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The purpose of the Delta Risk Management Strategy (DRMS) analysis is to assess the risks to the Sacramento–San Joaquin Delta (Delta) and the state that result from Delta levee failures. Delta and statewide risks are evaluated in terms of the economic, environmental, and public health and safety impacts that levee failures may have.

To start, this section describes the risk problem being evaluated. This is followed by a presentation of a conceptual model of events in the Delta that are modeled in the DRMS risk analysis, the risk analysis methodology, the DRMS risk model, and finally the steps in the quantification process. As part of the discussion, Delta risks not addressed are also identified.

4.1 THE RISK PROBLEM

As discussed in Section 2, the DRMS study is intended to evaluate the risks of levee failures in the Delta and Suisun Marsh. The hazards or stressing events that are considered are defined in the DRMS project work scope (JBA 2006a, 2006b) and parallel those identified in Assembly Bill 1200.

The DRMS study must also assess how risks may change into the future (over the next 200 years), taking into account environmental factors such as subsidence and climate change that alter the landscape of the Delta, changes in the potential for future hazards (i.e., earthquake occurrences, flood events), population growth and development in the Delta, and the state's reliance on the Delta as a water source. An analysis of future risks is limited by the availability of projections in each topical area (e.g., future population growth). Nonetheless, information on short-term projections to 2050 and in some cases to 2100 are available, making it possible to project how current risks may change in the future. The approach for considering future risks is generally described in Section 4.9 and presented in detail in Section 14.

The following sub-sections describe the elements of the DRMS risk problem and the analysis conceptual model. In addition, hazards and risks that are not addressed in the DRMS analysis are identified.

4.1.1 Threats and Hazards that Affect the Delta

As in any other region or community, the Delta and Suisun Marsh face a number of hazards or threats that can initiate a sequence of events that result in damage or loss. The Delta is unique in terms of the natural and man-made hazards that threaten it (e.g., earthquakes, floods, winds, and industrial accidents) and the exposure to loss (discussed further in Section 5), which includes the local population, a valued and varied ecosystem, local and regional infrastructure (pipelines, state highways, and rail lines), a water export system that relies on levee integrity for conveyance, and local, regional, statewide, and national business interests.

Events that pose a threat to the Delta include the following:

- Natural hazards:
  - Earthquakes
  - High winds
  - Wind waves
  - Hydrologic events

  - Wildfires
  - Surges due to low-pressure meteorological systems
- Man-made hazards:
  - Oil, gas or chemical spills
  - Terrorist acts
  - Highway accidents
  - Vandalism
  - Rail accidents
  - Commercial shipping accidents
  - Recreational boating accidents
  - Commercial or private aircraft accidents
  - Military aircraft accidents
  - Explosions associated with any of the above man-made events
  - Man-caused fires
  - Accidents or events outside the Delta or Suisun Marsh that may affect the Delta, such as upstream toxic spills or dam failures
- Environmental/Ecological:
  - Invasive (non-native) species
  - Processes (currently not well understood) associated with the observed pelagic organism decline in the Delta and Suisun Marsh
- Intrinsic Factors/Forces that affect levees:
  - Hydrostatic Forces
  - Tidal variations
  - Channel flow variations due to State Water Project (SWP) and Central Valley Project (CVP) pumping (a man-made hazard which is intrinsic to the current operation of the Delta)
  - Ambient waves
  - Animal burrowing in levees
  - Internal erosive or deteriorating effects of through- or under-seepage in levees
- Public Health-Related Events:
  - Disease
  - Contaminated foods
- Public Safety:
  - Crime
  - Public unrest

The foregoing list of threats or initiating events is not exhaustive, but is indicative of the range of events that could adversely affect the Delta, Delta levees, the ecosystem, the public, and Delta infrastructure.

Looking to the future, there are a number of drivers of change that affect the Delta landscape and the chance and magnitude of future hazards. These drivers of change (identified in Section 2 and repeated here) include[1]:

- Subsidence
- Global Climate Change – Sea-level Rise
- Regional Climate Change – more winter floods and less snow pack
- Seismic Activity
- Introduced Species

As these changes evolve, they will change the Delta landscape, affect the severity and likelihood of occurrence of future hazards, , the performance of Delta levees, and the future of the Delta ecosystem.

4.1.2 Scope of the DRMS Risk Analysis

Although the hazards and risks that may impact the Delta are varied, the DRMS risk analysis is focused on specific events and a limited number of hazards that may initiate them. The focus of DRMS is to analyze the risks to the Delta and the state that are the result of levee failures only. Further, the threats to Delta levees that are considered are limited to (JBA 2006a, 2006b):

- Earthquakes
- Hydrologic events (floods)
- Wind waves
- Combinations of the above
- Intrinsic forces or factors (as identified in Section 4.1.1)

Hereafter in this report, the intrinsic forces/factors that affect levees are referred to as “normal” or “sunny-day” events. In evaluating the potential for levee failure in the future, the DRMS risk analysis also addresses environmental factors that could change the Delta landscape. These include (JBA 2006a, 2006b):

- Subsidence
- Climate change (as it may effect sea level, changes in hydrologic patterns, winds, and air temperature)

In evaluating these hazards and environmental factors, consequences that could occur in the Delta, but are not the result of a levee failure, are not addressed in the DRMS analysis. For instance, the impact of hydrologic events in the Delta that are not associated with levee failures (damages that occur as a result of flooding not associated with levee failure), are not evaluated in the DRMS risk analysis. DRMS is levee-centric; the risk analysis evaluates the performance of Delta levees and the impact their failure has on the Delta itself and the state as a whole. Other

[1] This subsection addresses only the threats or hazards the Delta is exposed to. Therefore, only drivers of change related to threats or hazards are listed.

hazards or threats, not identified above as specifically considered in this analysis, even if they could adversely impact Delta levees, are not addressed.

4.1.3 Conceptual Model of Hazards, Levee Failures, and the Response of the Delta

An analysis of any system, natural or man-made, begins with an initial characterization of the events/processes to be evaluated; a conceptual model. This characterization is followed by the development of a model that is an analytic representation of the events of interest that serves as the basis for quantification. The model is a representation of a "real" system and how it performs or reacts to the hazards or conditions it may be exposed to. Such a representation is limited by the state of knowledge (i.e., scientific understanding and data). As a result, a model is an approximation. In this sense, the DRMS risk analysis is a model of the events that can lead to levee failure and the events that ensue, including levee damage, the hydrodynamic response of the Delta to levee breaching and island flooding, and the consequences of these events. This subsection presents a conceptual model of events considered in the DRMS risk analysis.

The conceptual model of levee failure events is shown in Figure 4-1. The following describes the elements of the model.

Initiating Events. A levee failure can be initiated by external hazards or intrinsic forces that can cause a failure (breach) or damage to a levee. The DRMS analysis considers external events such as earthquakes, hydrologic events, and wind waves. Intrinsic forces/factors are persistent day-to-day, year-to-year for Delta levees, and periodically result in a local instability and a levee failure. These intrinsic factors include hydrostatic forces, tidal cycles, burrowing animals, ambient wave action, and the cumulative effects of deterioration.

Levee Performance and Failure. When an external hazard occurs in the Delta, levees are exposed to transient forces that affect part of and even the entire Delta. These forces may lead to single or multiple levee failures during a single event (e.g., earthquake or flood). If all the levees on an island survive (do not fail and are not damaged), island flooding does not occur, and post-event repair is not required. Alternatively, if one or more reaches were to fail, island flooding occurs. When an external event does occur, the performance of Delta levees can be characterized into the following three general states:

- **OK (no failure or significant damage).** A levee is modeled as "OK" if neither damage nor failure has occurred anywhere along the levee system that protects an island tract. External events, particularly earthquakes, can cause damage to levees that require repair after the event and may be susceptible to post-event damage or failure.
- **Non-breach damage.** This term applies if a levee experiences damage, but not a failure (i.e., no breaching). In the DRMS risk analysis, non-breach damage to levees is only considered in the case of earthquakes.
- **Failure (breach).** Levee failure (a breach) occurs when it has been damaged to the point that it does not remain stable. As a result, it loses its hydraulic integrity (its ability to prevent uncontrolled inflow to an island) and island flooding occurs.

In the Delta, an island or tract is protected by a system of levee reaches. For example, there is over 126,000 feet of levee that protects Sherman Island. This system of levees, which varies in its characteristics around the island, is modeled by a series of reaches based on levee characteristics (referred to as vulnerability classes in Section 6). If one or more of the levee reaches on Sherman Island fails, flooding results.

Island Flooding. When one or more sections of levee on an island fail – waters in adjacent sloughs enter the island, until levels on the island and the sloughs have reached equilibrium. The inflow to a flooding island results in the opening of an initial breach, which may grow to a final width of 200 feet or more. In addition there is scour that occurs in the slough adjacent to the breach, in the levee foundation and on the island (DWR 2004). This scour can be a cause of damage to structures located on the island and contributes to the volume of material required to close a breach. Depending on the island's volume below sea level, the time to flood an island may take about 1 to 3 days. For example, it took about 3 days to flood Upper and Lower Jones Tract in June 2004, an area of over 12,000 acres.

Hydrodynamic Response of the Delta. As islands breach and flood, the normal flow patterns in the Delta are disrupted. Water that floods islands is replaced by river inflows and/or saltwater from San Pablo and San Francisco Bays[2]. Beyond the initial disruption of the Delta caused by island flooding, the response of the Delta will depend on upstream water operations (see below), and the rate of breach closures and island dewatering. The interaction of these factors produces a dynamic system that affects the level of salinity intrusion into the Delta, which in turn has implications for water quality and the impacts on the ecosystem.

Water Operations. The intrusion of saltwater into the Delta can be managed to a degree by controlled releases from upstream reservoirs and curtailing/halting exports from the Delta. The decision to release water depends on a number of factors, including the magnitude of the levee failure event (how many islands are flooded), available upstream reservoir storage, and the type of water year.

Emergency Response and Repair. After a levee failure and island flooding, repairs are initiated to stabilize and close the breach and dewater the island. In addition, as evidenced by the Jones Track event in 2004, once an island floods winds can generate waves that lead to erosion of levee interior slopes. For cases involving multiple levee breaches and/or non-breach damage on multiple islands, the order and timing of breach closures and levee repairs impacts the timing of repairs to damaged structures (residences, businesses, and infrastructure), the return of residents and workers, and the hydrodynamic response of the Delta. The order of island closures alone affects the salinity intrusion into the Delta and the duration of SWP and CVP export disruptions (JBA 2005).

An island whose levees are damaged following an earthquake (non-breach damage) is vulnerable to seepage, further slumping, overtopping, and wind-wave damage. Not only has the internal integrity of the levee been compromised (possibly with extensive cracking), the riprap protection on the levee exterior slope is likely to have been disrupted, and substantial crest loss (in the case of liquefaction failures) will mean that failure can occur from only a moderate high tide, wind waves, or a flood. Whether or not failure occurs will depend on how quickly this damage is addressed to stabilize the levee. During this period, the chance of a moderate challenge to the levee from tides, surge, wind waves or flood is high. If several islands are damaged but not

[2] The degree to which saltwater intrudes into the Delta depends on whether the levee failures occur during a flood or another type of event.

breached during an earthquake, the wait for repair attention may leave an island vulnerable to subsequent breaching.

Consequences of Levee Failure and Island Flooding. When a levee failure event occurs, there are a number of varied impacts that could occur in the Delta and the state. These can include:

- Public health and safety impacts of island flooding
- The direct flood-related damages to structures, infrastructure (pipelines, roads, and rail lines), and crops on flooded islands
- The local and regional economic consequences to residents and businesses
- The environmental impact to Delta and Suisun Marsh habitat and species
- Water quality effects and the disruption of water exports
- The economic impact of export disruptions

The impacts that are realized from a levee failure event depend on the number of and which islands are flooded, the water operations following the levee failures and levee repair operations. At one extreme, experiences in the Delta and modeling studies suggest that individual island failures have little impact on Delta exports. Historically, disruptions that have occurred have been short-lived and thus would have little effect outside the Delta (see Section 4.4.5). At the other extreme, studies of more extensive levee failure events indicate salinity intrusion and export disruptions can be extensive. For example, analysis of a levee failure event involving 21 islands resulted in export disruptions of approximately 23 months and considerable statewide economic impact (JBA 2005).

4.2 FRAMEWORK OF THE RISK ANALYSIS

This section describes the general framework of the risk analysis. The elements of the analysis that correspond to quantitative modules are illustrated schematically in Figure 4-2. The figure and subsequent descriptions are oriented principally with respect to the evaluation of external hazards such as earthquakes and floods. For levee failures that occur during normal conditions (sunny-day levee breaches), the elements of the risk analysis are essentially the same. The exception is the fact that varying levels of loading and fragility (conditional probability of failure) do not apply.

The following paragraphs summarize the elements of the risk analysis.

Hazard Analysis. The hazard analysis assesses the frequency of occurrence and the magnitude of hazards (loads) that may impact Delta levees. In the case of seismic events, the hazard is characterized in terms of peak ground acceleration for a reference site condition. For floods, the hazard is defined in terms of the peak water-surface elevation at a levee. The characterization of hazards must take into account their correlated spatial distribution to model the simultaneous loading that occurs at many (possibly all) levees throughout the Delta. For example, the seismic hazard analysis estimates the ground motions throughout the area that will occur as a result of an earthquake event (e.g., an earthquake of a given magnitude, which occurs on a specific fault). In sum, the purpose of the hazard analysis is to assess the frequency of occurrence of events that can compromise the integrity of Delta levees.

In the Delta, normal or intrinsic events are ongoing forces that persistently load and challenge the structural and ultimately the hydraulic integrity of levees day-to-day. Per se there is no frequency of occurrence that is evaluated for these forces.

Levee Vulnerability Analysis. Given the occurrence of a hazard (loads on levees), the levee vulnerability analysis assesses the conditional probability of levee breach or damage as a function of 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 exactly known, the conditional probability of failure or damage will vary. It will be low (zero) at low hazard (load) levels and ultimately rise to a conditional probability of failure of one (certain failure) at some much higher level. This result is called a fragility curve.

For normal or intrinsic events, the levee vulnerability analysis assesses the frequency of occurrence of levee failures as opposed to a conditional probability, as in the case for the external hazards.

System Model. Given the occurrence of a hazard that challenges the water detention capability of Delta and Suisun Marsh levees, a model is required to evaluate the potential combination of events and levee failures/damage that can occur. The system model defines the relationship between hazards and their possible combination to assess the state of the Delta immediately after an event (e.g., an earthquake of magnitude [**M**] 6 on the Hayward Fault). The term "state-of-the-Delta" refers to the condition of all levees and islands immediately after the event. Given an earthquake and the probabilistic nature of levee performance (see levee vulnerability above), numerous combinations exist in which various levees will breach and different islands flood. The system model describes the potential combination of events and the framework for calculating their frequency of occurrence. Each combination of flooded islands is referred to as a levee failure sequence.

The system model also models 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 or the type of hydrologic water year, are also included in the system model because of their importance in assessing the hydrodynamic response to and consequences of levee failures.

Risk Quantification and Uncertainty Analysis. This element in the risk analysis combines all of the elements of the analysis and calculates the frequency of occurrences and their consequences that are considered. As part of the quantification, the uncertainties (epistemic, discussed in the next subsection) are also evaluated.

4.3 METHODOLOGY

This section describes the methodology used in the DRMS risk analysis. As summarized in the previous section, the occurrence of levee failures and their effects (consequences) depends on the occurrence and combination of many factors and events. The relationship of these events and their combination (joint, simultaneous occurrence) 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.

From historic experience in the Delta and risk modeling experience in general for spatially distributed systems (e.g., earthquake engineering lifeline risk analysis), the performance of Delta and Suisun Marsh levees and the state of the “levee system” (which levees failed and which did not) determines the extent of damage on Delta islands, the impact on businesses, the adverse (or beneficial) affect on the ecosystem, and the impact on the state water system. The effect of levee failures depends on the details of the events that occur; time of year, how many and which islands are flooded, how much flushing of the Delta is attempted (water operations), and the order and timing of levee repairs. The frequency of occurrence of a given sequence (the coincident combination) of events depends on the frequency and magnitude of the initiating event and the probability of events in the sequence. To model the risks of levee failures and the consequences that result, an event-based approach is used. This approach is represented by an event tree that models the random events that relate initiating events to levee failures and their consequences (Baecher and Christian 2003; Hartford and Baecher 2004).

4.3.1 Uncertainty

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

The second source of uncertainty is attributed to lack of knowledge (information, scientific understanding, and data). For example, the ability to estimate the frequency of occurrence of an event requires that certain data or a model be available. If the amount of data is adequate, the estimate of frequency may be quite accurate. However, if only limited data are available, the estimate will be uncertain (i.e., statistical confidence intervals on parameter estimates will be large).

This 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. This source of uncertainty is 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 4-3 illustrates the effect of epistemic uncertainty on 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). The figure shows a probability distribution on the estimated frequency of flooding. If no epistemic uncertainty existed (for example, in the estimated frequency of occurrence of future earthquake ground motions or floods in the Delta, or in the failure frequency of levees due to normal events), there would be no probability distribution in Figure 4-3, but rather a single point estimate. The uncertainties that contribute to this distribution are the amount of data available, the accuracy of engineering methods to model the performance of levees, and the uncertainty in the estimate of hazards (e.g., uncertainty in the frequency of earthquake occurrences and the ground motion attenuation models).

The distinction between what is aleatory and what is epistemic uncertainty can 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.

The identification and evaluation of epistemic uncertainties can vary, depending on the subject, the development of scientific or engineering understanding, and observational and modeling experience. For example, in a field or topical area where considerable observational experience exists and models are used to develop predictive tools, the analysis of epistemic uncertainties may be an integral and in-depth part of the state-of-practice. 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, and comparisons of model predictions with observations. In areas where direct observation of events/parameters of interest is limited, competing models and/or scientific interpretations exist, it is often necessary to elicit input from experts to evaluate and quantify epistemic uncertainties (Morgan and Henrion 1990; USNRC 1996; SSHAC 1997).

4.3.2 Definition of Risk

In this analysis, risk is defined as the likelihood (expressed as a 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: frequency of occurrence, loss or consequence, and probability as a measure of uncertainty (Kaplan and Garrick 1981).[3] These are denoted as follows:

$$\{v, C, p\} \tag{4-1}$$

where

$v =$ frequency of occurrence

$C =$ a consequence metric (e.g., economic cost)

$p =$ probability

Here probability is a measure of the relative degree to which an estimate of v is the true value. Figure 4-3 is an example of this characterization of risk. In this example, the figure denotes that the adverse event or consequence is levee failure and island flooding. A frequency of occurrence of this event is determined and the uncertainty in the estimate of the frequency of this event is quantified by the probability density function shown. For consequences such as economic impacts or fatalities that may vary over a range of possible values, expression 4-1 is represented in terms of a frequency of exceedance distribution. This representation is denoted as follows:

$$\{\lambda(C_i > c), p\} \tag{4-2}$$

where $\lambda(\,)$ is the frequency of exceedance.

In this analysis, risk is evaluated for a number of metrics. The measures of risk that will be evaluated are:

[3] While the focus of the DRMS risk analysis is the analysis of risk as defined above, it is worth noting that modeled events may involve benefits (for example, the possible benefit of levee failures on the ecosystem).

- Frequency of levee failure and flooding of individual Delta islands.
- Frequency of exceedance distribution on the number of islands that flood during a single event (e.g., hydrologic event)
- Frequency of exceedance distribution for fatalities that occur as a result of a single event (e.g., a hydrologic event) that causes levee failures.
- Frequency of exceedance distribution for a number of different economic consequence metrics (see Section 4.8)
- Frequency of exceedance distribution for a number of ecosystem metrics (see Section 4.8).
- Frequency of exceedance distribution on the time to extinction of aquatic species.

The evaluation of these risk metrics is described later in this section.

4.3.3 Analysis of Uncertainty in Risk Estimates

As described previously, risk for this study is expressed in terms of the exceedance frequency curve that shows the annual frequency of exceeding different consequences (e.g., the annual frequency of exceeding economic losses of 1, 10, and 100 billions of dollars). As described above, the probabilistic framework for the risk analysis incorporates both *aleatory* and *epistemic uncertainty*.

The main components of the risk analysis are the hazard, levee vulnerability, hydrodynamic response of the Delta, emergency levee repair, and the consequences of levee failures. For the first two components – hazard and levee fragility, the risk analysis methodology explicitly models both types of uncertainty; aleatory and epistemic. However, other parts of the analysis are performed using deterministic methods in which the best estimates are developed, but neither type of uncertainty is formally assessed.

In principle, all aleatory and epistemic uncertainties (at least those important to the analysis results) would be identified, evaluated, and incorporated in the analysis. However, a number of factors contributed to the approach used, including the level of probabilistic development with respect to the modeling of aleatory and epistemic uncertainties, and time and resources available to perform the necessary evaluations.

In some topical areas in the risk analysis, the explicit modeling and evaluation of aleatory and epistemic uncertainties is an integral part of standard practice. This is true in probabilistic seismic hazard analysis for example (SSHAC 1997), in geotechnical engineering (CALFED 2000; Baecher and Christian 2003), and to a degree in flood hazard analysis (USACE 1996). In other topical areas that are a part of the DRMS, the practice of evaluating uncertainties (in particular epistemic uncertainties) is not considered at all. For instance, in the evaluation of climate change, the pace of scientific development is considerable. Although the range of estimates for sea-level rise is wide, evaluations of epistemic uncertainty in the estimates that have been made do not exist (Climate Change Technical Memorandum [TM] [URS/JBA 2008b]).

The effort to quantify uncertainties in topical areas where little has been done would be large in terms of both the cost and schedule. The constraints of the DRMS study precluded such an effort. With respect to the economic consequences analysis, this subject was discussed with two advisors to the project. These advisors, two economics professors at University of California, Berkeley, confirmed the difficulty (level of effort and scope) that would be required to undertake such an evaluation.

The development and implementation of probabilistic models are even less common in the evaluation of ecological impacts, because numerical measures may not be readily available for such impacts and qualitative indices of impact are often used. Further, it is often difficult and time consuming to make best estimates of ecological impacts. Analyzing probabilities of different ecological impacts is not a common practice.

In the DRMS risk analysis, the following approach was followed with respect to the consideration of uncertainties. For the analysis of levee failures, mean estimates of the frequency of island flooding (for individual and multiple islands) was evaluated. The estimate of the mean frequency of island flooding takes into account the aleatory and epistemic uncertainty in the hazard and the levee vulnerability. The epistemic uncertainty in the frequency of island flooding was estimated taking into account the uncertainty in both the frequency of occurrence of the hazard (i.e., earthquake ground motions, peak flood elevations) and levee vulnerability (see Figure 4-3). The epistemic uncertainty in the frequency of island flooding was combined with estimates of the consequences of levee failures (e.g., economic costs and impacts) to estimate the uncertainty in the frequency of distribution of consequences.

4.3.4 Event-Based Approach to Risk Analysis

The risk analysis for this study requires evaluating a large network of levees that protect islands under a number of hazards. Two broad approaches to risk analysis could be used. One is the traditional "single site" approach and the other is an "event-based" approach. A brief discussion of the two approaches and the reason for selecting the latter approach follows.

In the "single-site" analysis approach, the levee protecting each island is analyzed separately under each hazard event, the risk of island flooding is assessed in terms of the expected consequences under each event, the total risk for each island is calculated by summing the risk from individual hazard events, and the total risk for the study area is calculated as the sum of the risks of individual islands. Although such an approach would be valid for a single island, it would substantially under-estimate the risk for a network of islands. This is because the consequences of *simultaneous* failures of given islands could be much higher than the sum of consequences of *isolated* failures of the same islands at different times.

One main difference in consequences of simultaneous versus isolated failures is in the disruption of water exports. The failure of a single island would have a minimal impact on the amount of the Delta water that would be drawn into the island. The salinity and water quality in the Delta, in turn, would not be significantly affected and there may be little disruption in water export (see Section 4.4.3). On the other hand, if many islands fail simultaneously during the same event, a large amount of Delta water could be drawn into the islands, the salinity intrusion would increase substantially, and water pumping may have to be halted for many months.

In an "event-based" approach, the performance of the entire network of levees in the study area is evaluated when subjected to each possible specific hazard event (e.g., an earthquake of magnitude 7.5 on the San Andreas fault). The probability and consequences of simultaneous failures of multiple islands are, therefore, properly analyzed. Simply stated, the "single-site" approach would not account for the possibility of a sequence involving the simultaneous failure of many islands, while the "event-based" approach does properly analyze such a sequence.

Within the general framework of an event-based approach, alternative methods of risk analysis are feasible. One method is to assess risk in terms of the expected consequences, which are calculated as the product of probability of undesirable outcome and consequences of such an outcome. In this method, no distinction is made between aleatory and epistemic uncertainties. Both types of uncertainties are combined in calculating the probabilities of undesirable outcomes. An advantage of this method is that it is computationally efficient. However, it does not provide a measure of the confidence in the risk analysis results. An alternative method, which was used in this study, is to treat the two types of uncertainties separately. Risk is assessed in terms of the frequency of exceeding different consequence thresholds, and the uncertainty in this frequency is estimated. This method is computationally more involved. However, it provides a good understanding of how data gaps for certain factors impact the confidence in the risk analysis results. It is also the recommended method for analyzing different risks (National Research Council 2000 for flood risks; EPA 2004 for health risks).

4.3.5 Analysis of Future Risks

The DRMS risk analysis must assess risks for current conditions, the current or base-case analysis, as well as in the future (50, 100, and 200 years from now). The analysis for 2005 (i.e., current conditions), 2050, 2100 are assessed under "business as usual" conditions. Specifically, it is assumed that no systematic program to improve levees or to change the current configuration of the levee network would be undertaken during the intervening years. Furthermore, it was also assumed that no major hazard event (such as a large earthquake) would occur in the future that would cause a simultaneous failure of many levees and flooding of many islands. If such an event were to occur, there would be two basic effects on the risk analysis. First, in the case of earthquakes, the occurrence of a major seismic event on a Bay Area fault would alter the estimated frequency of occurrence of future events. Second, a major event could dramatically change the current integrity or configuration of the Delta levees. For example, some of the islands may be abandoned or the most vulnerable Delta levees may be reconstructed. Under those circumstances, an assessment of the failure risks in the future that is based on the current integrity and configuration of Delta levees would not be meaningful.

For each analysis year, the risk was assessed by combining the estimated annual frequency of hazard events, the probabilities of different levee failures sequences given each event, and the consequences of levee failures for the conditions that are estimated to exist in that the time. The assessed risk in the analysis years is a snapshot, an "instantaneous" measure, of the risk in each year.

In the DRMS analysis, snapshot or instantaneous estimates of the frequency of events (risk metrics; see Section 4.4.1) are made for current (2005) conditions, 2050, and 2100.[4] These estimates are made for conditions that are estimated to exist at that time (in the evaluation year) assuming business-as-usual with respect to the operations and management of the Delta and assuming natural or other man-caused events do not change processes that are understood to be

[4] Note, risk estimates for 2200 are not explicitly evaluated. As described in Section 14, little or no information is available to support a quantification of risks 200 years from the present.

occurring presently (e.g., increasing strain on major Bay Area faults, climate change). The analysis provides point estimates of risk, for the conditions that are estimated to exist at that time (e.g., the drivers of change as described above), in the future evaluation years considered. The result, for a given risk metric, is illustrated schematically in Figure 4-4.

The analysis for assessing risks in the future uses the 2005 results as a benchmark. Estimates are then made of the percentage change that is estimated to occur between the evaluation year (e.g., 2050) and the base year (2005) with respect to the major elements in the risk analysis; frequency of hazards, levee vulnerability, and consequences. The changes in these elements of the analysis are combined to estimate change in risk with respect to the basis year. The approach is discussed further in Section 14.

4.4 RISK MODEL

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

The analysis is performed first for 2005 conditions. (The approach for addressing risks in future years is described in Section 4.9.) As described in Section 4.3.1, the measure of risk for a consequence, C, is denoted:

$$v_i = \text{frequency of flooding for island i}$$

and

$$\lambda(C_k > c) = \text{frequency per year that a consequence metric } C_k\text{, will exceed a value c} \qquad (4\text{-}3)$$

As described in Section 4.3.5, the 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 and floods), which are assumed to be independent. The total risk for a given metric, considering the hazards to which Delta and Suisun Marsh levees may be exposed, can be determined according to:

$$v_{T,\,i} = \sum_j v_{ij} \qquad (4\text{-}4)$$

and

$$\lambda_T(C_k \;\geq\; c) \;=\; \sum \lambda_j(C_k \geq c) \qquad (4\text{-}5)$$

where the sum is carried out for the initiating events considered.

Note, as discussed earlier, subsidence and climate change are not considered hazards in the sense of random events that impose transient loads/forces on a levee system. Rather, they are addressed as ongoing processes that change the state of the Delta landscape and are considered in the assessment of future years (see Section 14). The task in the risk analysis is to estimate the consequences associated with each hazard, $\lambda_j(C_k > c)$, in Equation 4-4. In the following sections, the risk analysis for external hazards and normal events is described.

4.4.1 Initiating Events

Initiating events that are explicitly evaluated in the analysis are:

- Normal events
- Earthquakes – ground motion
- Hydrologic events – peak water-surface elevation

Wind waves – Not evaluated as an initiating event. Wind waves are considered in combination with failures initiated by other events. As described in Section 7.10, wind-wave action on the exterior slopes of levees was not explicitly considered in the analysis as an event that could initiate levee failures. Excluding floods and earthquakes, and considering the existing waterside slope riprap projection and human intervention, this particular hazard was considered relatively insignificant and, hence was not considered explicitly as an initiating event.

4.4.2 Event Tree

To model the sequence of events that may result in levee failure and which affect the consequences of failure an event tree approach is used. An event tree is a graphical construct that can be used to model the logical combination of events that lead to outcomes of interest (Baecher and Christian 2003; Hartford and Baecher 2004). In this analysis, the following events contribute to the sequence of events related to levee failures in the Delta and the consequences that may result:

- Hydrologic conditions at the time of the event
- Month of the year the initiating event and levee failures occur
- Time of day
- Initiating event (earthquake or flood)
- Levee performance on each island in the Delta
- Secondary levee failures on non-flooded islands
- Levee repair sequences following an event
- Delta hydrodynamic response to levee failure events
- Consequences (life safety, economic, environmental)

Figure 4-5 illustrates a generalized event tree with these events. Each event is summarized in the following paragraphs. For each event in the event tree that is modeled probabilistically (has random outcomes that could be realized), branches are defined in the tree for each outcome/value that is modeled.

Moving from left-to-right in the tree along a branch for each event to its termination defines a combination of events, a sequence, that defines the state of levees in the Delta and the conditions under which failures occurred.

Hydrologic Conditions. The consequences of levee failures in the Delta, particularly with respect to water quality depend on the hydrologic conditions that exist at the time (prior to and after the event) of the occurrence of the initiating event and levee failures. The importance of hydrologic conditions to the hydrodynamic response of the Delta and the water quality and conveyance is described in Section 11 and the Water Analysis Module (WAM) TM (URS/JBA 2007e). In this analysis the historical record is used to model the randomness of hydrologic conditions that may exist at the time of a levee failure.

Month. The month when an initiating event and levee failure occurs has implications with respect to upstream water storage, agricultural consequences, SWP, and CVP pumping. In combination, the hydrologic conditions and the month of the year when an event occurs are important factors in assessing the consequences of levee failures.

Time of Day. For most events in the analysis the time of day is not an important variable. However, to estimate the life safety consequences of levee failures, the time of day (daytime versus nighttime) is an important factor.

Initiating Events. As identified above, three initiating events are considered in this analysis. For hydrologic events and earthquakes, the initiating event is defined in terms of the size of the event and the spatial distribution of the hazard. In the case of a flood the initiating event is a water-surface elevation event that has a frequency of occurrence and defines a spatial field of water-surface elevations throughout the Delta. Section 7 and the Flood Hazard TM (URS/JBA 2008a) describe the hazard analysis methodology to estimate the frequency and magnitude of flood events. For earthquakes, the initiating event is an earthquake of a given magnitude that occurs on a fault and generates a spatial field of ground motions throughout the Delta.

For normal events, the initiating event is the group of intrinsic factors/forces that persist and challenge the levee day-to-day.

Levee Performance. Given the occurrence of an initiating event, the state (condition) of each levee reach on each island is evaluated to determine which islands have flooded and which levee reaches have been damaged or breached and thus require repair after the event.

Secondary Levee Failures. When a seismic event occurs, extensive non-breach damage to levees can occur, leaving them vulnerable to wind waves and high water levels due to floods (see Section 6 and the Levee Vulnerability TM [URS/JBA 2008c]).

Levee Repair. As discussed above, the repair of levees following an event is not considered a random variable, however it is an important event in the chain to assessing the hydrodynamic response of the Delta and the economic consequences of an event.

Delta Hydrodynamic Response. Similar to levee repair, the hydrodynamic response of the Delta and associated water management actions are not a random part of the analysis.

Consequences. Best-estimates of the consequences of levee failures are evaluated in all cases with the exception of life safety. In the analysis of life safety, the potential for fatalities from levee failures is assessed probabilistically.

An event tree can also be used to quantify the sequence events by simple enumeration of all the combination of event branches to define the collectively exhaustive set of sequences that could occur. For this analysis, such an enumeration is not possible due to the large number of combinations that would result.

Alternatively, for events that involve a large number of possible outcomes, simulation methods are used. For instance, simulation methods are used to estimate sequences of levee failures for different initiating events (water-surface elevation events and earthquakes). Similarly, simulation methods are used to simulate the large number of possible hydrologic conditions and months of occurrence when the initiating event and failures might occur.

For purposes of assessing risk, event sequences that consider the combination of multiple island breaches and/or damage are modeled. In addition, other factors that impact the assessment of consequences are also considered. Table 4-1 lists the primary events to be considered in the assessment of Delta sequences.

4.4.3 Evaluation of Island Flooding Frequencies

The initial step in the risk analysis is the assessment of island flooding frequencies:

$$v_{ij} \text{ and } \lambda_j(N \geq n),$$

where i denotes the island and j is the index on the initiating event. N corresponds to the number of flooded islands that could occur during a single event. The approach to evaluating the frequency of island flooding for each initiating event is described.

Normal, sunny-day events. As described in Section 9, 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, the deteriorating effects that rodents have). 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 historical rates and expert evaluations of the condition, effectiveness of maintenance practices, and vulnerability of levee reaches to failure.

The mean frequency of failure of individual Delta islands is estimated by the following expression:

$$\overline{v}_{i,N} = \overline{\varphi} \times L_i \tag{4-6}$$

where

$\overline{\phi}$ = mean rate of Delta levee failures per year per mile

L_i = Length of island i (miles)

N = the subscripted N denotes normal events

As described in Section 9, an estimate of the mean rate of levee failures has been made for Delta levees and Suisun Marsh levees.

The epistemic uncertainty in the estimate of the frequency of island failures is attributed to the length of the historic record. An analysis of this uncertainty estimates the coefficient of variation in the mean rate is 0.44 (or a logarithmic standard deviation of 0.18). The uncertainty in the frequency of normal event failures is assumed to be lognormally distributed. The estimate of the uncertainty in the rate of levee failures is described in Section 9.

The significant difference between external hazards (discussed later) and normal events is the potential for multiple, simultaneous levee breaches during the same event.. Historically, these events have occurred as single isolated events involving individual islands. They do represent some potential for impacting adjacent islands due to increased seepage or as a result of erosion of levee interiors on the flooded islands due to wave action or overtopping of low spots (e.g., Jones Tract). If additional breaches do occur (due to wave action for example), adjacent islands may be exposed to wind-wave effects associated with the additional fetch that may exist and thus possible erosion. In this analysis, the potential for additional levee failures following an initial sunny-day breach is not modeled. Historic experience indicates the annual frequency of occurrence of sunny-day failures for an individual island is low compared to other initiators of failure under present (2005) conditions. As a result, the possibility of further (secondary) failures that follow these events is also low and thus not considered. As a result,

$$\lambda_N(N \geq n) = \nu_{i,N} \qquad n = 1 \tag{4-7}$$

$$\lambda_N(N \geq n) = 0.0 \qquad n > 1 \tag{4-8}$$

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).

Hydrologic Events. When a flood event occurs in the Delta, high water-surface elevations may be experienced over a large area. The analysis of hydrologic events and the probabilistic estimate of their frequency of occurrence are described in Section 7 and in the Flood Hazard TM (URS/JBA 2008a).

The modeling of the performance of Delta levees to the hazards posed by hydrologic events (floods) is similar to that for earthquakes, with a few exceptions. As has been the case historically, floods can result in multiple levee failures on different islands (for example, in 1986 and 1997).

In the analysis of hydrologic events and the performance of levees, it is assumed that only one breach occurs on an island and that non-breach damage that might occur due to wind waves, overtopping is relatively minor. Thus, it is assumed that non-breach damage does not occur to the extent that it requires emergency levee repair. However, erosion of levee interiors as a result of wave action is considered and does require emergency repair.

Given the occurrence of elevated water elevations at an island, the frequency of island flooding is determined by:

$$\nu_{iH} = \sum_j \nu(wse_j)\, P(F_i / wse_j) \tag{4-9}$$

where

$\nu(wse_j)$ = frequency of occurrence of water-surface elevation event j

$P(F_i/wse_j)$ = mean conditional probability of island i flooding given water-surface elevation event j; this is the island fragility curve.

The summation is carried out for all water-surface elevation events.

The flooding of an island occurs if one of more levee reaches on the island fails. Section 7 describes how the reaches on an island are defined for the hydrologic risk analysis and how levee fragility is estimated. The Levee Vulnerability TM (URS/JBA 2008c) describes the estimation of the levee fragility for flooding in detail.

To estimate the frequency of multiple flooded islands during a hydrologic event, a Monte Carlo simulation approach is used. This approach is equivalent to sampling from the event tree (see Figure 4-5) that would enumerate all the possible combinations of levee performance (failure or non-failure) and thus island flooding events for a given flood. The simulation is carried out as follows. For a given water-surface elevation event wse_j, which defines the water level at each levee in the Delta, the state of each island in the Delta is randomly sampled from the levee fragility curves (see Figure 4-6). For a flood event, wse_j, the state of each levee (and thus each island) is determined – a random sample from the fragility curve determines whether a levee has failed or not and thus whether an island is flooded. The process is carried out for each levee in the Delta. At the conclusion of the simulation for the flood (wse_j), the state of each island is known. A simulation defines a (random) sequence of island flooding events.

For each water-surface elevation this process is repeated, generating a series of flooded island sequences for each hydrologic event (each wse_j). The frequency of occurrence of each sequence is:

$$v\left(S_{Hjk}(n)\right) = v\left(wse_j\right) \times p \tag{4-10}$$

where

$S_{Hjk}(n)$ = hydrologic sequence k associated with water-surface elevation event j and n is the number of flooded islands

p= probability associated with each simulation

= 1/(number of Monte Carlo simulations)

The frequency of occurrence of numbers of islands flooding, $v_H(n)$, is determined by summing over all water-surface elevation events and all sequences that generate the same number of flooded islands.

Based on the number of islands that flood in each sequence, the frequency distribution on the number of flooded islands, $\lambda_H(N \geq n)$, is determined.

Seismic Events. In the event an earthquake occurs in the vicinity of the Delta, ground motions will be experienced over a potentially large area, depending on the magnitude of the earthquake and its location in proximity to Delta levees. The ground motions generated by the earthquake will challenge the stability of levee embankments and their foundation. Section 6 and the Seismology TM (URS/JBA 2007a) describe the probabilistic analysis of earthquake ground motions in the Delta. For a moderate to large magnitude earthquake, particularly one that occurs in or near the Delta (say, on the Southern Midland Fault), all island levees are likely to experience ground motions that could result in damage or failure.

The frequency of failure of a single levee (due to earthquakes on a single fault) is determined by:

$$v_{Levee\,Reach} = \sum_m v(m_i) \sum_r P(R = r_j \mid m_i) \sum_a P(A = a_k \mid m_i, r_j) P(f \mid a_k) \tag{4-11}$$

where

$\nu(m_i)$ = frequency of occurrence of an earthquake of magnitude m_i

$P(R = r_j \mid m_i)$ = probability that an earthquake occurs a distance r_j from the levee given an earthquake of magnitude m_i.

$P(A = a_k \mid m_i, r_j)$ = probability of ground motions equal to a_k, given an earthquake of magnitude m_i and distance r_j.

$P(f \mid a_k)$ = conditional probability of failure of the levee reach (levee fragility) due to a ground motion of level a_k[5].

The elements in equation 4-11, with the exception of the levee fragility, are the same as in the seismic hazard analysis and are described in the Seismology TM (URS/JBA 2007a). The development of the levee fragility is described in Section 6 and in the Levee Vulnerability TM (URS/JBA 2008c).

In the seismic risk calculation, the ground motion predicted in the seismic hazard model and the characterization of the levee fragility is defined at a common reference site condition (see Section 6 and the Levee Vulnerability TM [URS/JBA 2008c]). The effects of site response are incorporated in the estimate of the levee fragility.

Each island in the Delta is modeled by a series of levee reaches, where each reach is defined according to the characteristics of the embankment and levee foundation (see Section 6 and the Levee Vulnerability TM [URS/JBA 2008c]). Island flooding occurs if one or more levee reaches fails during an earthquake. Equation 4-11 can be re-written to take into account the multiple reaches that protect an island.

$$\nu_{IslandFlooding} = \sum_m \nu(m_i) \sum_z P(Z = z \mid m_i) \sum_a P(a(\underline{x}) \mid m_i, z) P(F \mid a(\underline{x})) \quad (4\text{-}12)$$

where

F = denotes the event that one or more levee reaches fail given an event of magnitude m and a ground motion field, $a(\underline{x})$

$a(\underline{x})$ = spatial field of earthquake ground motions given an earthquake of magnitude m that occurs at a location Z=z on a fault.

$P(a(\underline{x})|m_i, z)$= probability of the ground motion field, given an earthquake of magnitude m_i and that occurs on a fault at a location z.

The probability of the event F (island flooding) is the probability of one or more reaches on an island failing during an earthquake. This depends on the ground motion that is experienced at each levee reach during the same seismic event. For the simple case of an island comprised of two levee reaches, R_1 and R_2, $P(F|a(\underline{x}))$ is determined by,

$$P(F|a(\underline{x})) = P(R_1 \text{ fails or } R_2 \text{ fails or both } R_1 \text{ and } R_2 \text{ fail}|a(\underline{R_1},\underline{R_2})) \quad (4\text{-}13)$$

$$= P(R_1 \text{ fails}|a(R_1,R_2)) + P(R_2 \text{ fails}|a(R_1,R_2)) - P(R_1 \text{ fails and } R_2 \text{ fails}|a(R_1,R_2))$$

[5] As described in Section 6 and in the Levee Vulnerability Technical Memorandum, the seismic fragility of levees depends on earthquake magnitude as well as ground motion. This dependence is considered in the risk quantification, but is not shown here for simplicity.

$= P(R_1 \text{ fails}|a(R_1,R_2)) + P(R_2 \text{ fails}|a(R_1,R_2)) - P(R_1 \text{ fails}|a(R_1,R_2)) * P(R_2 \text{ fails}|a(R_1,R_2))$

where $a(\underline{R_1},\underline{R_2})$ denotes the ground motion at the location of levees R_1 and R_2.

The ground motion generated by an earthquake, $a(\underline{x})$, is random. A typical logarithmic standard deviation for the aleatory variability in ground motion is 0.6. This variability has two components; the inter-event and the intra-event variability. The randomness in ground motions is denoted by,

$$\sigma_T^2 = \tau^2 + \sigma_I^2 \qquad (4\text{-}14)$$

where

σ_T^2 = total aleatory variability (variance) of ground motions

τ^2 = inter-event variability

σ_I^2 = intra-event variability

Estimates of the aleatory variability in ground motion are made as a part of ground motion attenuation model development (Boore and Atkinson 2007).

The inter-event variability, τ, models the systematic (though random) variation that is observed in ground motions for earthquakes of the same magnitude. Due to differences in the details of earthquakes of the same size (earthquake magnitude), ground motions from one event may be systematically higher or lower than the median motion for all events of that magnitude at all sites.

The intra-event variability of ground motions captures the randomness of motions within events of a given size. Ground motion studies have shown this variability is spatially correlated (Boore et al. 2003; Park et al. 2007), meaning the motion at nearby sites (levee reach locations) is correlated due to the commonality of wave travel path and earthquake source characteristics. This correlation varies as a function of the separation distance between sites, as illustrated in Figure 4-7. The figure shows the correlation model developed by Boore et al. (2003) that is used in this analysis in conjunction with the intra-event variability in equation 4-14.

Each of these components of ground motion variability has implications with respect to risk analysis for spatially distributed systems such as the network of levees in the Delta (Park et al. 2007). Park et al. (2007) show the importance of the inter-event variability and the spatial correlation in estimating the magnitude and frequency of occurrence of consequences of interest for spatially distributed assets (levee failures or economic consequences in the example of Park et al. [2007]).They show that the magnitude of the consequences (damage to structures and thus economic consequences) can be significantly under-estimated if the inter-event variability and the spatial correlation of ground motions is not considered.

For this analysis, ground motion correlations for the Delta were modeled using the Boore et al. (2003) model. A dataset of random, spatially correlated (in the Delta and Suisun Marsh) variables was generated using the methods described by Park et al. (2007) (AIR Corporation 2007).

The quantification of equation 4-13 to estimate the frequency of island flooding due to seismic events was carried out through a combination of numerical integration and Monte Carlo simulation. The numerical integration is carried out over earthquake magnitude and distance as it is performed in the seismic hazard analysis. The integration with respect to earthquake ground motion and levee performance is carried out by simulation.

For an earthquake of a given magnitude and distance, three random variables are simulated; the inter-event variability, the intra-event variability and the levee performance. The inter-event and intra-event variability (including the spatial correlation of ground motions) were simulated for each earthquake in the analysis and for each levee reach location on an island. For each levee reach, its performance was simulated (failed or not), given the simulated ground motion (in the same manner that levee performance was simulated in the hydrologic analysis [see Figure 4-6]). This process was used to estimate the frequency of flooding of individual islands and to estimate the frequency of exceedance distribution of multiple flooded islands.

The total frequency of failure for an individual island is obtained by summing over all seismic sources considered in the analysis as follows:

$$\nu_{i,S} = \sum_{AllFaults} \nu_{ij,S} \tag{4-15}$$

where the subscript S denotes seismic events and i is the island index. Similarly, the frequency distribution on multiple flooded islands considering all seismic sources, $\lambda_S(N \geq n)$, in the analysis is estimated in the same manner.

To model the occurrence of multiple flooded islands from the same earthquake, sequences of levee failure and island flooding events, the same simulation approach described for hydrologic events was used. For purposes of estimating levee repairs and evaluating the hydrodynamic response of the Delta, non-breach damage as well as levee failure were also considered in the simulation.

4.4.4 Emergency Response and Repair of Damaged Levees

For each levee failure sequence that is modeled, the timing and cost of repairs is estimated using the emergency response and repair model described in Section 10 and in the Emergency Response and Repair (ER&R) TM (URS/JBA 2008d). As described in Section 10, the repairs to levees are made according to a priority system. As part of the analysis, which is a time simulation of repairs, the expected erosion that could occur on flooded islands due to wind waves is modeled. Based on an analysis described in the Emergency Response and Repair TM (URS/JBA 2008d), island and direction specific erosion curves are used to estimate the amount of erosion on the interior face of a levee occurs as a function of time. The erosion model, which was calibrated to the 2004 Jones Track experience and the observed erosion that occurred on Franks Tract in the years immediately following the flooding of that island, estimates the expected amount of erosion that would occur in time as an island remains flooded.

For flooded islands there are three levels of repair that are carried out – closure of the levee breach(es), interior levee slope protection and repair, and in the case of seismic events, repair of non-breach damage. As described in the Levee Vulnerability TM (URS/JBA 2008c), the extent of non-breach levee damage from an earthquake can be considerable. Thousands to tens of thousands of feet of levee may be damaged as a result of earthquake ground motions.

As described in Section 4.8, the ER&R analysis is deterministic and represents a best estimate of the timing and cost of levee repairs. The results of the ER&R analysis serve as input to the

WAM (hydrodynamic) analysis and the economic consequence analysis. The inputs to the WAM analysis include the timing of breach closures on each flooded island and the timing and volume of island dewatering. The inputs to the economic consequence analysis include the cost of levee repairs and the timing of island dewatering.

In the event of an earthquake, islands may be damaged but not breached. Damaged levees will typically be slumped and have reduced freeboard; there will be damage to the exterior face of the levee and riprap, and cracking of the embankment. As a result, the integrity of damaged levees will be compromised in terms of protection against overtopping, wave action, and internal erosion (see the Levee Vulnerability TM [URS/JBA 2008c]). For levee failure sequences that involve multiple islands, the time to stabilize and repair damaged, non-flooded islands can be considerable. To approximate the random sequences of secondary failures that could occur following a seismic event, two cases are considered. One case considers that all damaged islands are stabilized after the event and no longer vulnerable (any more than they were prior to the earthquake). As described in Section 10, stabilizing these non-flooded islands is given the highest priority. The second case considers that all of the non-flooded islands breach and flood during the repair period. For the case involving many islands, flooded or not, the period of repair may be considerable (many months). Depending on the time of year when the earthquake occurred, the probability that high water-surface elevations (relative to the post-event crest elevations of slumped and damaged levees) are experienced due to one or more causes, including a hydrologic event, or a surge, high tides, and/or wind waves is relatively high. Further, the vulnerability of an island that has thousands to tens of thousands of feet of damaged levees to overtopping or failure due to seepage and piping, is also high. These two cases are not models of actual events that could occur, but rather are bookends of the range of random, secondary failures that could occur.

4.4.5 Estimating the Hydrodynamic Response of the Delta

When levee failures occur in the Delta, they disrupt the normal hydrodynamic patterns. The WAM model, developed as part of the DRMS project (see Section 11 and the Water Analysis Module TM [URS/JBA 2007e]), is used to evaluate the hydrodynamic response of the Delta to levee failure events. The inputs to the WAM model, for each levee failure sequence, are generated by the ER&R model (described above).

For each levee sequence that is evaluated, a range of hydrologic years and start dates (defined by the month the failure occurs) are considered. Historic experience and detailed hydrodynamic modeling show the hydrologic conditions prior to, during and after a levee failure event impact the water quality consequences. To account for the hydrologic conditions that may exist at the time of a seismically initiated levee failure sequence, the distribution of historic hydrologies is used. There are 910 month-year pairs in the historic record that are randomly sampled (using a stratified sampling approach) for each levee failure sequence.

Outputs from the WAM analysis for a levee failure sequence include:

- Duration of water export disruption – months until water exports return to normal
- Reservoir storage (end of month, for each modeled reservoir)

- Water deliveries to SWP and CVP contractors
- Ambient Delta water salinity (monthly average, for a reference point for selected islands, µmhos/cm).

As described in Section 4.8 the hydrodynamic calculations are deterministic, with the exception that random hydrologic conditions are used to generate a distribution of hydrodynamic results for each levee failure sequence.

Historic experience and detailed hydrodynamic studies indicate the salinity impacts to the Delta water quality are not significant when levees fail and islands flood as a result of flood events, nor when they occur as individual failures as a result of intrinsic or normal (sunny-day) events. As a result, the WAM model is not used to evaluate the water quality impact of levee failures during these events. This limits the economic consequences of levee failures during hydrologic (flood) events and normal events to those that occur in the Delta (e.g., direct damages due to flooding, damage to infrastructure, impact to businesses). The following provides the historic and analytic basis for this.

Hydrodynamic Response During Hydrologic Events. Salinity impacts due to multiple breaches on multiple islands that are caused by inflow floods are not expected to have significant impacts on Delta salinity or export pumping. High Delta inflows that occur during major floods force the fresh/saline water interface downstream from its typical dry-season location. If the flows (or coincident high tides or storm surges) are so high that they cause several breaches and island floodings, the continuing high inflow provides a substantial volume of island flooding water, and any additional water needed that moves upstream from Suisun Bay is generally low in salinity – much lower than the drinking standard. Since 1978, there have been four large inflows flooding two or more Delta islands, as indicated in Table 4-2.

In each of these cases, electrical conductivity (EC) at Antioch stayed in the neighborhood of 200 µmhos/cm (800 µmhos/cm is the approximate drinking water standard). Although the upstream EC (at Holland Cut) closer to export locations was higher (up to about 400 µmhos/cm), however this reflects salinity in the Delta already, not salinity drawn in by the levee breaches. The largest inflow flood (1997) flushed this upstream salinity out of the system even though it had a larger number of breaches and flooded islands.

In January 1980, flooding occurred on Webb and Holland almost simultaneously. These islands are near enough to the flow path to the pumps that one might see a salinity impact if it were going to occur. EC at several stations in the vicinity was between 160 and 300 µmhos/cm (seemingly unaffected by the breaches), and thus not a concern for export water supply.

These observations indicate there has been no experience involving immediate salinity problems from floods. In contrast, there could be some effect in the long term if many islands were flooded by a very large flood event. Hypothetically, if the repairs occur over many months, tidal mixing may occur in subsequent low flow seasons that may allow some intrusion of salinity. At the same time, this tidal mixing would occur not as a result of the initial, large intrusion of saltwater at the time of the failures (which does not occur, as described) above, but rather as a result of the fact that islands that remain open provide greater volumes for tidal exchange and mixing than is normally the case (when islands are not open and flooded). The effect of this tidal mixing if it were to have an impact on water quality could be mitigated during the levee repair process by simply closing breaches to a point so that tidal mixing involving flooded islands does not occur. Further modeling would be required to address these longer term effects.

Normal Events. The most dramatic example of historical salinity intrusion due to a levee breach and island flooding is the Brannon-Andrus event on June 21, 1972, which occurred during the dry season of a "Below Normal[6]" water year. There was significant salinity intrusion, but the extent of disruption of water exports amounted to reduced CVP and SWP pumping for about two weeks and moderately increased salinity for about two months. Drinking water quality standards for salinity were violated at Contra Costa Water District's (CCWD's) Rock Slough intake and, although some fresher water was available for blending, total compliance with the standard was not achieved by CCWD. Overall, however, the magnitude of the disruption was not major. Details are summarized below, based primarily on the testimony provided on behalf of the California Department of Water Resources (DWR) and the United States Bureau of Reclamation at legislative hearings the following September (California Senate, 1972).

- The Bureau of Reclamation began to reduce CVP Tracy Pumping Plant exports on the day of the breach (normally 4,300 cfs) and reached one-pump operation (900+/- cfs) on June 23, the third day of the event. Salinity, measured as chlorides, increased dramatically at Antioch within 1 day of the breach. The salt influx upstream at water intake locations was anticipated and motivated the pumping decreases. On June 29, the Bureau began increasing its pumping, reaching the normal, maximum rate on July 3 with the explicit strategy of removing the salt from the Delta channels by exporting it. The period of decreased pumping was effective in keeping salinity from intruding further toward the export pumps until flushing water from Sacramento River reservoirs arrived and repulsed as much of the salinity as could be accessed by those flows. Salinity at the Bureau's Tracy Pumping Plant peaked at 165 milligrams per liter (mg/l) chloride—that is, less than the 250 mg/l drinking water standard (for salinity expressed as chloride), but substantially above the pre-breach level of approximately 70 mg/l. Elevated salinity at the Bureau intake persisted for approximately 1 month.
- CCWD had little storage and was dependent on continued pumping from the Delta. Their intake location at Rock Slough peaked at 440 mg/l chloride on July 4, substantially above the drinking water salinity standard of 250 mg/l as chloride. They continued pumping after the breach and were able to lessen the impact on most of their customers by blending with the limited storage available from Contra Loma Reservoir and an intertie with the East Bay Municipal Utility District's Mokelumne Aqueduct (implemented by July 4 through cooperation with East Bay Municipal Utility District and expedited construction). Even with blending from storage and the aqueduct, customers upstream of the dilution sites on the Contra Costa Canal had to use the salty Delta water. Chloride concentrations of CCWD Delta withdrawals exceeded 250 mg/l chloride for about 15 days.
- SWP stopped diversions from the Delta into Clifton Court Forebay within several hours of the breach. After a few days, the SWP commenced partial Delta diversions in order to serve the South Bay Aqueduct. Only the South Bay Aqueduct was served with Delta water until July 23 and that Delta water was blended with lower salinity water stored in Del Valle Reservoir (near Livermore).

[6] As defined by the Sacramento Index

Both the CVP and the SWP used San Luis Reservoir storage to serve their south of Los Banos demands on their respective canals. Delta pumping was disrupted for two weeks. Additional salt exported by the CVP and the SWP was estimated at 53,000 tons. But only CCWD and some in-Delta water users in the Central/Western portion of the Delta experienced salinity levels in excess of the drinking water standard.

Since Brannon-Andrus is one of the larger islands and is located in a crucial position relative to salinity intrusion and water exports, the above experience indicates that flooding of one-island can generally be managed to make the economic consequences minimal – although they are important to the water users that have to absorb saltier water. There was no time during the event when all export pumping was halted.

Economic Consequences to Exports from 3 to 4 Months of No Pumping. Economic consequences to water export due to a levee breach event rise as the length of export disruption increases. Consequences are estimated to be particularly severe when the salinity intrusion into the Delta dictates a total shut down of export pumping. Even then, no pumping durations of up to 3 to 4 months are estimated to have low economic consequences.

Based on analyses performed for this report, the export water supply consequence estimates indicate that disruptions of less than 4 months are not significant to the risk analysis results. For disruptions of less than 2 months, the costs are largely insignificant (i.e., potentially just millions of dollars). From 3 to 4 months, cost estimates may be approximately $200 million, depending on the time of year and other factors. So, depending on the distribution of those months, it seems reasonable in the context of the risk analysis to: (a) use a threshold of 3 months, and (b) assume economic consequences are limited to about $200 million for disruptions of 3 or 4 months. Note that this only addresses export costs; all other costs need to be addressed separately.

Seismic Events. Table 4-3 summarizes the results from a series of hydrodynamic calculations carried out using the WAM model using all of the first-of-month event start times (910 start times) for the years 1923 to 1998 for seismic failure sequences involving from 1 to 30 flooded islands (These cases correspond to Cases 2 through 6 in this series. The analysis is described in the Water Analysis Module TM [URS/JBA 2007e, Appendix D]).

As shown in Table 4-3, Cases 2 and 3 both involved three flooded islands. Case 3 also assumed some non-breach damage to other islands that did not flood, but required repairs before the flooded islands could be addressed. For Cases 2 and 3 the following detailed information about periods of no pumping was obtained:

- Case 2 – Start times with no pumping > 90 days = 66 (of 910); 29 percent of these were wet season breach events (December thru April)
- Case 2 – Start times with no pumping > 120 days = 21 (of 910); 62 percent of these were wet season breach events (December thru April) concentrated in drought years when it just didn't rain (e.g., 1931 and 1977)
- Case 3 – Start times > 90 days = 86 (of 910); 27 percent were wet season events
- Case 3 – Start times > 120 days = 23 (of 910); 65 percent were wet season events with the same concentration as Case 2.

In general, events that flood as many as three islands do not result in more than 4 months of no exports. If the event occurs even during the wet season of a year that has few or no storms, a longer period of no pumping could result.

4.4.6 Consequences of Levee Failures

For each initiating event, the consequences of levee failure sequences are evaluated. The risk metrics for which risks are assessed are given in Section 4.4.7.

Normal Events. For Normal events that involve individual island failures, the consequences are generally limited to those that occur in the Delta or to Delta businesses. In cases where state highways or other regional infrastructure is impacted, the assessment of consequences is described in Section 12. For each risk metric, the frequency distribution, $\lambda_N(C_k \geq c)$, is determined.

Hydrologic and Seismic Events. For hydrologic events, the consequences are determined for each hydrologic sequence that is evaluated. For each sequence, S_H, the consequences C_k are estimated as described in Section 12. Similarly, for each seismic sequence, S_S, consequences are estimated.

4.4.7 Risk Metrics

The risk metrics evaluated in the analysis are listed in Tables 4-4 and 4-5. These metrics include measures of Delta island vulnerability (flooding), economic impacts and costs, environmental consequences, and public health and safety consequences. Section 12 describes the elements of each consequence measure.

4.5 CO-LOCATED EFFECTS

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 there is the potential for additional 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 other water system assets in and beyond the Delta are assessed to the extent that levee breaches and island flooding cause damage to these assets. For example, damage to the Mokelumne Aqueduct as a result of a breach and scour that results in pipeline failure is addressed. 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. With the exception noted above, co-located effects are not addressed in the DRMS risk analysis.

4.6 IMPLEMENTING BUSINESS AS USUAL

The objective of the DRMS study is to identify and evaluate alternative risk management strategies for managing the Delta in the future. To do this, the risk analysis is performed, assuming a "business-as-usual" approach to the management, operations, and use of the Delta. The assessment of risks will be referred to as the "business-as-usual (BAU) scenario."

Implementing a BAU approach will apply to many aspects of the risk analysis. These include:

- Environmental factors (e.g., continuation of estimated rates of subsidence)
- Hazards (e.g., non-occurrence of a major earthquake that changes the rate of future earthquake occurrences)
- Levee maintenance and repair practices (e.g., level of expenditures for levee maintenance and raising as might be effected by sea-level rise)
- Water management following an event in the Delta (potentially involving significant salinity intrusion)
- Water management practices as it might be effected by climate change
- 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

The BAU approach is 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 been explicitly contemplated in the development of current policies or procedures (e.g., emergency response to multiple levee failures, operations for upstream reservoirs after a significant island flooding and salinity intrusion into the Delta occurs). As a result, some interpretation and/or discussion with DWR and others was required to fill these policy gaps to establish the BAU approach as implemented in the risk analysis.

In addition, it also requires that lessons or insights learned as a part of this effort not be used to make more informed choices or decisions. A BAU approach must be uninformed by the Phase 1 DRMS analysis. Lessons or insights will be considered as part of the Phase 2 evaluation and the consideration of risk reduction options.

4.7 RISK ANALYSIS IMPLEMENTATION

To perform the DRMS risk analysis required a multidisciplinary team of professionals to address the broad range of subject areas. From the perspective of actually conducting the analysis it was important for the team members to develop a common foundation of understanding. This understanding was required at a number of levels, including:

- Project scope and objectives

- Elements of the risk analysis
- Perspective and approach with regard to modeling uncertainty
- Risk model development approach
- Technical interface requirements
- Project schedule

For purposes of developing the DRMS risk model, topical area teams were formed corresponding to the different topical areas in the analysis. In general, the teams consisted of professionals from different organizations.

Table 4-6 identifies elements of the risk analysis (see Figure 4-2) and the topical areas within each element that were identified at the start of the project, and areas around which teams were formed.

As part of the startup for the project, a 2-day workshop was convened. The purpose of the workshop was to acquaint and train the team with respect to the topics listed above. In addition, the workshop also served as a starting point for teams to define a detailed work scope in each topical area.

After the workshop, each team submitted an initial technical framework paper that outlined the technical problem being addressed, the approach to be taken, the interface requirements with other technical areas, and the project tasks.

One of the objectives of the risk analysis was to estimate the uncertainty (aleatory and epistemic) for each part of the analysis. For the hazard and levee vulnerability evaluations, it was possible to carry out this estimation. For other parts of the analysis, this objective proved difficult due to the development effort to gather information and build the foundational model, coupled with the time available for the project in general. These factors, coupled with the varying levels of probabilistic modeling "experience" in different topical areas (a great deal exists in the seismic hazard area and relatively little in the economic and ecosystem areas), resulted in assessments that are best estimates of the outcomes of interest (i.e., economic consequences).

4.8 RISK QUANTIFICATION

This section describes the steps in the risk quantification and the interface between the different parts of the risk model. The steps as described are performed for each initiating event. These results are then combined to assess the total risk.

The steps in the quantification are:

1. Estimate the Frequency of Island(s) Flooding
2. Generate Levee Failure Sequences for use in the levee repair and hydrodynamic analysis
3. Perform Levee Emergency Response and Repair Analysis
4. Evaluate Delta Hydrodynamic Response
5. Estimate the Consequences for Each Sequence
6. Combine the Results of Steps 1, 2, and 5 to Estimate Risk

7. Estimate the Uncertainty in the Frequency of Levee Failure
8. Combine the Results for the Individual Initiating Events (Steps 1–7) to Estimate the Total Risk

The steps in the quantification process are listed in Table 4-7. The following describes each step in the quantification.

1. Estimate the Frequency of Island(s) Flooding

In this first step of the quantification, two calculations are performed:

- Estimate the frequency of levee failure and island flooding, ν_{ij}, for each island (i) in the Delta and selected islands in Suisun Marsh, and each initiating event (j),
- Estimate the frequency that multiple islands (N) could be flooded during a single event (e.g., a single earthquake or hydrologic event), $\lambda_j(N \geq n)$, for each initiating event (j).

In this analysis, the assessment of the frequency of levee failure for external and intrinsic (normal) events is different as described in the text.

2. Generate Levee Failure Sequences

For hydrologic and seismic events, levee failure and island flooding sequences are generated by Monte Carlo simulation. For the range of events (floods and earthquakes of different magnitude) considered in the estimation of the frequency of island failure, sequences that define the state of each island (flooded or not) in the Delta are generated. For hydrologic events, sequences are denoted, $S_{Hi}(n_f)$ where i is the index on the number of sequences and n_f is the number of flooded islands.

For seismic events, sequences are denoted $S_{Si}(n_f, n_d)$, where n_f is the number of flooded islands and n_d is the number of damaged (but non-breached/flooded) islands[7]. The subscript i denotes the sequence number.

3. Perform Levee Emergency Response and Repair Analysis

For each levee failure sequence, the ER&R analysis is carried out to estimate the time to close (all breaches) and dewater flooded islands and the costs of island repair and dewatering. The results of the ER&R analysis are input to the hydrodynamic analysis (WAM model) and the economic consequence analysis. Figure 4-8 shows the inputs and outputs of the ER&R analysis.

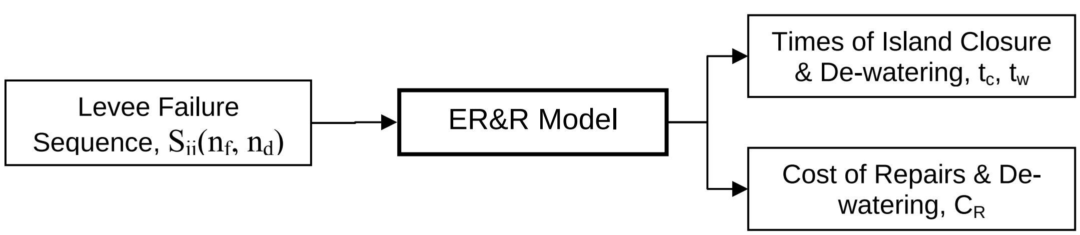

Figure 4-8 Inputs and outputs for the ER&R analysis

The ER&R analysis is described in Section 10.

[7] Damaged, non-breached islands are only considered in the seismic analysis.

4. Evaluate Delta Hydrodynamic Response

For each levee failure sequence, $S_{ij}(n_f, n_d)$, the hydrodynamic response of the Delta to island flooding is evaluated by the WAM model. The WAM analysis is carried out for a series of event start times that are simulated from the historic hydrologic record. The results of the WAM analysis serve as input to the ecosystem analysis, the In-Delta Infrastructure analysis, and the economic consequence analysis. The inputs and outputs to the WAM model are shown in Figure 4-9.

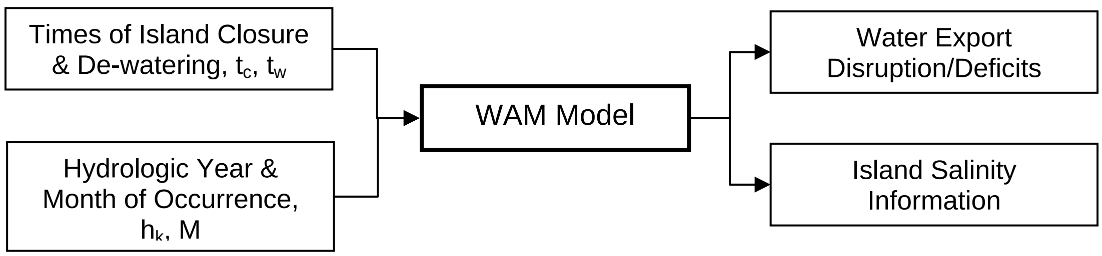

Figure 4-9 Inputs and outputs for the WAM analysis

The WAM model is described in Section 11.

5. Estimate the Consequences for Each Sequence

For a sample of the sequences that are evaluated in the hydrodynamic analysis, the In-Delta and statewide consequences are evaluated. As described in Section 12, best-estimates of the consequences of levee damage and island flooding are evaluated. Figure 4-10 shows the inputs and outputs to the economic consequence analysis, which includes the evaluation of damage costs associated with island flooding (In-Delta Infrastructure Model) and the costs of levee repair. Figure 4-11 shows the inputs and outputs to ecosystem consequence analysis.

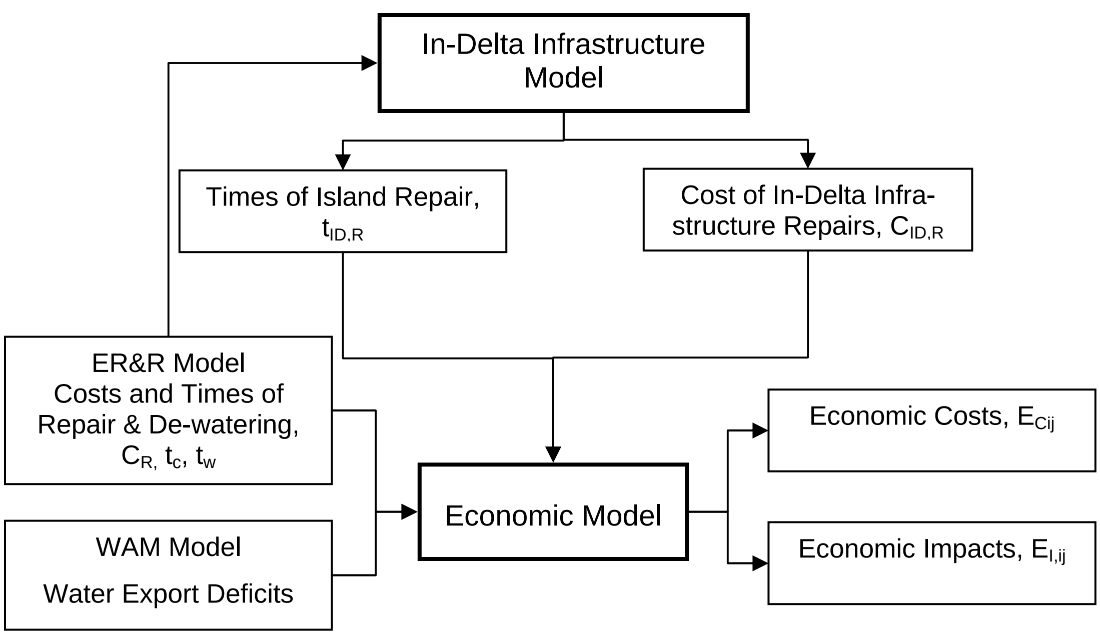

Figure 4-10 Inputs and outputs of the economic impact model

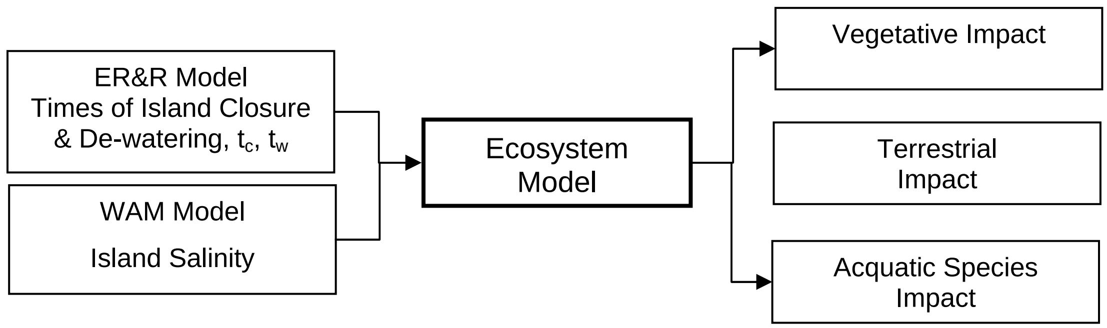

Figure 4-11 Inputs and outputs of the ecosystem impact analysis

6. Combine the Results of Steps 1 and 5 to Estimate Risk

The results of the frequency of island flood evaluation (Steps 1 and 2) and the consequences for each sequence are combined to determine the frequency distribution of each consequence (risk metric).

7. Estimate the Uncertainty in the Frequency of Levee Failure

As described in Section 4.3, the uncertainty in the hazards and levee performance are evaluated and combined with the best estimates of the economic and life safety consequences to estimate the uncertainty in each risk metric.

8. Combine the Results for the Individual Initiating Events (Steps 1-7) to Estimate the Total Risk

For each risk measure (e.g., island flooding, economic consequences) the total risk is determined by combining the results of all initiating events. With respect to levee failure, these results are determined by the following expressions. The total frequency of flooding island i is:

$$\nu_i = \sum_j \nu_{ij} \tag{4-16}$$

where the sum is carried out over all initiating events.

The total frequency distribution on the number of flooded islands is:

$$\lambda(N > n) = \sum_j \lambda_j (N > n) \tag{4-17}$$

The summations in equations 4-17 and 4-18 are carried out over all initiating events.

With respect to consequences of levee failures, the total risk is:

$$\lambda(C_k \geq c) = \sum_j \lambda_j (C_k \geq c) \tag{4-18}$$

where k denotes the risk metric (e.g., economic impact, economic cost, life safety).

4.9 RISKS IN THE FUTURE

To meet the requirements of Assembly Bill 1200, an analysis of risks 50, 100, and 200 years from the present must be made. This assessment must be based on existing information (models and data). Table 4-8 shows a timeline that indicates the availability of projections for hazards and environmental factors that threaten the Delta. Table 4-9 provides a similar summary of information available to assess future risks with respect to Delta assets and infrastructure.

It is common in risk studies to estimate the frequency of occurrence of events, based on available information and, assuming events are Poissonian (time-independent), 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 system failure do not vary over the project lifetime. For the Delta, the current state-of-knowledge makes it 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 do not permit a simple projection of lifetime risks.

To assess risks in the future, the approach taken is to estimate the change in individual factors (i.e., changes in earthquake occurrence rates and changes in the Delta population) relative to the base case 2005 analysis. These factors are then combined and used to estimate the degree of change in future risks relative to the estimate of the current (2005) risks. Ideally, a reassessment of the ”instantaneous” frequency of occurrence of events of interest in future years would be made. However, the availability of information limits the opportunity to make a detailed quantitative assessment.

To evaluate the degree of change of risk, relative to 2005, the following will be considered:

- Update the state of the environmental factors (e.g., subsidence and climate change) that may influence the performance of levees or the size or occurrence of hazards for an evaluation year (e.g., 2050, 2100, 2200).
- Estimate the effect that changes in these environmental factors have on levee performance, Delta hydrodynamics, and future consequences.
- Modify the rate of occurrence of events based on available information and changes to the environment; the frequency of occurrence per year of events at the time (e.g., earthquakes or floods in future years).
- Estimate the change in the in-Delta and statewide exposure (e.g., increasing population and property development, ecosystem changes) to the effects of levee failures.
- Assume (based on BAU) 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.

Consideration of natural processes, such as subsidence and climate change, that produce an ongoing change in the Delta and Suisun Marsh are assessed based on BAU responses to these evolving processes. For instance, assuming current trends of levels of funding for levee maintenance and repair, it is likely that Delta islands and Suisun Marsh may be under water when considering future sea-level rise. Increasing funding to upgrade all levees to keep pace with sea-level rise would not be BAU. Similarly, as subsidence continues in the Delta, an effect may occur to levee stability, agriculture, and island conditions due to increased seepage or other factors.

For each evaluation year (present, 2050, 2100, and 2200) the relative effect (increase, decrease, or neutral) with respect to the 2005 analysis is assessed. The assessment considers:

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

Conducted over the study period, the results provide an assessment of the evolution of risk as measured by the change in the frequency of occurrence. The results of this evaluation of risk changes in future years are presented in Section 14.

Table 4-1 List of Events/Variables

Type	Event	Description	States/Values
State of Nature	Condition Variables in the Delta & 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 (annual runoff amounts and patterns and frequencies of floods) 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.	CALSIM 82-year trace based on historic data is used to model the randomness of the availability of water
	Month of the Year	The time of the year when an event occurs, plays an important role in the consequences (economic, environmental) in the Delta.	
	Time of Day	The of day that levee failures occurs plays a role in the potential for loss-of-life	Day/Night
Initiating Events (Hazards)	Seismic Events Hydrologic Intrinsic Events (Normal Events)	Each hazard type is defined in terms of individual events. This definition 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.	The full range of events is considered and a hazard appropriate characterization as defined by the hazard analysts and the levee vulnerability team. For seismic events, the full range of earthquake sizes (e.g., **M** 7. 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.

Table 4-1 List of Events/Variables

Type	Event	Description	States/Values
	Non-breached Levee Damage	Given the occurrence of a seismic event, the levee reaches that have been damaged are identified.	Damaged levee reaches for each island.
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 (including breaches on flooded island interiors, as well as breaches on initially nonflooded 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 and cost of individual island repairs.

Table 4-1 List of Events/Variables

Type	Event	Description	States/Values
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 levels; export disruption durations

Table 4-2 Salinity During Inflow Flood Levee Breaches

Year	Dates	Islands[a]	Inflow (annual peak day, cfs)[b]	Number of Delta Breaches	Peak EC (umhos/cm)[c] Antioch	Peak EC (umhos/cm)[c] Holland Cut
1980	January 18	Holland, Webb	339,000 (2/22)	2	129 (1/24)	301 (1/18)
1983	January 27-30	Grizzly, Van Sickle, Mildred, Fay, Shima, Prospect (1/30)	422,000 (3/4)	6	240 (1/30) Blind Pt.	393 (1/29)
1986	February 19-25	Dead Horse, McCormack-Williamson, Tyler, New Hope (2/20), Shin Kee (2/25)	661,000 (2/20)	5	210 (2/23)	342 (2/27)
1997	January 3-10	Dead Horse, McCormack-Williamson, McMullin Ranch, Paradise Jct., River Jct., Stewart, Walthall, Wetherbee Lake, Prospect, Pescadero (1/10)	562,000 (1/7)	10	212 (1/07)	137 (1/05)

[a] URS 2006. Delta Levee Failures_Water Level Levee Breaches 121106.xls

[b] Flood Hazard TM (URS/JBA 2008a), Table 2-4.

[c] Interagency Ecological Program, 2008. http://iep.water.ca.gov/cgi-bin/dss/dss1.pl

Table 4-3 Duration of No Exports

(Percentage of Start Times Exceeding Indicated Number of Days or Months)

Case*	3 Months	4 Months	6 Months	9 Months	12 Months	18 Months	36 Months	42 Months
2	7.9%	2.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
3	9.8%	2.8%	0.4%	0.0%	0.0%	0.0%	0.0%	0.0%
4	51.4%	44.7%	22.3%	3.7%	0.4%	0.0%	0.0%	0.0%
5	88.0%	86.0%	81.7%	68.1%	46.7%	11.2%	0.0%	0.0%
6	95.2%	93.7%	90.2%	84.8%	71.6%	46.0%	5.2%	0.0%

***** These cases are described in the Water Analysis Module (WAM) TM (URS/JBA 2007e).

Table 4-4 List of Economic Risk Metrics

Category	Metrics
Delta Island Vulnerability	Individual Island Flooding Multiple Islands Flooding
Economic Impacts	Value of Lost Output
	Lost Employment (Jobs)
	Lost Labor Income
	Lost Value Added
Economic Costs	In-Delta Cost
	Statewide Cost
	Total Cost

Table 4-5 List of Environmental Risk Metrics

<table>
<tr><td rowspan="8">Fish Species Quantified

Fish impacts are estimated by considering specific scenario occurrences for factors that affect fish populations or habitat conditions and totaling to a “score” for that scenario and species.</td><td>Delta Smelt</td></tr>
<tr><td>Chinook Salmon</td></tr>
<tr><td>Green Sturgeon</td></tr>
<tr><td>Inland Silverside</td></tr>
<tr><td>Longfin Smelt</td></tr>
<tr><td>Steelhead</td></tr>
<tr><td>Striped Bass</td></tr>
<tr><td>Threadfin Shad</td></tr>
<tr><td rowspan="7">Wildlife

Wildlife impacts are estimated by totaling the portion (of the acres) of that species’ habitat that is flooded.</td><td>California Black Rail</td></tr>
<tr><td>California Clapper Rail</td></tr>
<tr><td>Greater Sandhill Crane</td></tr>
<tr><td>Saltmarsh Common Yellowthroat</td></tr>
<tr><td>Saltmarsh Harvest Mouse</td></tr>
<tr><td>Suisun Ornate Shrew</td></tr>
<tr><td>Waterfowl (ducks, geese, and swans)</td></tr>
<tr><td rowspan="14">Vegetation

Vegetation impacts are estimated by totaling the portion (of the acres) of that habitat category that is flooded.</td><td>Alkali Marsh High</td></tr>
<tr><td>Alkali Marsh Low</td></tr>
<tr><td>Alkali Marsh Mid</td></tr>
<tr><td>Aquatic Vegetation</td></tr>
<tr><td>Herbaceous Upland</td></tr>
<tr><td>Herbaceous Upland, Ruderal</td></tr>
<tr><td>Herbaceous Wetland, Perennial</td></tr>
<tr><td>Herbaceous Wetland, Seasonal</td></tr>
<tr><td>Herbaceous Wetland, Seasonal, Ruderal</td></tr>
<tr><td>Shrub Upland</td></tr>
<tr><td>Shrub Wetland (Riparian)</td></tr>
<tr><td>Tree Upland</td></tr>
<tr><td>Tree Upland, Non-native</td></tr>
<tr><td>Tree Wetland (Riparian)</td></tr>
</table>

Table 4-6 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
Emergency Response	Emergency Response and Repair of Delta Levees
Water Analysis Management	Water Operations
	Hydrodynamics
Geomorphology	Geomorphology of the Delta
Consequences	Economic Consequences
	In-Delta Infrastructure
	Ecosystem Consequences

Table 4-7 Summary of the Risk Quantification Steps

No.	Quantification	Products
1	Evaluation Levee System Performance (see Sections 6 – 9)	a. Frequency of failure of individual islands. b. Frequency of sequences of multiple island breaches and damage
2	Emergency Response and Repair (ER&R) Evaluation (see Section 10)	a. Prioritize levee repairs for each sequence for damaged and flooded islands. b. Evaluate the repairs for each island, estimating the volume of materials, costs, and time to complete each repair type and dewater flooded islands.
3	WAM Evaluation (see Section 11)	For each sequence WAM calculations are performed to evaluate the water quality impact (salinity intrusion). These calculations are performed for the CALSIM historic trace to account for the randomness in hydrologic conditions and event months. The results of this calculation are: a. Estimate of the time for storage recovery b. Estimate of export deliveries during the period of disruption c. Estimate of the water quality impact required to evaluate environmental consequences
4	In-Delta Consequence Assessment (see Section 12)	For each sequence estimate: a. Direct economic consequences of island flooding b. Time to repair/recover island infrastructure after dewatering c. Damage to an island infrastructure (e.g., pipelines or bridges) due to levee breaches and scour
5	Economic Consequence Assessment (see Section 12)	For each sequence estimate: a. Statewide economic impact, including impact to in-Delta businesses, costs associated with water export disruptions, and job losses b. Total economic costs and impacts associated with levee repair, in Delta costs, and statewide impacts
6	Environmental Consequences	For each sequence, estimate the various environmental metrics (aquatic species, terrestrial species, and vegetation), the impact of levee failures, and water quality.

Table 4-8 Summary of the Information Available to Evaluate Future Hazards and Environmental Factors

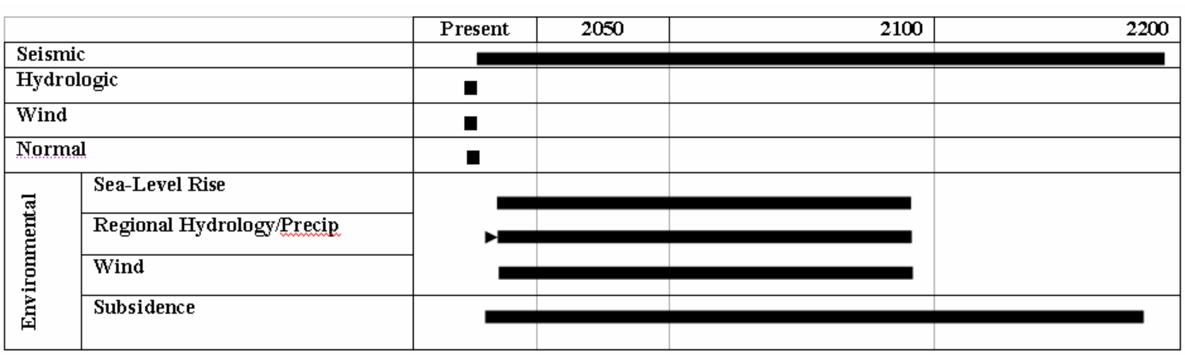

Table 4-9 Summary of the Information Available to Evaluate Future Delta Risks

	Present	2050	2100	2200
Levee Vulnerability	Direct data to support levee conditions in the future are not available. Projections and conditions can be based on past experience and practices. Factors such as subsidence can be projected and taken into account.			
Water Supply/ Demand/ Operations	Models and data are available to 2030. Hydrologic projections to 2100 are available to take into account			
Hydrodynamic	No data are available to account for bathymetry changes in the Delta. Sea-level rise effects are being considered as part of DRMS. Factors such as subsidence can be projected and taken into account.			
Environmental	Projections of species populations are not available. Observation of pelagic organism decline is not understood. Habitat restoration goals are identified; however, data to support model projections accounting for all factors (e.g., land use, restoration) are not available.			
Economic	Models and data are available to 2030.			
Delta Infrastructure	Projections of land use and population changes are available to 2030. For commercial infrastructure, specific projections for change/growth are not available.			

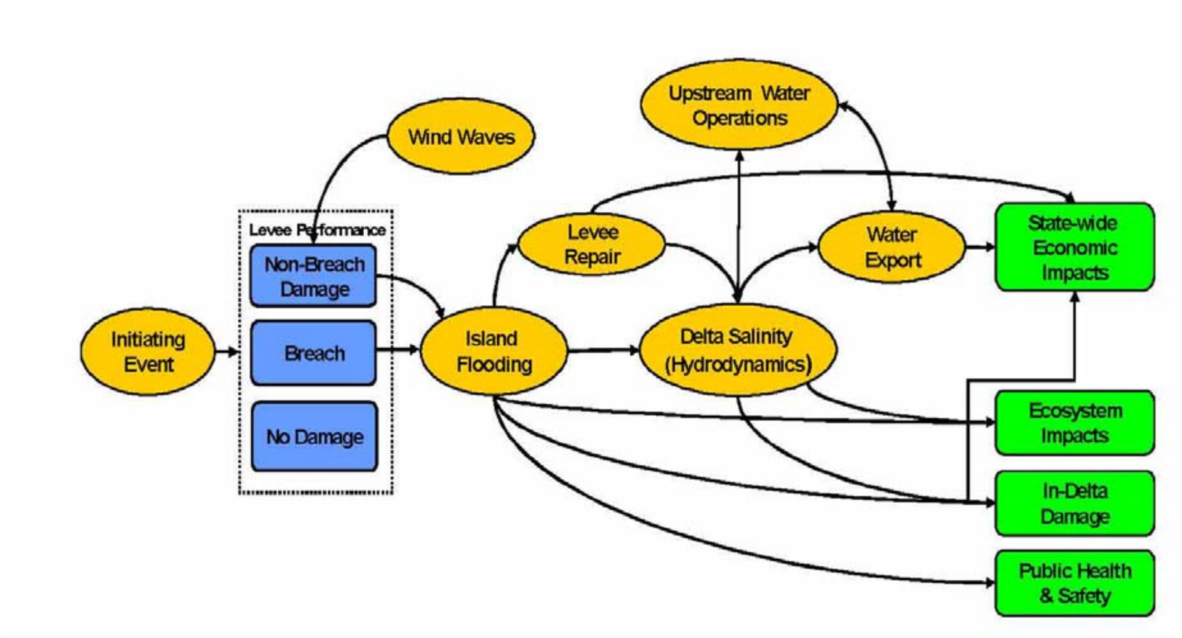

Figure 4-1 Influence diagram illustrating the basic elements of levee performance, repair, and Delta hydrodynamic response after a seismic event

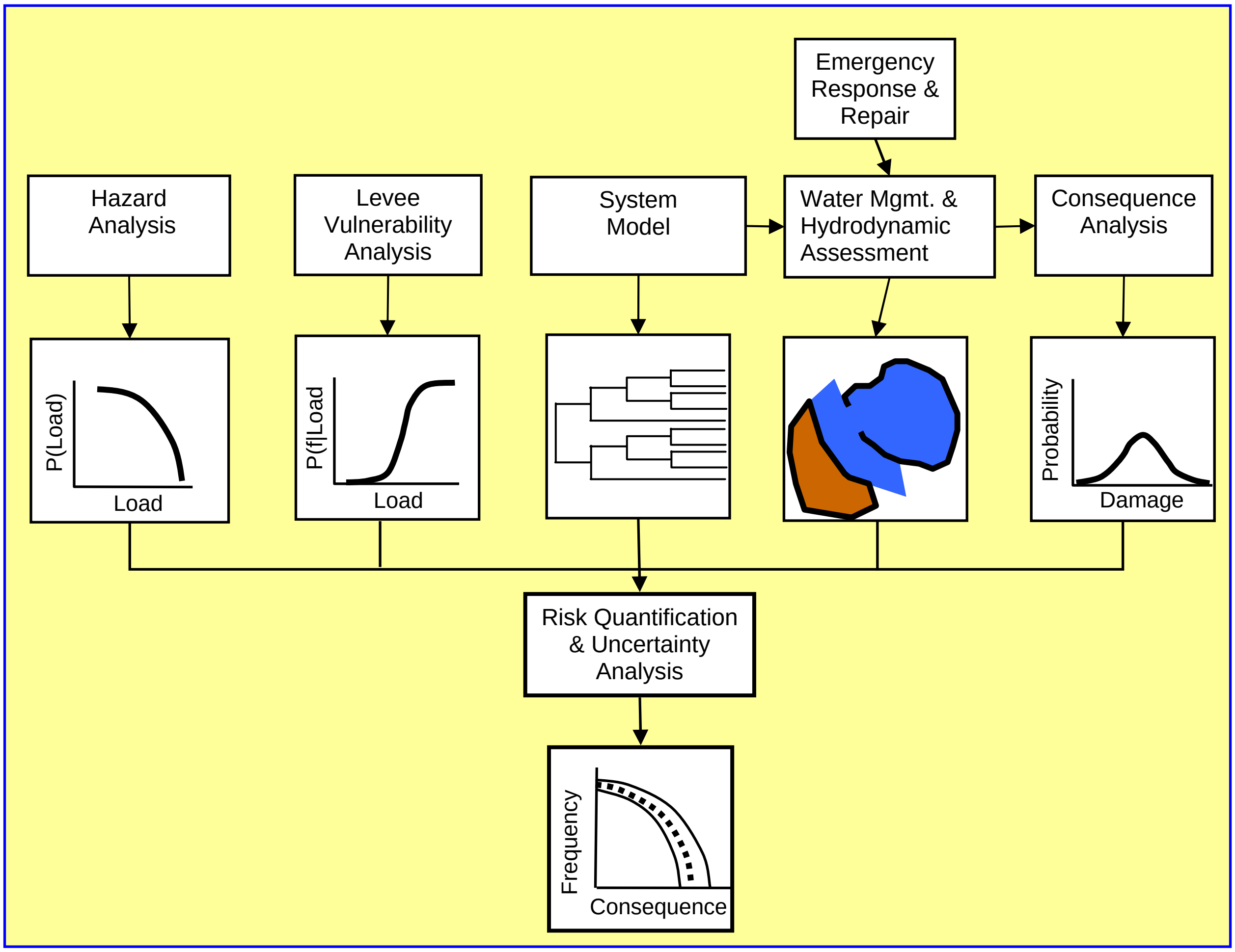

Figure 4-2 Schematic illustration of the elements of the risk analysis

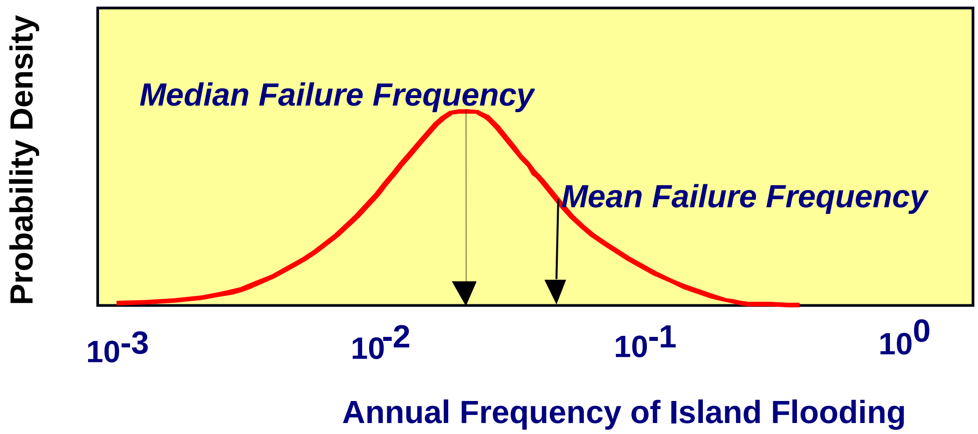

Figure 4-3 Illustration of the epistemic uncertainty in the estimate of the annual frequency of island flooding due to levee failure

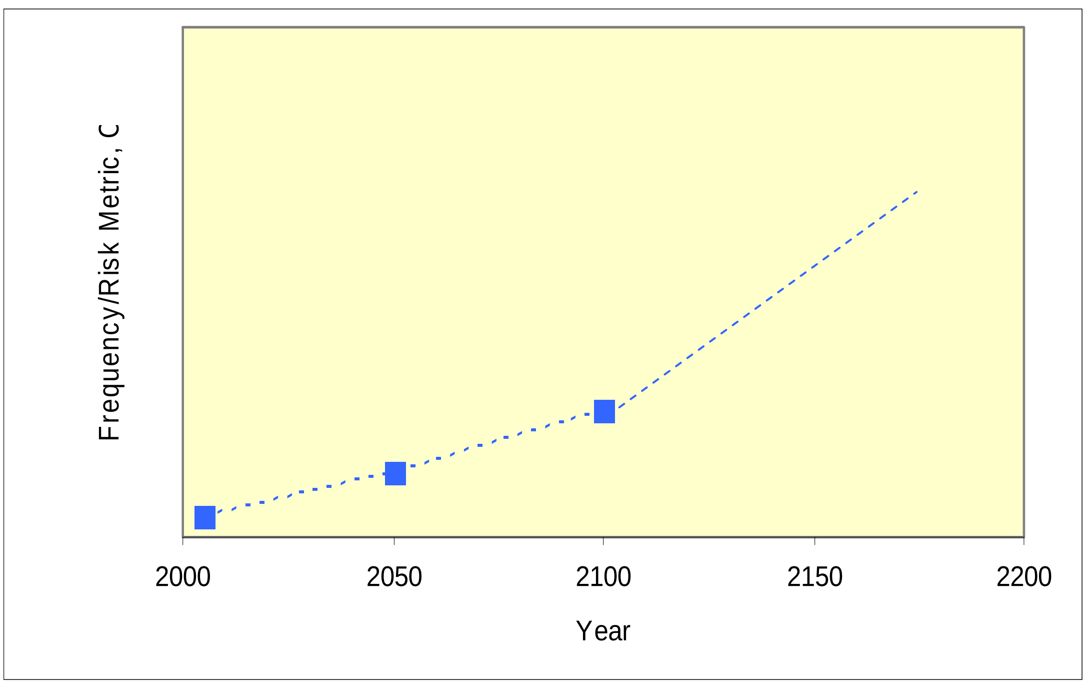

Figure 4-4 Illustration of time-varying estimates of risks in the Delta

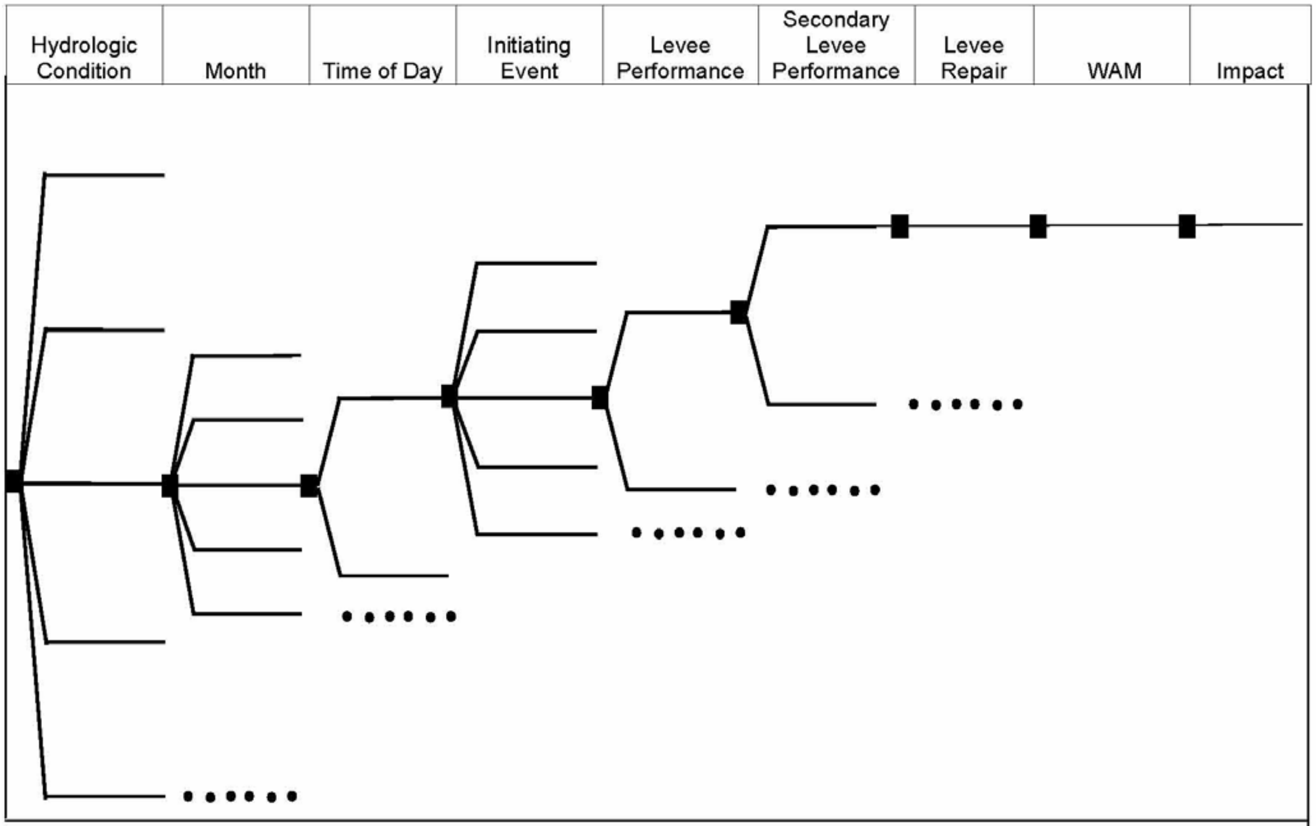

Figure 4-5 Illustration of an event tree used in the system model to organize and assess sequences

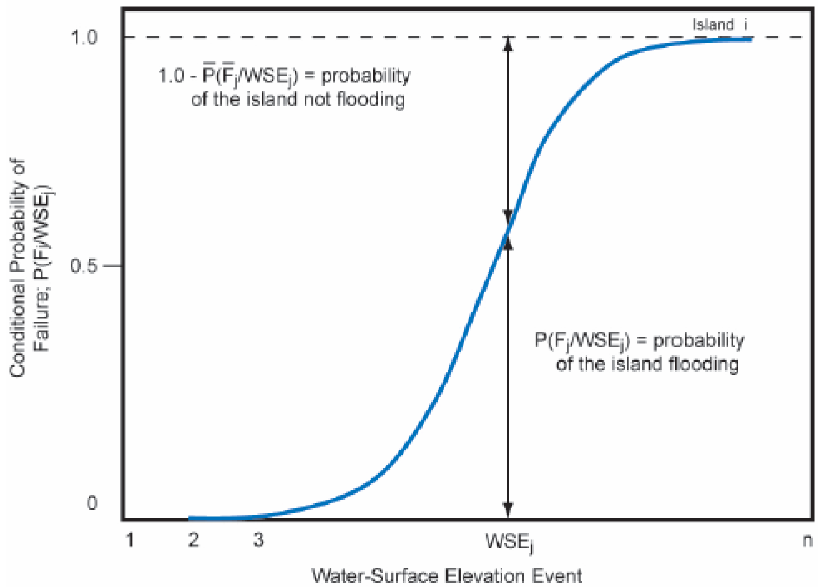

Figure 4-6 Illustration of an island hydrologic fragility curve and the simulation of island flooding

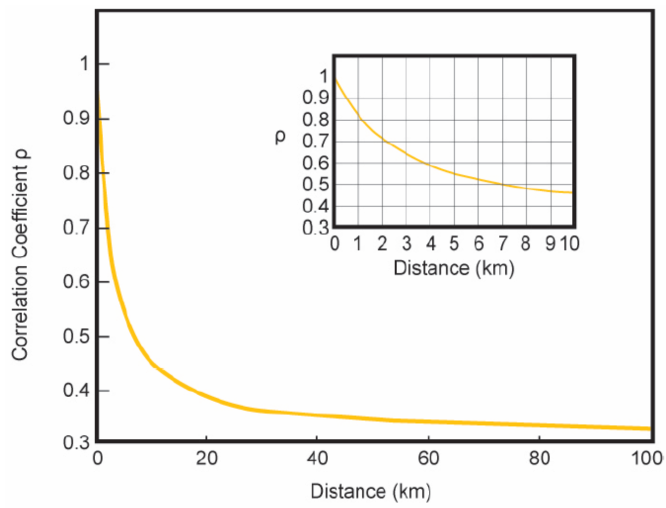

Figure 4-7 Ground motion correlation model developed by Boore at al. (2003)