The Sacramento-San Joaquin Delta (Delta) and Suisun Marsh are critically important to the state and the nation for a wide variety of environmental and economic services (benefits derived from the area). Approximately 1,115 miles of levees in the Delta and 230 miles of levees in Suisun Marsh define the configuration of the waterways and landform of the area. Most of these levees hold back water 365 day per year. Over the years, many state and federal agencies and stakeholders have voiced concern over the condition of the Delta and Suisun Marsh levees and the consequences when they fail.

DRMS progress can be followed on the Delta Risk Management Strategy web portal:

http://www.drms.water.ca.gov/

1.1 PURPOSE

The overall purpose of the Delta Risk Management Strategy (DRMS) is to assess the performance of Delta and Suisun Marsh levees and the potential economic, environmental and public health and safety consequences of levee failures to the Delta region itself and California as a whole and to develop and evaluate risk reduction strategies. This report presents the methodology and results for Phase 1 of the work, the risk assessment. A future report will evaluate risk reduction strategies.

The Record of Decision for the CALFED Bay-Delta Program (CALFED 2000) called for a DRMS to be completed by 2001. The California Department of Water Resources (DWR), California Department of Fish and Game (CDFG), and U.S. Army Corps of Engineers (USACE) initiated DRMS in response to Assembly Bill (AB) 1200.

Delta Facts

- Approximately 1,115 miles of levees protect 700,000 acres of lowland in the Sacramento-San Joaquin Delta. In Suisun Marsh, approximately 230 miles of levees protect over 50,000 acres of marsh land.
- Only about a third of the Delta levees (385 miles) are Project Levees, which were part of an authorized federal flood control project for the Sacramento and San Joaquin River systems. However, the vast majority of Delta levees, over 730 miles, and about 210 miles of Suisun Marsh levees are nonproject (local) levees.
- Local levees were constructed, enlarged, and maintained over the last 130 years by local reclamation districts. In general, the levee work by these districts was financed by the owners of the lands protected by the levees. Over about the last 30 years, the State of California has provided supplemental financing for levee maintenance and emergency response.
- Flooding from levee failures can influence the following services:
  - Land use (agriculture, urban, and conservation areas)
  - Flood management
  - Ecosystem
  - Water supply
  - Water quality management
  - Transportation
  - Utilities
  - Recreation and Tourism
  - Local and state economics

1.1.1 Assembly Bill 1200

AB 1200 (Laird, Chaptered October 2005) required the DWR to evaluate the potential impacts on water supplies derived from the Delta resulting from a variety of risks.

The bill amends Section 139.2 of the Water Code, to read, “The department shall evaluate the potential impacts on water supplies derived from the Delta based on 50-, 100-, and 200-year projections for each of the following possible impacts on the delta:

1. Subsidence
2. Earthquakes
3. Floods
4. Changes in precipitation, temperature, and ocean levels

5. A combination of the impacts specified in paragraphs (1) to (4) inclusive”

In addition, Section 139.4 was amended to read: (a) The department and the Department of Fish and Game shall determine the principal options for the delta. (b) The department shall evaluate and comparatively rate each option determined in subdivision (a) for its ability to do the following:

1. Prevent the disruption of water supplies derived from the Delta.
2. Improve the quality of drinking water supplies derived from the Delta.
3. Reduce the amount of salts contained in Delta water and delivered to, and often retained in, our agricultural areas.
4. Maintain Delta water quality for delta users.
5. Assist in preserving Delta lands.
6. Protect water rights of the “area of origin” and protect the environments of the Sacramento-San Joaquin river systems.
7. Protect highways, utility facilities, and other infrastructure located within the Delta.
8. Preserve, protect, and improve Delta levees.…”

DRMS was developed to address the provisions of Sections 139.2 and 139.4 of AB 1200.

1.1.2 Goals and Objectives

The sponsors, together with the Steering Committee, developed objectives for the DRMS work in accordance with the provisions of AB 1200:

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

1.2 RISK ANALYSIS OVERVIEW

In meeting the requirements of AB 1200, the DRMS project is divided into 2 parts. Phase 1, the work covered by this report, involves the development and implementation of a risk analysis to evaluate the risks from various stressing events to Delta and Suisun Marsh levees. The DRMS Phase 1 Risk Analysis provides a framework for evaluating major threats, or hazards, to the Delta levee system and the consequences of levee failures. Phase 2 of the project, to be covered in a future report, will include risk reduction and risk management strategies for long-term management of the Delta.

The risk analysis report draws information from 12 technical memoranda (TMs). The topics covered by each TM are listed in the table below. Each TM presents the scientific and engineering data and assumptions, the methodology applied to each topic area, and the analysis results, which become input to the risk analysis. The risk analysis report summarizes selected relevant information from the TMs to provide a context and background for the risk analysis. Readers should review relevant TMs to access more information on their topics of interest.

The TMs can be found at the DWR DRMS web site: http://www.drms.water.ca.gov

1. Climate Change	7. Levee Vulnerability
2. Flood Hazard	8. Emergency Response/Erosion
3. Seismic Hazard	9. Hydrodynamic/Water Management
4. Wind Wave Hazard	10. Ecological Impacts
5. Subsidence	11. Impact to Infrastructure
6. Geomorphology	12. Economic Impacts

This Risk Analysis Report provides an abbreviated compilation of this information and summarizes risk results for 2005 and future conditions. Risk is first evaluated under 2005 base year conditions assuming that existing management practices (policies, funding, maintenance, etc.) continue ("business as usual").

1.2.1 Hazards

The hazards evaluated in this report for 2005 include:

- Seismic events (earthquakes) that cause levees or their foundations to fail
- Floods (high storm runoff) that can rise above the tops of the levees or increase pressure for seepage through and under the levees and cause them to fail
- Normal sunny day events caused by undetected problems, such as rodent activity, that fail levees during normal, nonflood flow periods ("sunny day events")
- High wind waves and erosion that can weaken levees, but are especially damaging to the interior of islands when they flood

DRMS includes an analysis of the frequency or rate that different magnitudes of these events occur. Smaller earthquakes and floods occur less often than the more extreme events, but they all

pose some risk to the levee system. Small events may fail only one levee, and larger events may fail multiple levees.

1.2.2 Consequences of Levee Failure

DRMS includes analysis of the consequences of levee failures for 2005, including the costs and other impacts due to the failures and resultant flooding. Damage to buildings, flooding of farmland, impacts to the ecosystem, and disruption of water supply are a few examples of consequences. Many of the economic consequences extend well beyond the Delta and Suisun Marsh, especially for the water supply that is exported from the Delta.

1.2.3 Risk

DRMS combines the various types of hazards, the frequency of different magnitudes of these hazards, and the consequences of failures under each condition in a probabilistic approach to compute the overall risks of levee failures for a base year of 2005. All these parts of the risk "equation" are described in more detail in later chapters. In performing this analysis, DRMS considers the risks due to flooding of individual islands and tracts of land, and for more severe flooding of multiple islands and tracts.

Definition of Risk

In this analysis, risk is defined as the likelihood (frequency) of adverse consequences that could occur as a result of levee failures in the Delta

1.2.4 Future Risk

In the future, the magnitude of the hazards, the frequency that they occur, and the consequences are expected to change. For example, sea level rise is expected to put more pressure on Delta levees in the future. Climate change is expected to increase high winter floods flows into the Delta. Increases in the population within the Delta will increase the consequences of levee failure and flooding. Therefore, DRMS estimates how conditions are expected to change for 50, 100, and 200 years from now. These future conditions allow computation of future risks.

1.2.5 Limitations

For the past few decades, the Delta has been the subject of intense data collection, analysis, and scientific investigation. Despite this new knowledge, a great deal about the Delta and Suisun Marsh is still unknown. These circumstances are not unique to the Delta and DRMS. Rather, they are common to risk analyses of complex natural and man-made systems (SSHAC 1997; USDOE 1998). DRMS includes an analysis of uncertainty.

A great deal about the Delta and Suisun Marsh is still unknown. DRMS includes an analysis of uncertainty.

The DRMS work relied on existing data and information. For example, no opportunity existed to conduct new topographic or bathymetric surveys, obtain subsurface borings to better define levee and foundation material, or conduct other new research. Some areas with data gaps required extrapolation of available data tempered by engineering judgment and experience.

A particular challenge for DRMS is the analysis of risks as they change from the present (2005 base year) over the next 200 years. As one might expect, the scientific and information uncertainties and data gaps increase when estimating conditions 50, 100, and 200 years from now, particularly with estimates for the ecosystem, population growth, and future changes in the state's economy.

Unlike other risk analyses involving the potential of flooding, DRMS is unique. Most flood risk analyses consider a single stressing event, like a major flood. For example a similar evaluation for New Orleans, would consider the risk associated with a hurricane on 350 miles of levees. The scale and complexity of DRMS for the Delta and Suisun Marsh has likely not been attempted by another evaluation of risk from flooding. The DRMS evaluations are conducted for:

- About 1,345 miles of levees, over 3 times the length for New Orleans
- An area of 1,315 square miles, almost 4 times the size of New Orleans
- Highly variable foundation conditions including compressible peat soils
- Levees that were constructed without the benefit of modern engineering and construction techniques
- Multiple hazard conditions including seismic, flood, wind wave, and even sunny day breaches from unforeseen conditions
- Changing future conditions including land subsidence, sea level rise, more winter flooding and an increasing risk of a moderate to severe earthquake occurring in the near future
- Consequences of levee failure that extend well beyond the boundaries of the Delta and Suisun Marsh to the entire State of California

To complicate the analysis even more, the Phase 1 risk analysis needed to be completed in about 1 year using only readily available information. The schedule for the second phase of the work, the evaluation of risk reduction actions, provides only about one-half year for that portion of the analysis.

The result of this risk analysis is a better understanding of risks that the Delta and Suisun Marsh face today and in the future. The risk results should be considered for the levee system as a whole rather than for any specific levee reach. Some readers may attempt to focus on an individual island or land tract for information – this tendency should be discouraged. The information in the report should not be used as a basis of design for any individual island or land tract. In essence, the risk results from this analysis can be considered as a more accurate indication of levee risk for the collective area than for a specific spot in the Delta and Suisun Marsh.

Use of Risk Analysis

The results of the risk analysis are intended to provide a broad indication of the risks associated with the Delta and Suisun Marsh levee system. The information in the report should not be used as a basis of design for any individual island or land tract.

As a result DRMS, parties interested in the future of the Delta will be in a position to begin to assess the relative importance of different hazards, and the nature (type and severity) of the risks that they face. The analysis will quantify and put into context how significant a threat that the ongoing, relatively frequent events and levee failures are to the future of managing the Delta. It

will also quantify what the state may face from a major catastrophe – our version of flooding of New Orleans from Hurricane Katrina.

1.3 PROJECT TEAM

1.3.1 Project Sponsors

The DWR, CDFG, and USACE serve as the project sponsors for DRMS. The sponsors are assisted by a stakeholder Steering Committee and a Technical Advisory Committee.

1.3.2 Steering Committee

Steering Committee members are policy advisors that represent interests of the Delta and interests of those outside the Delta who rely on the Delta infrastructure. The role of the Steering Committee members is to assure proper coordination among agencies, the public, and the DRMS Consultant are maintained. The members are expected to speak with authority on the positions of their constituency and have access to policy makers within their organization when needed. The Steering Committee provides policy advice to the project sponsors and the DRMS Consultant.

1.3.3 Technical Advisory Committee

The Technical Advisory Committee, which is a de-facto member of the Steering Committee, has the same roles and responsibilities as those described above for the Steering Committee. In addition, the Technical Advisory Committee members are technical subject matter experts, and serve, at the direction of the project sponsors, as independent reviewers of the DRMS project work. The Technical Advisory Committee reviews interim and final work products of the DRMS consulting team. The committee provides written comments and advice on the appropriateness of the methods used in the development of the technical products. In its role as an independent reviewer, the committee does not produce or generate work on the DRMS project.

1.3.4 DRMS Consulting Team

The project sponsors selected the consulting team of URS Corporation and Jack R. Benjamin & Associates, Inc., to perform the DRMS work. The team was given authorization to proceed with work in March 2006. The work schedule called for drafts of the Phase 1 work to be completed in Spring 2007 and drafts of the Phase 2 work to be completed in Fall 2007.

The consulting team includes 23 firms located in the Sacramento/Bay Area/Stockton region. These local firms bring extensive local experience with the Delta in their respective field of specialization. The firms and the services they provided are described below. Figure 1-1 shows the program functional organization. (Tables and Figures can be found at the end of each section.)

URS Corporation: Risk Analysis, Geotechnical Engineering, Seismic Hazard and Earthquake Engineering, Hydraulic/Hydrology, Flood Hazard, Water Quality, Vegetation and Habitat Analysis, Infrastructure, GIS

Jack R. Benjamin & Associates, Inc. (JBA): Risk Analysis and Modeling, Water Management

Resource Management Associates (RMA): Delta Hydrodynamic Modeling

MBK Engineers: Reservoir Operation and Water Management

Bay Modeling-Hydrodynamics (Bay Modeling): 3-D Hydrodynamic Modeling, Sea Level Rise Simulation

Watercourse Engineering, Inc. (WE): Hydrodynamics and Water Management

Geomatrix Consultants, Inc.: Seismic Hazard, Earthquake Engineering, Geotechnical Engineering

Kleinfelder, Inc.: Geotechnical Engineering

Hultgren & Tillis Engineers (HTE): Geotechnical Engineering

HydroFocus, Inc.: Subsidence

WLA Consulting, Inc.: Seismic Geology, Fault Characterization

Pacific Engineering & Analysis (PE&A): Ground Motions and Site Response

Phillip Williams Associates (PWA): Geomorphology, Wind-Wave Modeling

Moffatt & Nichol Engineers (MNE): Emergency Response, Erosion

Economic Insight (EI): Economic Analysis

RM Econ: Economic Analysis

Western Resource Economics (WR Economics): Economic Analysis

M-Cubed: Economic Analysis

Redars Group (RG): Traffic Impact Analysis

Hanson Environmental, Inc. (HEI): Environmental and Ecosystem Impact Analysis

Stevens Consulting: Environmental and Ecosystem Impact Analysis

Science Applications International Corporation (SAIC): Terrestrial Habitat

Jones & Stokes: Water Quality, Environmental Impacts

1.3.5 Topical Work Groups

The DRMS consulting team was organized into 15 topical work groups. The topical groups and the lead for each group are listed below.

1) **Seismic Hazard:**
   Lead: Ivan Wong (URS)
   Patricia Thomas (URS)
   Walt Silva, PhD (PE&A)
   Robert (Bob) Young (Geomatrix)
   Jeffrey Unruh (WLA)
   Kathryn Hanson (Geomatrix)
   Kevin Coppersmith, PhD (I)
2) **Flood Hazard:**
   Lead: Thomas MacDonald, PhD (URS)
   Phillip Mineart (URS)
   Joe Countryman (MBK)
3) **Subsidence:**
   Lead: Steven Deverel (HydroFocus)
4) **Climate Change:**
   Lead: Philip Duffy, PhD (LLNL)
   Louis Armstrong (URS)
5) **Levee Vulnerability:**
   Lead: Said Salah-Mars, PhD (URS)
   Rajendram Arulnathan, PhD (URS)
   Faiz Makdisi, PhD (Geomatrix)
   Edward Hultgren (HTE)
   Kevin Tillis (HTE)
   Segaran Logeswaran (URS)
   Thang Kanagalingam, PhD (URS)
   Scott Shewbridge, PhD (Kleinfelder)
   Ron Heinzen (Kleinfelder)
   Lelio Mejia, PhD (URS)
   Michael Forrest (URS)
   Ulrich Luscher, PhD (I)
6) **Geomorphology:**
   Lead: David Brew (PWA)
   Chris Bowles, PhD (PWA)
7) **Emergency Response:**
   Lead: Rick Rhoads (MNE)
   Ingrid Maloney (MNE)
   Curtis Loeb (MNE)
   H. Frank Du (MNE)
8) **Wind-Wave Modeling:**
   Lead: Nick Garitty (PWA)

(I) = Independent Consultant

9) **Hydrodynamic Modeling:**
   Lead: John DeGeorge, PhD (RMA)
   Edward Gross, PhD (Bay Modeling)
   Michael MacWilliams, PhD (Bay Modeling)
   Nicholas Nidzieko (Bay Modeling)
10) **Water Management:**
   Lead: Will Betchart (JBA)
   Walter Bourez (MBK)
   Michael Deas (WE)
   Stacy Tanaka (WE)
11) **Infrastructure:**
   Lead: Michael Forrest (URS)
   Danielle Lowenthal-Savy (URS)
   Liz Elliott (URS)
12) **Economic Impacts:**
   Lead: Wendy Illingworth (EI)
   Roger Mann (RM Econ)
   Steve Hatchet (WR Economics)
   David Mitchell (M-Cubed)
   Liz Elliott (URS)
   Stewart Werner (RG)
   George Muehleck (URS)
   Steve Ottemoeller (URS)
   Lance Johnson (URS)
13) **Ecological Impacts:**
   Lead: Chuck Hanson, PhD (HEI)
   Kristie Karkanen (HEI)
   Alexandra Fraser, PhD (URS)
   Jeannie Stamberger, PhD (URS)
   John Rosenfield, PhD (I)
   Peter Rawlings. PhD (SAIC)
   Craig Stevens (Stevens Consulting)
   Terry Cooke (URS)
   Elizabeth Nielsen (URS)
14) **Risk Modeling and Analysis:**
   Lead: Martin McCann, Jr., PhD (JBA)
   Said Salah-Mars, PhD (URS)
   Ram Kulkarni, PhD (URS)
   Chi-Wah Wong (URS)
15) **GIS Support:**
   Lead: Amy Keeley (URS)
   Douglas Wright (URS)
   Sarah Lewis (URS)

1.3.6 Risk Resources Group

The team included also a Risk Resources Group convened to advise the DRMS team on risk modeling issues in the various topical groups. The Risk Resources Group consisted of the following experts:

Allen C. Cornell, PhD (Stanford University): Risk Analysis, Uncertainty, Seismic Hazard
Gregory Baecher, PhD (University of Maryland): Probability, Reliability, Geotechnical
Des Hartford, PhD: Policy and Risk Analysis, Geotech, Flood
Ralph Keeny, PhD (Purdue University): Decision Analysis, Public Policy
James H. Cowan, Jr., PhD (LSU): Aquatic Fishery
Mark T. Stacey, PhD (UCB): Fluid Mechanics/Hydrology
Michael W. Hanemann, PhD (UCB): Economics
Stuart W. Siegle, PhD: Wetland, Estuarine and Riparian Ecosystem
Mark A. Snyder, PhD (UCSC): Climate Change
Jeff Hart, PhD: Delta Botanicals & Restoration
Chris Kjeldsen, PhD: Delta Botanicals & Restoration

1.4 RELATIONSHIP TO OTHER INITIATIVES

1.4.1 Delta Vision

The role of the Delta Vision initiative (Governor Schwarzenegger's Executive Order S-17-06) is to identify a strategy for managing the Delta as a sustainable system for all environmental and economic services that the Delta provides. The Delta Vision initiative is a significant public process designed to find substantial agreement on recommendations among elected officials, government agencies, stakeholders, subject matter experts, and affected California communities on:

1. The multiple uses, resources, and ecosystem in the Delta that can be sustained over the next 100 years or more
2. The array of public policies and resource management strategies needed to move toward this strategic vision for the Delta
3. A near-term (next 25-50 years) contingency and emergency response plan for a catastrophic event in the Delta.

While the DRMS focuses on the Delta levees and the affects of flooding, the Delta Vision initiative will directly consider the needs of a wide variety of resources and activities within the Delta and Suisun Marsh.

A key principle is to build the Delta Vision initiative around existing Delta planning, technical, and scientific efforts, and avoid creating redundant organizational structures. In this way, DRMS will become a major source of scientific and technical information on the Delta and Suisun Marsh levees. Prior to the Delta Vision initiative, DRMS has already considered and taken on many of the same goals, activities, and functions as the Delta Vision initiative relating to levees. The Delta Vision initiative will build on the information developed from the DRMS effort. The

Delta Vision initiative will use many work groups that will work closely with, and preferably include, subject matter experts from on-going Delta evaluations, such as the DRMS.

A key component of Delta Vision is a Governor-appointed independent Blue Ribbon Task Force that is responsible for recommending future actions to achieve a sustainable Delta. The process includes a diverse Stakeholder Coordination Group and broad public outreach to evaluate different Delta visions and management scenarios. The Task Force will submit a Delta Vision Report by the end of 2007 and a Delta Strategic Plan in October 2008. A recommendation for conveyance should be included in the plan. A Cabinet-level Delta Vision Committee will submit the Delta Strategic Plan to the Governor and Legislature by December 31, 2008.

1.4.2 Bay-Delta Conservation Plan

The BDCP is a Natural Community Conservation Planning effort to address water operations and facilities in the legal Delta. The BDCP will focus primarily on aquatic ecosystems and natural communities, but may also cover adjacent riparian and floodplain natural communities. Among other things, the plan will:

- Provide for conservation and management of covered species
- Preserve, restore, and enhance aquatic, riparian, and associated terrestrial habitats
- Provide clear expectations and regulatory assurances for the water operations and facilities

The results from DRMS will provide levee risk information to inform the BDCP process. BDCP will work on a conservation strategy from early 2007 through late 2008. The Final BDCP is expected to be completed in October 2009.

1.4.3 CALFED End of Stage 1

CALFED is preparing an assessment of performance towards objectives during Stage 1 (first 7 years of implementation) and the likelihood the program will meet its objectives in the future. Levees play a major role in the landscape of the Delta and how the CALFED program is implemented in the future. CALFED will use results of DRMS to inform their planning process.

1.4.4 Other Initiatives

The results of DRMS could prove useful to other initiatives in the region including:

- Delta Regional Ecosystem Restoration Implementation Plan (DRERIP)
- Habitat Management, Preservation, and Restoration Plan for Suisun Marsh (Suisun Marsh Plan) currently being prepared by the Suisun Marsh Charter agencies
- Planning activities by state and federal agencies and local entities
- Other new initiatives

1.5 REPORT ORGANIZATION

Following this introduction, this report contains many chapters and appendices that collectively describe the risk to Delta and Suisun Marsh levees:

- **Chapter 2** provides an overview to the Delta and Suisun Marsh for those unfamiliar with the region. It is based largely on the recent report, *Status and Trends of the Delta-Suisun Services* (URS 2007).
- **Chapter 3** is an overview of the scope of work for the risk analysis.
- **Chapter 4** summarizes the risk analysis methodology.
- **Chapter 5** provides the technical basis for the 2005 Base Case, the current conditions used for the risk analysis.
- **Chapter 6** summarizes the seismic risk analysis.
- **Chapter 7** summarizes the flood risk analysis.
- **Chapter 8** summarizes the wind and wave risk analysis.
- **Chapter 9** summarizes the sunny day high tide risk analysis.
- **Chapter 10** summarizes the response to levee breaches.
- **Chapter 11** summarizes salinity impacts and use of the Water Analysis Module (WAM).
- **Chapter 12** summarizes the consequences modeling.
- **Chapter 13** summarizes the risk analysis for the 2005 Base Case, under the existing regulatory and management practices.
- **Chapter 14** summarizes the risk analysis for future conditions in the Delta and Suisun Marsh.
- **Chapter 15** summarizes the observations from all the analyses.
- **Chapter 16** describes the limitations of the analyses.
- **Chapter 17** provides the references consulted to prepare the report.

The report is supported by 12 TMs that provide background and other technical information used in the risk analyses. The following TMs can be found on the DWR DRMS web site (http://www.drms.water.ca.gov):

1. Climate Change
2. Flood Hazard
3. Seismic Hazard
4. Wind Wave Hazard
5. Subsidence
6. Geomorphology
7. Levee Vulnerability
8. Emergency Response/Erosion
9. Hydrodynamic/Water Management
10. Ecological Impacts

11. Impact to Infrastructure
12. Economic Impacts

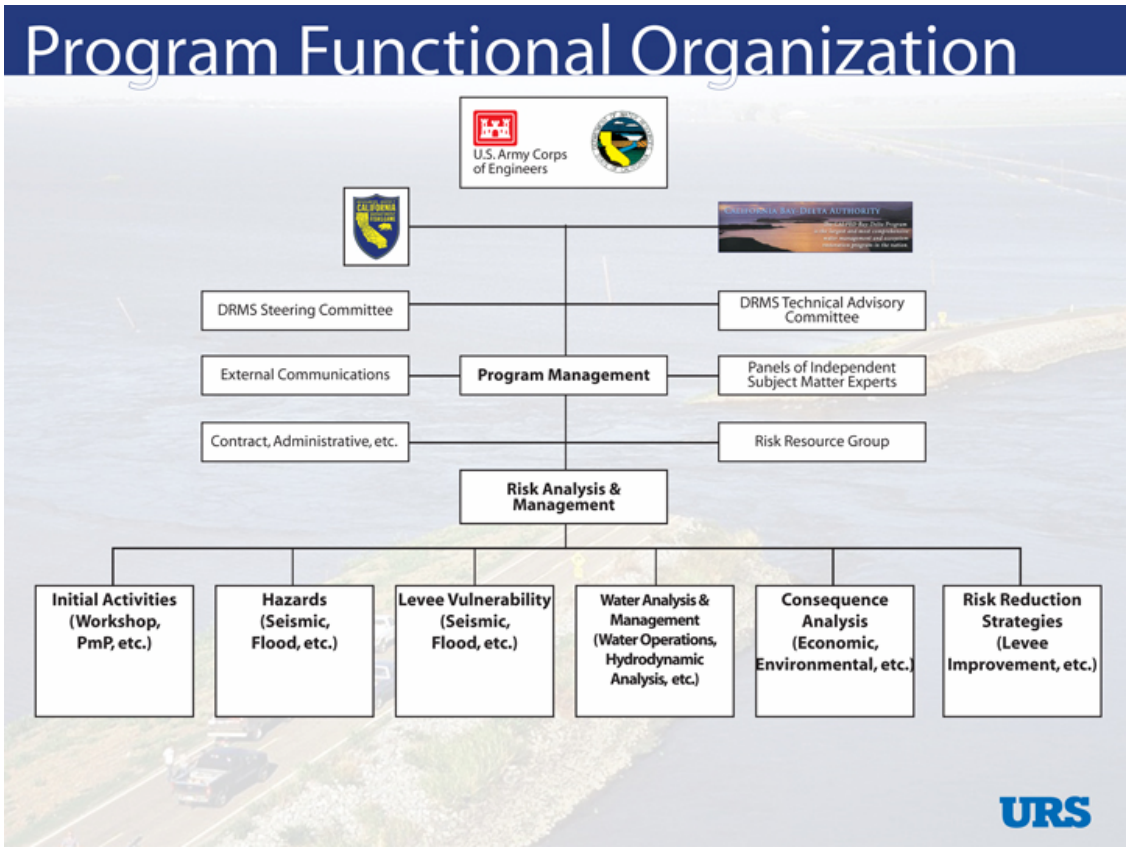


Figure 1-1 Program Functional Organization

2.1 LOCATION

The Sacramento-San Joaquin Delta and Suisun Marsh are at the confluence of the Sacramento River and San Joaquin River basins, which provide drainage to about 40 percent of California (Figures 2-1 and 2-2). Unlike the Mississippi River Delta and other river deltas that form where rivers drop their sediments as they enter the ocean, the Sacramento-San Joaquin Delta is an interior delta with its western side about 50 miles upstream from the Golden Gate. The major rivers entering the Delta are the Sacramento River flowing from the north, the San Joaquin River from the south, and the Cosumnes, Mokelumne, and Calaveras rivers from the east.

The Delta and Suisun Marsh, together with the greater San Francisco Bay, make up the largest estuary on the west coast of North America. The Delta and Suisun Marsh together cover approximately 1,315 square miles in portions of 6 California counties. Although the Delta and Suisun Marsh make only about 1 percent of California's area, the region is at the heart of many of California's resource issues.

2.2 HISTORICAL PERSPECTIVE

About 20,000 years ago, sea levels were approximately 400 feet lower than they are today and the coast line was near the Farallon Islands, about 30 miles west of the Golden Gate and about 80 miles west of the present Delta. About 130,000 years ago, sea levels were as much as 10 feet higher than they are today. During these dramatic swings in sea level, the Delta would have existed in its current location only at times when sea level was near the present day level.

The rich organic peat soils in the Delta and Suisun Marsh built up over about the last 5,000 years as the sea level rose and as marsh plants grew and died in the swampy environment. Because the land was waterlogged and anaerobic (devoid of oxygen), organic soils accumulated faster than they could decompose, forming large expanses of organic soil. The Delta and Suisun Marsh consisted of hundreds of miles of tidally influenced sloughs and channels, and hundreds of thousands of acres of marsh and overflow land. The braded channels surrounded many natural islands. The river systems accommodated large populations of anadromous fish that passed through and spent parts of their lives in the Delta. The region once supported large mammal species such as the grizzly bear, tule elk, and gray wolf. Native Americans hunted, fished, and foraged for food.

During the gold rush beginning in 1849, the Delta waterways were used to transport supplies and prospectors to the gold fields. In the 1850s, farmers began to recognize the great potential of the rich Delta soils. Natural levees existed along some river channels where sediments had been deposited when high water overflowed the channel banks. Farmers began to reclaim the land areas to grow crops by building small levees, 3 to 5 feet high, on the tops of the natural levees. High water periodically caused these levees to fail and some were rebuilt only to fail again.

Large-scale reclamation of the Delta for agriculture began in 1868. Levee building became more aggressive, accomplished with both hand labor and mechanical equipment. Large-scale land development companies were formed with one firm accumulating 250,000 acres. This period of development ended around 1900. By this time, most of the lands with mineral-organic soils had been reclaimed. With the exception of Bouldin Island, lands with organic soils in the central Delta were generally not reclaimed.

The final period of Delta reclamation occurred between 1900 and 1920 on lands in the Delta's interior. These lands contain mostly organic soils, which make levee construction difficult because of their high organic matter. Figure 2-3 shows which islands and tracts were reclaimed from 1868 through 1921. The result of these reclamation efforts is largely what is seen as the Delta today – approximately 700 miles of meandering waterways with levees protecting over 538,000 acres of farmland, homes, and other structures. Many of the levees are considered relatively fragile with respect to today's design and construction standards.

With the construction of levees and draining for agriculture, the organic soils were exposed to the atmosphere since most agricultural practices require an aerated root zone. Some soil has blown away with the wind, some has burned as part of an agricultural process, but the major portion has simply decomposed, producing land subsidence. The aerobic (oxygen rich) condition favors microbial oxidation, which consumes the organic soils. Most of the carbon loss is emitted as carbon-dioxide gas to the atmosphere. In addition, large volumes of organic soil were used for levee construction. Over the past 150 years, as much as half of the original soil volume that accumulated over 5,000 years has disappeared placing much of the Delta 15 feet or more below sea level. Many of the Delta islands and tracts have flooded multiple times. Since 1900, levee failures have flooded Delta islands and tracts 166 times (see Figure 2-4 for historic island flooding since 1900). Some, like Franks Tract, were never recovered.

Significant diversion and modification of stream flows in Delta watersheds began during the gold rush to facilitate placer and later hydraulic mining. The upstream mining sent large volumes of sediment into the rivers that flow to the Delta. Sediment that migrated to the Delta reduced channel capacity and contributed to flooding. The federal government passed the Caminetti Act of 1893 that led to the creation of the Yolo bypass and prescribed Delta levee heights. In 1960, the Sacramento River Flood Control Project was completed by the USACE, improving flood protection for much of the Sacramento Valley and a portion of the Delta. About a third of the Delta levees are part of the Sacramento River Flood Control Project and eligible for USACE's support for rehabilitation. The remaining levees are not part of a state/federal flood control project. The majority of these local levees were constructed by local landowners, reclamation companies, and reclamation districts.

History of Delta Conflict Up to the 1994 Delta Accord

Throughout the 1970s, 1980s, and 1990s, as water users attempted to increase their use of water from the Delta in response to growing demands, conflicts between urban users, agricultural and the environmental water users continued to escalate. This led to a crisis that resulted in the CALFED Bay-Delta Program.

By 1994, Governor Pete Wilson became increasingly concerned about the declining state of the Delta ecosystem, the increasing uncertainty associated with Delta water supplies for urban and agricultural uses, and the increasing amount of rancor and litigation surrounding SWRCB's unsuccessful 16-year effort to establish Delta water quality standards. He led an effort to bring together the numerous federal and state agencies with responsibilities in the Delta, and stakeholder representatives to work toward a resolution of the conflicts over the Delta. In December 1994, the Delta Accord was signed which set interim water quality standards and established the CALFED Bay-Delta Program to develop long-term Delta water quality standards, coordinate operations of the state and federal water projects, and develop a long-term solution for the Delta.

Because of the importance of the Delta levee system, the CALFED Record of Decision in 2000 called for preparation of a Delta Risk Management Strategy. This report summarizes Phase 1 of DRMS.

In the 1970s, the California Legislature recognized that the Delta levee system benefits many segments and interests of the public and approved a preservation plan. The Delta Levee Maintenance Subventions Program (Subventions Program) was established in 1973 and amended by the Delta Flood Protection Act of 1988. The Delta Flood Protection Fund was created to provide for local assistance under the subventions Program and for Special Delta Flood Protection Projects (Special Projects) to protect services such as roads and utilities, urbanized areas, water quality and recreation.

Water development has significantly shaped the inflows to the Delta and changed its hydrodynamics. Construction of upstream dams has lowered peak flows and raised dry weather flows to the Delta, significantly changing the inflow pattern to the Delta. In 1921 the California legislature authorized the development of a comprehensive water plan for the state. This plan was largely complete in 1932 and identified Delta salinity control as a major issue for northern water users and Delta facilities as a major component of the plan. By 1939 the federal government had initiated construction on the Central Valley Project's (CVP) Friant, Shasta, and Contra Costa (Delta) Divisions. A portion of the water for the Delta division was to be exported to San Joaquin River users in exchange for their existing San Joaquin River rights. This arrangement was necessary for two reasons: to allow San Joaquin River water to be exported south and because it was acknowledged that sufficient flow was needed at Antioch and Pittsburg to repel seawater. Work has continued on the CVP for many years, with Trinity Dam completed in 1962. San Luis reservoir completed in 1967, while New Melones reservoir was not completed until 1978.

In 1957, the State of California released Bulletin 3, The California Water Plan. Bulletin 3 called for the construction of dams, canals, pipelines, and significant alteration of northern streams to meet expected water demands south of the Delta. The 1957 State Plan proposed immediate construction of the Oroville Dam and reservoir project on the Feather River. This reservoir was completed in 1967 and is the major storage reservoir for the State Water Project (SWP). Construction of the Delta facilities began in 1963 and included Clifton Court Forebay, the Harvey O. Banks pumping plant and San Luis Reservoir. The initial capacity of the Banks pumping plant was 6,400 cubic feet per second (cfs), later expanded to 10,300 cfs in 1991, although diversion into Clifton Court Forebay is still limited to 6,400 cfs.

Today, the Delta is managed as a fresh water system to support in-Delta agriculture and export water supplies. The changes in hydrodynamics (flow and salinity) have contributed to a significantly altered the ecosystem from 150 years ago. Today, about ¼ of the urban water used in California is diverted from the Delta; about 2/3 of Californians get some portion of their drinking water from the Delta. Also, approximately 3 million acres of agricultural land gets a portion of its irrigation water from the Delta.

2.3 STATUS OF THE DELTA AND SUISUN MARSH

Most of the Delta is agricultural land and most of Suisun Marsh is managed wetlands and other lands managed for waterfowl hunting and conservation. Out of almost 840,000 acres, the 2004 land use consisted of about 9 percent urban, 67 percent agricultural, 14 percent conservation and other open lands, and 10 percent water. Small unincorporated communities and historic towns (Clarksburg, Courtland, Hood, Locke, Ryde, and Walnut Grove) within the Delta's Primary Zone (see Figure 2-2) serve as social and service centers for surrounding farms. A small portion

of Rio Vista lies within the Primary Zone. The incorporated city of Isleton and portions of Stockton, Pittsburg, Antioch, Oakley, Elk Grove, Tracy, Lathrop, Sacramento, and West Sacramento are within or just outside the Delta's Secondary Zone (see Figure 2-2). The expanding cities of Fairfield and Suisun City are encroaching on the edges of Suisun Marsh secondary management area, creating population pressures on all services.

About 65 major islands and tracts in the Delta rely on the levee system. The levee system generally provides low levels of protection for adjoining lands. Most levees have been locally built and maintained. All of the existing services provided by the Delta and Suisun Marsh rely on existing levee system. The *Status and Trends of the Delta-Suisun Services* (URS 2007) provides information on 9 key services (bullet list below). The following provides some observations on the status of the key services:

- Land use (agricultural, urban, and conservation)
  - The Delta includes about one-half million acres of highly productive farmland
  - Since 1990, about 40,000 acres of farmland have been converted to urban and conservation uses
  - About 165,000 dwellings and a population of about 470,000 are within the area protected by Delta and Suisun Marsh levees (2000 census); Delta islands and tracts house only about 26,000 people
  - The region is surrounded by some of the fastest growing areas in California
- Flood management
  - Land subsidence on the interior of islands and tracts has created large areas below sea level; some areas are as much as 25 feet below sea level
  - Levee failures are possible at any time since they hold back water 365 days per year
  - Levee failures during moderate to low Delta inflow times can result in salt water from Suisun Bay flowing upstream as islands flood
  - Land subsidence in some area continues at the rate of 0.5 to 1.5 inches of soil loss per year
- Ecosystem
  - The region provides unique habitat for hundreds of species of resident and migratory fish, birds, plants, mammals, and insects, some listed as federally threatened or endangered species
  - The region is very different from historical ecosystem in which the native organisms evolved
  - The ecosystem is subject to rapid change
  - More than 10 percent of California's remaining wetlands are in Suisun Marsh
  - Biomass in benthic samples typically is 95 percent or more from nonnative species
  - The decline of pelagic (open water) organisms, such as Delta smelt and longfin smelt, has increased concern over the sustainability of the Delta

- Water supply
  - The Delta channels serve as water conveyance for millions of acre-feet of export water per year
  - The Delta is one of few estuaries in the world used as a major drinking water supply
- Water quality management and discharges
  - About 42,500 square miles drain to Delta
  - Water quality can be negatively affected by upstream discharges, in-Delta discharges, and seawater intrusion
  - Both the Delta and Suisun Marsh are managed to control salinity
- Transportation
  - Most corridors serve other areas of the state or nation (highways, shipping channels, and rail)
  - Pipelines crossing the Delta deliver gasoline, diesel and aviation fuel to Northern California, northern Nevada and the Central Valley
  - Transportation within the Delta and Suisun Marsh follows more of a maze pattern than a straight corridor
  - Bridges and auto ferries connect Delta islands
- Utilities
  - A wide variety of utilities (electrical transmission, natural gas pipelines and wells, and water pipelines) cross the area
  - Most utilities serve large areas of the state
- Recreation/tourism
  - Recreation is focused on water-based activities
  - Private land ownership limits land-based recreation
  - The Delta and Suisun Marsh support a wide range of activities including boating, fishing, waterfowl and upland game bird hunting, wildlife viewing, bird watching, sightseeing and photography
- Local and state economics
  - The asset value protected by Delta levees is about $56 billion
  - Areas protected by Delta levees provide more than 205,000 jobs
  - The Delta contributes to statewide economy, especially through water exports

2.4 TRENDS FOR THE DELTA AND SUISUN MARSH

The Delta and Suisun Marsh levees and waterways are a complex network. Water volumes, velocities, salinity, and pollutants all affect the ecosystem, agriculture, and drinking water supply. Changes in one area can create changes in other areas. A number of influences or "drivers," generally beyond human control, may change the Delta-Suisun Marsh in the future (see textbox).

Drivers of Change

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

Key observations about future trends from *Status and Trends of Delta-Suisun Services* (URS 2007) include:

- Land subsidence will continue where organic soils are conventionally farmed.
- Rates of land subsidence can far outpace rates of sea level rise.
- Changes in agricultural management and crop types may help stabilize or increase Delta elevations.
- More pressure will be exerted on levees from continued sea-level rise by at least another 0.6 foot to 1.9 feet by 2100, with a possible additional 0.5-foot rise if the rate of Greenland ice melt increases.
- Sea level rise will increase salinities in the Delta.
- More winter precipitation will fall in the mountains as rain rather than snow (decreased mountain snowpack by as much as 25 percent by 2050).
- Average winter flood flows to the Delta will likely to become larger.
- Natural summer flows will likely to be lower, adding to dry season water supply and quality problems.
- About a 2 out of 3 chance exists of at least one magnitude 6.7 or greater earthquake in the Bay Area before 2032 with potential for multiple islands flooded from levee failures.
- Some islands may remain permanently flooded after a levee failure.
- Species known to be problems in other regions, such as northern pike, zebra mussel, and various aquarium plants, are likely to invade the Delta-Suisun.
- Over the next decade, 130,000 new homes will be built within the Delta-Suisun protected area.
- Urbanization of available land within the Secondary Zone could add 600,000 to 900,000 people.
- Population growth and urbanization will place more demand on the Delta-Suisun's services (recreation, transportation, utilities, water supply, and urban runoff).

- Urbanization will place more pressure on agriculture and other open space uses.
- Urbanization will cover more land and reduce options for future management choices for other resources.

2.5 RECENT GROWTH OF CONCERN

Recognition of the importance of the Delta-Suisun as a changing, dynamic system is growing. Within the past several years, the Delta-Suisun area has gained an unprecedented level of political, public, and funding support.

The CALFED Bay-Delta program environmental documentation culminated in the Record of Decision (ROD) in 2000. The ROD laid out a program to simultaneously meet objectives for water supply reliability, ecosystem, water quality, and levee system integrity. The ROD included the need to prepare the DRMS.

Since the CALFED ROD, billions of dollars have been spent towards achieving the four objectives, although only about 20 percent of the funds identified for Delta levees during the 2000–2007 period were actually made available.

Several events in recent years have heightened concern over the sustainability of the Delta in its current form:

- Many people relate potential levee failures with high winter flood flows in the rivers. Although 7 Delta levees had previously failed during low flow periods, the June 2004 failure of a Jones Tract levee provided a reminder that the Delta levees have water against them 365 days per year and failures at any time are possible. This one island failure resulted in nearly $100 million in repair, recovery and damage costs. The levee failure did not significantly affect the Delta water exports, but highlighted the risks of potential impacts if islands flood in other locations or multiple islands flood at the same time.
- Hurricane Katrina and the resulting damage to the Gulf Coast, and especially flooding in New Orleans, was on the front pages of newspapers and on the evening news for weeks during August 2005. The public, politicians, and scientists and engineers became concerned about potential parallels between flooding in New Orleans and potential flooding in the Delta. While this lesson wasn't necessarily new, it was a vivid reminder about the vulnerability of Delta levees and the possible statewide and national impacts of catastrophic levee failures.
- Although climate change is not a new concept, it has received wide attention since the turn of the century. California's climate is expected to become warmer during this century. Climatologists have already documented changes in California's climate during the latter half of the 20th century. By the end of the century, depending on future heat trapping emissions, statewide average temperatures are expected to rise between 3 and 10.5 °F. Estimates indicate that more winter flooding will occur and that sea levels will continue to rise. Both these pose significant threats to the Delta levees.
- On the basis of research conducted since the 1989 Loma Prieta earthquake, the U.S. Geological Survey (USGS) and other scientists conclude that a 62 percent probability exists of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2032 (USGS Open-File Report 03-214). It can

be noted that no Delta levee has ever failed from an earthquake. However, the current network of levees has not experienced a large earthquake. While the 1906 magnitude 7.8 San Francisco earthquake was a significant event, levees were not as tall as they are now. The last 100 years of land subsidence has made the Delta islands deeper and resulted in building the levees higher. These levees now are more susceptible to failure during an earthquake than they were in 1906.

- Preliminary estimates by DWR (2006) indicate potential $30 billion to $40 billion statewide loss from a large earthquake causing significant levee failures and island flooding. Such an event could lead to multiyear disruptions in water supply, water quality degradation, and permanent flooding of multiple islands. Much of this cost comes from the realization that a significant portion of the state's water supply would be vulnerable to massive levee failures.
- Since the CALFED ROD for the 2000 Programmatic Environmental Impact Statement/Report, a continued pelagic organism decline has occurred in the Delta. These are open water organisms such as Delta smelt and longfin smelt.
- The varied success of implementation of the CALFED Bay Delta Program have caused some to question whether it is possible to achieve all four CALFED objectives at the same time. The four CALFED interrelated objectives are:
  - **Levee System Integrity** – Reduce the risk to land use and associated economic activities, water supply, infrastructure and the ecosystem from catastrophic breaching of Delta levees.
  - **Ecosystem** – Improve and increase aquatic and terrestrial habitats and improve ecological functions in the Bay-Delta to support sustainable populations of diverse and valuable plant and animal species.
  - **Water Supply Reliability** – Reduce the mismatch between Bay-Delta water supplies and current and projected beneficial uses dependent on the Bay-Delta system.
  - **Water Quality** – Provide good water quality for all beneficial uses.
- CALFED is currently reevaluating its program after the first 7 years of implementation and considering whether its preferred alternative is capable of meeting the four objectives
- Recognition is also growing that prior Delta planning efforts have been too narrowly focused on a few resources and haven't adequately included the many Delta uses and resources.
- In AB 1200, the Legislature found and declared the following:

  (a) Substantial water supplies are derived from the Sacramento-San Joaquin Delta for the greater Silicon Valley area, Alameda County, eastern Contra Costa County, Napa County, Solano County, the San Joaquin Valley, and southern California.

  (b) In a document entitled "Seismic Stability of Delta Levees," the DWR estimated that a single 100-year earthquake would result in 3 to 10 delta levee breaks and that a single 1,000-year earthquake would result in 18 to 82 delta levee breaks.

  (c) A report to the California Bay-Delta Authority Independent Science Board estimated that sea-level rise caused by climate change, continuing subsidence of Delta lands, floods, and earthquakes have a 64 percent probability of resulting in catastrophic flooding of Delta

islands over the next 50 years. The state's economy, and the governmental programs that are dependent on a healthy economy and a healthy environment, cannot afford a catastrophic disruption of the water supplies derived from the Delta (Mount et. al. 2006).

All of these concerns have combined to new action on making the Delta more sustainable into the future. Although knowledge about the area is growing, the area's complexity continues to present data gaps and uncertainties. New studies and initiatives aimed at making the area, and its services, sustainable are under way. Some of the actions that have been taken to address these concerns within the past few years include:

- In November 2006, California voters entrusted DWR with about $5 billion in new bond funds for flood management, a portion of which will be available for the Delta
- DRMS work was initiated to evaluate the risks associated with levees in the Delta and Suisun Marsh and evaluate ways to mitigate that risk
- The Delta Vision initiative was initiated to devise a strategy for the Delta and Suisun Marsh sustainability that considers all services
- The Public Policy Institute of California (2007) evaluated nine alternatives and concluded that several promising alternatives deserve more study; all are different than the current system

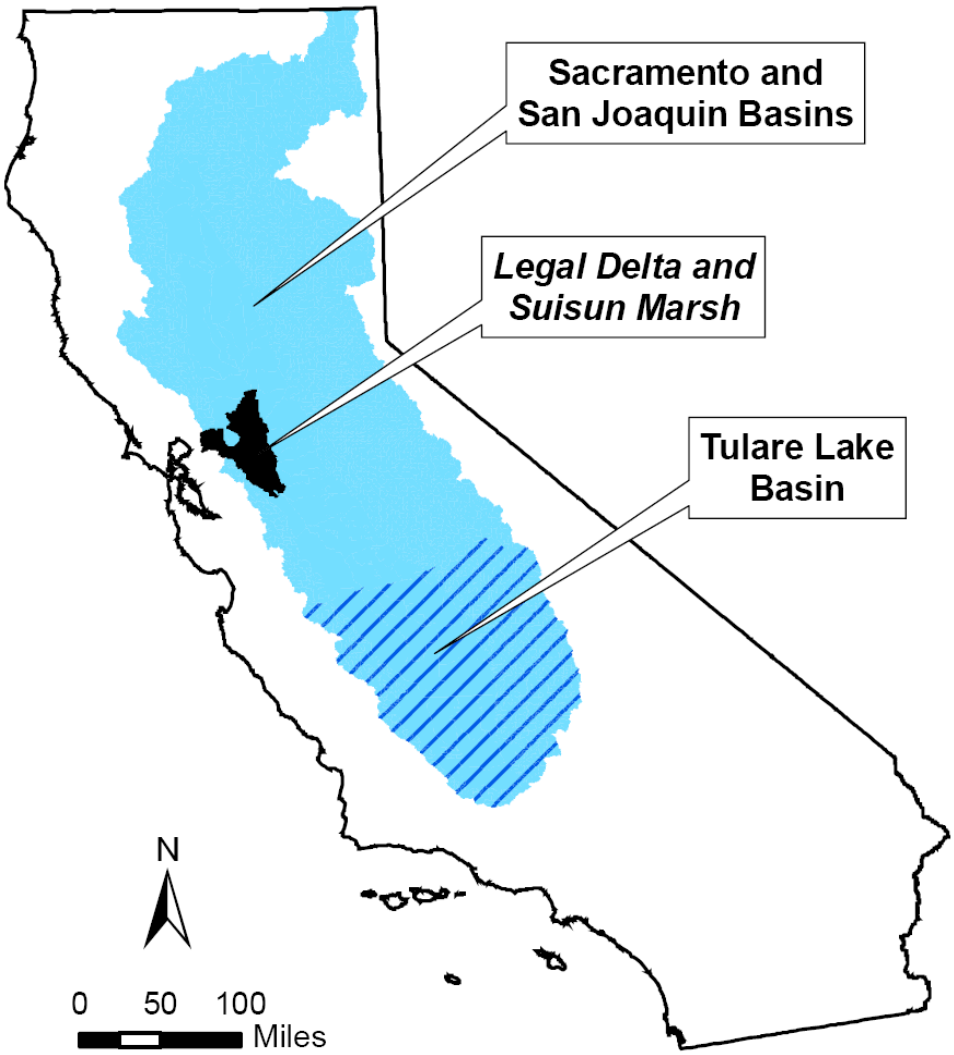
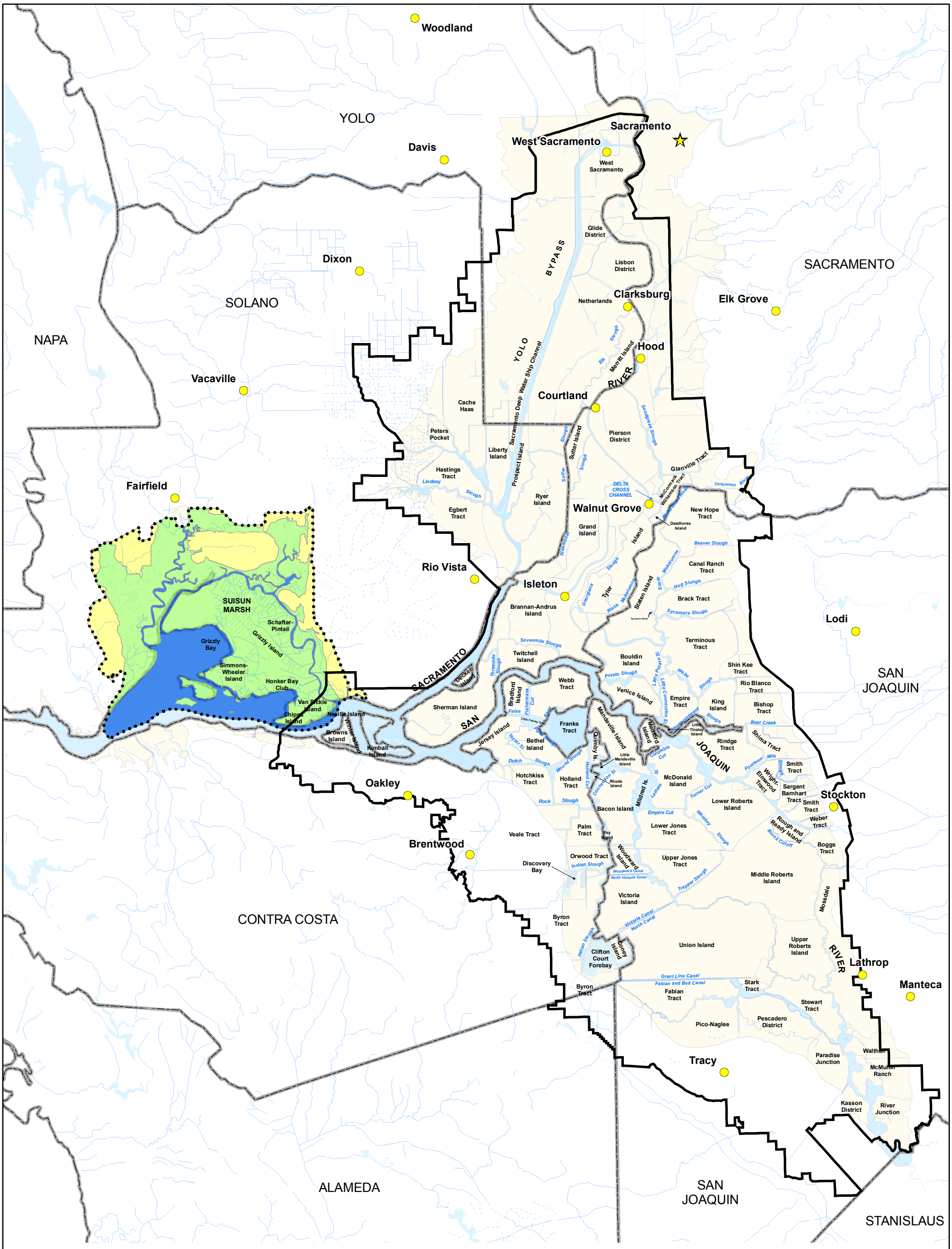


Figure 2-1 Watershed for Delta and Suisun Marsh



Legend

- CA Counties
- Legal Delta
- Suisun Marsh

Suisun Marsh:

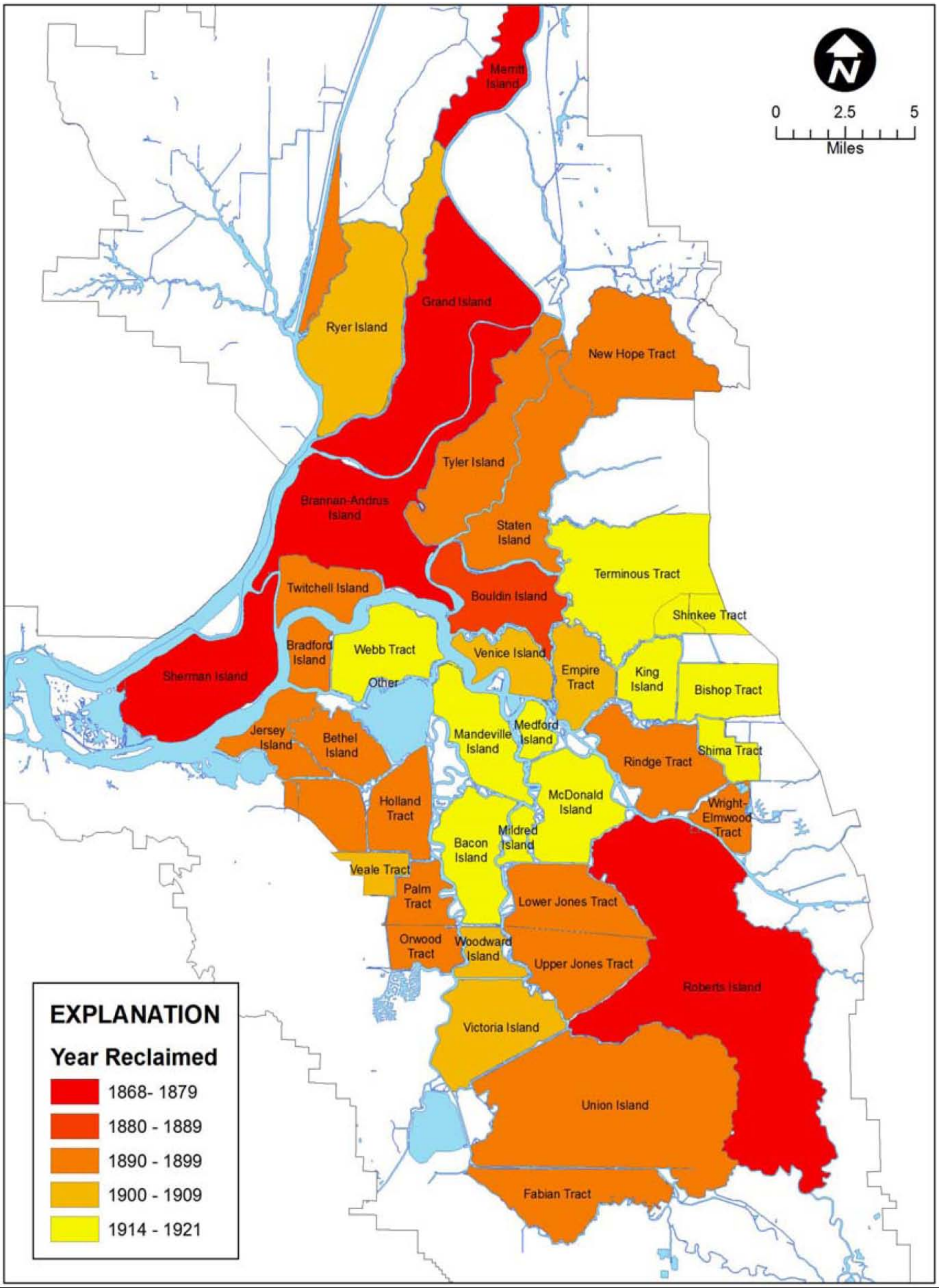
- Primary Management Area
- Primary Management Area - Water
- Secondary Management Area

- Intermittent canal, ditch, aqueduct, stream, river, or wash
- Perennial canal, ditch, or aqueduct; stream, river; reservoir
- CA Water

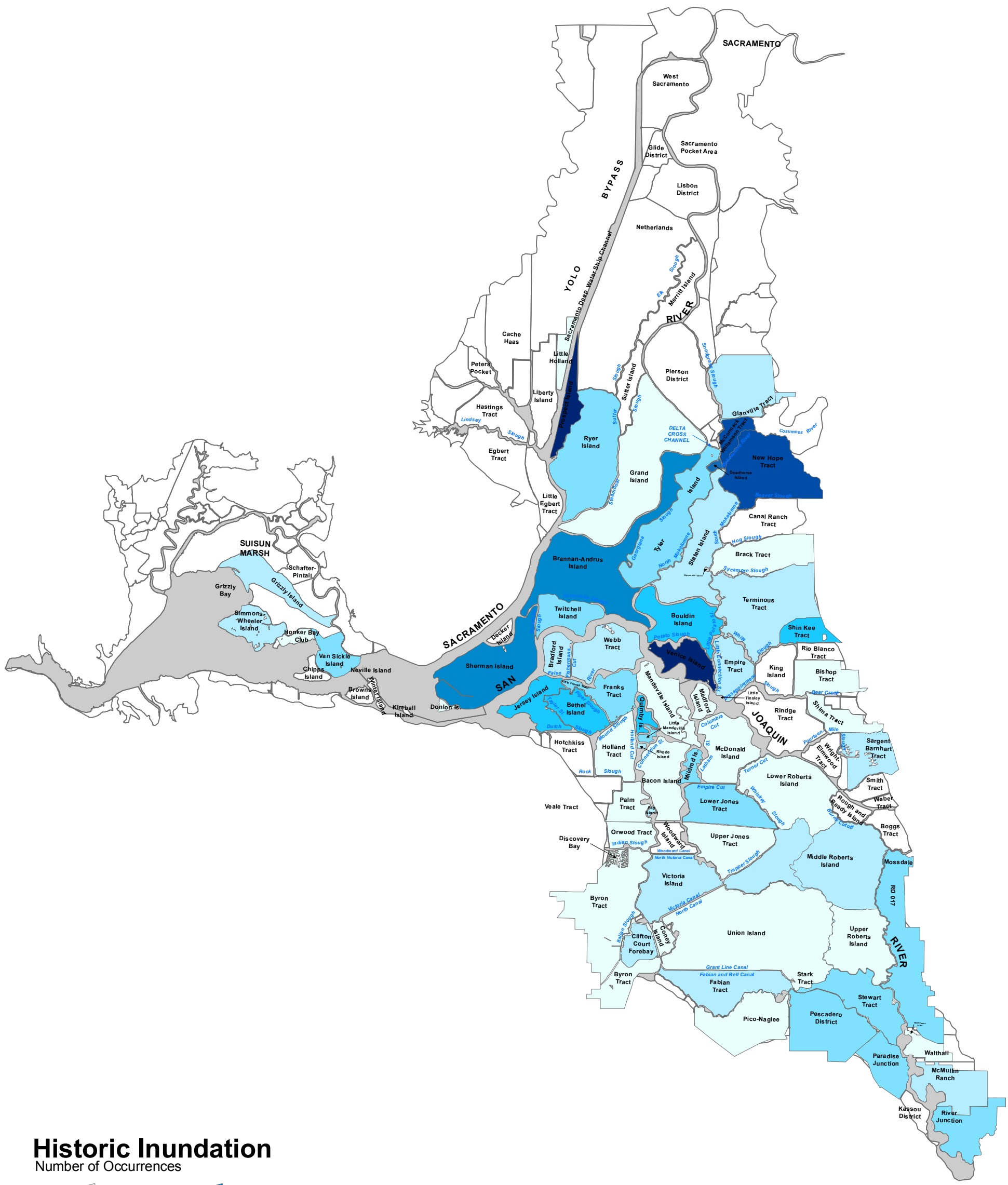
0 5 10 Miles

URS	DRMS	Delta Islands & Sloughs	Figure 2-2
	26815431		

URS Corporation P:\GIS\GIS_Project_Files\MXD\Current Working Documents\Infrastructure\tech_memo_R1_010507\2-1 delta islands and sloughs.mxd Date: 1/5/2007 9:14:10 AM Name: smlewis0



Delta Risk Management Strategy (DRMS) Levee Fragility		Year of Initial Drainage	Figure 2-3
URS	Project No. 26815621		



URS	DRMS	Historic Island Flooding in the Delta and Suisun Marsh Since 1900	Figure 2-4
	26815431		

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In this analysis, risk is defined as the likelihood (frequency) of adverse consequences that could occur as a result of levee failures in the Delta. Quantitatively, risk is defined in terms of three entities; loss or consequence, frequency of occurrence and probability as a measure of uncertainty (Kaplan and Garrick 1981). While the focus of the DRMS is the analysis of risk as defined above, it is worth noting that the events that are modeled may involve benefits, such as potential changes for the ecosystem.

This section defines the scope and the limits of the risk analysis, especially what is included in the analysis and what is not included. The DRMS project is not a planning study, rather it is and quantitative analysis of risk and alternative risk-informed strategies for managing the Delta. By itself, this information will not be the basis for future decisions with respect to managing the Delta, nor will it provide planning-type information to guide design activities. The risk analysis results and the identification of risk-informed management strategies will inform the Delta Vision initiative, BDCP, the assessment of CALFED End of Stage 1, and other initiatives.

3.1 OVERVIEW

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

3.2 GEOGRAPHIC AND EVALUATION SCOPE

With respect to the evaluation of levee systems, the geographic scope of the DRMS risk analysis includes the area of the Delta and Suisun Marsh:

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

This area is identified on Figure 2-2 and is the area within which the failure of levees and island flooding, including impacts on infrastructure, are evaluated. However, the consequences of levee failure within this area can extend well beyond the boundary defined above to other regions and the entire state. For example, while outside the Legal Delta, parts of Sacramento could be flooded as a result of levee failure in the Delta. Therefore the economic impacts of levee failures are evaluated for the entire area that could be flooded because of a failure of any levees within the Delta and Suisun Marsh.

An assessment of risks and the evaluation of risk management strategies must be made on the basis of the current state-of-knowledge (information, data). To the extent the present state of

knowledge is incomplete, making an assessment of risk is uncertain. The effect these uncertainties have on the study results will be included in the assessment. This analysis of risks associated with Delta levee failures is a complex and significant undertaking. The following precepts guide the Delta risk analysis:

- The DRMS project must be carried out, for the most part, using existing information (data and analyses). The project schedule does not afford the opportunity to conduct field studies, laboratory tests, or research investigations.
- The analysis should include an assessment of the epistemic uncertainty in the analysis that reflects the uncertainty associated with the current state of knowledge (data, information and engineering and scientific understanding) with respect to the events and consequences that are modeled.
- Measures of risk (e.g., risk metrics) should be assessed that reflect the impacts (e.g., public health and safety, economic, environmental) that must be considered in the evaluation of risk management strategies called for in AB 1200.
- A "business-as-usual" (BAU) approach will be taken to guide the analysis with respect to modeling the current risk as well as in making projections of future risks. This approach assumes that existing regulatory and management practices are carried forward into the future. More discussion on BAU and its influence on the risk analysis can be found in Section 3.4.

3.3 DELTA DYNAMIC AND FUTURE

Several factors, or drivers of change, will affect future conditions in the Delta-Suisun. These are factors like forces of nature over which little human control exists, such as earthquakes, or factors like urbanization for which no single oversight exists given existing regulatory and management practices. The Delta and Suisun Marsh is facing changes that may be gradual or sudden.

- **Subsidence** – Land subsidence has placed most of the Delta land below sea level. Subsidence varies with location, but rates of 0.5 to 1.5 inches of soil loss per year are common in the Delta. This historical subsidence has left multiple islands with average land elevations as much as 15 feet or more below mean sea level. Several islands have areas as great as 25 feet below sea level. The dramatic reduction of land elevation on Delta islands has increased the differential head between landside and the water surface elevations in the channels. Although the areal extent and rate of subsidence of Delta islands and tracts have reduced in recent years, subsidence is still continuing in many areas. Continued subsidence will increase levee vulnerability and add to both the chance of levee failure and consequence of levee failure.
- **Global Climate Change and Sea Level Rise** – Sea levels have been rising for approximately the past 20,000 years, but the rate appears to have increased during the past century. Current estimates by the Intergovernmental Panel on Climate Change indicate that sea level will rise by about 0.6 foot to 1.9 feet over the next 100 years, with a possible added 0.5 foot if the rate of Greenland ice melt increases. Other estimates predict even more rise. If levees are to be maintained, the continued enlargement of the levee system is required and both the chance of levee failure and consequences of levee failure are increased.

- **Regional Climate Change and More Winter Flooding** – By the end of the century, depending on future heat trapping emissions, statewide average temperatures are expected to rise between 3 and 10.5 °F. The estimates show more winter precipitation occurring as rain and less as snow, leading to more winter flooding. Higher flood stages in the Delta would increase the chance of levee failure and consequence of levee failure.
- **Seismic Activity** – On the basis of research conducted since the 1989 Loma Prieta earthquake, the USGS and other scientists conclude that a 62 percent probability exists of at least one magnitude 6.7 or greater quake, capable of causing widespread damage, striking the San Francisco Bay region before 2032 (USGS Open-File Report 03-214). This shaking has the potential to fail multiple levees in the Delta.

3.4 BUSINESS AS USUAL

During the Phase 1 analysis, various predictive models of future stressing events and their consequences are estimated. The events resulting from uncontrollable natural and physical processes are estimated using engineering and scientific tools readily available or having a broad consensus among the practicing community. Such events include the likely occurrence of future earthquakes of varying magnitude in the region, futures rate of subsidence given continued farming practice, the likely magnitude and frequency of storm events, the potential effects of global warming (sea level rise, climate change, temperature change) and their effects on the environment. The estimate of risk to the Delta and the state will be made for the 50-, 100-, and 200-year projections. It becomes apparent that projections and/or assumptions defining the future "look" of the Delta be established. The Delta will change in the next 50, 100, and 200 years. The question facing the DRMS project is: what type of Delta one should assume in these future year projections.

Again recognizing that risk-informed decisions will be made to shape the Delta of the future, one must establish for the Phase 1 risk analysis the BAU scenario. Defining a BAU Delta is required, since one of the objectives of this work is to estimate whether continuation of existing management practices provides for a sustainable Delta for the foreseeable future. Furthermore, setting a BAU scenario helps establish an unbiased measure of risk for the Delta and removes potential speculations.

The BAU scenario can only be defined as far as the limited duration of existing agreements, policies, and practices, and hence longer time spans may not be covered by such policies or apply for current practices. The study assumes that current policies and practices are maintained to the extent possible for the longer periods of time (50, 100, and 200 years). Exceptions to this assumption may potentially arise in conditions where the changes in the Delta overwhelm the financial and human resources normally devoted to maintaining the Delta. Examples are presented below to illustrate these potential conditions.

Furthermore, instances will occur where procedures and policies may not exist to define standard emergency response procedure during a major (unprecedented) stressing event in the Delta or restoration guidelines after such a major event. In such conditions, prioritization of action will be based on: 1) existing and expected future response resources, and on highest value recovery/restoration given available resources.

Below are some examples illustrating the development of the BAU scenario:

- **Flood Protection** – Flood protection levees will be maintained in urban areas to provide the same level of protection (e.g., 100 year flood) for the period of study considered (e.g., 50, 100, 200 years from now).
- **Delta Levees** – Levees in the Delta will be maintained in accordance with current maintenance practices as defined by available and reasonably projected resources. That is, it will be assumed that current trends in subvention and special projects funding will continue at the current rate. For example, should the expected sea level rise by several feet in the next 100 years and beyond, raising the levees to keep up with the sea level rise will not be considered as BAU. The resources and funding required to built and maintain several feet taller levees will clearly exceed the current and expected future available resources.
- **Emergency Response (Levee Repair)** –- During a major disruption to the Delta (earthquake, flood, etc.), the emergency response as it relates to the repair of levees (breaches and nonbreach damage) will be limited by the available human and financial resources at the time. As an example, if tens of levees breach during a major event in the near future, the state, federal, and local entities may not have enough resources to reclaim them all. The remaining islands will be stabilized to prevent future deterioration. The islands selected for full recovery will be based on the highest benefit for the available resources (public health and safety, infrastructure, water supply and water quality, habitat, etc.). Furthermore, during a flood fight, prioritization may be considered, depending on available resources, to protect those islands with highest opportunities first.
- **Delta Improvements** – Delta Improvements in the planning stage will be considered if those projects are funded and approved in the 2006 calendar year. Planning studies under consideration for future years will not be considered in the Phase 1 risk analysis. Such examples include: the planned upgrades of the levees to bring them to a PL84-99 status, or other south of Delta improvement planning studies. Although, these potential projects will not be considered in the BAU scenario for Phase 1, they will be included in the risk reduction evaluation in Phase 2. They may likely turn out to be prime candidates for improvements.
- **Land Use** – Urbanization and land use for the phase 1 BAU scenario will be based on the assumption that the Delta's Primary Zone will continue to be free from urban development. However, development in the Secondary Zone will continue at the current trend based on current and projected urban development plans.
- **Habitat Restoration** – A certain level of habitat restoration has been underway for 5 years. The analysis assumed a static ecosystem without further increases in restoration.
- **Water Operations** – Operations following an event in the Delta will be based on current project operating procedures (including reservoir operation guidelines, any formalized standing orders and emergency procedures, pre-action consultation procedures with fisheries agencies or others) and stated priorities as expressed to the DRMS team by the State Water Board staff. These water allocation priorities are first for human health, and second for endangered species to the extent mechanisms exist to implement them, and then other uses according to water rights.

Major levee failures are difficult and expensive to repair. The recent 2004 failure of a Lower Jones Tract levee caused about $100 million in damage and repair costs. Multiple levee failures

caused by a single earthquake or flood would have a devastating effect on the Delta and on the entire state economy. All of the Delta and Suisun Marsh services would be impacted.

3.5 HAZARDS AND ENVIRONMENTAL FACTORS

The risk analysis focuses on natural hazards that have the potential to cause the failure of levees and subsequent flooding of islands. The specific hazards considered in the analysis include:

- Floods
- Earthquakes
- Sunny day failures (nonflood flow)
- Winds/waves

The analysis considers appropriate combinations of these hazards (e.g., an earthquake followed by a flood or a wind/wave event). Time dependent processes (such as subsidence and climate change) that impact the frequency of and severity of future hazards or impact the vulnerability of Delta levees are analyzed as characteristics of the Delta environment in each given analysis year.

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

3.6 CONSEQUENCES OF LEVEE FAILURES

The consequences of levee failures are many:

- Risks to life and safety
- Damage to residences
- Damage to businesses
- Damage to public buildings and disruption of public services
- Damage to contents of structures
- Damage to utilities
- Damage to transportation corridors
- Change in Delta salinity
- Changes in ecosystem conditions that can have a wide variety of impacts
- Disruption or cessation of in-Delta and export water supplies

- Loss of crops and future agricultural production
- Loss of use for residences, businesses, utility infrastructure, recreation, etc.
- Repair and recovery costs including debris removal
- Additional loss to the economy through economic linkages
- Potential permanent flooding of some island and tracts or portions of islands and tracts

These are discussed in more detail in Chapter 12.

3.7 ESTIMATING RISK IN THE FUTURE

AB 1200 called for DWR to estimate potential impacts on water supplies derived from the Sacramento-San Joaquin Delta based on 50-, 100-, and 200-year projections. Estimating conditions even 10 years into the future is difficult, if not impossible for some aspects of risk, especially since these evaluations are based only on readily available information.

However, after evaluating risk under the 2005 Base Case (Chapter 13), the report projects future risk (Chapter 14) based on best available information. Like any projections of this type, they should be relied upon only until better information becomes available to make better estimates.

The overall purpose of the DRMS risk analysis is to assess the likelihood of future adverse performance of Delta levees (their failure and subsequent island flooding) and the economic, environmental and public health and safety impact these failures may have on the Delta itself and California as a whole.

To start, this section describes the risk problem being evaluated, the elements of the risk analysis, and the risk methodology. As part of the discussion, Delta risks not addressed are also identified.

4.1 THE RISK PROBLEM

As a first step in presenting the risk analysis methodology the "risk problem" being evaluated is described. As discussed in Section 2, the DRMS study is intended to evaluate the risks associated with levee failures in the Delta and Suisun Marsh. The hazards or stressing events that can cause levee failure are defined by AB 1200 and are identified in the DRMS project work scope.

The DRMS study must also provide an assessment of how risks may change into the future (over the next 200 years), taking into account environmental factors such as subsidence and climate change that change the landscape of the Delta, changes in the potential for future hazards (i.e., earthquake occurrences, flood events), population growth and development in the Delta, reliance of the state on the Delta as a water source, etc. An analysis of future risks is limited by the availability of future projections in key topical areas. Nonetheless, short-term information projects (to 2030 or 2050) are available in many areas and can be used, making it possible to assess trends with respect to future risks. The approach for considering future risks is discussed in Section 4.8 and those risks are evaluated in Section 14.

4.1.1 Risks Evaluated in DRMS

Like any region or community, the Delta and Suisun Marsh (residents, the ecosystem, businesses, recreational users, etc.) face a number of varied threats and risks. The region is unique in terms of the hazards that threaten it (earthquakes, floods, winds, industrial hazards, etc.) and the exposure to loss, which includes the local population, a valued ecosystem, local and regional infrastructure, statewide water users, etc. A partial list of Delta risks includes:

- Effects of natural hazards such as seismic events, floods, wind waves, etc. on Delta infrastructure (exclusive of levees)
- Levee failures that may occur due to any number of different causes (natural hazards, intrinsic forces and random processes that contribute to random failures) and their effects on individual islands, the environment, state water supply system, etc.
- Events or processes that contribute to the observed pelagic organism decline in the Delta and Suisun Marsh and the related or additional impacts of invasive (nonnative) species
- Industrial accidents (i.e., oil or gas spills, shipping accidents, etc.)
- Highway and rail transportation accidents leading regional road closures, toxic spills, etc.
- Public health and safety risks (disease, exposure, crime, etc.)
- Recreational (boating) accidents
- Among numerous others

Of the risks facing those who live or depend on the Delta and Suisun Marsh, the DRMS is addressing only those associated with levee failure. Other prevailing risks are not addressed.

4.1.2 Modeling Levee Failures and Response of the Delta

An analysis of any system, natural or human-made, involves a characterization of the events/processes of interest (a conceptual model). This characterization is followed by the development of a model, an analytic tool, that is a quantitative representation of the events of interest and that serves as the basis for prediction. A model is a representation of the real-system and how it performs or reacts to the stressors or conditions it may be exposed to. Such a representation is limited by the state-of-knowledge (scientific understanding, data, etc.). As a result a model is an approximation of the real world. In this same sense, the DRMS risk analysis is a model of the events that can lead to levee failure and the events that ensue, including levee damage, the hydrodynamic response of the Delta to levee breaching and island flooding, and the consequences of these events.

As a first step in presenting the DRMS risk analysis approach, a summary of the events that are modeled is provided. This summary starts with seismic events, and is followed by a description of hydrologic events, and lastly normal or sunny day levee failures. Figure 4-1 shows an influence diagram of the basic elements of the DRMS evaluation for seismic events. These elements are discussed below.

Seismic Events

The evaluation of Delta seismic risks requires consideration of the earthquake hazard, performance of levees, repair of levee damage and breaches, hydrodynamic response of the Delta to island flooding, and the direct and statewide consequences of these events.

Seismic Hazard –Considerable potential exists for earthquakes to occur in or near the Delta that could impact the stability of levees. For purposes of estimating risk, and in particular the potential for catastrophic events, the performance of Delta levees must be considered on an event-by-event basis (an earthquake occurring on a particular fault, at a particular location, and of a given magnitude). Each earthquake and the spatial field of ground motions it generates, is random and at the same time unique from one event to the next. The dependence of ground motions on fault location (relative to the Delta levees), fault type, and the spatial field of correlated ground motions are important factors in estimating the performance of spatially distributed systems (such as Delta levees) (Bazzuro and Baker 2006). Consideration of the spatial field of ground motions that may occur throughout the Delta is particularly important in analyzing the consequences from large events that may cause simultaneous breaching and flooding of many areas.

Seismic Fragility – Historic performance of levees during seismic events demonstrates the potential for damage over extended lengths along a levee and breaching (in the case of levees with water up against them at the time of the event). Depending on the size of the earthquake, this damage can involve considerable disruption of the levee and its foundation and occur over extended lengths of the levee system, as was seen in 1940 in the Imperial Valley.

Given the occurrence of an earthquake in or near the Delta, the performance of a levee can be characterized in one of three mutually exclusive states:

- **OK (no significant damage)** – An island is modeled as OK, if neither damage nor failure has occurred anywhere along the levee system that protects an island. A levee system that is OK does not require repair following the earthquake.
- **Substantial, nonbreach damage** – If any part of a levee system experiences damage, but no failure of any section occurs (i.e., no breaching), no flooding occurs, but the levee will require repair soon after the earthquake. The extent of damage (the number of lineal feet that is damaged) is a function of the levee vulnerability class (see Section 6).
- **Failure (breach)** – A breach in a part of a levee system causes an island or land tract to flood.

In the Delta, an island or tract is protected by a collection or system of levee reaches. For example, over 126,000 feet of levee protects Sherman Island. This system of levees, which varies in its characteristics around the island, is modeled to evaluate whether a failure (and flooding) occurs anywhere along its full length. In the DRMS analysis, a levee system that protects an island is divided into a series of levee sections based on vulnerability class (levee characteristics). Each section is analyzed for damage or failure. See Section 6 for a description of levee seismic vulnerability classes.

The extent of levee damage that occurs is based on the assumption that performance of contiguous sections of levee that belong to the same vulnerability classes are perfectly correlated, and as a result, the entire vulnerability class will be damaged. Thus, when an earthquake occurs, the potential exists that an extensive length of levee will be damaged; an entire contiguous section in a particular vulnerability class may be a mile or more long on a given island. This scenario conforms to empirical experience – as was seen in 1995 in Kobe, Japan.

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

When the risk model considers that one or more levee sections have breached, it is assumed the entire length of levee belonging to the same vulnerability class is also damaged. That is, for modeling purposes a given vulnerability class is assumed to have a single breach[1] and nonbreach damage over its remaining length. In other vulnerability classes on the same island, the potential for other breaches and/or nonbreach damage is also modeled, allowing for the possibility of multiple breaches on an island. The important recognition in the levee seismic performance model is that when a breach occurs, other levee reaches are also assumed to be damaged and must be repaired to make the island's levee system functional again. Thus an island may have

[1] Here the working model of a breach is associated with a localized erosion of a levee section (due to internal erosion or overtopping) that results in an opening that leads to island flooding and formation of a scour hole that must be repaired.

only a portion of its levees seismically damaged, or it may have the majority of its levees damaged following an earthquake.

Emergency Response and Repair – In responding to a seismic event, repairs will be initiated to stabilize nonflooded islands first, followed by repair of breached and flooded islands. In the case of flooded islands, protection/repair must also be provided for the exposed interior levee slopes that are subject to ongoing erosion due to wind wave effects.

For a given sequence involving damaged but nonflooded islands, and flooded islands, a priority system directs efforts first toward islands that have nonbreach damage – that is, islands with levee reaches that are damaged, but have not yet flooded. The immediate goal is to prevent flooding of additional islands.

In the case of a seismic event, stabilization or repair of (nonbreached) damaged levees is more extensive than minor buildup of material on the remnants of the damaged levee. Large volumes of material and significant work times are required. Thus, for an event that involves many islands that have been damaged and/or flooded, an island that is low on the priority list may have to wait a substantial time to receive attention from marine repair resources. As a result, it has a significant likelihood of failure before its nonbreach damage is repaired.

When all nonflooded islands have been repaired, emergency response efforts are turned to flooded islands. Each flooded island is addressed in priority order – its breach ends are capped, the breaches are closed, interior slopes are protected and/or repaired, other damage is addressed and the island is pumped out.

Salinity Impacts – For any seismic sequence that results in one or more levee failures, the Delta salinity impacts are evaluated based on the specific islands that have flooded, the breach locations, the repair schedule for breach closures and island pump out. The evaluation of salinity impacts is considered with respect to the effects on in-Delta water use, suitability of water for export, management of upstream and south of Delta reservoirs, and south of Delta deliveries.

Hydrologic Events

The modeling of the performance of Delta levees to the hazards posed by hydrologic events (floods) is similar to that for earthquakes, with a few exceptions. As has been the case historically, floods can result in multiple island failures (for example 1986, 1997, etc.). Following these events, the risk model computes the efforts to close the breaches and dewater the islands.

Hydrologic events have two primary differences with respect to seismic events. First, when Delta islands breach as a result of hydrologic events, other damage that might occur is assumed to be relatively minor and is not modeled. Thus it is assumed that nonbreach damage does not require emergency repair. However, erosion of levee interiors as a result of wave action is considered and does require emergency repair.

A second difference has to do with the hydrodynamic response of the Delta during and following a hydrologic event involving levee failure. Hydrodynamic calculations for flood events involving 20 and 30 island failures (numbers that far exceed historic experience) indicate little possibility of salinity intrusion impact that adversely affects Delta water quality and export, irrespective of the time of year or water year types. As a result hydrodynamic evaluations following flood-initiated levee failures have not been modeled.

Normal Events

Historically, normal or sunny-day levee breaches (nonflood, nonseismic initiated failures) occur from time to time (e.g., Jones Tract, June 2004). Historically, these events have occurred as single isolated events involving individual islands, usually associated with an unusually high tide. They do represent some potential for impacting adjacent islands due to increased seepage or as a result of erosion of levee interiors on the flooded islands due to wave action or overtopping of low spots (e.g., Jones Tract). If additional breaches do occur (due to wave action for example), adjacent islands may be exposed to wind wave effects associated with the additional fetch that may exist and thus possible erosion. In this analysis, the potential for additional levee failures following an initial sunny day breach is not modeled. Based on historic experience the annual frequency of occurrence of sunny-day failures for an individual island is low compared to other initiators of failure under present (2005) conditions. As a result, the possibility of yet further (secondary) failures that follow these events is also low and thus not considered.

For sunny-day failures, which can occur on any island, breach repair and levee interior erosion protection and repair is modeled and considered in the cost of the event.

Analysis of salinity impacts for single island failures in the Delta indicate they are limited and do not compromise water quality for any extended period of time. As a result, hydrodynamic evaluations for single island failures are not performed. (Note, this case also applies to single island seismic as well as normal events.) This scenario contrasts with the historic experience on Brannon-Andrus in 1972, when significant salinity intrusion and a noticeable water supply disruption occurred. On the overall scale of risks, even that level of disruption (less than three months) is set aside here as an essential analytical simplification.

4.2 ELEMENTS OF THE RISK ANALYSIS

Figure 4-2 shows a schematic of the elements of the risk analysis and their basic relationship. The figure and subsequence descriptions are oriented principally with respect to the evaluation of external hazards such as earthquakes, floods and/or winds. For levee failures that occur during normal conditions ("sunny-day levee breaches"), the elements of the risk analysis are essentially the same. The exception is the fact that varying levels of loading and fragility (conditional probability of failure) do not apply.

The following summarizes the various elements of the risk analysis.

Hazard Analysis – The purpose of the hazard analysis is to estimate the frequency of occurrence and the magnitude of hazards that may impact Delta and Suisun Marsh levees. In the case of seismic events, the hazard will be characterized in terms of peak ground acceleration. For floods, the hazard is defined in terms of the peak water-surface elevation at a levee. The characterization of the hazards takes into account their correlated spatial distribution that a representation of the simultaneous loading (forces) that can occur for all levees throughout the Delta and Suisun Marsh. For example, the seismic hazard analysis estimates the ground motions throughout the study area that will occur as a result of each relevant earthquake event (e.g., an earthquake of a given magnitude, which occurs on a specific fault).

Levee Vulnerability Analysis – Given the occurrence of a hazard, the levee vulnerability analysis estimates the conditional probability of levee breach or damage as a function of the hazard characterization parameter (e.g., peak ground acceleration for seismic events or peak

water-surface elevation for floods). Since the hazard level that causes failure is not exactly known, the conditional probability of failure or damage will vary. It will be low (zero) at very low hazard levels and ultimately rise to a conditional probability of failure of one at some, much higher level. This result is called a fragility curve. Fragility curves are developed for each levee reach in the study area.

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

Emergency Response and Repair Analysis – Following an event that has resulted in levee breaches and/or damage, the process begins for repairing breaches and stabilizing damaged areas to prevent further deterioration that results in additional island flooding. This part of the risk analysis models the material, equipment and time required to stabilize islands, close breaches, protect levee interior slopes on flooded islands, and dewater flooded islands.

Water Management and Hydrodynamic Analysis – As islands breach and flood, the normal flow patterns are disrupted. Water that floods islands is replaced by river inflows and/or saltwater from San Pablo and San Francisco Bays[2]. The intrusion of saltwater into the Delta can be managed to a degree by controlled releases from upstream reservoirs and curtailing/halting exports from the Delta. These factors, coupled with the rate of breach closures and island dewatering, and ongoing tidal cycles result in a very dynamic system that is modeled to assess the impact on water quality (i.e., salinity levels), and the time that water exports will be disrupted at the SWP and CVP and other pump stations.

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

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

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

4.3 UNCERTAINTY

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

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

Figure 4-3 shows the epistemic uncertainty in the estimate of the frequency of occurrence per year that a Delta island may be flooded as a result of levee failure (due to any cause; earthquakes, floods, etc.). The figure shows a probability distribution on the estimated frequency of flooding. If no epistemic uncertainty existed (for example, in the estimated the rate of occurrence of future earthquake ground motions, floods in the Delta, or in the performance of levees given a stressing event), no distribution would occur, but rather a single point estimate of the frequency of flooding. The uncertainties that contribute to this distribution are the amount of data that are available, the accuracy of engineering methods to model the performance of levees,

the uncertainty in the estimate of hazards that could cause failure (e.g., uncertainty in the rate of earthquake occurrences, ground motion attenuation models, etc.).

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

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

4.4 RISK ANALYSIS APPROACH

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

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

4.4.1 Definition of Risk

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

uncertainty (Kaplan and Garrick 1981).[3] In this analysis, risk is evaluated for a number of metrics that consider the assets at risk. These metrics are given in Section 4.4.7.

4.4.2 Risk Model

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

In this analysis, risk estimates will be made on a per annum basis for 2005 conditions. (The approach for addressing risks in future years is described in Section 4.8). This measure of risk, for a consequence C, is denoted:

$\lambda(C_k > c)$ = frequency per year that a consequence metric C_k, will exceed a value c (4-1)

As described in Section 4.4.7, the risk analysis will be conducted for a number of risk metrics.

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

$$\lambda_T(C_k > c) = \sum \lambda_i(C_k > c) \quad (4\text{-}2)$$

where the sum is carried out for the hazards considered in the risk analysis. Note, subsidence and climate change are not considered hazards in the sense of random events that impose transient loadings/forces on a levee system. Rather, they are addressed as ongoing processes that change the state of the Delta landscape and are considered in the assessment of future years (see Section 14). The task in the risk analysis is to estimate the consequences associated with each hazard, $\lambda(C_k > c)$, in Equation 4.2. In the next subsections, the risk analysis for external and normal hazards is described.

In this analysis, the frequency of events and the frequency of consequences is an 'instantaneous' frequency for the time the analysis is conducted (current, 2050, 2100, etc.). This instantaneous rate can be used to calculate a probability of occurrence of an event of interest in a given year; or over a limited period of time. To assess the probability over a longer period of time (say the next 100 years), the variation in the frequency of occurrence must be considered.

4.4.3 External Hazards

External hazards such as earthquakes and floods are spatially distributed phenomena that can stress a large part of levees in the Delta and Suisun Marsh simultaneously, presenting the potential for multiple simultaneous levee breaches during the same event. When a seismic event occurs, the ground motion that is experienced is a function of the size of the event and its location with respect to Delta and Suisun Marsh levees. Thus, for a given seismic event, the ground motions that occur at levees in the area are correlated because they have occurred as a result of the same seismic event and levees in proximity to one another are founded on the same

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

near-surface materials. Thus the correlation of ground motions between different levees is a function of distance. For levee reaches close to one another, ground motions will be highly correlated, whereas the ground motions will be independent (given an event) as the separation distance between levees becomes large. Incorporating these correlations is an important factor in estimating risk and the potential for multiple island breaches.

The consequences that occur as a result of levee failures exposed to a given hazard depends on the size of the event (e.g., earthquake ground motion throughout the region) and the state of the Delta given the occurrence of a stressing event, such as an earthquake. For a given hazard event (flood, earthquake, etc. of a given size), the performance of Delta levees is random (due to the variability in their response as estimated in the levee vulnerability part of the analysis). Some levees may fail, others may be damaged without failing and flooding an island, and still others may experience no damage at all. The possible outcomes (states of levee performance given an event (i.e., an earthquake)) define a sequence or state of the Delta, where each sequence defines the state of each island in the Delta (OK, damaged, failed and damaged). Given the number of islands in the Delta and the number of possible performance states for each island, a large number of sequences may be realized. Modeling these sequences is important when considering the water quality impacts in the Delta, the economic and environmental consequences, and the water export impacts that may result, particularly in the case of seismic events. Based on historic experience and the results of hydrodynamic studies performed in this project, this is less so in the case of flood-related levee failures. In this analysis an event tree approach is use to structure or organize the model for evaluating Delta sequences. Figure 4-4 provides a schematic illustration of an event tree.

Each sequence that is evaluated defines the performance of Delta and Suisun Marsh levees to a hazard, where the performance of levees includes the number of breaches and their location (and thus the number of flooded islands), and the extent of nonbreach damage.

For each sequence the development of any secondary levee breaches as a result of ambient wind conditions and/or the occurrence of a wind event (involving high velocity winds) and erosion of levee interiors on flooded islands is considered.

4.4.4 Normal, Sunny-Day Events

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

Given the random occurrence of a levee breach on an island during normal conditions, the risk analysis is carried out in the same manner as discussed above for external hazards. The primary difference is that only a single event of a given type occurs as opposed to multiple events (e.g., earthquakes of varying sizes and locations).

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

4.4.5 Modeling Delta Sequences

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

4.4.6 Combinations of Events

Following an event involving levee failures and nonbreach levee damage, ambient winds as well as random wind events can occur in the Delta and Suisun Marsh. Given recent experience (e.g., Jones Tract, 2004), it is likely that winds could occur and cause further damage and even breaching on other, nonflooded islands. The erosion and potential of additional breaches is considered. In particular the erosion that occurs on the interior of flooded islands is addressed and included as part of the additional work required to repair a flooded island.

Some technical people consider it possible that wind/waves across an island and through a breach may impact an adjacent island (across the channel from the breach). This possibility is not now included in the risk model because it only seems possible relative to the initial breach, which seems unlikely. Also, it is judged that the likelihood of increased seepage on adjacent islands leading to an adjacent island levee breach and resulting in additional islands flooding is small.

Although the particular risk of a flood during the upcoming wet season after substantial earthquake damage may have a significant impact on damaged but unflooded islands, the present version of the risk model does not address this impact on an individual random event basis. It is only considered as a general exposure during the period a damaged, unflooded island is awaiting repair.

4.4.7 Risk Metrics

The primary risk metrics to be evaluated in analysis are listed in Tables 4-2 and 4-3. These metrics include measures of Delta island vulnerability (potential for flooding), economic impacts and costs, environmental consequences.

4.5 CO-LOCATED EFFECTS

The risk analysis will address events (e.g., earthquakes, floods, climate change) that impact the performance of Delta levees and the consequences that may ensue. These same events present a hazard to other parts of California and thus potential for consequences that may further impact the state. For instance, the consequences associated with a major seismic event east of San

Francisco Bay could be substantial outside the Delta (e.g., damage to the Contra Costa county water distribution system). The impact to other water system assets in and beyond the Delta will be assessed to the extent that levee breaches and island flooding cause damage to these assets. For example, damage to the Mokelumne Aqueduct as a result of a breach and scour that results in pipeline failure is addressed. The simultaneous occurrence of island flooding and the failure of co-located water system assets could significantly increase the interruption of local water supply and/or statewide water export. With the exception noted above, co-located effects are not addressed in the DRMS risk analysis.

4.6 IMPLEMENTING BUSINESS AS USUAL

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

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

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

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

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

4.7 RISK ANALYSIS IMPLEMENTATION

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

- Project scope and objectives
- Elements of the risk analysis
- Perspective on uncertainty
- Risk model development approach
- Technical interface requirements
- Project schedule

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

Table 4-1 identifies elements of the risk analysis (see Figure 4-1) and the topical areas within each element that were identified at the start of the project and areas around which teams were formed.

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

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

One of the objectives of the risk analysis was to estimate the uncertainty (aleatory and epistemic) for each of the parts of the analysis. For the hazard and levee vulnerability evaluations, it was possible to carry this estimation out. For other parts of the analysis this proved difficult due to

the development effort to gather information and build the foundational model, coupled with the time available for the project in general. These factors, coupled with the varying levels of probabilistic modeling 'experience' in different topical areas (a great deal exists in the seismic hazard area and relatively little in the economic and ecosystem areas), resulted in assessments that are best estimates of the outcomes of interest (i.e., economic consequences).

4.8 RISKS IN THE FUTURE

To meet the requirements of AB 1200, an analysis of risks 50, 100, and 200 years from the present must be made. This assessment must be based on existing information (models and data). Table 4-5 shows a timeline that indicates the availability of projections for hazards and environmental factors that threaten the Delta. Table 4-6 provides a similar summary of information available to assess future risks with respect to Delta assets and infrastructure.

It is common in risk studies to estimate the frequency of occurrence of events, based on available information and, assuming events are Poissonian, to calculate lifetime risks. This approach is reasonable and appropriate if events (hazards) are Poissonian and if conditions (i.e., integrity of the systems being analyzed), and the assets that are exposed in the event of the system failure do not vary over the project lifetime. Based on the current state-of-knowledge it is apparent these conditions do not exist. In fact, it is anticipated that significant changes are taking place in and around the Delta and Suisun Marsh that do not permit a simple projection of lifetime risks.

To assess risks in the future, an approach is taken to estimate the impact of individual factors (i.e., earthquakes, economic losses, etc.) relative to the base case 2005 analysis. Ideally, a reassessment of the 'instantaneous' frequency of occurrence of events of interest in future years would be made. However, the availability of information limits the opportunity to make a detailed quantitative assessment.

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

- Update the state of the environmental factors (e.g., subsidence and climate change) that may influence the performance of levees or the size or occurrence of hazards for an evaluation year (e.g., 2050, 2100, 2200).
- Modify the rate of occurrence of events based on current information and changes to the environment; the frequency of occurrence per year of events at the time (e.g., earthquakes or floods in the year 2050) is determined.
- Update the in-Delta and statewide exposure (i.e., increasing population and property development, ecosystem changes, etc. that are at risk) to the effects of levee failures.
- Assume that no major event (hazard or a proactive policy) occurs in the intervening years that would result in a significant change in the integrity or configuration of the Delta system.

Consideration must also be given to natural processes, such as subsidence and climate change that produce an ongoing change the Delta and Suisun Marsh. These are assessed based on business-as-usual response to these evolving processes. For instance, assuming current trends of levels of funding for levee maintenance and repair, it is likely that Delta islands and Suisun Marsh may be under water when considering future sea level rise. Increasing funding to upgrade all levees to keep pace with sea level rise would not be business-as-usual. Similarly, as

subsidence continues in the Delta, an effect may occur to levee stability, agriculture, island conditions due to increase seepage, etc.

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

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

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

4.9 RISK QUANTIFICATION

The risk quantification (the combination of the different parts of the risk model) is carried out in a series of steps. These steps are summarized in Table 4-7.

The results of the quantification process are presented in Chapters 13 and 14.

Table 4-1 List of Events/Variables

Type	Event	Description	States/Values
State of Nature	Condition Variables in the Delta & Suisun Marsh	These events/factors relate to the characterization of the Delta and Suisun Marsh for the time the risk estimates are made. In the DRMS risk analysis, the variables/ factors that characterize the state of nature include climate change and subsidence. Climate change will impact the loads (static hydraulic head) and hazards (e.g., flood size, timing) that occur.	Sea Level Rise Hydrologic (annual runoff amounts and patterns and frequencies of floods) Amount of Subsidence
Event Timing	Type of Year	The availability of water varies substantially from year to year and plays a role in the severity of consequences.	CALSIM 82-year trace based on historic data is used to model the randomness of the availability of water
	Season of the Year	The time of the year when an event occurs, plays an important role in the consequences (economic, environmental) in the Delta.	
Initiating Events (Hazards)	Seismic Events Floods Wind Events (also see below) Normal Loads	Each hazard type must be defined in terms of individual events. This definition preserves the correlations within an event that are important for assessing consequences. For example, for seismic events, an event is an earthquake of a given magnitude, on a specific fault, and at a particular location on the fault.	Full range of the hazard events must be defined and a hazard appropriate characterization as defined by hazard analysts and the levee vulnerability team. For seismic events, the full range of earthquake sizes (e.g., **M**: 5 – maximum magnitude) and their possible locations on a fault are considered and the hazard is characterized in terms of the spatial, random distribution of peak ground acceleration.
Levee Performance – Primary Response	Levee breaches	Given the occurrence of a stressing event, the number of levee breaches, the islands where the breaches occur, and the breach locations on an island are considered.	For each island, the number and location of possible levee breaches is defined.
	Nonbreached Levee Damage	Given the occurrence of a stressing event, the levee reaches that have been damaged by a stressing event are identified.	Damaged levee reaches for each island.

Table 4-1 List of Events/Variables

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

Table 4-2 List of Economic Risk Metrics

Category	Metrics
Delta Island Vulnerability	Frequency of Island Failure (total and due to individual hazards)
Economic Impacts	Value of Lost Output
	Lost Employment (Jobs)
	Lost Labor Income
	Lost Value Added
Economic Costs	In-Delta Cost
	Statewide Cost
	Total Cost

Table 4-3 List of Environmental Risk Metrics

Fish Species Quantified Fish impacts are estimated by considering specific scenario occurrences for factors that affect fish populations or habitat conditions and totaling to a "score" for that scenario and species.	Delta Smelt
	Chinook Salmon
	Green Sturgeon
	Inland Silverside
	Longfin Smelt
	Steelhead
	Striped Bass
	Threadfin Shad
Wildlife Wildlife impacts are estimated by totaling the portion (of the acres) of that species' habitat that is flooded.	California Black Rail
	California Clapper Rail
	Greater Sandhill Crane
	Saltmarsh Common Yellowthroat
	Saltmarsh Harvest Mouse
	Suisun Ornate Shrew
	Waterfowl (ducks, geese, and swans)
Vegetation Vegetation impacts are estimated by totaling the portion (of the acres) of that habitat category that is flooded.	Alkali Marsh High
	Alkali Marsh Low
	Alkali Marsh Mid
	Aquatic Vegetation
	Herbaceous Upland
	Herbaceous Upland, Ruderal
	Herbaceous Wetland, Perennial
	Herbaceous Wetland, Seasonal
	Herbaceous Wetland, Seasonal, Ruderal
	Shrub Upland
	Shrub Wetland (Riparian)
	Tree Upland
	Tree Upland, Nonnative
	Tree Wetland (Riparian)

Table 4-4 List of Topical Areas

Category	Topical Area
Hazards	Probabilistic Seismic Hazard Analysis
	Flood Hazard Analysis
	Wind-Wave Action
	Normal Hazards
	Climate Change
	Subsidence
Levee Vulnerability	Levee Vulnerability
Emergency Response	Emergency Response and Repair of Delta Levees
Water Analysis Management	Water Operations
	Hydrodynamics
Geomorphology	Geomorphology of the Delta
Consequences	Economic Consequences
	In-Delta Infrastructure
	Ecosystem Consequences

Table 4-5 Summary of the Information Available to Evaluate Future Hazards and Environmental Factors

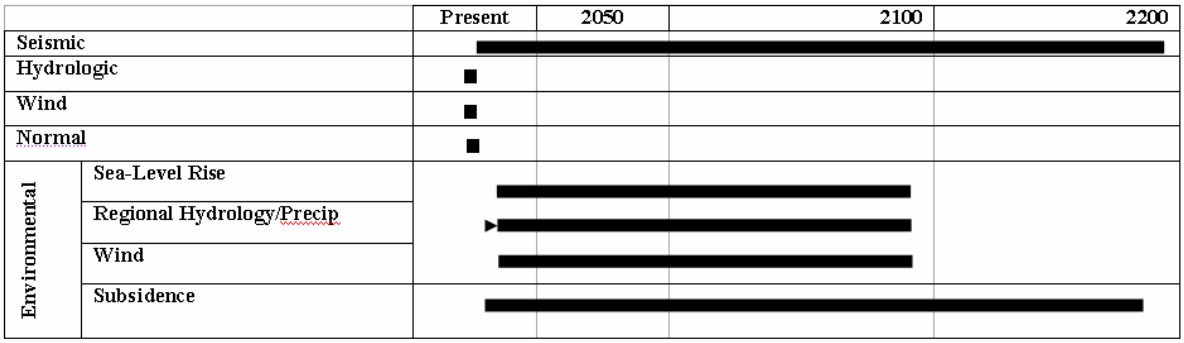

Table 4-6 Summary of the Information Available to Evaluate Future Delta Risks

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

Table 4-7 Summary of the Risk Quantification Steps

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

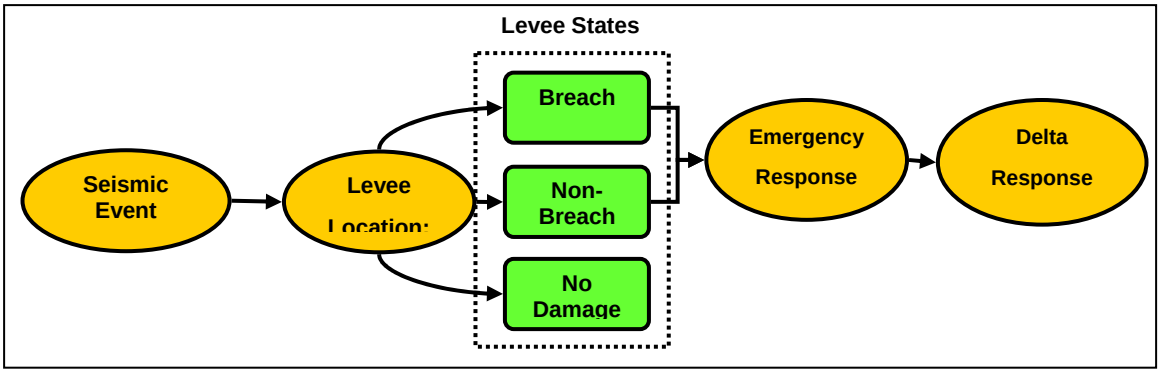

Figure 4-1 Influence diagram illustrating the basic elements of levee performance, repair, and Delta hydrodynamic response following a seismic event

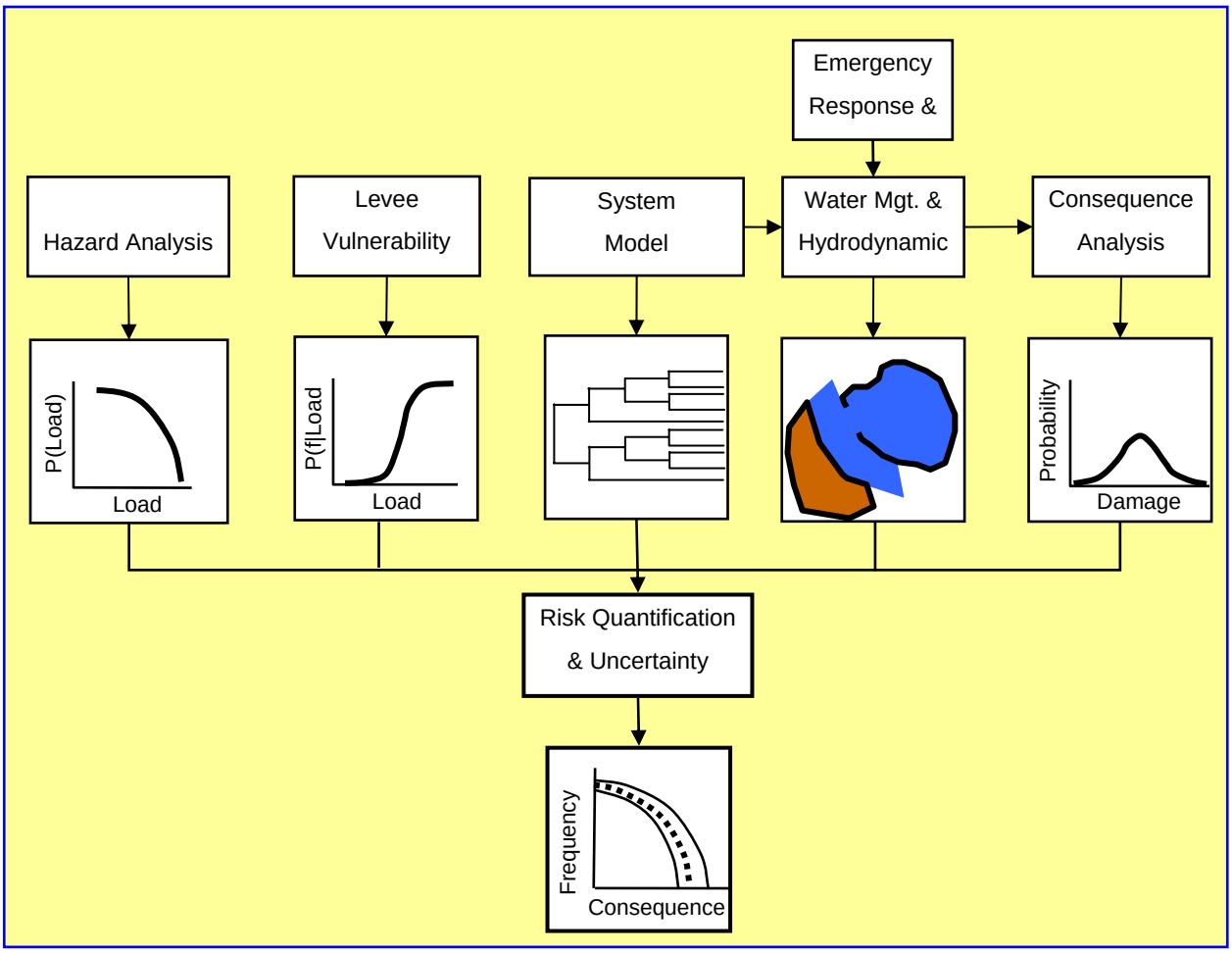

Figure 4-2 Schematic illustration of the elements of the risk analysis

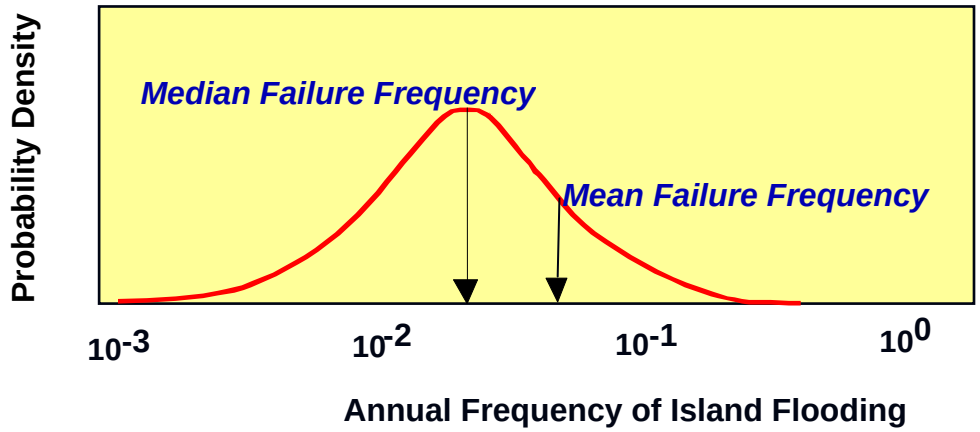

Figure 4-3 Illustration of the epistemic uncertainty in the estimate of the annual frequency of island flooding due to levee failure

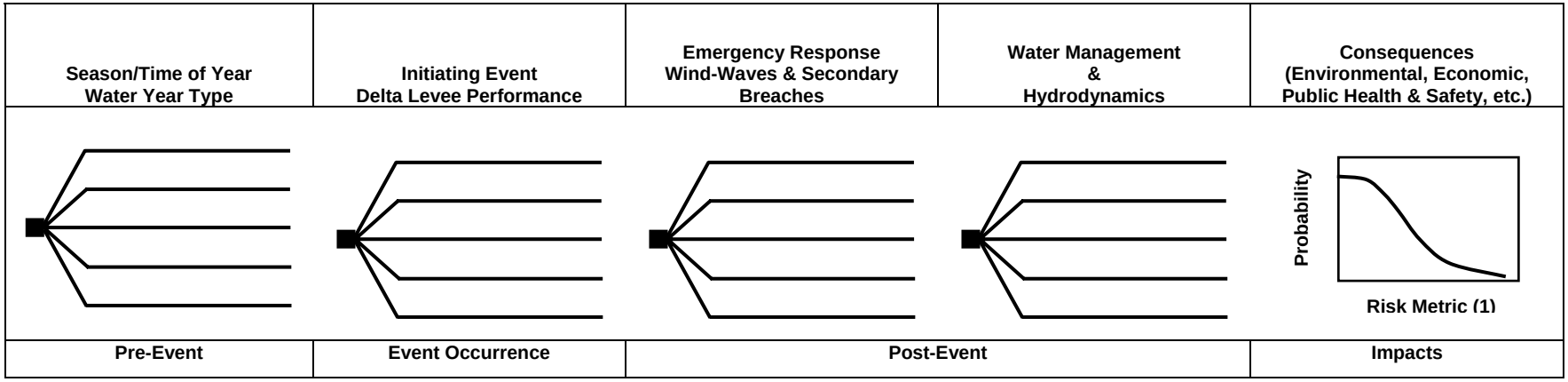

Figure 4-4 Illustration of an event tree used in the system model to organize and assess sequences