ASSESSING THE LIFE SAFETY PERFORMANCE OF INTEGRATED EMERGENCY ACTION PLANS

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Introduction

Dam and levee failures can create rapid-onset, catastrophic conditions in which the floodwaters arrive before the population can fully mobilize and evacuate to safe locations, resulting in significant human losses. While extremely rare, the potential for significant consequences creates the need to control and reduce risk [1]. Examples of this type of event include the St. Francis Dam failure of March 1928 in Southern California [2, 3] and the Malpasset Dam failure of December 1959 in France [4]. These events share common factors such as low detectability, rapid breach formation, rapid arrival of highly destructive floodwaters, close proximity of a vulnerable population, minimal or no warning of impending failure, and few available safe havens for those close to the breach.

Developing Emergency Action Plans (EAPs) is a key preparedness activity to minimize the consequences of a pending or imminent dam failure or to manage situations in which downstream communities are inundated during an extreme flood event. EAPs can be tested and verified using drills, table top exercises, functional exercises, and full-scale exercises [5, 6]. As a part of this testing, emergency planners need to assess whether or not the community at risk can evacuate to safe locations in sufficient time to avoid the damaging floodwaters. Exercising selected elements of the dam owner's EAP can only provide limited information regarding potential losses and the effectiveness of the EAPs, and conducting full-scale exercises can be expensive or infeasible to perform.

This issue has also been raised by the Federal Energy Regulatory Commission (FERC) through their Time-Sensitive EAP initiative [7]. In their approach, a sudden failure assessment develops conservative estimates of the time spans for detection, verification and notification, the time for the downstream flood to significantly impact the first non-project downstream structure, and the time required to warn and evacuate the critical residences close to the dam [7]. These time spans are then used to estimate the "excess response time" which compares the time required to detect, notify, warn, mobilize, and evacuate, with the time required for the floodwaters to arrive. A negative response time indicates that there may be insufficient time to protect the downstream population.

Given these considerations, there is a need to assess performance using a framework that considers an *Integrated EAP* which reflects the combined capabilities and actions of both the dam owner and the community, and a need to develop new methods to assess the effectiveness of the combined plans. It is proposed that life safety performance can be estimated and available EAP testing methods can be enhanced by combining estimates or simulations of flood hazards with models of community protective actions. This new approach could help planners to assess and compare alternatives and help to demonstrate the feasibility of protective actions to the community at risk.

Community Protection Systems

The combined set of people, systems, infrastructure and processes used to detect, prepare for, and respond to an extreme flood or dam emergency can be viewed as a Community Protection System (CPS, see Figure 1). A CPS combines the capabilities of many different organizations, such as federal, state, and local governments, the private sector, and non-government groups, who work together to reduce risk. A CPS provides three main services:

Monitoring / notification provides the capability to forecast, detect, diagnose the hazard and its causes, to initiate abatement control actions, and to notify the community. Monitoring and inspections by the dam owner, identification of unsafe conditions by local residents or passersby, or forecasts of extreme weather conditions, can facilitate early mobilization of the abatement and control services.

Hazard abatement / control can engage the hazard directly to stop the event from progressing to full failure or to reduce impacts within the community. These services may be passive, such as dikes or flood setbacks, or active, such as drawing down the reservoir or deploying flood barriers within the community.

Evacuation / sheltering encompasses the protective actions taken by the population at risk. Each person in the hazard zone can either shelter in place, or evacuate to a safe haven along a pathway.

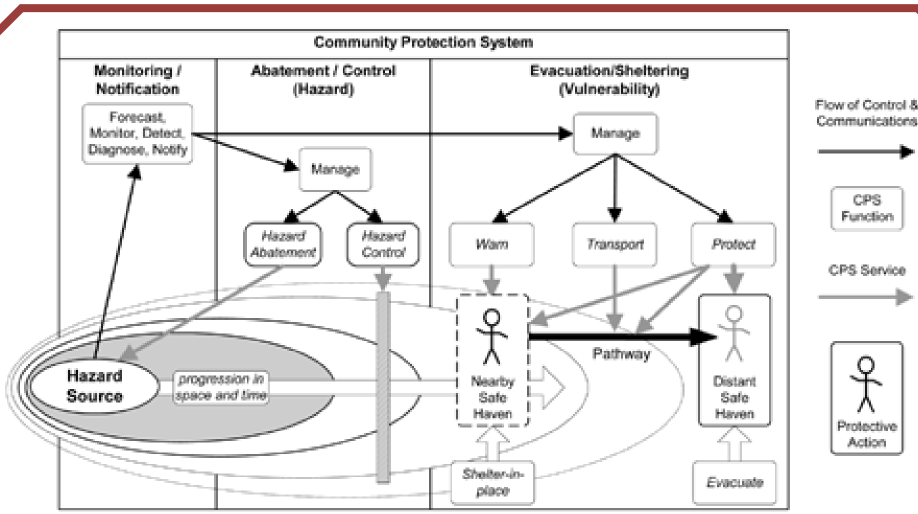

Figure 1. Hazard Sources and Community Protection System (CPS)

Developing and Testing Integrated EAPs

Dam owners who are developing dam-specific EAPs can find guidelines and examples from many sources [5, 6, 8-12]. These plans include notification flowcharts, procedures, responsibilities, preparedness actions, and inundation maps. Supporting details can include descriptions of failure modes and speed of breach formation; hydrodynamic models, inundation maps and time series of flood hydraulics; detailed descriptions of the communication methods and public messaging; and lists of organizations and key contacts. In parallel, communities can develop their own community-specific EAPs based on information provided by the dam owner (see Figure 2). A large body of literature and courses is available for use by community emergency planners [12-14]. Each community will need to work with the dam owner to develop, maintain and test the notification methods, and to develop an understanding of the possible timing of these notifications. We propose that in order to be able to assess life safety performance, these plans should be tested as a single *Integrated EAP*. This can be thought of as a unified command and control of the CPS.

Figure 2. Concept of Integrated Emergency Action Plan

The full scope and timeline of the activities at the dam and within each community needs to be considered. Figure 3 presents an example of the timelines for a typical event, including hazard characteristics, communications between the dam owner and the communities, the community response, and loss and survival outcomes. The upper portion of the figure shows dam owner activities. An initiating event can trigger a process in which the dam owner confirms that an event is in progress, notifies the community Emergency Operation Centers (EOCs) that an event has been detected, and then gathers additional information to make a diagnosis and decision. If events progress towards an imminent breach or the need to route an extreme flood through the facility, then a notification to take protective action is issued to the downstream communities, with each community being responsible for its own evacuation. The lower portion of the figure shows parallel activities within the community. Early actions can include mobilization of the community EOCs in preparation for an evacuation order. The community response curves summarize the proportion of the population that is warned, evacuating, and safe. The floodwaters eventually arrive within the community and the loss and survival outcomes are realized.

While the majority of EAPs assume evacuation as the protective action, there can be cases where sheltering-in-place should also be considered. For example, in impact zones with rapid hazard arrival times, high hazard severities, and strong nearby safe haven assets, sheltering in place may save more lives. To ensure that all options have been considered, planners may want to assess the "evacuate all", "shelter all", and intermediate alternatives. We use

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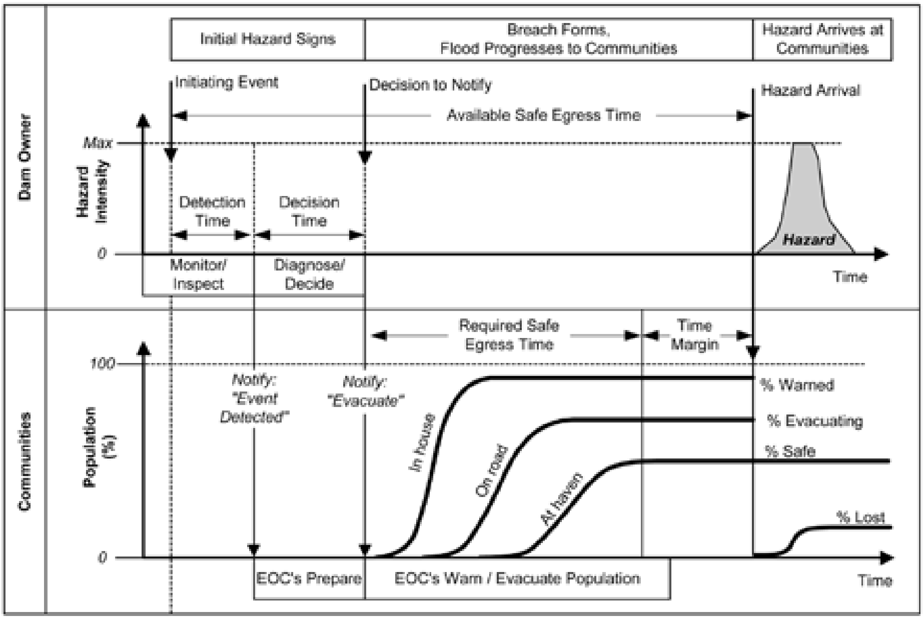

Figure 3. Timelines and Community Response (after Frieser et al [15])

the terms "evacuability" and "shelterability" to describe the first two options. Some communities may be more "evacuable" than others.

Life Safety Performance Measures

We propose an approach which considers the sufficiency of time for the population at risk to move to safe havens, and the sufficiency of protection offered while people move to safety, and while they shelter at each haven until the all clear is issued. The life safety performance can be assessed by estimating whether each person is provided with sufficient time and protection to reach a safe haven, and whether or not the safe haven itself can resist the hazard. Loss or survival can be estimated by considering how each person is directly impacted by being swept downstream by the floodwaters, or indirectly by being caught in a vehicle that is swept downstream or by being trapped in a building. This can be described using the following composite life safety performance function expressed in safety margin terms:

$$G_{LSP}(\underline{x}) = \begin{cases} G_{Time}(\underline{x}) = Haz_{Time}(\underline{x}) - CPS_{Time}(\underline{x}) \\ G_{Protection}(\underline{x}) = CPS_{Protection}(\underline{x}) - Haz_{Intensity}(\underline{x}) \end{cases}$$

where G_{LSP} is a composite limit state function which simultaneously assesses the ability of a CPS to help each person reach the safe haven in sufficient time, and for the haven to offer sufficient protection; G_{Time} assesses time sufficiency; $G_{Protection}$ assesses protection sufficiency; and the vector $\underline{x}$ contains variables that characterize the hazard, the CPS and each person. The demand of the hazard is described by Haz_{Time} and $Haz_{Intensity}$ which describe the elapsed time from event initiation to when the hazard reaches each person, and the impact of the hazard on each person or safe haven, respectively. The capacity of the CPS is defined by CPS_{Time} and $CPS_{Protection}$ which describe the time required for each person to reach a haven as a function of the full chain of events; and the ability of each person to resist the hazard while moving to the haven, and the ability of the haven to offer protection; respectively. The units of G_{Time} can be minutes, hours or days, and the units of $G_{Protection}$ can be a physical measure of intensity that can be related to strength. One example of a physical measure that can be used is the product of flow depth and velocity [16].

Examples of Performance Assessment

Example 1: Analysis of Integrated EAP Performance

Two examples demonstrate how these concepts can be used to assess integrated dam safety EAPs. The first is a hypothetical example of a small community facing a dam failure event. Figure 4 presents a plan and cross-sectional view of the community. Three Emergency Planning Zones have been defined, each of which contains a number of buildings and people, and evacuation routes that lead to a safe haven. Zones B and C have direct access to the havens, while people evacuating from Zone A must pass through Zone B. The cross-sectional view shows the relative elevations of each zone and the haven locations. Three types of protective action can be assessed: everyone evacuates, everyone shelters in place, or combinations in which some evacuate and some shelter in place.

To develop the performance estimates, we employ the life safety performance function given in Equation 1 and define random variables that characterize the hazard, the dam owner's detection and decision times, community's vulnerabilities, and the times required for protective actions within each zone (see Johnstone and Lence [17] for the range and distributions for these variables). In this analysis, we assume that the random variables are uncorrelated. Table 1 presents example formulations of the life safety performance function that may be used to assess evacuation and sheltering for Zone A. The contributions of the hazard, dam owner and community to each calculation are also indicated. Similar functions are developed for Zones B and C.

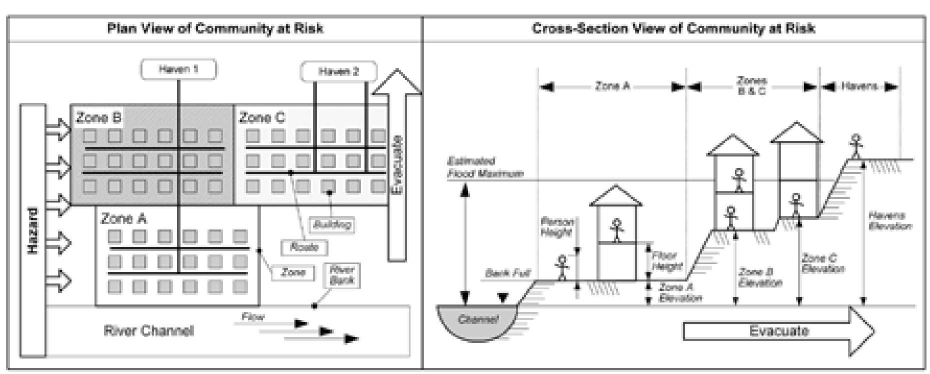

Figure 4. Plan and Cross-Section Views of Community at Risk

Table 1. Examples of Life Safety Performance Calculations for Zone A

G_{LSP} for Zone A - Shelter in Place:		G_{LSP} for Zone A - Evacuate:	
G_{Time} =	**Hazard Arrival Time** -	G_{Time} =	**Hazard Arrival Time** -
	[*Detection Time* +		[*Detection Time* +
	Decision Time] +		*Decision Time*] +
	[Mobilization Time +		[Mobilization Time +
	Sheltering Time]		EvacTimeZoneA +
			EvacTimeZoneB]
$G_{Protection}$ =	[Elevation of Zone A +	$G_{Protection}$ =	Haven Elevation -
	Height of Second Floor] -		**Flood Height at Haven**
	Flood Height at Building		

Contributions to the equations by the Hazard are shown in **bold**, by the Dam Owner in *italic*, and by the Community in underline.

The analysis in Figure 5 uses G_{Time} from the right-hand column above with:

X1 = Detection Time + Decision Time, and

X2 = Mobilization Time + EvacTimeZoneA + EvacTimeZoneB

could affect outcomes. By treating the total time required by the dam owner to detect, diagnose, and decide to notify as variable X1, and the total time required by the community at risk to mobilize and evacuate as variable X2, and by using the estimated minimum and maximum times for the hazard to arrive as constraints (which in this case are 50 and 60 minutes, see [17]), it is possible to estimate G_{Time} and to evaluate the range of values for G_{Time} for which survival is expected to occur. These are shown as the solid and dashed lines in Figure 6, for the minimum and maximum times of hazard arrival, respectively. If the sum of X1 and X2 is less than 50 minutes, there would be sufficient time to evacuate Zone A. If the sum is greater than 60 minutes, then the evacuation may not be successful. The results of a Monte Carlo Simulation for 500 realizations of the life safety performance for one person evacuating from Zone A are also plotted in Figure 5. This example demonstrates the possible trade off between the time required by the dam owner to travel to a facility and ensure that an event may be progressing to a full breach, and the time required to ensure that the community is fully warned and evacuated before the floodwaters arrive. Figure 6 also provides a visualization of how (in this hypothetical case) the community response times may have a stronger influence on the effectiveness of the integrated EAP than the dam owner's detection and decision times.

Figure 5 presents the results of one realization of the random variables for a community of 1500 people (500 in each zone) in which 20% of the population in each evacuation zone shelter in place, and 80% of the population evacuate. Figure 5a shows the estimated life safety performance measures (G_{LSP}, $G_{Protection}$, and G_{Time}) for each member of the population, and Figure 5b and 5c show the estimated marginal distributions of time and protection, respectively, for Zones A, B, and C. In Figure 5a, each dot corresponds to the outcome for one individual, with the survival regions in each plot highlighted in green and the loss regions highlighted in red. As would be expected from inspection of the parameter values, people in Zone C are offered the best protection within their own zone, and the shortest times to the nearby safe haven. By comparison, the people in Zone A face a shortfall both in terms of time because they must pass through Zone B, and in terms of protection because they are at the lowest elevation closest to the river. A more robust set of results may be obtained by performing a Monte Carlo Simulation for the example community, yielding mean values of performance for each individual and expected marginal distributions for time and protection.

Given that the people in Zone A might experience the greatest challenge in having sufficient time to evacuate it would be useful to assess how the combined actions of the dam owner and the community

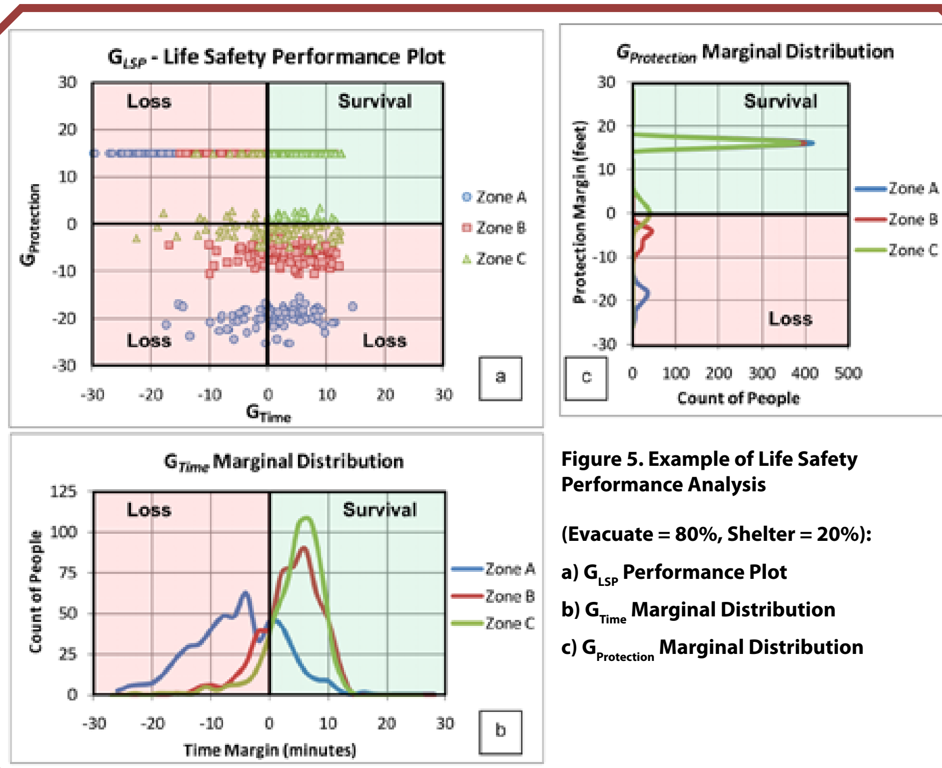

Figure 5. Example of Life Safety Performance Analysis

(Evacuate = 80%, Shelter = 20%):

a) G_{LSP} Performance Plot

b) G_{Time} Marginal Distribution

c) $G_{Protection}$ Marginal Distribution

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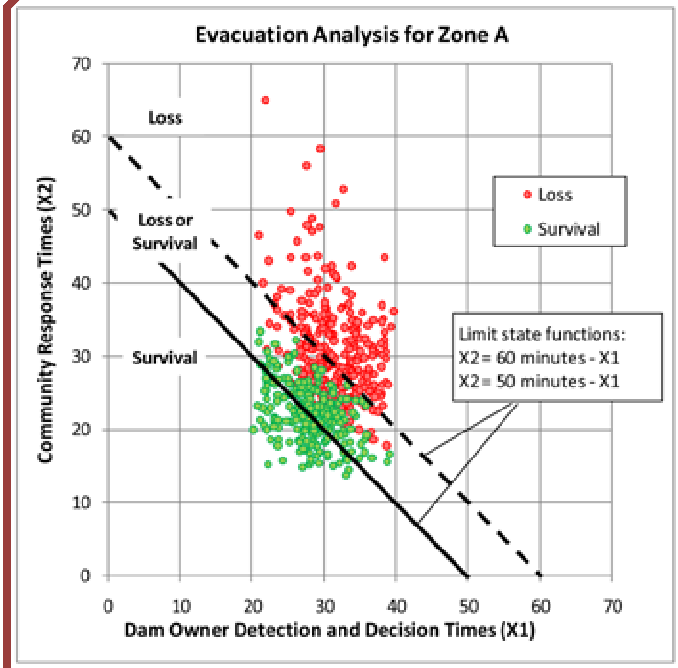

Figure 6. Analysis of Evacuation Performance for Zone A

Example 2: The St. Francis Dam Failure

In the second example, we use the proposed approach to assess what value might have been provided if a monitoring and warning system had been put in place before the St. Francis Dam failure. At three minutes to midnight on March 12, 1928, the St. Francis dam failed catastrophically. The floodwaters moved south and then westward down the Santa Clara Valley towards the Pacific Ocean, 54 miles away. The initial floodwaters were estimated to be more than 125 feet high. By the time the flood arrived at Santa Paula, 42 miles downstream, the waters were 25 feet deep. Many houses, bridges, orchards and sections of railway and roads were destroyed, and the estimated loss of life ranges between 420 and 600 people [2, 18].

Tables 2 and 3 summarize key activities before and during the event [3]. The failure was detected quickly, but some delays were encountered in confirming the event and in warning the communities. For those living within the first 18 miles of the dam, warning and evacuation were not possible. A rough breakpoint between "no warning" and "warning" can be placed at the Edison camp, where 84 of 150 sleeping workers were killed [3]. Many factors increased vulnerability and losses. From the dam to the Edison camp, the CPS offered no warning and little physical protection. Contributing to the time shortfall were the delayed diagnosis and notification. A missed opportunity to raise the alarm via telephone at the Edison camp may have contributed to a high loss of life at that location. Problems with risk perception were also observed. In one town, news of the oncoming flood drew more than one hundred people to a local bridge in the hopes of seeing the flood pass by. They were moved off the bridge by the police before the wave arrived and destroyed the structure. [3]

Many factors also reduced losses. Communities downstream of the Edison camp were sufficiently distant to allow time for the event to be diagnosed and for notifications to reach key public safety personnel. They, in turn acted immediately to warn people up and down the valley. The power, telephone, and public safety organizations all had

Table 2. Timing of Key Hazard Events for the St. Francis Dam Failure [3]

Event	Date/Time	Comment
Catastrophic Dam Failure	March 12, 1928 11:57:30 pm	Indication of dam failure at Southern California Edison Company's Saugus substation: transmission line shorts out.
First Detection of Failure	12:00:00 am	Phone call attempted from Powerhouse No. 1 to No. 2. Phone lines dead.
Additional Indications of Failure	12:02:30 am	Total blackout for Ventura County. LA. Powerhouse No. 1 calls Los Angeles dispatcher to state problems building power on 110kv transmission lines.
Second Detection / First Limited Warning Issued	12:40:00 am	SoCal Edison superintendent of transmission finishes rapid drive from LA to Saugus in time to see flood wave and damage. He attempts to warn the Edison camp.
Broader Warning Issued	1:15 am	SoCal Edison dispatcher requests that a Pacific long distance operator call and warn Santa Paula police chief and other peace officers in the Santa Clara Valley.
Warning Dissemination	1:30 am+?	Notification spreading. Telephone exchange operators in downstream towns pass on warnings to peace officers, highway patrolmen, and customers in flood zone. Town fire halls now spreading warning.
Direct Warnings by Police	1:30 am	Heroic effort to warn citizens in the Santa Paula area by patrolman on motor-cycle. Joined at 2:00 am by second officer. County sheriffs drive north to warn other communities.
Use of Sirens	2:15 am	Fire department joins warning effort. Use of auxiliary fire alarm in Santa Clara.

Table 3. Location and Timing of Key Vulnerabilities, Warnings, Evacuations and Losses [3]

Key Vulnerabilities	Distance (miles)	Arrival Time	Warning and Evacuation
1. Dam Tender's House	0.25	12:01 am	Warning not possible without detection and diagnosis before failure. Water depth 100' to 140'.
2. Powerhouse No. 2	1.5	12:03 am	Warning not possible without detection and diagnosis before failure. 3 survivors of at least 30 people at risk. One rides a rooftop to safety.
3. Ranches, Saugus	6.5	12:35 am (33 min)	Families and ranch-hands become self-aware. Some survive.
4. Castaic Junction	12.0	12:50 am (52 min)	Families and ranch-hands become self-aware. Some survive.
5. Edison camp at Kemp	17.4	1:20 am (82 min)	84 of 150 workers in SoCal Edison tent city area killed. A SoCal superintendent attempted to warn them, but phone service was cut.
6. Filmore & Bardsdale	30.1	2:20 am	Warning started before wave arrived.
7. Santa Paula	42.0	3:05 am	Warning started before wave arrived. Some people stand on bridge and wait for flood.
8. Saticoy	49.0	4:05 am	Warning started before wave arrived.
9. Pacific Ocean	53.8	5:25 am	Warning started before wave arrived. Trains and buses held back from crossing bridges.

night staff either working or on call, and the towns were connected via a redundant network of telephone lines. Once news of the failure had reached the communities, staff disseminated the warnings quickly. The network of paved roads and bridges allowed the police to move rapidly through the communities and neighbors helped to spread the word. There were numerous examples of individual initiatives taken to save lives.

The performance of the *ad hoc* CPS for the St. Francis Dam event is notable because there was no dam safety or integrated EAP in place, the community was generally not aware of the potential extent of the hazard impact zone or the severities, the community had to respond to warnings in the middle of the night, people did not know which locations offered sufficient protection, and parts of the valley experienced a power outage. The courage, creativity and speed of response of the telephone operators and police officers was remarkable [3].

Figure 7 presents a conceptual analysis of the life safety performance provided by this *ad-hoc* CPS. The sites directly below the dam had significant shortfalls in both available protection and time. People located at sites further downstream were close to safe havens, but did not receive the warning in time. Sufficient time and protection was available for the locations downstream of the Edison camp at Kemp. Based on this assessment, we can ask how loss of life might have been mitigated had a detection and warning system been in place. A more effective warning system would shift the performance curve to the right; therefore, the hypothetical value of such a system is shown via the second sequence of points. Losses at sites such as the ranches and the Edison camp might have been greatly reduced or eliminated; however, given the rapid failure mode of the dam, there would probably have been insufficient time to detect the hazard, and then warn, mobilize and evacuate the people who were immediately downstream of the St. Francis Dam.

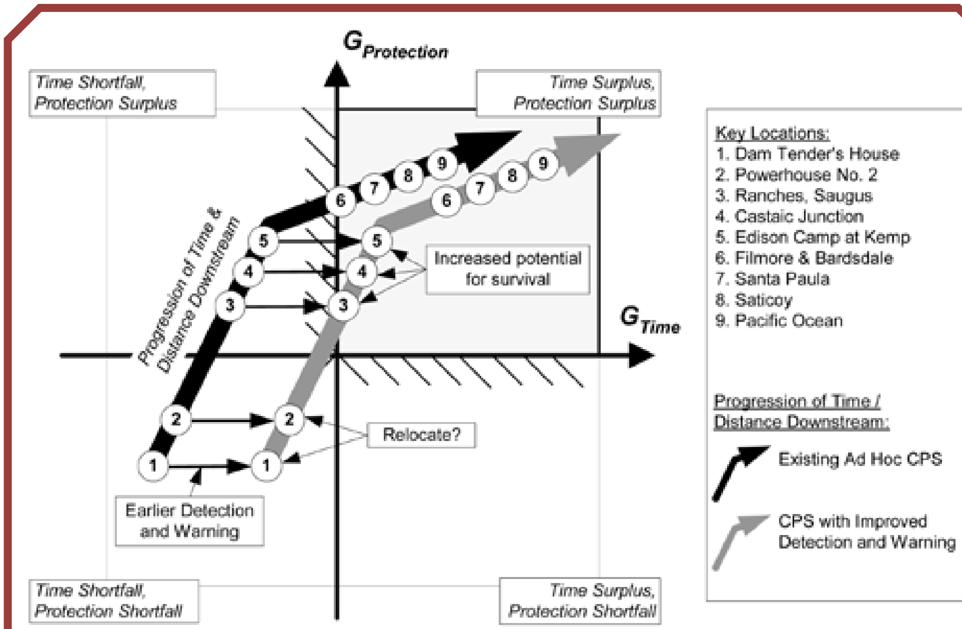

Figure 7. Qualitative Assessment of the St. Francis CPS circa 1928, Value of Improved Detection and Warning

Discussion and Future Work

The approach presented here unifies the response capabilities and resources of the dam owner and communities into a single framework; provides an integrated view of all relevant systems; can consider timeline, geographic, organizational and communications aspects; allows for a probabilistic approach to incorporate uncertainties into the estimation process; can support risk- and reliability-based analysis; facilitates balanced decision-making and trade-offs; and can be used to draw insights as to which factors contribute to shortfalls or increases in safety. This approach can also enhance tabletop, functional, and full-scale exercises when combined with interactive environments that can simulate flood hazards and community protective actions [16]. Dam safety analysts and community emergency planners could work through scenarios, supported by visualizations that provide interactive feedback and different outcomes based on initial conditions and operational decisions during each exercise. This could increase the sense of realism in the exercise and help planners determine which protective actions work best. Important challenges include the continued development of extreme flood, dam breach, flood wave hydraulics and structural damage models, and the need to incorporate models of sociological responses to flood hazards. FERC's Time Sensitive EAP Initiative is also raising awareness of this important issue within the dam safety community [7]. We are currently working to expand and complete the theoretical formulation of the life safety performance measures and CPS concepts, and to demonstrate their use by developing a number of hypothetical and real-world examples.

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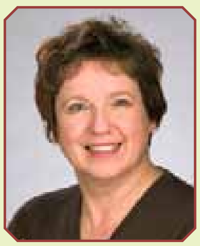

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