

# Quantifying the Benefit of a Flood Warning System

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**Abstract:** A flood warning system yields direct and indirect, tangible and intangible benefits. To achieve this, the system includes hardware, software, plans and procedures, and personnel that work in an integrated manner to increase the mitigation time available prior to the onset of flooding. This mitigation time increase is a consequence of a reduction in the time required to collect data, to evaluate and identify the flood threat, to notify emergency personnel and the public, and to make decisions about the appropriate response. The direct tangible benefit—the inundation damage reduction—can be computed with standard expected damage computation procedures, using modified depth-damage functions that include mitigation time as an independent variable and accounting for improvements to the efficiency of response due to the implementation of the flood warning system. This proposed method is applicable for benefit evaluation for any flood warning system; it is illustrated here with an example from the Sacramento River basin of central California.

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## Time Slips Away

Willie Nelson sang about ... how time slips away. When a flood occurs, time slipping away leads to property damage, injury, or loss of life. The timeline in Fig. 1 illustrates how this happens. The triangles in this figure represent milestones in the occurrence of a flood. The first milestone is the beginning of the precipitation that causes the flood, and the last is exceedence of a water level threshold at which property is damaged, injuries occur, or lives are lost. Actions taken by the public or public servants between these milestones may mitigate the damage, injury, or loss of life.

The time between initiation of precipitation and threshold exceedence is the *maximum potential warning time* (USACE 1996a). Theoretically, this is the maximum time that is available for action. Of course, the maximum time varies from storm to storm and location to location within a watershed. For example, if the point of interest—say, the location of damageable property in a watershed—is near the watershed outlet and if a short duration thunderstorm is centered near the outlet, the maximum potential warning time will be small. In that case, little can be done to protect lives and property. On the other hand, if the storm is centered at the far extent of the watershed or if a forecast of the precipitation is available before it actually occurs (a quantitative precipitation forecast), the maximum potential warning time for this same location will be greater, and more effective actions can be taken. Likewise, the watershed state plays a role in determin-

ing the maximum potential warning time. If the watershed soils are saturated, the time between precipitation and runoff is less than if the watershed soils are dry.

Even if the storm is centered far from the outlet and the soils are dry, the time available for mitigation may be small because we are not able or willing to respond to a flood threat from the very onset or prediction of precipitation. For example, we would not close roads, move property, and evacuate simply because a tipping-bucket rain gauge tips in the upper reaches of a watershed. Thus, the actual warning time—the time that we truly have available to take action to protect people and property—is less than the maximum potential warning time. The time between initiation of precipitation and exceedence of the threshold is spent completing other tasks.

Some time is required to detect the event. We collect and transmit hydrometeorological data from sensors in the field to a central site to be examined. The time required for this is labeled Data collection in Fig. 1. At the central site, knowledge is applied to the data to create information necessary to recognize a potential or actual flood threat. For example, an analyst may examine observed rainfall depths to determine if the rate of rainfall is dangerously great, or an automated decision support system may compare measured water level with bank elevation to determine if the level is near the threshold for overflow. The time required for this is labeled Evaluation in Fig. 1.

If a threat is recognized, time is required to provide relevant information to emergency responders. This time is labeled Notification in Fig. 1. Once notified, the responders consult plans and policy and procedure manuals to make a decision about their response. They may, in turn, notify the public, who also will take time to decide how to respond to the threat. The time required for this is labeled Decision making in Fig. 1.

Finally, response begins. The time following notification and decision making, before the water-level threshold is exceeded, is the Action (mitigation) time shown in Fig. 1. Actions can be taken during this time that will protect people and property from the rising water.

For example, suppose that the maximum potential warning time for a storm over a watershed was 6 h. If floodplain occupants began emergency response immediately upon initiation of rainfall

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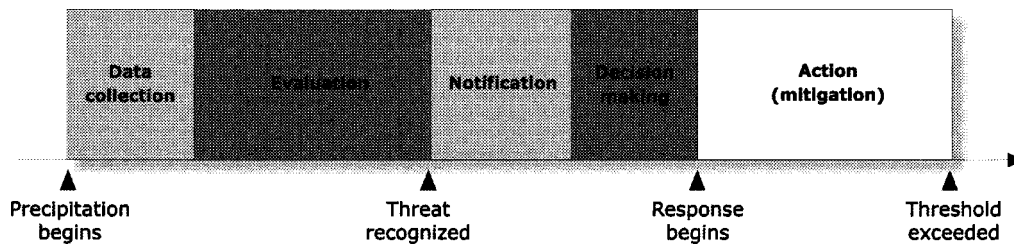


Fig. 1. Flood timeline

in that watershed, the mitigation time available to them would be 6 h. But this kind of response is unlikely, because the other activities described consume the time available. If 4 h is spent collecting and evaluating data, making decisions, notifying responders, and so on, the time actually available for mitigation would be 2 h. During that time, the floodplain occupants might

- Move to higher ground, out of the floodplain, and hence, out of harm's way.
- Elevate property to a higher floor or move property outside of the floodplain. Examples of property that can be relocated are included in Table 1. With 1/2 h of warning, high value, relatively small items can be moved. As the warning time is increased, more items can be removed from or elevated in the structure.
- Build temporary walls with sandbags to keep water out of a structure and thus away from property.

On the other hand, if the floodplain occupants spend excessive time interpreting data or trying to make decisions about what to do and when to do it, they could squander the entire potential warning time. In that case, there is no mitigation time, and an appropriate response prior to flooding is not possible.

### Flood Warning Gives Us Just a Little More Time

While Willie Nelson was singing about time slipping away, the vocal group Chairmen of the Board was appealing for someone to ... give me just a little more time. A flood warning system (FWS) that is properly planned, constructed, and operated does exactly that: It gives property owners and floodplain occupants and those responsible for their safety more time to respond to a flood threat before the threshold is exceeded. With this increased mitigation time, lives and property are protected.

To yield the desired mitigation time increase, a FWS must include components illustrated in Fig. 2. Preparedness planning is

key to the success of a FWS; the components at the 10 o'clock position in Fig. 2 represent the activities and products associated with preparedness. A vulnerability assessment identifies people, property, and environmental resources at risk. Thus, we will know, for example, that the Froggy Hollow Day Care Center is vulnerable to flooding and the occupants of this property have special needs. A threat recognition plan coordinates the vulnerability information with hydrologic, hydraulic, and meteorological indices. With that plan, we will know, for example, that the Froggy Hollow Center will be inundated initially when the water level in the adjacent creek reaches an elevation of 5.5 m. Evacuation, mass care, temporary protection, and vital services maintenance plans identify specific actions to take and resources to use when a threat is recognized and a warning is issued. Public education ensures that people at risk and those who assist them will know in advance what is included in those plans and what to do during a flood emergency. A postflood recovery plan provides for orderly restoration after the threat passes.

Data collection uses components shown at the 2 o'clock position in Fig. 2. Watershed, channel, and weather conditions necessary for flood threat recognition are measured with a surface observation system or sensed remotely. For example, water level may be measured with a shaft encoder mounted on a bridge or atmospheric moisture sensed with weather radar. These data are transmitted to a central site, where they are managed and used as input to the threat evaluation. The transmission may use radio, satellite, the Internet, or other telecommunication technology.

The components shown at the 4 o'clock position in Fig. 2 are those that apply knowledge to the data to derive information for threat recognition and those that notify people at risk if a threat is recognized. Decision support tools are used to visualize rainfall patterns, forecast future water levels, map floodplains, and so on. The threat evaluation and recognition component uses the results of the vulnerability assessment to identify thresholds soon to be or already exceeded. The information dissemination and notifica-

Table 1. Residential Contents Protected with Warning (Adapted from Chatterton and Farrell 1977)

1/2-h warning	2-h warning	4-h warning	>4-h warning
Color television (console)	Carpet sweeper	Largest appliances, such as dryer and refrigerator	Appliances such as dishwasher, oven, freezer, and washer
Color television (portable)	Larger appliances, such as microwaves, blenders, toaster ovens	Bookcases	Kitchen utensils
Stereo equipment	Items in cupboards	Dining table and chairs and other furniture	Central heating system
Smallest electric appliances	Expensive clothing	Food	Piano
Vacuum cleaner	Curtains and drapery	Some carpet	Dressers
Personal effects	Vehicles	Additional clothing and personal effects	Beds
	Additional personal effects		Linoleum/tiles

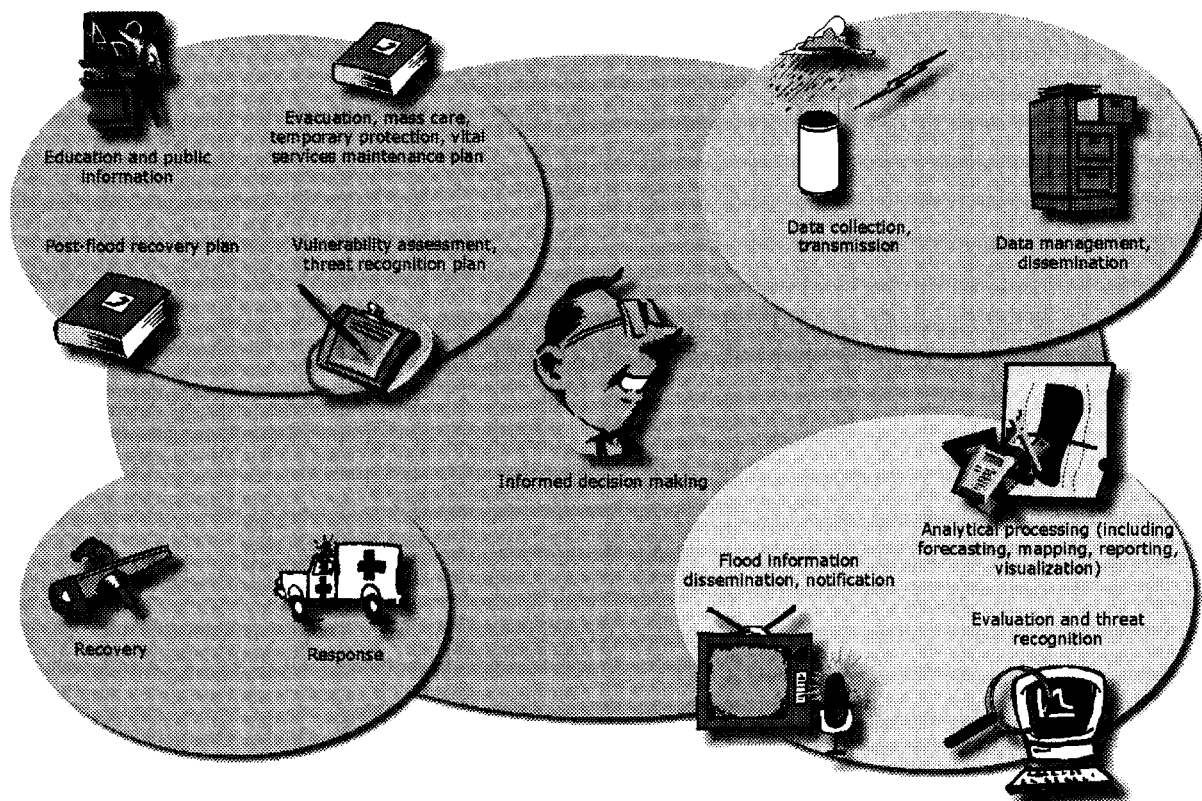


Fig. 2. Flood warning system components

tion components then provide that information to the public and emergency responders so that they can act.

When warnings are issued, response begins in earnest. People and property are protected, following procedures in the plans developed beforehand. Finally, after the flood, recovery takes place, following the plans developed prior to the flood, i.e., cleaning up the floodplain, restoring public services, and resuming safe use of property.

If properly planned, designed, constructed, and operated, the components shown and described here will have an impact on the timeline shown in Fig. 1. An automated data collection system, for example, will reduce the time required to gather observations of precipitation in the watershed and get those data to a central site, where they can be evaluated. Automated analytical processing systems will speed up the forecasting of future water levels and compare those with previously identified thresholds. Modern telecommunications systems, such as alphanumeric pagers, will disseminate information quickly regarding the flood threat, thus reducing the time required for notification. Well-designed preparedness plans will speed decision making and eliminate ad hoc response. The net impact of all this is that response will begin sooner, shifting the milestone in Fig. 1 and increasing the time available for action.

### More Time Yields Benefits

Actions taken because of increased mitigation time yield benefits in four categories (USACE 1994):

1. *Direct tangible benefit.* Tangible benefits are those to which monetary value can be assigned, and direct benefits are those that accrue to people and property who are “protected” by the system. Table 2 shows actions that will yield such ben-

efit, either by reducing the inundation related damage or by reducing the economic cost of a flood emergency.

2. *Direct intangible benefit.* Intangible benefits are those accrued within the floodplain that cannot be readily measured in monetary terms. Table 3 shows examples of such benefits that may be accrued as a consequence of increased mitigation time.
3. *Indirect tangible benefit.* These are economic benefits to those who are outside the area protected by the response system. They include benefits shown and described in Table 4.
4. *Indirect intangible benefit.* These are noneconomic benefits that accrue to those outside the floodplain as a consequence of reduced stress. For example, the mental health of families and friends can suffer if word of a flood arrives and they cannot establish contact with floodplain occupants. The orderly disruption of communication networks possible with flood warnings can reduce such problems and thus provide a benefit.

### Inundation-Reduction Benefit can be Computed with Standard Methods

As noted previously, a portion of the direct tangible benefit of a flood damage reduction project is due to inundation reduction, lessening damage due to flooding of structures and other property. Mathematically, we compute this inundation-reduction benefit  $B_{IR}$  as

$$B_{IR} = X_{\text{without}} - X_{\text{with}} \quad (1)$$

in which  $X_{\text{without}}$  = without-project economic flood-inundation damage; and  $X_{\text{with}}$  = economic damage if the project is imple-

**Table 2.** Actions after Warning That Yield Direct Tangible Benefit (Adapted from USACE 1994)

Action	Description
Temporary removal of property from floodplain	Floodplain property owners can move belongings such as televisions, stereos, computers, important documents, and personal memorabilia.
Moving property to a safe elevation within the floodplain	Residents and businesses occupying multi-story buildings may have the opportunity to protect moveable property by relocating it from basements and ground floors to higher levels.
Temporary flood proofing	Warnings issued with sufficient mitigation time allow property owners to temporarily flood proof property with, for example, temporary closures of windows and doors. These activities that can reduce flood damages by preventing inundation.
Opportune maintenance	A warning system can provide officials and individuals with more time to undertake opportune maintenance, such as closing a shut-off valve on a gas line, halting discharge of certain materials into the sewage system, or safeguarding water supplies and sewage treatment plants.
Early notification of emergency services	Increased warning time can reduce the cost of emergency shelter and emergency care as individuals have more time to arrange to stay with relatives, friends, or elsewhere. The cost of public assistance and long-term emergency shelter for evacuees can be reduced if these evacuees have time to secure their property and prepare before evacuation. Communities with limited emergency personnel and other resources will benefit from additional time to ready emergency services.
Orderly disruption of network systems	Warning and response systems offer opportunities for network systems (phone systems, utilities, pipelines, cable TV services, transportation patterns and traffic levels, and local area networks) to prepare for disruption in a more orderly and cost-effective manner. With sufficient warning time, businesses may make alternative plans for their network services.
Suspension of sensitive works	For products that require lengthy production processes, sufficient warning time may provide the opportunity to suspend the production processes to minimize the destruction of the product or minimize the possibility of hazardous materials seeping into the waterways. Similarly, sufficient warning may allow crews to sequence repair work in a way that minimizes disruption to a utility.
Related effects of emergency cost, cleanup cost, and business losses	Warning systems may reduce emergency costs and cleanup costs by allowing emergency responders and residents to take preventative actions. Similarly, warning systems may allow for reduced unemployment and income loss, smaller losses in sales, and smaller reductions in taxes collected by increasing the chances of a quick recovery. Also, the cost for flood insurance may be reduced as warnings result in decreases in the amount of coverage required by residents and businesses.
Traffic control	Advance flood warning may provide the opportunity for authorities to decide which roads to close and which to keep open before flooding begins. Traffic can be re-routed in a more efficient manner and personnel can be deployed in a timely manner to block access to potentially dangerous areas as well as to direct traffic on detour routes.

mented. In the case of urban flooding, annual maximum damage is used in this computation. To account for the variability of damage due to floods of various magnitudes, the “Economic and environmental principles and guidelines for water and related land resources implementation studies” (U.S. Water Resources Council 1983) stipulates use of expected annual damage (EAD), which is computed as

$$E[X] = \int_{-\infty}^{\infty} x f_x(x) dx \quad (2)$$

in which  $x$  = random value of annual damage that occurs with probability  $f_x(x)$ . This computation commonly is accomplished by (1) developing a water-surface elevation-probability (frequency) function for the location of interest, using principles of hydrology and hydraulics; (2) developing an elevation-damage function from information about location and value of damageable property in the floodplain; and (3) using the latter function to transform the former, thus yielding the required damage-probability function, which is integrated numerically to compute the EAD. The transformation and integration can be done conveniently with a computer program. The Corps of Engineers’ computer program (HEC 1998) was designed specifically for this.

Damage-reduction measures alter the elevation-frequency function or the elevation-damage function. For example, a channel modification will yield changes to the elevation-frequency

relationship; the elevation will be less for a specified frequency as modification improves the conveyance. This change, which can be evaluated with hydrologic and hydraulic models, will yield a reduction of damage for a given frequency. Thus, the EAD with the modification will be less than the value without. The expected inundation-reduction benefit then can be computed as the difference

$$E[B_{IR}] = E[X_{\text{without}}] - E[X_{\text{with}}] \quad (3)$$

The benefit of preventative actions taken with increased mitigation time can be evaluated similarly. For example, temporary removal of property from the floodplain will alter the elevation-damage relationship, which will reduce the damage for a given probability and hence the EAD. The inundation-reduction benefit associated with the increased mitigation time thus can be computed, at least conceptually.

## How Others Compute Flood Warning Inundation-Reduction Benefit

### *Proposals for Computing Damage Reduction*

Conceptually, we can identify actions that will be taken if a warning system increases mitigation time. The challenge is to estimate in a practicable manner just how damage will be reduced due to

**Table 3.** Examples of Direct Intangible Benefit (Adapted from USACE 1994)

Example	Description
Protection of human health and safety	Flood warning and preparedness systems can result in the timely and orderly evacuation of a floodplain, which reduces risks to evacuees. The warning time is especially necessary for the evacuation of institutionalized populations in hospitals, nursing homes, schools, and prisons. Timely warnings would protect volunteers and emergency personnel by minimizing the need for them to conduct rescues.
Incidental benefit from use of system for other disasters	Flood warning and preparedness programs may help put into place the process for dealing with other emergencies (earthquake, fire, storms, and hazardous materials accident). Once established, lines of communication and warning dissemination patterns have broad, long-lasting impacts.
Reduction in impact of employment disruption	Warning systems provide time that allows firms to suspend business and prepare for the flood in a manner that would minimize the time and expense of getting back to business after the flood. Unemployment has been shown to cause an increase in crime, suicide, spousal and child abuse, and substance abuse of all kinds, increases in mental breakdowns, stress-related illnesses, and inattention to health problems. An effective response system may reduce these impacts.
Reduced stress	Loss of life and injury can cause stress to the family of the victim and to the injured victim. Reducing the number of these events through warnings would lessen flood-related stress. The mere presence of a warning system provides many floodplain occupants with the reassurance that someone would tell them to act to protect themselves and their property. This reassurance would reduce stress.
Reduction in family disruption	A warning system can provide authorities with the time to make better decisions about closing schools and other facilities. This would reduce family schedule disruption and associated chaos. Families would have more time to reunite and verify the safety of kin, thus reducing stress significantly.
Benefit due to reduction of loss of memorabilia	Warning can provide the time and instruction necessary for people to gather and remove their most prized possessions, such as photographs, and memorabilia.

these actions. A search of available literature yielded three approaches potentially useful for general application:

1. *Day's method*: Day (1970) proposed that the tangible benefit of a FWS could be estimated as a function of warning time due to the system. By considering the value and spatial distribution of property in the Susquehanna River basin and the historical response of property owners, he developed what is commonly referred to as the Day curve, shown in Fig. 3. This predicts damage reduction in terms of percentage of maximum potential inundation damage as a function of the mitigation time. If the warning time is 0 h, the curve predicts that the flood warning system will provide no tangible benefit. If the warning time is 12 h, the Day curve predicts that the damage will decrease by 23%. For example, if the damage without warning is \$1,000,000, and a flood warning system increases the mitigation time to 12 h, the damage reduction will be \$230,000. This is the inundation-reduction benefit shown in Eq. (1). The Day curve also suggests that no matter how great the warning time, the maximum possible reduction is about 35% of the total damage due to the

flood. This is logical, as some property, including most structures, simply cannot be moved.

2. *Institute for Water Resources (IWR) methods*: A report by the Corps' IWR (USACE 1994) proposes two methods for estimating the benefit of a flood warning system:
  - *Using the concept of the Day curve*: The IWR report suggests that Day's "...methodology is perfectly applicable today," but notes that the actual Day curve should not be used. Instead, the report suggests that the Day curve should be calibrated to account for the differences in the contents of residential structures of 1970 and the present and for other regional and system differences.
  - *Shifting the depth-damage curve*: The report suggests a 0.3 or 0.6 m parallel shift in the stage-damage curve to account for actions taken as the mitigation time available is greater. However, the duration of mitigation time with which this shift corresponds is not reported. The report further suggests, "The simplest way to [adjust the stage-damage curve] is to assume some percentage in reduction in damages at each stage. The extent of the assumed re-

**Table 4.** Indirect Tangible Benefit Categories (Adapted from USACE 1994)

Category	Description
Production benefit	Firms far from floodplains may have their fate tied to floodplain firms or services. For example, a restaurant owner who makes pasta sauce relies on a tomato farmer who is in a floodplain. If the tomato farmer's machinery is inundated, so that the crop cannot be harvested, the restaurant owner is impacted as well. Thus, the restaurant owner benefits indirectly from enhancements to the response system. With such physical or economic ties between floodplain and nonfloodplain firms and activities, direct tangible benefits to floodplain firms and activities probably are accompanied by such indirect tangible benefits to nonfloodplain firms.
Consumption benefit	Consumers who shop in, study in, recreate in, or otherwise use the floodplain would benefit from a more rapid recovery from flooding. Residents of nonfloodplain properties may be dependent upon floodplain activities for their jobs. They would benefit from an enhanced response system. For example, a warning system could get an employee who works in, but does not live in, a floodplain back to work sooner. Likewise, an employee of a floodplain firm may avoid layoffs because a FWS permits actions that avoid loss of business.

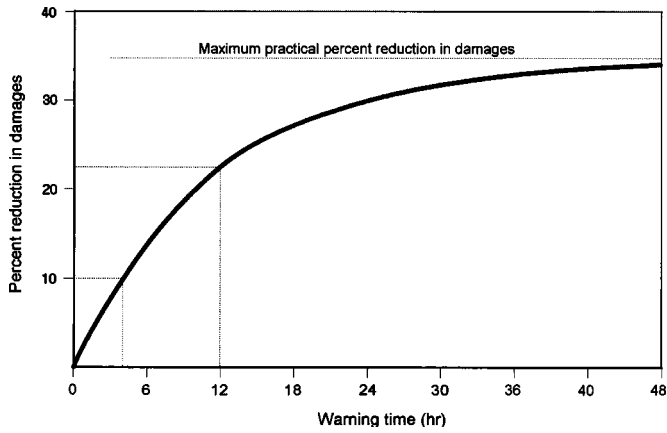


Fig. 3. Day curve

duction in damages used in the model can be determined based on explicit knowledge of the floodplain community, results from similar studies, the literature, a Delphi or other consensus building approach, or professional judgment.” A model in which this concept can be applied is presented. In the model, uncertainty in the mitigation time and behavioral response is included to develop a distribution of project benefits. Details required for application of this model are not included in this research report.

3. *Flood Hazard Research Center (FHRC) methods:* The FHRC of Middlesex University, United Kingdom, has researched flood warning system performance in the United Kingdom and published reports on the benefits of those systems. Methods proposed for benefit evaluation are similar to those by Day and the IWR.

Based upon analysis of historical flood damage and simulation, Chatterton and Farrell (1977) concluded “...eventual depth of water in the building is an important factor influencing the effectiveness of a flood warning. The damage-reducing effects of flood warning are likely to be greater for high rather than for low flood stages.” They propose a relationship in which damage reduction is a function of both depth and mitigation time. Fig. 4 shows an example of the relationship for residential structures and contents due to flooding at various depths; similar relationships are proposed for commercial and industrial structures. This shows, for example, that with 4 h of mitigation time, the damage due to a flood depth of 1.5 m could be reduced by 72%. If this result is combined with the depth-damage relationship of Fig. 5, it

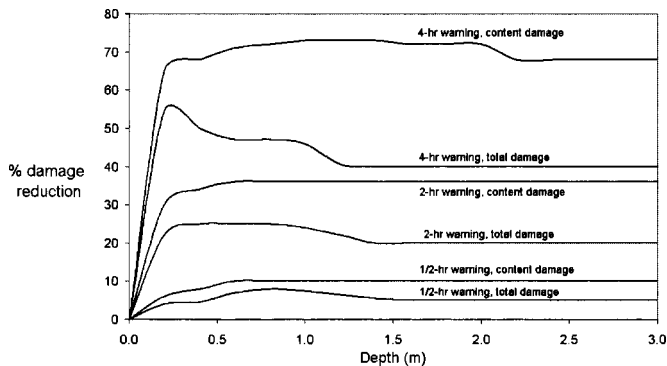


Fig. 4. Damage-reduction estimates for residential structures (Chatterton and Farrell 1977)

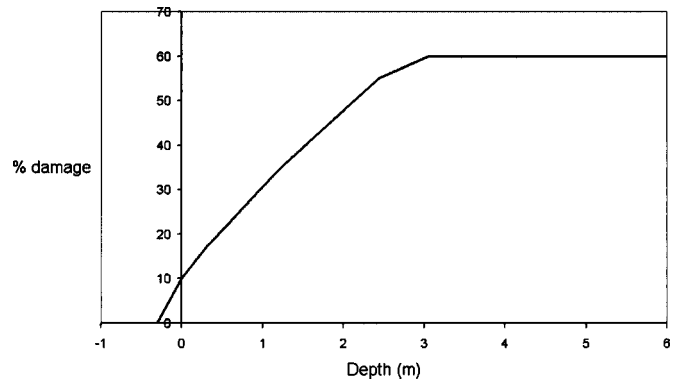


Fig. 5. Residential content depth-damage relationship (USACE 1991)

can be concluded then that the damage at this depth would be reduced by 72%: from the originally predicted 40% of total value to 11.2% of total value. If the total value of the content of a structure is \$100,000, the damage with warning now is reduced from \$40,000 to \$11,200, a savings of \$28,800 for the structure. This savings is attributable to the components of the flood warning system. The damage reduction for other flood depths and warning times can be estimated in a similar manner. With the modified functions, cost savings for a single event can be computed, as can reduction in EAD.

### Proposals for Evaluating System Efficiency

The damage reduction predicted with Day’s curve and the other methods described previously are optimistic; they presume that when notified, property owners will act rationally and efficiently. Further, without some correction, they presume that all property owners will be notified and will thus have the opportunity to act. Unfortunately, this is not always the case. Some floodplain occupants may not be notified, others who are notified may not know what to do, and some who are notified and know what to do may not be capable of acting to protect property. Unless these are accounted for, the benefit computed will overestimate the true benefit.

The FHRC reviewed flood response in the United Kingdom and suggested that actual flood damage avoided,  $D_a$ , can be computed as

$$D_a = D_p R P_a P_r P_e \quad (4)$$

in which  $D_p$  = maximum potential flood damage avoided with a fully effective system;  $R$  = reliability of the flood warning system;  $P_a$  = fraction of residents available to respond to a warning;  $P_r$  = fraction of households who will respond to a flood warning or have others who will do so for them;  $P_e$  = fraction of households who respond effectively (Parker 1991). Each of the factors ranges from 0.00 to 1.00, representing the efficiency of system components. Table 5 shows FHRC’s description of these factors and recommended values. FHRC researchers reported that the response of people to floods and flood warnings is “...greater and more effective in flood zones which are frequently flooded than in zones which are infrequently flooded” (Parker 1991).

The FHRC also published a slight variation of Eq. (4) to account explicitly for the importance of flood forecasting. This equation replaces the reliability term of Eq. (4) with the probability that a forecast is made and disseminated in time (Green and Herschy 1994).

**Table 5.** FHRC Efficiency Factors (Parker 1991)

Factor	Description	Recommended values
$P_a$	Fraction of households in which at least one adult is at home and awake to receive the flood warning.	If warnings are limited to “loudhailer” or siren warnings: 0.55; in situations where “flood wardens” are used along with other warning methods: 0.65; with warning lead times of 6 to 8 h: 0.80.
$P_r$	Fraction of households where residents are capable of moving or removing the contents of their home or who have family or friends who can do so for them.	Without help from friends or family: 0.75; with help from friends or family: 0.80.
$P_e$	Fraction of households who move the content of their home to a higher floor or who remove the content to a location out of the inundation area.	0.70–0.95

Sorensen and Mileti (1988) presented another quantitative assessment of the efficiency of flood warning. Their assessment considers the fraction of people that could possibly be warned in a given time and the fraction of people that will evacuate when ordered or advised to do so. This research suggests that the number of people who will receive a warning increases as mitigation time increases, as predicted with the empirical relationships shown in Table 6. Sorensen and Mileti did not offer a similar model for response rate. Rather, they suggest that evacuation rates (fraction of people who leave the hazardous area) range from 0.32 to 0.98. Evacuation rates under conditions of perceived high risk range from 0.40 to 1.00.

Drabek (2000) published a review of factors that influence response to warnings. He notes that few comparative studies, such as those by the FHRC and Sorensen and Mileti (1988), have been completed, in spite of the need. However, qualitative research is available that describes the many factors that influence how the public responds to warnings.

## New Method for Computing Flood Warning Inundation-Reduction Benefit

### Overview

The strategy described here for quantifying the benefit of increased mitigation time due to a FWS is to develop and use in EAD computations a modified depth-damage function for residential contents, appropriate for specific durations of mitigation time. This approach incorporates the general procedure proposed by FHRC. However, instead of using historical flood damage data (which are seldom available) to develop the function, this damage predictor is instead based upon opinions elicited from specialists in floodplain management and flood damage assessment. With standard EAD computation procedures with the modified function, we find and compare without-project and with-project damage to define the benefit.

**Table 6.** Fraction of Public Warned Given Varied Mitigation Time (Modified from Sorensen and Mileti 1988)

Mitigation time	Equation
0.8 h (50 min) or less	Fraction warned = $0.8183 t^{3.488}$
0.8 to 3 h	Fraction warned = $0.5958 t^{0.4753}$
3 to 7 h	Fraction warned = $0.6663 t^{0.2089}$

Note:  $t$  = mitigation time, in hours. Original equations computed percent warned. For simplicity in calculations, the writers converted the equation to fraction warned.

Next, system efficiency is estimated, which is a fraction of the maximum potential damage reduction that can be achieved by the FWS. This is a function of the completeness and quality of components included in the system. With this, the benefit is scaled accordingly to account for failure of the system to notify floodplain occupants, lack of knowledge by occupants regarding proper response, or inability of occupants to act to protect property. So, for example, if we assess the proposed system and find that it is only 75% efficient, we will credit the system with economic benefit equal to 0.75 of the difference in inundation damage without the warning system and inundation damage with the additional mitigation time provided by the system.

### Modified Elevation-Damage Functions

For uniformity and convenience in flood damage computations, the Federal Emergency Management Agency (FEMA) developed representative relationships between elevation and damage for residential, commercial, and industrial structures and contents (USACE 1991). These functions are published in dimensionless form, with damage shown as a percentage of total value related to depth of flooding above the first floor of a structure; Fig. 5 illustrates the FEMA depth-percent damage function for contents of a 1-story residential structure. The Corps of Engineers and other agencies have used these functions for economic analyses in flood damage-reduction planning studies and for postflood assessments. The Corps of Engineers recently has developed and published a revised set of functions (USACE 2000).

For EAD computations, the depths in the depth-percent damage function are transformed to elevations by adding the first-floor elevation of the structure of interest. Similarly, the percent damage values are transformed to actual damage by multiplying by the economic value of the property. For example, Fig. 5 predicts that 40% of the total content value will be damaged if the depth of water is 1.5 m above the first-floor elevation of a structure. If the total value of the contents of a structure is \$100,000, the damage thus would be \$40,000. If the first-floor elevation of the structure is 30.5 m, this corresponds to a water surface elevation of 32.0 m.

During September and October 2002, we provided the depth-percent damage function for residential content to a panel of 11 floodplain management and flood damage experts. We asked each expert to indicate how the damage incurred would change with 1, 6, 12, 24, 36, and 48 h of mitigation time. We noted that in all cases “no change” was an acceptable answer. We collected the responses and computed statistics of the results. The resulting function that predicts the percent of damage as a function of depth and mitigation time is shown in Table 7.

**Table 7.** Residential Content Depth-Percentage Damage Relationship with Flood Mitigation Time

Depth (m)	Mitigation time, hrs						
	0	1	6	12	24	36	48
-0.91	0	0	0	0	0	0	0
-0.61	0	0	0	0	0	0	0
-0.30	0	0	0	0	0	0	0
0.00	10	8	6	5	4	4	4
0.30	17	15	12	11	9	9	8
0.61	23	21	17	16	13	11	11
0.91	29	26	22	21	16	15	14
1.22	35	32	27	27	23	20	19
1.52	40	37	33	32	27	25	23
1.83	45	42	36	36	31	27	25
2.44	55	51	44	43	38	33	30
3.05	60	55	48	46	40	35	31
4.57	60	55	48	47	40	35	31
6.10	60	55	48	47	40	35	31

Note: Values shown in columns 2–8 are damage as percentage of content value.

To use this function to estimate the direct tangible benefit of a flood warning system, EAD without the warning system in place is computed, using the damages shown in column 2 of Table 7 (presuming that the without-project condition has no warning). Then the mitigation time due to the warning system components is estimated, and the EAD computations are repeated, with the appropriate values from Table 7. For example, if the warning system increases the mitigation time to 6 h, the values from column 4 will be used. Eq. (3) yields the inundation-reduction benefit: the difference in EAD without the system and EAD with the system.

### System Efficiency

The following simplified model is proposed to measure efficiency of flood warning

$$\text{eff} = F_{rw}F_wF_c \quad (5)$$

in which  $\text{eff}$ =efficiency of flood warning;  $F_{rw}$ =fraction of the public that receives a warning;  $F_w$ =fraction of the public that is willing to respond;  $F_c$ =fraction of the public that knows how to respond effectively and is capable of responding (or has someone to help them). A new system with all required components and with a high probability of proper operation and maintenance will achieve an efficiency near 1.00, and an incomplete, poorly operated and maintained system will have a much lower efficiency. This assessment admittedly is subjective in the current state of development. However, it does provide for a systematic evaluation, the details of which can be reported and displayed.

### Inundation-Reduction Benefit Computation

Mathematically, our estimate of inundation-reduction benefit is

$$E[B_{IR}] = (E[X_{\text{without}}] - E[X_{\text{with}}])\text{eff} \quad (6)$$

in which all terms are as defined earlier. Thus, if the expected annual damage without the system is \$10 million and the damage with the system is \$8 million, the maximum potential damage reduction due to warning is \$2 million. However if the system notifies only 50% of the floodplain occupants, 80% of whom

respond, and if only 75% of those know how and are capable, we will credit the system with the damage reduction predicted with the modified depth-damage functions multiplied by 0.30, the system efficiency. Thus, we would claim a benefit of only \$600,000.

### Sources of Uncertainty

The method proposed here relies on two key factors: mitigation time and efficiency of the flood warning system. Although it is clear *what* mitigation time is, as illustrated in Fig. 1, *quantification* of mitigation time is very much unclear. Quantification of time requires estimates for each of the contributing factors: data collection, evaluation, notification, and decision-making time. Additional research is required to establish procedures for estimating these with greater certainty for a specific watershed. That might include ex post facto data collection of how time was spent during past flood events. Additional research should be conducted on the efficiency of the system for the same reason. Although Mileti and others have conducted research in the past, a vast body of knowledge is not available on what percentage of the public receives warnings, are willing to respond, know how to do so, and are capable of doing so. Analysis of data from past disasters may lead to better estimates of efficiency.

## Application of Benefit Computation Procedure in California's Central Valley

### Background

California's Central Valley is vulnerable to regional river flooding from the Sacramento and San Joaquin Rivers. After devastating flooding in 1983, 1986, 1996, and 1997, Congress authorized the Corps of Engineers to conduct a region-wide assessment (known as the Comprehensive Study) of the Central Valley's flooding problem and flood management system. The California State Reclamation Board is the Corps' cost-sharing and technical partner in this study (USACE and The Reclamation Board 2002).

The Comprehensive Study investigated and described the hydrology, hydraulics, and economics of the Central Valley's flooding problem through rigorous data collection and modeling of basin conditions. Armed with this new information, Corps and State planners formulated a variety of plans to reduce flood damage, protect the public, and enhance the environment. Among the plans formulated is a plan to enhance flood response and emergency preparedness; this is referred to as EFR&EP.

The Central Valley of California is somewhat unique in the U.S. because the without-project condition includes an efficient flood response and emergency preparedness system that reduces damage. Components of this system are owned, operated, and maintained by local government agencies, the California Department of Water Resources, the California Governor's Office of Emergency Services, the U.S. National Weather Service, the U.S. Bureau of Reclamation, the U.S. Army Corps of Engineers, the U.S. Geological Survey, and private power and water utilities. With the cooperation of these public and private institutions, floodplain occupants are warned of threats, and actions are taken to protect lives and property. The mitigation time in the basins varies from 0 to 36 h, depending on the location, hydrologic characteristics, and local response plans. Alternatives proposed for EFR&EP will increase the mitigation time by expanding and enhancing various system components shown in Fig. 2.

As with all proposed Federally funded water resource projects, the EFR&EP project must contribute to national economic devel-

opment (NED). The standard for the contribution is that the project's tangible benefit must exceed the project's acquisition, operation, maintenance, replacement, and repair costs. To demonstrate that this is so, the inundation-reduction benefit due to project measures must be computed. While similar Corps flood warning projects have used the Day curve for such estimates (USACE 1996b), project planners here determined that because of the potentially high cost and high visibility, a more rigorous analysis was appropriate. Accordingly, the procedures described herein were developed specifically to meet the Comprehensive Study needs and prosed for use in that study.

To apply the methods proposed here, we must compute EAD without and with the proposed project. To do so, Corps and state economists first surveyed damageable property throughout the Central Valley and developed an extensive structure inventory database. This includes information about structure location, value, and type, with which elevation-damage functions can be developed by transforming the average depth-percent, damage-mitigation time functions. Data were collected for approximately 100 geographic areas, referred to as impact areas; these include cities of Sacramento, Fresno, West Sacramento, Stockton, Yuba City, and Marysville. Watershed and channel studies by the Corps and state engineers and hydrologists yielded appropriate elevation-frequency functions throughout the system with which the elevation-damage functions can be transformed to damage-frequency functions that are integrated to compute EAD. These same economic data and frequency functions are used to compute both without-project and with-project damage. But the choice of the depth, damage, mitigation time function depends upon the status of the flood warning system. The computations are illustrated here for two cases.

#### **Example 1: No Mitigation Time in Without-Project Condition**

The first example illustrates application of the proposed method to compute the inundation-reduction benefit for an impact area for which no effective mitigation time is available in the without-project condition. In this case, mitigation time is zero because the time required for notification and decision making exceeds the forecast lead time—the time between threat recognition and threshold exceedence. However, the computations for this case are identical to those required for a watershed for which no flood warning exists in the without-project condition.

The impact area of concern here is approximately 14.2 km<sup>2</sup> and could be inundated if levees protecting it are overtopped or fail. Total damages from the 500-year (0.002 annual exceedence probability) event would amount to approximately \$2 million. The current level of protection is approximately the 100-year (0.01 annual exceedence probability) event.

**Without-Project Damage.** To compute the without-project damage, we use the elevation-frequency functions developed with hydrologic and hydraulic models (USACE 2002). We use the surveyed structure and content values, selecting the appropriate depth-damage function, depending on the mitigation time. For the impact area, state and federal forecasters estimate that with the existing warning system components, they can recognize a flood threat 12 h prior to threshold exceedence, on the average. Through systematic assessment of the available response plans, notification capabilities, and other warning and response capabilities for this impact area, it was concluded that 18 h are required

for notification and decision making for this impact area. Therefore, because the notification and decision-making time exceed the forecast lead time, no time remains for mitigation.

To compute EAD, standard structure depth-damage functions were used. However, to estimate damage to content, we select and use the appropriate depth-damage function from Table 7. In this case, that is the function in column 2, which accounts for no damage reduction due to available mitigation time. The without-project EAD thus computed is \$1,454,740.

**With-Project Damage.** With the proposed EFR&EP measures in place, forecasters estimate they could recognize a flood threat for this impact area 21 h prior to threshold exceedence, and the time for notification and decision making will decrease to 12 h. Thus, the mitigation time is 9 h, and damage will be reduced accordingly. By using the damage values from Table 7, interpolating as necessary, we find the with-project EAD with 9 h of mitigation time is \$1,337,950.

**Benefit.** The total damage reduction for the impact area, and hence, the inundation-reduction benefit will be \$116,790 if the enhanced system is fully efficient in this impact area. However, it cannot be. It is estimated that with the improvements the efficiency will increase to 0.81. Thus, the actual EAD reduction achieved is 81% of the predicted damage reduction, or \$94,600.

#### **Example 2: Mitigation Time in Without-Project Condition**

Computing the benefit enhancements or improvements to an existing flood warning system is slightly more complex. In that case, computation of the without-project damage must consider the mitigation time and efficiency of the existing system. Without-project damage is compared with this to establish the benefit. This is illustrated here with data from a second impact area from the Sacramento River basin. This impact area is 69.9 km<sup>2</sup>, and total damages from the 500-year (0.002 annual exceedence probability) event would amount to approximately \$18,594,000. Flood damages begin to occur at approximately the 10-year (0.10 annual exceedence probability) event.

**Without-Project Condition.** Forecasters estimate that they can recognize a flood threat 18 h prior to threshold exceedence, and it was concluded that 15 h are required for notification and decision making. The difference, 3 h, is the mitigation time available in the without-project condition. The EAD with this mitigation time, using the values in Table 7 for content damage and interpolating as necessary, is \$1,282,090. EAD with no mitigation time is \$1,286,700. This investigation of available notification procedures and historical response to flood warning indicates that the efficiency of the current system is 0.60. Thus, the damage reduction of the current system is 0.60 of the difference between the damage with no mitigation time and the damage with 3 h mitigation time, or \$2,766 annually. The without-project EAD is the damage with no mitigation time less the actual damage reduction, or \$1,283,934.

**With-Project Condition.** With the EFR&EP measures in place, the mitigation time will increase from 3 to 10 h, and system efficiency will increase from 0.60 to 0.81. The EAD and resulting damage reduction of the system for this impact area would be

\$1,275,090 and \$6,170, respectively, if the enhanced system was fully efficient. The actual damage reduction is \$4,998. The with-project EAD is the damage with no mitigation time less the actual damage reduction, or \$1,281,702.

Note that improvements in system efficiency increase damage reduction, regardless of whether mitigation time is increased.

**Benefit.** The with-project inundation-damage reduction is the without-project EAD (adjusted for efficiency) less the with-project EAD (also adjusted) for this impact area, or \$2,232 annually.

## Summary and Conclusions

A flood warning system includes hardware, software, plans, and procedures, and personnel that work in an integrated manner to increase the mitigation time available prior to the onset of flooding. This mitigation time increase is a consequence of reduction in the time required to collect data, to evaluate and identify the flood threat, to notify emergency personnel and the public, and to make decisions about appropriate response.

The increase yields direct and indirect, tangible and intangible benefits. The direct tangible benefit—the inundation damage reduction—can be computed with standard expected damage computation procedures, using modified depth-damage functions that include mitigation time as an independent variable. The writers developed these modified functions through expert elicitation.

The damage reduction predicted with the modified functions is optimistic; it does not account for failure of the flood warning system to notify all floodplain occupants and for all the occupants to be ready, willing, and able to act to protect themselves and their property. The writers account for that with a factor that represents the system efficiency.

The writers proposed the procedure described herein for plan evaluation in California's Central Valley. However, the procedure is applicable in any area, with or without an existing flood warning system.

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