Delta Risk Management Strategy

INITIAL TECHNICAL FRAMEWORK PAPER

SACRAMENTO–SAN JOAQUIN DELTA RISK ANALYSIS APPROACH AND BASIS OF ANALYSIS

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Sacramento–San Joaquin Delta Risk Analysis
Approach and Basis of Analysis

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Foreword

The purpose of the Delta Risk Management Strategy (DRMS) Initial Technical Framework (ITF) paper is to guide the analysis of specific technical topics as they relate to assessing potential risks to Delta levees and assets resulting from various potential impacts (e.g., floods, earthquakes, subsidence, and climate change). These ITFs are considered "starting points" for the work that is to proceed on each topic. As the work is developed, improvements or modifications to the methodology presented in this ITF may occur.

This ITR paper describes the scope, methodology, and precepts for the risk analysis that will be performed for the Sacramento–San Joaquin Delta and Suisun Marsh (the Delta) as part of the DRMS project. The overall purpose of the analysis is to assess the future performance of Delta levees and the potential economic, environmental, and public health and safety impacts of levee failures to the Delta region itself and California as a whole. A subsequent document will describe the approach to developing and evaluating risk reduction strategies.

In this project risk will be measured in terms of the annual frequency of exceedance (occurrence) of defined consequence metrics (e.g., economic impact or impact to species) that result from failure of Delta levees and other assets. The risk analysis for the Delta is a significant undertaking that involves a multi-disciplinary evaluation. The analysis will consider the effects of a range of natural hazards (such as earthquakes, floods, and wind waves) on Delta levees and the occurrence of normal or sunny-day levee failures, the hydrodynamic effects (e.g., intrusion of saltwater from San Francisco Bay into the Delta) that occurs as levees breach and islands flood, and the effectiveness of emergency operations (e.g., repair of breached levees and the protection of exposed levee interiors to wind waves and damaged but not-breached levees). The analysis will also assess the impact of levee failures, including in-Delta and statewide economic consequences, duration of water export disruptions, and environmental consequences (both adverse as well as favorable).

As with any engineering assessment, the purpose of a risk analysis is to assess the performance of the system when exposed to various challenges and to assess the consequences that result. As with most systems, the risk to the Delta (the ecosystem, the public that lives and works there, businesses, etc.) and the state as a whole, which relies on the Delta for freshwater conveyance, is a function of the physical performance of the system's elements (e.g., levees) to events such as earthquake ground shaking and the response of the system owners, operators, and stakeholders in the aftermath of these events as manifested in emergency response and repair efforts, etc. Thus, an important element of the DRMS risk analysis is to gather information about the Delta system (e.g., levee physical characteristics) and on the policies and practices that guide the response to events in the Delta so the risk analysis can provide a best (unbiased) measure of the likelihood and severity of events and their consequences.

The ITR paper lays out the approach taken to model aleatory and epistemic uncertainties. The paper discusses the basic aleatory probabilistic model for estimating risk and the approach for modeling epistemic uncertainties. Epistemic uncertainties are attributable to our current state of knowledge (e.g., lack of data and scientific understanding) about the Delta and the effects that levee failures may have. The quantification of epistemic or knowledge-based uncertainties will identify the elements of the analysis where lack of data and/or information contributes to uncertainty in the results.

In response to the requirements of Assembly Bill 1200, the analysis must also consider the evolution of risks over the next 200 years. This ITF paper discusses the approach that will be taken to estimate risk over that period. The approach, which must be based on existing information, will consider the increasing potential for a major seismic event, the effects of climate change (e.g., sea level rise or hydrologic impacts), changes in land use, and the increasing exposure of people and property in the Delta to the effects of island flooding, and the growing exposure of the state to the effects on water export disruptions.

This ITF paper also describes the implementation approach that is being carried out to develop the Delta risk model. As part this approach, a series of topical areas have been established to develop different elements (modules) of the risk model. The model development in the individual topical areas cannot be carried out independently. An important part of the development process is the interface (information, probabilistic, developmental, etc.) between these elements.

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1.0 INTRODUCTION

The Delta Risk Management Strategy (DRMS) project has two primary areas of focus. The first is to analyze the risks to the Sacramento–San Joaquin Delta and Suisun Marsh (the Delta and Suisun Marsh) and the state that may result from Delta levee failures. The second is to develop risk-informed strategies for managing the Delta in the future. Broadly stated, an evaluation of strategies must meet the requirements of Assembly Bill (AB) 1200, which calls for an assessment of:

> *the potential impacts on water supplies derived from the Sacramento-San Joaquin Delta based on 50-, 100-, and 200-year projections for each of the following possible impacts on the delta: (1) Subsidence, (2) Earthquakes, (3) Floods, (4) Changes in precipitation, temperature, and ocean levels, (5) A combination of the impacts specified in paragraphs (1) to (4), inclusive.*

Further, AB 1200 requires the Department of Water Resources (DWR) and the Department of Fish and Game (DFG) to "determine the principal options for the delta."

This ITF paper describes the approach and basis for conducting a Delta risk analysis. A subsequent document will discuss the approach for the evaluation of options/risk management strategies.

1.1 Risk

In this analysis, risk is defined as the likelihood (frequency) of adverse consequences that could occur as a result of levee failures in the Delta. Quantitatively, risk is defined in terms of three entities; loss or consequence, frequency of occurrence and probability as a measure of uncertainty (Kaplan and Garrick 1981).[1]

The focus of the DRMS study is the assessment of risk to the Delta and the state associated with levee failure. The risk analysis will address events (e.g., earthquakes, floods, climate change) that impact the performance of Delta levees and the consequences that may ensue. These same events present a hazard to other parts of California and thus potential for consequences that may further impact the state. For instance, the consequences associated with a major seismic event east of San Francisco Bay could be substantial outside the Delta (e.g., damage to the Contra Costa County water distribution system). The impact to the other water system assets in and beyond the Delta will be assessed to the extent that such impact is caused by the same events that also trigger levee breaches and island flooding. The simultaneous occurrence of island flooding and the failure of co-located water system assets could significantly increase the interruption of local water supply and/or statewide water export, and hence will need to be modeled.

1.2 Study Precepts

The Delta is a vital part of California. It is a diverse, dynamic, and treasured ecosystem, a vital part of the state's water resources infrastructure, the location of many communities, and a valued recreation destination. It is also a complex environment that is, in many respects, not well understood. It is for example, a region that is an ongoing focus of environmental and scientific research. From the perspective of the DRMS project, an assessment of risks and the evaluation of

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[1] While the focus of the DRMS risk analysis is the analysis of risk as defined above, it is worth noting that events which are modeled may involve benefits. For example, this may be the case with respect to impacts of levee failures on the ecosystem.

risk management strategies must be made on the basis of the current state-of-knowledge (information, data). To the extent our present state of knowledge is incomplete, making an assessment of risk is uncertain. The effect these uncertainties have on the study results will be included in the assessment.

An analysis of risks associated with Delta levee failures is a complex and significant undertaking. The following precepts guide the Delta risk analysis:

- The DRMS project must be carried out, for the most part, using existing information (data and analyses). The project schedule does not afford the opportunity to conduct field studies, laboratory tests, or research investigations.[2]
- The analysis should include an assessment of the epistemic uncertainty in the analysis that reflects the uncertainty associated with the current state of knowledge (data, information and engineering and scientific understanding) with respect to the events and consequences that are modeled.
- Measures of risk (e.g., risk metrics) should be assessed that reflect the impacts (e.g., public health and safety, economic, environmental) that must be considered in the evaluation of Delta risk management strategies called for in AB 1200.
- A "business-as-usual' approach will be taken to guide the analysis with respect to modeling the current risk as well as in making projections of future risks. The notion of business-as-usual and its implementation in the risk analysis are discussed further in Section 4.

These precepts and their implication with respect to the model development are discussed further in the ITR paper.

1.3 Scope

Section 2 defines the geographic bounds of the study region.

Section 3 provides a summary of the Delta and gives an overview of events that could occur as a result of levee failures. This discussion provides a perspective with respect to the range of events and their consequences when levees fail and serves a guide to building a risk model.

Section 4 provides an overview of the scope of the DRMS risk analysis. Topics discussed include the various bounds of the assessment (geographic, temporal, etc.).

In Section 5, salient features of assessing risks for the Delta are discussed.

Section 6 describes the risk analysis methodology.

Section 7 gives an outline of the approach that is being implemented to develop the Delta risk model.

Section 8 identifies major assumptions and limits of the DRMS risk analysis.

In Section 9 a summary of the primary products of the risk analysis is provided.

References cited are provided in Section 10.

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[2] It is anticipated the risk analysis will provide insight into where sources of uncertainty (e.g., limited data, scientific uncertainty are important to the assessment of risk).

In addition to describing the overall risk analysis approach and basis for the analysis, this ITR paper also provides an outline the elements of the risk analysis and the integration of the various parts of the analysis to build the risk model. This discussion serves to tie the various parts of the analysis together.

The DRMS project is not a planning study. Rather it is intended to develop quantitative risk information and risk-informed strategies for managing the Delta. By itself this information will not be the sole basis for future decisions with respect to managing the Delta, nor will it provide planning-type information to guide design activities. The risk analysis results and the identification of risk-informed management strategies will support the Delta Visioning process and provide information that can be used in subsequent planning studies.

The DRMS project will focus on estimating risks (economic, environmental, in-Delta and state-wide), including altered consequences resulting from risk management. It will not optimize risk management strategies, provide detailed cost information, or perform cost-benefit analyses of risk management options.

2.0 STUDY GEOGRAPHIC AREA

With respect to the evaluation of levee systems, the geographic scope of the DRMS risk analysis includes (DWR 2005):

- Suisun Marsh east of the Benicia-Martinez Bridge on Interstate 680; and
- Legally defined Sacramento–San Joaquin Delta as defined in Section 12220 of the Water Code

This area is identified in Figure 1. The study area is defined in the context of the region within which the failure of Delta levees and island flooding, and failure of other in-Delta infrastructure are evaluated.

As discussed later in this ITR paper, the geographic scope does not apply to the assessment of the consequences associated with levee failures. Consequences (e.g., economic impacts) will be evaluated on a state-wide scale.

3.0 THE SACRAMENTO–SAN JOAQUIN DELTA AND SUISUN MARSH

The Delta and Suisun Marsh covers an area of approximately 750,000 acres (see Figure 1). This section provides an overview of the Delta, Delta levees, and its role in California's water system.

3.1 Delta Levees, Water Supply, and the Environment

The purpose of the DRMS study is to assess the risks to the state associated possible future levee failures and to consider strategies for managing this risk. In the study region there are 1,345 miles of levees in an area of 750,000 acres. Much of the land that is protected by these levees is below sea level. As a result, Delta levees are active water retention structures. Figure 2 shows a schematic cross section of a typical Delta "island."[3]

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[3] The notion of a Delta island is a misnomer as illustrated in Figure 3-1 since these "islands" are located below sea-level.

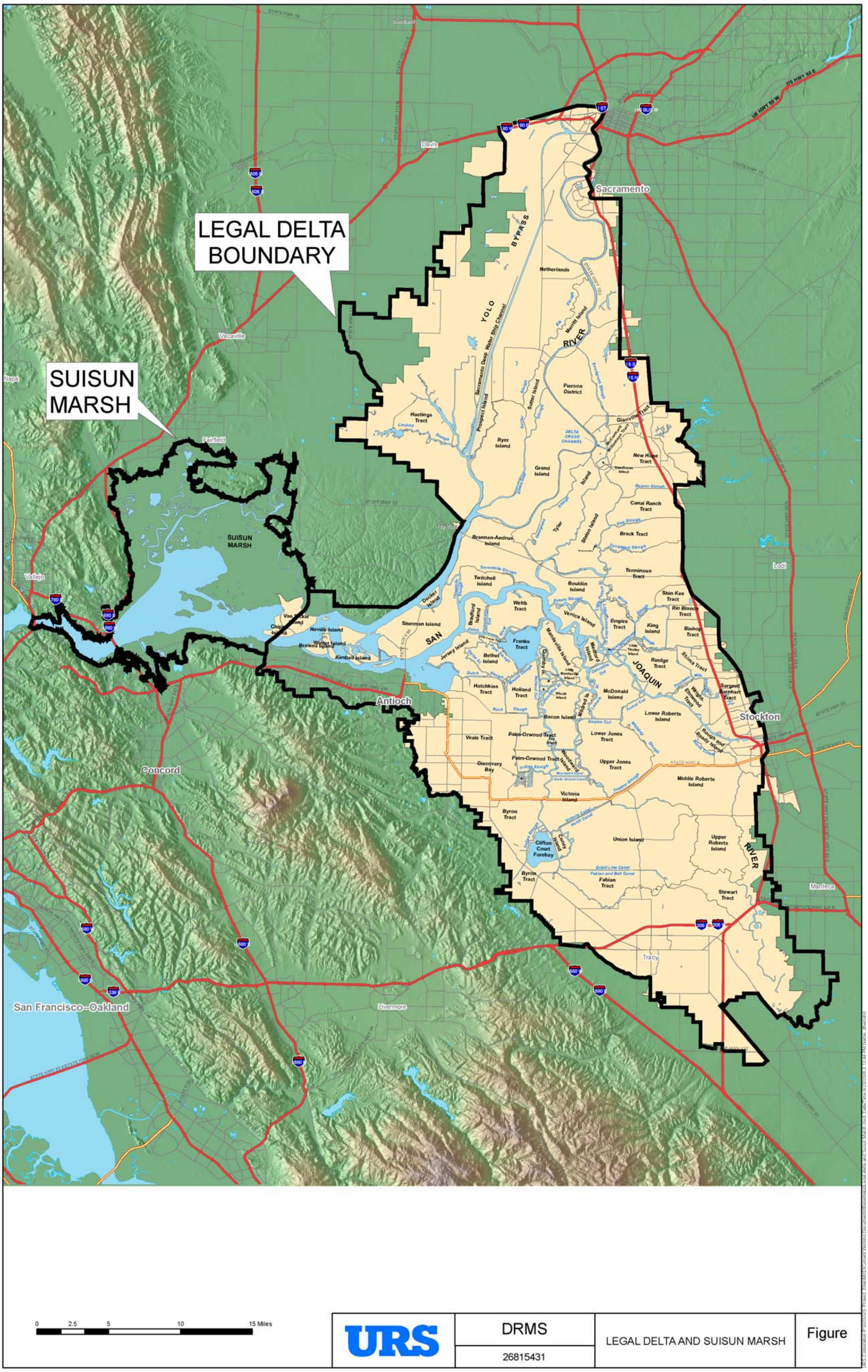

Figure 1: Map Showing the Study Area.

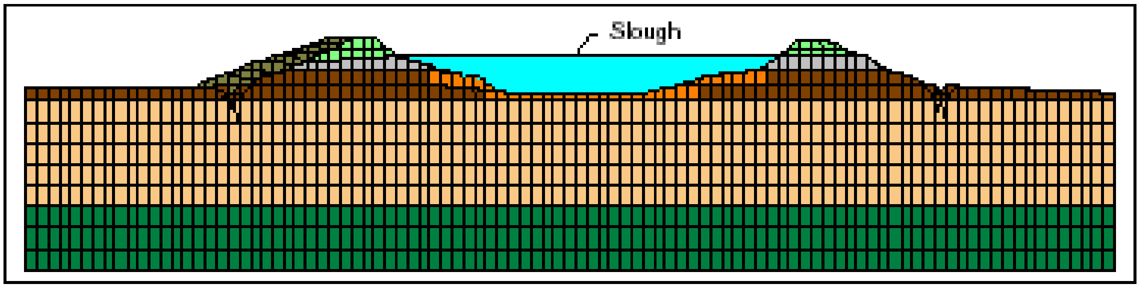

Figure 2: Schematic Cross Section of a Typical Delta Island.

Most levees are local levees that began over a century ago as 3 to 5 foot high dikes of peaty soil to protect croplands. These levees have been raised and improved over the years by local reclamation districts and thus they have not evolved in conformance to present-day design or construction standards.

The Delta is centrally located in California (see Figure 3) and is a key element of California's water supply system. Approximately 47 percent of California's runoff drains into the Delta. Fresh water that enters the Delta from the Sacramento–San Joaquin Rivers as well as other rivers is exported to the Central Valley Project (CVP) operated by the U.S. Bureau of Reclamation (Reclamation) and the State Water Project (SWP) operated by DWR. These distribution systems divert about 20 to 70 percent of the natural flow in the system depending on the amount of runoff available in a given year (CALFED 2000).

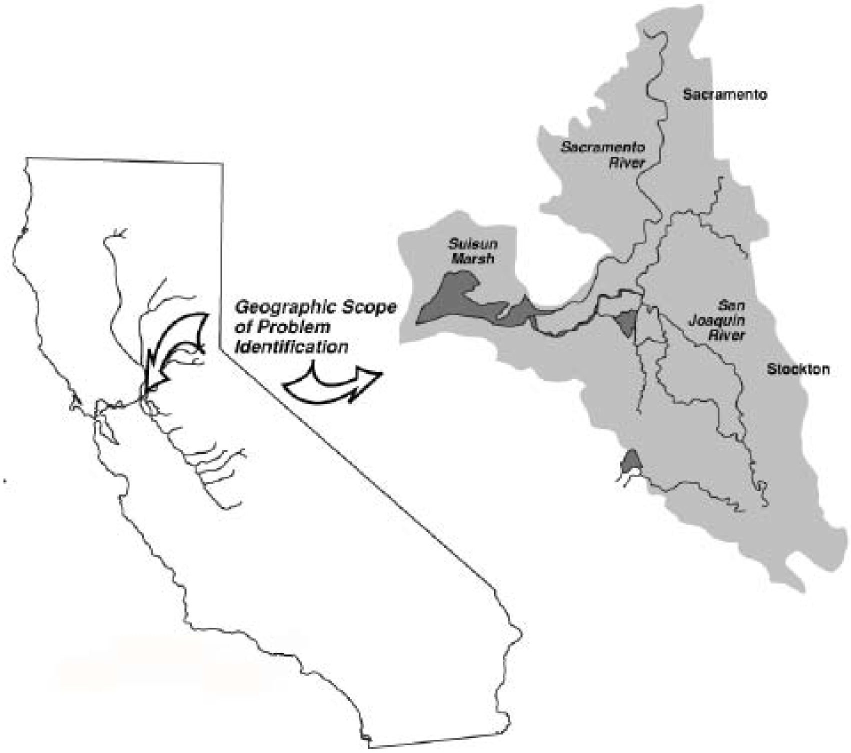

Figure 3: The Sacramento–San Joaquin Delta and Suisun Marsh (CALFED 2000).

Delta fresh water, including exports is a source of water supply for about two of every three Californians. In addition, the Delta is a source of irrigation for over 7 million acres of agricultural land in the Delta, the San Joaquin Valley, etc. (CALFED 2000).

The Delta is home to over 400,000 residents and an region of continuing community development.

Located in the Delta is an extensive infrastructure of state and local roads, railroads, pipelines, shipping ports, etc. Table 1 provides a general summary of infrastructure within the Delta.

As the largest marine estuary on the west coast, the Delta and Suisun Marsh is an environmentally diverse region that is home to over 500 species.

3.2 Impact of Levee Failure

When a levee breach occurs in the Delta or Suisun Marsh there can be significant consequences both in the Delta and statewide. The initial impacts occur as water rushes in to the breach and floods an island. This results in extensive scour and erosion at the breach location and in the interior of the island and in the slough or waterway where the breach occurred.

The immediate impact of a breach is the direct consequence to the flooded island (e.g., public health and safety effects, property damage to structures (commercial and residential), and the economic impact of direct damages or disruption (e.g., business income losses) of commercial activities, and environmental effects (e.g., fish mortality, habitat damage).

Table 1
Delta Infrastructure

Category	Entity
Highways and Roads	Interstate 5, 80, 205 State Highways 4, 12, 160
Railroad	Southern Pacific, Union Pacific, Atchison, Topeka & Santa Fe, Sacramento Northern
Electrical Transmission	Pacific Gas and Electric
Shipping	Deep water channels to Sacramento and Stockton
Aqueducts (in or Around the Delta)	San Francisco Public Utilities Commission East Bay Mud Utility District (Mololume Aqueduct)
Gas Fields or Storage	Tanks, pipelines
Marinas	Docks, channels, fuel stations, operations facilities, etc.
Agriculture	Over 500,000 acres
Water Diversion Facilities	Contra Costa, SWP, CVP, agricultural users, etc.

Following a breach event, there are emergency response and repair costs associated with closing the breach, protecting other, non-breached levees from further damage, dewatering of the island once the breach has been closed, and on-island repairs, etc.

The recent Jones Tract breach that occurred in June 2004 flooded Lower and Upper Jones Tract and provides some limited, but clear insights to the potential consequences of levee failures in the future.

While the Jones Tract event involved just a single breach, it resulted in economic impacts that exceed $100 million (DWR 2004). This event, which involved a single breach, flooded approximately 11,000 acres. Costs included repair costs, agricultural losses, damage to a rail overpass and the Mokelumne Aqueduct, etc.

The water that floods an island is ‘replaced’ in the Delta by salt water drawn from the Bay. This salt water “gulp’ depends on a number of factors, including the volume of flooded islands, time of year, etc.[4]

The economic impact of events involving multiple flooded islands can be extensive. In addition to the in-Delta effects associated with the direct impact of island flooding (e.g., damages, economic impact, emergency response and repair costs), there are significant state-wide impacts that result from the water delivery failures that effect agriculture and urban water users. DWR recently estimated that a 30-breach event could result in statewide impacts of $30 to $40 billion during the first five years and that the state’s water export capability might not be fully restored due to levee breaches that progress to total island failures (Snow 2005). These consequences can only increase with time as the state’s urban growth depends even more on Delta water exports and as Delta-area development puts more residential neighborhoods behind levees.

In addition to the in-Delta and state-wide economic impacts that could result, there could be significant environmental effects as well. Depending on the circumstances of event (e.g., time of year, islands flooded, etc.) the effects on the ecosystem will vary. Concerns range for possible extinction of particularly vulnerable species to transient disruptions that have minimal impact and are recoverable once the Delta returns to its prior state.

Delta experience and engineering studies suggest the potential impact (economic, environmental, etc.) of levee failures depends on a number of factors and can vary significantly. For example, in an earlier study (JBA 2005), the economic consequences of levee breaches was found to vary significantly depending on the time of year the event occurred and the hydrologic conditions that precede the event. An event that occurs in July during a period of normal hydrologic conditions has essentially no impact on Contra Costa county (due to available storage in Los Vaqueros reservoir). However, if the same event were to occur in January (under the same hydrologic conditions) when storage in Los Vaqueros is low, the impact could be significant). Similarly, if the same event were to occur a year or more into a drought, the impact would be far greater for northern and southern California (JBA 2005).

Delta levees face substantial challenges from several hazards. A primary concern is a seismic or a flood that may cause several levee breaches, on multiple islands simultaneously. Wind waves also pose a hazard to levees and may be especially devastating when they impact a weakened or damaged levee (e.g., levees that are damaged, but do not breach following a seismic event), or when they impinge on the unprotected interior levee slopes of a flooded island such as occurred during the Jones Tract event.

In addition, ongoing subsidence and climate change are additional hazards that increase the risk to the Delta levees over time and may allow earthquakes and floods or even high tides and seepage to have much more severe impacts in the future.

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[4] The amount of salt water that comes into the Delta from the Bay may be limited if the levee breach occurs during a flood event.

4.0 DRMS RISK ANALYSIS: SCOPE AND PERSPECTIVE

This section defines the general scope of the DRMS risk analysis as specified in the project contract. It also provides a perspective on the specific expectations from the risk analysis and the spatial, temporal, and methodological boundaries on the scope of the analysis.

4.1 DRMS Scope

As defined in the RFQ for the DRMS project the scope of the risk analysis is (DWR 2005):

- Evaluate the risk and consequences to the State (e.g., water export disruption and economic impact) and the Delta (e.g., levees, infrastructure, and ecosystem) associated with the failure of Delta levees and other assets considering their exposure to all hazards (seismic, flood, subsidence, seepage, sea level rise, etc.) under the present as well as foreseeable future conditions. The evaluation should assess the total risk as well as disaggregation of the risk for individual islands.
- Propose an acceptable risk criterion for consideration of potential risk management strategies and for the State's use in management of the Delta and the implementation of risk informed policies.
- Develop a Delta Risk Management Strategy, including a prioritized list of actions to reduce and manage the risks or consequences associated with Delta levee failures.

This ITR paper addresses the first objective of the risk analysis. The scope of the proposed risk analysis to achieve this objective includes an evaluation of the probabilities and consequences of failure of Delta levees and other in-Delta assets under all potential hazards. This evaluation should be performed under present Delta conditions as well projected conditions over the next 200 years assuming the current policies, practices, and Delta uses and trends continue and no significant pro-active improvements are made to the Delta levees (i.e., "business-as-usual" policy).

The results of the DRMS study are intended to support DWR and DFG's effort to report to the California Assembly in response to AB 1200. The bill directs DWR to develop risk information on continuing present trends in light of several distinct hazards (e.g., subsidence, earthquakes, floods, changes in precipitation, temperature, and ocean levels), and for the combination of those hazards based on projections for 50, 100, and 200 years into the future. The products of the DRMS project are also intended to support the Delta Vision Process (DVP), which is a public process designed to find substantial agreement on recommendations among elected officials, government agencies, stakeholders, subject matter experts, and affected California communities on the future management of the Delta.

The DRMS project has many of the same goals and will carry out many of the activities and functions envisioned by the DVP. As such, the DVP will build on the information developed from the DRMS effort. Specifically, the DVP will be able to use the quantitative risk estimates generated by the DRMS to make risk-informed decisions on how to manage and maintain the Delta levee system.

4.2 Scope Bounds

To guide the DRMS risk analysis methodology, one needs to clearly define what is within the scope of the DRMS risk analysis and what is not. The important questions to address in defining a detailed scope of risk analysis are:

- What is the geographic boundary of the study area within which assets are considered to be at risk?
- What specific assets are to be analyzed for the risk of failure?
- What are the hazard events whose impact on the performance of the assets is to be evaluated?
- What are analysis years during which the occurrence of the hazard events and threats to the assets are to be evaluated?
- What are the temporal and spatial boundaries within which consequences of failures of the Delta assets are to be assessed?

These questions are addressed below.

Geographic Boundary of Study Area

The geographic boundary of the study area was identified in Section 2 and displayed in Figure 1. As was noted in Section 2, this boundary defines the region within which the Delta assets at risk will be evaluated. Assets outside this boundary will be considered in the risk analysis only to the extent that they are impacted by the same initiating events that cause levee failures in the Delta. However, the risk analysis will include consequences of levee failure associated with water export disruptions and in- and beyond-Delta economic consequences of levee failure. Both in-Delta and statewide consequences of the Delta asset failures will be evaluated.

Assets Included in the Risk Analysis

The assets whose risk of failure is to be analyzed include the Delta levees and infrastructure and resources within the Delta islands and waterways that could be impacted by the same events that pose a threat to the Delta levees (see Appendix A). The risk analysis will exclude assets and infrastructure outside the study area that are unaffected by the events that could cause a failure of the Delta levees. Thus, for example, the failure potential of dams and reservoirs upstream of the study area would not be considered in the risk analysis. On the other hand, such co-located facilities as the pumping stations and canals within the study area will be analyzed with regard to their risk of failure under the same hazard events (earthquakes, flooding, etc.) that could cause a failure of the Delta levees. It is important to analyze scenarios of simultaneous failure of the Delta levees and co-located assets because such scenarios could increase the duration and severity of consequences of levee failures. For example, a simultaneous failure of levees and pumping stations could increase the duration of water export disruption.

Hazard Events

The focus of the risk analysis will be on natural hazards that have the potential to cause the failure of levee breaches and subsequent flooding of islands. The specific hazards considered in the analysis will include earthquakes, floods, and winds/waves. Appropriate combinations of these hazards (e.g., an earthquake followed by a flood or a wind/wave event) will also be considered. Time dependent processes (such as subsidence and climate change) that impact the frequency of and severity of future hazards or impact the vulnerability of Delta levees will be analyzed as characteristics of the Delta environment in each given analysis year.

For floods and winds/waves, the analysis will consider both normal (i.e., ambient) conditions that occur each year and transient events that are stochastic in nature; that is, each event has a certain probability of occurrence in any given year. The impacts of these hazards will be combined with subsidence and climate conditions as projected for each specified analysis year. The risk analysis will not consider a hazard event that could cause a failure of a co-located Delta asset, but poses no threat to the Delta levees. Thus, for example, the failure of a gas pipeline within the Delta due to corrosion would not be considered, since such an event would not put the Delta levees at risk. Furthermore, man-made hazard events (such as vandalism or a terrorist act) also will not be considered in this analysis.

Analysis Years for the Occurrence of Hazard Events

In keeping with the requirements of AB 1200, the risk analysis must consider the evolution of risks over the next 200 years. Specifically, the risk will be evaluated in response to hazard events that occur in Years 0 (i.e., baseline year), 50, 100, and 200. The probability of occurrence of hazard events and potential failures of Delta levees and co-located assets will be evaluated in each of these analysis years. However, as noted below, the consequences of failures may extend beyond the analysis year and will be included in the risk analysis.

4.3 Temporal and Spatial Boundaries of Consequences of Failure

The occurrence of hazard events will be analyzed in the specific analysis years (i.e., 2005, 2050, 2105, and 2205) and within the study area. However, consequences of failures caused by a hazard event will be evaluated in the analysis year and beyond, considering impacts both within and outside the study area. Thus, for example, the impact to statewide water exports will be evaluated and included in the risk analysis. Any direct, long-term environmental impacts caused by the flooding of islands and subsequent salinity intrusion will also be included.

4.4 Business-as-Usual

An objective of the DRMS study is to identify and evaluate alternative risk management strategies for managing the Delta in the future. A first step in this process is analysis of risks over the study period, assuming a “business-as-usual” approach to the management, operations, and use of the Delta. This estimate of risks will be referred to as the “business-as-usual scenario”.

The business-as-usual approach will be carried out assuming current trends, policies and practices are continued over the duration of the study period. Implementing such an approach requires some interpretation. For instance, the risk analysis will consider events that have not occurred in the past and may not have they been explicitly contemplated in the development of current policies or procedures (e.g., operations for upstream reservoirs following an event involving a significant island flooding and salinity intrusion into the Delta). As a result, some interpretation and/or discussion with DWR and others will be required to fill these policy gaps to establish the “business-as-usual” approach.

Implementing a “business-as-usual” approach (for the study period) will apply to many aspects of the risk analysis. These include:

- Hazards (e.g., continuation of estimated rates of subsidence, occurrence/non-occurrence of a major earthquake),
- Levee maintenance and repair practices (e.g., level of expenditures for levee maintenance and raising)
- Water management following an event in the Delta (potentially involving significant salinity intrusion)
- Levee repair operations
- Land-use and development in the Delta
- Growth of the state economy
- Water demand and supply
- State of the ecosystem over time.

Establishing the business-as-usual scenario will require individual areas be examined to identify what policies, practices and trends exist, and where there are gaps that must be filled.

5.0 DRMS RISK ANALYSIS PROBLEM

The purpose of this section is to provide an overview of the events that can cause levee failures in the Delta and Suisun Marsh, events that determine the state of the Delta following an event, and the factors that effect the consequences that may result. The result is to summarize the features of the risk analysis problem that must be evaluated and key requirements for the risk analysis methodology. The overall framework for the DRMS risk analysis is described in Section 6.

5.1 When Levees Fail

Levee failures are not particularly unique events in the Delta and Suisun Marsh. There have been at least 160 failures in the last 100 years or so. Most of these have occurred during flood events, although there have been a handful that have occurred on ‘sunny days’, such as the Jones Tract failure in June 2004. As is well known, Delta and Suisun Marsh area levees are active water retention systems because the land they protect is below sea level. When a levee breach occurs, the “islands” are flooded, and remain so until the breaches are closed and the island dewatered.

Levee Failure and Island Flooding

When an event such as an earthquake or flood occurs that initiates levee breaches, the water that rushes through a breach creates a significant scour (as much as 90 or more feet deep) at the levee footprint, in the slough and on the island.

In addition to breaches that occur, an earthquake or a flood may also cause damage but no breach (non-breach damage) to thousands of feet of levee. This damage could occur on islands that have breached as well as other, non-breached islands. The implication of this additional damage is discussed below.

The water that rushes onto the islands creates a void that is replenished by salt water from San Pablo and San Francisco Bays. The ‘Gulp’ of salt water that now intrudes into the Delta and Suisun Marsh can dramatically change the salinity distribution and alter the water quality for a considerable period of time. The volume of the gulp and the impact on water quality depends on a number of factors, including the number of islands that have been breached, their volume, their location in the Delta or Suisun Marsh, etc.

Repair and Recovery

Once islands have flooded and water levels are equalized, repair operations are undertaken to stop breaches from deteriorating further (getting longer), closing the breaches, and dewatering the islands. The process of closing a single breach and dewatering an island is a lengthy process. It can take a month to close a single breach and many months to dewater an island (depending on the island volume, number of pumps available). For a multi-breach scenario, the period of repair can be significant depending on the number of breaches and availability of equipment and material to carryout repairs.

In addition to the repairs required to close breaches, recovery operations must also focus on two other problems. The first is the stabilizing of levees that have experienced non-breach damage. Historically, wave action on levees can readily erode and deteriorate a levee that is adequately protected. As a result of a major earthquake, there may be damage (slumping, crest settlement, etc.) to the outer levee slopes, increasing the potential for the levee to deteriorate and breach, particularly if the rip rap has been disrupted. If these breaches occur on islands that have not flooded, the extent of the in-Delta damage, salinity intrusion, environmental impact, etc. will be expanded as a result of these secondary breaches. Of course, additional breaches may also result on islands that have already been breached.

For flooded islands, there is another opportunity for additional damage and breaching to occur. As a result of an island flooding, the interior ‘lake’ that is formed creates a potentially large fetch for wind waves to be generated, which will impact the interior levee slopes. Since the levee interiors are not protected against wave action, they are particularly vulnerable to erosion and breaching. During the Jones Tract event, considerable effort was undertaken to prevent such an event from occurring. If these interior breaches occur and are not closed in a timely manner, they can expose adjacent islands to the same wind fetch (across the flooded island, through the breach, and across the slough), creating a potential for further cascading.

In the event of a multi-breach scenario, the repair and recovery effort will involve a considerable operation involving prioritization of repair operations, allocation of resources, stabilization of vulnerable, but non-flooded islands, closure of flooded islands, and dewatering. The situation may be very dynamic as breaches continue to grow until the ends are capped; levee interior and exterior slopes erode due to wave action; and as wind events occur and accelerate the rate of erosion and ongoing damage.

The rate of repair efforts will impact in-Delta recovery as well as water quality. Until all islands are closed and dewatered, the hydrodynamics of the Delta and Suisun Marsh are impacted.

Hydrodynamics and Water Quality

When there is a levee breach event, water exports which occur in the south Delta and at some west Delta locations are reviewed and may be interrupted or scaled back until the impact of the event is understood. The initial interruption of exports, which may have to be continued for a considerable period of time depending on the magnitude of the event, avoids contributing to greater intrusion of salinity into the Delta and further drawing salinity into the south Delta and closer to the pumps.

The hydrodynamic response of the Delta and Suisun Marsh to levee breach events will depend on a number of factors, including the hazard that initiated the breaches (floods, seismic events, etc.), the number of islands flooded and their volume, breach locations on each island, the time of year, operations of upstream reservoirs which can be used to limit the salinity intrusion into the Delta, the timing of islands closures and dewatering, and export operations during the period of repair.

Hydrodynamic simulations of various multi-breach scenarios, as well as experience during historic events have estimated the extent of salinity intrusion and the impact on water exports. The results suggest that export disruptions could last years for scenarios involving as many as 50 breaches (JBA 2005).

Impacts

When levee failures occur in the Delta and Suisun marsh, there are a number of impacts or consequences that may occur. These range from the direct damages (breach and non-breach damage) to the levees and Delta infrastructure on flooded islands, to public health and safety impacts, economic consequences to in-Delta residents and businesses, impacts to those who derive water from the Delta if exports are disrupted, and the impacts (positive and negative) to the Delta ecosystem.

The impact of levee breach scenarios will vary considerably depending on the nature of the event. For instance, the length of export disruptions and the effects of salinity intrusion on the Delta and Suisun Marsh ecosystems depend on a number of factors, starting of course with the number of islands that have flooded. Other factors include the time of year the event occurs, the hydrologic cycle at the time (e.g., dry versus a wet year), the type of event that initiated the failures (e.g., earthquake or flood), and decisions with respect to managing upstream water resources that are made immediately following the event. Depending on the circumstances at the time, water stored in upstream reservoirs can be used to manage the extent of the salinity intrusion into the Delta. A decision to use upstream storage to control salinity levels itself depends on a number of factors including the storage available at the time, projections with respect to the upcoming water year (e.g., again a dry versus wet year), etc.

The range of impacts that can occur, even for a fixed number of levee breaches, is estimated to be considerable (JBA 2005; Snow 2005). Simulations for a 50 breach case involving flooding of 21 islands resulted in approximately 400 billion gallons of salt water entering the Delta from the bay. The results of these and other simulations coupled with estimates of economic impact suggest losses could easily exceed $10s of billions. For this same event, the results would be very different (much higher) if the range of possible event occurrences with respect to the time of year or type of water year were considered.

It is clear the magnitude and extent (that is how many different types of impacts may be experienced) of impacts that could result from levee failures is not well understood. For instance, the Jones Tract failure in 2004 was alarming from the perspective of the rather limited nature of the event (a single breach) and the high cost associated with closing the breach, dewatering the island and protecting the levee interior slopes, and the on-island damages that occurred. This event, which had an estimated economic impact of $100 million, had no effect on water exports and limited environmental impact, suggests that even ‘sunny-day’ failures can have meaningful economic consequences.

5.2 Modeling Risk Due to Levee Failures

The foregoing general summary of events and consequences of levee failures in the Delta and Suisun Marsh provides insights as to an approach to take in model risks. These insights include:

- The consequences of levee failures depends initially (and quite obviously) on the number of breaches that have occurred and on the number of islands that are flooded, which in turn depends on the size of the hazard event (flood, earthquake, etc.) that initiates the failures and damages.
- The hydrodynamic effects of levee breaches depends on the above, as well as reservoir releases early in the event and the order and timing of islands closures (breach repairs and dewatering).
- The timing of an event during the year and during a particular hydrologic cycle (dry versus wet years).
- The potential for secondary failures, following the initial breaches and damage that occurs as a result of an initiating event (e.g., earthquake or flood), could be an important issue with respect to emergency response and levee repairs and the potential for flooding additional islands.

With regard to the consequences of levee failures,

- A single levee breach and island flooding event can be fairly costly, certainly tens if not hundreds of millions dollars, even though the breadth of the impacts may be limited (e.g., little or no water export disruption, limited environmental impact). This observation provides some insight into the need to reasonably estimate these consequences since they provide a measure of the ongoing (year to year) risk costs of current management of the Delta and Suisun Marsh, absent more disastrous events involving multiple islands, which of course increase significantly the risk costs to California.
- The consequences (economic, environmental, etc.) dependent to a large degree on the details of levee breach scenarios (all of the items listed above).
- Studies to date do not make it clear what type of events (seismic, flood, etc.) or how many levee breaches and islands that are flooded, or what combinations of events are the primary contributors to risk and are the most important to the development of strategies for managing the Delta in the future. It is unclear for example whether the fundamental problem and future decisions is limited to and should focus only on catastrophic events of the size experienced in New Orleans as a result of hurricane Katrina, or is the risk dominated by much smaller

events such as Jones Tract and somewhat larger that may occur much more frequently and which could become unmanageable if secondary failures progress to the point that repair operations cannot keep up with ongoing deterioration.

The idea that combinations of various factors or possible events can occur and combine to influence the consequences of levee failures is illustrated schematically in Figure 4. For example, the figure shows factors prior to the event that may influence consequences such as time of the year, etc. Next is the size of the hazard (e.g., magnitude of the earthquake) and the performance of levees to these events. This is followed by the effectiveness of emergency response and repair operations and then hydrodynamic response of the Delta and water management operations. And finally, the resulting consequences depend on the combination of these upstream events.

The foregoing suggests an analysis that takes an events-based approach that models the combination of events which can occur (e.g., earthquakes of different size) and other factors that impact potential consequences (time of year, etc.). Further, the modeling process should consider the full range of event sizes such that the complete distribution of consequences is reasonably modeled and the contribution of different events and other factors can be determined.

6.0 RISK ANALYSIS APPROACH

This section describes the basic probabilistic framework for the DRMS risk analysis for the Delta and Suisun Marsh. As summarized in the previous section, the occurrence of levee failures and their effects (consequences) depends on the occurrence in combination of many factors and events. The relationship of events and their combination can be independent (random), such as the time of year an earthquake occurs, to events that are causally related, such as the liquefaction of a levee foundation due to earthquake ground motion. The development of the risk model must take into account the combination of events that have important consequences and thus should be considered in the analysis of risks.

From historic experience in the Delta and risk modeling experience in general (e.g., earthquake engineering lifeline risk analysis), the performance of Delta and Suisun Marsh levees and the state of the ‘system’ after a single event (such as an earthquake) could cause a large number of levee failures that result in flooding of many islands and could cause severe impacts to the state water exports. Furthermore, such an event could weaken levees, which then could fail when subjected to ambient wind/wave conditions or floods. Therefore, one must assess the joint probability of simultaneous failures of Delta levees and other assets when subjected to a given initiating event and additional failures that could be caused by on-going exposure. A proper analysis of this risk requires an event-based approach, in which the simultaneous impact of each initiating event and on-going exposure on the whole Delta system is assessed.

This section describes the approach that will be used to develop a risk model for events that can occur in the Delta and Suisun Marsh. The description will discuss:

- Elements of the risk model
- Definition of types of uncertainty
- An overall aleatory risk model – to estimate the frequency of levee failures, distribution of consequences
- Modeling the combination of events (breaches and Island flooding)
- Evaluation of temporal risk

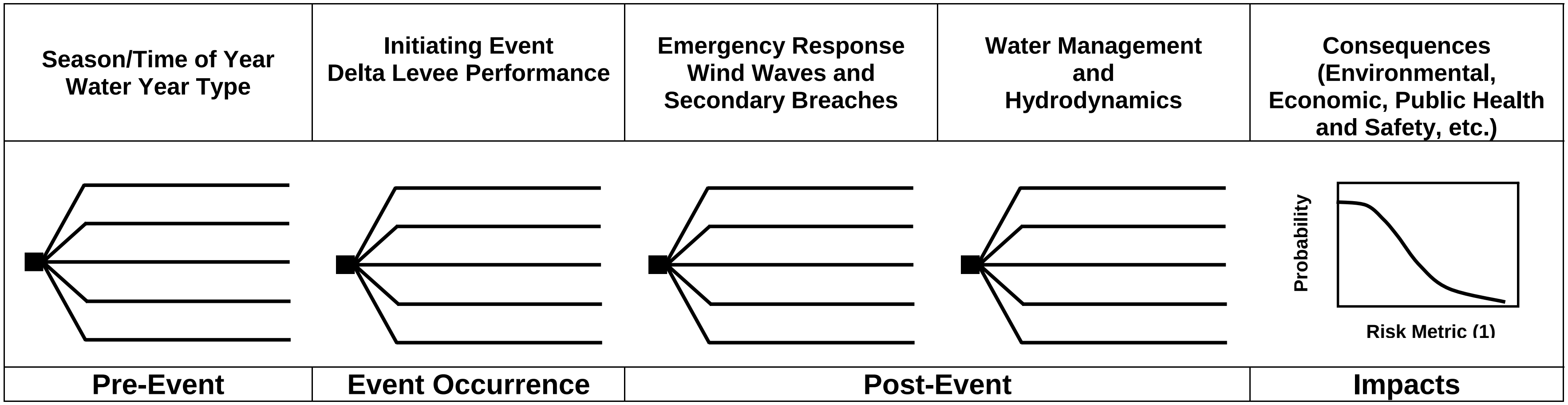

Figure 4: Schematic Illustration of the Events and Their Range of Values/Sizes That Impact Consequences of Levee Failures in the Delta and Suisun Marsh.

6.1 Elements of the Risk Analysis

As a starting point, the general elements of the risk analysis are summarized. The description is oriented principally with respect to the evaluation of external hazards such as earthquakes, floods, and/or winds. For levee failures that occur during normal conditions ("sunny-day levee breaches), the elements of the risk analysis are essentially the same.

Figure 5 shows a schematic of the elements of the risk analysis and their basic relationship. Each element is briefly summarized.

Hazard Analysis

The purpose of the hazard analysis is to estimate the frequency of occurrence and the magnitude of hazards that may impact Delta and Suisun Marsh assets. In the case of seismic events, the hazard will be characterized in terms of a ground motion parameter (e.g., peak ground acceleration). The characterization of the hazards considered must also take into account their correlated spatial distribution in order that a reasonable representation of the simultaneous loading (forces) that can occur for all levees throughout the Delta and Suisun Marsh.

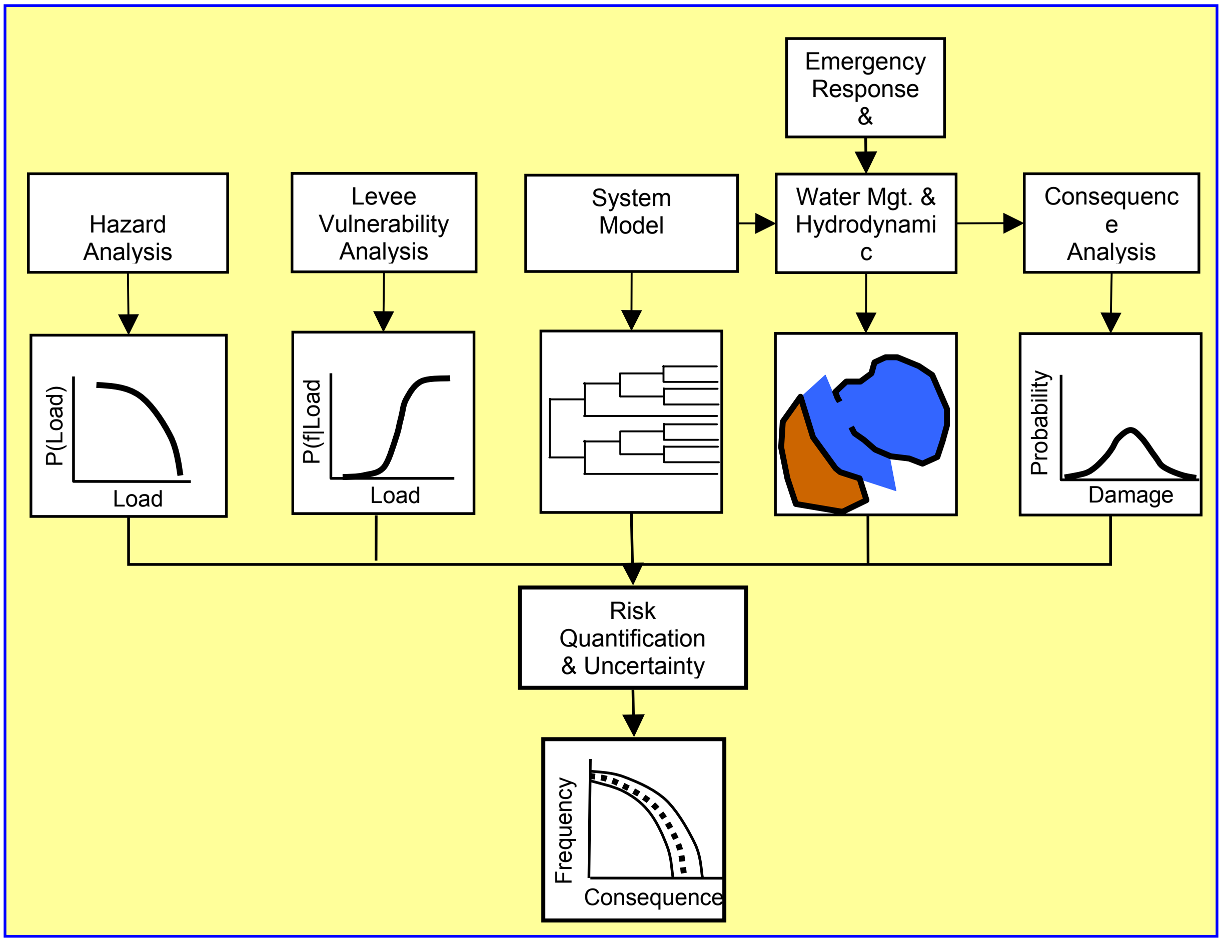

Figure 5: Schematic Illustration of the Elements of the Risk Analysis.

For example, the seismic hazard analysis must estimate the ground motions throughout the study area that will occur as a function of earthquake events (e.g., an earthquake of a given magnitude, which occurs on a specific fault).

Levee Vulnerability Analysis

Given the occurrence of a hazard, the levee vulnerability analysis estimates the conditional probability of levee breach or damage as a function the hazard characterization parameter (e.g., peak ground acceleration for seismic events or peak water surface elevation for floods). Since the hazard level that causes failure is not known exactly, the conditional probability of failure or damage will vary. It will be low (zero) at very low hazard levels and ultimately rise to a conditional probability of failure at some, much higher level. This result is referred as a fragility curve. Fragility curves will be developed for each levee reach in the study area.

System Model

Given the occurrence of a hazard that challenges the water retention capability of Delta and Suisun Marsh levees, a model is required to evaluate the potential combination of events and levee failures that can occur. The system model defines the relationship between events and their possible combination in order to assess the state of the Delta immediately following the event (e.g., an earthquake of magnitude (**M**) 6 on the Hayward Fault). The term, state of the Delta, refers to the condition of levees and islands, immediately following the event. Given an earthquake and the probabilistic nature of levee performance (see Levee Vulnerability, above), there are numerous combinations of which levees will breach and islands that flood. The system model describes the potential combinations of these events and the framework for calculating their probability of occurrence. Each possible combination of flooded island is referred to as a sequence (a sequence or combination of events). The system model will also model islands that have not flooded, but whose levees may be damaged and could deteriorate (as a result of wave action) and result in further island flooding. Other factors or random events such as the time of year an event occurs, the type of hydrologic water year, etc. are also included in the system model because of their importance in assessing the hydrodynamic response and consequences to levee failures.

Emergency Response and Repair Analysis

Following an event that has resulted in levee breaches and/or damage, the process of repairing breaches and stabilizing damaged areas from further deteriorating and resulting in additional island flooding begins. This part of the risk analysis models the material, equipment and time required to stabilize islands, close breaches, and dewater flooded islands.

Water Management and Hydrodynamic Analysis

As islands breach and flood, the normal flow patterns are disrupted. Waters that flood islands is replaced by salt water from San Pablo and San Francisco Bays.[5] The intrusion of salt water into the Delta can be managed to a degree by controlled releases from upstream reservoirs and curtailing/halting exports from the Delta. These factors, coupled with the rate of breach closures and island dewatering, and ongoing tidal cycles result in a very dynamic system that is modeled

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[5] The degree to which salt water intrudes into the Delta depends on whether the levee failures occurred during a flood or other event, which islands have flooded, etc.

to assess the impact on water quality (e.g., salinity levels, turbidity), and the time that water exports will be disrupted at the State Water Project and Central Valley Project and other pump stations.

Consequence Analysis

The purpose of the consequence part of the analysis is to assess the effect that levee failures have. These can include public health and safety impacts of island flooding, the direct damages on flooded islands, the economic impact to residents and local businesses, the environmental impact to Delta and Suisun Marsh habitat and species, water quality effects, the disruption of water exports, the economic impact of export disruptions, etc. Whereas the risk analysis will model a wide range of island flooding, emergency response and water management and hydrodynamic sequences, the consequence part of the risk analysis provides an assessment of the impact for the full range of sequences considered.

Risk Quantification and Uncertainty Analysis

This step in the risk analysis combines all of the elements of the analysis and calculates the risk for the range of consequences that are considered. As part of the quantification, the uncertainties (epistemic, discussed in the next section) for each part of the analysis are propagated through the risk calculations to determine the uncertainty in the results.

6.2 Definition of Uncertainty

One of the reasons for conducting a risk analysis is to quantitatively consider the uncertainties that relate to events of interest (i.e., the performance of levees subjected to earthquake ground motion, the consequences of flooding, the impact of events on the environment, etc.). There are fundamentally different sources of uncertainty that affect an assessment of the likelihood of events. The first source is attributed to the inherent randomness of events in nature (e.g., a role of the dice, the occurrence of an earthquake or flood). It represents unique (often small-scale) details of material properties, the small-scale variability not explained by a 'model'. Given a model, one cannot reduce the aleatory uncertainty by collection of additional information. One may be able, however, to better quantify the aleatory uncertainty by using additional data. These events can only be predicted in terms of their probability or rate of occurring. This source of uncertainty is known as aleatory uncertainty and is, in principle, irreducible.

The second source of uncertainty is attributed to lack of knowledge (information, scientific understanding, data) (USNRC 1996). For example, the ability to determine the rate of occurrence of an event requires that certain data be available. If the amount of data is adequate, the estimate of a rate may be quite accurate. On the other hand, if only limited data are available, the estimate of likelihood will be uncertain (i.e., statistical confidence intervals on parameter estimates will be large). A second type of knowledge uncertainty is attributed to our lack of understanding (e.g., knowledge) about a physical process or system that must be modeled. These sources of uncertainty are referred to as epistemic (knowledge-based) uncertainty. In principle, epistemic uncertainty can be reduced with improved knowledge and/or the collection of additional information.

Figure 6 shows the epistemic uncertainty in the estimate of the frequency of occurrence per year that a Delta island may be flooded as a result of levee failure (due to any cause; earthquakes, floods, etc.). The figure shows a probability distribution on the estimated frequency of flooding.

If there were epistemic uncertainty for example in estimated the rate of occurrence of future earthquake ground motions, floods in the Delta, or in the performance of levees given a stressing event, there would be no distribution, but simply a point estimate of the frequency of flooding. The uncertainties that contribute to this distribution are the amount of data that are available, the accuracy of engineering methods to model the performance of levees, the uncertainty in the estimate of hazards that could cause failure (e.g., uncertainty in the rate of earthquake occurrences, ground motion attenuation models, etc.).

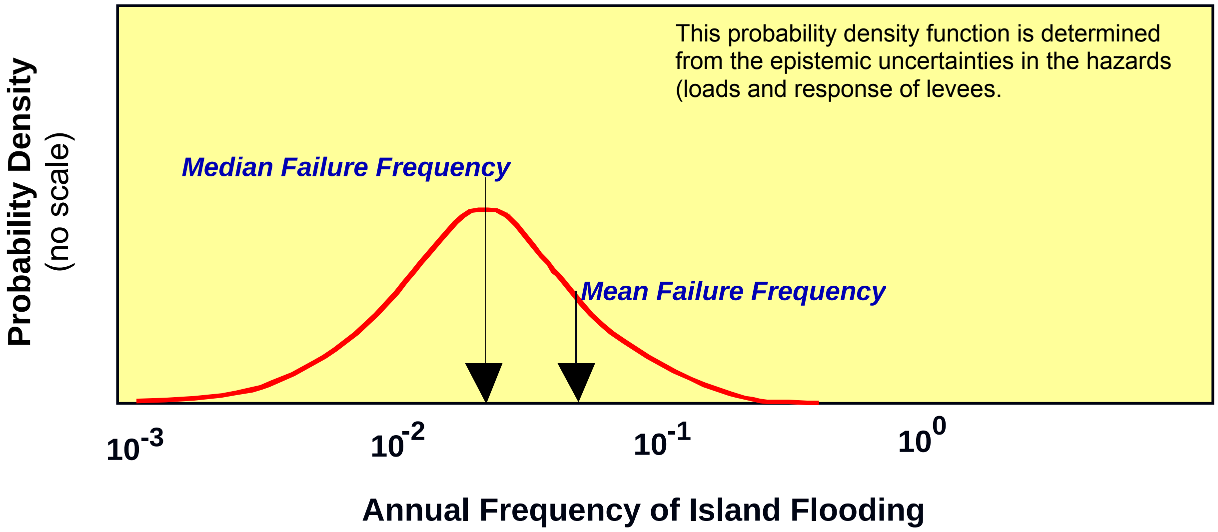


Figure 6: Illustration of the Epistemic Uncertainty in the Estimate of the Annual Frequency of Island Flooding due to Levee Failure.

The distinction between what is aleatory and what is epistemic uncertainty may be unclear. For example, the distinction depends on the models that are used in a particular analysis. As part of a given probabilistic analysis (e.g., seismic hazard, levee vulnerability), it is useful to develop a taxonomy of uncertainty, identifying the sources of different types and how they can be estimated. Appendix B of this ITF paper provides a general description of the taxonomy of uncertainty.

The assessment of epistemic uncertainties can vary, depending on the subject, the development of scientific or engineering understanding, observational and modeling experience, etc. For example, in a field or topical area where there is considerable observational experience and empirical models are used to develop predictive tools, the epistemic uncertainty in the model estimates can be developed by statistical methods. In other fields, direct observational evidence may be limited and predictive models are based on theoretical models, estimates of the model parameters, the analysts experience, comparisons of model predictions with observations, etc. In areas where direct observation of events/parameters of interest is limited, there are competing models or scientific interpretations, it is often necessary to elicit input from experts to evaluation and quantify epistemic uncertainties (Morgan and Henrion 1990; SSHAC 1997; USNRC 1996).

SSHAC (1997) give a guide for the objective for the evaluation of epistemic uncertainty. It is, ‘to assess the composite distribution of the informed technical community,’ where the distribution may be estimated for the inputs to a given model, or it may the distribution of alternative models that are based on alternative interpretations, assumptions, etc. by the informed technical community for modeling the events or physical processes under consideration.

Different levels of analysis (levels of detail and depth of evaluation) for estimating epistemic uncertainties based on alternative expert interpretations can be used depending on the complexity of a problem and its importance to the overall evaluation (e.g., risk analysis results). SSHAC (1997) describe four levels of evaluation that can be used.

6.3 Risk Model

The purpose of the DRMS risk analysis is to estimate the risk of consequences of interest (i.e., public health and safety, economic, environmental) that may occur as a result of levee failures in the Delta or Suisun Marsh.

In this analysis, risk estimates will be made on a per annum basis. (The approach for addressing risks in future years is described in Section 6.5). This measure of risk, for a consequence C, is denoted:

$$\lambda(C_k > c) = \text{frequency per year that a consequence metric } C_k \text{, will exceed a value c} \qquad (1)$$

As described in Section 6.4, the risk analysis will be conducted for a number of risk metrics.

The potential for levee failures will be evaluated for a number of different hazards (e.g., earthquakes, floods, etc.). The total risk for a given metric, considering the hazards Delta and Suisun Marsh levees may be exposed to can be determined according to:

$$\lambda_T(C_k > c) = \sum \lambda_i(C_k > c) \qquad (2)$$

where the sum is carried out for the hazards considered in the risk analysis. Note, subsidence and climate change are not considered hazards in the sense of independent, random events that occur as transient stressing events at any time. Rather, they are addressed as ongoing processes that change the environment. How these “hazards” are considered in the risk analysis is discussed in Section 6.5. The task in the risk analysis is to estimate the consequences associated with each hazard, $\lambda(C_k > c)$, in equation 2. In the next subsections, the risk analysis for external and normal hazards is described.

In this analysis, frequency of events and the frequency of consequences is an ‘instantaneous’ frequency for the time the analysis is conducted (current, 2055, etc.). This instantaneous rate can be used to calculate a probability of occurrence of an event of interest in a given year; however, it cannot be used directly to estimate a lifetime or study period (e.g., 100 years) probability. The results of the DRMS analysis, which will estimate the variation of the frequency of events over a 200-year period, can be used to estimate the probability of events over the study period duration.

External Hazards

External hazards such as earthquake, floods, and winds are spatially distributed phenomena that can stress a significant part of levees in the Delta and Suisun Marsh simultaneously. This presents the potential for multiple simultaneous levee breaches during the same event. When a seismic event occurs, the ground motion that is experienced is a function of the size of the event and its location with respect to Delta and Suisun Marsh levees. Thus, for a given seismic event, the ground motions that occur at levees in the area are correlated because they have occurred as a result of the same seismic event and levees in proximity to one another are founded on the same near-surface materials. Thus, the correlation of ground motions between different levees is a function of distance. For levee reaches close to one another, ground motions will be highly correlated, whereas the ground motions will be independent (given an event) as the separation distance between levees get large. Incorporating these correlations is an important factor in estimating risk and the potential for multiple island breaches.

In principle, similar correlations exist for flood and wind events, and must be considered in the risk analysis.

The consequences that occur as a result of levee failures exposed to a given hazard depends on the size of the event (e.g., earthquake ground motion throughout the region) and the state of the Delta (DS) given the occurrence of a stressing event, such as an earthquake. For a given hazard event (flood, earthquake, etc. of a given size), the occurrence of a Delta state can be estimated by:

$$\nu(\mathrm{DS}_{ij} \mid e_i, t_n) = \nu_i \int P(t_n) P(\mathrm{DS}_{ij} \mid h(\underline{x}), t_n)\; f(h(\underline{x}) \mid e_i, t_n)\, dh \tag{3}$$

where,

ν_i = Annual frequency of occurrence of event e_i (events per year)

t_n = Event timing n, including the time of year and hydrologic cycle

$h(\underline{x})$ = Spatial field of loading (throughout the study area) for event i; peak ground acceleration in the case of earthquakes

$P(\mathrm{DS}_{ij} | h(\underline{x}))$ = conditional probability of Delta state ij given the loading, $h(\underline{x})$, from event i

DS_{ij} = Delta state j for event i

$f(h(\underline{x}) | e_i)$ = conditional probability density function on the loading given the event e_i; this density function accounts for the spatial correlation of the loading that may exist.

The integration in equation 3 is carried out for the range of hazards (e.g., ground motions that occur at each levee reach that is considered in the Delta state, DS_{ij}.

A Delta state defines the:

- Performance of Delta and Suisun Marsh levees to a hazard, where the performance of levees includes the number of breaches and their location (and thus the number of flooded islands), and the extent of non-breach damage, and

- Development of any secondary levee breaches as a result of ambient wind conditions and/or the occurrence of a wind event (involving high velocity winds), and
- Emergency response activities to repair levee breaches and damage (including island dewatering), and
- Water management and hydrodynamic response of the Delta, given the prior events.

Within each Delta state, a realization of the events listed above defines the state of the Delta for purposes of estimating the consequences to a defined set of levee failures.

Due to the number of factors (some not listed above), the number of levees, the possible number of levee breaches that occur during any one event, there is a large number of possible Delta states that can occur. The approach to modeling the set of Delta states is discussed below.

The frequency of a given delta state can be obtained by summing over all events that can be generated by a given hazard type:

$$v(DS_j) = \sum \sum v(DS_{ij} \mid e_i, t_n) P(t_n) \qquad (4)$$

where the summations in equation 4 are carried out over the number of events for the hazard type and the timing of events.

For a given hazard (earthquake, flood, etc.), the consequences can be estimated according to:

$$\lambda(C_k > c) = \sum_n \sum_i \nu_i \sum_j \int P(C_k > c \mid DS_{ij}, e_i, t_n) P(t_n) P(DS_{ij} \mid h(\underline{x}), t_n) \; f(h(\underline{x}) \mid e_i, t_n) dh \qquad (5)$$

where $P(C_k > c|DS_{ij}, e_i, t_n)$ is the conditional probability distribution on the consequences (C_k) given Delta state, ij, event I and event timing, t_n. The summations in equation 5 are carried out over the number of Delta damage states, and the number of events that are modeled for the hazard (e.g., earthquakes), and the event timing factors.

Normal Hazards

Historically, levee failures have occurred during normal or 'sunny-day' conditions. The cause of these failures is not always known (e.g., piping through the embankment during normal high tides, including the deteriorating effects of rodents). Estimating the potential for these failures cannot be assessed using mechanistic models similar to what is done in the case of seismic stability or embankment overtopping. Alternatively, the rate of occurrence of levee breaches during normal conditions can be estimated on the basis of historic rates and expert evaluations of the condition, effectiveness of maintenance practices, and vulnerability of levee reaches to failure.

Given the random occurrence of a levee breach on an island during normal conditions, the risk analysis is carried out in the same manner as discussed above for external hazards. The primary difference is the fact there is just a single event of a given type as opposed to multiple events (e.g., earthquakes of varying sizes and locations; see the summation in equations 4 and 5 over the number of events).

The significant difference between external hazards and normal hazards is the potential for multiple, simultaneous levee breaches during the same event. In the case of external hazards, this potential is high. As a practical matter, this is not likely to be the case for normal hazards. As a result, the Delta states that result from normal hazards will be reduced in number and complexity given that multiple breaches at the same time are not likely to occur (e.g., Jones Tract breach in 2004).

Modeling Delta States

As discussed in Section 5, consequences of levee failures in the Delta and Suisun Marsh depend on the joint occurrence of random and/or causally related factors and events. For purposes of estimating risk, the complete distribution of these events (and their joint occurrence) must be considered (at least to some frequency level of interest).

Table 2 lists the primary events to be considered in the assessment of Delta states.

Event tree modeling will be used to define the logic of events and event combinations (Hartford and Baecher 2004). Event trees will be developed for each initiating event or hazard type (e.g., seismic, flood, etc.). Event trees are well suited to modeling the logic of sequences or combinations of events that define the state of the Delta and which are important to the assessment of consequences. Event trees are also a convenient graphical to display the events being modeled and an effective, easy computational tool to determine the frequency of Delta states (sequences of events).

Combinations of Hazard Events

Generally in risk studies, it is not necessary to evaluate the risk associated with the joint occurrence of events such as earthquakes and floods. While such combinations can occur, their joint probability is typically sufficiently low, compared to the occurrence of either event and thus consideration of the joint occurrence of events does not contribute significantly to the risk results. This may not be the case in this risk analysis.

As discussed in Section 5, following an event involving levee failures and non-breach levee damage, ambient winds as well as random wind events can occur in the Delta and Suisun Marsh. Given recent experience (e.g., Jones Tract 2004), it is likely that winds could occur and cause further damage and even breaching on other, non-flooded islands. The degree to which random wind events must be considered in the analysis will be studied. If such occurrences need to be considered, an assessment will be made to determine the probability to which they must be considered.

Table 2
List of Events/Variables

Type	Event	Description	States/Values
State of Nature	Condition Variables in the Delta and Suisun Marsh	These events/factors relate to the characterization of the Delta and Suisun Marsh for the time the risk estimates are made. In the DRMS risk analysis, the variables/ factors that characterize the state of nature include climate change and subsidence. Climate change will impact the loads (static hydraulic head) and hazards (e.g., flood size, timing) that occur.	Sea Level Rise Hydrologic Amount of Subsidence
Event Timing	Type of Year	The availability of water varies substantially from year to year and plays a role in the severity of consequences.	Wet, Normal, and Dry OR Wet, Above Normal, Below Normal, Dry, and Critical
	Season of the Year	The time of the year when an event occurs, plays an important role in the consequences (economic, environmental) in the Delta.	Oct 1, Jan 1, Apr 1, and July 1 OR first of each of 12 months
Initiating Events (Hazards)	Seismic Events Floods Wind Events (also see below) Normal Loads	Each hazard type must be defined in terms of individual events. This preserves the correlations within an event that are important for assessing consequences. For example, for seismic events, an event is an earthquake of a given magnitude, on a specific fault and at a particular location on the fault.	Full range of the hazard events must be defined and a hazard appropriate characterization as defined by hazard analysts and the levee vulnerability team. For seismic events, the full range of earthquake sizes (e.g., **M**: 5 – maximum magnitude) and their possible locations on a fault are considered and the hazard is characterized in terms of the spatial, random distribution of peak ground acceleration.
Levee Performance – Primary Response	Levee breaches	Given the occurrence of a stressing event, the number of levee breaches, the islands where the breaches occur, and the breach locations on an island are considered.	For each island, the number and location of possible levee breaches is defined.
	Non-Breached Levee Damage	Given the occurrence of a stressing event, the levee reaches that have been damaged by a stressing event are identified.	Damaged levee reaches for each island.

Table 2
List of Events/Variables

Type	Event	Description	States/Values
Hazard (secondary)	Wind waves	In the period following an event that has resulted in levee breaches and/or damage, ambient waves or those generated during a wind event can result in deterioration of levees (see below).	Levels of wind waves and duration
Levee Performance - Secondary Response	Levee breaches	Given ongoing wave action or waves caused by wind events, the number of levee breaches that develop as a result of erosion of levee interiors (on flooded islands) and on islands where levees have been damaged, the islands where the breaches occur, and the breach locations on an island are considered.	For each island, the number and location of secondary levee breaches that develop. This will include breaches on flooded island interiors, as well as breaches on initially non-flooded islands.
	Non-Breached Levee Damage	Ongoing wave action and wind events can result in erosion of levees and deterioration of initially damaged levee reaches. These events require additional emergency response resources and increase the time required to stabilize vulnerable levee reaches.	Damaged levee reaches for each island.
Response and Repair	Response and Repair	Given the primary response of levees to the hazard event, and then the subsequent secondary damage that could occur, repairs are undertaken to stabilize breached and vulnerable islands, and to undertake levee repairs (e.g., closure of breaches).	Timing of individual island repairs.
Water Management	Reservoir Management Hydrodynamic Response	This event includes two coupled elements of the analysis; management of water resources (upstream reservoirs) following the breach event and the hydrodynamic response of the Delta and Suisun Marsh to the breaches that have occurred (primary and secondary), water management actions, and the timing of island breach closures.	Delta salinity outcome states; export disruption durations

6.4 Modeling Consequences

The focus of the DRMS risk analysis is to assess the risk associated with levee failures. As described in Section 2, the geographic region for evaluating levee performance is clearly defined (see Figure 1). However, as discussed in Section 4, the assessment of consequences goes beyond the geographic scope of the levee study region.

To begin, the consequences to be assessed will include those occurring as a result of levee breaches and flooding of islands in the study region (see Figure 1). This category of consequences will consider the impact of island flooding to the facilities, infrastructure assets, and land uses within the islands or in the sloughs and waterways in the Delta. In addition, certain consequences that could occur without flooding of islands would also be included. This category of consequences will consider the damage to water system assets in and beyond the Delta caused by the same hazard event that could cause levee breaches and island flooding. The damage to these assets will be included in this analysis if it could significantly increase the impact to local water supply or to statewide water export that would have been caused by the island flooding alone.

Thus, for example, an earthquake that could cause levee breaches could also pose a threat to the Los Vaqueros reservoir. The probability and consequences of a failure of the reservoir due to an earthquake will be considered in this analysis, in conjunction with the consequences of any levee breaches and island flooding caused by the same earthquake. The simultaneous occurrence of island flooding and loss of the Los Vaqueros reservoir could significantly increase the duration of water supply interruption to the local communities. Other water system assets that will be considered in the evaluation of consequences include water export pumping stations in the Delta and the Hetch Hetchy Aqueduct. On the other hand, the risk analysis will not consider the failure potential of the Los Vaqueros reservoir due to a hazard that poses no threat to the Delta levees (e.g., an operating error).

Table 3 provides a preliminary summary of the consequences to be evaluated as part of the DRMS project. The list of consequences in Table 3 will be further reviewed as the consequence models develop.

It is important to also note the risk analysis must consider metrics that satisfy the requirements of AB 1200. AB 1200 requires an assessment of risks that considers:

- Disruption of water supplies derived from the Sacramento–San Joaquin Delta,
- Drinking water quality derived from the delta,
- Preservation of delta land,
- Protection of water rights of the “area of origin”,
- Protection of the environments of the Sacramento–San Joaquin river systems,
- Protection of highways, utility facilities, and other infrastructure located within the delta.

Table 3
Preliminary Summary of Consequences to be Considered in the DRMS Project

Category	Areas
Economics	1. In-Delta losses: These include: • Lost use of structures and businesses in the Delta (for example, loss of use of homes, and loss of business incomes) • In-Delta agricultural losses • In-Delta recreation losses 2. Disruption of water exports (State Water Project [SWP], Central Valley Project [CVP]) and the conveyance facilities crossing the Delta (Mokelumne Aqueduct and Hetch Hetchy Aqueduct) 3. Statewide impacts resulting from loss of infrastructure located in the Delta that provide services to the state as a whole: These include impacts from disruption of facilities such as: • Major roads crossing the Delta, • Electric transmission lines, gas fields, pipelines and storage, telecommunications facilities, railways and ports. 4. The impacts resulting from changed operation of reservoirs, including the loss of hydroelectric generation and recreation opportunities. 5. Short-term employment and personal income impacts 6. Long-term changes to the economy that might result from the disruption
	7. Levee Repair and island dewatering costs
	8. Infrastructure (public and private) repair costs
	9. Private property repair costs
	10. Emergency Response Costs
In-Delta Infrastructure	Direct damage to Delta infrastructure (see list in Appendix A).
Environmental	Consequences to be evaluated for a series of species and habitats as determined by the ecosystem consequence assessment team.
Public Heath and Safety	Fatalities Injuries Homeless (people requiring shelter) Healthcare

When levee failures occur, potential benefits may result. For instance, the intrusion of salt water into parts of the Delta may have certain environmental benefits at the same time that other adverse impacts occur. The quantification of in-Delta benefits will be addressed. Benefits or negative impacts that might occur beyond the Delta will not be explicitly modeled.

6.5 Temporal Variation of Risk

To meet the requirements of AB 1200, an analysis of risks 50, 100 and 200 years from the present must be made. It is common in risk studies to estimate the frequency of occurrence of events, based on available information, and assuming events are Poissonian, to calculate lifetime risks. This approach is reasonable and appropriate if events (hazards) are Poissonian and if conditions (i.e., integrity of the systems being analyzed), and the assets that are exposed in the event of the system failure do not vary over the project lifetime. Based on the current state-of-knowledge it is apparent these conditions do not exist. In fact, it is anticipated that significant changes are taking place in and around the Delta and Suisun Marsh that does not permit a simple projection of lifetime risks. Table 4 provides a partial list of events that are changing and will impact the analysis risk over the study period.

Table 4
Partial List of Events/Conditions Changing in and Around the Delta

Topic	Description
Seismic Events	Increasing likelihood of large magnitude events on major faults (WGCEP 2003).
Climate Change	Increased atmospheric greenhouse gases lead to elevated flood risk include sea level rise, more intense daily precipitation events, and shifts in the seasonal timing of river flows. All of these may be occurring now or may occur in the future in California, and could contribute to increased flood hazards.
Subsidence	Subsidence of Delta organic soils is caused by microbial oxidation of organic carbon. This process removes over 60,000 cubic yards of soil and creates an equivalent volume below sea level.
Flood Hazards	See climate change
Ecosystem	The Delta and Suisun Marsh is a dynamic system that is undergoing constant change. Currently, there is a pelagic organism decline that is not fully understood. The nature of the Delta as it may exist 50, 100 and 200 years from now is not well understood.
Land-use in the Delta	Increasing development (residential, commercial) in the Delta; increasing the public health and safety risks.

To assess risks in the future, an approach is taken to estimate the frequency of events (i.e., earthquakes, economic losses, etc.) in the evaluation year. That is, an 'instantaneous' frequency of occurrence of events of interest is determined in a given year. To make such an assessment, the following will be considered:

- Update the state of the environmental factors that may influence the performance of levees or the size or occurrence of hazards for an evaluation year (e.g., 2055, 2105, 2205).
- Modify the rate of occurrence of events based on current information and changes to the environment; the frequency of occurrence per year of events at the time (e.g., in the year 2055) is determined.
- Update the In-Delta and state-wide exposure (i.e., increasing population and property development, ecosystem changes, etc. that are at risk) to the effects of levee failures.
- Assume that no major event (hazard or a proactive policy) occurs in the intervening years that would result in a significant change in the integrity or configuration of the Delta system.

Assessments of conditions or the state of the environment in the future must take into account the uncertainty in such estimates. In the case of subsidence, estimates will be made of the accumulated subsidence that has occurred from the present, up to the evaluation year being considered (e.g., 2050). Similarly for climate change where there is considerable epistemic uncertainty in the amount of sea level rise that may occur over the next 100 years (see the climate change ITR paper). This uncertainty will be taken into account and represented in logic trees.

In the case of natural processes such as subsidence and climate change which produce an ongoing change to the environment, consideration must also be given the impact they have on the Delta and Suisun Marsh. This impact will be assessed based on business-as-usual response to these evolving processes. For instance, assuming current trends with respect to levels of funding for levee maintenance and repair, it is likely that depending on the amount of sea level rise that is estimated to occur in the next 100 years, Delta islands and Suisun Marsh may be under water. Similarly, as subsidence continues in the Delta there may be an effect on levee stability, agriculture, island conditions due to increase seepage, etc.

For each evaluation year (present, 2055, 2105, and 2205) the risk will be estimated based on:

- An update of the state of the Delta levees (updated levee vulnerability taking into account subsidence, maintenance practices, increased sea level, etc.),
- Changing frequency and severity of hazard events (earthquakes, floods, normal forces), and
- Changing Delta assets such as increased population on Delta islands, decline/improvement or changes in the ecosystem.

Conducted over the study period, the results will provide an estimate of the evolution of risk as measured by the change in the 'instantaneous' frequency of occurrence.

7.0 IMPLEMENTATION

To facilitate the development of the DRMS risk model, a series of topical areas were identified. Each topical area addresses a key subject area. A technical team has been assigned to each topical area and each team has prepared an ITR paper that describes the issues and analysis approach that will be taken and the tasks to be performed. Further, each ITR paper when initially prepared identifies the interface between different topical areas by identifying the inputs required from, and output provided to, other topical areas.

The modular design of the topical areas supports the division of work, and the development of the risk model. It facilitates the integration of the products of each topical area into an overall risk analysis model. This approach also makes the risk model flexible and adaptable to future updates.

The topical areas are identified and described in Section 7.1. topical area summaries are provided in Section 7.2.

The DRMS risk model will be developed as a series of modules. The module concept facilitates the development process and provides the flexibility to make modifications and upgrades to the risk model as new information becomes available or as new models are developed. These modules follow, but do not explicitly map to the ITR paper topical areas. The risk model and the individual modules are described in Section 7.3. This section also maps the topical areas to the risk modules.

The advantages of the modular approach at the same time places an emphasis on the interface between different topical areas. Section 7.4 discusses the areas of interface.

7.1 Topical Areas

Table 5 identifies the basic elements of the risk analysis (see Figure 5) and the topical areas within these categories that were identified at the start of the risk analysis. The following sub-sections briefly summarize each topical area.

Table 5
List of Topical Areas

Category	Topical Area
Hazards	Probabilistic Seismic Hazard Analysis
	Flood Hazard Analysis
	Wind-Wave Action
	Normal Hazards
	Climate Change
	Subsidence
Levee Vulnerability	Levee Vulnerability
	Wave Erosion
	Levee Breaching
Emergency Response	Emergency Response and Repair of Delta Levees
Water Analysis Management	Water Operations
	Hydrodynamics
Geomorphology	Geomorphic Response to Delta Levee Island Failure
Consequences	Economic Consequences
	In-Delta Infrastructure
	Ecosystem
	Public Health and Safety

7.2 Topical Area Summaries

In this section a summary is provided of each topical area. The summary identifies the objective, approach, and areas of interface with other topical areas.

Probabilistic Seismic Hazard Assessment

<u>Objectives</u>

The objectives of the probabilistic seismic hazard analysis are to:

- Estimate probabilities of occurrences of earthquake events, defined by their locations and magnitudes, in specified analysis years, and
- Identify appropriate ground motion attenuation relationships.

<u>Approach</u>

The main steps in this analysis will be to:

- Identify seismic sources in the region of interest that could generate strong ground shaking at the locations of the Delta levees.
- Characterize seismic sources in terms of location, geometry, sense of slip, maximum earthquake magnitude, and earthquake recurrence rates.
- Select appropriate stochastic model(s) of earthquake recurrence.
- Select appropriate ground motion attenuation relationships.
- Estimate site response
- Develop logic tree models to quantify epistemic uncertainties.

Probabilities of earthquake occurrences will be estimated in each of the study years, present (i.e., baseline year), and 2055, 2105, and 2205. The probabilities in future years will be estimated, assuming that no major earthquake occurs in the intervening years. The analysis will account for both time-dependent (i.e., non-Poissonian) and time-independent (i.e., Poissonian) models of earthquake recurrence.

Interface to Other Topical Areas

The DRMS risk analysis needs to estimate the probability of multiple/simultaneous levee failures caused by the same earthquake event. To achieve this, the output of the seismic hazard topical area will be developed in terms of a suite of earthquake events, characterized by the magnitude and location of each event and its probability of occurrence; and appropriate ground motion attenuation relationship(s) along with estimates of inter- and intra-event uncertainties. This output will be used in the overall risk analysis that integrates the results of all topical areas.

Flood Hazard Analysis

Objectives

The objectives of the flood hazard analysis are to:

- Assess probabilities of different total inflows into the Delta in each specified analysis year;
- Estimate water surface elevations (WSEs) at different locations throughout the Delta for each inflow event, concurrent tides and wind/wave conditions; and
- Assess the uncertainties in the estimated WSEs. The analysis needs to account for the impact of climate changes in future years on the frequency of high total inflow events, sea level elevations, and tide levels.

Approach

The basic approach will be to compile historic records of Delta inflows and Bay tides and perform a statistical analysis of the data. The results of this analysis will be used to develop probabilistic models of occurrence of different total inflow events, distribution of the total inflow among different rivers/streams, variations in tide levels, and estimates of WSEs at different locations. The analysis will account for seasonal variations and type of water year (wet, dry, or average).

A probabilistic model of events (such as the Log-Pearson Type III) will be fitted to the data on total inflow. Regression analysis will be used to estimate the distribution of the total inflow among different sources and to estimate WSEs as a function of inflows at different locations and tide levels. Estimated wind wave heights will be added to the WSE estimates developed from inflows and tides. These WSE estimates, which reflect the full range of inflows, tides and wind waves in the study area will be used by the levee vulnerability group to assess levee failure probabilities. Estimates of average hydrologic conditions will be assumed when evaluating levee failure probabilities from earthquakes and other non-hydrologic events.

The effect of forecasted climate changes in future years will be incorporated by appropriately adjusting the frequency and magnitude of total inflow events, sea level elevations, and tide levels.

Interface to Other Topical Areas

The topical area of climate changes will need to define climate changes in future analysis years and the effect of these changes on rainfall events, sea level elevations, and tide levels.

The DRMS risk analysis needs to estimate the probability of multiple/simultaneous levee failures caused by the each given flood event. To achieve this, the output of the flood hazard analysis will be developed in terms of WSEs throughout the Delta for each specified inflow event. This output will be used in the overall risk analysis that integrates the results of all topical areas.

Extreme flood events often occur concurrently with extreme wind storm events. During such conditions, wind-generated waves will increase the WSEs caused by the floods. The topical area of wind waves will have to provide joint probabilities of flood and wind storm events and the additional wave runup generated by the winds.

Wind Waves

Objectives

The objectives of this topical area are to:

- Assess the probabilities of wind storm events in different portions of the Delta;
- Estimate wind wave parameters (height, wave runup, and cumulative wave power) at different Delta levees;
- Estimate wind wave parameters at interior levees on flooded islands; and
- Assess the uncertainties in the estimated parameters.

An additional objective is to assess the joint probabilities of flood and wind storm events, and estimate the increase in the WSEs due to concurrent wind waves. The analysis of wind waves will be needed both for normal seasonal weather conditions and transient storm events.

Approach

Based on existing topography and historical wind measurements, the Delta and Suisun Bay will be divided into climate zones differentiated by seasonal and extreme wind data. With historical wind data, each zone will be assigned a seasonal wind climate in graphical format such as a wind rose. Extreme high wind speeds will also be analyzed in order to assign wind speeds for rare events (say return periods of 2, 5, 10, 25, 50, and 100 years). Probability distribution functions such as the Fisher-Tippett I, Gumbel, or Weibull distributions will be used to characterize extreme wind data in each zone. Wind speed-duration relationships from the Coastal Engineering Manual (CEM) (USACE 2003) will be used to convert both seasonal and extreme wind speeds into appropriate values for use in the simplified wind wave growth equations. Methods to predict wave height and wave period will be a result of simplified equations for wind wave growth from the CEM. Historic events that include coincident water level and wind data will be used to approximate the probability of joint occurrence.

Interfaces with Other Topical Areas

The wind/wave topical area output will be used in the flood hazard topical area to combine the probabilities and effects of flood and wind storm events. The output will be estimated WSEs based on combined flood water levels, tide levels, and wind waves.

The topical area of climate change will need to define climate changes in specified analysis years and the effect of these changes, if any, on patterns of wind storms.

Normal Conditions

Objectives

The objectives of this topical area are to assess WSEs in different seasons under normal wind wave and tide conditions; and to estimate uncertainties in these elevations. This information will be used in the topical area of levee fragility to assess the probability of levee failures under normal conditions (i.e., "sunny weather" failures).

Approach

Historic data on water surface elevations will be used to estimate WSEs in different seasons under normal conditions. The topical area of wind waves will provide estimates of wind wave parameters under normal seasonal conditions.

Interfaces with Other Topical Areas

The data for the analysis for this topical area will be developed in the topical areas of flood hazard analysis and wind waves.

Climate Change

Objectives

The objectives of the climate change analysis are to:

- Assess the impact of climate change due to increased atmospheric greenhouse gases ("global warming") on sea level, hydrologic events, and wind events.
- Assess the uncertainty in these estimates.

The key quantities needed to estimate climate-change impacts on the Delta are projections of sea-level rise, daily-timescale flows on rivers feeding the Delta and local wind speeds and directions.

Approach

Global-scale sea-level rise will be assessed using projections published in scientific journals and reports, and then combined into a distribution possibly weighted by subjectively ranking the credibility and applicability of each source. Effects of climate change on daily-timescale river flows and uncertainties in the estimated flows will be assessed using simulated unimpaired flows from published models and adjusting these flows based on results of simple reservoir operations models. Effects of climate change on in-Delta wind velocities will be assessed using results of limited fine-resolution climate simulations of California.

Interfaces with Other Topical Areas

The output of this topical area will be needed in other topical areas, including flood hazard analysis, wind waves, and ecosystem consequences.

Subsidence

Objectives

The overall objective of the subsidence evaluation is to estimate future depths of subsidence and island surface elevations. Specific objectives are to:

- Estimate the spatial distribution of current and future subsidence rates in the area of organic soils in the Sacramento–San Joaquin Delta.
- Estimate current and future depths of organic soils.
- Estimate future island surface elevations before and after flooding events.
- Estimate uncertainty and randomness in subsidence predictions.

Approach

Future subsidence rates will be estimated based on a statistical evaluation of the recent subsidence rates. Correlations between subsidence rates, and soil organic matter and oxidation rates will be analyzed and the results will be used to validate and modify the statistics-based forecasts of subsidence rates for those islands for which good information about soil organic matter and oxidation rates is available. Data on current elevations will be collected at select locations to better estimate temporally changing subsidence rates.

Interfaces with Other Topical Areas

The projected subsidence rates developed in this topical area will provide the means to estimate island surface elevations in future analysis years; specifically, Years 0, 50, 100, and 200. The estimation of island surface elevations will take into account any planned response actions to the on-going subsidence, as defined in the baseline (“business-as-usual”) conditions. The projected island surface elevations will be used in the topical areas of levee fragility, hydrodynamics, and ecosystem consequences.

Levee Vulnerability

Objectives

The objective of the levee vulnerability analysis is to assess the response of levees to different hazard events and estimate probabilities of different damages states as a function of levee response. The hazards to be considered are earthquakes, floods, and wind storms (and resulting waves). In addition, levee failures under normal seasonal weather conditions (i.e., “sunny weather” failures) will also be evaluated. Three specific damage states of levees will be considered in this analysis - breached, damaged (but non-breached), and non-damaged. Some of the levees that are damaged, but not breached during the initial hazard event may not be repaired during a specified recovery period and could be breached due to on-going exposure to seasonal water levels in the Delta, winds/waves, and tides. The conditional probability of such secondary breaches will also be evaluated in the levee vulnerability module.

Approach

For a seismic event, levee reaches will be categorized into seismic vulnerability classes based on such levee characteristics as peat thickness and geometry. A typical levee cross section will be defined for each vulnerability class. Regression equations will be developed to estimate the mean deformation as a function of ground motion and the standard deviation of deformation. Limit states on deformation will be defined for the three damages states based on engineering judgment. The probability of each damage state will then be calculated based on an assumed probability distribution for deformation.

For a flooding event, levee reaches will be categorized into flood vulnerability classes based on such characteristics as levee crest elevation and type of levee construction. The probability of a breach due overtopping will be assessed by calculating the probability that the water surface elevation due to the combined effects of inflows, tides, and wind waves would exceed the levee crest elevation for a typical levee reach in each flood vulnerability class. The probability of a breach due to seepage will be estimated based on WSE and type of levee construction. The total probability of a beach will then be the sum of the individual probabilities.

Levees that are damaged, but not breached by the initial hazard event, and not repaired during a defined recovery period, will be further exposed to normal seasonal wind/wave conditions and tides. The probability of a breach due to this exposure will be assessed based on engineering judgment and available data on past failures.

Interfaces with Other Topical Areas

This topical area will need input from the topical areas of seismic hazard, flood hazard, wind waves, normal seasonal conditions, and subsidence. The output of the levee vulnerability analysis (e.g., conditional probability of failure as a function hazard levels) will serve as a direct input the risk analysis.

Emergency Response and Repairs of Delta Levees

Objectives

The objective of the emergency response and repair analysis is to develop a model to estimate the time required for repair of Delta levees which breach or are damaged during an event (e.g., an earthquake), material requirements, and costs associated with a sequence of events (a scenario) that involves an identified number of levee breaches. In addition, the model must also estimate the time for island dewatering. The model must be applicable for the range of sequences that will be modeled in the risk analysis. The range of sequences will be defined in terms of the number of breaches, the number of islands that may be flooded, the range of breach sizes, and set priorities for breach closures and levee repairs.

Approach

The model will determine the response and repair times based on a strategy for responding to multiple breach scenarios that is based on the prioritization of levees and islands as defined by the Hydrodynamic and Water Quality team. This strategy will include the prioritization of islands, levees, and work tasks (i.e., capping ends and closing breaches) for completing the emergency repairs. In addition, the emergency repair and response model will calculate the material demands and cost (in 2006 dollars) for repairing each levee breach as well as dewatering each island.

Interface with Other Topical Areas

This topical area will require input from the levee fragility topical area on the range of number of breaches and damaged levee reaches caused by each hazard event. The model to estimate response and repair times for different failure scenarios developed in this topical area will be used in the topical area of risk analysis calculation.

Water Management Analysis

Objectives

The objectives of this topical area are to:

- Simulate the water management decisions that must be made following a levee breach incident – in particular, their effects on upstream reservoir releases, in-Delta uses, exports, and Delta outflow.
- Simulate the hydrodynamic and water quality responses to a levee breach incident (sequence) – characterizing Delta salinity (in space and time) as needed to estimate required module outputs.
- Calculate (output) a priority order for breach capping and closure based on the initial salinity intrusion or other hydrodynamic characteristics occurring in the sequence.
- Provide, for each simulation output, the probabilistic model necessary to characterize epistemic and aleatory uncertainty.

Approach

A series of submodels will be developed to evaluate the impact of different scenarios of levee breaches and island flooding on water quality and export. These submodels are as follows:

First, an ***initial flooding submodel*** will be required to simulate island flooding caused by levee failures. It must characterize the initial salinity intrusion due to water migrating upstream from Suisun Bay to fill the breached islands.

A ***water management submodel*** will be needed to simulate the way in which water system managers will react to the incident represented by each sequence. In particular, for each sequence, the model will need to calculate Delta inflow versus time for each significant Delta tributary based on hydrologic inflows, upstream storage, a set of storage management and release rules, and a set of other state variables reflecting the incident progression. This model may draw on or use portions of CalSim or other existing water management models.

A ***hydrodynamics and water quality submodel*** will be required to compute the distribution of salinity and other water quality constituents though out the repair and recovery period. The distribution of water quality determined by this submodel in conjunction with water quality needs will be used to determine requirements for Net Delta Outflow and allowable exports. Selected outputs from this submodel will also be passed on as inputs to the Environmental Module. Details on the hydrodynamics submodel are provided below.

A ***Delta island water availability and use submodel*** will be required to indicate whether islands that are not flooded will have access to fresh water from adjacent Delta channels for use in irrigation or desalting. This submodel will also need to estimate the adjusted values of DICU.

Finally, a ***water export submodel*** will be required to represent decision making on whether to pump and how much to pump for each month from each Delta export pumping station.

A great deal of interconnection and feedback will be required among these submodels in order to reflect incident progression for all five submodels and to guide the Delta toward water quality improvements until in-Delta water use and pumping are reestablished and then to provide required Delta inflows to support these uses without unacceptably degrading water quality. For this reason, all these submodels will be incorporated into an overall “Water Analysis Module” to address the need for interconnection and feedback by modeling the time series as steps – so that each temporal state can be a function of the relevant prior states represented in the other submodels.

Interface with Other Topical Areas

The water analysis module will need input from seismic hazard module, flood hazard module, levee vulnerability module, and emergency response and repair module. The hazard modules and levee vulnerability module will define failure scenarios for each hazard event. For a given initial hazard event, each scenario will define the levee reaches that would be breached or damaged, the islands that would be flooded, and other Delta assets involved in water export that would be damaged. The emergency response and repair module will define the sequence and timing of levee repairs and island restoration. The levee vulnerability module will also define on-going breaches on levee reaches that are damaged, but not breached during the initial event; are not repaired during each time step (such as one month); and are breached due to on-going exposure to winds/waves and tides during the time step.

The water analysis output will be needed in the evaluation of impacts to water export, ecosystems, and in-Delta land uses. Specific outputs will include:

- Water export and salinity (by month) throughout the incident and recovery period at each of the five Delta water export pumping stations for use in the Statewide Economic Consequences Module.
- Water availability (based on salinity) at the channel takeout points for each unflooded island for use in the In-Delta Economics Module.
- Salinity (monthly average) at key locations for the Ecosystem Module.

Hydrodynamics

Objectives

Hydrodynamics is a submodel within the water analysis module. The objective of this submodel is to simulate hydrodynamic and water quality responses to levee breach incidents. Important water quality parameters include salinity, temperature, and dissolved or total organic carbon.

Approach

The hydrodynamic and water quality analysis submodel will use multiple modeling tools to estimate the hydrodynamic response to different levee breach sequences. The tools will range from sophisticated two and three-dimensional hydrodynamic models to one or more simplified models. The sophisticated models will be applied to a relatively small number of scenarios, while the simplified model will be less computationally intensive so that it can be applied to a large number of scenarios. The application of multiple tools will allow estimation of model uncertainties associated with the simplified model.

Development of the hydrodynamic and water quality risk analysis module will proceed along three tracks:

1. Identifying important “bookend” levee breach sequences and performing detailed modeling of those cases.
2. Developing a simplified model for rapid evaluation of the water quality consequences that can be for many sequences.
3. Developing the uncertainty estimates for the detailed and simplified models.

Interface with Other Topical Areas

As noted above, the hydrodynamics and water quality submodel will be incorporated within the overall water analysis module. It will have to be coupled with the other submodels within the water analysis module so that the sequence of events and impacts is modeled consistently.

Geomorphic Response to Delta Levee/Island Failure

Objectives

The objective of this topical is to evaluate the geomorphic response to levee failure(s) that can be used to assess the impact of the Delta morphology may have on the analysis risk over the study period. Forecasts of both short-term, local-scale and long-term landscape-scale impacts to the Delta geomorphology will be considered.

Approach

Three interacting analyses will be performed:

1. Predicting Channel Geomorphic Response using Hydraulic Geometry

Empirical hydraulic geometry relationships will be used to predict channel erosion responses to increases in upstream tidal prism caused by levee failure.

2. Predicting Morphologic Response and Habitat Changes using Hypsometric Analysis

This analysis will estimate changes in hypsometry due to sedimentation, subsidence, and sea level rise. These changes will then be translated into projected changes in the area occupied by habitat zones, with assumptions made regarding the colonization elevation of tule marsh.

3. Projecting Changes in Sediment Budget that Influence Bathymetry and Habitats in Suisun and San Pablo Bays

This analysis will outline the conceptual understanding of the existing sediment budget, exploring source, supply, storage areas, and suspended sediment fluxes between these areas. This understanding will be used to assess how the sediment dynamics will change after levee failure, and what impact this change will have on bathymetry and habitat response in Suisun Bay and San Pablo Bay.

Interface with Other Topical Areas

Levee failure scenarios will need to be defined so that the geomorphology response of the Delta environment to each scenario can be assessed. Each scenario needs to define the number, location, size and phasing of island breaches. This information will be developed in the levee vulnerability module. Estimates of subsidence rates beneath both submerged and non-submerged sites, and assumptions regarding subsidence of remnant levees will be developed in the subsidence topical area. Estimates of subsidence rates beneath both submerged and non-submerged sites, and assumptions regarding subsidence of remnant levees will also be developed in the subsidence topical area. Habitat zones will be defined in the ecosystem topical area. Data on tidal prism and tidal range will be developed in the hydrodynamics topical area.

Impacts to Public Health and safety

Objectives

The objective of this topical area is to assess the impact of levee failures and island flooding, and the resulting water contamination, on public health and safety.

Approach

The analysis will assess the impact of levee breaches to the public taking into account the timing of levee breaks, the high velocity flows associated with the levee breach as well as the slower rising waters that occur during island flooding.

Interfaces with Other Topical Areas

Information on population-at-risk inside Delta islands and in the flood exposure area will be obtained from existing state projects. Information on water volumes and velocities as a result of levee breaches and island flooding will be developed in the flood hazard module.

Economic Consequences

Objectives

The objective of this topical area is to quantify economic impacts, including economic damages and costs, caused by a wide range of Delta levee failures. The economic impacts will be measured relative to an economic baseline to be defined in the methodology. The methodology must be flexible enough to consider a full range of baseline and event conditions involving level of development, season, water supply conditions, and event scenarios. In the case of seismic events, the types and duration of other (non-Delta levee) infrastructure damages must be considered.

Approach

The economic analysis will develop cost functions that relate the physical, institutional, and operational responses to a levee failure event to the level of economic consequence. For example, the cost of lost use of housing will be related to the number of houses lost, the duration for which they are lost, and availability of replacement housing. Likewise, the cost of inundated agriculture will be related to the number of acres inundated, the duration of inundation and recovery, and the mix of crops grown on the inundated land. Further descriptions of the causative relationships are provided later in this section.

There are several existing economic models we are proposing to bring into the analysis. We propose to examine DWR's LCPSIM model's approach to modeling local water supplies and costs. We will also examine the use of IMPLAN, and DWR's agricultural IO model, to estimate economic impacts in terms of jobs and personal income. Useful information may be included in the Hydrologic Engineering Center's Flood Damage Analysis (HEC-FDA) computer program, and in FloodEcon, a flood damage estimation software program under development by the National Water and Climate Center, among others.

For most categories of losses, the team will search for applicable information in the following priority: 1) models that are readily applicable or can be modified, 2) information from published literature regarding parameters or data for the cost functions, and 3) expert opinion. The work will include obtaining opinions and information from knowledgeable experts within each industry. This will enable the team to use information that is not otherwise published, and will allow for increased credibility for the final results.

Interface with Other Topical Areas

Information on current and projected Delta land and marine uses will be developed in the In-Delta infrastructure topical area. Information on the severity and duration of water supply disruption will be developed in the water management module. Information on Delta infrastructure disruption will be developed in the Delta infrastructure module.

Ecosystem Impacts

Objectives

The primary objective of the ecological effects analysis is to evaluate the conditional probability distribution of environmental impacts/benefits to the aquatic and terrestrial species/habitats within the Delta in response to floods, seismic events, wind waves, etc. that could result in scenarios involving single or multiple levee breaches which effect a number of islands of the Delta. The ecosystem effects analysis is designed to capture and describe the affects on a range of scales from effects on individuals within a population, to one or multiple cohorts of a species, to an entire population, to ecosystem-level changes.

Approach

The ecosystem assessment will evaluate the impact of levee failures to a series of species and/or habitats that are judged to be appropriate risk metrics. A varied approach will be used to assess ecosystem impacts. Three types of models will be considered: quantitative, semi-quantitative, and qualitative. The choice of models will be selected on the basis of the state of information available to implement a particular model type (e.g., quantify model parameters). It is generally recognized there is significant epistemic uncertainty in making scientific evaluations of the impact of levee failures. It is anticipated, expert elicitation methods will be used, to different levels of analysis, to make ecosystem impact assessments.

Interface with Other Topical Areas

Changes to key water quality parameters (such as salinity, temperature, and dissolved or total organic carbon) will be analyzed in the water analysis module.

7.3 Risk Model

The elements of the risk analysis were identified in Section 6 and the summary of the ITR papers and their interface with other topical areas identified in the previous subsection. In this section, the mapping of the ITR papers to risk modules (computational elements of the risk model) is provided.

Table 6 gives the mapping of the ITF papers and the risk modules. The risk modules are identified generically, independent of the hazard type. The relationship of the ITR papers to the risk model is illustrated in Figure 7.

The ITF paper on geomorphology is not shown in Figure 7. At this time, it judged that the geomorphic changes that take place during the "normal" events in the Delta and Suisun Marsh, including the breaching of levees will not significantly impact the assessment of risks. This would however, not be the case if the risk analysis were modeling the abandonment of islands. Nonetheless, an evaluation of geomorphic changes and the impact on hydrodynamic response will be conducted to verify this.

The relationship of the risk modules is summarized in Table 7.

Table 6
Mapping of ITF Papers and Risk Modules

Risk Module	ITF Paper
Hazard	Seismic Flood (Normal hazards included in the Flood paper) Wind and Waves
Levee Performance a. Primary b. Secondary	Levee Vulnerability – Seismic, Flood, Wind Erosion, Normal Wind Waves
Levee Breach and Damage Repair	Emergency Response and Repair
Water Analysis	Water Operations Hydrodynamics Geomorphology
Risk Logic Model	Risk Analysis
Consequence	Economics In-Delta Infrastructure Ecosystem Public Health and Safety

Table 7
Interrelationship Between the Risk Modules and ITF Papers

Risk Module	Description and Interrelationship	ITF Papers
Hazard	The ITR papers that provide input to the Hazard module define the frequency of occurrence of events and the spatially distributed and correlated characterization of the stressing event.	Seismic Flood and Normal Wind Waves
Levee Performance a. Primary b. Secondary	The initial part of the event tree model models the sequences of levee breaches, damage and island flooding that occur as a result of a stressing event (e.g., earthquake). The input to this calculation is the conditional probability of failure or damage of levee reaches as a function of the stressing event characterization. Following the occurrence of the stressing event, the logic model estimates the number and location of secondary breaches that occur as a result of wind	Levee Vulnerability Wind Waves Risk Analysis

Table 7
Interrelationship Between the Risk Modules and ITF Papers

Risk Module	Description and Interrelationship	ITF Papers
	wave erosion of damaged levees and exposed island interiors.	
Levee Breach and Damage Repair	Defines the frequency of occurrence, duration and magnitude of wind waves on damaged levees and exposed levee interiors.	Emergency Response and Repair
Water Analysis	This module evaluates the response of the Delta and Suisun Marsh to levee failures, taking into account upstream reservoir management, Delta water operations, Delta island water use the sequence of repairs, and the sequence of levee repairs.	Water Operations (including upstream reservoir management, Delta water operations, Delta island water use) Hydrodynamics
Consequences	This part of the risk model maps the consequences to the Delta states.	Economic Ecosystem In-Delta Infrastructure Public Health and Safety
Risk Quantification	This final part of the risk model combines the estimates of the Delta states with the consequences to estimate risk. The process includes the final risk results and the deaggregation of risks (see Section 9)	Risk Analysis

7.4 Interface Between Topical Areas

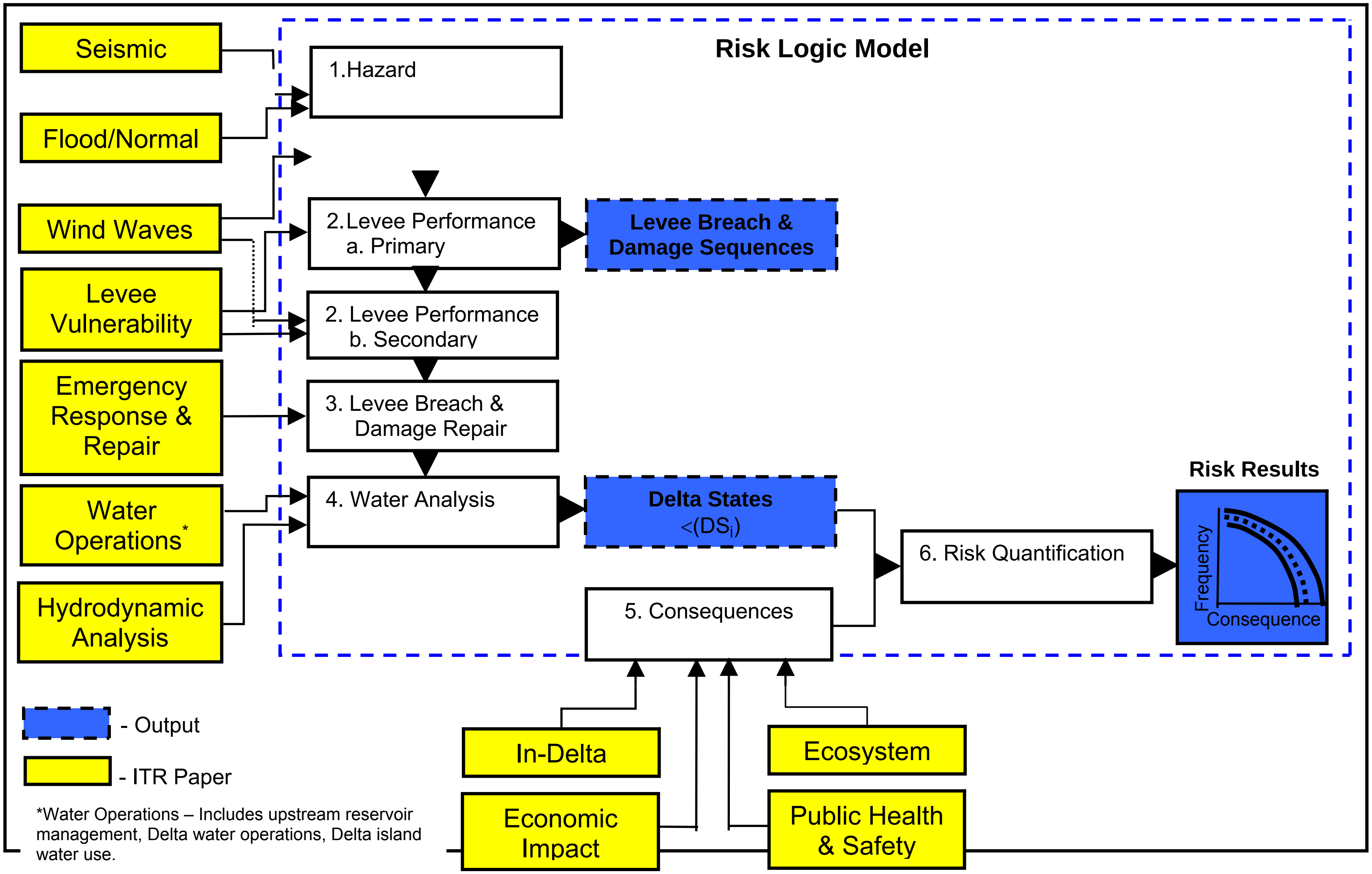
An important part of the risk model development is the interface between the modules. This interface includes:

- Probabilistic interface required to quantify risk
- Collection and utilization of common datasets
- Coordination of intermediate evaluations

The probabilistic interface refers to the consistent modeling of random variables and dependencies as defined in the risk logic model. For example, the assessment and characterization of flood hazards in the Delta must be made in a manner that is consistent with the approach that is used to define the fragility (conditional probability of failure) of levees that are exposed to flood hazards. These areas of interface are important throughout the risk model.

There are a number of parts of the risk analysis that will utilize the same datasets. For example topographic and bathymetry data is required by the levee vulnerability team and the hydrodynamic modeling team. Similarly, the economics team and the in-Delta infrastructure evaluation team require common information on Delta assets. In these and other areas a coordinated effort is required to collect and manage this information so the same datasets are used in the analysis.

The final area of interface involves areas of coordination and distribution of results between teams. A good example of this involves the in-Delta infrastructure assessment and the economic evaluation. In order for the economics team to assess the impact to businesses in the Delta of



*Water Operations – Includes upstream reservoir management, Delta water operations, Delta island water use.

Figure 7: DRMS Risk Model.

damage that results from levee failures and island flooding, they need to know how long it will be until repairs can be made and facilities returned to full use. This information will be used by the economic evaluation team to obtain information for and to model the business impact of the damages and resultant period for repair.

8.0 BASIS OF ANALYSIS

The DRMS risk analysis is a model of the potential for levee failure in the Delta and Suisun Marsh and the consequences that may result. As a 'model' it is a representation of the physical systems, events, operations, and outcomes that may occur. The guiding principle for establishing a basis for the risk analysis and ultimately the development of the 'baseline risk scenario' is the business as usual precept. This precept will be the primary guide for assessing the state of the Delta and Suisun Marsh and the state as a whole in future years (50, 100 and 200 years from the present).

A limiting factor of the DRMS risk analysis, as with any study, is the state-of-information (e.g., availability, accuracy, completeness) that is available at the time to support the evaluations that must be conducted.

Areas where limitations of the state-of-information which impact the modeling include:

- Policy Guidance – There are a number of areas where existing policy does not cover the range of events that will be addressed in the risk analysis. These areas include water management and the response and management of levee repairs that covers the range of scenarios involving a large number of breaches and islands. In addition, looking to future years, existing policies have not been explicitly established with time horizons that cover the period to be studied in the DRMS analysis.
- Technical Data – There are a number of areas where the state of technical information limits the evaluations that can be performed. For example, existing climate change studies that look at sea level rise, have been carried out to 2100. Estimates have not been made for 2200. Similar informational (data, analysis results) shortcomings exist in other topical areas as well (e.g., economics, environmental, etc.).

From the perspective of the DRMS study, guidance from DWR and the study partners will be sought as necessary to bridge these gaps and to develop the 'business-as-usual' input to the risk model.

9.0 PRODUCTS

This section provides an overview of the results that will be generated by the DRMS risk analysis. As described in Section 1 and further presented in Section 6, risk is defined as the likelihood of adverse consequences, which is measured in terms of the annual frequency of exceedance distribution for given metric (e.g., economic impact). Due to the diversity of impacts that levee failures could have in the Delta and the state as a whole, a number of metrics will be used to provide a measure of risk associated with levee failures. The risk metrics will include measures of public health and safety impacts, economic consequences, environmental effects, and water export disruptions. Within these areas, there may be multiple metrics. For instance, it is anticipated there will be a number of metrics, developed as part of the environmental consequence assessment, which collectively are designed to capture the range of impacts that levee failures could have on the ecosystem.

In addition to the ‘primary’ risk measures discussed above, the risk analysis will provide a number of secondary or intermediate results. For example, the analysis will provide a deaggregation of the risk with respect to the various hazards (e.g., earthquakes as compared to floods) that are evaluated, the contribution of different size events (e.g., different magnitude earthquakes), different entities (e.g., islands), etc.

The various categories of risk analysis products are summarized in Table 8.

Table 8
Risk Analysis Results

Category	Description
Risk Measure	Frequency of exceedance distribution for selected risk metrics (e.g., fatalities, economic impact).
Secondary/Intermediate Results	a. Frequency of island flooding due to all initiating events and each event individually. b. Conditional probability of island flooding as a function of hazard levels (e.g., ground motion).
Deaggregation of Risk	a. Risk associated with particular hazard or initiating event. b. Risk for a particular entity (e.g., a Delta island) c. Relative contribution (marginal distribution) of a variable, event, etc. to risk d. Contribution of sequences of events (e.g., island flooding/levee failures) to risk.
Risk Trends	Display of risk measures and secondary/intermediate results as a function time.

As discussed in Section 6, the risk analysis will be conducted for future times (e.g., 50, 100, and 200 years from the present), in addition to the current risk. These time-dependent estimates provide the opportunity to examine risk trends and thus are another product of the analysis.

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Appendices

Appendix A
Delta Assets

Table A1
List of Delta Assets

Facilities	Assets
Delta/Suisun Levees and Channels	Levees Channels
Islands and land uses	Agriculture Residential Environmental Habitat Recreational
Infrastructure	Shipping Channels Buildings: commercial, residential Communication facilities Health care facilities (hospitals, nursing and health facilities) Police and Fire stations Public facilities Construction Material and Industrial Gas Plants Marinas Port facilities Roads Railroad Mokelumne Aqueduct Gas Storage and Pipelines Gas and oil wells Power generation facilities High-Voltage Power Transmission Wastewater Solid and hazardous waste Misc. Transportation
State/Federal Water Project Facilities	Delta Cross Channel Clifton Court Forebay Banks Pumping Plant (SWP) Tracy Pumping Plant (CVP) Contra Costa Water District Pumping Plants South Delta Barriers South Bay Aqueduct Pumping Plant California Aqueduct Delta-Mendota Canal South Bay Aqueduct Vallejo Intake North Bay Aqueduct Intake/Pumping Plant Suisun Marsh Salinity Control Gates

Appendix B
Taxonomy of Uncertainties

As a guide for each part of the risk analysis we want to develop a taxonomy of the uncertainties in the analysis. For a given element of the risk analysis, the characterization of uncertainty can be thought of in terms of model and parametric uncertainties (Abrahamson, et.al, 1990).

This partition is as follows:

> Modeling Uncertainty - Represents differences between the actual physical process (hurricane, embankment failure) and the simplified prediction model. Modeling uncertainty can be estimated by comparing model predictions to actual, observed events/performance.
>
> Parametric Uncertainty - Represents uncertainty in the values of model parameters (e.g., central pressure). Parametric uncertainty is quantified by observing the variation in parameters inferred (either in a direct or indirect manner).

It is important to recognize that the distinction between modeling and parametric uncertainty is model-dependent. For instance, one may reduce the scatter in the predictions by making the model more complete; that is, by introducing new parameters in the model. Unless these new parameters are known a-priori, there will be additional parametric uncertainty, thereby transferring some modeling uncertainty into parametric uncertainty, without varying the total uncertainty.

Both the modeling and parametric uncertainties contain epistemic and aleatory components. For instance, observed scatter that is not accounted for by the model and varies from event to event is aleatory modeling uncertainty, whereas statistical uncertainty (due to limited data) regarding model bias is epistemic modeling uncertainty.

Table B1 gives a descriptive breakdown of model and parametric uncertainties for the flood hazard analysis and their characterization in the risk analysis in terms of aleatory and epistemic.

It is important to recognize that the distinction between modeling and parametric uncertainty is model-dependent. For instance, one may reduce the scatter in the predictions by making the model more complete; that is, by introducing new parameters in the model. Unless these new parameters are known a-priori, there will be additional parametric uncertainty, thereby transferring some modeling uncertainty into parametric uncertainty, without varying the total uncertainty.

Both the modeling and parametric uncertainties contain epistemic and aleatory components. For instance, observed scatter that is not accounted for by the model and varies from event to event is aleatory modeling uncertainty, whereas statistical uncertainty (due to limited data) regarding model bias is epistemic modeling uncertainty. Table B1 illustrates this two-way partition of total uncertainty.

This taxonomy should include:

- Identification and description of the sources of uncertainty in the analysis – model and parametric.
- Characterization of the sources of uncertainty into different types - aleatory and epistemic
- Description of the approach (analysis, data, expert assessment) that will be used to estimate each type of uncertainty.

Table B1 can serve as a guide or type of checklist to identify the sources/types of uncertainty with the objective of developing a list that can be used to develop a model of the total uncertainty.

If there are uncertainties we cannot model/estimate due to limitations in time or data (or both), these should be identified. These may be current limitations of the present analysis and something that could be evaluated in the future.

As a side note, the identification of the sources of uncertainty is important from a defensibility perspective, whether we can explicitly evaluate them or not. It is important to consider the uncertainties, what their impact on the risk analysis is (qualitatively), and to estimate them (if possible, as noted above).

Table B1
Partition of Uncertainty: Example for the Flood Hazard Analysis

		Types of Uncertainty	
		Epistemic	**Aleatory**
Hydrologic Hazard Analysis	**Modeling**	Uncertainty about the hydrologic events in the Delta. This uncertainty could relate to the overall modeling approach as it 'models' floods in the Delta. Other model uncertainties include the flood frequency model (e.g., Log-Pearson III, versus others). There will also be epistemic uncertainty in the hydrologic model as climate change impacts are incorporated.	For a given hydrologic event, there is unexplained variation in river discharges (also fraction of discharges from different rivers), and water-surface elevations. These variations are due in part to factors that not included in the hydrologic model. This variability is captured in part (maybe totally for practical purposes) in the statistical analysis (e.g., variation in water surface elevations given discharge).
	Parametric	Uncertainty about the estimates of the parameters of the various parameters in the model (Log-Pearson II parameters, discharge-water surface elevation model parameters, etc.).	Similar to above, all hydrologic events are not the same and likely are not represented by a single set of model parameters. This variability represents an event-to-event variation in floods and is an aleatory variability that may be considered independent from event to event.