The previous section presented risk analysis results associated with Delta levee failures for 2005 base conditions. For purposes of looking ahead to support policy makers, stakeholders, and the DRMS partners, an assessment of how risks may change in future years is required. The focus on future risks has various dimensions:

1. The changing landscape of the Delta due to climate change and subsidence alter the likelihood of levee failures.
2. The likelihood of natural hazards (such as earthquakes or floods) occurring and compromising the integrity of levees is expected to increase in the future.
3. The consequences of levee failures change with time. With development in the Delta and the state as a whole, and reliance on water exports from the Delta, the exposure to the effects of levee failures will also increase. The salinity impact of a given levee failure will increase due to the changing landscape (subsidence, sea level rise, and decreased availability of water supply due to decreased snowpack). The ecosystem will experience increased pressure and sensitivity when levee failures occur in the future.

As a separate factor, risks escalate with longer exposure periods. That is, the risk (the probability of adverse consequences of concern) increases as the number of years considered increases. Thus, risks may look tolerable if one is only considering the next year. But risks are much greater if one considers a number of years into the future, -- say the next fifty, one hundred, or two hundred years.

There are two factors to consider when evaluating future years – (1) the likelihood that an event will occur in any future year is increasing and (2) the likelihood that an event will occur at least once over a number of years grows even higher.

In the case of the Delta and the state’s risk associated with levee failures, the increasing risk is compounded by the factors listed above which work together to increase the future probability of adverse consequences in the Delta. And, when an exposure period of several years is also considered, the likelihood of an unwelcome event becomes high.

As discussed in Section 4, information is not available to conduct a comprehensive analysis of future risks. However, information is available to estimate the relative increase in risks with respect to the 2005 base case results. The purpose of this chapter is to present the analysis of these potential increases.

## 14.1 CHANGING RISK FACTORS

To consider the changing risks in the Delta and Suisun Marsh, there are factors that have large-scale temporal and/or spatial impacts that may influence future risks. In this analysis, 2005 is used as the base year. This analysis estimates how risks may change relative to 2005 in future target years of 2050, 2100, and 2200. The conditions evaluated are business-as-usual (BAU) – circumstances that are a continuation of existing management practices (see Section 3.4).

Risks factors can change dramatically with location within the Delta and Suisun Marsh. Rather than estimating 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 estimates, recognizing that changes for specific areas may be somewhat different from the regional scale assessment presented.

There is, as discussed in the technical memoranda (TMs), considerable uncertainty 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 the analysis of future risks, the evaluation considers best or medium estimates. More detailed information on the respective topics, including ranges of estimates and uncertainties are provided in the TM for each topical area.

### 14.1.1 Environmental/Landscape Changes

Relative to 2005 conditions, the Delta's future environment/landscape may change in significant ways. These include:

**Subsidence –** The DRMS analysis of subsidence has provided an analysis of the rates and amounts of subsidence both historically and projected into the future. An example of these findings is given in the subsidence map for 2100 (Figure 14-1). The subsidence TM has similar maps for 2050 and 2200. To summarize, the following characterizes a medium expectation of future subsidence for the Delta and Suisun area:

- 2050 Conditions – Approximately 3 feet of additional subsidence is expected in areas with highly organic soils under BAU conditions. This will constitute an increase in below-sea-level accommodation space (in absence of sea level rise) of approximately 20 percent compared with the 2005 base case.
- 2100 Conditions – Approximately 6 feet of subsidence beyond 2005 is expected in areas with highly organic soils under BAU conditions. This will result in a total increase in below-sea-level accommodation space (not considering sea level rise) of approximately 40 percent compared with 2005.

**Climate Change (sea level rise) –** The DRMS analysis of climate change considered the recent scientific work on sea level rise and recommended four different projections (encompassing a substantial range). From these projections, the following characterizes a medium expectation for future years:

- 2050 Conditions – Approximately one foot of sea level rise should be expected above the 2005 base case.
- 2100 Conditions – Approximately 2.5 feet of sea level rise should be expected above the 2005 base case.

**Climate Change (seasonal change of runoff) –** The DRMS analysis includes a review of recent studies regarding the changing seasonal pattern of runoff, including additional sample analyses of climate change model simulations for inflows to Shasta and Oroville. The details of these reviews and analyses and their implications for future water supply availability are presented in the WAM TM. Briefly, the warming climate is expected to continue causing more winter precipitation to occur as rain rather than snow. The decrease in snowpack and its earlier melting is expected to decrease spring and summer runoff into the state's water supply reservoirs, as illustrated in Figure 14-2. This will decrease the yield of the present water supply system. The following characterizes the medium expectation for future years:

- 2050 Conditions – For both Oroville and Shasta, available climate simulations, though variable, indicate approximately a 10% decrease in April through June inflow compared with 2005. This loss of snowpack runoff combined with other runoff changes, has been estimated to result in approximately a 7% decrease in State Water Project median yield and approximately a 10% decrease in Central Valley Project south-of-Delta median yield, both compared with 2005.
- 2100 Conditions – For both Oroville and Shasta, available climate simulations, though variable, indicate approximately a 20% decrease in April through June inflow compared with 2005. This loss of snowpack runoff combined with other runoff changes, has been estimated to result in approximately a 15% decrease in SWP median yield and approximately a 20% decrease in CVP south-of-Delta median yield, both compared with 2005.

**Climate Change (higher temperatures) –** This aspect of climate change will have the additional effect of increasing evaporation and transpiration and thus water demand upstream and in the Delta. The increase in transpiration may be mitigated to some degree by decreases in transpiration due to increased atmospheric CO2. The overall additional impact on risks related to Delta levee failures is expected to be relatively minor.

**Climate Change (wind and waves) –** Climate change may cause changes in the winds that occur in the Delta region. Although this was considered, there is no clear evidence to indicate whether winds will change, whether wind speeds will increase or decrease, nor what magnitudes of changes might occur.

**Climate Change (more frequent winter floods) –** This last manifestation of climate change, the increasing frequency of floods, is addressed below in the discussion of changing hazards.

### 14.1.2 Hazards

The hazards are forces that initiate levee failure events. Unfortunately, all the significant hazards that initiate levee failures are increasing with time. These hazards and their trends are:

**Seismic –** The time-dependent hazard curves developed as part of the probabilistic seismic hazard analysis were used to estimate the increase in likelihood of peak ground accelerations (PGA) for future years: 2050, 2100, and 2200. Those curves, presented in the Seismic Hazard TM, indicate the mean annual frequencies of exceedance of 0.20g PGA at Sherman Island, for the base year, 2050, 2100, and 2200, are $1.7 \times 10^{-2}$, $1.9 \times 10^{-2}$, $2.0 \times 10^{-2}$, and $2.4 \times 10^{-2}$ respectively. These increases can be summarized as follows:

- 2050 Conditions – The frequency of exceedance of 0.20g PGA will increase by 10% over 2005.
- 2100 Conditions – The frequency of exceedance of 0.20g PGA will increase by 20% over 2005.
- 2200 Conditions – The frequency of exceedance of 0.20g PGA will increase by 40% over 2005.

The assessment of the future increase in 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.

**Floods, Part 1 – Increased Frequency of Delta Peak Inflows –** The Climate Change TM describes the expected changes in runoff patterns due to a warming climate. 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, they can be summarized in terms of the medium expectation of increasing future flood frequencies as follows:

- 2050 Conditions – There will be approximately a 50% increase (over 2005 conditions) in the frequency of the total Delta inflow discharge that presently has an annual frequency of exceedance of 0.01 (i.e., the year 2000, 100-year flood). Therefore, a flood that can now be expected to occur about once in 100 years can be expected to occur once in about 67 years by 2050.
- 2100 Conditions – There will be approximately a 100% increase (over 2005 conditions) in the frequency of the total Delta inflow discharge that presently has an annual frequency of exceedance of 0.01 (i.e., the year 2000, 100-year flood). Therefore, a flood that can now be expected to occur about once in 100 years can be expected to occur once in about 50 years by 2100.

Another way to interpret this change is to recognize that the peak flows during large floods of a given frequency will increase. The larger the event, the larger the expected increase in flow above base year conditions. In 2000, the 50-year event has a peak Delta inflow of about 700,000 cfs. The peak inflow during a 50-year event is expected to increase to about 800,000 cfs in 2050 and to 900,000 cfs in 2100. The present 100-year event has a peak Delta inflow of about 900,000 cfs. The peak inflow during the 100-year event is expected to increase to about 1,100,000 cfs in 2050 and to 1,500,000 cfs in 2100. These increases of Delta inflow mean that floodwater surface elevations will increase, especially in the vicinity of major inflow tributaries. In turn, the areas impacted by a given frequency event (e.g., the 1 percent or 100-year flood) will increase and accurate 100-year flood plain maps will envelope a greater area.

**Floods, Part 2 – Increased Flood-Water Surface Elevations Due to Sea-Level Rise –** Increasing sea level will have a backwater effect on floodwater surface elevations that will lead to a rise in the stage caused by a given inflow. Water-surface elevations were compared to current crest elevations of individual islands to assess the potential for overtopping during floods for the base case (see Section 7). During the 100-year flood under present (base case) conditions, approximately twelve to eighteen Delta levee are expected to failures (See Section 13).

For this assessment of future conditions, the levee crests were initially assumed to be the same for both base and future years (i.e., no levee raises were included). This was the result of a main premise of the BAU definition – that state or federal funding for levee improvements would not be sufficient to increase levee crest elevations for the entire Delta and Suisun Marsh at a pace that keeps up with sea level rise. Assuming this definition of BAU conditions in the Delta, future sea level rise poses a major threat of island flooding. Analyses indicate that the majority of Delta islands would be flooded by levee overtopping with occurrence of the present 100-year flood and the 2.5 feet of sea level rise expected for year 2200. This result would be unacceptable and is therefore considered unrealistic.

Using a modified interpretation of BAU, all reclamation and levee districts are expected to perform some levee improvement in an attempt to keep up with sea level rise. However, funding shortages at all government level must be expected to lead to delays. Some levee maintaining agencies may be able to improvement levees adequately keep up with sea level rise for awhile and others would not. For the majority of the Delta, attempting to raise the levees may temporarily delay the effects of sea level rise, but is unlikely to prevent the effects in the long-term. Eventually, sea level rise will reach a level where it becomes too expensive to continue to raise the levees and more extensive overtopping by inflows must be expected. The following increase in overtopping represents a medium expectation for the same flood, due only to the change in sea level:

- 2050 Conditions – Approximately a 100% increase in levee overtopping compared with 2005 conditions.
- 2100 Conditions – Approximately a 200% increase in overtopping compared with 2005 conditions.

Note, the assessment presented in this paragraph does not include the increase in estimated flood-water surface elevations that is expected due to the increased inflow of the future 100-year floods. It only considers sea level rise. Increased inflow was considered in Part 1, above.

**Floods, Parts 1 and 2 Combined –** Based on the projections of increased flood flows for a given frequency discussed in Part 1, flood stages where tributaries enter the Delta can be expected to increase due to increased flows from climate change. These higher stages are expected to gradually decrease in the downstream direction to a point in the western Delta where they are absorbed by normal (increased) sea level and tidal fluctuations. When the increasing frequencies of given flood flows are considered, the 2050 condition described above represents expected overtopping failures from a 67-year flood, and the 2100 condition represents expected overtopping failures from a 50-year flood. Both are equivalent in size to a 100-year flood today.

**Normal High Tides and Surges –** It is not clear there will be any significant change in tidal patterns or low-pressure surges in the future.

Observations of changing tidal amplitudes specific to San Francisco Bay are briefly reviewed in Appendix H3 of the WAM Technical Memorandum. There is no indication that tidal amplitudes will decrease. There are observations that tidal amplitudes may be increasing. If tidal amplitudes do increase over the next 50 to 100 years, this could increase the hazard to Delta and Suisun Marsh levees from normal tides. This would be in addition to the increased hazard from sea level rise by itself.

Similarly, there could be a changing pattern of low-pressure, storm surges in the Bay and Delta area. Analyses have been performed on short-time-scale, sea-level traces generated from global climate model simulations over the 21st century. These assessments do not indicate substantial changes in monthly maxima of higher-high water.

In view of the limited data on whether tidal amplification or higher low-pressure surges will occur, these factors were not included in the assessment of changes in future risk.

Therefore, the only change in water level hazard for normal, sunny day failures will be the sea level increases described above in 14.1.1, which are:

- 2050 Conditions – Approximately one foot of sea level rise should be expected above the 2005 base case.
- 2100 Conditions – Approximately 2.5 feet of sea level rise should be expected above the 2005 base case.

### 14.1.3 Levee Vulnerability

**Seismic Fragility –** Sea level rise and increased subsidence will combine to increase the effective hydraulic head on levees by approximately 4 feet in 2050 and 8.5 feet in 2100 compared with 2005 conditions. This is expected to increase (to some extent) the seismic fragility of all levee vulnerability classes. The increase in levee fragility (conditional probability of failure) has not been evaluated in detail. The increased water level (due to sea level rise) will not substantially increase vulnerability to liquefaction because the liquefiable sands are already saturated. The increased subsidence (3 feet and 6 feet) may weaken interior toe support to some extent, but the subsidence may be less in the vicinity of the levee toe. Based on preliminary analyses, the following estimates of increased fragility due to the increased loading from greater hydraulic head are used:

- 2050 Conditions – Seismic fragility is expected to increase by approximately 2% over 2005 conditions.
- 2100 Conditions – Seismic fragility is expected to increase by approximately 6% over 2005 conditions.

Note, the increase in future seismic ground shaking hazard was considered in the previous section.

**Flood Fragility –** For islands that would not overtop, the increase in probability of failure was estimated considering the increase in under-seepage, and through-seepage. The probability of failure for under-seepage was estimated using the fragility curves that have been developed for base case conditions. These curves are defined in terms of residual freeboard. For future years, the increase in seepage hydraulic head would be equal to subsidence and sea level rise. The average increase in probabilities of failure considering five representative islands within the Delta (Webb Tract, King Island, Sherman Island, Union Island, and Merritt Island) are the basis for the following estimates:

- 2050 Conditions – The fragility (conditional probability) of seepage failures are expected to increase by 10% over 2005 conditions.
- 2100 Conditions – The fragility (conditional probability) of seepage failures are expected to increase by 20% over 2005 conditions.

**Sunny-Day Event Fragility –** Similar to the description above, subsidence and sea level rise will increase the hydraulic head for a given water surface elevation for normal-day, high-tide exposure of levees. The increased head from subsidence will occur only in areas with highly organic soils. This will increase their vulnerability to under-seepage and through-seepage as described above for flooding:

- 2050 Conditions – One foot of sea level rise is not expected to result in overtopping failures due to normal-day extreme-tide events, even considering storm surge and wind/wave contributions. One foot of sea level rise combined with three feet of subsidence in areas with highly organic soils is expected to lead to an increased frequency of normal-day, high-tide seepage failure by approximately 10 %, as in the case of flooding. This will mean that the frequency of normal-day, high-tide failures will be approximately 0.16 events per year.
- 2100 Conditions – Two and one half feet of sea level rise (from the 2005 base) are not expected to lead to normal-day, extreme-tide overtopping events, even in conjunction with low-pressure surges and wind and waves. Two and on-half feet of sea level rise combined with 6 feet of subsidence in areas with highly organic soils are expected to increase the probability of normal-day high-tide seepage failure by approximately 20%. This will mean the frequency of normal-day, high-tide failures will be approximately 0.17 events per year.

### 14.1.4 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, which has 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.

### 14.1.5 Salinity Response

Hydrodynamics and salinity in the Delta are expected to change in future years both 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 Water Analysis Module Technical Memorandum, Appendix H3). Figure 14-3 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 three feet), assuming that today's normal summer flows are maintained. (Note that 1 psu is the same as 1 part per thousand.) The 2.5 feet of sea level rise discussed above for 2100 would have somewhat less intrusion, but nearly as much as shown in Figure 14-3. This intrusion of salinity will require an increase in Net Delta Outflow to repulse salinity and meet BAU water quality standards.

The increase in Delta outflow has been estimated at approximately 10% of the present typical summer season outflow in 2050 (for one foot of sea level rise) and 20 % of typical summer outflow in 2100 (with 2.5 feet of sea level rise). This will combine with the reduced availability of upstream reservoir inflow (see Section 1.1.1), to further decrease both the amount of reservoir storage available and the yields of the SWP and the CVP. There will be less water available when a levee breach occurs, and water will be more valuable due to scarcity.

When a levee breach occurs, the volume of water that floods the island(s) will increase over the condition today because of subsidence (20% increase in island volume by 2050 and 40% by 2100) and due to higher sea level (one foot in 2050 and 2.5 feet in 2100). This increased flooding volume will be saline water intruding from the Bay. 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 repulse the salt and reestablish Delta water quality, but less water will be available for this purpose. Thus, recovery times will increase.

For smaller events (three flooded islands or fewer) in 2050, the modest Delta recovery times calculated for 2005 are estimated to double. For somewhat larger events in 2050, Delta recovery times of several months are estimated to increase by more than 50%. 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 fresh water conditions in the Delta. In 2100, the same pattern of change will occur with larger impacts on the time required for Delta recovery.

### 14.1.6 In-Delta Population, Infrastructure, and Property

The people and material assets located in the Delta and Suisun area 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. However available data reported in the DRMS "Status and Trends" report indicate that population on Delta/Suisun islands is expected to increase from 26,000 to 67,000 from 2000 to 2030 -- that is by approximately 160%. In other words, there will be 2.6 times as many people living in the Delta/Suisun area in 2030. Similarly, the six county area that encompasses the Delta/Suisun area 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 approximately 470,000. It is estimated that full development of the secondary zone could lead to a population of nearly a million people. No time is tied to this estimate, but these areas are now experiencing high rates of growth. Given the above, the following estimates are provided for the specific years of interest compared with the 2005 base year:

- 2050 Conditions – Compared with 2005, there may be a 300 to 400% increase in the number of people living on Delta/Suisun Islands by 2050, with a total exposed population approaching 100,000. These residents would be directly exposed to the flooding effects and increased likelihood of levee failures in the future.

  For the secondary Delta zone, where areas are also protected from large floods by Delta levees, there may be in the range of an 80 to 120% increase in population by 2050. 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%. These people may have a more modest initial exposure to flooding than people within the primary zone but, with increasing hazards from sea level rise and larger, more frequent floods, secondary zone risks will steadily increase. Overall, the legal Delta area population could approach or exceed a million people by 2050.

- 2100 Conditions – Under BAU policies, there is no indication that the above population growth rates on Delta islands and in the surrounding secondary zone will decrease. In absence of changed development policies a doubling of 2050 populations appears reasonable.

**Infrastructure and Public and Private Property –** The DRMS infrastructure analysis has provided an assessment of assets subject to flooding from levee failures keyed to both Mean Higher High Water (MHHW) and the 100-year flood plain. Their assessment can be summarized as follows:

- 2050 Conditions – The MHHW and 100-year flood asset values subject to flooding are expected to increase by about 20% to 25%.
- 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 14-1 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 entire State. Between 2000 and 2030 gross regional product and earnings are expected to double and employment is expected to increase 50 to 80 percent. There is no useful projection for economic activity after 2030; however, business activity can be expected to continue growing with population.

Business sales on Delta Islands and Suisun Marsh for businesses located below the MHHW were about $3 billion in 2000. Agriculture, natural gas production, and recreation are important economic activities in the primary Delta. DWR 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. 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.

### 14.1.7 State-wide Exposure to Disruptions from Future Levee Failures

**Population –** The California Department of Finance (DOF) develops population projections for state agencies. Those projections are available as follows:

- 2050 Conditions – The DOF projection for 2050 California population is approximately 55 million people, roughly a 50% increase over 2005.
- 2100 Conditions – No official state projection is available. However, even a conservative estimate would be in the vicinity of 90 to 100 million people. For this section, assume a 200% increase over 2005 (approximately 110 million people).

**State Economic Implications –** Although disruptions from Delta levee failures are seen to have regional and statewide economic repercussions, the economic concern with the most widespread consequences is the disruption of the state’s water supply system. The amount of state-wide water demanded from the Delta will remain fairly constant because the state and federal project demands are capped by contract amounts. But the value of exported water will increase.

Irrigation water demand is expected to stay fairly constant, but conversion to high-value and perennial crops will increase the value of water used in agriculture, especially in dry conditions. This will also increase the magnitude of damages due to supply disruptions. As urban agencies contract for more dry-year transfers from agriculture, agricultural use may decline more in dry years relative to the past. Small losses in irrigated acreage to urbanization are also expected. These overall changes will be noticeable by 2030 and more so by 2050.

In urban areas, increased conservation programs and replacement of old appliances and fixtures will cause urban water use to increase at a slower rate than the population. Similarly, increased use of local water supplies including recycled water, brackish water desalination, and groundwater will assist in meeting future increases in demand. However, as urban area water use efficiency and tapping of local resources increase demand hardening will occur. This means that it will be much more difficult to reduce urban water use in a drought or another emergency. As a result, the impacts from disruptions caused by Delta levee failures, especially prolonged disruptions, will be greater.

### 14.1.8 Ecosystem

The Ecosystem Technical Memorandum provides an assessment of future changes that are likely to influence aquatic species (especially fish), important classes of terrestrial vegetation, and key wildlife habitat. Briefly, the anticipated changes in sea level, temperatures, hydrologic regime, and the continuing evolution of land use are expected to have substantial impacts on many species – especially native species that are already showing stress. Changes in sea level and the impacts on inter-tidal wetlands are of particular note. Calculations show differential loss of area of marsh zones, with particularly high rates of loss of the high biodiversity ecotone, the high marsh. The species of vegetation and wildlife occupying them are particularly vulnerable. Some introduced species may benefit from the continuing changes.

Levee breaches will continue to have mixed impacts depending on the specifics of the event. However, considering a given levee breach event either now or in a future year, one can first look at the increased depth of flooding in levee-protected areas that are of ecological value and the increase in salinity that would intrude during the event. These factors alone lead to an escalation of negative consequences. For fish, the picture is more complex. However, for important native species, there are no expectations of positive changes from warmer temperatures, more flooding depth, additional salinity intrusion and less fresh water for low-flow season levee breach event management and recovery.

Thus, on balance, it is expected that 2050 conditions will present increased ecosystem risks associated with a given levee breach event and that 2100 conditions will present yet further increases in risks.

### 14.1.9 Combined Consequence Impacts of Expected Changes

The combined effect of the changes for future years of the factors discussed in the foregoing sections is presented below, by addressing seismically initiated events, floods and sunny-day, high-tide events. The relative importance of risk factors to future changes for each of these types of failure events is illustrated (approximately) relative to its respective base case for 2050 in Figure 14-4 and for 2100 in Figure 14-5. A different presentation of the same relative increases is provided in the tables inserted below.

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

**Seismic Risk Factor Increases Relative to 2005**

| Risk Factor | 2050 | 2100 |
|---|---|---|
| Seismic Hazard (frequencies) | 10% | 20% |
| Seismic Fragility (due to sea level and subsidence loading) | 2% | 6% |
| Increase in Expected Frequency of Island Flooding[a] | 12% | 27% |
| Salinity (increased periods of disruption due to sea level, subsidence, less water supply available) | 50% | 100% |
| Consequences (population growth, land use, increased pressure on ecosystem, increased dependence on export water export supplies) | 70% | 200% |
| Estimated Increase in Expected Losses[b] | 90% to 150% | 250% to 600% |

[a] Increased frequency in island flooding reflects increased hazard and fragility (e.g., 1.1 x 1.02).

[b] Lower bound reflects increase in expected frequency of failure and consequences. Upper bound includes the effects of subsidence, sea level and less available water supply on salinity intrusion and periods of disruption.

**Floods –** As indicated in the table below, the climate change shift to more frequent major floods will be a major factor in increased future flood risk. In addition, sea level rise will increase the possibility of overtopping due to floods. The fresh water inflow from the floods will generally prevent immediate salinity intrusion, but long levee repair periods may present problems in subsequent periods of low flow. Large in-Delta impacts from additional flooding are expected, due especially to increased population and development and increased pressure on the ecosystem.

**Flood Risk Factor Increases Relative to 2005**

| Risk Factor | 2050 | 2100 |
|---|---|---|
| Flood Hazard (increased high water level frequencies and overtopping due to sea level rise and more frequent high flows) | 200% | 500% |
| Flood Fragility (due to extra hydraulic head and resultant seepage) | 10% | 20% |
| Increase in Expected Frequency of Island Flooding[a] | 230% | 620% |
| Salinity (increased periods of disruption due to sea level, subsidence, less water available) | Nil | Nil |
| Consequences (population growth, land use, and increased pressure on ecosystem) | 100% | 200% |
| Estimated Increase in Expected Losses[b] | 500% to 670% | 1700% to 2100% |

[a] Increased frequency in island flooding reflects increased water level hazard, overtopping, and seepage.

[b] Lower bound reflects increased water levels and consequences. Upper bound includes the effects of seepage.

**Normal-Day, High-Tide Failures –** As indicated by the table below, sea-level rise is expected to increase the frequency of normal-day, high-tide failures. Frequency reflects the expected occurrence of extreme high tides relative to Mean Sea Level. However, given the BAU premise that a Delta-wide program of levee raises to keep up with sea-level rise will not occur, the conditional probability of overtopping failures will increase. They will rise gradually throughout the century. 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 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 such events begin to occur on two to four islands at a time, and especially if breaches are not repaired, impacts will escalate.

**Sunny Day Factor Increases Relative to 2005**

| Risk Factor | 2050 | 2100 |
|---|---|---|
| High Tide Hazard (frequencies) | Nil | Nil |
| Fragility (due to sea level and subsidence loading and overtopping) | 10% | 20% |
| Increase in Expected Frequency of Island Flooding[a] | 10% | 20% |
| Salinity (increased periods of disruption due to sea level, subsidence, less water available) | 20% | 50% |
| Consequences (population growth, land use, increased pressure on ecosystem, increased dependence on export water supplies) | 20% | 50% |
| Estimated Increase in Expected Losses[b] | 30% to 60% | 80% to 250% |

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

[b] Lower bound reflects increase in expected frequency of failure and consequences. Upper bound includes the effects of subsidence, sea level and less available water supply on salinity intrusion and periods of disruption.

### 14.1.10 Conditions in 2200

Useful data are generally not available for addressing the conditions in 2200 and the effects on future risks from Delta levee failures. 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. An alteration in the rate of increase of seismic hazard requires that a major stress-relieving earthquake occurs in the intervening period. Other factors are not so easy to predict. However, in light of the discussion and assessments in the previous sections, there is no reason to expect that risks in 2200 will remain the same or decrease relative to the assessment for 2100. Thus, the risks from Delta levee failures are expected to continue to increase.

## 14.2 SUMMARY ON CHANGING RISK FACTORS FOR FUTURE YEARS

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 (i.e., Delta population). The overall likelihood of a major event is increasing and the magnitudes of consequences from a given event are also rising.

## 14.3 IMPLICATIONS OF EXPOSURE PERIOD

Although the trends in factors that influence the estimate of future risks combine to indicate steadily increasing risk 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 one percent annual event has a 26% chance of being equaled or exceeded. In 50 years, the chance is 39.5% and in 100 years, the chance is 63.4%. Figure 14-6 also illustrates the increasing probability of failure for other annual frequencies. It is just a matter of time (exposure period) until a severe event occurs.

## 14.4 SUMMARY PERSPECTIVE ON FUTURE RISK

The 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 even higher increases in expected losses. When combined, the increases in risks related to Delta levee breaches compared to the 2005 base case are estimated to be several hundred percent by 2050 and more than 1,000% by 2100. 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 high present risks from Delta levee failures (and assuming no future increases in risk), 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.

### Table 14-1 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 data

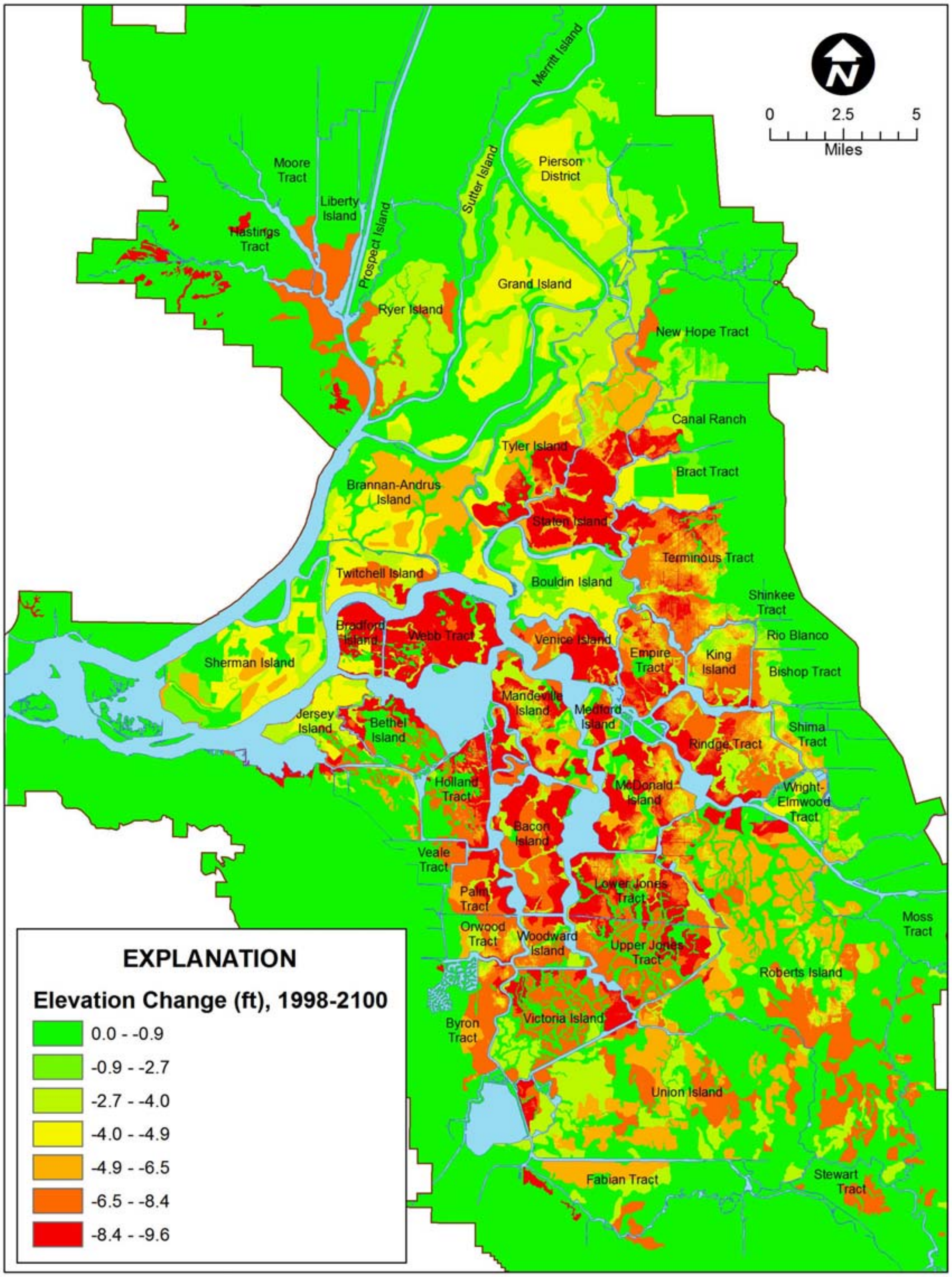
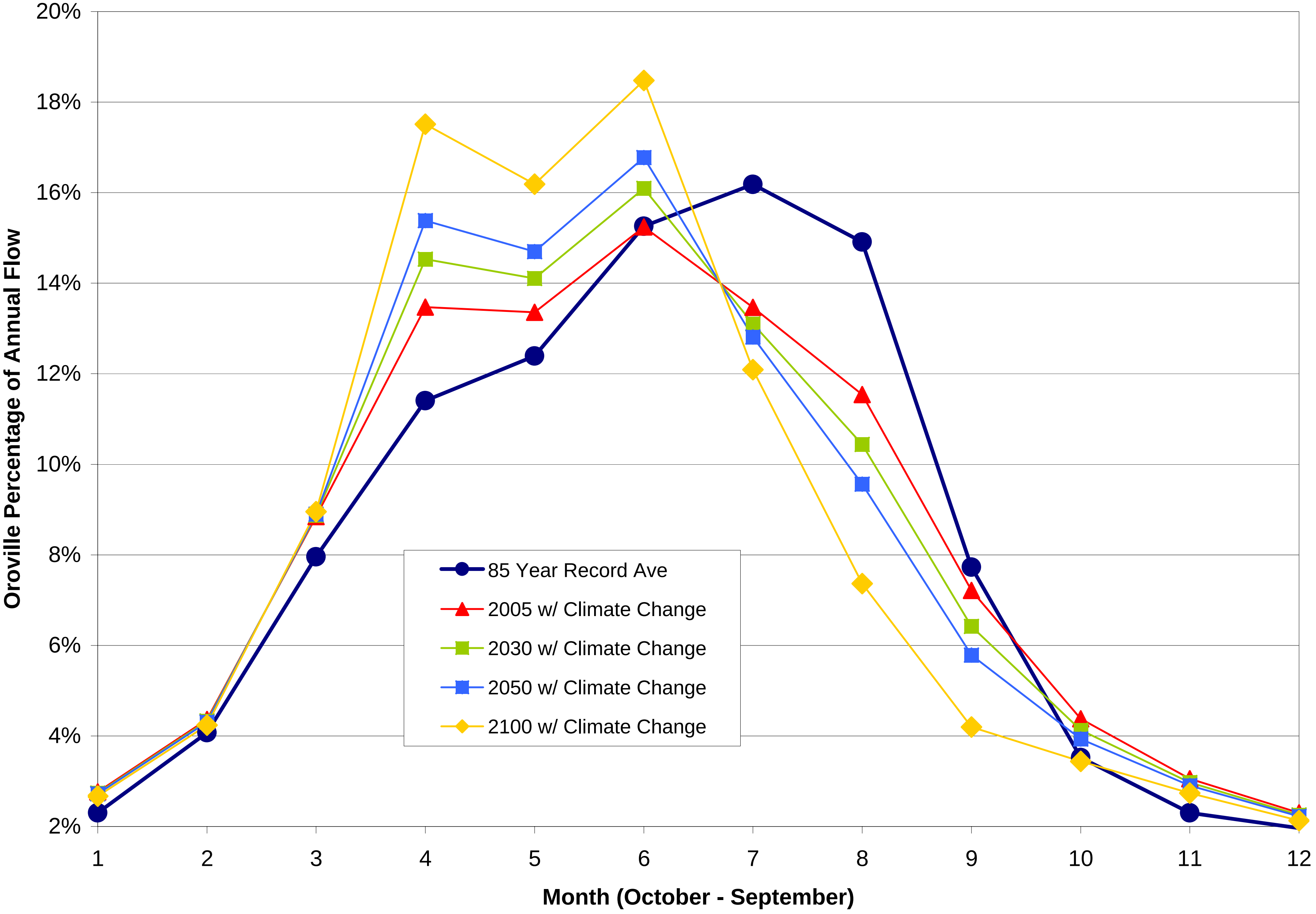


Figure 14-1 Additional Subsidence 2005 to 2100

Figure 14-2. Oroville Changes in Monthly Runoff Pattern
(One of Four Simulations; SRESa2, gfdl).



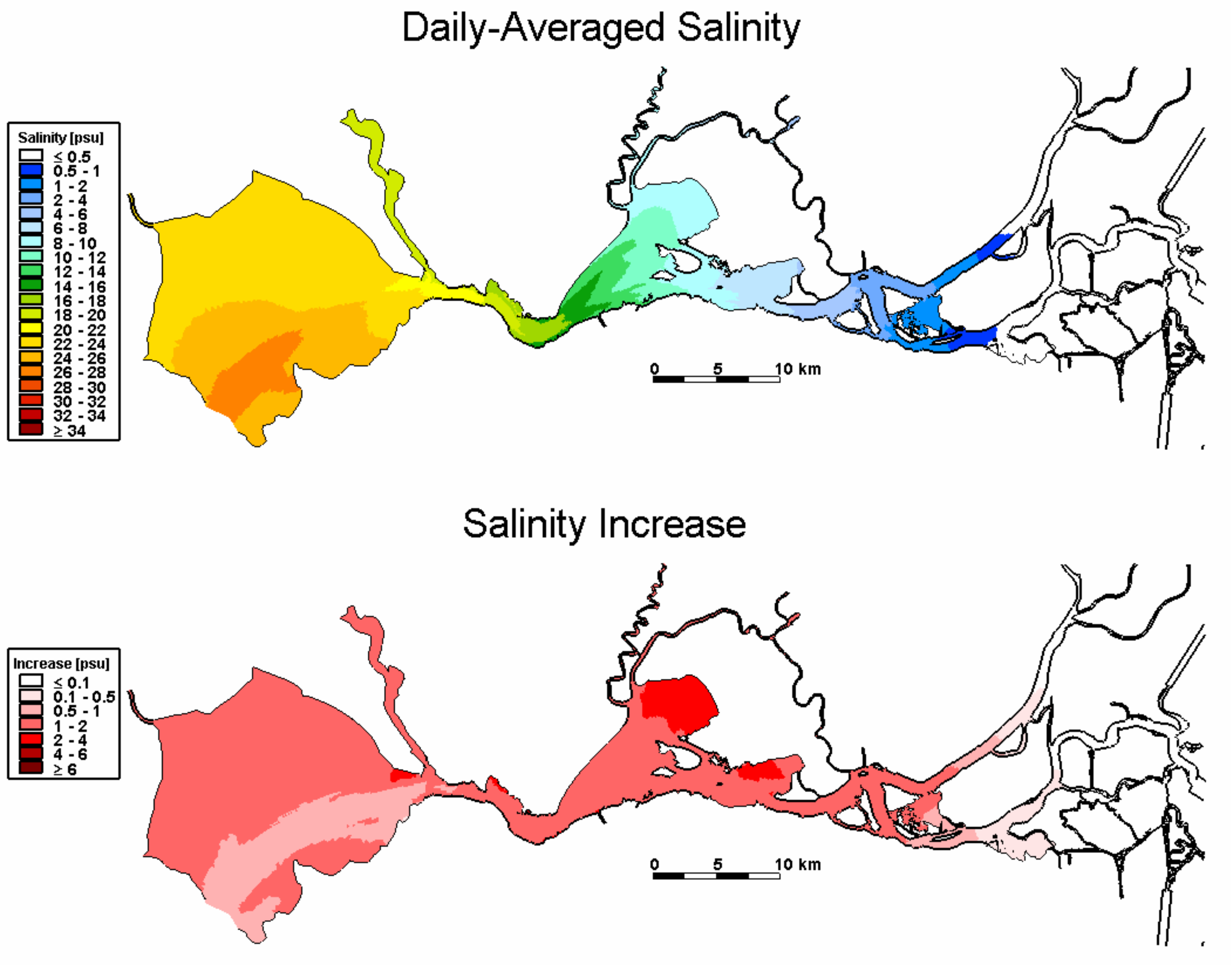
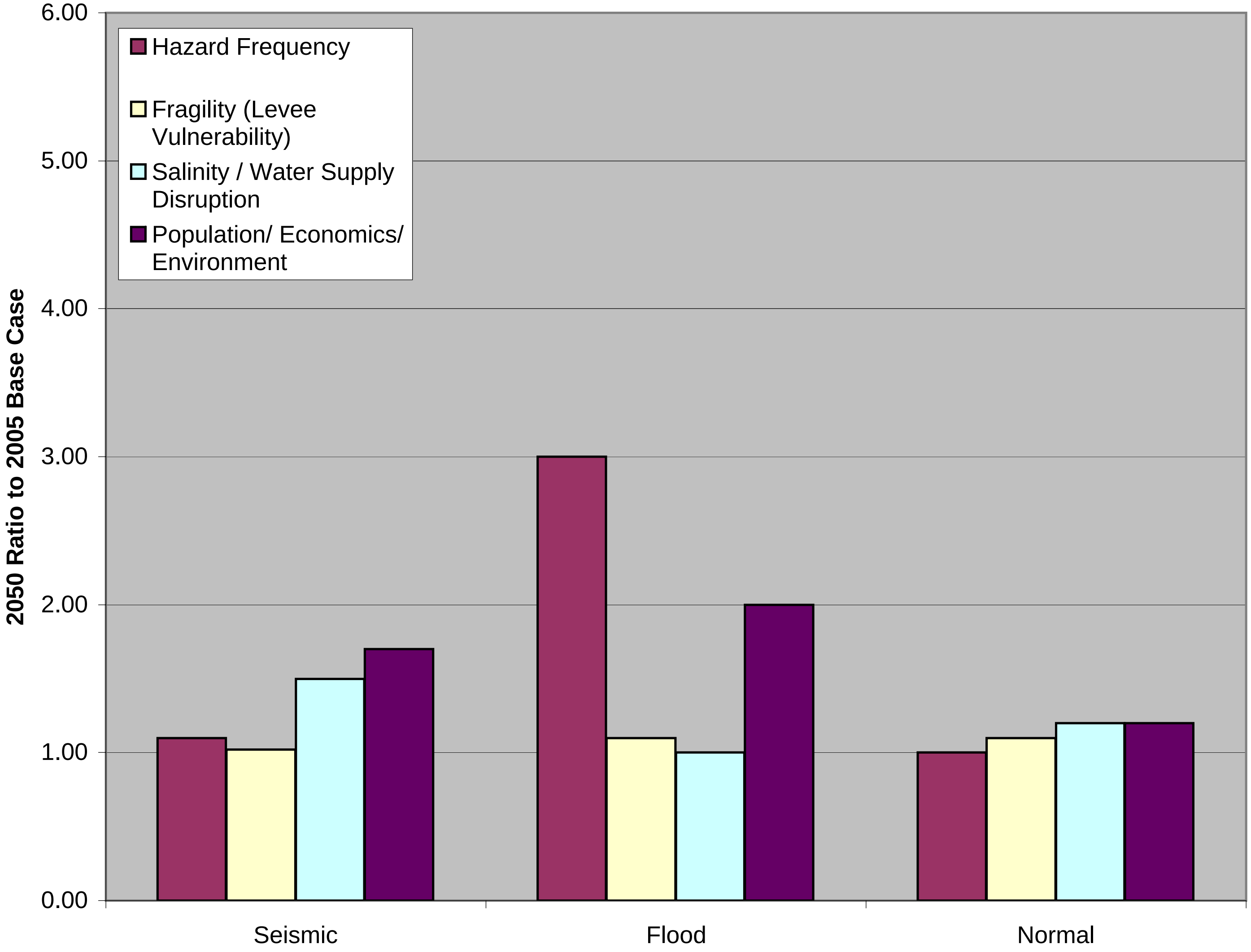
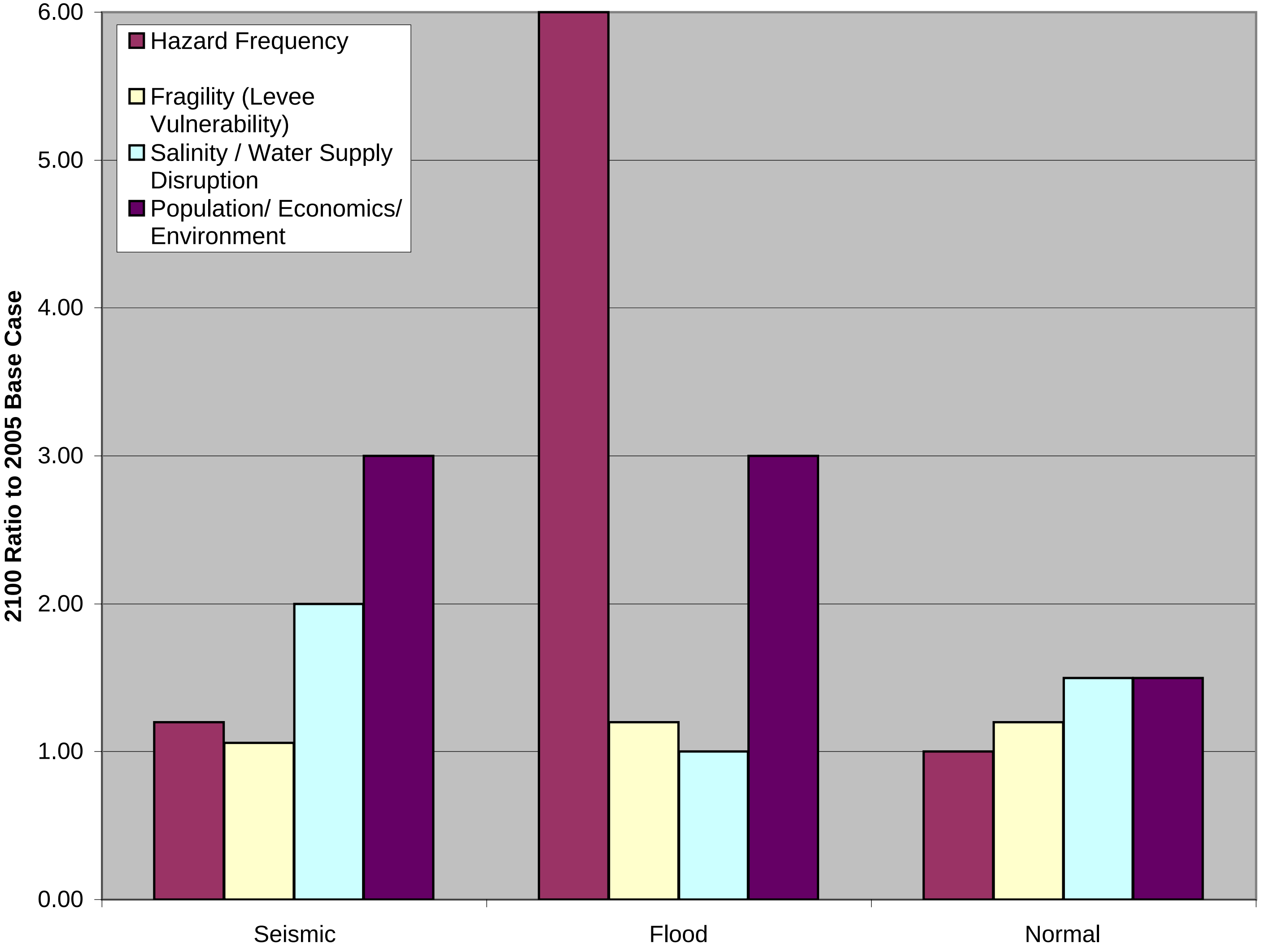


**Figure 14-3** Depth-averaged and tidally-averaged salinity at tidally-averaged steady state conditions for the 90 cm MSL Rise and increase in salinity relative to the Baseline scenario

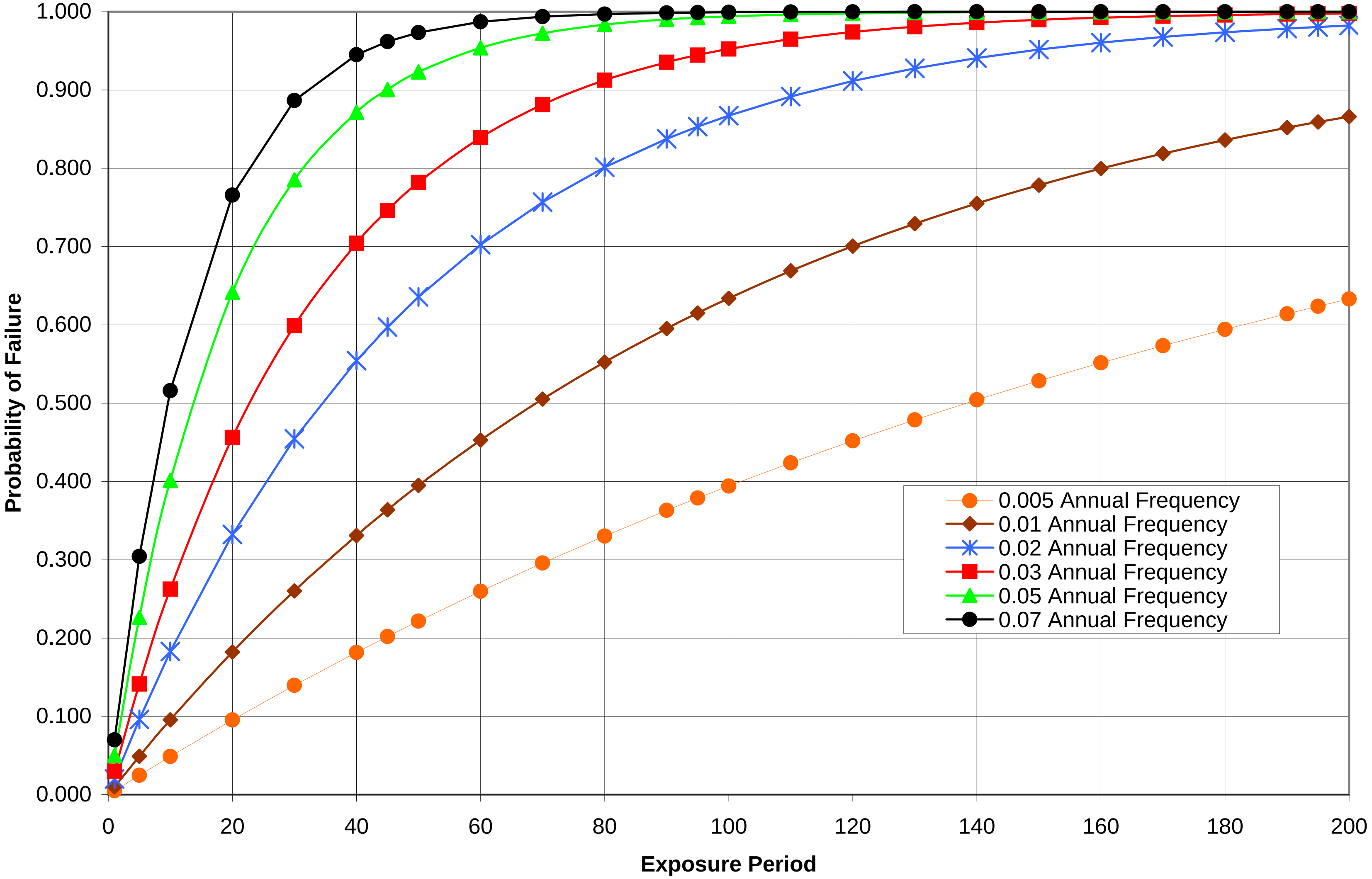
Figure 14-4. Risk Factor Ratios for 2050



## Figure 14-5. Risk Factor Ratios for 2100



## Figure 14-6. Failure Probability Versus Exposure Period



The risk analysis was carried out, for the most part, using existing information (data and analyses). The project schedule does not afford the opportunity to conduct field studies, laboratory tests, or research investigations. As the analysis progressed, the team noted several data gaps that contribute to the limitations and the uncertainties of the analysis results. Consideration should be given to filling these data gaps prior to any post-DRMS evaluations or designs of Delta levees:

- DRMS addressed the risk of levee failures (under various hazards and stressors) and estimated the consequential impacts on ecosystem, water export, water quality, land use, economics, etc. DRMS does not address other stressors and their impacts on the various resources and assets in the Delta and Suisun Marsh. For example, the impact of nonnative species on native species and the impact of changes to water quality on the native species are not addressed. On the other hand, the impact of levee failure on the habitat, water quality, and their effects on the Delta ecosystem and water exports are addressed.
- To have a common basis of risk comparison, a BAU scenario was assumed for the current and the future Delta and Suisun Marsh. Earlier sections of the report describe details for the meaning and definition of BAU, the continuation of existing policies and management practices. While a common basis for comparison is essential for the analysis, real world continuation of BAU is not likely. However, DRMS had no basis for projecting future policies and management practices as the basis for its analysis.
- The engineering analyses conducted for this risk analysis were developed at a regional level using broad interpolation and smoothing of the engineering and scientific parameters that are naturally highly variable across a large area such as the Delta and Suisun Marsh. The analysis was conducted at a risk study level for a coarse data grid, hence carrying less site-specific and locally detailed typically associated with a specific engineering and design projects.
- Topographic and bathymetric base maps are essential for the development of the levee vulnerability assessment. These data are of first order importance to the entire risk analysis presented in this report. The current data used for this study are a compilation of various topographic data sets prepared at different times, with different reference datum, and by different methods and entities. The need to generate and utilize current, unified, and comprehensive topographic and bathymetric base maps will greatly improve the reliability of the findings in this report.
- Improved Delta topography is necessary for more accurate estimation of salinity intrusion associated with island flooding.
- Accurate mapping of upland topography on the periphery of the Delta is required to estimate the change in tidal prism associated with sea level rise.
- It is assumed that scour depth is a direct function of peat thickness (scour depth=peat thickness). The validity of this assumption should be further investigated to determine whether other parameters, such as island area or volume, are better predictors of scour depth.
- Breach depth is important in estimating the quantity of rock for breach closure and repair times.
- Net Delta consumptive uses are a major source of water demands in the Delta, especially in low-flow years. Existing estimates are useful, but data and modeling limitations may

contribute significant errors to the water balance in dry and critical years. Better estimates of the timing and distribution of Delta consumptive use is important for calibration of Delta models and simulation of levee breach consequences.

- The order of flooded island repair is extremely significant when considering the time necessary to flush the Delta of intruded salinity and return to a stable salinity regime that supports normal in-Delta water use, ecosystem functions, and water exports. Although assumed order of repair (for salinity) used in the analysis has improved, it is still based on professional judgment rather than on an explicit analysis of changing results from using different orders of repair.
- Although CalSim is a powerful and useful tool, it is a limitation on how water issues can be analyzed. Two major limitations result from use of the historical hydrologic sequence to drive CalSim. The historical series is likely to trend through time, since it is now recognized that global warming and climate change have been with us for at least 30 to 40 years. Also, the historical record includes less than half of the 125 potential 3-year sequences of water year types.
- Delta salinity impacts of levee breaches may be more strongly influenced by the wetness or dryness of the winters following a breach event than by hydrologic conditions earlier in the event year or in the year preceding the event. Under BAU conditions, a winter with significant San Joaquin River flows may be required to flush the southern Delta if salinity significantly intrudes the area.
- Future water demands relevant to Delta levee breaches have not been characterized in detail, but seem certain to increase. Population and demands upstream of the Delta seem likely to increase, leaving less inflow available for managing the Delta during either normal times or during levee breach incidents. Although the demands for Delta exports are limited by contract amounts and other factors, population growth will likely cause available export water to be used more intensively for higher value uses. The effect of climate change is less certain; some indication exists that increased water demand due to increased temperatures may be counter balanced by less vegetative water requirements due to increased atmospheric carbon dioxide.
- The relative importance of populated areas, infrastructure, in-Delta water use, ecosystem values, water exports, and island dewatering for agricultural recovery is not yet analyzed in any quantitative or objective way.
- One of the most important outstanding questions is the impact of unrepaired flooded islands with active tidal prism on Net Delta Outflow (carriage water) requirements. This study has not had enough time to provide conclusive quantification of flooded islands on carriage water requirement. Numerical experiments using particle tracking and salt transport simulation under a variety of flow and breach conditions provide insight, but clear relationships are not evident because changes in tidal mixing vary by island and breach location resulting in both increases and decreases in salinity across the Delta. Besides changing the tidal dynamics, flooded islands act as capacitors that buffer seasonal salinity variation. In general, breached islands tend to increase mixing near the breach locations and reduce mixing away from the flooded island. Additional tidal mixing due to flooded islands located near Sherman Island

appears to be particularly effective in mixing salt into the Delta, and, therefore, is likely to have a large effect on carriage water requirements.

- Improved net (tidally averaged) flow observations (specifically at the key flow split locations of Three Mile Slough on the Sacramento and False rivers, Turner Cut, Old River near Franks Tract, and Old River at Head on the San Joaquin River) with uncertainty estimates throughout the Delta will support calibration of all Delta models as well as allowing better parameterization of net flows for the WAM-HD.
- It is important to recognize the limitations inherent in characterization of ecosystem impacts. The results presented here primarily assess the number of individuals or area of habitat impacted, which is similar to the coarse scale used to evaluate the impact of levee failure on life and safety through measuring the number of residents exposed to flooding. Therefore, these results provide a sense of the order of magnitude of the risk, primarily for the immediate impacts of levee breaches, which last for a relatively short duration but cause widespread mortality during the time that they are in operation.
- For many of the species and impact mechanisms, data were not available to support predictive response relationships to a levee failure event. Therefore, a number of assumptions were made that contribute to a high degree of uncertainty in the ecosystem risk analysis. The risk assessment model identifies assumptions and required data and provides a framework with which to incorporate new data and to evaluate the effects of alternative assumptions on the impact to ecosystems of levee failure.
- Consequences such as impacts of toxics released, water quality impacts, impacts extending across food chains, long-term impacts of levee breach on organisms, and the nonlinear impacts of multiple mechanisms of impacts on organisms are examples of further impacts of levee breaches, which are not quantitatively assessed here but which may have far-reaching impacts on the ecosystem.
- The region queried for the purposes of measuring regional plant impacts was defined as those 12 counties that include and border the Delta and the San Francisco Bay. The results of the California Natural Diversity Database query overlaid with flooding patterns indicate that levee breaches and subsequent repair activities can greatly reduce the population size of sensitive plant species, thereby increasing the probability of species extinction. However, exhaustive surveys of rare plant locations and species-specific response to low population size would be required to fully quantify the impact of levee breaches on species extinction.
- The DRMS Risk Analysis considered damage to infrastructure assets that could result from levee breaching and island flooding. Infrastructure assets that would not be damaged by levee failure (e.g., pumping plants and power plants) are beyond the scope of the DRMS Risk Analysis. Because some asset types lack attribute information, it was not always possible to estimate asset costs from the GIS data. In these cases, definition of quantitative attributes is insufficient to evaluate reliable replacement and repair costs, and assumptions had to be made so that damage loss could be estimated. Also, some assets were not available in the GIS database. Further characterization of the Delta infrastructure assets would reduce the uncertainty in the damage estimates. Because of the lack of information on repair times (due to the absence of historic experience), especially for multi-island failures, judgment was used to estimate repair times.

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