Summary of Section 14, Risk Analysis for Future Years

Purpose:

The purpose of this section is to evaluate how the risks identified in Section 13 for the 2005 base year evolve and compound into the future.

Methods of Analysis:

This evaluation of future risk considers the changing landscape of the Delta due to subsidence and sea-level rise as a result of climate change, the changing probabilities of natural hazards (e.g., earthquakes and floods), and other evolving exogenous factors (e.g., changes in the population of the state and region, local land use patterns, economic activities, and the ecosystem of the Delta). A separate, yet constant factor that contributes to future risk is time. As we look ahead over the next 50, 100, or 200 years, the probability that an large earthquake or flood event will occur in the Delta increases. At the same time, the probability of adverse consequences also increases as the economy and the population continue to grow. As with the risk analysis for the 2005 base case, future risks are evaluated based on business as usual (BAU), which assumes that existing (2005) management practices are continued. BAU assumes that no major rehabilitation projects or changes in policies and practices occur. The BAU assumption supports the objectives of analyzing Delta risk and preparing risk management strategies in that it assesses whether current practices and policies are sustainable into the future. These baseline results can then be used in Phase 2 of the Delta Risk Management Strategy project to assess the risk reduction benefits of project alternatives and changes in policy or management practices.

Main Findings:

The future risk from earthquakes or floods is expected to increase by manyfold in the next 50, 100, and 200 years relative to the present-day risk.

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14.1 INTRODUCTION AND APPROACH

The previous section presented risk analysis results associated with levee failures in the Sacramento–San Joaquin River Delta (Delta) for 2005 base conditions. The purpose of this section is to evaluate how these risks evolve and compound into the future. The evaluation of risks for the future has various dimensions:

- The changing landscape of the Delta due to climate change and subsidence.
- The changing probabilities of natural hazards such as earthquakes and floods.
- Other evolving exogenous factors such as state and regional population, local land use, economic activity, and ecosystem affected by levee failures.

A separate, yet constant factor that contributes to future risk is time. As we look ahead over the next 50, 100, or 200 years, in addition to the ongoing sea-level rise and subsidence, the probability of an event (an earthquake or major flood) occurring in the Delta increases. At the same time, the probability of adverse consequences also increases as the economy and the population continue to grow.

In reference to the 2005 base case risk analysis of the Delta and the State due to levee failures, the analysis of risks for the future years considers the “business as usual” (BAU) assumption—the continuation of present (2005) management policies and practices. As discussed in Section 4, a full range of reliable information is not always available or adequate to conduct a detailed, quantitative analysis of future risks. The rationale behind using BAU as a point of reference is described in Section 14.1.3.1.

14.1.1 2005 Base Case Levee Failure Risks

Previous sections of this report have focused on assessing Delta levee failure risks for 2005 base-year conditions. Figure 14-1 presents the influence diagram that illustrates the relationship between events that occur in the Delta and the impacts to the state and the Delta. A risk model was developed to evaluate these interactions and to assess risk. A given earthquake may or may not occur, and if it were to occur, it may occur at any time during the year. The year may be relatively wet or dry. And a given flood may or may not occur, and if it were to occur, it might occur at any time during the flood season.

The risk model also recognizes uncertainty in the relationships between the various elements (topical areas) in the diagram. When a reliable probabilistic model was available, the Delta Risk Management Strategy (DRMS) consulting team used it to estimate the outcome of that element of work and its formal representation of the uncertainty. When probabilistic models did not exist, the consulting team used known factors for the key elements (sea-level rise, subsidence) to develop ranges around mean values.

Section 13 provides the quantitative results of these 2005 base case risk analyses and also presents uncertainty bands. The results consider the full range of variability of 2005 events that may have occurred – that is, all potential earthquakes, floods, hydrologic conditions, and event time dependency.

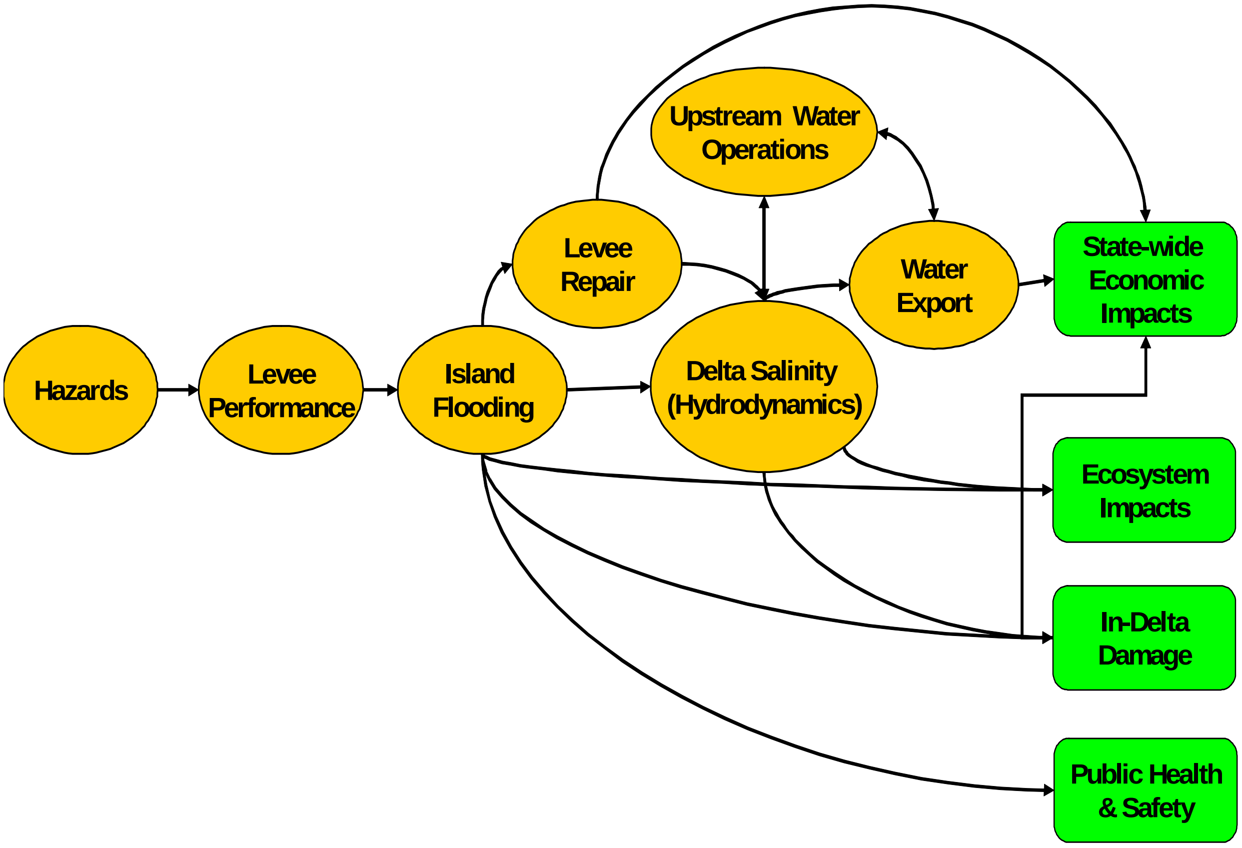


Figure 14-1 2005 Base Case Risk Model Overview: Chain of Causation

14.1.2 Information to Evaluate Risks in Future Years

To evaluate future risks, information was gathered on the drivers of change – factors that change the Delta landscape, the capabilities and condition of levees, the growth of the state economy and population, infrastructure and environmental changes in the Delta. The amount of information across the range of topical areas varies considerably, particularly looking out 200 years. The search for information focused on existing data, models, or modeling results that either assess conditions in future years or provide a model or basis for projecting to future years. Table 14-1 summarizes the state of information available to assess risks in future years (details of this information are discussed subsequently). The availability of information is projected on a time scale in Figure 14-2.

Table 14-1 Summary of Information Available to Assess Future Risks

Topical Area	Available Future Info	Information Reliability
Climate Change	Projections to 2100	Wide uncertainty bands
Subsidence	Projections to 2200	Moderately wide uncertainty
Geomorphology	No future information	N/A
Seismic Hazard	Projections to 2200	Minor uncertainty bands
Flood Hazard	Projections to 2100 from Climate Change	Wide uncertainty bands
Wind and Wave	No useful projections	N/A
Levee Vulnerability	Projections to 2200	Minor uncertainty
Emergency Response & Repair	No useful information	Uncertainty on key topics
Water Management	Projections to 2100 from Climate Change	Moderate uncertainty bands
Hydrodynamics	Use Subsidence and Sea Level Projections	Moderate additional uncertainty
Infrastructure	Projections to 2100	Large uncertainty
Economic Impacts	Projections to 2030	Moderate uncertainty
Ecological Impacts	No useful information	N/A

A review of Table 14-1 and Figure 14-2 indicates that beyond 2030, the availability of information to assess risks begins to fall off. For instance state estimates of economic activity have not been made beyond 2030. There is very little information on changes to the ecosystem (although there are some probabilistic projections for extinction of aquatic species). Additional information limitations occur after 2050; official state or regional population projections are not available after this date.

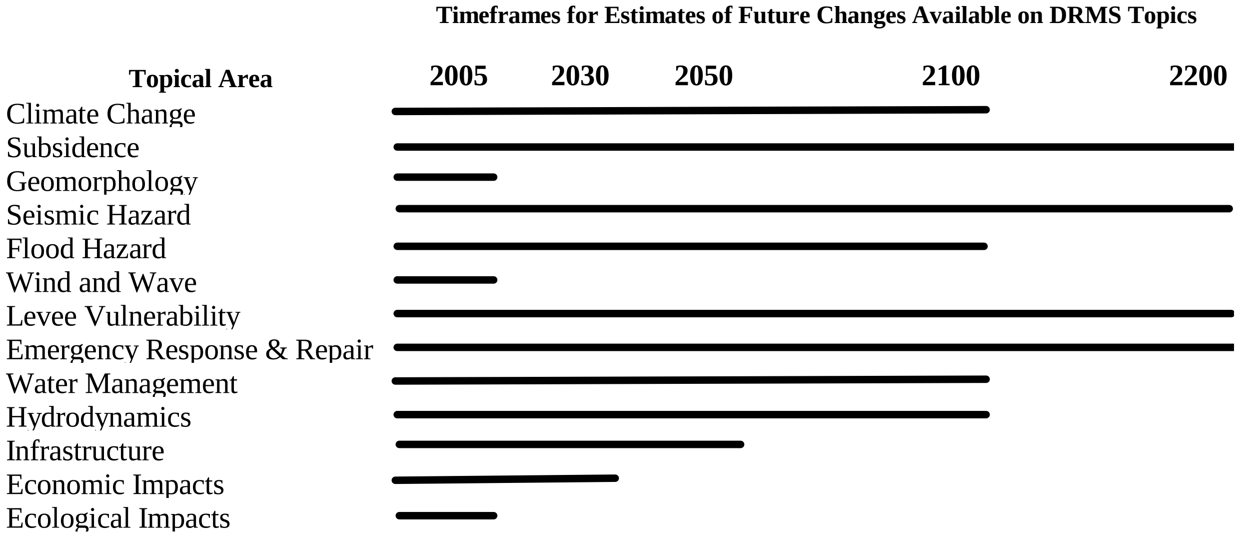


Figure 14-2 Availability of Information in Various Topical Areas versus Future Years

14.1.3 Approach for Considering Risk in Future Years

The methodology for assessing Delta risks as they evolve 200 years into the future is not simple, and often requires making broad assumptions. The assumptions are mostly driven by the trend; less so by their absolute future values. The uncertainties are mostly driven by the lack of available, reliable information in key topical areas. To overcome the inherent difficulty, a two-part evaluation is reported. In the first part, a conceptual model is developed to obtain a sense of how the drivers of change are progressing and how they will alter risks in future years. The second part is the development of the quantitative evaluation.

A consideration of future risks begins from the same starting point as for the 2005 model, as displayed in Figure 14-1.

14.1.3.1 Business as Usual

As with the base case analysis, future risks are evaluated based on BAU – which assumes that existing (2005) management practices are continued (see Section 3.4). BAU assumes that major rehabilitation projects and/or changes in policies and practices do not occur. Therefore, the BAU assumption supports the objectives of the Delta risk analysis and risk management strategies in that it allows an assessment of whether current practices and policies are sustainable in the future. These baseline results can then be used later, in Phase 2 of the DRMS project, to assess the risk reduction benefits of various project alternatives and changes in policy or management practices.

14.1.3.2 Drivers of Change in the Delta

The “Status and Trends” document (URS 2007) prepared for Delta Vision identifies the following “drivers of future change” for the Delta:

- Subsidence
- Global Climate Change – Sea-Level Rise
- Regional Climate Change – More Winter Floods
- Seismic Activity
- Introduced Species
- Population Growth and Urbanization

These broadly stated drivers of change can be expanded and characterized in a bit more detail as summarized in Table 14-2. The additional detail is designed to facilitate assessment of future risks due to levee failures.

Table 14-2 Drivers of Change Relative to Delta Levee Risks

Driver	Availability	Summary
Sea Level	Projections to 2100	All increase, high uncertainty
Tidal Amplitude	Limited past trend	May increase but unreliable
Storm Surge Frequency	No connection established	May increase but unreliable
El Nino Southern Oscillation (ENSO) Frequency	No connection established	No direction established; nothing useable
Inflow Flood Frequency	Projections (CC) to 2100	All increase, high uncertainty
Wind/Wave Event Frequency	No reliable information	Nothing useable
Seismic Frequency	Projections to 2200	All increase, relatively reliable
Subsidence	Projections to 2200	All increase, modest uncertainty
Seasonal Runoff	Projections (CC) to 2100	Less spring/summer, uncertain
Water Supply Yield	Projections (CC) to 2100	Generally less, uncertain
Water Supply Demand	No reliable projections	Nothing useable
Delta Area Population	Limited projections 2050	All increase, high uncertainty
Delta Land Use/Infrastructure	Limited projections	All increase, high uncertainty
Delta Area Economic Activity	Limited projections 2030	All increase, high uncertainty
Regional and State Population	Limited projections 2050	All increase, high uncertainty
State Economic Activity	Limited projections 2030	All increase, high uncertainty
Introduced or Lost (extinct) Species	No projections, some probability of extinction	Highly uncertain

14.1.3.3 Conceptual Model of Changing Delta Levee Risks

The drivers of change influence or alter the inputs to or interactions within the basic risk model illustrated in Figure 14-1. The basic risk model is enhanced at a conceptual level to evaluate the drivers of change in the Delta and capture a sense of the direction and importance of their influence in future risks from levee failures. The conceptual model puts the drivers of change into context. It identifies the mechanisms by which they influence other parts or intermediate variables within the risk model and thus progress through the model to alter future risks. The conceptual model also establishes the framework for a more-detailed, quantitative evaluation.

14.1.3.4 Quantitative Analysis

The quantitative analysis will use available, reliable quantitative information and established relationships to implement the model of future risk to the extent that is practical.

14.2 DEVELOPING AND APPLYING THE CONCEPTUAL MODEL

Figure 14-3 illustrates the expanded risk model needed to incorporate the drivers of future change and their influences on future risk. The following subsections address the inputs, interactions and outputs of the underlying model at a conceptual level. Topics include the directions of expected future changes, their relative importance, and the degree of certainty (or uncertainty) associated with each variable or interaction. Some drivers of change are discussed but, because of uncertainty on their magnitudes or importance, they are not shown in Figure 14-3 and will not be addressed in additional discussion of the conceptual model. Additional detail, to the extent it is available, is provided in Subsection 14.3.2.

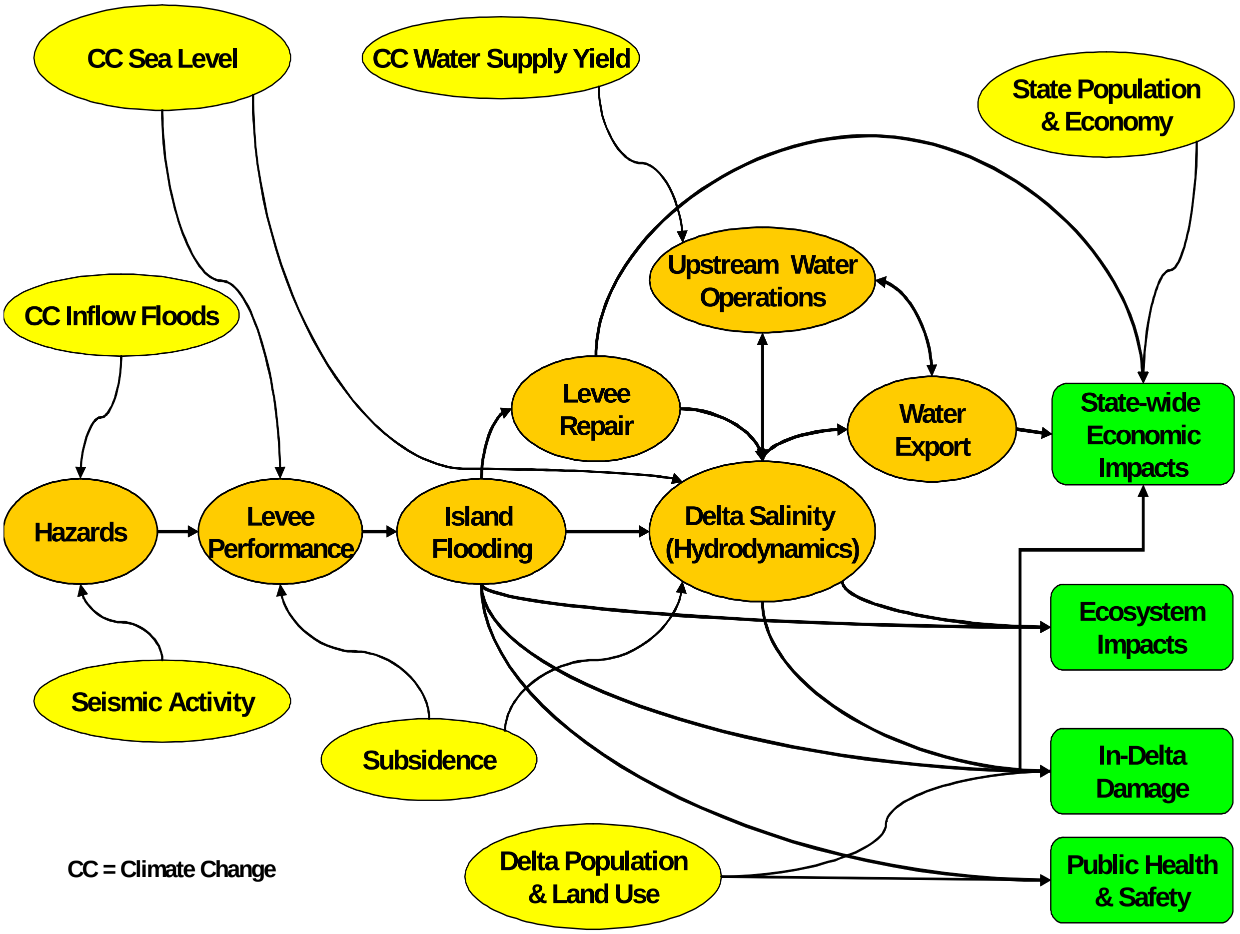


Figure 14-3 Risk Model Overview with Principal Drivers of Future Change: Simplified Chain of Causation

14.2.1 Exogenous Drivers – Magnitudes and Directions of Change for Model Inputs

The following paragraphs summarize the drivers of change and their directions and magnitudes of future evolution, to the extent information is available.

Changes in Sea Level. Rising mean sea level is expected as a result of global warming, (see Climate Change Technical Memorandum [TM] [URS/JBA 2008b]). Higher sea levels produce higher hydrostatic loads against a levee as well as increased internal seepage gradients. The amounts of sea-level rise recommended in the Climate Change TM (URS/JBA 2008b) for use in modeling future risks are:

- For 2050: between 4 and 16 inches
- For 2100: between 8 inches and 4.6 feet

In line with the BAU definition, the DRMS consulting team assumed that levees will be raised to keep up with sea-level rise.

Changes in Tidal Amplitude. Observations of modest increases in tidal amplitudes (range) specific to San Francisco Bay have been noted from existing records during the last century, coincident with increasing mean sea level (see Flick et al. 2003; URS/JBA 2007e, Appendix H3). The future change in tidal amplitude is uncertain. Based on the available data, one would expect continuing increases, if there is any future change. A simulation performed to test the effects of tidal amplitude changes on salinity intrusion (see the Water Analysis Module [WAM] TM, Appendix H3 [URS/JBA 2007e]), showed that tidal amplitude increases are likely to cause increased salinity and increased risk consequences. However, because of its uncertainty and limited evidence regarding direction and magnitude, it is not further addressed in the conceptual model.

Changes in Storm Surge Frequency. Storm intensities or frequencies are expected to change as a result of regional climate change. There are expectations of more frequent, intense precipitation events (storms) with future climate change (IPCC 2007, WG1, 750). It also appears these events will be accompanied by more intense low-pressure systems resulting in increases in sea-level surge. The United Nations Intergovernmental Panel on Climate Change's (IPCC's) recent report indicates increased frequency of more severe strong cyclones in mid latitudes and a decrease in the central pressure of such storms (IPCC 2007, WG1, 789). Such conditions would be expected to cause more frequent occurrence of sea-level storm surges. This is potentially important to water levels relative to Delta levees, especially in combination with sea-level rise and potentially increasing tidal amplitude. However, the available science does not yet offer complete set of modeling tools that could be used in this analysis, and hence this driver was not further considered.

Changes in El Nino Southern Oscillation. There has been some suspicion that there will be increased effective sea level in the Delta due to increased storms and surges as El Nino Southern Oscillation (ENSO) events increase. However, according to the IPCC (2007, WG1, 751), "there is no consistent indication at this time of discernible changes in projected ENSO amplitude or frequency in the 21st century." This is similar to the finding by van Oldenborgh and Burgers (2005). Accordingly, ENSO changes are not incorporated in the conceptual model.

Changes in Inflow Flood Frequency. Flood frequencies (high Delta inflows) are expected to increase due to the regional impacts of global warming. This will result in more winter precipitation as rain rather than snow, and in more frequent high intensity precipitations. Expected changes in runoff patterns due to a warming climate are described in the Climate Change TM (URS/JBA 2008b). Although the total amount of yearly precipitation may not change substantially, increases in winter precipitation as rainfall rather than snow and increasing frequencies of large storm events are predicted.

The climate change team was able to provide four different scenario/simulations of daily, unimpaired runoff at key sites tributary to the Delta. These data were analyzed by the DRMS flood hazard team to quantify the trends in the frequency of major storms. Although the results vary among the four simulations (see the Flood Hazard TM [URS/JBA 2008a]), each simulation indicates increasing frequencies of the seven-day Delta inflow that represents the year 2000 1 percent annual frequency (i.e., 100-year) flood event, referred to here as the Standard Inflow Flood. The ranges of frequency increases are indicated below:

- For 2050: Frequency increases of standard inflow flood are between 40 percent and 500 percent
- For 2100: Frequency increases of standard inflow flood are between 130 percent and 1,140 percent

Changes in the Frequency of Wind/Wave Events. A regional alteration in temperatures and weather pattern frequencies or intensities may lead to increased or decreased frequencies of wind-wave events of given magnitude, direction or duration. However, simulated wind velocities for future climate and weather conditions in the Delta are unreliable at this time. Even state-of-the-art nested models are probably incapable of making trustworthy projections of wind speed responses on the small spatial scales of interest (see the Climate Change TM [URS/JBA 2008b]). Thus, although the possibility of future changes in the frequencies of particular intensities, directions, and durations of wind-wave events are recognized, no probabilistic quantitative assessment tool for future wind models is available. This driver is not addressed in the conceptual model.

Changes in the Frequency of Seismic Activity. The time-dependent hazard curves developed as part of the probabilistic seismic hazard analysis (see the Seismology TM [URS/JBA 2007a]) were used to assess the increasing probability of ground motions for the future years 2050, 2100, and 2200. The peak ground acceleration (PGA) was used as a gauge for estimated percent increase in future earthquake hazards. The expected increases in frequency of a 0.20g PGA event are given below as percentages of the 2005 (base year) frequency:

- For 2050: Frequency increases by 10 percent
- For 2100: Frequency increases by 20 percent
- For 2200: Frequency increases by 40 percent

The assessment of the future seismic hazard is based on the assumption that a major seismic event does not occur on one of the major Bay Area faults between now and the future evaluation years (2050, 2100, and 2200). As a result, tectonic strains are not released. Instead, they keep building up, thus increasing the probability of occurrence of future earthquakes.

Progression of Subsidence. The ground surface elevations in areas of the Delta-Suisun that have organic (peat) soils are expected to continue subsiding if current management practices are not altered. The DRMS analysis of subsidence has provided an analysis of the rates and amounts of subsidence both historically and projected into the future (see the Subsidence TM [URS/JBA 2007d]).

Subsidence rates are expected to decrease as the organic content percentage of the soil decreases and ultimately cease when the organic-rich layer is depleted. The duration of subsidence is dependant on the presence and thickness of the peat and organic deposits which are highly variable across the Delta (see the Subsidence TM [USR/JBA 2007d]). These effects largely counterbalance each other and the nominal subsidence for typical central Delta histosol is expected to be relatively constant at about 2.2 centimeters (cm) (0.9 inch) per year, until the organic content is largely depleted. An uncertainty band on this subsidence rate of +40 percent and -30 percent is stated. Subsidence rates in Suisun Marsh are expected to be much lower, because of a different management of the Suisun Mash.

An example of the result is given in the subsidence map for 2100 in Figure 14-4. The Subsidence TM (USR/JBA 2007d) has similar maps for 2050 and 2200. The medium expectation for future subsidence for the Delta and Suisun area with highly organic soils in terms of decreases in surface elevation and cumulative area-wide increases in accommodation space relative to 2005 sea level are:

- For 2050: Up to 3 feet of subsidence and about a 25 percent increase of accommodation space
- For 2100: Up to 8 feet of subsidence and about a 50 percent increase of accommodation space
- For 2200: Up to 17 feet of subsidence (accommodation space not estimated)

Note that these estimates of accommodation space increases are based only on progression of subsidence. Additional accommodation space increases will result due to any increases in mean sea level.

Changes in Seasonal Runoff and Water Supply Yield. With warming temperatures, more precipitation in the Sierra Nevada mountains will fall as rain and less as snow, snow pack will not be as large and will melt earlier and, thus, less spring and early summer runoff will be captured for water supply. This will decrease water supply yields that are tributary to the Delta. The DRMS analysis includes a review of recent studies regarding the changing seasonal pattern of runoff, including analyses of climate change model simulations for inflows to Shasta and Oroville, the primary reservoirs for the Central Valley Project and State Water Project, respectively. The details of these reviews and analyses and their implications for future water supply availability are presented in the Water Analysis Module TM (URS/JBA 2007e, Appendix F). Figure 14-5 illustrates the decrease in snow pack, its earlier melting and resultant decrease of spring and summer runoff (into the state’s water supply reservoirs) for Oroville. There is a major shift of the monthly fractions of annual runoff from late spring and summer months to winter months. This will decrease the yield of the present water supply system. Available estimates of decreased median South of Delta yields are:

- For 2050: Median yields for the CVP will decrease between 4 percent and 16 percent from 2005 and, for the SWP, decreases will be between 4 percent and 11 percent from 2005
- For 2100: Median yields for the CVP will decrease between 7 percent and 34 percent from 2005 and, for the SWP, decreases will be between 4 percent and 27 percent from 2005

Variations among the climate simulations indicate uncertainty, with at least one simulation indicating no or only slight decreases in yield and others indicating more decreases. There is substantial uncertainty in these estimates due to variations among climate simulation models and to approximations in subsequent analyses.

Changes in Water Supply Demand. Increased temperatures may lead to increased water demand, especially in terms of evaporation and transpiration (see the Water Analysis Module TM [URS/JBA 2007e, Appendix G]). This is potentially important, especially for agricultural and landscape water use upstream of the Delta, in the Delta, and in the service areas south of the Delta. There is, however, a counterbalancing mechanism in operation; increased atmospheric CO_2 is believed to decrease the amount of water needed for evapo-transpiration (DWR 2006a). Although, the amount of water consumed is likely to increase just due to evaporation increases, the overall magnitude of increase may not be substantial. At present, this driver is considered uncertain, although water demand is likely to increase to some extent and thereby increase future consequences of Delta levee breaches.

Changes in Delta Area Population, Land Use, and Economic Activity. The forecasts for Delta area population and land use under current policies foresee infill in the present Primary Zone communities and intensive development in the Secondary Zone in the Delta (URS 2007; URS/JBA 2007f [Impact to Infrastructure TM]; URS/JBA 2008f [Economic Consequences TM]). Thus, the people, material assets, and economic activity located in the Delta and Suisun area are expected to increase. This will lead to increased consequences to in-Delta life safety and assets in the event of levee failures.

***Population* –** Data and projections of Delta area population are difficult to obtain because they are typically developed for cities and counties, while the Delta comprises fractions of the cities and counties. However, available data reported in the “Status and Trends” report (URS 2007) indicate that population on Delta/Suisun islands is expected to increase from 26,000 to 67,000 from 2000 to 2030, which is about a 160 percent increase.

The population of the legal Delta in 2000 was about 470,000. “Status and Trends” indicates an increase in Delta-Suisun population of 600,000 by 2050, pointing to a 2050 total population of 1,070,000. Full development of the Secondary Zone is estimated to lead to a Delta-Suisun population of well over a million people. These areas are now experiencing high rates of growth. These estimates of future population are very uncertain and they will be quite variable geographically during any particular period. For example, housing units on Stewart Tract, Bishop Tract, Shima Tract, and Sargent Barnhart Tract are expected to increase from 1,700 to 14,200 units between 2000 and 2030, an increase of over 800 percent.

***Infrastructure and Public and Private Property* –** The DRMS infrastructure analysis provides an assessment of assets subject to flooding from levee failures keyed to both Mean Higher High Water (MHHW) and the 100-year floodplain. That assessment is summarized below.

- For 2050 conditions, the MHHW and 100-year flood asset values subject to flooding are expected to increase by about 20 percent to 25 percent.
- For 2100 conditions, in addition to continuation of normal asset growth, both the MHHW and 100-year flood exposures are expected to cover increased areas because of sea-level rise and the increasing magnitude of the 100-year flood. Some of the additional areas that will be exposed to flooding are now highly developed urban areas or are in the path of urban development.

There is no indication these development trends will slow under BAU policies.

Business and Recreation Activities – Business activity is usually reported in terms of the value of output, employment and labor income. Projections for these measures were developed to 2030 by Woods and Poole (2006), (see the Economic Consequences TM [URS/JBA 2008f]). Those projections for 2030 that address Delta area counties and combined statistical areas are:

- Regional product: 100 to 160 percent increases over year 2000 values
- Earnings: 90 to 150 percent increases over year 2000 values
- Employment: 50 to 80 percent increases over year 2000 values

Agriculture, natural gas production and recreation are important economic activities in the primary Delta. Natural gas and agricultural production values will probably not increase significantly in the future. Recreation-related expenditures in the Delta were recently estimated to be over $500 million annually (see the Economic Consequences TM [URS/JBA 2008f]). These recreation expenditures will probably increase in the future with population increases in the Delta and the larger Bay Area region. Economic activity tied to residential development will increase dramatically by 2030 on some Delta islands near Stockton and can be expected to continue increasing thereafter. There is no useful projection for economic activity beyond 2030; however, business activity is expected to continue growing with population.

Changes in Regional and State Population and Economic Activity. Available forecasts (see the Economic Consequences TM [URS/JBA 2008f]) indicate continuing population and economic growth for the Delta and Bay regions and for the state as a whole. This will result in an increased dependence on infrastructure that traverses the Delta and especially on the water supplies that are conveyed through the Delta (see URS 2007; DWR 2005c; URS/JBA 2008f [Economic Consequences TM]).

Population – The California Department of Finance (DOF 2007a) provides state population projections to 2050. These projections estimate that 59.5 million people will reside in California by that date, a 61 percent increase over the 2005 base year. Although official projections are not available beyond 2050, the “Status and Trends” report indicates the possibility of 90 million people by 2100, a 143 percent increase.

Economic Activity –The historical data available from DOF (2007b) indicate that economic activity is closely tied to population growth. As with population, official projections are not available for the long term. The state DOF provides forecasts through 2010 (DOF 2007c). The projections to 2030 by Woods & Poole (2006) are:

- State product: 94 percent increase over year 2000
- Earnings: 87 percent increase over year 2000
- Employment: 47 percent increase over year 2000

Introduced or Lost (Extinct) Species. Changes in the species present in the Delta and in their relative populations certainly must be expected over the next several decades, given the threats of extinction for existing Delta species and the record of exotic species introductions over the past several decades (URS 2007; URS/JBA 2008e [Impact to Ecosystem TM]). Not enough information is available to forecast long-term changes to the diverse and dynamic Delta ecosystem 50, 100, or 200 years from now.

Translating such changes into an assessment of whether risks to the ecosystem from a given levee breach incident will increase or decrease in the future is similarly daunting. Present trends, including endangered and listed species and the introductions of exotic species, make it difficult to argue that BAU will result in a more robust and healthy ecosystem. Some assessments of impacts to habitat and species from levee failures indicate adverse outcomes (Impact to Ecosystem TM [URS/JBA 2008e]). A simple probabilistic model that represents the primary and short term impacts and probable extinction of aquatic species was developed and is presented in the Impact to Ecosystem TM (URS/JBA 2008e). The testing and execution of the model have not been completed due to schedule constraints.

For purposes of the analysis in this section, we assume (optimistically) that the future ecosystem (without levee breaches) is similar to today’s ecosystem. Obviously, there is massive uncertainty in this “forecast.” However, this assumption will allow us to focus on how other future changes might result in greater or lesser risks to the ecosystem.

14.2.2 Uncertainty and Further Analysis

The foregoing discussion of drivers of change for Delta levee risk can be summarized in a further development of Table 14-2, as shown in Table 14-3. For 2050 and 2100, the relative magnitudes of driver of changes are shown, based on a medium estimate. Two major points may be recognized from Table 14-3:

Table 14-3 Directions and Apparent Magnitudes of Drivers of Change Under BAU

Driver	Increase or Decrease Risk?	Large or Small Relative Increase?
Sea Level	Increase	Moderate to Large
Tidal Amplitude	Not Clear; Maybe Increase	? Unknown; Small/Moderate
Storm Surge Frequency	Not Clear, Maybe Increase	? Unknown; Maybe Moderate
El Nino Southern Oscillation (ENSO) Frequency	Not Clear	? Unknown
Inflow Flood Frequency	Increase	May be Large to Very Large
Wind/Wave Event Frequency	Not Clear, Maybe Increase	? Unknown
Seismic Frequency	Increase	Moderate
Subsidence	Increase	Moderate to Large
Seasonal Runoff	Increase	Moderate
Water Supply Yield	Increase	Moderate
Water Supply Demand	Not Clear	? Unknown
Delta Area Population	Increase	Large
Delta Land Use/Infrastructure	Increase	Moderate to Large
Delta Area Economic Activity	Increase	Moderate to Large
Regional and State Population	Increase	Large
State Economic Activity	Increase	Large
Introduced or Lost (extinct) Species	Not Clear	? Unknown

- For the six items that have uncertain impact as drivers (indicated by ?'s), part of the uncertainty is due to lack of an obvious major impact. Although these items could ultimately prove to be significant, better understanding must be achieved before they will deserve emphasis as important drivers of change in an analysis of future Delta levee risks. Thus, they were not included in Figure 14-3 for use in the conceptual model.
- For the 11 other items, there is a clearer impact of anticipated change and the magnitudes of some of them demand careful attention. In particular, the potential magnitude of sea-level rise , the increased frequency of major inflow floods, the Delta region's changing population and land uses, and the state's growing population and economy may substantially increase the consequences felt from Delta levee breaches in future years. Furthermore, the importance of these factors seems to increase more dramatically as the time horizon is lengthened, although it is recognized that these drivers are very difficult to project.

The "conceptual model" of changing levee risks in future years will then focus on the items indicated above and in Figure 14-3. The other six "unknown" items are not being dismissed, but are not included in this future risk assessment at this time.

The following sections will work through a sequential analysis of the impacts of these drivers within the Delta levees conceptual model to gain insights on the overall magnitude of prospective changes in Delta levee failure consequences—that is, changes in risk.

14.2.3 Effects of Exogenous Drivers within the Risk Model

To consider the changing risks in the Delta and Suisun Marsh, there are factors that have large-scale temporal and/or spatial variability that may influence future risks. In this discussion, 2005 is used as the base year. This analysis assesses how risks may change relative to 2005 in future target years of 2050, 2100, and 2200.

Risks factors can change dramatically with location within the Delta and Suisun Marsh. Rather than assessing future risk at many different locations, this section discusses an evaluation of risks for the region as a whole. Therefore, the Delta and Suisun Marsh are considered as one area in the assessments, recognizing that changes for specific areas may be somewhat different from the regional scale assessment presented.

As discussed in the DRMS technical memoranda, considerable uncertainty exists in projections of future conditions in the Delta and Suisun Marsh (subsidence, sea level) and the potential increase in future hazards and their frequency of occurrence. For purposes of this conceptual discussion of future risks, the evaluation relies only on the direction and apparent importance of the expected change. More detailed information on the respective topics, including ranges of estimates and uncertainties, are provided in Subsection 14.3.2 and in the TM for each topical area.

14.2.3.1 Sunny-Day, High-Tide Events

Considering the conceptual model representation in Figure 14-3 and describing the evolution of model intermediate variables that are implied for sunny-day, high-tide events, the following points are noted:

- Increased sea level will increase the hydrostatic load on the levee, the seepage gradient within the levee, the possibility of overtopping the levee and, thus, the frequency of sunny-day, high-tide failures.
- Increased subsidence will also increase the hydrostatic loading and seepage gradients for at least some sections of levees and will increase levee vulnerability to sunny-day, failure in those cases.
- More levee failures will require more repair effort (cost).
- Increased sea level and the progression of subsidence together will create more accommodation space that has to be filled with water when a breach occurs. This will mean additional salinity intrusion (when significant intrusion occurs) and increased pump-out costs. Salinity intrusion into the Delta is not presently a major impact of a sunny-day breach that floods a single island. With increased accommodation space, however, this impact will definitely increase and could become problematic. In any case, additional water for flushing will be required.
- Disruptions for both in-Delta water users and exports, to the extent that they occur will be lengthened and more severe.

In summary, no relationship within the conceptual model suggests an improved outcome for an intermediate variable that is important to risk. All the intermediate variables will escalate in the direction of increasing risk under the changes expected for future sunny-day events.

14.2.3.2 Seismic Events

Considering the conceptual model representation in Figure 14-3 and describing the evolution of model intermediate variables that are implied for seismic events, the following points are noted:

- Future increases in the frequency of seismic events (increasing probability of occurrence) for given earthquake magnitudes on a given fault will translate into comparable increases in frequencies of seismic levee failures.
- Increased sea level will increase the hydrostatic load on the levee, the seepage gradient within the levee, and the conditional probability of a seismic failure.
- Increased subsidence will also increase the hydrostatic loading and seepage gradients for at least some sections of levees (if the subsidence is within the “zone of influence” for the levee) and will increase levee vulnerability to seismic failure in those cases.
- Thus, a given seismic event will occur more frequently and result in an increased number of levee failures and will likely flood additional islands.
- More levee failures and flooded islands will require longer repair periods and more repair effort (cost).
- Increased sea level and the progression of subsidence together with more islands flooded will create more accommodation space to be filled with water. This will mean additional salinity intrusion into the Delta and will require additional time and water for flushing
- Disruptions for both in-Delta water users and exports will be lengthened and more severe.

In summary, no relationship within the conceptual model suggests an improved outcome for an intermediate variable that is important to risk. All the intermediate variables will escalate in the direction of increasing risk under the changes expected for future seismic events.

14.2.3.3 Flood Events

Considering the conceptual model representation in Figure 14-3 and describing the evolution of model intermediate variables that are implied for flood inflow events, the following points are noted:

- Future increases in flood frequencies for given inflow magnitudes will translate into comparable increases in frequencies of flood-caused levee failures.
- Increased sea level will increase the hydrostatic load on the levee, the seepage gradient within the levee, the possibility of overtopping the levee and, thus, the conditional probability of a flood failure.
- Increased subsidence will also increase the hydrostatic loading and seepage gradients for at least some sections of levees and will increase levee vulnerability to flood failure in those cases.
- Thus, a given flood inflow will occur more frequently and result in an increased number of levee failures and will likely flood additional islands.
- More levee failures and flooded islands will require longer repair periods and more repair effort (cost).
- Increased sea level and the progression of subsidence together with more islands flooded will create more accommodation space that needs to be filled with water. This will mean additional pump-out costs. Salinity intrusion into the Delta is not expected to be an immediate occurrence during inflow flood events. However, if the repair period is prolonged into the dry season for very large events, salinity could develop as a problem due to intrusion with tidal exchange. If so, it will require additional water for flushing.

In summary, no relationship within the conceptual model suggests an improved outcome for an intermediate variable that is important to risk. All the intermediate variables will escalate in the direction of increasing risk under the changes expected for future flood events.

14.2.4 Changes to Model Outputs – Risk Consequences

The combined effects of the changes for future years from the factors discussed in the foregoing sections are presented below, focusing on the key risk model outputs indicated in Figure 14-3 (the consequences of Delta levee breach events). The following points are noted:

- Public Health and Safety – The risk consequences for public health and safety (endangerment of peoples lives) must be expected to increase in future years because there will be more frequent events involving the flooding of more islands and, with increases in Delta population and urbanization, more people will be exposed.
- In-Delta Damage – The consequential damages to in-Delta infrastructure, property and economic activity and the cost of levee repairs are expected to increase in future years as a

result of the increasing likelihood of the hazards and the decreasing reliability of the levees, as discussed above**.** More frequent flooding involving more islands and more salinity intrusion for longer durations can only mean that damage levels escalate. In addition, more people and higher levels of land use and economic activity will be exposed. This will further escalate in-Delta damages.

- State-wide Economic Impacts – The consequences to California's economy will certainly increase in future years. The above-described in-Delta damage escalation will be part of the increasing impact to the state. However, with less water supply yield and more frequent Delta levee breach events involving more islands and more salinity intrusion, the disruption of Delta water exports will be more severe.

  Even if target amounts of water export remain unchanged, more people and higher values of economic activity will be exposed to disruptions of their water supply. Thus, the consequences to the California economy will be driven higher by multiple forces.
- Ecosystem Impacts – More frequent levee breach events involving more islands with more salinity intrusion for longer duration will, in the short term, increase the adverse impacts (e.g., entrainment, turbidity, loss of water quality, pump out, loss of habitat, and increased predation) as well as offer opportunities (e.g., new habitat or temporary interruption of water export). A few species may see beneficial impacts (see the Impact to Ecosystem TM [URS/JBA 2008e]). However, an increased threat to sensitive species must be expected.

14.2.5 Results of Conceptual Model Analysis

14.2.5.1 Annual Risks Increase in Future Years

As discussed in Subsection 14.1.2, the input information regarding the future becomes less available and less reliable as one looks further ahead. Economic projections are available only to 2030, and population projections are not available beyond 2050. Climate change inputs have broad uncertainty bands for 2050, much broader uncertainty bands for 2100, and no information beyond 2100. However uncertain they are, all risk variables point to increasing future risks, and no evidence has been found that indicates any exogenous driver or risk model relationship will reverse direction. Therefore, risk consequences in future years are expected to continue escalating through 2050, 2100, and into the years beyond.

Useful data are generally not available for addressing the conditions in 2200 and the effects on risks from Delta levee failures in that time frame. The two exceptions are subsidence and seismic hazard. Under the concept of BAU, both subsidence and seismic hazard will continue to increase. An altered rate of subsidence requires changes in land use or management practices, and an alteration in the rate of increase of seismic hazard requires that a major stress-relieving earthquake occur during the intervening period. Other factors are not so easy to predict. However, in light of the discussion and assessments above, there is no reason to expect that risks in 2200 will remain the same or decrease relative to risks for 2100. Thus, the risks from Delta levee failures are expected to continue to increase between 2100 and 2200 under the BAU assumption.

No significant risk factor has been identified that decreases the likelihood of Delta levee failures or decreases associated consequences. In contrast, all significant risk factors are increasing as one looks forward to 2050 and 2100 – some are increasing modestly, while others are expected to increase significantly (e.g., Delta and state-wide population and economic activity). The overall likelihood of a major event is increasing and the magnitudes of consequences from a given event are also rising.

14.2.5.2 Implications of Exposure Period

Although the trends in factors that influence the assessment of future risks combine to indicate steadily increasing annual risks from Delta levee failures, there is another important dimension in considering future risk. That dimension is the exposure period to an already high-risk situation.

In performing a risk analysis, engineers usually work with annual frequency of events. The important concept about such events is they have the same likelihood of occurrence every year.

The risk of adverse events increases as longer periods of exposure are considered. Figure 14-6 indicates how the likelihood of an occurrence increases as the length of the exposure period grows. In 30 years of exposure, a 1 percent annual event has a 26 percent chance of being equaled or exceeded. In 50 years, the chance is 39.5 percent and in 100 years, the chance is 63.4 percent. Figure 14-6 also illustrates the increasing probability of failure for other annual frequencies.

In the Delta, the likelihood of severe levee breach incidents is more likely than an annual frequency of 0.01. The figures in the previous chapter show annual frequencies of failure ranging from 0.005 to 0.07 for the Delta. However, the frequency of failure is much higher in the Suisun Marsh. These frequencies are also illustrated on Figure 14-6. It is just a matter of time (exposure period) until a severe event occurs.

14.2.5.3 Summary Perspective on Future Risk

The annual risks from Delta levee failures are already high and are increasing. Each initiating cause (seismic, flood, and high-tide/sunny-day) is expected to result in an increased likelihood of island flooding and increases in expected consequences. When combined, these initiating causes must be expected to yield escalating risk consequences as each future year is considered in turn. These increases depend, of course, on how future conditions such as climate change, subsidence, and Delta-area population growth and land use materialize.

Although the increase in yearly risk is important, one must remember to consider exposure periods. With only the present risks from Delta levee failures (and assuming no future increases in annual risks), the people of California face a 50/50 chance of a major-impact incident within the next few decades. This risk from exposure period deserves special consideration by decision makers.

Thus, the principal findings so far regarding future risk are the following:

- No factor (under a BAU scenario) was found that is expected to significantly decrease the risk of Delta levee failures in the future. All factors considered point to increasing risk. And the increasing risk is compounded because the factors are all working together to increase the probability of future adverse consequences from levee failures in the Delta.

- When an exposure period of 25 years, 50 years, 100 years, or 200 years is considered, as set forth in the project scope), the likelihood of a major adverse event becomes very high, almost unavoidable.

14.3 QUANTITATIVE ANALYSIS

14.3.1 Organizing a Quantitative Analysis of Future Risks Including Uncertainty

Conducting a properly organized and quantitatively meaningful analysis of future risks, including characterization of uncertainties, is a challenging undertaking. It is challenging in terms of the complexity of the analysis required and it is extremely demanding in terms of the information needed as inputs. The following subsections address organizational concepts, information limitations, and the approach to be taken.

14.3.1.1 Organizing the Analysis – The Logic Tree

Figure 14-7 presents a logic tree, the tool used to organize analysis of future Delta levee risks including uncertainty. It is built based on several columns each identifying key variables (exogenous drivers of change or intermediate relationships) that can take on different values in the analysis. Branching is used in proceeding from left to right through the tree to indicate that each value in the next column defines a different state of the system – a unique scenario that may prevail. When considering all the branching, the logic tree has potential to grow very large. The tree in Figure 14-7 is relatively simple, mainly because we do not have alternate values for several of the variables that are important to the analysis, for example estimates of Delta area and State population and economic activity. Thus, Figure 14-7 has only 216 branches rather than a much larger number.

When a column takes on several values, the consideration of each is the vehicle for including uncertainty in the analysis. For example, in the Subsidence TM (URS/JBA 2007d), uncertainty was assessed as "-30 percent to +40 percent" relative to the best estimate of subsidence. Thus, the subsidence column has three unique entries indicating the best estimate of subsidence, a higher value and a lower value. Ideally, each of the values in a column has a probability weight that indicates its likelihood of that value being true. The weights of the values in the column sum to one, so it is clear that only one of the alternatives can prevail and one of them must prevail. By this branching to alternate values and including each (with its weight) in the risk analysis, uncertainty is recognized and quantitatively assessed. Unfortunately, alternate subsidence values do not have associated weights, a situation that is a common shortcoming in such analyses.

Such a tree would be fully developed (including a column for each significant factor) for each future year being addressed. Thus, we would create trees for 2050, 2100, and (perhaps) 2200.

Figure 14-7 illustrates the logic tree applicable for performing an analysis of levee risks for 2050. Although it may seem quite elaborate and complex (it would certainly be busy if all 216 branches were explicitly shown), it already includes many simplifications dictated by information limitations as described in the next subsection.

14.3.1.2 Information Limitations

The specific information limitations for a 2050 analysis that are reflected by the logic tree presented in Figure 14-7 are:

- Sea-level rise estimates should be associated with each climate change scenario/model, since sea-level rise will not occur independently of the scenario and model.
- The IPCC scenarios considered only two of the six IPCC marker scenarios. A more comprehensive analysis of future risk and uncertainty would include more scenarios.
- The general circulation models addressed are limited to two of the 15 to 23 models that are generally reported and discussed.
- The estimates of water supply yield are based on preliminary analyses, again with few scenarios and models.
- The calculated changes in flood frequency are similarly limited and preliminary. The frequency changes are large and merit further study.
- The ER&R model does not reflect any future change that may deviate from the 2005 situation for availability of rock to be used for levee repairs. The epistemic uncertainty incorporated into the model should also be characterized but is not.
- The WAM model has not been assessed to characterize epistemic uncertainty although calibration and limited verification indicate it provides satisfactory representation of salinity. This modeling uncertainty should be included in the uncertainty analysis.
- Although an estimate of 2050 Delta-Suisun population has been found, the uncertainty band for this estimate should be substantial. No uncertainty characterization was found.
- Economic activity specific to the Delta-Suisun area is not projected for future years.
- The state population projection for 2050 has no associated uncertainty band.
- State economic activity is not projected beyond 2030 and no uncertainty characterization is provided for the 2030 projection that is available.
- The models for estimation of economic consequences also have substantial epistemic uncertainty that has not been estimated.
- It is particularly important to note that the information limitations are more severe on the right side of the logic tree – involving the social topics that may have very large changes.
- To perform a formal risk analysis, it is necessary to have a probability weighting at each branching point. For example, we need to assign a probability to each of the four estimates of future sea level (and the four probabilities must sum to 1.0). Those probability weights are not available. And the IPCC, for example, insists on not assigning them to their SRES scenarios. Without those probabilities an overall quantitative assessment of risk cannot be performed.

A similar logic tree can be developed for 2100, but with even more information limitations. Rather than burden the reader with another diagram, a summary of the information that is available for use in a 2100 evaluation will be provided in table format.

14.3.1.3 Approach

Given the information limitations described above, it does not make sense to perform 216 analyses (one for each branch in Figure 14-7) for 2050 and a similar number for 2200. In addition to being unwieldy, these analyses might give a false sense of accuracy or precision and the impression of far less uncertainty than a more comprehensive analysis would make apparent. Instead, quantitative assessments will be performed for high, medium, and low examples of the branches to the extent that available data and relationships allow.

14.3.2 Exogenous Driver Inputs Available

The following paragraphs present the quantitative information available for input.

Changes in Sea Level. Rising mean sea level is expected everywhere as a result of global warming. The San Francisco Bay area is no exception, as is recognized by DRMS background work on Climate Change (see Climate Change TM [URS/JBA 2008b]). It is obvious that higher sea levels mean higher risks of levee failure, given BAU (assuming the levees are raised to keep up with sea-level rise, but strengthening the levee beyond current condition is not included). The amounts of sea-level rise recommended for analysis by the DRMS climate change team are set forth in Table 14-4. They constitute a significant percentage of the 1.5 feet of freeboard required over the 100-year flood elevation as a PL 84-99 design standard. Note that the range of estimates presented indicates considerable uncertainty regarding what will actually occur as the future presents itself.

Table 14-4 Estimates of Future Delta–Suisun Marsh Sea-level Rise

	Centimeters (cm)	Inches (in)	Feet (ft)
Estimates for 2050			
Low	11	4.3	0.36
Med Low	20	7.9	0.66
Med High	30	11.8	0.98
High	41	16.1	1.34
Estimates for 2100			
Low	20	7.9	0.66
Med Low	50	19.7	1.64
Med High	90	35.5	2.96
High	140	55.1	4.59

Changes in Seasonal Runoff and Water Supply Yield. With warming temperatures, more Sierra precipitation will fall as rain and less as snow, and the snow pack will not be as large and will melt earlier. Thus, less spring and early summer runoff will be available for capture for water supply. This change will decrease water supply yields that are tributary to the Delta. The DRMS analysis includes a review of recent studies regarding the changing seasonal pattern of runoff, including analyses of climate change model simulations for inflows to Shasta and Oroville, the primary reservoirs for the Central Valley Project and State Water Project, respectively. The details of these reviews and analyses and their implications for future water supply availability are presented in the Water Analysis Module TM (URS/JBA 2007e;

Appendix F). The decrease in snow pack accumulation, the earlier melting of the smaller snow pack and the resultant decrease of spring and summer runoff (into the state's water supply reservoirs) is illustrated in Figure 14-5 for Oroville. There is a major shift of the monthly fractions of annual runoff from late spring and summer months to winter months. This will decrease the yield of the present water supply system. Table 14-5 summarizes the available results for the various climate change scenarios/models being considered for 2050 (DWR 2006a, 4-17 to 4-21) and 2085 as an estimate of 2100 (Vicuna 2006). Variations among the simulations indicate uncertainty, with at least one simulation indicating no or only slight decreases in yield and others indicating more.

There is substantial uncertainty in these estimates due to variations among climate simulations and also due to approximations in subsequent analyses. More detailed analysis is possible to markedly reduce analysis approximations. Different climate scenarios would still provide varying results representing substantial remaining uncertainty. There are other scenarios that are worthy of consideration (see Vicuna 2006).

Table 14-5 Estimates of Change in Future Water Supply Median Yield (from previous studies)

Year/Scenario/Model	Central Valley Project (CVP)	State Water Project (SWP)
Base Year (1976 based on 1961-1990)	base	base
Estimates for 2050		
SRES-a2, GFDL (based on 2035-2064)	-15%	-11%
SRES-a2, NCAR/PCM (based on 2035-2064)	-7%	-10%
SRES-b1, GFDL (based on 2035-2064)	-11%	-11%
SRES-b1, NCAR/PCM (based on 2035-2064)	No Change	-1%
Estimates for 2100		
SRES-a2, GFDL (based on 2070-2099)	-31%	-27%
SRES-a2, NCAR/PCM (based on 2070-2099)	-14%	-7%
SRES-b1, GFDL (based on 2070-2099)	-20%	-19%
SRES-b1, NCAR/PCM (based on 2070-2099)	-8%	-4%

Progression of Subsidence. The ground surface elevations in the areas of the Delta and Suisun Marsh that have organic (peat) soils are expected to continue subsiding if current management practices are not altered. The DRMS analysis of subsidence has provided an analysis of the rates and amounts of subsidence both historically and projected into the future (see Subsidence TM [URS/JBA 2007d]). Subsidence rates are expected to decrease as the percentage organic content of the soil decreases (due to previous oxidation) and to increase with increasing future ambient temperatures. These effects largely counterbalance each other and the nominal subsidence for typical central Delta histosol is expected to be relatively constant at about 2.2 cm (0.9 inch) per year, until the organic content is largely depleted. An uncertainty band on this subsidence rate of +40 percent and –30 percent is stated. Subsidence rates in Suisun Marsh are expected to be much lower because land management practices. An example of the result is given in the subsidence map for 2100 in Figure 14-4. The Subsidence TM (URS/JBA 2007d) has similar maps for 2050 and 2200. Table 14-6 summarizes the medium expectation for future subsidence for the Delta and Suisun area with highly organic soils in terms of decreases in surface elevation and cumulative area-wide increases in accommodation space relative to 2005 sea level:

Table 14-6 Estimate of Future Subsidence Relative to 2005 for Delta and Suisun Marsh

Year	Expected Subsidence (ft)[c]	Accommodation Space Relative to 2005 Sea Level (maf)[b]	Accommodation Space Relative to 2005 Sea Level (% Increase)
2005[a]	Base case	1.97	base
2050	Up to 3+ feet	2.47	25%
2100	Up to 8+ feet	3.01	53%
2200	Up to 17+ feet	Not estimated	Not estimated

[a] 2005 values are interpolated using 1998 values from the Subsidence TM (URS/JBA 2007d).

[b] maf = million acre feet

[c] Values shown above, apply only to areas with that thickness of peat/organic deposits or thicker. Other areas with less peat available will be limited by their peat thickness.

Note that these estimates of accommodation space are based only on progression of subsidence. Additional accommodation space increases will also result due to increases in mean sea level.

Changes in the Frequency of Seismic Activity. The time-dependent hazard curves developed as part of the probabilistic seismic hazard analysis (see the Seismology TM [URS/JBA 2007a]) were used to estimate the likelihood of peak ground accelerations (PGA) for the future analysis years: 2050, 2100, and 2200. Table 14-7 presents the expected frequency of a 0.20g PGA event in 2005 and future years, and also shows the percentage frequency increase over 2005 (base year).

Table 14-7 Estimated Mean Annual Frequencies of 0.20g PGA Events at Sherman Island

Year	Frequency	% Increase Over 2005
2005	1.7×10^{-2}	base
2050	1.9×10^{-2}	10%
2100	2.0×10^{-2}	20%
2200	2.4×10^{-2}	40%

The assessment of the future seismic hazard is based on the assumption that a major seismic event does not occur on one of the major Bay Area faults between now and the future evaluation years (2050, 2100, and 2200). As a result, tectonic strains are not released. Instead, they keep building, thus increasing the expected frequency of earthquakes or the magnitude of resultant ground motions when the earthquake finally occurs.

Changes in Inflow Flood Frequency. Flood frequencies (high Delta inflows) are expected to increase due to the regional impacts of global warming, occurrence of more winter precipitation as rain rather than snow, and more frequent occurrence of high intensity precipitation events. Expected changes in runoff patterns due to a warming climate are described in Climate Change TM (URS/JBA 2008b). Although the total amount of yearly precipitation may not change substantially, increases in winter precipitation as rainfall rather than snow and increasing frequencies of large storm events are predicted. The climate change team was able to provide four different scenario/simulations of daily, unimpaired runoff at key sites tributary to the Delta. These data were analyzed by the DRMS flood hazard team to quantify the trends in the frequency of major storms. Although the results vary among the four simulations (see the Flood Hazard TM [URS/JBA 2008a]), each indicates increasing frequencies of the seven-day Delta inflow representing the year-2000 one percent annual frequency (i.e., 100-year) flood event as indicated in Table 14-8. The results indicate occurrence of present day 100-year floods 1.35 to 6.0 times as often in 2050 and 2.3 to 12.4 times as often in 2100, substantially increasing Delta levee risks.

Table 14-8 Median Probability of Exceedance of Year 2000 1 Percent Annual Frequency Delta Inflow Floods

Scenario[a]	Year 2000	Year 2025	Year 2050	Year2075	Year 2100
SRES-b1, GFDL	0.01	0.010	0.017	0.020	0.023
SRES-b1, NCAR	0.01	0.018	0.060	0.092	0.124
SRES-a2, GFDL	0.01	0.014	0.027	0.030	0.034
SRES-a2, NCAR	0.01	0.010	0.014	0.031	0.048

[a] See the Flood Hazard TM (URS/JBA 2008a) for a description of the scenarios.

Changes in Delta Area Population, Land Use, and Economic Activity. The forecasts for Delta area population and land use under current policies foresee infill in present Primary Zone communities and intensive development in the Secondary Zone of the Delta (URS 2007; URS/JBA 2007f [Impact to Infrastructure TM]; URS/JBA 2008f [Economic Consequences TM]). Thus, the people, material assets, and economic activity located in the Delta and Suisun Marsh that will be exposed to future levee failures and flooding are expected to increase. This increased exposure in the event of levee failure contributes to increased risk.

Population – Data and projections of Delta area population are difficult to obtain because they are typically developed for smaller or larger geographic areas. However, available data reported in the DRMS “Status and Trends” report (URS 2007) indicate that the population on Delta and Suisun Marsh islands is expected to increase from 26,000 to 67,000 from 2000 to 2030 -- that is to about 260 percent. In other words, there will be 2.6 times as many people living on Delta and Suisun Marsh islands in 2030. Similarly, the six-county area that encompasses the Delta and Suisun Marsh is projected to have 2.3 times as many people in 2050 as were resident in 2000. The population of the legal Delta in 2000 was about 470,000. The “Status and Trends” report provides an estimated population increase for Delta-Suisun of 600,000 people by 2050. Thus, it is estimated that full development of the Secondary Zone could lead to a population of over a million people. Given the above, Table 14-9 provides estimates of Delta population for the specific years of interest compared with the 2000:

Table 14-9 Population Forecasts for the Delta and Suisun Marsh

	Delta–Suisun Marsh Islands	Legal Delta
2000	26,000	470,000
2030	67,000	Not Available
2050	Not Available	1,070,000
2100	Not Available	Not Available

These estimates of future population are very uncertain but no quantitative characterization of the uncertainty is available. For the secondary Delta zone, where areas are also protected from large floods by Delta levees, there may be a population increase of more than 120 percent by 2050. But a small change in expected subdivision development could mean many more or many less new people. For example, housing units on Stewart Tract, Bishop Tract, Shima Tract and Sargent Barnhart Tract are expected to increase from 1,700 to 14,200 units between 2000 and 2030, a localized increase of over 800 percent. State and local agencies do not have population projections beyond 2050. However, under BAU policies, there is no indication that the population growth rates given for Delta islands and the surrounding Secondary Zone will decrease substantially until all the available land is developed. In absence of changed development policies a continuing increase beyond the 2050 populations appears to be a reasonable working assumption in looking toward 2100.

Infrastructure and Public and Private Property – The analysis in the Impact to Infrastructure TM (URS/JBA 2007f) provides an assessment of assets subject to flooding from levee failures keyed to both MHHW and the 100-year flood plain. Their assessment is summarized below.

For 2050 conditions, the MHHW and 100-year flood asset values subject to flooding are expected to increase by about 20 percent to 25 percent.

For 2100 conditions, in addition to continuation of normal asset growth, both the MHHW and 100-year flood exposures are expected to cover increased areas because of sea-level rise and the increasing magnitude of the 100-year flood. Some of the additional areas that will be exposed to flooding are now highly developed urban areas or are in the path of urban development. There is no indication these development trends will change under BAU policies.

Business Activity – Business activity is usually counted by value of output, employment and labor income. Table 14-10 shows year 2000 and 2030 business activity for the State and for selected Delta region economies. In general, the Delta region is expected to grow faster than the State. Between 2000 and 2030 gross regional product and earnings are expected to double and

Table 14-10 Economic Indicators for California and Delta Regions, 2000 and 2030

	Regional Product			**Earnings**			**Employment**		
	Billions 2005 $			**Billions 2005 $**			**(Thousands)**		
Region	**2000**	**2030**	**% Inc**	**2000**	**2030**	**% Inc**	**2000**	**2030**	**% Inc**
California	$1,443	$2,804	94	$977	$1,831	87	19,626	28,924	47
Combined Statistical Areas									
Sac-Arden	$73	$191	161	$49	$125	152	1,141	2,081	82
Stockton	$15	$29	101	$10	$19	95	259	388	49
Vallejo-Fairfield	$10	$22	130	$6	$14	124	160	273	70
Counties									
Contra Costa Co	$37	$81	122	$25	$53	114	478	769	61
Sacramento Co	$50	$130	161	$34	$85	152	729	1,318	81
San Joaquin Co	$15	$29	101	$10	$19	95	259	388	49
Solano Co	$10	$22	130	$6	$14	124	160	273	70
Yolo Co	$7	$15	130	$4	$10	123	108	177	64

Woods and Poole 2006.

employment is expected to increase by 50 to 80 percent. There is no useful projection for economic activity after 2030; however, business activity is expected to continue growing with population.

Business sales by Delta island and Suisun Marsh businesses that are located below the MHHW were about $3 billion in 2000. Agriculture, natural gas production and recreation are important economic activities in the primary Delta. The Department of Water Resources estimates the annual value of Delta agricultural production over the 1998 to 2004 period averaged $680 million in 2005 dollars. Average annual value of natural gas production in 2004 and 2005 was over $300 million. Natural gas and agricultural production values will probably not increase significantly in the future. Recreation-related expenditures in the Delta were recently estimated to be over $500 million annually. These recreation expenditures will probably increase in the future with population in the Delta and the larger Bay Area region. Economic activity tied to residential development will increase dramatically by 2030 on some Delta islands near Stockton and can be expected to continue increasing thereafter.

Changes in Regional and State Population and Economic Activity. Available forecasts indicate continuing population and economic growth for the Delta and Bay regions and for the state as a whole. This will result in an increased dependence on infrastructure that traverses the Delta and especially on the water supplies that are conveyed through the Delta (URS 2007; DWR 2005a; URS/JBA 2008f [Economic Consequences TM]).

Population **–** The California Department of Finance (DOF 2007b) provides state population projections to 2050. They estimate 59.5 million people will reside in California by that date, a 61 percent increase over the 2005 base year. Official DOF projections are not available beyond 2050. Table 14-11 summarizes available projections, including one provided in “Status and Trends” for 2100. The uncertainties in future state population are quite large, but not quantified.

Table 14-11 Estimated Future California Population

Year	Population (million)	Percent Increase Over 2005	Source
2005	37.0	base	DOF 2007
2050	59.5	61%	DOF
2100	90	143%	URS 2007

Economic Activity **–** Economic activity is closely tied to population growth. Historical data are available from DOF (2007a). As with population, official projections are not available for the long term. The state DOF provides forecasts through 2010 (DOF 2007b). Table 14-10 presents available projections to 2030 by Woods and Poole (2006). They show an expected 94 percent increase in gross state product from 2000 associated with an expected population increase of 41 percent.

Based on the above input information that is available, the scenarios to be analyzed quantitatively are defined in Tables 14-12 for 2050 and 14-13 for 2100. If no quantitative input information is available for the particular year of interest, the analysis will use the next earlier estimate that is available.

Table 14-12 Risk Analysis Scenario for 2050

Variable	Low Risk Scenario	Medium Risk Scenario	High Risk Scenario
Sea-level rise	11 cm (4.3 inches)	20 cm (7.9 inches)	41 cm (16.1 inches)
Accommodation Space Due to Sea-level rise[a]	0.09 MAF (+4.7%)	0.17 MAF (8.7%)	0.35 MAF (+17.7%)
Water Supply Yield	-1%	-10%	-13%
Subsidence (Accommodation Space)	0.35 MAF (+13%) 2.1 ft	0.5 MAF (+19%) 3 ft	0.7 MAF (+27%) 4.2 ft
Seismic Frequency	+10%	+10%	+10%
Flood Frequency	+35%	+194%	+500%
In-Delta Population	+128%	+128%	+128%
In-Delta Economics	Unknown	Unknown	Unknown
State Population	61% Increase	61% Increase	61% Increase
State Economy[b]	94% Increase	94% Increase	94% Increase

[a] The part of the Delta–Suisun Marsh area that is below sea level is about 260,000 acres.
[b] Woods and Poole estimate for 2030.

Table 14-13 Risk Analysis Scenario for 2100

Variable	Low Risk Scenario	Medium Risk Scenario	High Risk Scenario
Sea-level rise	20 cm (7.9 inches)	90 cm (35.5 inches)	140 cm (55.1 inches)
Accommodation Space Due to Sea-level rise[a]	0.17 MAF (+8.7%)	0.77 MAF (39%)	1.19 MAF (+61%)
Water Supply Yield	-6%	-15%	-29%
Subsidence (Accommodation Space)	0.73 MAF (+35%) 5.6 ft	1.04 MAF (+51%) 8 ft	1.46 MAF (+71%) 11.2 ft
Seismic Frequency	+20%	+20%	+20%
Flood Frequency	+130%	+458%	+1,140%
In-Delta Population	Unknown	Unknown	Unknown
In-Delta Economics	Unknown	Unknown	Unknown
State Population	143% Increase	143% Increase	143% Increase
State Economy[b]	Unknown	Unknown	Unknown

[a] The part of the Delta–Suisun Marsh area that is below sea level is about 260,000 acres.
[b] Woods and Poole estimate for 2030.

14.3.3 Details on Changing Risk Factors as They Progress Through the Risk Model and Become Consequences

An assessment is presented below of future year risks based on the quantitative input information in the above tables. The assessment generally follows the conceptual model presented in Figure 14-3 and the branches visible in the logic tree of Figure 14-7. Sunny-day/high-tide events, seismic events and floods are addressed separately and the risk results are then combined.

14.3.3.1 Sunny-Day Risk Assessment

Sunny-Day Failure Frequency. Sea-level rise will directly influence the stage versus frequency curve for every Delta location under tidal influence and, thus, the frequency of sunny-day, high-tide failures. A given Delta levee has a fragility (conditional probability of failure) that is related to its hydraulic head. Table 14-14 calculates the increased probability of failure (higher gradients) as a result of sea-level rise. The increased probability of failure relates to the exit gradient. The higher the gradient, the higher the probability of failure (see Section 7.0).

Table 14-14 Effects of Sea-level Rise on Sunny-Day Failures

Year/Scenario	Sea-level rise (feet)	Increase in Probability of Failure (%)
2050 Low Risk	0.36	2.3
2050 Medium Risk	0.66	4.2
2050 High Risk	1.34	8.5
2100 Low Risk	0.66	4.2
2100 Medium Risk	2.96	18.7
2100 High Risk	4.59	29.0

Accordingly, Table 14-15 indicates the subsidence induced hydraulic head increases and their effect on sunny-day, high-tide fragilities. The increased head from subsidence will occur only in areas with highly organic soil that happen to be within the “zone of influence” for the levee. This will increase the vulnerability of these levees to failures caused by under-seepage and through-seepage.

Table 14-15 Effects of Subsidence on Sunny-Day Failures

Year/Scenario	Subsidence (feet)	Increase in Probability of Failure (%)
2050 Low Risk	2.1	13
2050 Medium Risk	3.0	19
2050 High Risk	4.2	27
2100 Low Risk	5.6	35
2100 Medium Risk	8.0	51
2100 High Risk	11.2	71

Expected Increases in Sunny-Day Failures. Since the above drivers directly affect the hydraulic head, they are additive to the overall increase in levee fragility and hence to the probability of failure, as shown in Table 14-16.

Table 14-16 Percent Increased Frequency of Sunny-Day, High-Tide Breaches Under BAU

Year	Low Risk Scenario	Medium Risk Scenario	High Risk Scenario
2050	16%	23%	35%
2100	40%	61%	100%

14.3.3.2 Seismic Risk Assessment

Seismic Hazard. Per Tables 14-12 and 14-13, the frequencies of seismic events will increase relative to 2005 – by 10 percent in 2050 and 20 percent in 2100.

Seismic Fragility. Sea-level rise and increased subsidence will combine to increase the effective hydraulic head on levees by about 4 feet (+/-) in 2050 and nearly 10 feet (+/-) in 2100 compared with 2005 conditions and hence reduce the stability of the levee by the amounts shown in Table 14-16.

Frequency of Seismic Flooding. The resulting increase in probability of island flooding from higher frequency seismic events is compounded by the increase in of the conditional probability of failure (levee fragility) producing the results shown in the Table 14-17.

Table 14-17 Percent Increased Frequency of Seismic Breach Events Under BAU

Year	Low Risk Scenario	Medium Risk Scenario	High Risk Scenario
2050	28%	35%	49%
2100	68%	93%	140%

14.3.3.3 Flood Risk Assessment

Flood Hazard. Per Tables 14-12 and 14-13, inflow flood frequencies equal to or exceeding the 2005 100-year flood (i.e., present frequency of 0.01/year) are expected to increase dramatically – from a 40 percent minimum increase (2050, low value) to 1,140 percent maximum increase (2100, high value). Other severe inflow flood frequencies are also expected to increase in similar ways but with somewhat different numbers. The key need for assessing the implications of these frequency changes is to have revised normal stage versus frequency curves at various points in the Delta that reflect future tides, sea-level rise, and today’s floods. The present day 0.01 frequency/year flood (the Standard Flood) occurs on the historical stage frequency curve – likely somewhere between the 0.01 and 0.02 frequency points because the curve may reflect extreme tides. Table 14-18 presents the percentage increase in frequency of inflow events, namely the 2005 1 percent flood (i.e., the Standard Flood used as representative for increased future flood frequency).

Flood Fragility. For levees that would not overtop, the conditional probability of levee failure is a function of remaining freeboard, but also considering hydraulic head and its influence on under-seepage and through-seepage. The hydraulic head will increase in the future due to sea-level rise and the progression of subsidence as shown in Table 14-16. Obviously, levees will overtop more frequently if not raised to keep up with increases in sea level.

Frequency of Inflow Flood Breaches. The resulting frequency of island flooding from high inflow events is expected to increase according to the Table 14-18, which combines the alterations to the flood frequency curves and the altered fragility curves due to subsidence and sea-level rise. Note that these frequency increases do not include overtopping. Raising levees to keep up with sea-level rise is assumed.

Table 14-18 Percent Increased Frequency of High Inflow Breach Events Under BAU

Year	Low Risk Scenario	Medium Risk Scenario	High Risk Scenario
2050	241%	261%	297%
2100	681%	798%	1016%

The number of digits do not represent accuracy in the results; they are simply the outcome of the calculations.

14.3.3.4 Emergency Response and Repair

Major changes in Delta levee damage response and repair technology are not expected. Availability of marine resources for levee repair is unpredictable, but is assumed not to change markedly. Availability of repair material in future years could be a major concern, since reliance is currently placed on obtaining rock from the San Rafael Quarry. Its unique advantage is its marine loading facilities. If this quarry were to close, exhaust its reserves or be unavailable for other reasons, the ability to repair Delta levees may be compromised and prolonged. These potential impacts have not been quantified.

14.3.3.5 Salinity Response

Hydrodynamics and salinity in the Delta are expected to change in future years both during normal operations (without levee breaches) and when levee breaches occur. In normal BAU operations (without levee breaches), sea-level rise will increase the driving forces (gravitational mixing and dispersion) for intrusion of saline water into the Delta (see the Water Analysis Module TM, Appendix H3 [URS/JBA 2007e]). Figure 14-8 provides an indication of the present-day salinity and the additional salinity intrusion that can be expected from 90 cm of sea-level rise (slightly less than 3 feet), assuming that today’s normal summer flows are maintained. (Note that 1 practical salinity unit is about the same as 1 part per thousand.) This intrusion of salinity will require an increase in Net Delta Outflow to repulse salinity and meet BAU water quality standards.

The increase in the Net Delta Outflow has been estimated at about 7 percent of the present typical summer season outflow in 2050 (for 1 foot of sea-level rise) and 20 percent of typical summer outflow in 2100 (with 2.5 feet of sea-level rise). This increase in outflow will combine with the reduced availability of upstream reservoir inflow to decrease reservoir storage and the yields of the SWP and the CVP. In addition, the decrease in reservoir storage reduces the water that will be available when a levee breach occurs.

When a levee breach occurs, the volume of water that floods the island(s) will increase over conditions today because of subsidence and higher sea level. Table 14-19 details the increased volumes under various future year scenarios. This increased flooding volume will be saline water intruding from the Bay, except in major floods. In addition, the increased dispersive forces mentioned above will be active. Salinity will intrude farther into the Delta. More water and more time will be required to complete repairs, repulse the salt, and reestablish Delta water quality, but less water will be available for this purpose. Thus, recovery times will increase.

Table 14-19 Increased Island Flooding Volumes Due to Subsidence and Sea-Level Rise

Year/Scenario	Increased Volume Due to Subsidence (%)	Increased Volume Due to Sea Level (%)	Increased Volume Total (%)
2050 Low Risk	17	4.7	22
2050 Medium Risk	25	8.7	34
2050 High Risk	35	17.7	53
2100 Low Risk	36	8.7	45
2100 Medium Risk	53	39	92
2100 High Risk	71	61	132

With higher sea level, more Delta outflow will be needed to repel the salinity and maintain Delta water quality (see the Water Analysis Module TM [URS/JBA 2007e, Appendix H3]). This will compound the reductions in water supply yield due to climate change. For smaller events (three flooded islands or fewer) until 2050, the modest Delta recovery times calculated for 2005 will remain modest, although they will increase. For somewhat larger events in 2050, Delta recovery times of several months will increase noticeably. For larger events (20 or 30 flooded islands), changes in Delta recovery times will be more strongly impacted by less water availability upstream in normal and dry years. Management and recovery from levee breach events that are now calculated to require several years may simply have to wait for one or more wet years to renew freshwater conditions in the Delta. In 2100, the same pattern of change will occur, with larger impacts on the time required for Delta recovery. Estimates of recovery period increases are provided below in Table 14-20. These estimates are quite sensitive to the amount of sea-level rise.

Table 14-20 Salinity Impacts

Year/Scenario	Extra NDO (%)	Less Water Supply (%)	Increased Flood Volume (%)	Recovery Time Increase (%)
2050 Low Risk	0	-1 - 0 = -1	22	5
2050 Medium Risk	1	-10 - 1 = -11	34	15
2050 High Risk	9	-13 - 5 = -18	53	25
2100 Low Risk	1	-6 - 1 = - 7	45	20
2100 Medium Risk	22	-15 - 15 = -30	92	60
2100 High Risk	33	-29 - 20 = -49	132	100

NDO = Net Delta Outflow

14.3.3.6 Potential Loss of Life

The number of people exposed to injury or loss of life due to island flooding is taken as the population of the Delta and Suisun Marsh. Increases in future years are calculated based on the increased population and the increased frequency of flooding. The only estimate of future population increase for the Delta and Suisun Marsh is 128 percent by 2050. The increase in the loss of life is calculated as directly proportional to the increase in population.

14.3.3.7 Economic Losses

For large events, the economic cost and impacts to the state dominate the measure of economic losses. Thus the percentage increase in economic losses will be based on the increase in state population and the increase in recovery time required relative to salinity. The state population is expected to have increased by 61 percent in 2050 and 143 percent in 2100.

14.3.4 Combined Risk Consequences in Future Years

The combined effect of the changes for future years of the factors discussed in the foregoing sections is presented below, by addressing sunny-day, high-tide events, seismically initiated events, and floods. The relative importance of risk factors to future changes for each of these types of failure events is illustrated in the tables identified below, and in Figures 14-9 and 14-10.

Sunny-Day High-Tide Failures. The effects of sea-level rise and subsidence will increase the vulnerability of the levees and their probability of failure. The combined effects of higher probability of levee failure and the increased consequences are shown in Table 14-21. Based on 2005 conditions, single levee breaches such as these were found to not have significant impacts beyond on-island flooding and repair costs. The largest island, if flooded, had a salinity recovery period of less than 90 days in the worst case. In the future, if such breaches occur one island at a time and are quickly repaired, the extended impacts are unlikely to increase in a substantial way. However, if sea-level rise causes such events to occur on two to four islands at a time, and causes additional salinity intrusion as well, impacts will escalate as indicated in Table 14-21.

Table 14-21 Expected Increase in Sunny-Day Risk in Future Years Over 2005

Risk Factor	*2050*			*2100*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Frequency of Island Flooding[a]	16%	23%	35%	40%	61%	100%
Potential Loss of Life	164%	180%	207%	N/A	N/A	N/A
Expected Economic Losses	136%	174%	227%	226%	400%	676%

Seismic Levee Breach Events. For the future years 2050 and 2100, the seismic risk factors are expected to increase approximately as indicated in Table 14-22. The risk of island flooding (hazard and levee fragility) increases modestly. The more significant increases are expected to be from impacts on in-Delta resources (population, property, ecosystem) and the statewide impact of salinity intrusion on the statewide population and economy, as indicated in Table 14-22.

Table 14-22 Expected Increase in Seismic Risk in Future Years Over 2005

Risk Factor	*2050*			*2100*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Seismic Hazard	10%	10%	10%	20%	20%	20%
Frequency of Island Flooding[a]	28%	35%	49%	68%	93%	140%
Potential Loss of Life	229%	249%	283%	N/A	N/A	N/A
Expected Economic Losses	160%	202%	260%	291%	500%	831%

[a] Increased frequency in island flooding reflects increased hazard and fragility.

Flood-Induced Levee Breach Events. The climate change shift to more frequent major floods will substantially increase future flood risk. The freshwater inflow from the floods will generally prevent immediate salinity intrusion, but long levee repair periods may present problems in subsequent periods of low flow. However, export disruptions have been capped in Table 14-23. Large in-Delta impacts from additional flooding are expected, due especially to increased population and development and increased pressure on the ecosystem. The primary driver of escalating impacts is the increased frequency of flooding. Economic loss escalations have been estimated based on Delta population growth (therefore, life loss and economic impacts are the same).

Table 14-23 Expected Increase in Flood Risk in Future Years Over 2005

Risk Factor	*2050*			*2100*		
	Low	*Medium*	*High*	*Low*	*Medium*	*High*
Flood Hazard	35%	194%	500%	130%	458%	1140%
Frequency of Island Flooding[a]	241%	261%	297%	681%	798%	1016%
Potential Loss of Life	676%	723%	803%	N/A	N/A	N/A
Expected Economic Losses	676%	723%	803%	NA	NA	NA

[a] Increased frequency in island flooding reflects increased hazard and fragility.

The assumptions and limitations associated with this work are discussed in Section 15. The executive summary provides an overall summary of the key findings and observations.

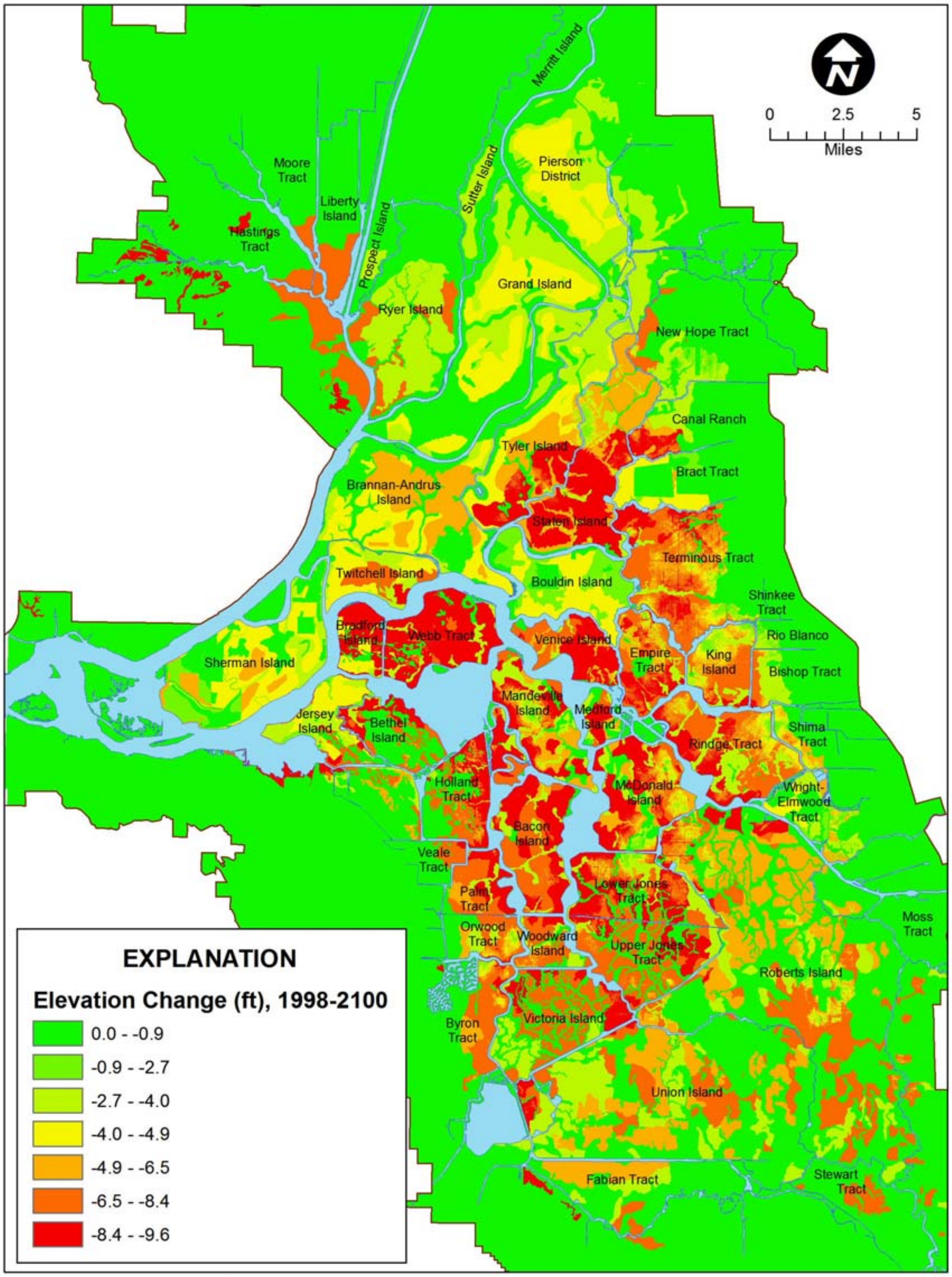


Figure 14-4 Additional Subsidence 1998 to 2100

Figure 14-5 Oroville Changes in Monthly Runoff Pattern (One of Four Simulations; SRESa2, gfdl).

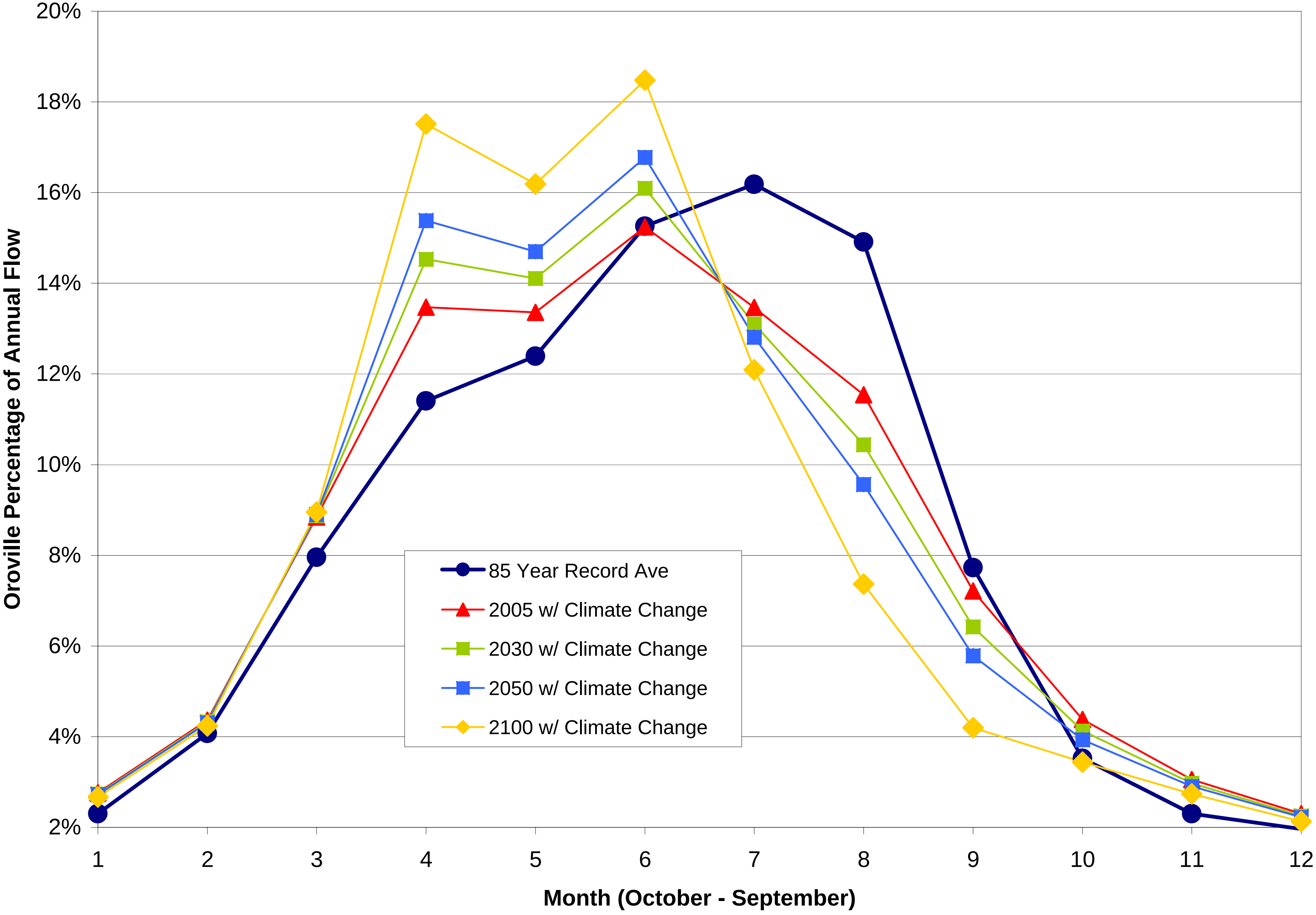
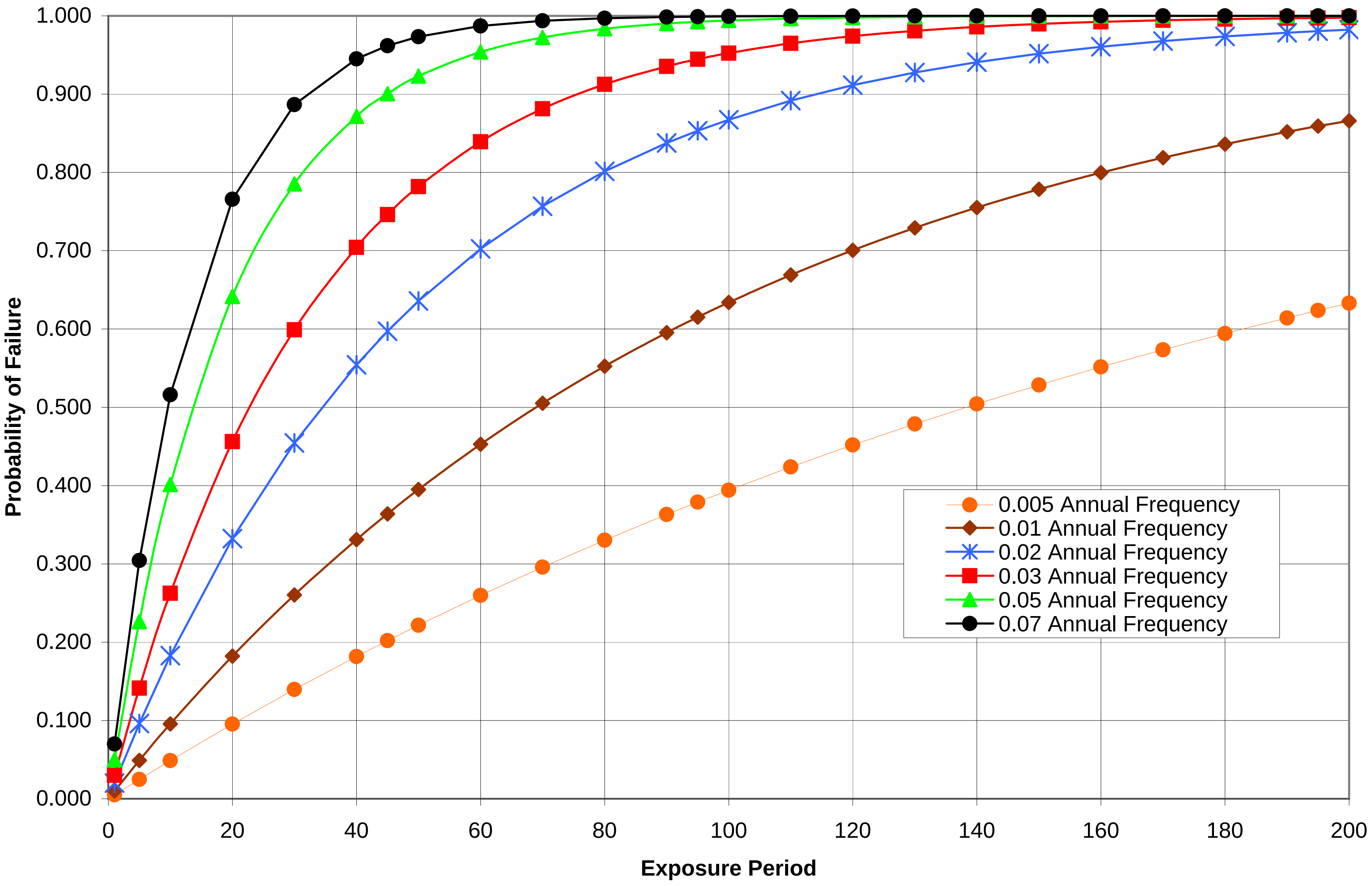


Figure 14-6 Failure Probability Versus Exposure Period



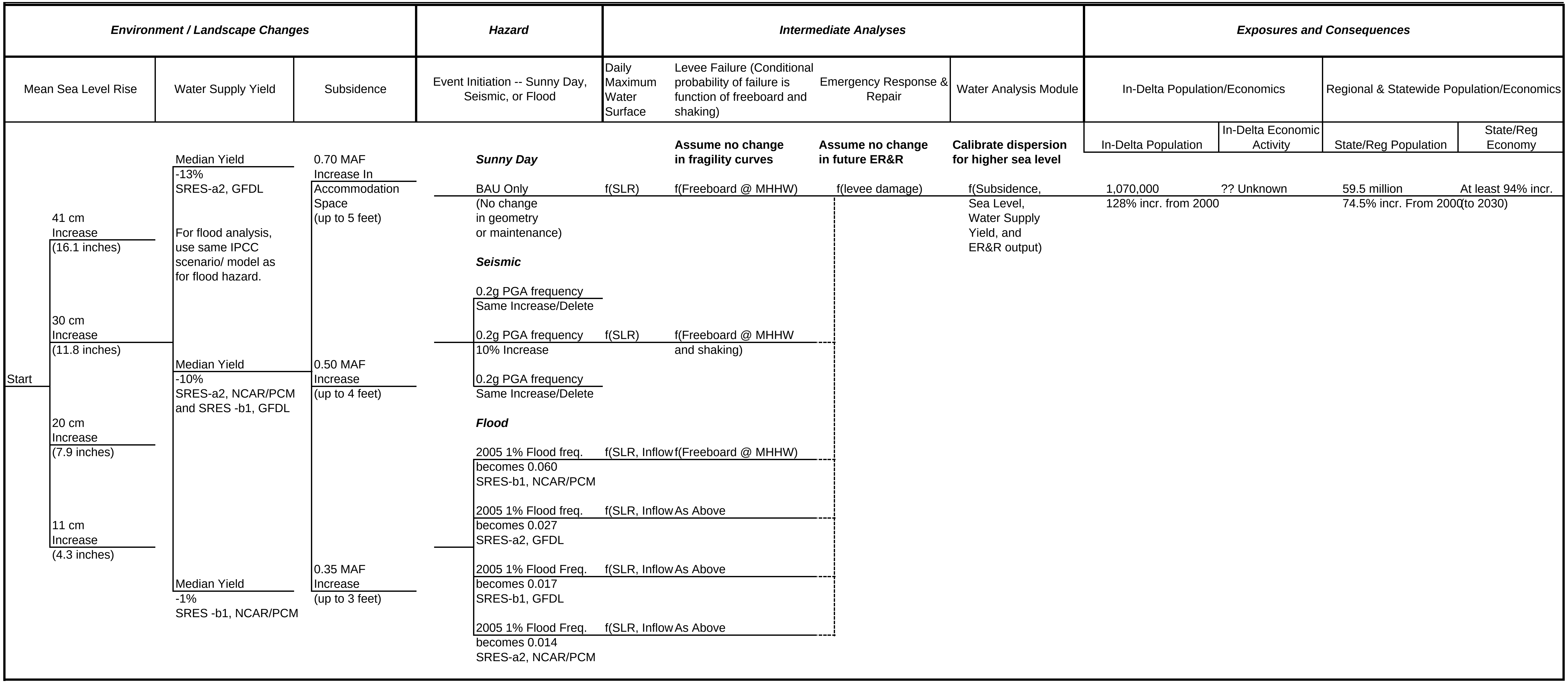


Figure 14-7 Logic Tree for Future Year Risk Analysis -- 2050

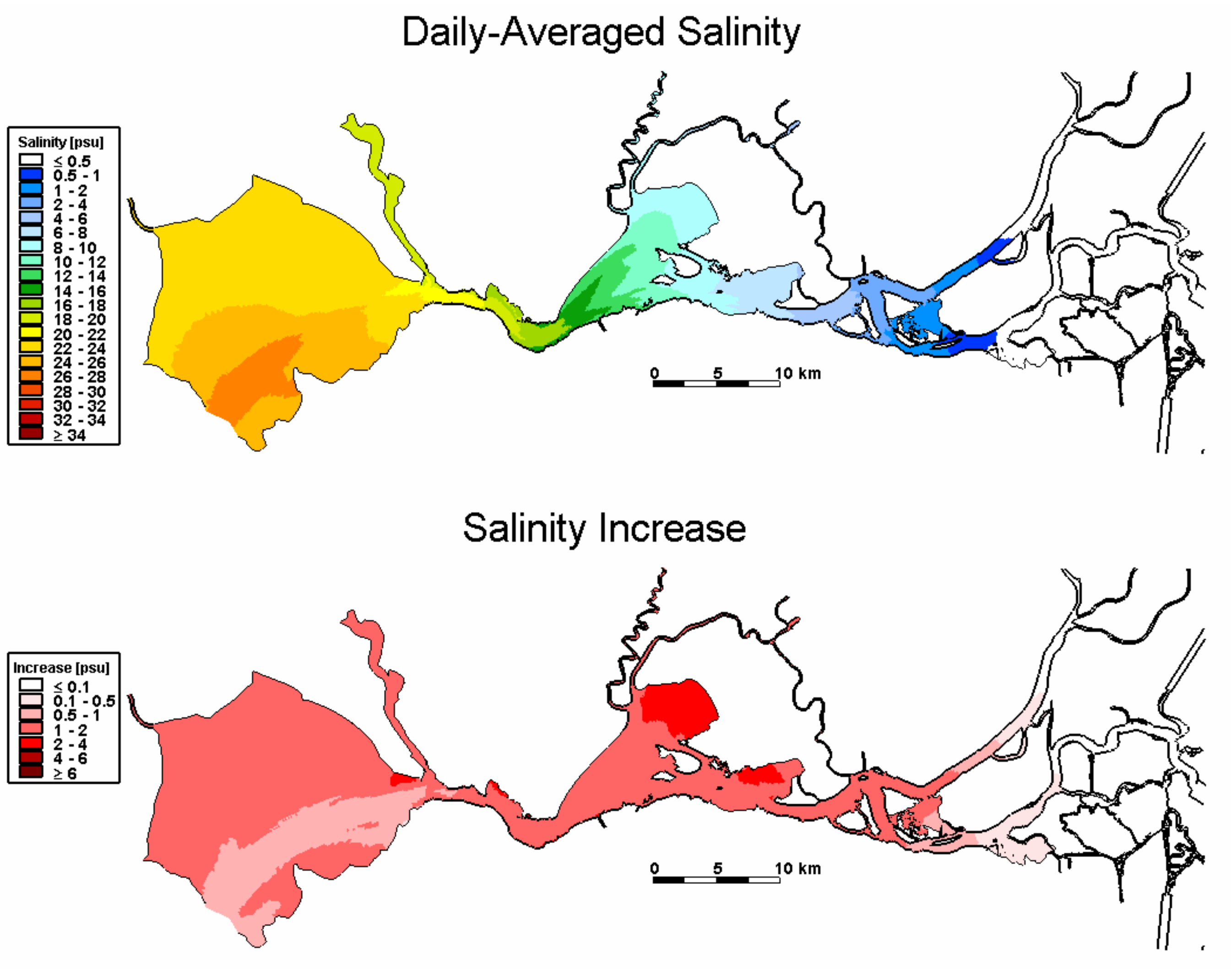


Figure 14-8 Depth-averaged and tidally averaged salinity at tidally averaged steady-state conditions for the 90 cm MSL rise and increase in salinity relative to the baseline scenario

Figure 14-9 Risk Factor Ratios for 2050

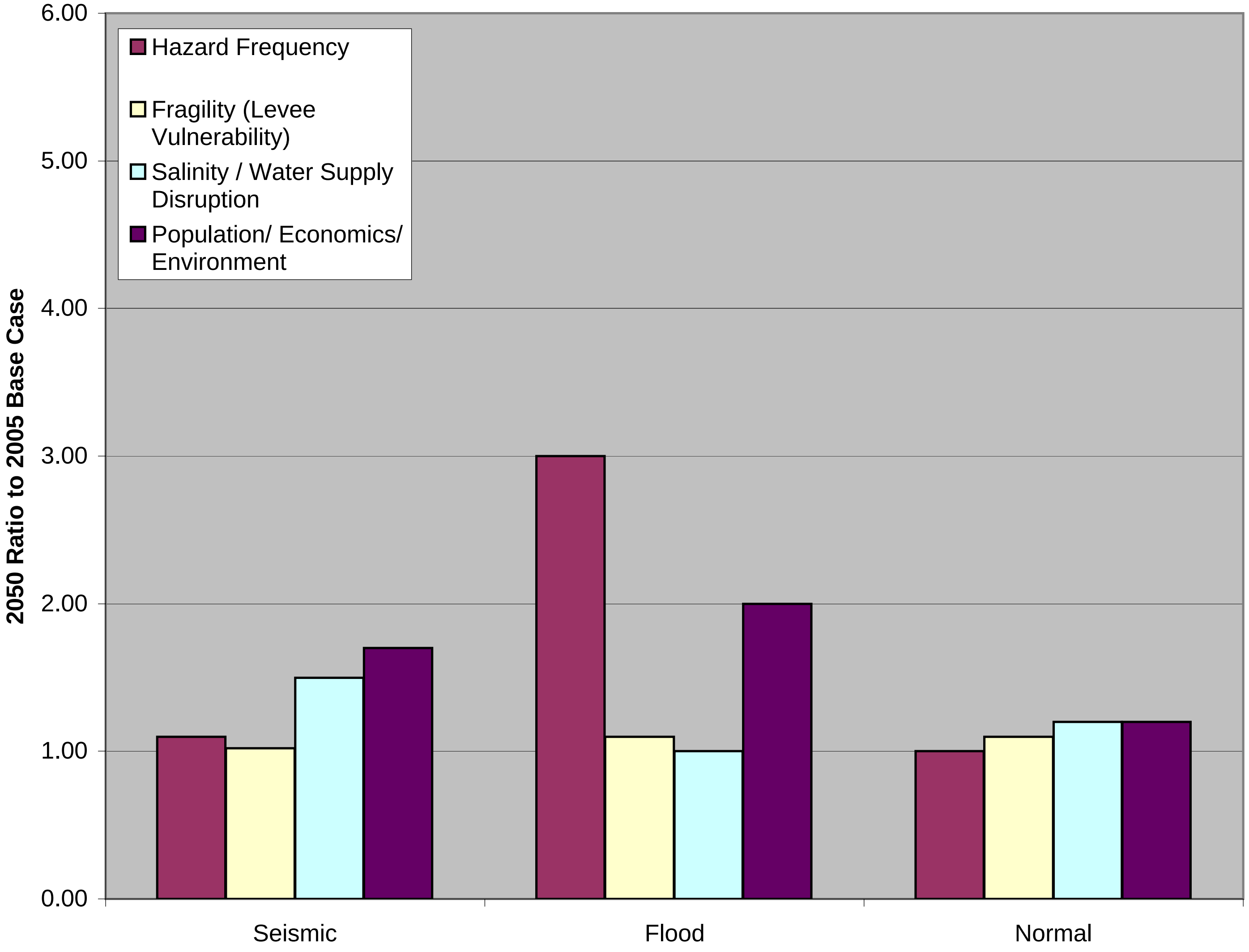


Figure 14-10 Risk Factor Ratios for 2100