an acceptable risk is a political decision that also considers the costs and other implications of the necessary risk reduction projects. The risk estimates as presented in this study will provide the input for these decisions.

Analysis of the Evacuation and Emergency Management System

The previous section shows that loss of life highly depends on the effectiveness of the Evacuation and Emergency Management system (EEM). This section discusses and analyzes the issues affecting the performance of the EEM system in the Natomas Basin.

Current emergency plan and response

When a levee is threatened, the Sacramento County Operational Area Emergency Operations Center (EOC) is mobilized to manage the evacuation process. In the event of “massive levee breaches or failures and flooding in one area, and/or combined imminent threats of failure in multiple locations” (Witt, 2008), state and federal agencies engage to provide an elevated level of technical assistance and mutual aid through the dynamic and flexible SEMS/NIMS EEM system.

The County of Sacramento and City of Sacramento have developed maps illustrating the progression of a flood for a hypothetical breach in the five most vulnerable levee sections (CCS, 2009). Flood depth maps indicate the time available before evacuation routes become impassable (0.3m water depth). Based on the arrival times of the inundation, the corresponding evacuation map identifies a ‘rescue zone’ (0.3m water level occurring 2 hours after breach) and ‘evacuation zone’ in each scenario. For the flood scenario with a beach near the Sacramento airport (Fig. 4), Interstate 5 would be impassable 2-3 hours after the levee breach. Within 18-24 hours, Interstate 80 will be impassable, affecting the densely populated Southwestern section of Natomas. The arrival time depends significantly on the breach location. If the breach

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occurs along the levees in the southern portion of the basin, critical local roads would be lost much more quickly. In all scenarios, the elimination of the major transportation routes poses challenges for the evacuation and the delivery of resources.

According to estimates from the Sacramento County Evacuation Plan (Witt, 2008), 80% of the population (approximately 80,000 persons) will self-evacuate in private automobiles along the major interstate highways and primary arterials. The remaining 20% (approximately 20,000 persons) will require transportation assistance such as public transit or specialized transportation (Witt, 2008).

Framework

A general timeline for evacuation can be characterized by means of four phases (Jonkman, 2007). Lindell et al. (2002) and Opper (2000) suggest similar general classifications of the evacuation process phases.

1. Detection & Decision Making: Emergency managers monitor the flood conditions and consider the trade-off between waiting and initiating evacuation.
2. Warning: A warning is issued to the population-at-risk through multiple channels including sirens, telephone, and the media.
3. Response: Residents within the affected areas perceive, interpret, and respond to the warning. Emergency responders are mobilized.
4. Evacuation: The population-at-risk evacuates independently or with the assistance of emergency responders to shelters within the flood zone or a safe location outside the flood zone.

The plot shown in Figure 8 (Jonkman, 2007) illustrates the relationships between time and evacuation effectiveness, i.e. the fraction of the population evacuated. Conceptual trajectories describe the four phases of the evacuation timeline. The shape of each curve depends on both human & organizational factors (e.g. the level of preparedness) and physical factors (such as the capacity of the evacuation routes). The slope of each curve describes the efficiency of the phase.

The success of an evacuation effort also depends on the time available between the occurrence and arrival of the physical effects (Jonkman, 2007). A rapidly developing event (i.e. an earthquake) leads to potentially lethal conditions faster than an event that progresses more gradually. The performance of the total EEM operation can be defined as the fraction of the population evacuated in the time-available. The efficiency of warning and response is reflected in the fractions “not-warned” and “non-compliant.” An effective EEM operation would lead to a relatively rapid evacuation over time and low not-warned/non-compliant fractions.

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Analysis of Evacuation and Emergency Management for the Natomas Basin

Research Questions & Methods

The analysis focuses on the following research questions:

1. What are the critical factors that influence the performance of the Evacuation and Emergency Management system for the Natomas Basin in each phase?
2. How prepared are critical facilities to respond to a flood event?
3. Is the framework from the previous section applicable to systematically assess EEM performance for the Natomas Basin?

The research questions were investigated using various methods. First, a background literature study included both reputable emergency management literature (see eg. Mileti et. al., 2000; Lindell et. al., 2002) and regional evacuation plans (see e.g. Witt, 2008). This was complemented by a review of After Action Reports and workshops, which evaluated the Sacramento County Office of Emergency Services (SACOES) simulation exercises (SACOA, 2005) and California Emergency Management Agency (CalEMA) Operations Center (CCRM, 2010). In addition, original interviews were conducted with emergency planners from CalEMA, SACOES, and a critical facility. The following sections present the findings for the research questions.

Critical Factors

Critical Factors are issues that negatively influence the performance of the evacuation and emergency management system. Table 2 summarizes findings from the interviews, literature, and exercise reviews. The impacts of these factors on their corresponding phases are described below.

Detection and Decision Making

Gathering intelligence about the flood conditions from a variety of specialized agencies and synthesizing this data into a common operating picture for EEM is central to the earliest phase of the evacuation process. A lack of situational awareness

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in a rapidly evolving emergency situation poses the risk that the decision to evacuate is delayed or not initiated because the information is not clear or transmitted early enough. For example, fragmented ownership of the Natomas Basin levee system affects the quality and consistency of the intelligence provided to the EOC. Some sections of the Natomas levees are government-owned while others are private property. The parties have different capacities to monitor their levees, and these disparities could compromise the entire system and impact evacuation effectiveness.

The functioning of the inter-organizational links in an integrated response is a major factor affecting performance. Assumptions about EOC units or other agencies' responsibilities lead to uncoordinated overlap or information gaps, which delay information transmission. The Sacramento training exercise evaluation concluded that in a developing event, the lack of communication in the chain of command could have done serious damage to public safety and harmed field personnel looking for support from the EOC (SACOA, 2005).

Warning

The timing of the warning is critical. Since the EOC's decision to order evacuation is dependent on situational factors, formulaic thresholds or automatic triggers for warning the public cannot be established. If, based on collaboration with subject-matter experts and intelligence, the flood threat is considered imminent, the EOC issues a warning message that is meant to be concise, consistent, and provided to everyone at the same time. Ambiguities or misinterpretations of the warning message may propagate and create confusion, with the EEM organization risking its credibility. In Natomas, a combination of various strategies will be used to disseminate the warning message including the media, a reverse 911 telephone system, sirens, door-to-door notification, patrol cars, and social media.

Response

Since many City and County employees live in the Natomas Basin, they may be in the process of evacuating and unable to do their job. To ensure continuity of operations, managers must decide in real-time what functions are critical to maintain and how to assign available staff.

Critical facilities including schools, senior centers, and hospitals are required to maintain independent response plans. During an evacuation, these plans need to be closely coordinated by the EOC (Witt, 2008). Emergency managers expressed concern about the level of preparedness of these facilities. The potential resource demand conflicts between facilities could overburden the EOC and reduce the evacuation effectiveness. For example, a specific transportation provider may have numerous separate contracts with different regional senior care facilities, but may lack the capacity to actually fulfill these

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agreements in an emergency situation. Resolving these resource demand conflicts will be difficult in a chaotic emergency. Secondly, the timing of the public's response whether proactive or delayed is one of the determining factors for the rest of the operation.

Evacuation

Emergency planners remark that the major freeways in Natomas experience heavy traffic during the daily commute causing concerns about traffic management during an emergency. The emergency responders that were interviewed indicated that the evacuation will be organized as a phased-process to provide extra time for vulnerable populations and limit the impacts on access routes, but there are several challenges to implement this systematic evacuation management plan in practice. During a flood, the evacuation routes will also depend on situational factors (eg. levee breach location and flood conditions). Unlike hurricane and tsunami-prone regions, the routes in Natomas cannot be identified in advance as the availability of infrastructure depends on the location of the breach and flooding process. Implementing a traffic management plan that can adapt dynamically to the flood condition and inform the public in real-time will be essential.

Critical Facility: Natomas School District

In the aftermath of Hurricane Katrina, many fatalities affected vulnerable populations at critical facilities including schools, hospitals, and senior care centers (Boyd et al, 2009). The facilities were not sufficiently prepared and had an inadequate disaster-response plan (Jonkman et. al., 2009). Although California state law mandates critical facilities to develop and manage their own emergency plans and maintain sufficient resources to shelter-in-place, the Sacramento Emergency planners are concerned about the self-sufficiency of these facilities and their potential to severely strain available resources in the event of a disaster.

To investigate this issue, the director of the preparedness program at the Natomas School District was interviewed. In the event of a high-water level, the school district relies on flood warnings from the City and County officials and will cancel classes as a preventative measure. If evacuation were necessary, school buses would bring students to a safe high-ground at near-by school sites where families could pick-up their children. Using flood progression maps developed by the City of Sacramento (CCS, 2009), the district constructed a timeline expressing the arrival time of three feet of water at the affected school-site. The evacuation procedure was practiced two years ago, but is not a regular exercise. Conducting and evaluating emergency drills is the responsibility of the school-site principals. Although additional district oversight would be beneficial

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to streamline the quality and frequency of the exercises and de-briefings, the director stated that a lack of resources does not make this possible.

The California Education Code requires all school districts to maintain updated Emergency Action Plans and the State Board of Education reviews these annually for compliance. In the Natomas School District, the management of the emergency planning and preparation of evacuation maps is delegated to the school principals. The director stated that currently, these documents are "on a shelf" at each individual school site. Posting the EEM plan on the internet could not only facilitate more district oversight, but also inform parents and students.

Another issue is the lack of emergency supplies at the school sites. The director stated that the district cannot afford the cost of providing these essentials. Furthermore, the discussion revealed a disconnect between the management and operators. Although the director expressed confidence in the staff and students' awareness of the program and training procedures, an office staff member was unable to provide any specific information about the EEM plan.

Clearly there is a need for more transparency and general awareness in the school district about the EEM procedure and there is an urgent need for emergency supply kits and provisions.

Although only one critical infrastructure facility was evaluated, the experience of Hurricane Katrina and the results of interviews with local emergency managers suggest that this case may be representative of a larger issue. There is a need to further investigate and verify the preparedness of other regional critical facilities.

Applicability of the Evacuation Effectiveness Framework

Interviews with emergency managers provided insight into the application of the EEM framework, system performance, and effectiveness in the Natomas Basin. They identified numerous improvements for this type of analysis, which will be discussed in the following subsections.

Phase construction

Although the four phases of the theoretical evacuation timeline are distinct and consecutive, discussions with emergency managers highlighted that significant overlap occurs in practical situations. For example, in a flood scenario, planners expect that detection/decision-making and the warning phases will operate to a certain extent in parallel. Since the weather can be

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forecast in advance, decision-makers will continuously monitor the storm progression as they prepare and activate the warning systems if evacuation is necessary.

Before evacuation is initiated, multiple "parallel" timelines are operating to forecast the flood conditions and inform the EEM process (e.g. weather forecasting, levee condition monitoring, flood-fighting). While the evacuation timeline determines the time-required, the parallel timelines describe the time-available. Throughout the evacuation, these interdependent timelines are interacting as critical information is exchanged between them. The signs and events related to levee performance and storm progression will drive the actions and decisions of the evacuation timeline.

Cascading Effect in terms of Time

The total time-required to complete all phases determines the evacuation effectiveness. The emergency managers expressed that a delay in one phase will cascade and impact all subsequent phases. For example, if the EOC does not develop a common operating picture, the response teams will not know the quantities of resources and types of responders needed in the affected area. The ultimate impact of the time delay on the evacuation effectiveness (percent of the population evacuated) will depend on the time-available before levee breaching. If this time buffer is large enough to absorb the delay, then the evacuation effectiveness will not be affected.

Evacuation Effectiveness & Performance Measures for EEM

The EEM critical factors highlight the uncertainties associated with this human system operating in a highly unpredictable environment. As a result, quantitative performance reliability measures can provide an order-of-magnitude estimate. Despite the large uncertainty, there is a need to develop analytic measures that can systematically shape preparedness efforts so a certain level of performance can be expected (Jackson et. al., 2010).

This is already routine for everyday emergencies such as a medical response to treat patients with time-sensitive conditions (e.g. heart attacks). The percent of responses where emergency units fail to arrive within the desired time-window can be tracked and changes are made to fix problems detected. However assessing the probability of failure for a complex, large-scale emergency requires experts to make judgments about potential performance that is only called upon rarely, if ever.

Many studies have assessed this human task-reliability (e.g. Williams, 1988). A more recent RAND study (Jackson et. al., 2010) focused on building fault trees for emergency response to identify failure modes. Based on expert judgment, the likelihoods of occurrence and corresponding severity of each failure mode were quantified.

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Although the probability of failure is a reasonable measure for assessing an individual EEM task, the emergency managers interviewed highlighted that the performance reliability of the EEM system cannot be represented as binary (fail or function). A definition of failure of an evacuation operation does not exist in the process-based world of emergency management. Instead, performance is a band-width ranging from very effective to ineffective, as the managers "do the best we can with the information and resources we have available." Time is the critical resource that determines the relative performance of the EEM phases. The evacuation effectiveness fraction expresses EEM performance and is a more suitable performance metric.

Application to the Natomas Basin

The analysis in the "risk to life due to flooding"section determined the loss of life for a range of evacuation effectiveness values. The emergency planners interviewed approximated the time required for the evacuation phases. The anticipated time elapsed between detection and warning is 1-2 weeks. Then the response and evacuation will be completed in 1 day.

Currently, evacuation effectiveness estimates are based on flood condition maps and transportation models. The emergency managers interviewed estimated that ranges for the Natomas Basin vary between 60% and 90% depending on the time of day the warning is issued. This range is consistent with the 80% evacuation effectiveness estimate of the Delta Risk Management Study (URS, 2009b).

Average estimates from literature indicate that approximately 5-10% of the total population will not comply with evacuation warnings (Boyd et al, 2009; Jonkman et al, 2009).

Discussion

Any evacuation and emergency management operation in Natomas will be interconnected and dependent on the flood conditions and emergency management capacities in the Delta. In these circumstances, the overall allocation and prioritization of emergency response resources will be critical. Since the region is densely populated, the Natomas Basin is likely to be a priority, but it is highly situational dependent.

In the flood scenario analyzed, emergency managers have a long lead time to evaluate conditions and plan these multi-jurisdictional and inter-agency prioritization agreements for response. However the Natomas Basin's flood defense system also faces unpredictable and catastrophic hazards due to earthquakes and sunny-day failures with no or very limited notice.

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This poses huge coordination challenges and evacuation effectiveness will be small. To date, Sacramento County has not experienced an unexpected flood in a populated, urban area like Natomas.

An evaluation of risk-awareness in the Delta concluded that residents of sub-sea-level neighborhoods were unaware of the true risks of living behind a levee (Ludy, 2012). Since residents of the Natomas Basin pay assessments on their properties for flood protection upgrades, planners point out that the public might be slightly more aware than average of the hazard. The public's perception of the risk will influence their understanding, belief, personalization, and response to an evacuation warning (Mileti et. al., 2000).

Interesting parallels can be drawn between this study's findings and pre-Hurricane Katrina, New Orleans. For example, critical facilities were insufficiently prepared and had an inadequate disaster-response plan leading to conflicts over stretched resources and a large number of fatalities in these critical facilities (Jonkman et al., 2009).

In addition, Hurricane Katrina provides many insights about emergency communication and response. Although forecasts predicted surging floodwaters in New Orleans 39 hours before the inundation occurred and mandatory evacuation orders were issued, 1 million people waited to evacuate until the day before the storm made landfall (Boyd et. al., 2009). As a result of an effective transportation management plan shaped by hard-learned lessons of prior hurricane evacuations, approximately 90% of the population evacuated before Katrina with few significant traffic problems. The remaining 10% did not comply with warnings and remained in the threatened area. In the post-storm response, multi-agency search-and-rescue operations focused on minimizing human exposure to the flood-waters, but were affected by numerous communication and coordination challenges. Furthermore, the continuity of operations deteriorated; vital resources (eg. public transit buses) had no operators and were abandoned. The deprivation and suffering in the disaster's aftermath demonstrated the consequences of these critical factors and provide valuable lessons for the Natomas Basin and other similar areas.

Concluding Remarks

The findings and recommendations of this study have been structured according to the three themes of the paper: loss of life and risk, critical factors in evacuation and emergency management, and integrated systems risk analysis. A discussion of the outlook and developments follows.

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Loss of Life and Risk

The methodology discussed in this paper can be used for a first screening of the approximate flood risk level and influences of several important factors. When applied to the Natomas Basin, the analysis indicated that more than 1000 fatalities may occur in a flood scenario and there is a high flood risk compared to other systems. More detailed estimates of levee failure probabilities, accurate flood simulations, and evacuation and traffic models could provide data for more comprehensive loss of life estimates and approximations of evacuation effectiveness.

Critical Factors in Evacuation and Emergency Management

This study's focus on identifying critical factors, which threaten the ability of the response operation to perform effectively, distinguishes our approach from most preparedness assessment methods. Major critical factors include a lack of situational awareness, inconsistent warning messages, coordination challenges, and traffic congestion along major evacuation routes. The EEM system report card presented in Table 2 provides observations that could form the basis for additional analysis.. These critical factors increase the time-required to complete the evacuation phases and the resulting delays will cascade through the evacuation timeline and affect the evacuation effectiveness. The presented estimates in this article show how evacuation effectiveness influences the expected loss of life due to various flood scenarios. Further research could investigate the impacts of the critical factors on the time required for evacuation by developing distribution curves of the four phases for the region (see Fig. 8).. These metrics could calibrate expectations of decision-makers, emergency responders, and the public and provide the inputs to prioritize improvements for the EEM system. Due to the current and increasing risk to life in Natomas, there is a need to develop new approaches and metrics to systematically shape preparedness efforts so a certain performance level can be expected. As part of further research it is also relevant to investigate how timing of the events (day / night), weather conditions, notifications and awareness affect evacuation.

Integrated Systems Risk Analysis

The analysis demonstrated the influence of evacuation and emergency management effectiveness on the risk to life. Therefore, a risk assessment of delta levee systems requires this type of integrated analysis including both technical and management and organizational factors.

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Furthermore, the study highlights the interfaces among organizations associated with designing, operating, and maintaining the physical, levee system as well as agencies responsible for managing the human and organizational EEM system. The study demonstrates the importance of communication, collaboration, and coordination among diverse stakeholder groups to protect the Natomas Basin from natural hazards.

Outlook/Developments

The threats to the Natomas Basin levee system have been long-standing, changes in the natural environment are elevating these hazards overtime, levees and roads have been allowed to deteriorate, and large housing developments have increased the flood risk. A very similar risk creep phenomenon was observed in New Orleans in the decades before Hurricane Katrina.

While the current Natomas levees do not meet the USACE 100-year flood protection standard, the population has more than tripled from 30,000 persons in 2000 to nearly 100,000 in 2010 (USCB, 2010).

Similarly, the emergency response capacities are not growing at the same rate as urbanization and development. Local, state, and federal budget cuts continue to reduce the resources, staff, and training programs. Consequently, coordination among agencies and communication among engineers, operators, and management has become more difficult.

The critical factors identified in the EEM plan of Natomas may be representative of a larger national emergency preparedness issue. A 2006 nation-wide DHS investigation reveals that only 25% of state emergency operations plans and 10% of municipal plans were "sufficient to cope with a natural disaster or terrorist attack." The majority of these plans "could not be characterized as fully adequate, feasible or acceptable to manage catastrophic events" (Flynn, 2007).

Awareness of the issues and initiatives to improve the status-quo

Addressing levee safety and improving EEM is on the agenda of agencies and organizations in the Natomas Basin. Currently the USACE is studying flood progression scenarios in the region and developing a Levee Screening Tool to rank levees by their relative risk (USACE, 2011). SAFCA and USACE are also implementing the Natomas Levee Improvement Project to raise the levees, construct cut-off walls, and install erosion protection so the flood defenses will meet the 100 and 200-year flood protection levels. When Congress authorizes the renovated levees, the building moratorium that has been in effect since

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December 2008 will be lifted (Johnson, 2011). In addition, CalEMA and the SACOES are continuing to develop training exercises to test their plans and build-up their capacities. The agencies are continuing to raise public awareness about the region's hazards and are harnessing new outreach opportunities such as social media.

Given the high risk and sub-standard levees, there is a need to improve EEM for the Natomas and Sacramento regions including improved coordination with critical infrastructure facilities, use of flood simulations to prioritize evacuation zones & routes, traffic analyses, and simulation exercises. Furthermore, a discussion to ascertain risk acceptance levels and evaluate risk reduction options related to levees safety standards, EEM capabilities, and land-use planning, is necessary in the Natomas Basin and other densely populated and flood prone areas in California and the US.

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References

Aboelata M., Bowles D.S., and McClelland, D.M. (2002). "GIS model for estimating dam failure life loss." *Proc. 10th Engineering Foundation Conference on Risk-based Decision-making*. Santa Barbara, CA, 126–145

Bea, R.G. (2002). "Human and Organizational Factors in Reliability Assessment of Offshore Structures." *Risk Analysis*. 22(1), 19-35.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

Boyd, E., Wolshon, B., and Van Heerden, I. (2009). "Risk Communication and Public Response During Evacuations: The New Orleans Experience of Hurricane Katrina." *Public Performance and Management Review*. 3(32), 437-462.

Center for Catastrophic Risk Management at the University of California Berkeley (CCRM) (2010). "Combined Notes of the Control Room-Emergency Response Table-top Exercise on Major Storm Scenarios for California's Sacramento-San Joaquin Delta." California Emergency Management Agency – State Operations Center, Sacramento, CA, August 24, 2010.

City and County of Sacramento (CCS) (2009). "Comprehensive Flood Management Rescue and Mapping Evaluation: Hypothetical Flood Depths Sacramento River-Sutter" and "Rescue & Evacuation Areas Sacramento River-Sutter." Prepared by Wood Rodgers. <http://www.msa.saccounty.net/waterresources/stormready/default.asp?page=maps> (March 2, 2011).

City of Sacramento Planning Department and County of Sacramento Planning Community Development Department (CSP) (2008). "Natomas Joint Vision Area: Existing Conditions and Planning Context." <http://www.cityofsacramento.org/planning/projects/natomas-joint-vision/documents/NJV_Background_Report.pdf> (June 30, 2011).

Dawson, R. J., Peppe, R., and Wang, M. (2011) An agent based model for risk-based flood incident management, *Natural Hazards* 59(1),167-189

Flynn, S. (2007). "Danger on the Delta." *The Edge of Disaster: Rebuilding a Resilient Nation.* Random House, New York, NY.

Gwynne, S., Galea, E.R., Owen, M., Lawrence, P.J., and Filippidis, L. (1999). "A Review of the Methodologies used in Computer Simulation of Evacuation from the Built Environment." *Building and Environment*. (34), 741-749.

Hanak, E., Lund, J., Dinar, A., Gray, B., Howitt, R., Mount, J., Moyle, P., and Thompson, B. (2011). "Managing California's Water from Conflict to Reconciliation." Public Policy Institute of California, San Francisco, CA.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

Hayward, J.S. (1983). "The Physiology of Immersion Hypothermia." *The Nature and Treatment of Hypothermia*. R.S. Pozos and L.E. Wittmers, eds., Croom Helm, London , 3–19.

Jackson, B., Faith, K., and Willis, H. (2010). "Evaluating the Reliability of Emergency Response Systems for Large-Scale Incident Operations." RAND Homeland Security Defense Center. Prepared for FEMA.

Johnson, R. (2011). "Natomas Levee Improvement Program Update." Sacramento Flood Control Agency (SAFCA). <http://www.cityofsacramento.org/dsd/planning/new-growth/north-natomas/documents/NLIP_Update_10-13-2011.pdf> (January 23, 2012).

Johnstone, W.M., Sakamoto. D., Assaf. H., and Bourban, S. (2005). "Architecture, modelling framework and validation of BC Hydro's virtual reality life safety model." In: Vrijling et al. (eds) Proceedings of the international symposium on stochastic hydraulics, 23-24 May 2005, Nijmegen.

Jonkman, S.N. (2007). "Loss of Life Estimation in Flood Risk Assessment: Theory and Applications." Doctoral Dissertation, Delft University of Technology, Delft, NL.

Jonkman, S.N., Vrijling, J.K., and Vrouwenvelder, A.C.W.M. (2008). "Methods for the estimation of loss of life due to floods: A literature review and a proposal for a new method." *Natural Hazards,* 46(3), 353-389.

Jonkman, S.N., Maaskant, B., Boyd, E., and Levitan, M.L. (2009). "Loss of life caused by the flooding of New Orleans after Hurricane Katrina: Analysis of the relationship between flood characteristics and mortality." *Risk Analysis,* 29(5), 676-698.

Lambo, W. and Pepperell, E. (1982). "Acceptable Risk at the Kawaski Refinery." Prepared for Toa Kogyo.

Lindell, M.K., Prater, C.S., Perry, R.W., and Jie Ying, W. (2002). "EMBLEM: an empirically based large-scale evacuation time estimate model." Hazard Reduction & Recovery Center, Texas A&M University, TX.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

Ludy, J. and Kondolf, G.M., (2012). "Flood risk perception in lands "protected" by 100 year levees" *Natural Hazards*, in press, DOI 10.1007/s11069-011-0072-6

MBK Engineers (2008). "Summary Report on Hydraulic Impact Analysis." Natomas Levee Improvement Program. Prepared for the Sacramento Flood Control Agency.

Mileti D.S. and Peek, L. (2000). "The Social Psychology of Public Response to Warnings of a Nuclear Power Plant Accident." *Journal of Hazardous Materials,* 75, 181-94.

National Academies: Committee on Flood Control Alternatives in the American River Basin (NA) (1995). "The Natomas Basin." *Flood Risk Management and the American River Basin: An Evaluation*. National Academic Press, Washington, DC, 166-176.

Opper, S. (2000). "Emergency Planning for the Hawkebury Nepean Valley." *40th Annual Conference of the Floodplain Management Authorities of NSW*, Parramatta. AU.

Pardue, J.H., Moe, W.M., Mcinnes, D., Thibodeaux, L.J., Valsaraj, K.T., Maciasz, E., van Heerden, I., Korevec, N., and Yuan, Q.Z. (2006). "Chemical and microbiological parameters in New Orleans floodwater following Hurricane Katrina." *Environmental Science & Technology*, 39(22), 8591–8599.

Parsons Brinckerhoff (PB) (2011). "Draft Engineer's Report: Sacramento Flood Control Agency Natomas Basin Local Assessment District." Prepared for The Sacramento Flood Control Agency.

Porter, K., Wein, A., Alpers, C., Baez, A., Barnard, P., Carter, J., Corsi, A., Costner, J., Cox, D., Das, T., Dettinger, M., Done, J., Eadie, C., Eymann, M., Ferris, J., Gunturi, P., Hughes, M., Jarrett, R., Johnson, L., Dam Le-Griffin, H., Mitchell, D., Morman, S., Neiman, P., Olsen, A., Perry, S., Plumlee, G., Ralph, M., Reynolds, D., Rose, A., Schaefer, K., Serakos, J., Siembieda, W., Stock, J., Strong, D., Wing, I., Tang, A., Thomas, P., Topping, K., and Wills, C.; Jones, L., Chief Scientist, Cox, D., Project Manager. (2011). *Overview of the ArkStorm scenario: U.S. Geological Survey*. Reston, Virginia.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

Reclamation District 1000 – Natomas Basin (RD) (2010). "Municipal Service Review and Sphere of Influence Update." Prepared by Peter Brundage, Sacramento Local Agency Formation Commission.

Resilient and Sustainable Infrastructure Networks (RESIN) (2008). "Assessing and Managing Failure Vulnerabilities of Complex Infrastructure Systems." National Science Foundation.

Sacramento Area Flood Control Agency (SAFCA) (2010). "Natomas Levee Improvement Program: Construction Phasing Map." <http://www.safca.org/documents/NLIPMasterSchedule/2010SEP8.constructionpermitphasing.pdf> (Aug. 1, 2011).

Sacramento County Operational Area (SACOA) (2005). "After Action Report: Operation Pathfinder," Sacramento, CA.

Sacramento-San Joaquin Delta Flood Response Group (FRG) (2011). "Delta Multi-Agency Coordination System Operations Manual."

Simonovic, S.P. and Ahmad S. (2005) Computer-based model for flood evacuation emergency planning. *Natural Hazards* 34:25-51

Suddeth, R.J., Mount, J., and Lund, J. (2010). "Levee decisions and sustainability for the Sacramento San Joaquin Delta." *San Francisco Estuary and Watershed Science* 8 (2).

United Research Services and Jack Benjamin & Associates (URS/JBA) (2007). "Delta Risk Management Strategy, Phase 1: Technical Memorandum, Topic Area, Seismology." Prepared for The California Department of Water Resources.

United Research Services (URS) (2009). "Delta Risk Management Strategy, Phase 1: Section 4, Risk Analysis Methodology." Prepared for The California Department of Water Resources.

URS (2009b). "Delta Risk Management Strategy, Phase 1: Section 12, Consequences Modeling." Prepared for The California Department of Water Resources.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

URS (2009c). "Delta Risk Management Strategy, Phase 1: Section 13, Risk Analysis, 2005 Base Year Results." Prepared for The California Department of Water Resources.

United States Army Corps of Engineers (USACE) (2011). "USACE Levee Safety Program." <http://www.usace.army.mil/LeveeSafety/Documents/fs_safety.pdf> (August 5, 2011).

USACE and SAFCA (2010). "Affected Environment." *Common Features Natomas/PACR/Phase4b Project.*<http://www.safca.org/documents/NLIP%20main%20page%20stuff/2010JUL2.DEIR.DEIS.Phase4b/4bDEISDEIRPart4.pdf> (June 30, 2011).

United States Census Bureau (USCB) (2010). "Census 2010: Summary File 1: GCT-P5 - Sacramento County, California: Population in Households, Families, and Group Quarters: 2010 - County -- Census Tract." <http://factfinder2.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t#none> (August 3, 2011).

Whitman, R. (1981). "Seventeenth Terzaghi Lecture." Presented at ASCE Convention and Exposition.

Williams, J.C. (1988). "A Data-Based model for Assessing and Reducing Human Error to Improve Operational Experience" *Proc. IEEE, 4th Conference on Human Factors in Power Plants*, Monterey, CA.

Witt and Associates (2008). "Sacramento County Evacuation Plan." *Sacramento Ready*. <http://www.sacramentoready.org/coswcms/groups/public/@wcm/@pub/@sacready/documents/webcontent/sac_018621.pdf> (July 20, 2011).

Wolshon, B., Catarella, M.A., and Lambert, L. (2006). "Louisiana highway evacuation plan for Hurricane Katrina: Proactive management of a regional evacuation." *ASCE Journal of Transportation Engineering*, 132(1), 1–10.

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

Fig. 1. The Natomas Basin System.

Fig. 2. Relationship between water depth and mortality for New Orleans after Hurricane Katrina (Jonkman et al., 2009)

Fig. 3. Loss of life estimates for the flood scenario for ranges of evacuation rates and water levels

Fig. 4. Population of the Natomas Basin by tract and spatial distribution of fatalities in a single levee breach, flood scenario with an 80% evacuation rate and a water level of +11.6m NAVD88. This event is estimated to lead to approximately 880 fatalities.

Fig. 5. Loss of life estimates for the sunny-day and seismic scenarios for ranges of evacuation rates and water levels.

Fig. 6. Loss of life as a function of water level and evacuation percentage for a case with continuous breaches.

Fig. 7. Comparison of flood risks for the Natomas Basin with estimated risk levels of related systems. The risk estimate areas for the Natomas Basin have been depicted as oblique since higher fatality events are associated with less frequent, high water level events.

Fig. 8. Distribution of time required for warning, response and evacuation and evacuation effectiveness (Jonkman, 2007).

Figure 1

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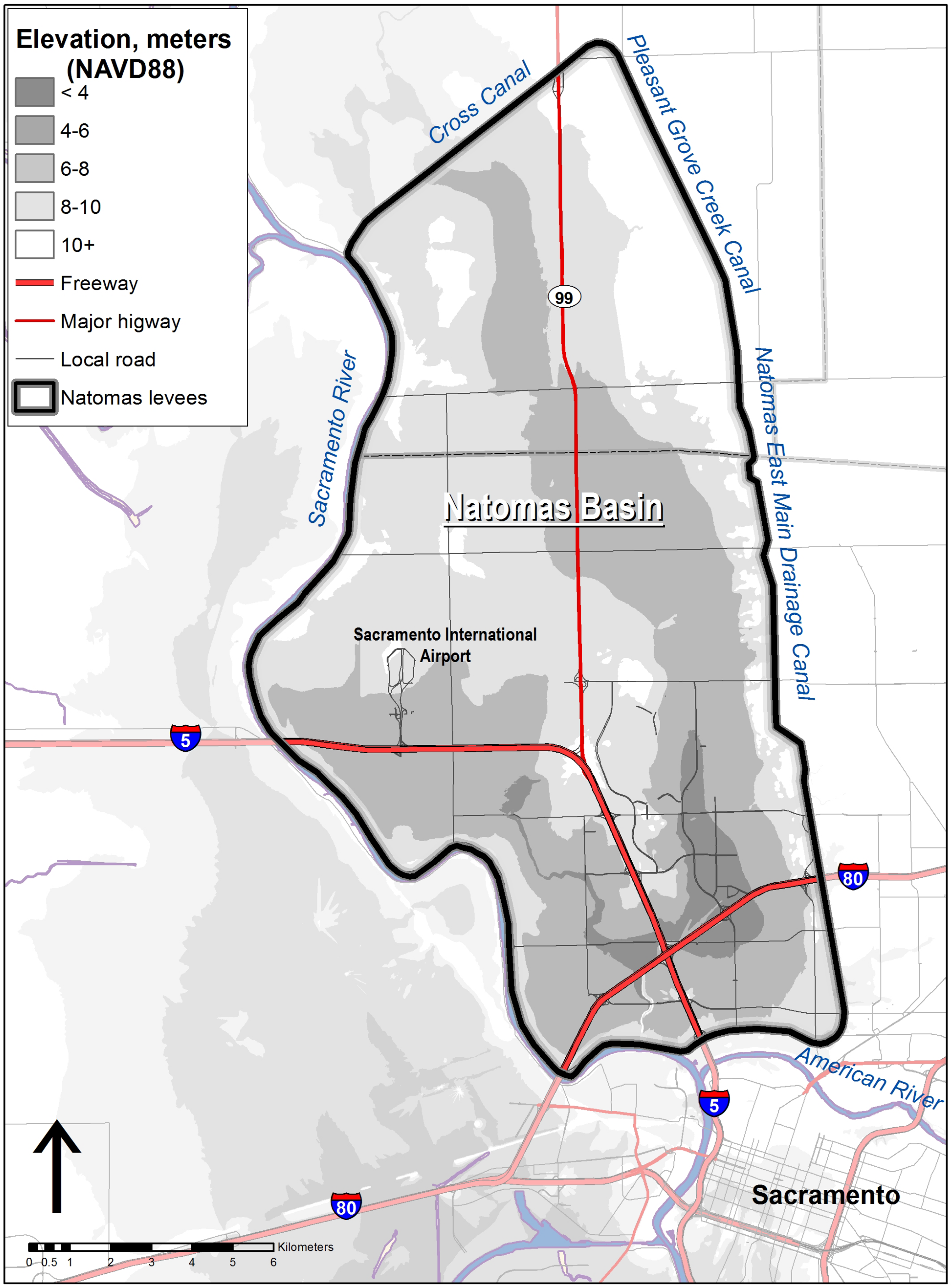

Figure 2

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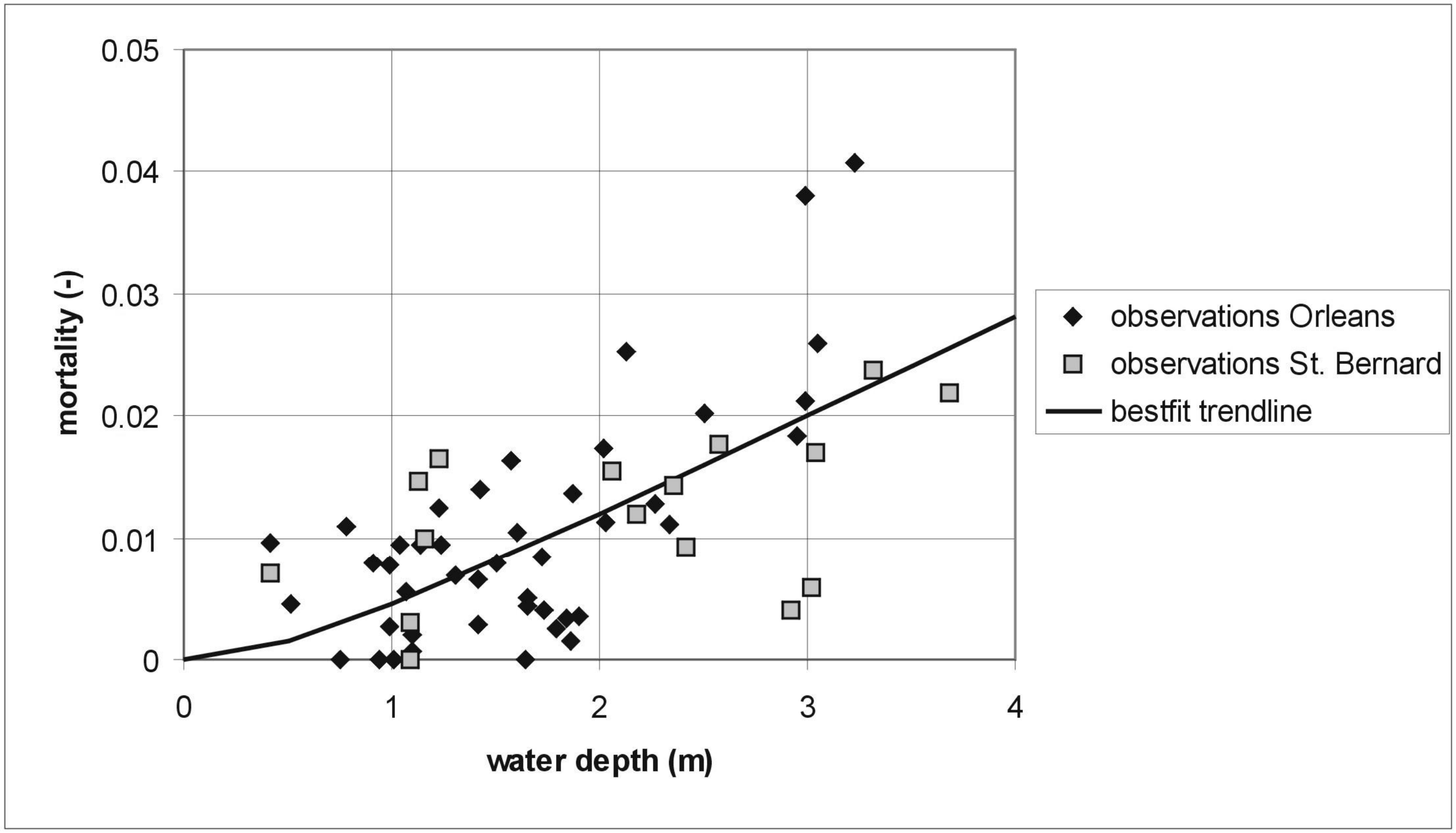

Figure 3

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

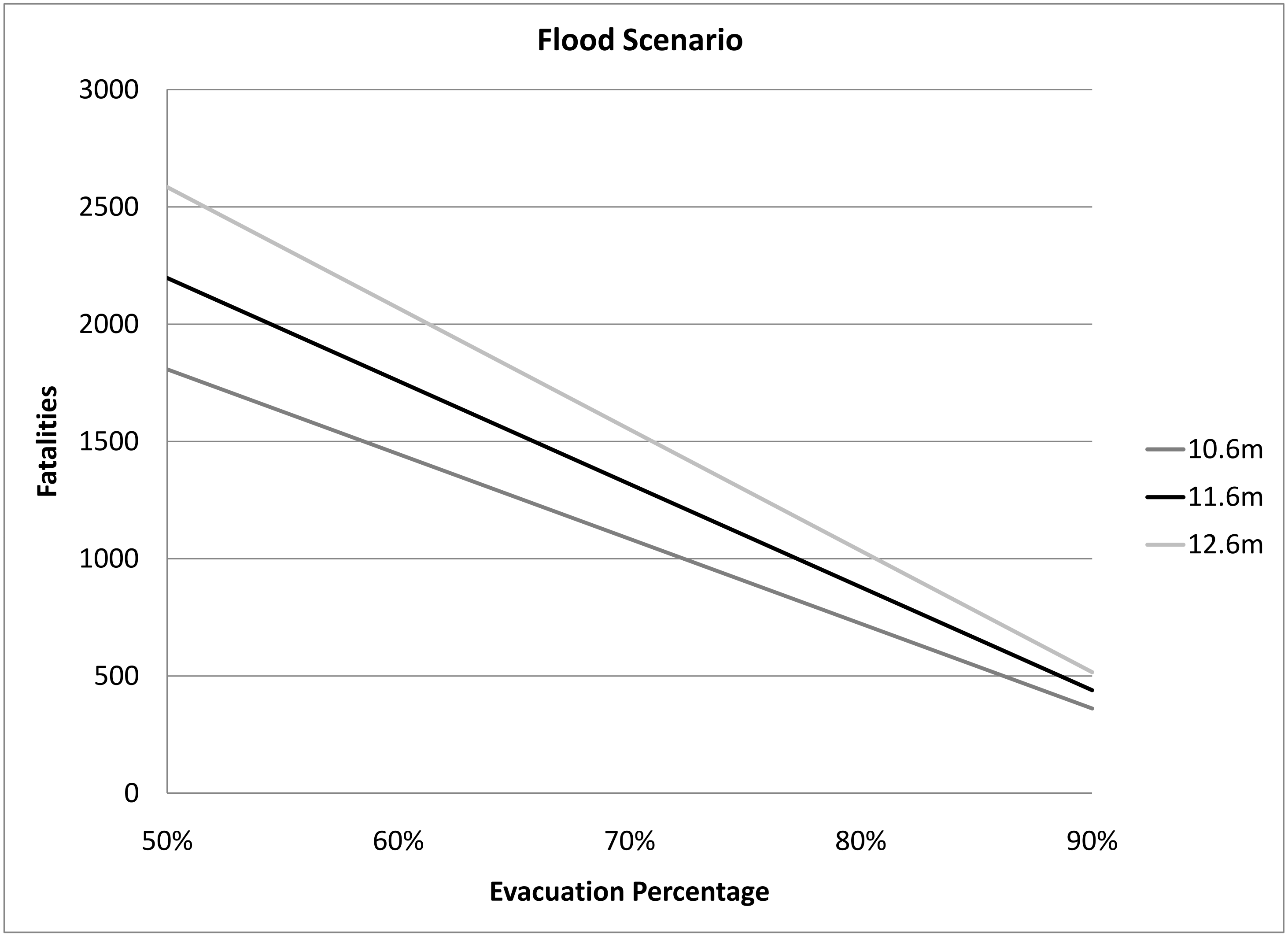

Figure 4

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

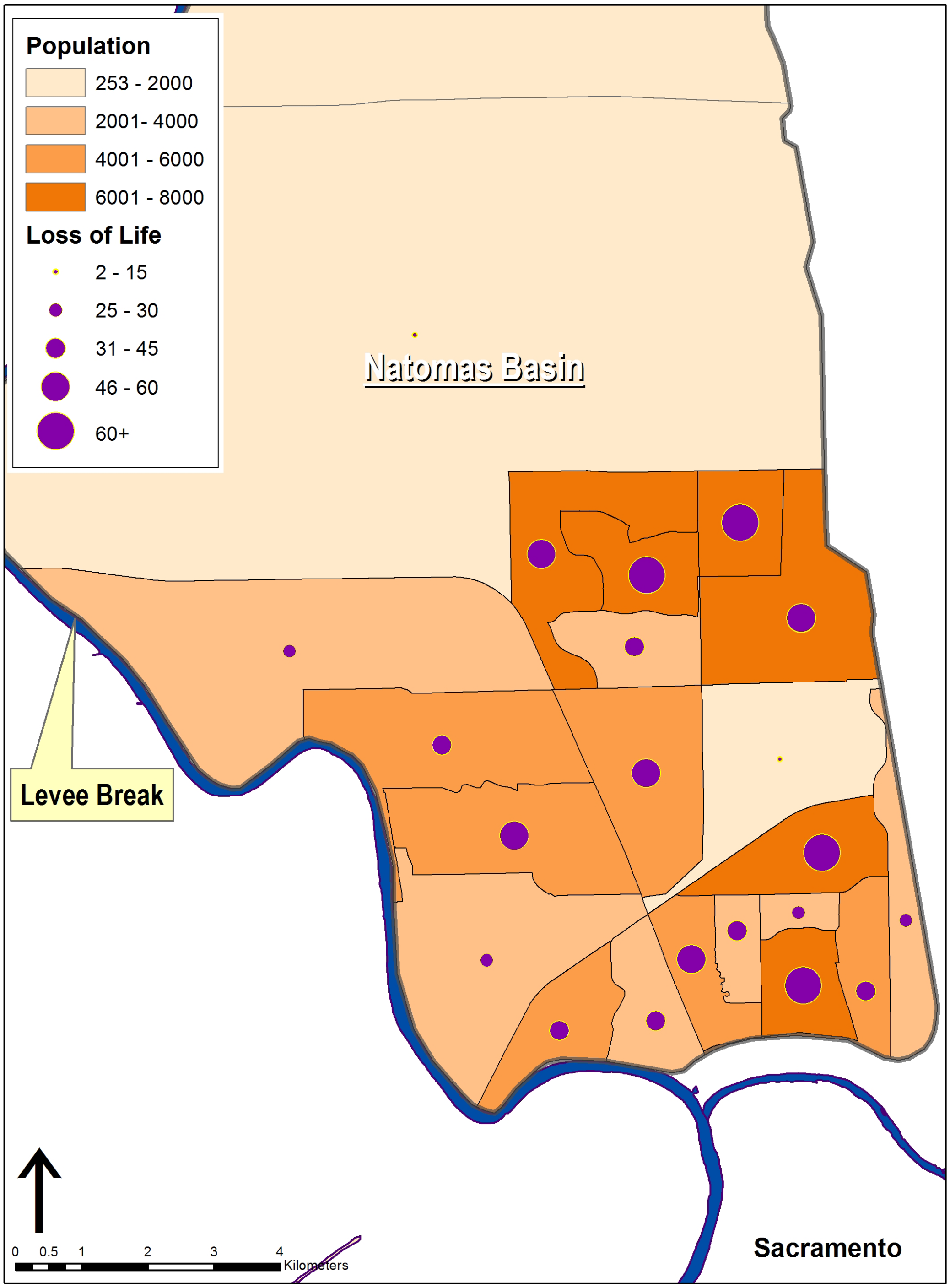

Figure 5

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

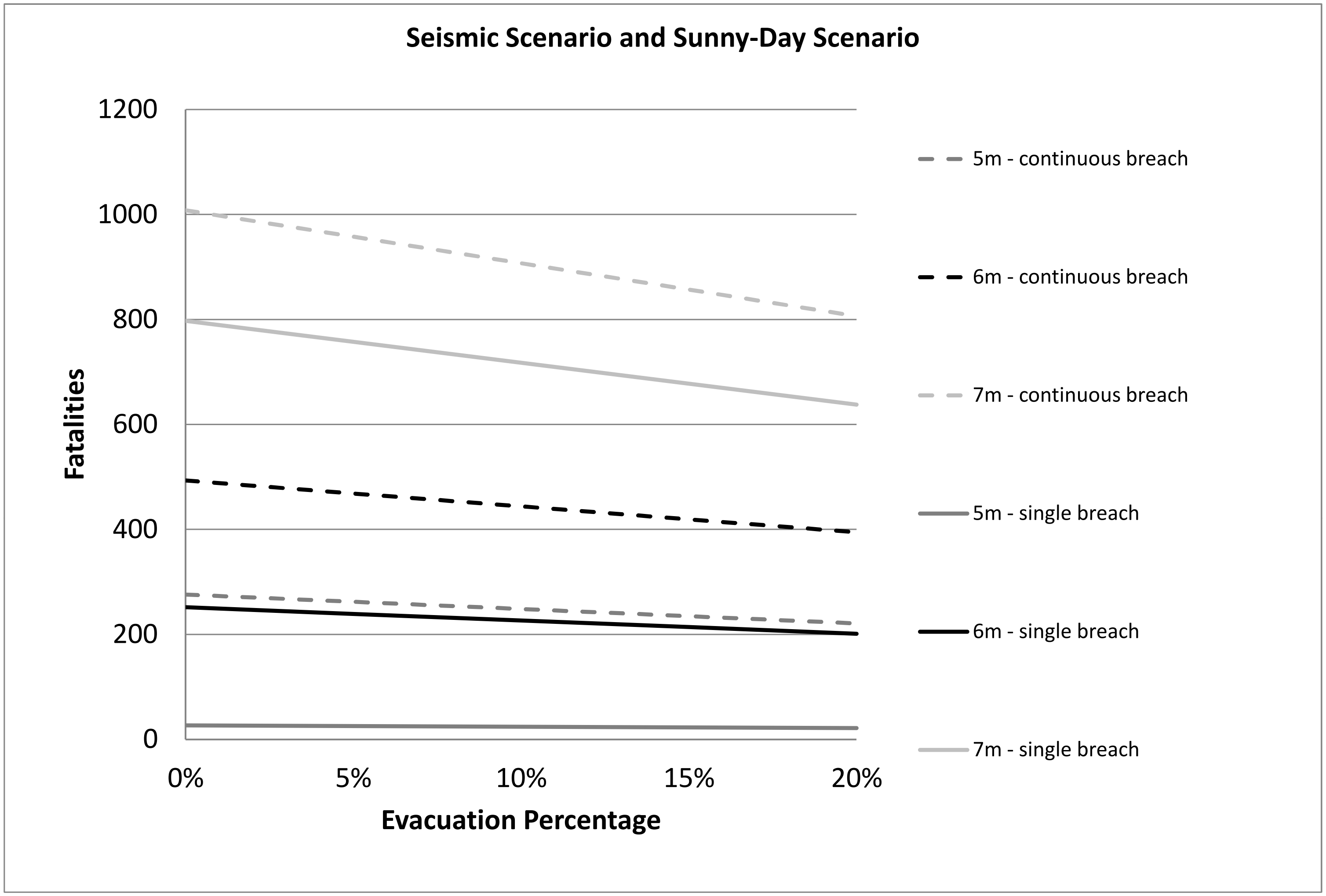

Figure 6

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

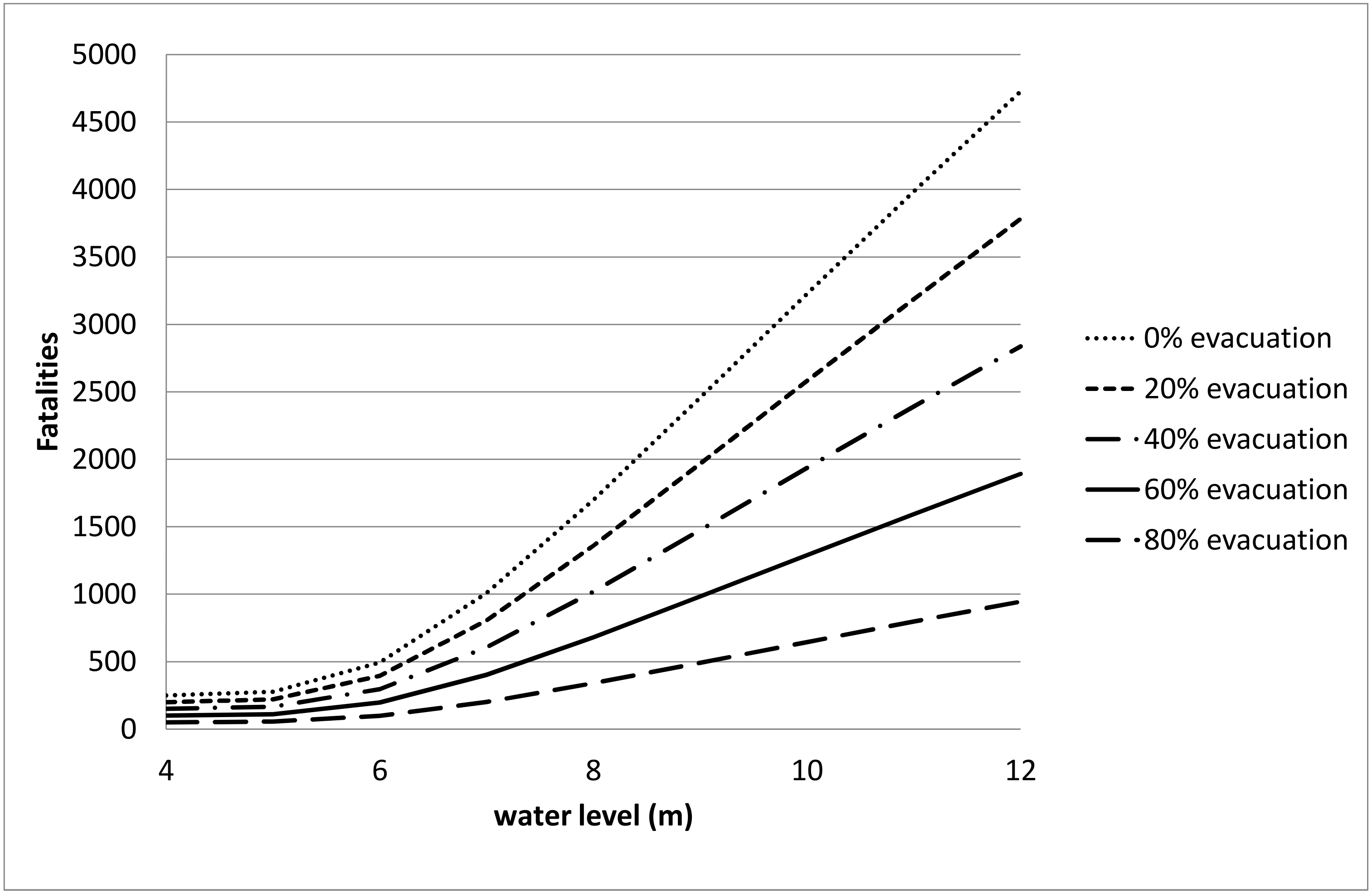

Figure 7

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

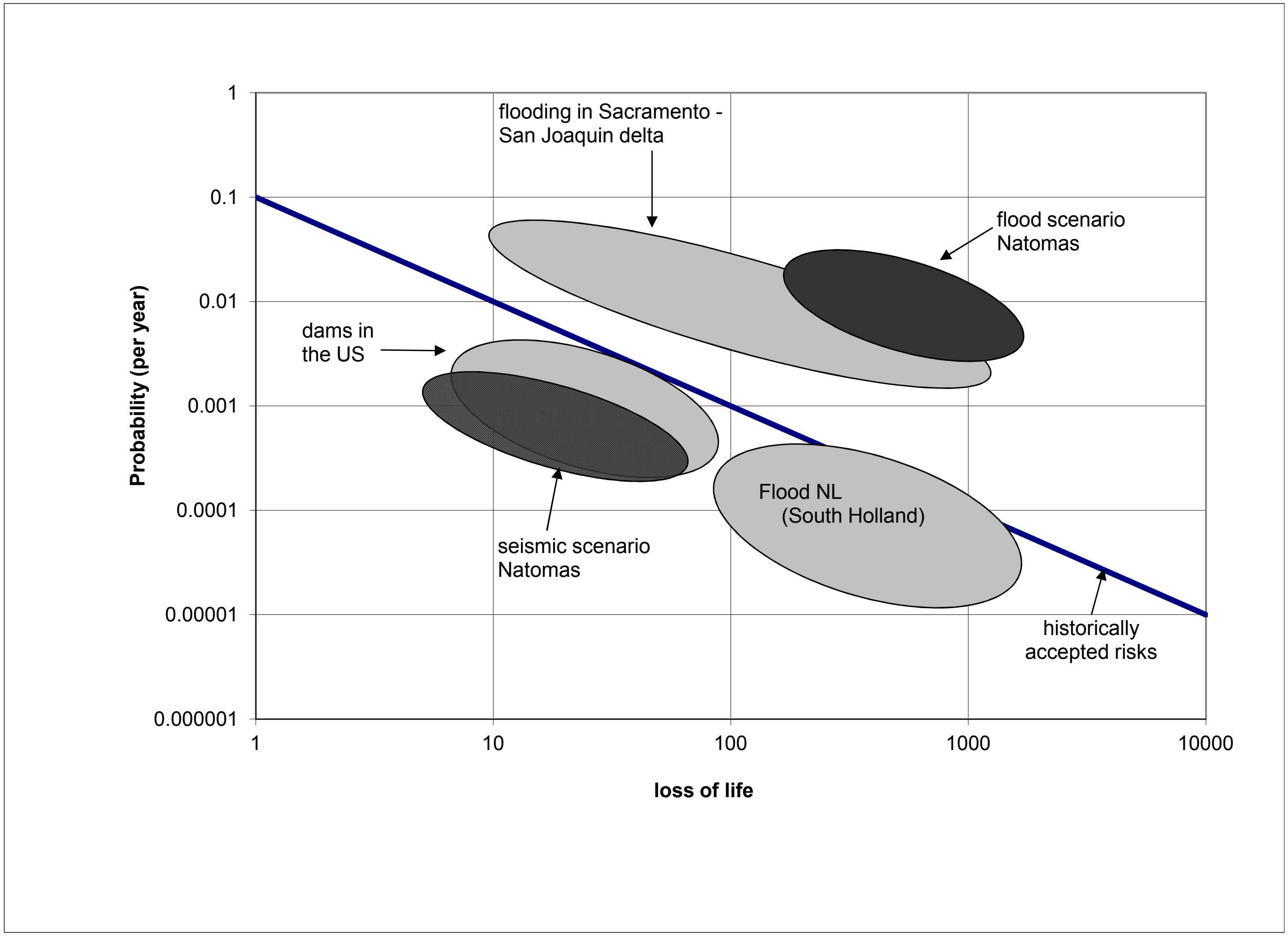

Figure 8

Natural Hazards Review. Submitted November 1, 2011; accepted March 16, 2012;
posted ahead of print March 20, 2012. doi:10.1061/(ASCE)NH.1527-6996.0000079

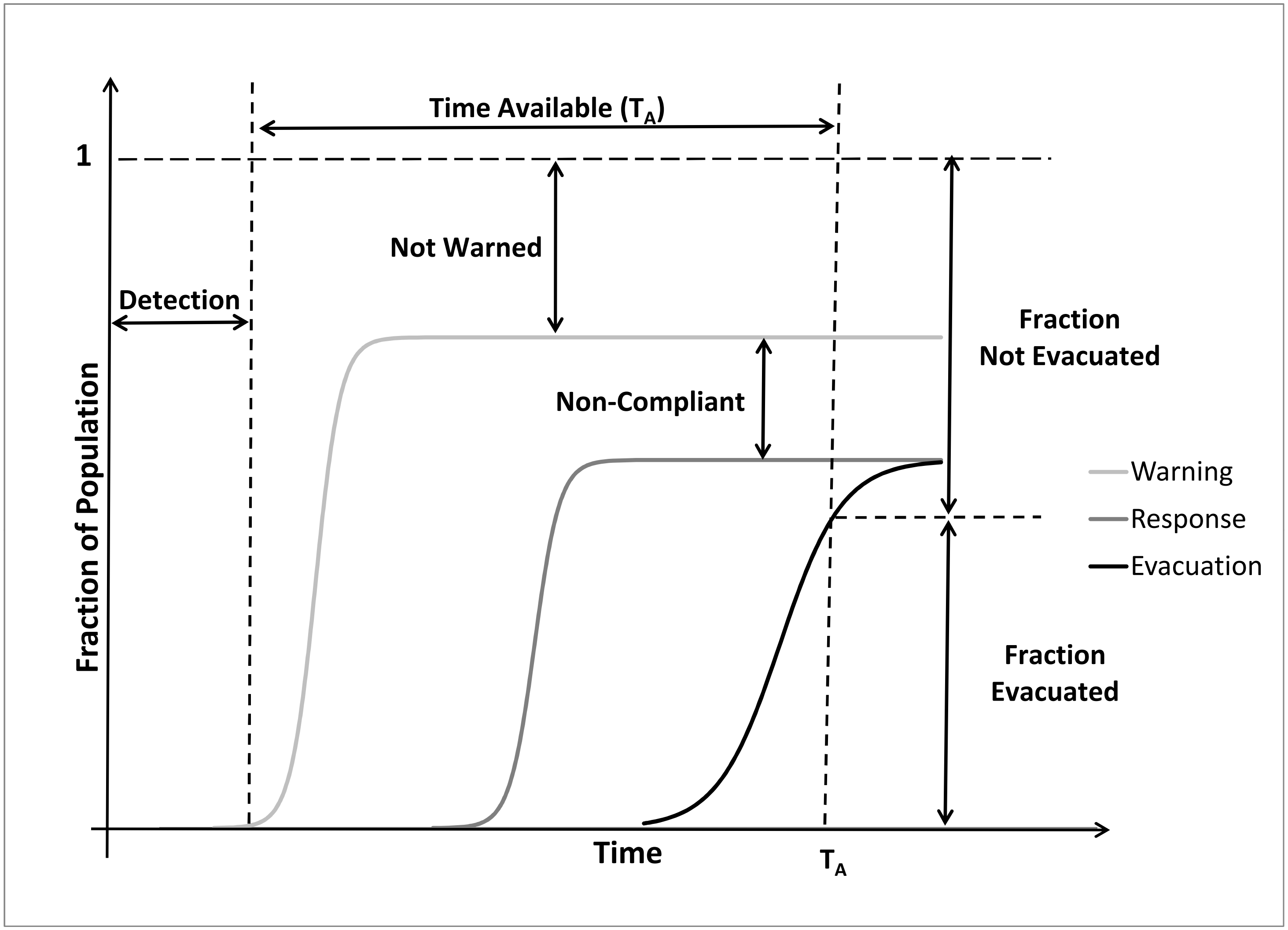

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Table 1. Overview of scenarios that could affect the Natomas Basin including estimated return period, characteristic water level, and evacuation rate

Scenario	Return Period (years)	River Water Level[a] (m)	Evacuation Fraction (%)
Flood	75 - 100	11.6	50-90%
Sunny-Day	-	6.0	10-20%
Seismic	200 - 2000	6.0	10-20%

[a]The water levels in the table and the paper have been defined relative to the established North American Vertical Datum of 1988 (NAVD88)). Based on information from DWR river gauges and other sources (MBK Engineers, 2008) the water levels have been estimated for a location near the Sacramento airport, which is approximately in the middle between the northern and southern system boundaries.

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Table 2. Critical Factors in Evacuation and Emergency Management System Performance of the Natomas Basin.

PHASE	CRITICAL FACTORS
DETECTION AND DECISION MAKING	
	Lack of Situational Awareness and a Common Operating Picture
	Lack of: • regular management briefings to all sections • established, verified information displayed on large, central status boards • training in computer/mapping programs and insufficient capacity of the systems • common terminology to describe flood risk, condition of levees, and geographic location • compliance with standardized EEM forms and protocols
	Ambiguities about Units' Responsibilities and Liaisons
	• Responsibilities and jurisdictions of EOC units and involved parties are not clearly defined
	Evacuation Decision is delayed
	• Decision makers are hesitant to decide to evacuate due to the large costs and consequences • The evacuation process is not initiated early enough
WARNING	
	Limited Communications Tools
	Warning does not reach the public • Reverse 911 only reaches registered numbers • Door-to-Door notification is time consuming • Social media outreach has not been fully harnessed
	Inconsistent Message
	• Different media channels communicate inconsistent or incorrect information to the public
RESPONSE	
	Impaired Continuity Of Operations
	• EOC staff and field response teams are unable to support the EEM operation.
	Lack of Coordination
	• Independent emergency response plans and operations of critical facilities are not coordinated with local and state EEM teams.
	Public is unaware
	• Lack of public awareness resulting in delayed response to emergency/evacuation warnings or non-compliance.
EVACUATION	
	Major Evacuation Routes are Impassable/Inaccessible
	• Traffic congestion occurs along major evacuation routes and life-lines are inaccessible as the flood progresses. Evacuating traffic must be re-routed.
	Non-Compliance and the allocation of Search & Rescue Resources
	• Dilemma for decision-maker to send responders back into increasingly dangerous conditions to rescue refugees of last resort