Delta Stewardship Council

Delta Levees Investment Strategy

Technical Memorandum 2.2: Levee Hazards, Risks, and Consequences

Peer Review (Draft Revision 0)

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ACRONYMS AND ABBREVIATIONS

AADT	Average annual daily traffic
cfs	cubic feet per second
Council	Delta Stewardship Council
CVFPP	Central Valley Flood Protection Plan
Delta	Sacramento-San Joaquin Delta
DLIS	Delta Levees Investment Strategy
DRMS	Delta Risk Management Study
DWR	California Department of Water Resources
EAALL	expected annual agricultural land loss
EAD_R	expected annual damage with rehabilitation
EAD_F	expected annual damage without rehabilitation
EAF	expected annual fatalities
FEMA	Federal Emergency Management Agency
NAVD88	North American Vertical Datum of 1988
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PAR	population at risk
p_c	proportion of population coming in contact with flood water
p_e	probability of a flood event
p_f	probability that coming contact with flood water is fatal
PFP	probable failure point
pga	peak ground acceleration
PNP	probable non-failure point
SRDWSC	Sacramento River Deep Water Ship Channel
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geologic Survey

1. INTRODUCTION

The Delta Stewardship Council (Council) is tasked with developing and recommending priorities for state investments in Sacramento-San Joaquin Delta (Delta) levees to reduce flood risk to people, property, and state interests; and to further advance the coequal goals of water supply reliability and restoring the Delta ecosystem. The objective of the Delta Levees Investment Strategy (DLIS) project is to provide the Council with a method that can be used to develop and evaluate strategic levee investments.

This technical memorandum, presenting the results of Task 1(b), Gather Data for Risk and Consequences Analysis, is one of a series of technical memoranda prepared for the Council that describe the review, analysis, and development of a strategic levee investments methodology and tools. This technical memorandum describes the processes the DLIS team is following to achieve the Task 2.2 objectives and presents the results of the team's review of the available data and analyses.

The objectives of Task 2.2 are to:

- Review and synthesize the available data and methodologies for the analysis of flood risks to the people, physical assets, crops, and infrastructure in the Delta and Suisun Marsh.
- Use the available data for levee hazards, vulnerability, and consequences analyses.
- Calculate expected annual monetary damages to assets and infrastructure from levee failure.
- Identify and qualitatively evaluate other damages, including expected annual fatalities, from levee failures that cannot be readily expressed in monetary terms.

Task 2.2 is specifically focused on flood risks to people and property. Flood risks to water supply reliability, ecosystem function, and other state interests are addressed in separate technical memoranda.

The results of the monetary damage calculations and qualitative damage assessments described in this and the other technical memoranda will be incorporated in a DLIS Planning Tool that is described in Technical Memorandum 3.1.

2. DATA AND METHODOLOGY SOURCES

The DLIS project intends to base its analysis on the best available existing data. Accordingly, the primary sources of existing data are studies completed by the California Department of Water Resources (DWR), the U.S. Army Corps of Engineers (USACE), the Delta Protection Commission, and the Central Valley Flood Protection Board. Each of the studies was initiated for somewhat different purposes, but the study reports are valuable sources for data on levee conditions, analysis of levee performance, and catalogs of island assets that can be cross-checked from study to study. The study reports used as data sources for the analyses are listed in the references section of this memorandum.

The previous studies were also used as a source for methodologies to perform levee hazard, vulnerability, and consequence analyses as described in this technical memorandum. Selected national and international journal articles, conference proceedings, reference works, and academic research were reviewed to evaluate the current practice and alternative analysis methodologies. The additional methodology sources are listed in the references section of this technical memorandum.

3. ANALYTICAL APPROACH

One-hundred-and-seventy-six distinct islands and tracts have been identified in the Delta and Suisun Marsh (Council 2015). Six of the islands or tracts are currently flooded, 142 are protected by one or more levees, and 28 have no levee protection. Among the 170 leveed and unprotected islands and tracts, 117 have populations ranging from a few people to more than 50,000, and 150 of these islands and tracts have physical assets, crops, or infrastructure (Council 2015).

Because of the large number of islands and tracts included in the analysis, a generalized analytical approach was taken. Furthermore, the level of detail in the information that is available for the islands and tracts varies considerably. Some islands and tracts have been studied in detail (DWR 2008b, 2012b, USACE 2013) while others have relatively little information available. The assumptions and generalizations that were applied to all islands and tracts are as follows:

- Each island and tract is assumed to have a level interior elevation equal to the island or tract average interior elevation.
- All island or tract levee segments are assumed to have a crest elevation equal to the average levee crest elevation for the island or tract.
- The levee(s) are assumed to fail at the weakest levee among all levee segments protecting the island or tract.
- A levee failure is defined as a breach sufficiently large to inundate the entire island or tract.
- Should a levee breach occur, inundation depth is assumed to be the river stage causing a breach minus the island and tract average interior elevation and the entire island or tract is assumed to be inundated to that depth.
- For an island or tract without levee protection, flooding is assumed to occur when the river stage exceeds the island or tract average interior elevation.
- For an island or tract without levee protection that floods, inundation depth is assumed to be the river stage minus the island or tract average interior elevation and the entire island or tract is assumed to be inundated to that depth.
- The likelihood and consequence of island or tract flooding are based on annualized probabilities and consequences and, therefore, an island or tract can only experience one flood event per year.
- The time of year and duration of flooding are not considered.

4. LEVEE HAZARDS

A hazard is a condition or circumstance that has the potential to cause harm to people or damage to assets. Thus, a levee hazards analysis consists of identifying and evaluating the conditions and circumstances that have the potential to damage the Delta and Suisun Marsh levees. The identification phase of the analysis consists of cataloging the naturally occurring events and human actions that can lead to levee damages. The evaluation phase consists of estimating the relative importance of the events and actions to potential levee damage and determining if sufficient data exist to develop relationships between an event or action and the level of potential levee damage.

The process of identifying levee hazards begins with an understanding of levee failure mechanisms. Although levees may be damaged without breaching, the DLIS project is only concerned with breaching failures. Levee failures without breaching may have cleanup and maintenance costs, but breaching levee failures will be significantly more dangerous to human health and safety and much more costly.

An understanding of failure mechanisms leads to a search for natural events and human actions that can initiate one or more of the levee failure mechanisms. It is important to note that a given hazard may be able to initiate one or more failure mechanisms and some failure mechanisms can be initiated by several different hazard types. The most commonly reported levee failure mechanisms are listed in Table 1.

Table 4-1. Levee Failure Mechanisms

Category	Mechanism
Geotechnical	Slope failure
	Sliding
	Subsidence, settling, cracking
Surface Degradation	Overtopping
	Erosion or other loss of levee prism
	Vegetation
Hydraulic	Seepage
	• Bottom heave
	• Internal erosion and piping
	• Liquefaction

Geotechnical failure mechanisms are related to the strength and compressibility of the levee and levee foundation soils. Surface degradation failure mechanisms are a consequence of changes to levee geometry that may reduce freeboard or over-steepen levee slopes. Hydraulic failure mechanisms are related to the levee's fundamental purpose of keeping water from a protected area. This mechanism is of particular importance because most of the Delta and Suisun Marsh levees are "wet" levees that continuously keep water from the protected areas as compared to "dry" levees that are built to keep water from protected areas only during a high river stage.

A comprehensive list of potential current and future Delta and Suisun Marsh levee hazards compiled by the DLIS team is shown in Table 2. Previous studies have focused on hydrologic/hydraulic, seismic, and wind hazards. However, it is important to consider all hazards to ascertain if their potential to cause levee failure is significant and can be incorporated in further analyses.

Table 4-2. Levee Hazards

Type	Source	Hazard
• NATURAL HAZARD	• Hydrologic / Hydraulic	• High volume inflow
		High flow velocity
		High head differential
		River morphology changes
		Rapid drawdown
	Climatic Change	Higher water level
		Greater head differential
	Wind	Wave run-up
		Storm surge
	Geologic / Geotechnical	Soft or organic soils below levee embankment
		Soft or organic soils on land side
		Earthquake
	• Ecologic	• Animal burrows
		Vegetation type or location
HUMAN ACTION HAZARD	Permanent or Periodic	Encroachments
		Channel dredging
		Deferred maintenance
		Upstream water management and storage
	Temporary	Boat and ship wakes
		Impact (ship, debris, ice)
		Fires / footpaths / camping

Some of the levee hazards in this list may lead to fundamental changes to another hazard. For example, climate change in the form of sea level rise represents a change in the hydraulic hazard. Other hazards can be a direct hazard or can be a contributing factor. For example, low strength soft or organic soils can lead to levee slope failure even in a “dry” levee, but soil strength is also a significant contributing factor to levee performance during an earthquake. It is essential that the interaction of hazard effects be considered to avoid double counting their impact on levee performance.

The potential relationships between levee hazards and levee failure mechanisms are illustrated in Table 3. In this table, the primary levee failure mechanism(s) are shown for each hazard; however, some hazard-induced levee failure mechanisms can cause secondary failures. For example, earthquake inertial forces can cause a levee slope failure directly, or the levee slope failure may be a secondary consequence of liquefaction in the levee foundation soil.

Based on a review of the previous studies (DWR 2008b, 2012b; USACE 2013), the most significant current hazards to the Delta and Suisun Marsh levees are hydrologic, hydraulic, and seismic hazards. Future hazards include changes to inflow caused by changing precipitation or snowmelt patterns in the Delta

Table 4-3. Levee Hazards and Levee Failure Mechanisms Matrix

			Levee Failure Mechanism								
			Geotechnical			Surface Degradation		Hydraulic			
Type	**Source**	**Hazard**	Slope failure	Sliding	Subsidence or settling	Over-topping	Erosion or other loss of levee prism	Seepage	Bottom heave	Internal erosion and piping	Liquefaction
• NATURAL HAZARDS	• Hydrologic / Hydraulic	High volume inflow	●			●	●	●	●	●	
		High flow velocities	●				●				
		River morphology					●				
		High head differential						●	●	●	
		Rapid drawdown	●								
	Climatic	High water level	●			●	●	●	●	●	
		High head differential						●	●	●	
	Wind	Wave run-up				●	●				
		Storm surge				●	●				
	Geologic / Geotechnical	Soft or organic soils below levee embankment	●		●						
		Soft or organic soils on landside	●		●						
		Earthquake	●	●	●						●
	• Ecologic	Animal burrows						●		●	
		Vegetation type or location					●	●		●	
HUMAN ACTION HAZARDS	Permanent or Periodic	Encroachments					●	●		●	
		Channel dredging	●				●	●			
		Deferred maintenance	●				●				
		Upstream water management and storage				●		●	●	●	
	Temporary	Boat and ship wakes					●				
		Impact (ship, debris, ice)					●				
		Fires / footpaths / camping					●				

drainage basins, changes to upstream water management practice or capacity, changes to flow through the Delta due to potential sea level changes, and continued subsidence.

The ecological and temporary human action hazards listed in Table 3 are relatively rare occurrences or are mostly supported by anecdotal evidence. Engineering judgment will be used to incorporate the effect of these hazards on levee performance evaluations by estimating the contribution of the effect to levee fragility curves. The permanent or periodic human action hazards listed in Table 3 will be incorporated in discharge-recurrence curves (upstream water management and storage) and levee fragility curves (encroachment, dredging, and deferred maintenance). The effects of upstream water management and storage will be reflected in the peak annual inflows used to develop a discharge-recurrence curve for the Delta. Engineering judgment will be used to incorporate the effect of encroachment, dredging, and deferred maintenance by estimating their contribution to levee fragility curves.

4.1 Hydrologic Hazard

4.1.1 Total Delta Inflow

The hydrologic hazard to the Delta and Suisun Marsh levees is related to the volume of water flowing into and out of the Delta. Inflow is the sum of the flows from the rivers and streams that flow into the Delta, and outflow is tempered by the tidal cycle at the western end of the Delta and by water exports and in-Delta water uses. Increased inflow and higher tide levels result in higher water levels in the Delta and Suisun Marsh and greater hydraulic pressure on the Delta and Suisun Marsh levees. Water exports and in-Delta water uses will tend to reduce water levels and hydraulic pressure on the Delta and Suisun Marsh levees.

Hydrologic hazards due to stream flows are typically analyzed using the statistical method outlined in U.S. Geological Survey (USGS) Bulletin 17B of the Hydrology Subcommittee (USGS 1982). The USGS method is used to develop a discharge-recurrence curve based on the historical record of annual extreme flow rates in a river. A discharge-recurrence curve relates extreme or peak flow rate (volume/time) to annual probability of exceedance or return period. This method was used in the Delta Risk Management Strategy (DRMS; DWR 2008a). The DRMS discharge-recurrence curve was adopted by the USACE for its most recent Delta and Suisun Marsh levee study (USACE 2013).

The data used to develop a discharge-recurrence curve are generally the annual peak flow rates for a single river for the period of record. In the case of the Delta, two major rivers, the Sacramento and San Joaquin rivers, and several smaller rivers and streams contribute to total Delta inflow. The approach used in the DRMS to calculate the peak annual inflow was to determine the date of the peak annual inflow from the Sacramento River and sum the Delta inflows from all rivers and streams for that date. Although all of the rivers and streams flowing into the Delta may not have peak annual flow rates at exactly the same time, all of these rivers and streams have similar climate and weather influences and will likely have peak annual flow rates at or near the same time. Furthermore, the inflow to the Delta from the Sacramento River, Yolo Bypass, and San Joaquin River represents, on average, 90 percent of the total Delta peak inflow for the 50-year period (water years 1956 to 2005) analyzed in the DRMS study (DWR 2008b).

Revised historical data and an additional eight years of peak annual flow data have been made available by the USGS since the completion of the DRMS study. The newer data were analyzed for the Sacramento and

San Joaquin rivers to determine if the newer data would substantially change the conclusions reached in the DRMS study.

The newer USGS data (USGS 2014a) for the Sacramento, San Joaquin, Mokelumne, and Consumnes rivers and Yolo Bypass were plotted versus water year along with the data used in the DRMS study to compare data sets. For example, graphs of peak annual discharge for the Sacramento River plus Yolo Bypass are shown on Figure 1. The differences between the DRMS data set and the currently available USGS data set are likely due to revisions made by the USGS since the DRMS study was completed. Similar differences were noted in the comparisons of DRMS data and current USGS data for the San Joaquin, Mokelumne, and Consumnes rivers.

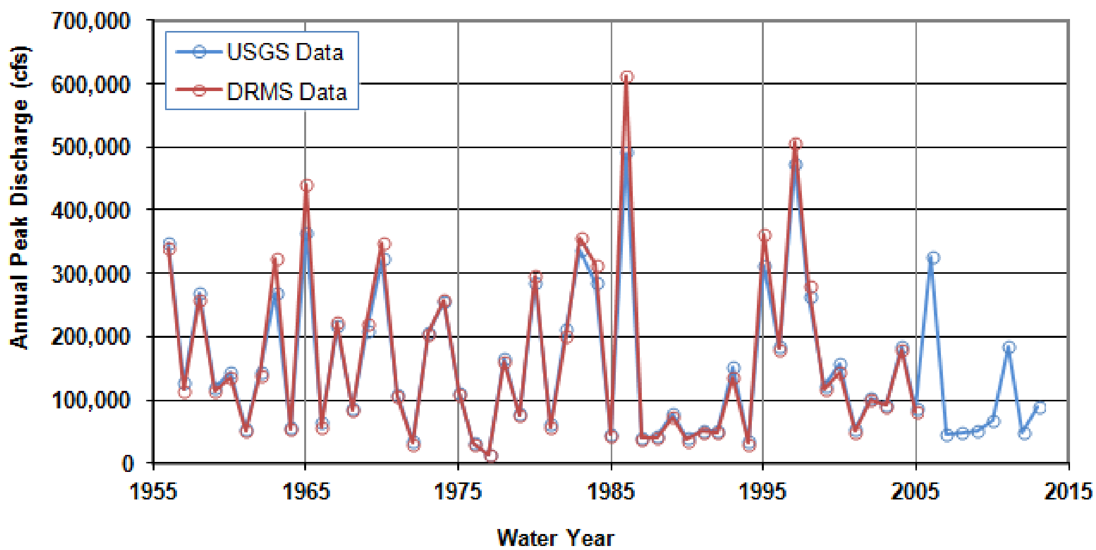

Figure 4-1. Peak Annual Discharge Sacramento River + Yolo Bypass
(Source: USGS 2014a; DWR 2008b)

The 1956 to 2013 Sacramento River plus Yolo Bypass data were analyzed using the USGS method to determine if the data revisions and new data could significantly change the discharge-recurrence curve. The results of the analysis are shown on Figure 2. The discharge-recurrence curve developed from the USGS data revisions and new data are generally less conservative than the discharge-recurrence curve presented in the DRMS study. For example, the predicted flow rate for a 100-year return period using the DRMS result is about 820,000 cubic feet per second (cfs) whereas the predicted flow rate for the same return period using the revised and new USGS data is about 701,000 cfs.

Because the peak annual inflow to the Delta is the sum of the flow of all rivers and streams into the Delta, not just the Sacramento and San Joaquin rivers, the combined discharge-recurrence curve was evaluated considering the newer data and it was concluded that the newer data did not substantially change the

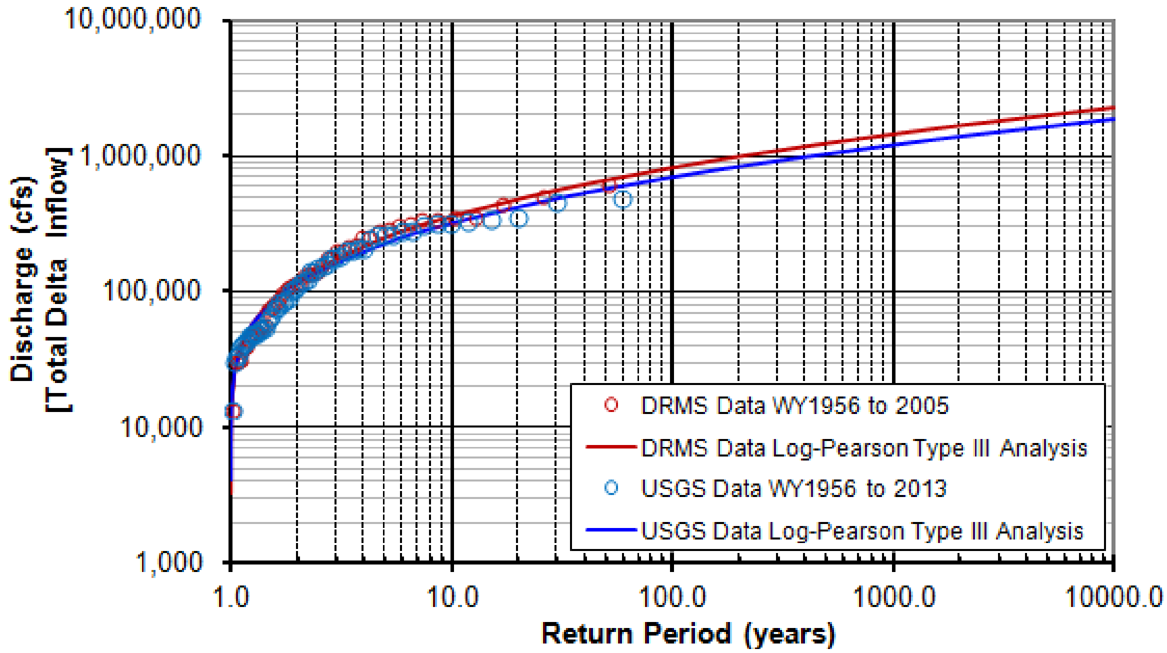

Figure 4-2. Discharge-Recurrence Sacramento River + Yolo Bypass

discharge-recurrence curve as presented in the DRMS report. Subsequent levee risk analyses completed by the DLIS team will use the discharge-recurrence curve presented in the DRMS report (DWR 2008b).

4.1.2 Tide Effects

Tidal fluctuations in the Delta and Suisun Marsh have a strong influence on water elevations and flows throughout the Delta and Suisun Marsh. The results presented in the DRMS study are based on readings from the San Francisco tide station (National Oceanic and Atmospheric Administration [NOAA] Station 9414290) with a range of approximately 3.8 to 9.2 feet (North American Vertical Datum of 1988 [NAVD88]). As described in the following section, these tide data are used in the calculation of stage-recurrence curves for the Delta and Suisun Marsh.

4.2 Hydraulic Hazard

Levee hydraulic hazards are generally proportional to the surface elevation of the body of water retained by the levee relative to the elevation of the ground protected by the levee. In addition, many of the Delta and Suisun Marsh levees are “wet” levees that are under continuous hydraulic pressure because the ground elevation on the land side of the levee is almost always less than the elevation of the body of water.

Levee hydraulic hazards are typically expressed as stage-recurrence curves that relate water elevation (stage) to annual probability of exceedance, or return period. A stage-recurrence curve for a specific location depends on the volume rate of flow, the hydraulic flow characteristics of the water channel at that location, and the magnitude of the tidal influence. A stage-recurrence curve can be developed from a discharge-recurrence curve and the hydraulic flow characteristics at the location of interest, or from direct stage measurements obtained over several years.

For the levee risk analysis undertaken in the DLIS study, the stage-recurrence equations presented in the DRMS study (DWR 2008b) have been extended to develop stage-recurrence curves for every Delta and Suisun Marsh island and tract. The DRMS investigators used a simplified model of channel hydraulic characteristics and multiple regression methods to develop equations that relate Delta inflow and tide level to water level at 15 gauging stations in the Delta (Figure 3 and Table 5). The equations are listed below. Equation (1) applies to the Lisbon and Freeport stations and equation (2) applies to all other stations. Equation coefficients developed by the DRMS investigators are shown in Table 4. Gauging station names are shown in Table 5.

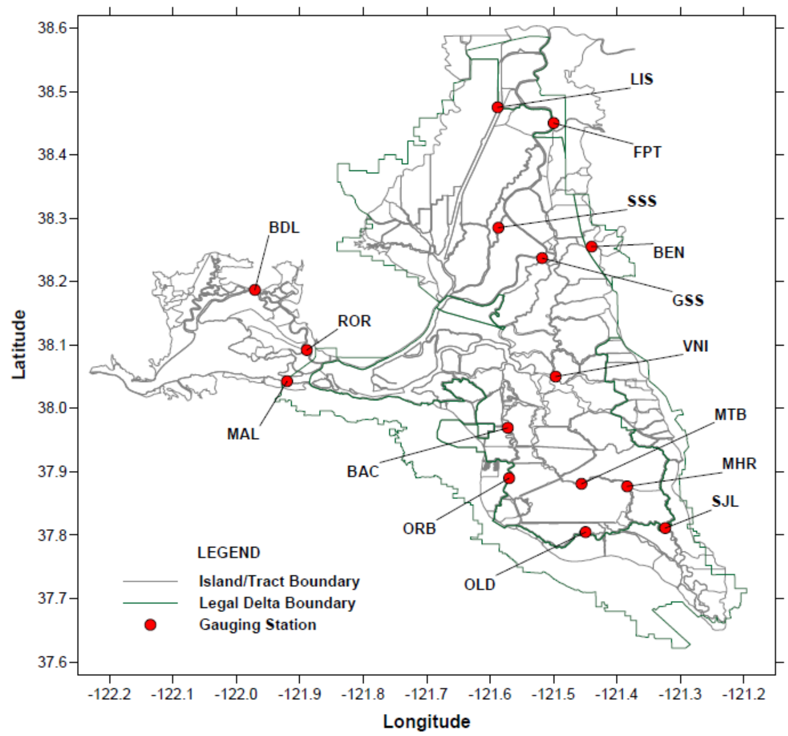

Figure 4-3 Gauging Stations
(Source: DWR 2008b)

$$WSE_i = aT + b(Q_{Sac})^b + c(Q_{Yolo})^c + d(Q_{SJ})^d + e(Q_{Cos})^e + f(Q_{Mok})^f + g(Q_{misc})^g \qquad (1)$$

$$WSE_i = aT + b(Q_{Sac}+Q_{Yolo})^b + d(Q_{SJ})^d + e(Q_{Cos})^e + f(Q_{Mok})^f + g(Q_{misc})^g \qquad (2)$$

where:

WSE_i = water-surface elevation at station "i"
T = Golden Gate maximum daily tide elevation
Q_{Sac} = Sacramento River inflow
Q_{Yolo} = Yolo Bypass inflow
Q_{SJ} = San Joaquin River inflow
Q_{Cos} = Cosumnes River inflow
Q_{Mok} = Mokelumne River inflow
Q_{misc} = miscellaneous inflow

Table 4-4. Estimated Coefficients "a" through "g" in Equations 1 and 2

• Station • ID	a Tide	b (Sac)	c (Yolo)	d (Sjr)	e (Csmr)	f (Moke)	g (Misc)
MAL	0.91	0.000247	NA	0.000363	0.000385	0.000000	0.000000
BDL	1.00	0.000123	NA	0.000696	0.000566	0.000000	0.000102
ROR	0.94	0.000302	NA	0.000148	0.000337	0.000000	0.000001
BEN	0.38	0.002020	0.000047	0.000750	0.013245	0.010418	0.006022
GSS	0.34	0.005067	0.000201	0.000000	0.000000	0.007334	0.000000
FPT	0.00	0.009705	0.000520	0.000000	0.001266	0.001466	0.000660
SSS	0.19	0.006071	0.000162	0.000003	0.000368	0.003880	0.000000
LIS	0.67	0.004997	0.001708	0.002487	0.000000	0.000000	0.000000
MHR	0.88	0.000431	NA	0.002279	0.002543	0.000000	0.000000
MTB	0.90	0.000312	NA	0.001652	0.001220	0.000000	0.000000
OLD	0.81	0.000294	NA	0.002717	0.002480	0.000000	0.000000
BAC	1.00	0.000306	NA	0.000113	0.003236	0.000000	0.000000
ORB	0.79	0.000531	NA	0.001602	0.002982	0.001474	0.000000
SJL	0.77	0.000181	NA	0.009743	0.001596	0.000000	0.000000
VNI	0.97	0.000387	NA	0.000925	0.000328	0.000000	0.000000

Table 4-5. Gauging Stations

Station Identifier	**Station Name**	**Station Identifier**	**Station Name**
BAC	Bacon Island at Old River	MTB	Middle River at Tracy Blvd.
BDL	Beldon Landing	OLD	Old River near Tracy
BEN	Benson's Ferry	ORB	Old River at Byron
FPT	Sacramento River at Freeport	ROR	Roaring River
GSS	Georgiana Slough at Sac River	SJL	San Joaquin R blw Old R near Lathrop
LIS	Yolo Bypass at Lisbon	SSS	Steamboat Slough
MAL	Sacramento River at Mallard Island	VNI	Venice Island
MHR	Middle River at Howard Road Bridge		

The DRMS report further suggests that it would be reasonable to use linear interpolation to estimate water levels at locations between gauging stations. Given the relatively small elevation change between each of the gauging stations and the approximations used in the DRMS analysis, a linear interpolation concept can be extended to planar interpolation so that the DRMS equations can be used to develop a stage-recurrence curve for any location in the Delta or Suisun Marsh.

The planar interpolation employed to develop a stage-recurrence curve consisted of dividing the Delta and Suisun Marsh area into triangles based on the locations of the 15 gauging stations used in the multiple regression analysis described in the previous paragraphs. The division of the Delta and Suisun Marsh area into triangular areas is illustrated on Figure 4. For each triangular area, a variable plane equation was derived from the equations at the triangle vertices. A stage-recurrence curve can then be developed by calculating a water level for a range of tide levels and total Delta inflows, and, because each inflow has a return period, the calculated water level can be related to return period.

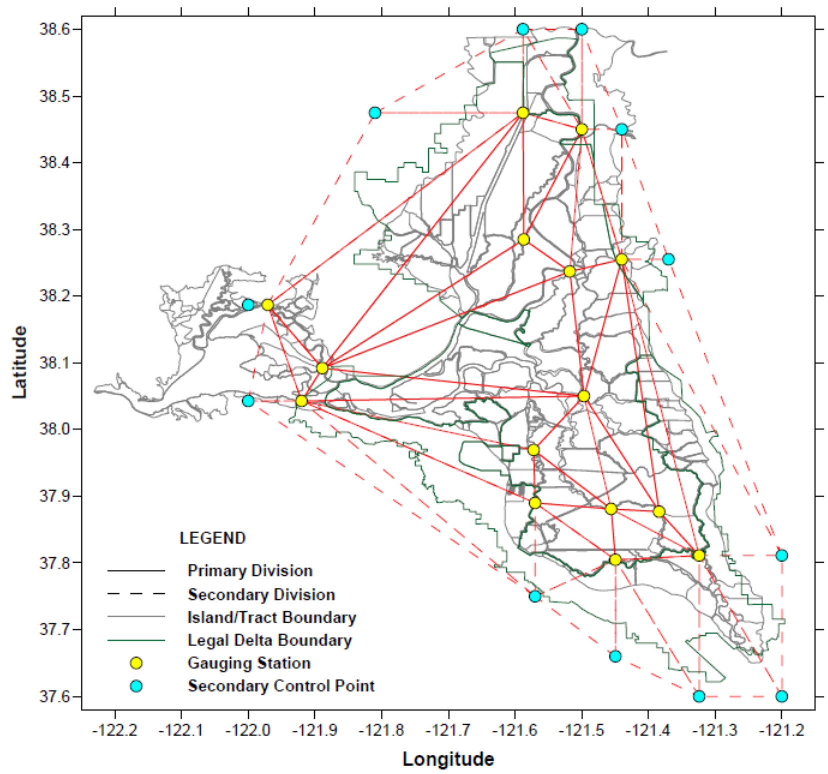

Figure 4-4. Triangular Division for Planar Interpolation

Stage-recurrence curves can be developed for any assumed tide level. An average maximum daily Golden Gate tide level was used to develop the curves shown in this memorandum and for baseline risk calculations.

To evaluate the effectiveness of the planar interpolation method, stage-recurrence curves developed by this method were compared to stage-recurrence curves developed in previous studies. Three stage-recurrence curves presented in the USACE study (USACE 2013) and two stage-recurrence curves presented in the Central Valley Flood Protection Plan (CVFPP) (DWR 2012a) from locations in the Delta are shown on Figure 5 along with stage-recurrence curves developed with the planar interpolation method. At these locations, there is good agreement among the different methods used to develop stage-recurrence curves.

The triangle scheme of interpolating river stage has limitations, especially near the Delta and Suisun Marsh boundaries. Stage-recurrence curves will be adjusted at locations for which the interpolation over estimates or underestimates river stage. The adjustment will be based on observed river stage data from the California Data Exchange Center (DWR 2014).

The tidal component of the DRMS multiple regression equations is a factored daily maximum tide level at Golden Gate that is added to the water level determined from total Delta inflows (see term aT in equations (1) and (2)). The DRMS investigators derived tide factors (see Table 4) for each of the 15 gauging stations. The tide factor is related to channel hydraulic characteristics and distance from the west Delta and varies from 1.00 in Suisun Marsh to 0.00 in the north Delta.

The planar interpolation concept used for calculating stage-recurrence curves was also applied to estimating the tide factor. The division of the Delta into triangular areas (see Figure 4) was used to estimate tide factors at any location in the Delta. Because of the strong tidal influence (NOAA 2014; also see tide factor for Lisbon gauging station in Table 4) in the Sacramento River Deep Water Ship Channel (SRDWSC) and lack of a sufficient number of gauging stations west of the SRDWSC, it was necessary to manually adjust the planar interpolation of tide factors at 14 islands and tracts in the north Delta. A contour map of estimated tide factors is presented on Figure 6, and the 14 adjusted tide factors are shown in Table 6. The contours were calculated from adjusted and unadjusted tide factors.

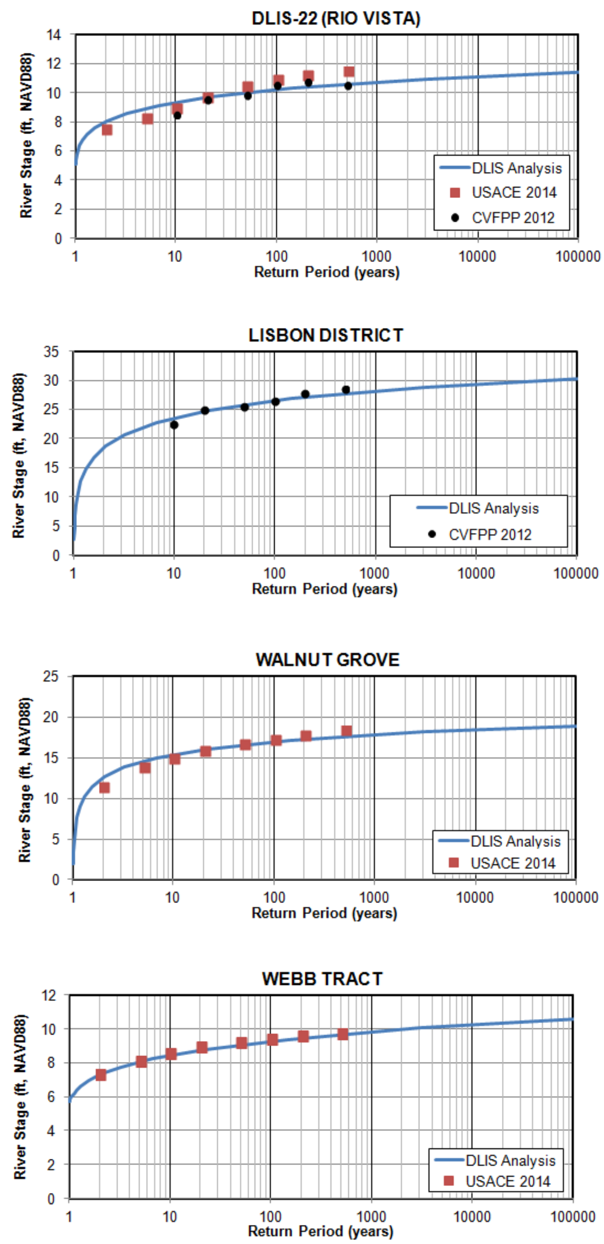

Figure 4-5. Stage-Recurrence Comparisons

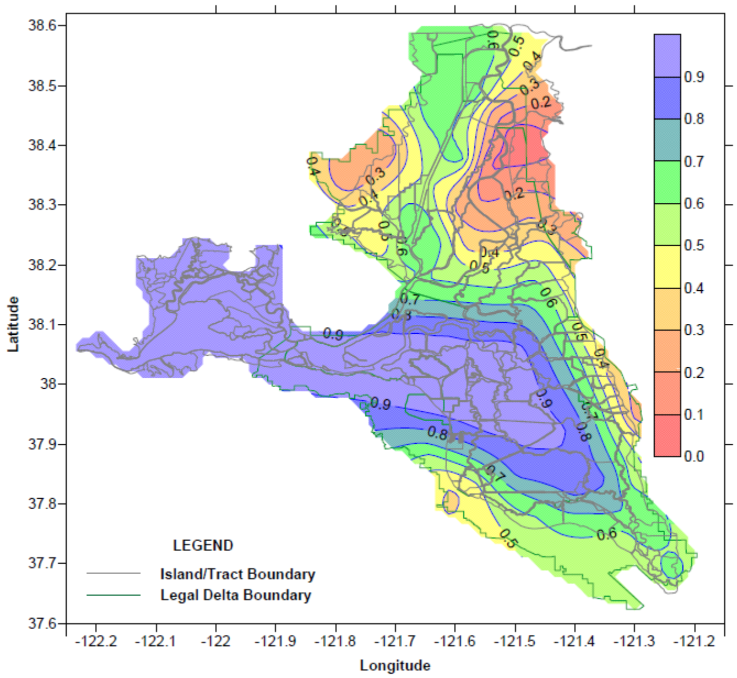

Figure 4-6. Tide Factor Contours

Table 4-6. Adjusted Tide Factors

Name	Tide Factor, Adjusted	Name	Tide Factor, Adjusted
Cache Haas Area	0.44	Little Egbert Tract	0.65
DLIS-20 (Yolo Bypass)	0.65	Netherlands	0.65
DLIS-21	0.20	Peters Pocket	0.44
Egbert Tract	0.44	Prospect Island	0.65
Glide District	0.65	Ryer Island	0.65
Hastings Tract	0.44	West Sacramento	0.65
Liberty Island	0.65	Yolano	0.20

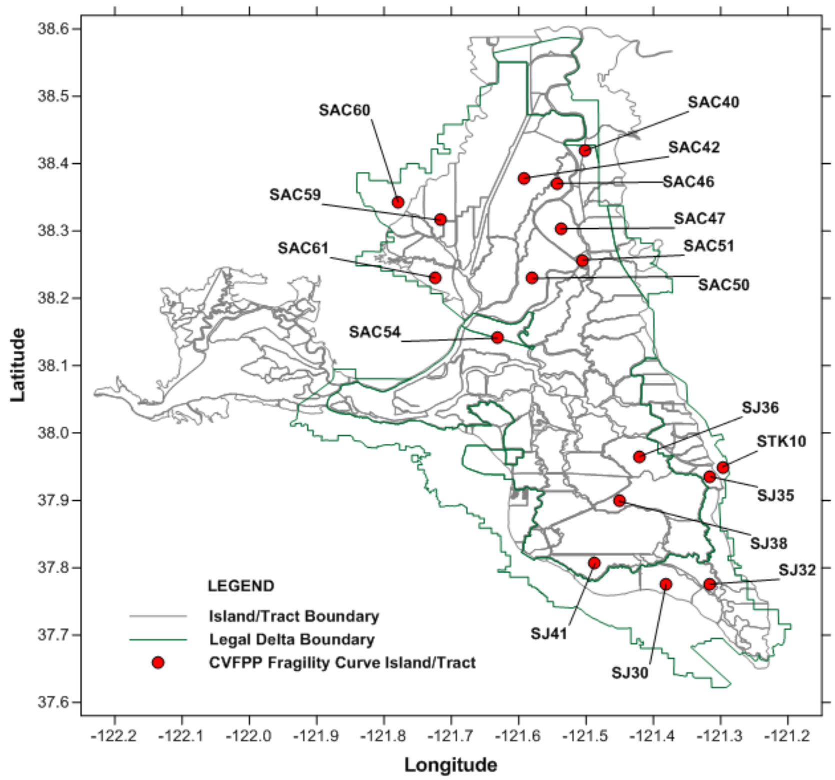

Figure 4-7. CVFPP Levee Fragility Curve Island and Tracts

5. LEVEE VULNERABILITIES

For the DLIS analysis and for the development of a DLIS Planning Tool, current and future levee vulnerability were considered. Current levee vulnerability addresses the likelihood of levee failure for the present condition of the levees and the magnitude and frequency of current levee hazards. Future levee vulnerability addresses the likelihood of levee failure under assumptions to be made about the future condition of the levees and changes to the magnitude and frequency of levee hazards.

For a risk-based analysis, levee vulnerability is typically expressed as one or more levee fragility curves that relate the magnitude of a hazard to the conditional probability of levee failure should that hazard occur. The joint probability of levee failure can be determined by integrating, over all hazard levels, the probability of the hazard multiplied by the conditional probability of failure.

Levee fragility curves are one of the key components used in analyzing current and future levee performance. Because the DLIS project intends to use the best available data, the levee performance analysis performed by the DLIS team will be based on the available levee fragility curves. The levee fragility curves available from previous studies do not cover every Delta and Suisun Marsh island and tract or may no longer represent current levee conditions. Estimated levee fragility curves will be developed for islands and tracts without existing curves.

As described earlier, the significant current levee hazards are hydrologic, hydraulic, and seismic hazards. Hydrologic and hydraulic hazards are often expressed in a single levee fragility curve that incorporates geotechnical, seepage, overtopping, and seismic failure mechanisms. However, seismic levee fragility will be addressed separately because flooding due to a seismic levee failure will happen with less warning than flooding due to a hydrologic event and, consequently, has a greater potential for fatalities and damage.

5.1 Hydrologic and Hydraulic Levee Fragility Curves

Detailed analyses were completed in previous studies (DWR 2008b, 2012b) to develop levee fragility curves that incorporate geotechnical, seepage, and overtopping failure mechanisms for hydrologic and hydraulic hazards. The major result of the DRMS studies (DWR 2008b) were levee failure rates per year per levee mile rather than levee fragility curves, but data and analyses from the DRMS study can be used to augment levee fragility curves for the DLIS project. The CVFPP study (DWR 2012b) produced levee fragility curves for approximately 100 areas in the Sacramento and San Joaquin river basins. About 25 of the areas are in the legal Delta, and

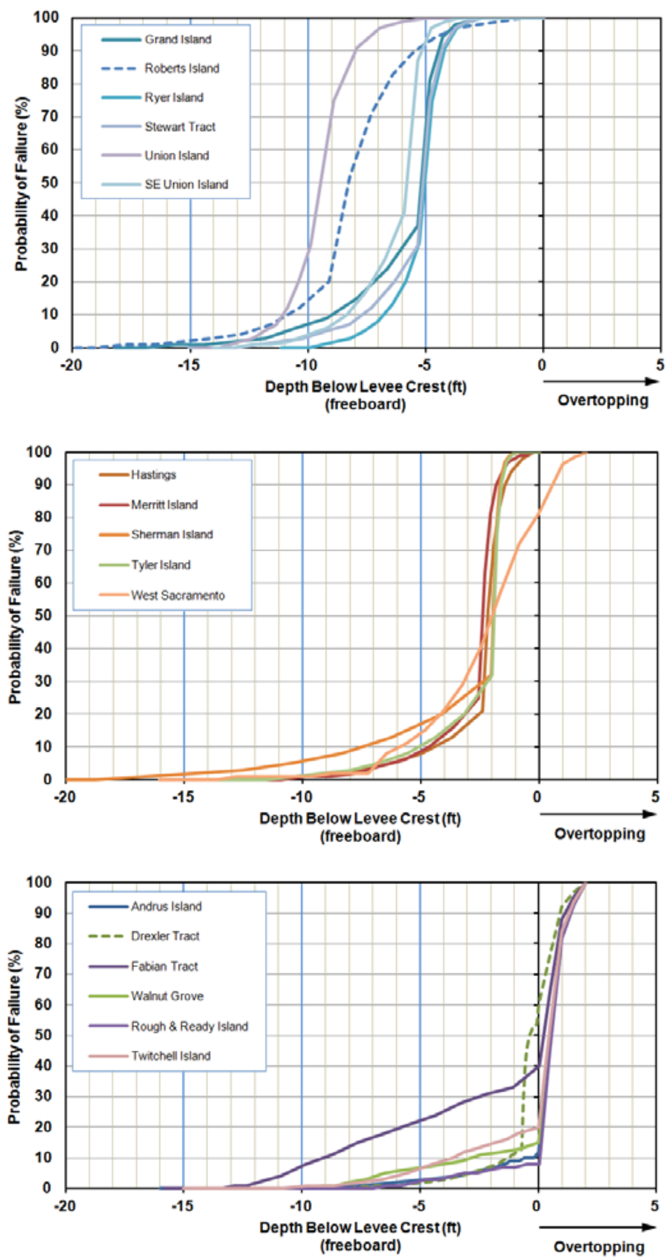

Figure 4-8. CVFPP Levee Fragility Curves

levee fragility curves from these areas will be used directly in further DLIS levee risk calculations. The location of several of the levee fragility curves from the CVFPP study that are within the Delta and Suisun Marsh area are shown on Figure 7, and CVFPP levee fragility curves are shown on Figure 8. Water level elevations for the levee fragility curves in the CVFPP study are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) datum. The water level elevations in the CVFPP curves will be converted to reference datum NAVD88 to be consistent with other elevations used in the DLIS project.

Because levee fragility curves are not available for all Delta and Suisun Marsh islands and tracts, a procedure similar to that outlined in the CVFPP study (DWR 2012b) will be used to develop additional curves. The procedure entails estimating a water level at which the probability of failure is expected to be zero (PNP, probable non-failure point), a water level at which the probability failure is expected to be 0.85 (assessment point), and a water level at which the probability of failure is expected to be 1.0 (PFP probable failure point, at levee crest or above if overtopping is necessary to fail the levee). This procedure is a modification of a USACE method (USACE 2010) and requires engineering judgment on the part of the DLIS team to estimate the three water levels. The engineering judgment will be informed by a review of the levee foundation soils data, current levee geometry, and current levee conditions.

5.2 Seismic Levee Fragility Curves

The impact of seismic activity on Delta and Suisun Marsh levees was thoroughly analyzed in the DRMS study (DWR 2007, 2008b). The USACE study (USACE 2013) used the results of the DRMS study. The CVFPP study (DWR 2012b) does not explicitly address seismic levee fragility.

The approach to be taken in the DLIS project will be to develop seismic fragility curves based on USGS data (USGS 2014b) and analyses completed in the DRMS study (DWR 2008b). Site-specific seismic hazard curves from the USGS will be used in conjunction with the probability of failure versus peak ground acceleration (pga) curves from the DRMS study. An example of a seismic hazard curve for several site classes from the USGS web site is shown on Figure 9 (near the center of Bacon Island). The site classes listed on the USGS web site refer to the characteristics of the subsurface conditions at the site. Because the Delta and Suisun Marsh sites generally consist of relatively thick, soft soils and peat, seismic hazard curves for site class D will be used.

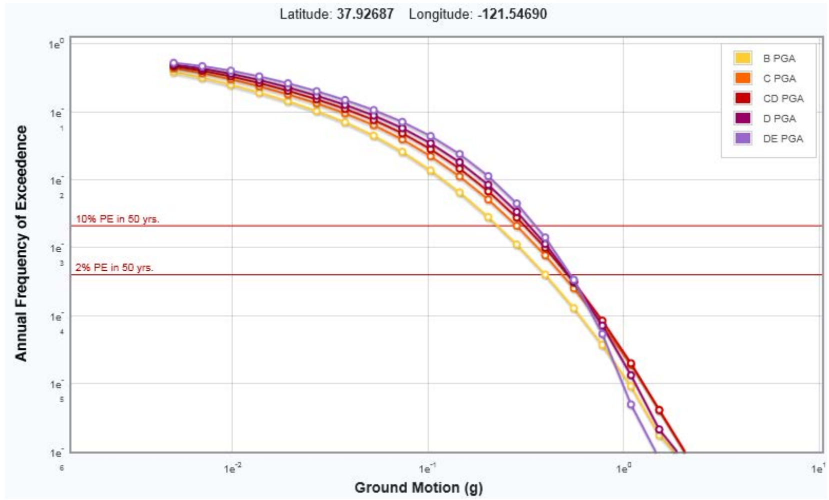

Figure 4-9. Sample Peak Ground Acceleration (pga) Recurrence Curves

Seismic fragility curves for 22 seismic vulnerability classes are presented in the DRMS report (DWR 2008c). Because each island and tract may have reaches with different seismic vulnerability and because each island and tract is analyzed as a whole, the worst seismic vulnerability for each island and tract will be used (weakest link concept). This approach will be used for those islands and tracts with reach length and seismic vulnerability reported in the DRMS data. For those islands and tracts not included in the DRMS data, the island's or tract's seismic vulnerability will

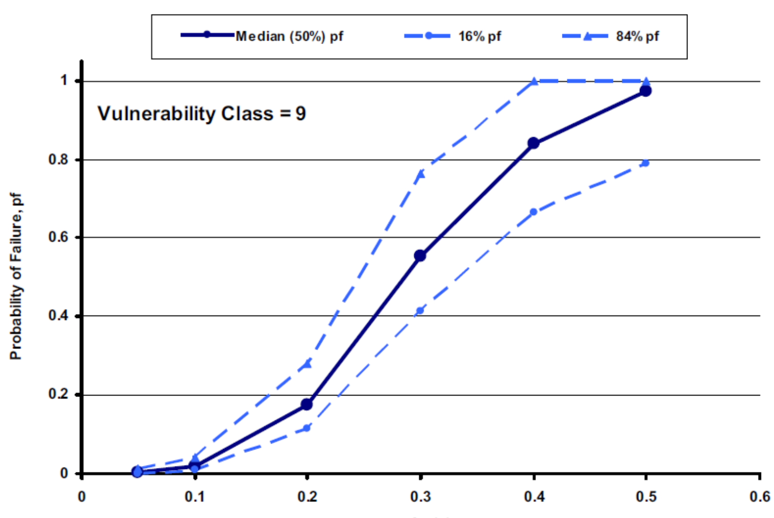

Figure 4-10. Sample Seismic Fragility Curve

be estimated based on known levee condition and proximity to islands with DRMS data. An example of a seismic fragility curve from the DRMS report (DWR 2008c) is shown on Figure 10.

The seismic fragility curves are conditional probability curves. The probability of failure at some acceleration, for example a pga of 0.2 gram (g), is conditioned on the probability of occurrence of that pga. Thus, the joint probability of seismic failure at 0.2g is the product of an 0.2 pga occurrence and the probability of failure at 0.2g. Integrating the product of occurrence probability and conditional failure probability over the entire range of accelerations yields the annual probability of seismic failure for all seismic events.

5.3 Wind and Wave Fragility

In general, wind and wave fragility is a function of wave run-up and storm surge. Storm surge creates additional water height and and waves have erosion potential. Methods are being developed to incorporate the additional water height into stage-recurrence curves and erosion potential into levee fragility curves. The adjustments to stage-recurrence or levee fragility would only be applied to islands facing open water with sufficient depth and fetch length.

6. LEVEE FAILURE CONSEQUENCES

A comprehensive analysis of levee failure consequences considers the immediate and long-term impacts to human health and safety; economic damage to assets; and other social, political, and environmental consequences. The DLIS project will address these consequences through calculation of expected monetary and non-monetary damages and development of a DLIS Planning Tool.

Levee failure consequences can be categorized as direct or indirect and tangible or intangible. Direct consequences are those that occur through contact with the flood waters, whereas indirect consequences are those created by the levee failure but occurring outside the flooded area, or after the flood is over. Tangible consequences are generally those damages that can be assigned a monetary value or can be enumerated (e.g., fatalities). Intangible consequences may be monetary in nature, but are generally more difficult to identify and calculate (e.g., ecosystem damages).

A matrix of direct-indirect and tangible-intangible levee failure consequence categories is shown in Table 7. Most of the assets in the direct, tangible consequence category will be addressed by estimating potential monetary damages. The other consequence categories listed in Table 7 will be addressed via non-monetary damage estimates or via the DLIS Planning Tool.

Table 4-7. Levee Failure Consequence Categories

	Tangible	Intangible
Direct	Buildings and contents Infrastructure Crops and livestock Erosion of agricultural soil Ecosystem Evacuation and rescue Repair and cleanup	Fatalities Injuries Psychological distress Cultural heritage loss
Indirect	Business disruption Public service disruption Traffic disruption Loss of tax revenue	Loss of trust in authorities Trauma

(Source: Merz et al. 2010)

7. EXPECTED ANNUAL DAMAGES

If an island or tract in the Delta and Suisun Marsh is inundated because of a levee breach, the choices facing decision makers and stakeholders would be to (a) rehabilitate the island or tract by repairing the levee breach and pumping the island or tract free of floodwater or (b) allow the island or tract to remain permanently flooded. An estimate of expected annual damages will depend on which of these two options is selected.

If the choice is option (a), rehabilitate the island or tract, the costs of flooding will consist of lives lost, cost of repairs to assets, cost of lost agricultural production, and the cost of repairing the levee and, in some cases, pumping flood water out of the island or tract (known as dewatering).

If the choice is option (b), allow the island or tract to be permanently flooded, the costs of flooding will consist of lives lost, the value of assets lost, the value of current and future lost agricultural production, and the value of the land lost. However, there would be no cost of repairing the levee and pumping flood water out of the island or tract.

Separate expected annual damages will be calculated for options (a) and (b) for every levee island and tract.

8. EXPECTED ANNUAL DAMAGES WITH REHABILITATION

Current or future direct economic loss due to levee failure is generally expressed as expected annual damage with rehabilitation (EAD_R). EAD_R is a risk-based calculation of the annual cost of flooding. EAD_R is calculated by integrating, over all possible flood levels, the product of the probability of levee failure and the potential economic damage. This risk-based metric is consistent with the state of practice in flood risk management and is comparable to methods used in USACE and Federal Emergency Management Agency (FEMA) flood damage assessment software (USACE 2008; FEMA 2009).

EAD_R is generally defined as the product of hazard, vulnerability, and exposure:

$$EAD_R = \Sigma hazard_i \bullet vulnerability_i \bullet exposure_i$$

where

- $hazard_i$ is the probability of hazard occurrence. Hazards are represented by an annual probability of recurrence. For example, water levels in the Delta waterways are represented by stage-recurrence relationships, which define the annual probability (recurrence) of each possible water level (stage).
- $vulnerability_i$ is the conditional probability of levee failure for hazard level i. A levee's vulnerability to each possible water level is represented by a fragility curve that defines the probability of levee failure given the height of water and the condition of the levee.
- $exposure_i$ is the value of assets that could be lost if the hazard were to occur and the levee were to fail. Stage-damage relationships are used to estimate the proportion of the value of a structure and contents that is damaged at the given flooding stage.

EAD_R for each Delta and Suisun Marsh island and tract will be calculated using the stage-recurrence and levee fragility curves described elsewhere in this memorandum. Delta and Suisun Marsh island and tract assets and asset values presented in Technical Memorandum 2.1 will be used in conjunction with stage-damage curves developed by USACE (2000, 2003) and FEMA (2009). Examples of USACE stage-damage curves are shown on Figure 11.

The USACE and FEMA stage-damage curves typically do not consider inundation depths greater than 10 feet. Inundation depths in the Delta and Suisun Marsh islands and tracts may be greater than 10 feet; thus, stage-damage curves will be projected linearly to greater depths as shown on Figure 11. Data and analyses from the DRMS study (DWR 2008a) and expert opinion will be used to develop stage-damage functions for assets not included among the USACE or FEMA stage-damage curves. Expert opinion, to be provided by members of the DLIS team, will be based on a review of damage reports from previous flooding in the Delta and Suisun Marsh area and flood damage reports from other locations with similar assets.

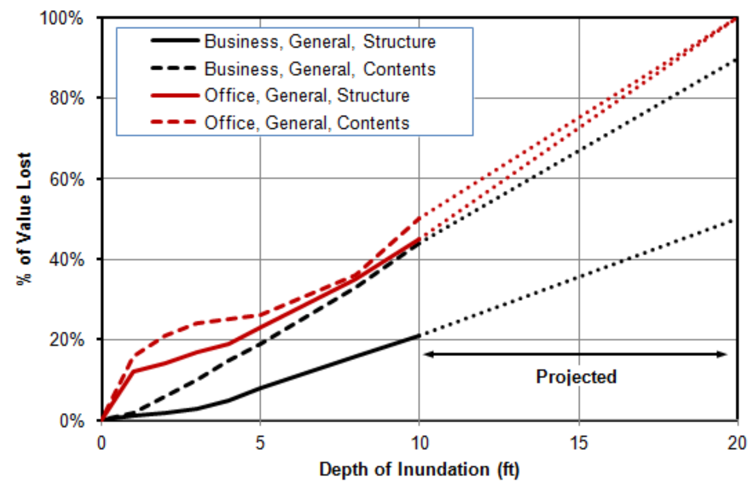

Figure 4-11. Stage-Damage Curves
(USACE 2003)

Damages to crops will be calculated based on crop type (field or orchard). A factor representing the multi-year impact of flooding will be applied to each crop type. For example, the lost value of a field crop due to flooding might be 100 percent in the year the flood occurred, 50 percent in the next year, and 10 percent in the second year after flooding. In this case, a factor of 1.6 would be applied to the current year value of the crop to account for subsequent year losses. A larger factor would likely be appropriate for orchard crops. Because EAD_R is an *annual* risk measure that considers average effects over a year, the time of year and duration of inundation are not explicitly considered in estimating crop damages.

In addition to calculating damages to assets on an island or tract, the EAD_R calculation will include the cost of rehabilitation of the island or tract. To understand the economic tradeoffs between options (a) and (b), it is necessary to calculate an expected annual rehabilitation cost, which estimates the average annual cost of rehabilitating a flooded island or tract. Note that the rehabilitation cost is estimated without regard to the source of rehabilitation funding (for example, the USACE's Public Law [PL] 84-99 Program).

A review of reported rehabilitation costs in the Delta and Suisun Marsh suggests that the cost of rehabilitating a flooded island or tract has several components; the most significant components are the costs to mobilize resources for recovery, the cost to repair a levee breach, and the cost to pump out the floodwater (DWR 2014; Suddeth et al. 2010; reclamation district 5-year plans). Rehabilitation costs are discussed in more detail in Technical Memorandum 3.1.

A baseline EAD_R will be calculated for each island and tract in the Delta using current hazards, levee vulnerability, and associated uncertainties. Potential future EAD_R values will be calculated by projecting future hazard levels, levee vulnerability, and asset values. Future hazard levels may change because of climate change effects such as sea level rise. Future levee vulnerabilities may improve because of investments in the Delta or worsen because of deterioration of unimproved levees. Future asset values may change because of population and economic growth or land and levee management strategies. The difference between future EAD_R values and baseline EAD_R will provide an economic measure of the likely benefit (positive or negative) of strategic levee investments.

9. EXPECTED ANNUAL DAMAGES WITHOUT REHABILITATION

The expected annual damages without rehabilitation (EAD_F) will be calculated for each island and tract in parallel with calculations of EAD_R with the following differences in method:

- The value of assets included in the EAD_F estimate for an island or tract that is not rehabilitated will be 100 percent of the asset value.
- 100 percent of the current year's lost crop value will be included in the EAD_F estimate.
- 100 percent of the value of the lost land will be included in the EAD_F estimate.
- The cost of levee repair and pumping will **not** be included in the EAD_F estimate.

10. NON-MONETIZED DAMAGES

10.1 Expected Annual Fatalities

First and foremost among the requirements of California Water Code section 85305(a) is to reduce risks to the people who live, work, and enjoy recreation in the Delta and Suisun Marsh. The risk to this group of people includes potential fatalities and injuries. The number of fatalities is often used as a proxy for fatalities and injuries; hence, an important metric to be used in the planning tool prioritization logic will be the impact of a strategic investment on expected annual fatalities (EAF).

EAF is a risk-based calculation of the average annual number of flood-related fatalities that would be anticipated in a region for a given set of potential flooding conditions. For example, a region may have a history of levee failures and flood-related fatalities from which the number of flood events per year (E / yr) and fatalities per flood event (F / E) could be calculated. Under an assumption that all flood events in this region are the same and that levee and river conditions remain unchanged, the calculation would be EAF = (E / yr) x (F / E). The goal of a strategic investment in this hypothetical region would be to reduce the number of flood events per year (e.g., by improving levees) or reduce the fatalities per event (e.g., by improving evacuation procedures) or a combination of the two.

In practice, of course, not all flood events are the same: there is uncertainty in the historical record of flooding and flood-related fatalities, and there will be uncertainty in predicting the impact of strategic investment on reducing the number of flood events per year or fatalities per event. Estimating EAF for the

Delta and Suisun Marsh will be challenging because, although flood frequencies are reasonably well known, very few, if any, flood-related fatalities have been recorded.

Flood-related fatalities are generally a consequence of one or more of the following flood event characteristics:

- Population at risk
- Water velocity
- Water depth
- Warning time
- Time of day or day of week (day or night, weekday or weekend)
- Floodplain area and topography
- Rate of rise
- Duration of flooding
- Water type (fresh, salt, temperature)

The population at risk in the Delta and Suisun Marsh includes permanent residents and a variable population of workers, recreation users, and travelers who are at risk only during the time they are in the Delta or Suisun Marsh.

The flood characteristics that lead to most flood-related fatalities are water velocity and depth. In the case of the Delta and Suisun Marsh, there can be a wide range of flood velocities and depths depending on the floodplain (island / tract) area and topography, distance from the levee breach, and size of the breach. The generally low temperature of flood waters in the Delta and Suisun Marsh presents an additional level of hazard to human health and safety.

Warning time is typically the most important factor in limiting fatalities during a flood event. However, the warned population must be able and willing to heed the warning. While warning systems and evacuation procedures are and will likely continue to be in place in the Delta and Suisun Marsh, it is likely that some portion of the population would not receive the warning or would be unable or unwilling to evacuate even if warned in time to do so.

The other flood event characteristics listed above generally have a lesser influence on flood-related fatalities, but may be important for certain islands or tracts in the Delta and Suisun Marsh and will be considered in the separate EAF calculations for each island and tract. For example, water velocity may be a more important factor for cases in which homes and businesses are located adjacent to a levee than for cases in which homes and businesses are some distance from a levee.

Several methods have been proposed for calculating EAF; for example, methods presented in the CVFPP (DWR 2012c), Delta Risk Management Strategy Risk Report (DWR 2008d), and Journal of Flood Risk Management (Jonkman and Vrijling 2008).

The general approach of each of these and many other methods is to determine the total population at risk (PAR), estimate the percentage of the population who will come in contact with the flood water (p_c), and estimate the percentage of fatalities among those who come in contact with the flood water (p_f). EAF is then the product of these three values and the probability that a flood event will occur (p_e); i.e.,

$$EAF = PAR \bullet p_c \bullet p_f \bullet p_e.$$

The more detailed of these methods consider the different flood levels that may occur and the different probability of each flood level. In this case, p_c, p_f, and p_e are estimated for each flood level and the EAF values that are calculated for each flood level are summed to obtain a total EAF.

The total PAR used in these methods is generally determined from census data, which can account for the permanent resident population and the variable population of workers. Other means must be used to estimate the average number of recreation users and travelers that may be part of the total population at risk. Some of the methods focus only on the permanent resident population; hence, those methods may underestimate EAF.

The procedure used to estimate the percentage of the total population at risk who will come in contact with the flood water (p_c) is somewhat different in each of the methods referenced above, but the methods generally consider some combination of the flood warning system effectiveness and evacuation efficiency. The type of breach (flood, seismic, sunny day), population proximity to a levee breach, time of day of the breach, rate of rise, and similar flood factors are considered when developing an estimate of p_c.

The procedure used to estimate the percentage of fatalities among those who come in contact with the flood water (p_f) is also somewhat different in each of the methods. The factors of water depth and velocity, rate of rise, water temperature, and duration of flooding are typically considered when developing an estimate of p_f.

The probability or probabilities of flood event occurrence (p_e) used for calculation of EAF will be the same as those used for calculating EAD_R, described in Section 8.

The method used to calculate EAF will be based on the general procedure outlined in the previous paragraphs. However, components from each of these methods will be used to estimate PAR and the percentages p_c and p_f taken rather than strictly following a single method. Each method has certain strengths that can be used to calculate EAF values that are supported by the available flood fatality data and are consistent with the level of detail used elsewhere in the DLIS analysis.

PAR will be obtained from current U.S. Census Bureau data for the population within the legal Delta and Suisun Marsh boundaries. An average annual recreation user population, to be derived from a California DWR estimate of annual recreation user days, and an average annual traveler population, to be derived from Caltrans average annual daily traffic (AADT) data, will be added to the census PAR to obtain a total PAR.

The percentage of the total PAR who will come in contact with the flood water will be based on the type of breach (flood, seismic, sunny day). Warning systems are assumed to be effective at some level for flood breaches, but warning systems will be less timely and less effective for seismic or sunny day breaches. The percentage of total PAR unaffected by warnings will be derived by examining the available studies and data for the Delta and Suisun Marsh and other similar locations. The percentage of fatalities among those who come in contact with the flood water will be estimated by examining the available studies and data for the Delta and Suisun Marsh and other similar locations.

10.2 Expected Annual Agricultural Land Loss

The direct economic impact of flooding of agricultural land (the immediate loss of current and near-term future crops) is included in the calculation of EAD_R. However, when done for potential strategic investments, this calculation does not consider the impact of agricultural land that may be converted to ecological habitat or permanently flooded. The EAD_R calculation alone may show that some strategies reduce the economic impact of agricultural flooding simply because the strategy reduces the available agricultural acreage. Therefore, an agricultural land loss metric is needed that can inform policy decisions that will arise from consideration of strategic investments that convert agricultural acreage to ecological habitat or allow an island to remain permanently flooded. The agricultural land loss metric will be net acres of agricultural acreage lost scaled by a non-monetary factor to reflect high, medium, and low agricultural productivity. A non-monetized metric for agricultural land loss will be used because of the uncertainty in predicting future agricultural land uses (crop type and/or crop value per acre).

Strategic investments that would result in agricultural land loss could include a scenario that converts agricultural land to ecological habitat and / or a scenario that allows a flooded island to remain permanently flooded. In the case of conversion to ecological habitat, it is assumed that every acre converted to habitat is an acre of agricultural land lost. In a scenario that allows a flooded island to remain permanently flooded, the agricultural acreage on the island would be risk-adjusted by the annual probability that the island's levee would be breached.

The calculation of expected annual agricultural land loss (EAALL) is similar to the calculation of EAD_R with the exception that asset value and likelihood of damage are replaced, respectively, by potential acreage lost and a scale factor representing high, medium, or low agricultural productivity.

$$EAALL = (HA + \Sigma p_i \bullet land\_loss_i) \bullet A_v$$

where

- HA is the acreage of agricultural land converted to habitat
- p_i is the annual probability of flood depth i

- $land\_loss_i$ is the acreage of agricultural land that could be lost at flood depth i
- A_V is a scale factor representing high, medium, or low agricultural productivity
- the summation Σ is over all flood depths

11. FUTURE LEVEE HAZARDS, VULNERABILITIES, CONSEQUENCES, AND DAMAGE COSTS

The probability of future levee failures will depend on assumptions regarding future levee hazards and vulnerabilities, which will lead to changes in predicted consequences and damage costs. The monetary and non-monetary analyses described in this memorandum will be based on existing conditions as well as a range of possible future conditions to evaluate the effect on the magnitude and uncertainty of the predicted consequences and damage costs.

Based on a review of the previous Delta and Suisun Marsh studies and the literature, it was concluded that the most significant uncontrollable variations in Delta and Suisun Marsh levee hazards would be from climatic changes and the most significant controllable hazard variations would be from levee deterioration.

Uncontrollable climatic changes that would alter the Delta and Suisun Marsh levee hazards include increased precipitation in the Delta drainage basin, earlier and higher elevation snowmelt in the Delta drainage basin, and sea level changes. Precipitation and snowmelt changes would alter the magnitude and frequency of total inflow to the Delta, and sea level change would alter flows through the Delta. The impact of climatic changes on the DLIS analyses would be to alter the discharge-frequency curve used to estimate total Delta inflow probabilities and the stage-recurrence curves used to estimate water level probabilities at each Delta and Suisun Marsh island and tract.

Another significant uncontrollable future hazard is continued subsidence of the islands and tracts. Continued subsidence, even in the absence of climatic changes, will increase the hydraulic pressure on the Delta and Suisun Marsh levees and will create groundwater control issues that may reduce agricultural productivity. The impact of continued subsidence on the DLIS analyses will be to alter the Delta and Suisun Marsh levee fragility curves to account for increased probability of seepage failure and will alter future agricultural asset values to account for reduced productivity.

With regard to seismic hazards, an uncontrollable hazard, the currently accepted time-independent seismic model that assumes that the probability of earthquake occurrence is constant over time (i.e., does not depend on time since the last event) is being used. Time-dependent seismic models that account for the time elapsed since the last event have been proposed but are not widely used. Consequently, future seismic hazards, within the framework of the 50 years considered in the DLIS study, will be considered to be the same as current seismic hazards.

The controllable hazard of levee deterioration is addressed by continued maintenance and by major levee improvements, including strategic investments in the Delta and Suisun Marsh that would be considered via the DLIS Planning Tool. Major levee improvements will alter the levee fragility and stage-damage functions used in the DLIS analyses. Consideration of new or improved levees will require alterations to levee fragility curves to reflect levee performance improvements. Consideration of non-structural alternatives (e.g., flood-proofing buildings) would require changes to stage-damage functions to reflect the lesser cost of flooding.

The analysis of future Delta and Suisun Marsh conditions will also consider the effects of land loss. Whether land is converted to habitat or an island is allowed to remain permanently flooded, assets (most likely agricultural assets) would be removed from the calculation of expected annual damages.

12. DATA GAPS AND UNCERTAINTIES

The significant data gaps that can affect the accuracy and certainty of the analyses described in this technical memorandum are presented below. In addition, methods to evaluate the significance of the data gaps and, where possible, to overcome the data gaps are described.

12.1 Predictability of River Stage Recurrence

The current method of predicting stage-recurrence curves at specific locations is based on a piecewise linear interpolation from 15 data points. Sensitivity analyses will be completed to judge the influence of uncertainty in stage-recurrence curves. However, location-specific analysis of observed peak stages could substantially reduce this uncertainty.

12.2 Hydrologic/Hydraulic Fragility

Location-specific levee hydrologic/hydraulic fragility curves are available for 30 of the Delta and Suisun Marsh leveed islands and tracts. Fragility curves for another 112 leveed islands and tracts are estimated by professional judgment using limited knowledge of levee and foundation conditions. Sensitivity analyses will be completed to judge the influence of uncertainty in fragility curves. However, additional studies of location-specific levee fragility could substantially reduce this uncertainty.

12.3 Seismic Fragility

The available seismic fragility curves are subject to wide discussion as to their validity and applicability. Sensitivity analyses will be completed to judge the influence of uncertainty in the seismic fragility curves. Resolution of this uncertainty will come from ongoing academic research and further synthesis of experience from other, similar locations.

12.4 Stage Damage Relationships

Stage-damage relationships and the uncertainty of those relationships for residences and businesses are reasonably well established. Sensitivity analyses will be completed to judge the influence of the known uncertainty. The uncertainty associated with stage-damage relationships for other assets (e.g., crops, roads, railroads, transmission lines) is less well established, but will be included in the sensitivity analyses.

An additional, detailed investigation of cost of asset recovery following previous Delta flood events could reduce this uncertainty.

12.5 Prediction of Fatalities

Estimates of the percentage of the population that would come in contact with flood waters and the mortality rate of this subset of the total population are based on typical rates observed at other, similar locations. Sensitivity analyses will be completed to judge the influence of uncertainty in the population in contact with flood water percentage and mortality rate; however, additional local knowledge and expert judgment will be elicited in an attempt to reduce this uncertainty.

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