Delta Stewardship Council

Delta Levees Investment Strategy

Technical Memorandum 3.1: Methodology

DRAFT

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DELTA STEWARDSHIP COUNCIL

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ACRONYMS AND ABBREVIATIONS

AADT	average annual daily traffic
ARCADIS	ARCADIS U.S., Inc.
BDCP	Bay Delta Conservation Plan
cm	centimeters
Council	Delta Stewardship Council
CVJV	Central Valley Habitat Venture
CVP	U.S. Bureau of Reclamation Central Valley Project
DLIS	Delta Levees Investment Strategy
Caltrans	California Department of Transportation
.csv file	comma separated value file
Delta	Sacramento-San Joaquin Delta
DPC	Delta Protection Commission
DRMS	Delta Risk Management Strategy Risk Report
DWR	California Department of Water Resources
EAALL	expected annual agricultural land loss
EACH	expected annual change in habitat
EAD	expected annual damage
EAD_F	expected annual damage without rehabilitation
EAD_R	expected annual damage with rehabilitation
EAF	expected annual fatalities
EARC	expected annual rehabilitation cost
EAW	expected annual water supply disruption risk score
EBMUD	East Bay Municipal Utility District
EFV	effective flooded volume

EHW	extreme high water
GIS	geographical information system
ICF	ICF International
MCDA	multi-criteria decision analysis
MHHW	mean higher high water
MIP	mixed-integer programming
MLLW	mean lower low water
NAVD	North American Vertical Datum
PAL	Projected Agricultural Land
PAR	population at risk
PCNCM	Projected Change in Natural Channel Margin
PDF	probability density function
PH	Projected Habitat
PL 84-99	Public Law 84-99
PPIC	Public Policy Institute of California
RD	reclamation district
RHJV	Riparian Habitat Joint Venture
SAV	submerged aquatic vegetation
SLR	sea level rise
SWP	State Water Project
TAF	thousand acre-feet
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

1. INTRODUCTION

The Delta Stewardship Council (Council) initiated the Delta Levees Investment Strategy (DLIS) project to develop a transparent strategy for prioritizing state-funded levee investments in the Sacramento-San Joaquin Delta (Delta). This project is in support of the requirements of California Water Code section 85305(a), which states:

> *The Delta Plan shall attempt to reduce risks to people, property, and state interests in the Delta by promoting effective emergency preparedness, appropriate land uses, and strategic levee investments.*
>
> *85306. The Council, in consultation with the Central Valley Flood Protection Board, shall recommend in the Delta Plan priorities for state investments in levee operation, maintenance, and improvements in the Delta, including both levees that are a part of the State Plan of Flood Control and nonproject levees.*

The DLIS project will support this Council charge by addressing the key questions shown on Figure 1-1, supported by a technical analysis. This technical memorandum describes the methodology for this analysis. It also provides preliminary documentation of the flood risk models and decision support tool under development for the project. In some cases, the details of how the methodology will be implemented are not yet known. As such, this document will be updated over time as the analysis proceeds and is refined.

As Figure 1-1 shows, the project begins by first identifying the Council goals for the project, including providing technical information and guidance to develop a strategy for State of California (State) levee investment. In accordance with the legislative and Council guidance, the DLIS considers four key objectives protecting lives and property; water supply reliability; ecosystem function; and Delta as a place (Figure 1-2).

Figure 1-1. Key Questions and Process of the Delta Levees Investment Strategy

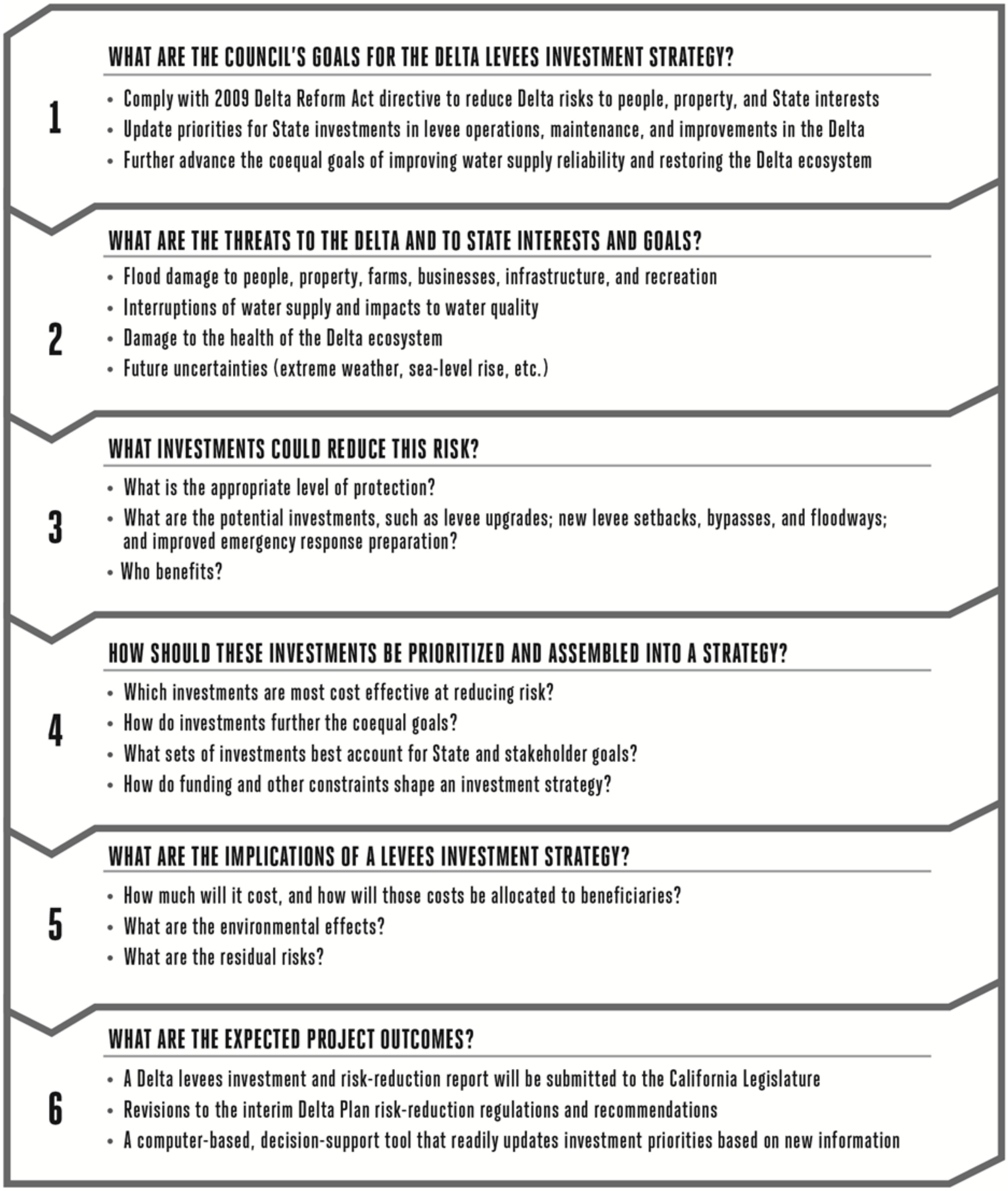
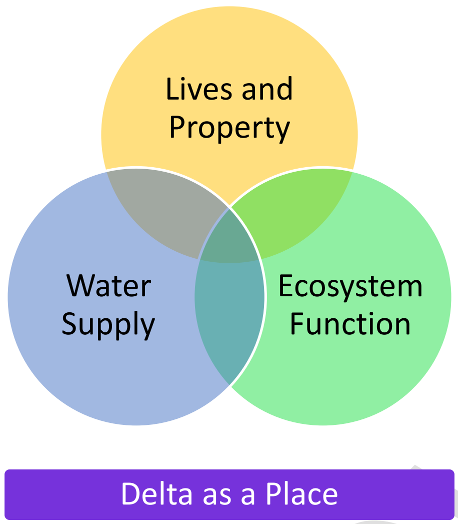


Figure 1-2. Key Objectives Addressed by the Delta Levees Investment Strategy



Second, the technical analysis estimates the threats to the Delta and the State's goals from floods due to levee failure. The threats are measured as different types of risks related to these objectives, such as lives lost, damage to assets including agricultural land, and water supply disruptions.

Third, the technical analysis identifies and evaluates investments to reduce these risks. The investments to levees include but are not limited to maintenance of current performance, improvements to levees, or replacement with or without alternative designs. Performance estimates for these investments will be made for current conditions and projections of conditions in 2030 and 2050, as explained later in this report. The technical framework is designed to evaluate both conceptual projects (such as the improvement of a levee to a particular levee design standard) and detailed projects specified by stakeholders and organizations (for example, by a levee reclamation district [RD]). The question of who benefits from these investments will be addressed in Technical Memorandum 3.2, *Cost Allocation Methodology*. To answer questions four and five on Figure 1-1, the estimates of the costs and effects of different levee investments are used to develop and evaluate portfolios of investments that are consistent with implementation constraints, such as funding availability. Developing and comparing different investment portfolios will support the Council in defining a levee investment strategy.

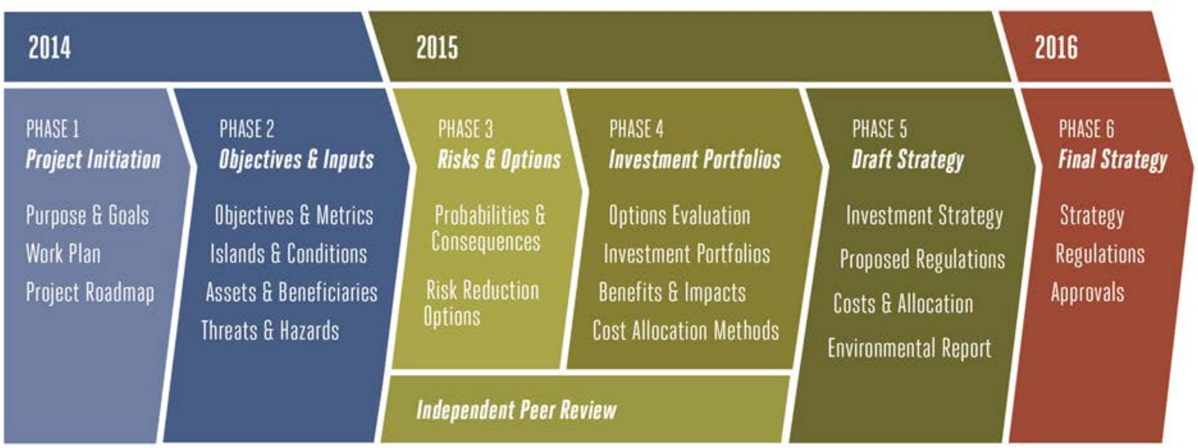
The planned project outcomes (question six on Figure 1-1) include the levee strategy, guidance for revisions to the Delta Plan, and a decision support tool.

The DLIS Planning Tool (hereafter, Planning Tool) is an interactive visualization and calculation decision support tool that summarizes technical information about risks to the Delta levees and the effects of investments on those risks and other Delta conditions. It will enable the Council to interactively develop various rankings of islands and tracts based on their associated risks, and various rankings of investments based on how well they mitigate different risks and at different costs. The Planning Tool will not dictate a single set of priorities. Instead, the Planning Tool will highlight key information about investment effects and trade-offs to support deliberations regarding prioritization. It will also ensure transparency of the analysis and outcomes to interested stakeholders and the public. Using this method, the available data, and the Planning

Tool in an iterative deliberation process, the Council will define an investment strategy that will meet the project objectives.

The project's Communications Plan describes the agency coordination and public outreach activities that are an integral part of the technical analysis. The Communications Plan explains the six phases of DLIS project activity leading to Council consideration of a proposed final DLIS (Figure 1-3).

Figure 1-3. Project Planning Process



In each of phases 2, 3, 4, and 5, outreach activities are organized to prepare for a series of public meetings and workshops at various locations in the Delta to discuss project data, information, and analysis, and to obtain input and feedback to inform the Planning Tool and the environmental analysis.

Section 2 of this report describes the methodology in detail. Section 3 presents the risk models and calculations that will be used to evaluate risks and the impacts of investments on State objectives. Section 4 describes the Planning Tool.

2. TECHNICAL METHODOLOGY

The technical analysis is proceeding through the following seven steps:

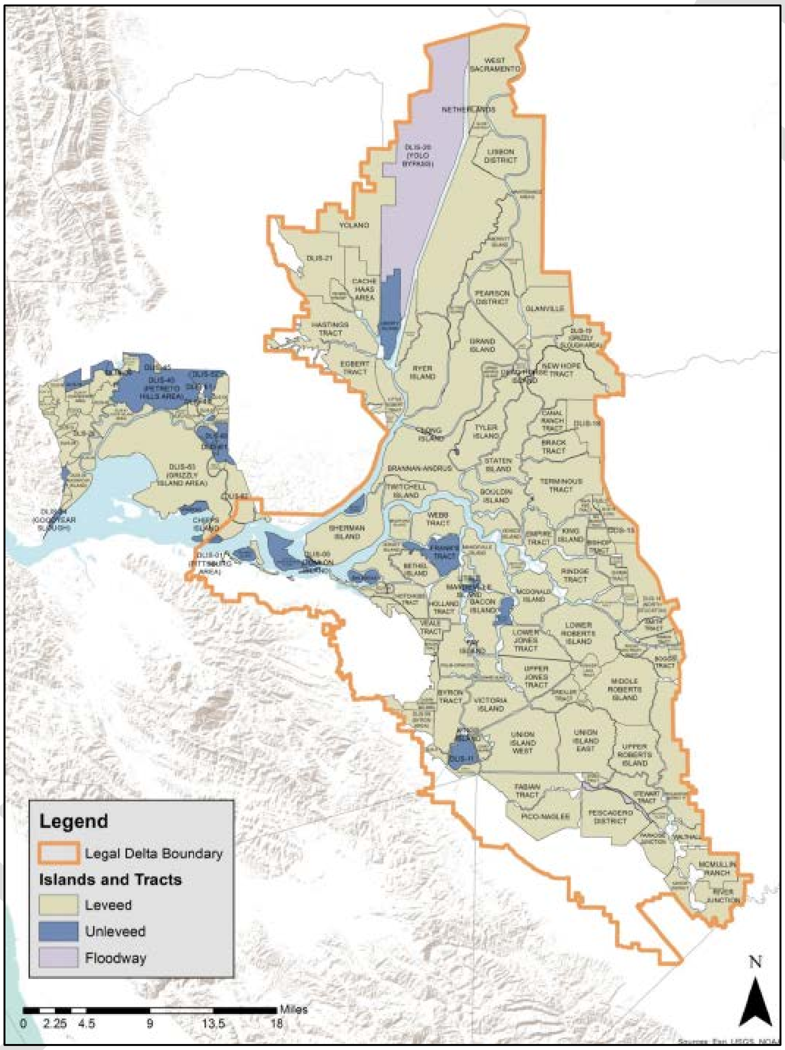
1. Inventory assets and identify hazards.
2. Evaluate risks without State investment.
3. Rank islands and tracts by risk.
4. Define levee investments.
5. Rank levee investments.
6. Evaluate risks with State levee investment.
7. Define DLIS.

While these tasks will be completed in sequence, there is considerable overlap in the schedule of their development. Stakeholder input and feedback have occurred and will continue to occur throughout the process in accordance with the project Communications Plan.

2.1 Inventory Assets and Hazards

The technical work began with an assessment of key hazards and the assets at risk from levee failures. The findings from this work are presented in Technical Memoranda 2.1 and 2.2. Assets have been inventoried for the 176 islands and tracts shown on Figure 2-1, and include built structures, public and private infrastructure, and public lands.

Figure 2-1. DLIS Islands and Tracts



Source: Technical Memorandum 2.1

The TMs identified a wide range of natural factors and human actions that may be hazardous to the levees (Table 2-1). The hazards that lead to significant flood risks were determined to be due to hydrologic conditions, climate conditions, and seismic events.

Table 2-1. Levee Hazards

Type	Source	Hazard
NATURAL HAZARD	Hydrologic / Hydraulic	High volume inflow
		High flow velocity
		High head differential
		River morphology changes
		Rapid drawdown
	Climatic Change	Higher water level
		Greater head differential
	Wind	Wave run-up
		Storm surge
	Geologic / Geotechnical	Soft or organic soils below levee embankment
		Soft or organic soils on landside
		Earthquake
	Ecologic	Animal burrows
		Vegetation type or location
HUMAN ACTION HAZARD	Permanent or Periodic	Encroachments
		Channel dredging
		Deferred maintenance
		Upstream water management and storage
	Temporary	Boat and ship wakes
		Impact (ship, debris, ice)
		Fires /footpaths/ camping

Source: Technical Memorandum 2.2

2.2 Evaluate Risks Without State Investment

2.2.1 Performance Metrics

The DLIS analysis seeks to prioritize investments based on how they meet important goals for the State—to reduce risks to lives and property, water supply reliability, and Delta ecosystem function, and to do so efficiently. Performance metrics help measure how potential levee investments affect each of these objectives. A baseline risk condition is first defined for each area of analysis over time, as measured by the performance metrics. Next, each levee investment is evaluated for its effects on each area of analysis, again using each performance metric. The effects are aggregated across all of these areas to estimate the Delta-wide impact of an individual investment. For example, levee investments on an island might decrease the habitat on the island, while increasing habitat in the adjacent waterway and reducing risk to water supply reliability. Metrics capture these effects and enable comparison of trade-offs. This, in turn, enables ranking of investments, developing and comparing portfolios of investments, and identifying investment priorities.

The Delta is complex, and its value or function can be measured in many ways. For instance, many biological, geochemical, and physical processes and components occur within an ecosystem, and many of these characteristics can be used to describe some aspect of ecosystem function. This includes biodiversity, water quality, habitat structure and connectivity, food web dynamics, nutrient cycling, and species population dynamics. Having too few metrics means possibly failing to assess important impacts of potential levee investments. However, having very many metrics makes it difficult for decision makers and stakeholders to see trends and trade-offs between options and find portfolios that balance their concerns. Additionally, there are complex interactions among potential levee investments and these characteristics. Often, the relationships among these factors are poorly understood, or are so complex that they cannot be readily understood and effectively used for making policy decisions.

This analysis seeks to develop simple but accurate and meaningful metrics that can be useful for prioritizing levee investments. A small number of metrics represent conditions in the Delta in each of the four objectives, for which credible relationships that facilitate prioritizing investments can be developed. The planning framework and tools are flexible and can accommodate new metrics if supporting data are developed.

Table 2-2 summarizes the metrics for the analysis. The first four metrics – expected annual fatalities (EAF), expected annual damage (EAD), expected annual water supply disruption risk score (EAW), and expected annual change in habitat (EACH) -- measure how levee investments affect different types of flood risk. Because floods are uncertain, these metrics assess the annual effects of flooding using the classical "probability x consequence" framing: the probability is the annual likelihood of the flooding while the consequence is the effect of the flood. This type of measurement is commonly incorporated in the concept of EAD. The EAD metric estimates the average annual monetary damage to assets due to flooding events. For this study, the EAD methodology is extended to apply to other areas of State interest. Unlike EAD, not all risk metrics are monetized. As Table 2-2 shows, several metrics are measured in their "natural units" such as the number of lives or acres of land. Box 2-1 explains that the decision to monetize is based on whether doing so would enhance the credibility and transparency of the DLIS analysis.

The last two metrics measure the costs of investing in levees. This includes the monetary cost of implementing a levee project, including construction and the cost of acquiring privately held land. It also includes non-monetary costs, such as loss of habitat. Note that habitat costs may be "negative" – some projects may create new habitat, or convert one type of habitat to another.

Table 2-2. Summary of Objectives and Metrics for Assessing Flood Impacts

What are the interests?	What types of impacts are measured?	What metrics measure each impact?
Lives and Property	Fatalities	(1) Expected Annual Fatalities (number of lives)
	Asset damage, including agricultural losses	(2) Expected Annual Damage (USD)
Water Supply	Water supply risk	(3) Expected Annual Water Supply Disruption Risk Score (unitless)
Ecosystem Function	Habitat area	(4) Expected Annual Change in Habitat (acres)
Investment Efficiency	Costs to the State	(5) Cost of Levee Investments (USD) (6) Effect on Habitat Area (acres) (7) Effect on Natural Channel Margin (miles)

For the Lives and Property objective, two metrics evaluate the probabilistic risks to lives (EAF) and to assets and property (EAD). EAF is an annualized calculation of expected fatalities due to flooding events. Fatalities are used as proxy for all human damages, including death and injury. EAD is an annualized measurement of the economic consequences of flooding, expressed in terms of value (dollars) per year, such as damage to homes, farms, and businesses as well as losses of crop value. Note that the EAD depends on whether a flooded island is recovered or left permanently flooded. In the former case, EAD includes the cost of island recovery. In the latter case, it does not involve a recovery cost, but includes permanent losses of land. We calculate EAD twice, once under each recovery assumption. Because agriculture is central to the Delta's past, present, and future, we disaggregate EAD by the agricultural and non-agricultural damages. The agricultural damages are reported in monetary terms and, in the case of land loss, also as the acres of agricultural land.

The Delta's complex configuration of waterways and associated levees support a water supply conveyance system and help ensure water supply reliability to water users south of the Delta and within the Delta. Levee breaches and resulting floods threaten to disrupt water supply. Water supply risk due to levee failure is measured with a score. This metric was developed uniquely for this project because the literature on the impact on water supply of individual islands flooding, and the resulting disruption consequences, are very limited. Like other metrics, EAW starts with an estimate of the likelihood of floods based on hazards and fragility analysis. The consequence is the likelihood of a disruption given a particular island or group of islands flooding. This likelihood is based on expert judgment of how important each island is to the integrity of the water supply corridor and water quality, based on island location, salinity effects, and whether or not the islands contain or support critical in-Delta water supply infrastructure. Because this metric has specifically been developed for this project, we treat it as a score that is useful for comparing the relative effects of islands and investments on water supply disruption. It should not be interpreted as a measure of the actual annual risk of disruption, because expert judgment alone cannot provide reliable estimates of this likelihood. For the baseline, this risk score is estimated for current conditions, near-term (2030), and long-term (2050).

According to the Delta Plan, “achieving the coequal goal of protecting, restoring, and enhancing the Delta ecosystem” means successfully establishing a resilient, functioning estuary and surrounding terrestrial landscape capable of supporting viable populations of native resident and migratory species with diverse and biologically appropriate habitats, functional corridors, and ecosystem processes (Council 2013). The elements that create ecosystem value are complex. For decision makers and stakeholders to understand and trade off the impact of projects on the ecosystem, the ecosystem metrics must be relatively simple and understandable and still capture the essential elements of ecosystem value. The effect on ecosystems will be measured by the quantity and quality of 17 different types of habitat maintained, created, or lost using three ecosystem metrics. Ecosystem function is evaluated using three metrics of how habitat area (acres of terrestrial or aquatic habitat) and length (miles of riparian corridor) will change due to levee investments and due to flooding events. The EACH is the average amount of habitat that would be lost or gained annually to floods. These metrics are further disaggregated by:

a. Habitat quality (e.g., the change in the amount of high-quality habitat)
b. Restoration potential (i.e., the change in the amount of habitat within locations prioritized for restoration in the Delta Plan), and
c. Proximity to fish migratory corridors (i.e., the change in the amount of habitat that is near fish migratory corridors, with the aim of focusing on maintaining functional corridors that connect priority native fishes with favorable habitats while minimizing movement into unfavorable or high-risk habitats).

We calculate all of these risks for current conditions, near-term (2030), and long-term (2050) as explained below.

The final category, investment efficiency, is the monetary and non-monetary costs of each levee investment. The monetary cost includes the construction costs for a levee project, as well as the cost of acquiring land in order to implement the project. Land effects will be reported out in both dollars and acres to capture the economic and land use effects of a project.

Projects may also have effects on habitat -- levee improvements could decrease terrestrial habitat or increase quality riparian habitat. Habitat effects will be reported in changes to habitat area (acres) and changes to linear natural channel margin (miles). Channel margins are particularly important as they support foraging fish. They may be affected by levee investments along the outboard length of the levee, such as placement or removal of rock armoring (also known as riprap or rock revetment). We will report this effect in total, and separately for natural channel margins along fish migratory corridors, where it is more likely to affect species of interest.

Box 2-1. Monetizing Metrics

Decision makers and analysts sometimes choose to evaluate decisions based on a monetary valuation of their outcomes. This can help them compare diverse effects of a decision in common terms. However, monetizing costs and benefits can be challenging in the absence of readily available market prices or if market prices do not adequately capture value. This can occur with outcomes that are inherently subjective (e.g., the value of cultural heritage), if the science of monetization is new and evolving (e.g., the value of ecosystem services), or if the monetary value of outcomes is highly controversial (e.g., the value of a human life).

In these cases, monetization can reduce credibility of the decision-making process if stakeholders and parties to a decision disagree with the way outcomes are monetized. Monetizing outcomes can also reduce transparency. It obscures the effect of a decision by applying a monetary multiplier (e.g., the dollar value of a human life) to the natural units (e.g., the number of lives lost). Stakeholders – particularly those who disagree with a monetization – may seek to "reverse engineer" a metric to understand the effects.

In this study, we monetize metrics to the extent that it enhances the credibility and transparency of the analysis. We take one of three approaches for each metric, depending on the characteristics of the metric. First, we monetize some metrics – EAD and levee investment costs – that are naturally expressed in dollar values and for which it is standard practice to do so. Where there is uncertainty about future values (e.g., of land), we use different scenarios that clearly state the underlying assumptions about socioeconomic conditions and other drivers of future value. We also report certain subcomponents of these metrics in their natural units. For example, EAD includes the value of lost agricultural land. We will report this in acres as well as dollars.

Second, for some metrics – in this study, EAF -- monetization is possible but uncertain or controversial (Viscusi and Aldy 2003; Aldy and Viscusi 2007). We therefore report out EAF in its natural units and, through the Planning Tool, give users the ability to apply different monetization multipliers. That is, we will report out EAF as the number of lives lost and allow individual stakeholders to choose from among different values of life that are found in the literature. This allows stakeholders to understand the effects of a levee investment decision in natural units and then interpret the effects based on their preferences for how those units should be monetized, without requiring agreement from all stakeholders on what the monetization should be.

Third, for some metrics -- EAW and EACH – appropriate valuations do not exist. For example, there have been many studies done on the value of ecosystem services. But it is not possible to credibly translate these studies to a "value per acre of habitat" multiplier for the Delta. The ecosystem services provided by the Delta are based on the complex functioning of a rich and diverse ecosystem that is not captured by counting the amount of habitat. Moreover, it is not possible to know how ecosystem services would change if one, two, or *n* islands flood. EAW faces a similar challenge. The Delta Risk Management Strategy Risk (DRMS) Report (DWR 2009f), for example, estimates the cost of specific water supply disruptions durations in two scenarios: the flooding of three islands or 20 islands. The DRMS noted that statewide costs vary by as much as 100 percent for different disruption sequences involving the same number of flooded islands. Thus, it is not possible to use these data to estimate costs when individual islands flood.

In sum, we report out the risk consequences of investment options in a variety of monetary and non-monetary terms. Does this make it more difficult to understand the effects of investments? Are we comparing apples to oranges? In fact, it can be *more helpful* to compare the proverbial apples and oranges than their dollar values, because the objectives we seek to achieve are inherently diverse. Kalra et al. (2014) note that using multiple distinct metrics has at least three major benefits:

> "First it helps stakeholders with different values reach consensus, since it does not require starting the analysis with an ex ante agreement on valuation techniques and relative prices… Second, by tracking diverse impacts along the analysis, multiple metrics help identify the major trade-offs implied by the decision…Third, identifying trade-offs helps design policy mixes in which complementary policies smooth or mitigate adverse effects for some stakeholders or in some sectors."

Consistent with this, we use the Planning Tool to show outcomes in natural units and allow different decision makers and stakeholders to attach their own weights – monetary or unitless – to the different outcomes to compare the performance of individual investments and portfolios of investments. Different stakeholders' preferences for weights will probably lead to different preferences for investments. The debates about which set of investments should ultimately be made will be difficult, but they can also be much more important and constructive than debates about whose preferences for weights are correct.

2.2.2 Evolution of Risks Over Time

The DLIS analysis will evaluate risks at three time periods:

- Current—2000-2015[1]
- Intermediate term—2030
- Longer term—2050

These time periods were selected to be long enough to span the length of California bond funding that would be used in many cases to fund State levee investments and correspond to standard time periods of reporting for data such as sea level rise (SLR) and land use projections.

The analysis of risks over time addresses two questions. First, what are the risks now and what will they be in 2030 and 2050 if the State does not make levee investments? This is the risk in a future without action.

[1] The time period for the data representing current conditions varies between the years 2000 and 2015.

Second, what would risks be now and what would they be in 2030 and 2050 if the State were to implement a particular project or a portfolio of projects now?

Estimates of future risk depend upon assumptions about how risk drivers will change in the future. For example, SLR over time will affect the height of water impinging on the Delta levees. Because sea level changes can affect the probability and consequences of levee failure, the estimates of risk over time vary due to projected SLR.

Table 2-3 identifies key future risk drivers and summarizes how these future risk drivers could affect outcomes. The key future drivers are based on judgment and are those that could significantly affect risks to State interests based on the key performance metrics. The size of the effects of these drivers on risks, however, is uncertain.

Table 2-3. Summary of How Future Risk Drivers Might Affect Outcomes

Future Risk Drivers and Categories		Performance Metric Categories		
		Flood Damage Reduction	Water Supply Reliability	Ecosystem Function
Climatological	Sea level rise	Affects river water level, probability of levee failure, flood depth, and consequence of flooding	Affects probability of flooding and effect of flooding on supply risk	Affects baseline and created habitat
	River flows	Affects river water level, probability of levee failure, flood depth, and consequence of flooding	Affects probability of flooding and supply risk	Affects probability of and consequence of flooding on baseline and created habitat
Geotechnical	Baseline fragility (hydrologic and seismic)	Affects baseline and future consequence of flooding	Affects the probabilities of levee failure	Affects the probabilities of levee failure
	Subsidence	Affects probability of levee failure, flood depth, and consequence of flooding	Affects probability of flooding on supply risk,	Affects baseline and created habitat
	Seismic risk	Affects baseline and future consequence of flooding	Affects probability of levee failure and therefore supply risk	Affects probability and consequences of levee failure and flooding
Economic	Population / demographics / land use	Affects consequences of flooding by changing people and assets (structures and agricultural areas) exposed to flooding		Affects baseline habitat
	Bay Delta Conservation Plan (BDCP) conveyance	Reduces river water levels which may reduce flood damage	Reduces risk of disruption	

There is much uncertainty about how future risks will evolve over time. For instance, while sea levels will increase, the magnitude and timing of these increases are uncertain. As another example, the likelihood of the magnitude, location, and timing of seismic events or levee breaches is uncertain: various studies suggest different plausible probabilities for these events. The effects of levee breaches on the Delta are also uncertain.

For example, the effects of individual levee breaches on water quality and ecosystem function are complex and not fully understood.

Rather than using a single set of assumptions about these conditions, the performance of projects and portfolios (as measured by the metrics) is assessed in different plausible futures. Suppose, for example, that there are *n* different conditions and characteristics that are uncertain. A plausible future has one plausible value for each of those *n* conditions and characteristics. While there are an infinite number of plausible futures, only a small number of futures derived from three key future risk drivers are considered (Table 2-4).

Table 2-4. Alternative Assumptions About Future Risk Drivers

Future Risk Drivers	Alternative Assumptions
Sea Level Rise	Nominal • Current: +2.0 inches (+5 cm) from year 2000 • 2030: +5.7 inches (+14.4 cm) from year 2000 • 2050: +11.0 inches (+28.0 cm) from year 2000 Higher Sea Level Rise • Current: +2.0 inches (+5 cm) from year 2000 • 2030: +11.7 inches (+29.7 cm) from year 2000 • 2050: +23.9 inches (+60.8 cm) from year 2000
Development And Future Assets At Risk	Nominal (see Technical Memorandum 2.1) Higher Development (under development)
Future Water Conveyance	Without BDCP conveyance in years 2030 and 2050 Without BDCP conveyance in year 2030 and with BDCP conveyance in year 2050 With BDCP conveyance in years 2030 and 2050

Sources: Sea level rise assumptions for current levels are consistent with the DRMS study (DWR 2009a), and assumptions for 2030 and 2050 are consistent with guidance from the National Academy of Sciences (2012).

These three uncertainties and alternative assumptions provide the basis for 12 preliminary futures. The methodology, risk models, and decision support tool are designed to support the evaluation of numerous futures, and additional futures may be defined. The sensitivity of other factors will be explored and, if found to have significant effects on risks, will be added to the list of futures, for example:

- Frequency, duration, and intensity of high inflow conditions, as reflected by discharge-recurrence curves.
- The strength and integrity of the levees, as reflected by levee fragility-flood stage relationships.
- The economic damage sustained during flood conditions, as reflected by the flood stage-damage relationships.

2.2.3 Risk Models

The DLIS project includes developing a set of risk models to estimate risks to the Delta as measured by each performance metric. These models will calculate risk over time and for the 12 futures. The models are high level and use existing information as much as possible. They are configured to calculate risk for each island and tract at different periods of time with and without different types of levee investments. Section 3, below, describes the DLIS risk models in more detail.

2.2.4 Baseline Risk

Using the assets and hazard data with the risk models, the DLIS project will develop baseline flood risk estimates for current conditions for each performance metric. Risks will be calculated for each island and tract individually and also summarized Delta-wide. This baseline serves as a condition against which future risks without potential investments are compared.

2.2.5 Future Risk Without Investments

The DLIS project will also develop estimates of future risk (at years 2030 and 2050) for each performance metric. As with the baseline, future risks will be calculated for each island and tract individually and also summarized Delta-wide. Futures without investment risks serve as a basis for comparing future investments.

2.3 Rank Islands and Tracts by Risk

The baseline risk results are summarized and presented in the Planning Tool (described in Section 4) both geographically and in tables by island and tract. User-adjustable settings will enable the islands and tracts to be ranked by different metrics for each of the 12 futures. Additionally, simple user-specified weights will enable considering the performance across all of the metrics simultaneously.

This step of the analysis is intended to enable a better understanding of how islands compare with respect to multiple risks considered concurrently. There is no single correct way to combine multiple metrics of different units and scale into a single ranking metrics. Therefore, the Planning Tool is configured to consider several different ways to scale and weight the different risk estimates.

2.4 Define Levee Investments

The DLIS analytic framework is designed to support the evaluation of a wide range of investment concepts or specific projects. The key information needs for an investment include:

- Location of project or investment by island and tract.
- Type and description of project or investment.
- Effect of the project or investment on the appropriate island's aggregate levee fragility estimates (see Section 3, Risk Models).
- Effect of the project or investment on the assets at risk to flooding and the consequences of flooding.
- Direct effect of the project or investment on the habitat and agricultural area on or adjacent to the island or tract.
- Cost of the project or investment.

The types of levee investments that are appropriately evaluated using the DLIS methodology include but are not limited to:

- Levee improvements such as raising, widening, or strengthening.
- Levee replacement with or without alternative designs such as setback levees.
- Levee maintenance solely to maintain current performance.

Projects reviewed will include projects proposed in the reclamation district 5-year plans, the Central Valley Flood Protection Plan, the Delta Plan, the Bay Delta Conservation Plan (BDCP), Regional Flood Management Plans, the Suisun Marsh Plan, and other efforts. These investments, while important inputs to the DLIS project, do not represent the full range of levee investments that the State may want to consider to meet the State objectives.

Conceptual projects may be developed for high-risk islands, as identified in Step 3. For each high-risk island, one or more alternative conceptual investments will be defined that are deemed appropriate for the particular island. For example, the specification of an investment for any high-risk island with significant life and property at risk may need to meet the 200-year level of protection as mandated by the State legislature for urbanized areas by 2025 (Water Code 65865.5(a) (3)). Alternatives may vary, perhaps in the extent of environmental attributes, which would also affect its cost.

The remainder of this technical memorandum assumes the development of a comprehensive list of projects supported by the requisite information identified above.

2.5 Rank Levee Investments

The Delta Plan indicates that it is necessary to prioritize investments “so that limited public funds are expended responsibly for improvements critical to State interests” (Council 2013, p. 262). The Planning Tool will help the Council reduce risks to people and property while striking a balance amongst water supply and ecosystem objectives. The Planning Tool will support the prioritization of the levee investments by first developing rankings of investments based on the four objectives shown on Figure 1-2. The Planning Tool will also allow the user to specify weights for the different metrics and time periods to develop a single ranking of investment for each future. Second, the Planning Tool will assemble portfolios that balance these objectives under different planning constraints and performance goals. See Section 4, DLIS Planning Tool, for more detail.

2.6 Evaluate Risks with State Levee Investment

The data, methodology, and Planning Tool will be used in a “deliberation with analysis” procedure (National Research Council 2009) with stakeholders to support Council and State decision making on levee investments. In this process, technical information about key trade-offs among different rankings will be presented to stakeholders and decision makers using interactive visualizations from the Planning Tool. Stakeholder feedback may suggest additional analyses that lead to a better set of choices—in this case a set of prioritized levee investments—which are presented again to the stakeholders and decision makers (Groves and Sharon 2013). The Planning Tool and methodology will be able to assimilate new information as it becomes available. For example, in the future, new information about levee stability; SLR impacts in the

Delta; precipitation timing and patterns, including extended periods of drought; earthquake risks; ecosystem factors; or project costs could be assimilated into the Planning Tool to inform revised priorities.

2.7 Define Delta Levee Investment Strategy

The technical analysis described in this memorandum will support the development of a DLIS by (1) identifying high risk and thus high priority islands and tracts; (2) comparing alternative investments by cost effectiveness to highlight where State investment will provide the greatest return; and (3) developing portfolios of high-performing investments that meet funding and other constraints and that address multiple State objectives in different ways. The Planning Tool will support the Council in exploring and understanding this information and thus enabling it to select the portfolio or portfolios that are most consistent with its legislative charge. Specifications are being developed for this final project outcome.

3. RISK MODELS

Estimates of current and future risks to Delta flooding are being developed based on existing data. To this end, models to estimate risks as defined by the various performance metrics are being prepared. These models will measure risks for each island and tract, with and without additional investment for the three time horizons (current, 2030, and 2050). Inputs to the risk models are stored in a database and comma separated files. The risk models are implemented in R—an open-source statistical analysis package—and are designed to be quick running and user adjustable to represent different futures (i.e., assumptions about the future) and levee investments. Outputs are stored in an SQLite database and visualized using the Planning Tool, which is described in detail in Section 4.

3.1 Probabilities of Flooding

The metrics to measure the impacts of floods have a common underpinning: the likelihood of flooding. While it is not possible to know precisely when a flood will occur, it is possible to estimate how *likely* a flood of a particular severity would be in any given year. This, combined with the various consequences of flooding, leads to various measures of risk. The annualized approach that is being used in the DLIS analyses assumes that an island or tract can only experience a levee breach once per year and, therefore, the consequences can only occur once per year. For example, a levee breach would result in flood damage to a home at most once per year or the loss of a single year's crop value. The probabilities of flooding are discussed in greater detail in Technical Memorandum 2.2, *Levee Hazards, Risks, and Consequences*.

3.1.1 Calculating Probabilities of Flooding

For a given island i, the annual probability of a flood of level d is written $p_{flood_{i,d}}$. This likelihood is itself a product of the likelihood of a hazardous event of severity h and the likelihood of a levee breach on the island if that event were to occur:

$$p_{flood_{i,d}} = p_{hazard_h} \times p_{breach_h} \quad (3\text{-}1)$$

The two most significant hazards that may cause a Delta levee breach are water levels in the Delta and seismic activity. See DLIS Technical Memorandum 2.2, *Levee Hazards, Risks, and Consequences*, for a discussion of other hazards. Because the timing of a particular hazard level is uncertain, the likelihoods are represented by *stage-recurrence* relationships, which define the annual likelihood (recurrence) of each possible water level (stage) and by *acceleration-recurrence* relationships, which define the annual likelihood of each possible level of peak ground acceleration from seismic activity. A levee's vulnerability to each possible hazard level is represented by a *fragility* curve that defines the likelihood of levee failure given the hazard level (height of water or the ground acceleration) and the condition of the levee.

Certain consequences of flooding depend on the severity of the flood. For example, as we will discuss under EAF, the fatality rate depends on how deep the water is when the island floods. Other consequences are binary and independent of depth. In this case, the concern is the annual likelihood of an island flooding. The annual likelihood can be calculated by summing equation 3-1 over all possible levels of hazard severity:

$$p_{flood_i} = \sum_h p_{hazard_h} \times p_{breach_h} \quad (3\text{-}2)$$

These values, $p_{flood_{i,d}}$ and $p_{flood_{i,}}$, will be used throughout the calculations of metrics.

The data required for calculating the probability of flooding are hazard recurrence curves and fragility curves. Hydrology data related to tidal effects and total Delta inflow are obtained from the DRMS (DWR 2009a; USGS 1982, 2014a) and stage-recurrence curves from the DRMS, the California Department of Water Resources (DWR), and the U.S. Army Corps of Engineers (USACE) (DWR 2014a, 2014b). Levee seismic vulnerability information is obtained from the DRMS (DWR 2009b, 2009c) and peak ground acceleration recurrence curves for seismic risk are from the U.S. Geological Survey (USGS) (2014b). Levee fragility curves draw on information from the DRMS, Central Valley Flood Protection Program, and USACE reports (DWR 2009c, 2012b; USACE 2013).

3.1.2 Probability of Flooding Over Time

A number of trends can affect the probability of flooding by altering the stage-recurrence curves and levee-fragility curves.[2] Stage-recurrence curves are affected by SLR, subsidence, changes in upstream water management practices, climate change, and future maintenance of the Delta levees. For example:

a. SLR will alter flow through the Delta and can increase the frequency of higher water levels.

[2] Note that peak ground acceleration recurrence curves are assumed to be constant over time. Seismic analysis of Delta levee fragility is based on a time-independent model that assumes that the probability of earthquake occurrence is constant over time.

b. Changes in upstream water management practices can alter total inflow to the Delta, thereby altering stage-recurrence curves.
c. Climate change effects, in addition to SLR, can alter total inflow to the Delta, thereby altering stage-recurrence curves.
d. The maintenance practices that can alter stage-recurrence curves include channel dredging, channel widening, or other alterations to local hydraulic flow characteristics.

Levee fragility curves are affected by State investments, subsidence, and maintenance levels. For example:

a. State investments in improving or replacing Delta levees will lead to new and appropriately improved levee fragility curves.
b. Continued subsidence will increase the water forces on the levees, thereby increasing the probability of levee failure at each river stage.
c. Maintenance, or lack thereof, can alter levee fragility curves. Regular and adequate levee maintenance may lead to maintaining existing levels of levee fragility. Deferred or inadequate maintenance may lead to increasing levels of levee fragility.

3.2 Expected Annual Fatalities

One of the key requirements of California Water Code section 85305(a) is to reduce risks to the people who live, work, and enjoy recreation in the Delta and Suisun Marsh. Fatalities are a key measure of the flood risk to the Delta population. Therefore, the impact of a strategic investment on EAF is an important metric for use in the Planning Tool prioritization processes. Because fatalities occur during a flood event, EAF is the same regardless of whether flooded islands are recovered.

Several methods have been proposed for calculating EAF; for example, methods presented in the Central Valley Flood Protection Plan (DWR 2012b), Best Practices in Dam and Levee Safety Risk Analysis (USDOI / USBR / USACE 2012), DRMS (DWR 2009d), and the Journal of Flood Risk Management (Jonkman and Vriling 2008).

A straightforward approach for calculating fatalities is the number of people that come into contact with flood water, multiplied by the fraction of fatalities among those people. Technical Memorandum 2.2, *Levee Hazards, Risks, and Consequences*, presents this approach in greater detail.

EAF is measured in terms of the number of lives lost. While it is theoretically possible to convert this into an economic value, for example using a statistical value of life, there is little consensus about such valuation and it is a source of significant disagreement. Applying a monetization in this case would also diminish transparency, as the underlying value of concern is the loss of life.

The risk to human life will also be illustrated using F-N curves as described in Technical Memorandum 2.3, *Tolerable Risk*, to help characterize risk. An F-N curve is a graphical representation of societal or group risk that relates the probability of N or more events per year to N, the number of events. A common use of F-N curves (and one that is used in the analysis of Delta risks) is to relate the probability of N or more fatalities per year to the number of fatalities.

The value of F-N curves is in the comparisons that can be made from the graphs to identify where risks are "unacceptable." Substantial probabilistic and sociological research has been devoted to identifying "acceptable" and "unacceptable" risk. The boundary between "acceptable" and "unacceptable" risk is considered to be indicative of the limit of "tolerable" risk, which is generally set by analysis and policy. F-N curves and the concept of "tolerable risk" are described in more detail in Technical Memorandum 2.3.

3.2.1 Calculating Expected Annual Fatalities

Flood levels have differential impacts on fatalities— in general, the greater the inundation depth, the greater the fatality rate. Therefore, EAF on a particular island i is calculated as the sum of the product of the annual likelihood of flooding and the estimated fatalities $fatalities_{i,d}$ at each potential flood level d:

$$EAF_i = \sum_d p_{flood_{i,d}} \times \ fatalities_{i,d} \qquad (3\text{-}3)$$

In turn, the number of fatalities on a particular island or tract for a given flood level is a product of the total population at risk (PAR), the percentage of the PAR that will come in contact with the flood water $p_{contact,d}$, and the percentage of fatalities among those who come in contact with flood water of a given depth $p_{fatalities,d}$:

$$fatalities_{i,d} = PAR \ \times \ p_{contact,d} \times \ p_{fatalities,d} \qquad (3\text{-}4)$$

The Delta-wide EAF is simply the sum of EAF on individual islands.

$$EAF_{delta} = \sum_i EAF_i \qquad (3\text{-}5)$$

3.2.2 Expected Annual Fatalities Over Time

Trends in the future will affect the expected annual fatalities over time by affecting the PAR, the contact rate, and the fatality rate. Increasing or decreasing Delta population will have a number of effects. First, it will affect the PAR. Second, it may alter the mortality rate by changing age and health demographics and by making evacuation routes more or less effective. SLR may alter the mortality rate through evacuation efficiency by reducing the number or capacity of evacuation routes, thereby affecting the fatality rate. State investments may also alter the mortality rate by improving evacuation efficiency by increasing flood awareness and improving evacuation routes and procedures.

3.2.3 Data Sources for Expected Annual Fatalities Metric

PAR is obtained from current U.S. Census Bureau data for the population within the legal Delta and Suisun Marsh boundaries. An average annual recreation user population, to be derived from a California DWR estimate of annual recreation user days (annually 12 million user days), and an average annual traveler population, to be derived from California Department of Transportation (Caltrans) average annual daily traffic (AADT) data (http://traffic-counts.dot.ca.gov/), will be added to the census PAR to obtain a total PAR.

The percentage of the total PAR estimated to come in contact with the floodwater is based on the type of breach (flood, seismic, sunny day). It is assumed that warning systems are effective at some level for flood breaches, but that warning systems will be less timely and less effective for seismic or sunny day breaches.

The percentage will be derived by examination of the available studies and data for the Delta and Suisun Marsh and other similar locations, but may be modified by expert opinion.

The percentage of fatalities among those who come in contact with the floodwater is estimated by examination of the available studies and data for the Delta and Suisun Marsh and other similar locations, but this percentage may be modified by expert opinion.

3.2.4 Caveats for Expected Annual Fatalities Metric

The EAF metric is often used as a proxy for all direct human flood risks (death, injuries, disease, psychological damages, etc.) to the people who live, work, and enjoy recreation in a floodplain. Other direct human risks may not be completely represented by the proxy of fatalities.

3.3 Expected Annual Damage

Flooding has a direct impact on infrastructure and other assets in the Delta. EAD captures current and future losses to Delta infrastructure and other assets in a year (see Technical Memorandum 2.2). This includes homes and commercial buildings, vehicles, transportation and energy infrastructure, agricultural infrastructure (buildings, machinery, etc.), agricultural land, and the value of lost crops. The contribution of each type of asset to EAD is calculated and summed to obtain a total EAD.

EAD is a monetized metric and is measured in dollars. Calculating EAD requires estimating the dollar value of assets and the fraction of that value that is lost in a flood. Future Delta asset and land values may change depending on population and economic growth, infrastructure improvements, Delta management strategies, and other factors, which are treated as uncertain future economic scenarios.

If an island or tract is inundated because of a levee breach, the choices facing decision makers and stakeholders would be to (a) rehabilitate the island or tract by repairing the levee breach and pumping the island or tract free of floodwater or (b) allow the island or tract to remain permanently flooded. An estimate of EAD will depend on which of these two options is selected.

If the choice is option (a), rehabilitate the island or tract, the costs of flooding will consist of lives lost, the cost of repairing or replacing assets, the cost of lost agricultural production, the cost of repairing the levee, and, in some cases, the cost of pumping floodwater out of the island or tract.

If the choice is option (b), allow the island or tract to be permanently flooded, the costs of flooding will consist of lives lost, the value of assets lost, and the value of the land lost (reported in both dollars and acres). In the case of agricultural land lost, the land value will include the lost value of future agricultural productivity. However, there would be no cost of repairing the levee and pumping floodwater out of the island or tract.

EAD will be calculated for options (a) and (b) for every leveed island and tract. As Technical Memorandum 2.2 describes, expected annual damage with rehabilitation (EAD_R) will include costs of rehabilitation while expected annual damage without rehabilitation (EAD_F) will not. Note that, as described in Box 3-1, the rehabilitation cost is estimated without regard to the source of rehabilitation funding (for example, the USACE's Public Law 84-99 [PL 84-99] Program).

A review of reported rehabilitation costs suggests that the cost of rehabilitating a flooded island or tract has several components, the most significant of which are the costs to mobilize resources for recovery, the cost to repair a levee breach, and the cost to pump out the floodwater (DWR 2008b; Suddeth et al. 2010, reclamation district 5-year plans).

Box 3-1. The Role of Public Law 84-99

PL 84-99 guidance is a minimum requirement established by the USACE for levees that participate in its Rehabilitation and Inspection Program (33 United States Code 701n) (69 Stat. 186). Delta islands or tracts that meet this standard may be eligible for USACE funding for levee rehabilitation, island repair and restoration after flooding, and emergency assistance. The PL 84-99 standard for levee geometry implies a minimum levee height and a factor of safety for slope stability. In 1987, the USACE developed a Delta-specific standard based on the Delta's soil and levee foundation conditions (Council 2013).

While eligibility in the PL 84-99 Program could reduce the local and state costs of repairing and rehabilitating a flooded island, the DLIS analysis reflects overall risks, consequences, and costs of flood damages irrespective of who will pay. This enables a more equal evaluation of risks and project impacts across islands and tracts, especially in the case where some islands would be eligible for federal assistance under the program and other islands would not be eligible. The metrics developed for DLIS to measure risk and evaluate trade-offs, however, do reflect whether islands are rehabilitated (EADr) or left permanently flooded (EADf).

Source: Council. 2013. *The Delta Plan*. Available from: http://deltacouncil.ca.gov/sites/default/files/documents/files/DeltaPlan_2013_CHAPTERS_COMBINED.pdf.

3.3.1 Calculating Expected Annual Damage

Different flood levels have different impacts on infrastructure and assets. Therefore, EAD on a particular island i is calculated as the sum of the product of the annual likelihood of flooding and the estimated economic losses $damage_{i,d}$ at each potential flood level d:

$$EAD_i = \sum_d p_{flood_{i,d}} \times damage_{i,d} \qquad (3\text{-}6)$$

The damage is itself a sum of the products of the value $value_a$ of each asset a multiplied by the percent loss in value $percentloss_{a,d}$ of that asset due to a flood of level d:

$$damage_{i,d} = \sum_a value_a \times percentloss_{a,d} \qquad (3\text{-}7)$$

The Delta-wide EAD is the sum of EAD on individual islands.

$$EAD_{delta} = \sum_i EAD_i \qquad (3\text{-}8)$$

3.3.2 Expected Annual Damage Over Time

EAD may change over time principally through the changes in flood risk and changes in population and socioeconomic conditions. These changes may affect the number and nature of assets in the Delta and the types of stage damage curves used in the calculations of value loss.

3.3.3 Data Sources

Calculating EAD requires data on exposed asset values obtained from the DWR (DWR 2013a). It also requires stage-damage curves, which define the percent of an asset's value that is lost at each flood level, for different types of assets. Stage-damage curves are obtained from the USACE for residences and businesses and for other assets from reported flood damage recovery costs.

3.3.4 Caveats for the Expected Annual Damage Metric

It is recognized that EAD cannot include all direct and indirect flood consequences in the calculation. For example, costs such as lost business revenue are difficult to accurately identify and quantify; or loss of certain islands or infrastructure may have unique, wide-ranging effects that cannot be readily incorporated in an EAD calculation. EAD must be viewed as a first-order metric that considers potential direct consequences to all islands and tracts equally. Once EAD is calculated for all islands and tracts, the results can be viewed in conjunction with the unique or more subjective measures of the indirect consequences of flooding.

3.4 Water Supply Disruption Risk Score

The Delta's complex configuration of waterways and associated levees support a water supply conveyance system and help ensure water supply reliability to water users south of the Delta and within the Delta. Approximately two-thirds of the State's water supply is routed through the Delta estuary. Freshwater flows from the Sacramento River and San Joaquin River systems mix in the Delta; a portion of that water is diverted to the large pumps in the south Delta for the DWR State Water Project (SWP) and the U.S. Bureau of Reclamation Central Valley Project (CVP). In an average year, water exports from the south Delta to central and southern California for agricultural and municipal use represent approximately 85 percent of the total water supply diversions from the Delta (Council 2013). Certain Delta channels, bounded by islands and levees, provide conveyance to the pumps, and, in combination with river flows and reservoir releases, help keep salinity from San Francisco Bay from impacting both the quality and quantity of water that can be exported at the Clifton Court Forebay pumps, other export diversions (North Bay Aqueduct, East Bay Municipal Utility District [EBMUD] intake facilities, etc.), and for in-Delta users.

Levee breaches and resulting floods threaten to disrupt water supply function. Island flooding can impact the integrity of the conveyance system by several mechanisms, for example by influencing the stability of the through-conveyance corridor and by changing salinity or introducing other potential contaminants that would adversely affect water supply. Depending on its location, a single flooded island may have little impact on reliability, but multiple flooded islands may have significant and complex effects that are not clearly understood. Note that not all islands and associated levees are necessarily beneficial for water supply reliability. Previous modeling has shown that flooding of some islands may actually decrease salinity, which would improve water quality and hence water supply reliability (DWR 2013b).

Potential disruptions would include disruption to exporters and water users that rely on diversions from the south Delta primarily through the State and federal water projects (the SWP and CVP), as well as potential disruption to both in-Delta water users and other important water supply infrastructure located within the Delta (e.g., Contra Costa Water District, North Bay Aqueduct, and EBMUD facilities).

Developing a Delta-wide method for the Planning Tool to assess potential water supply disruption risks associated with levee failures and island flooding requires a simplified approach. Island-specific water supply metrics have been formulated by considering water supply disruption impacts associated with potential changes to salinity and that salinity response is sensitive to specific island location and flooded island volume. Limited existing data are available that explicitly measure water supply disruption risk for a range of flood events associated with potential Delta levee failures. However, a recent DWR modeling study on salinity impacts from the flooding of Delta islands has been utilized in combination with a variety of additional data to inform this relationship.[3] The EAW has been developed to consider potential water supply disruptions that could be associated with island levee failures in the Delta. Note that this metric is a risk *score* rather than risk because there are many uncertainties associated with the actual relationship between flooding and water supply disruption, including the duration, severity, and specific consequences of disruption. Consequently, this risk *score* is best used to assess the relative likelihood of disruptions from different islands flooding and the relative impact of levee investments. It should not be used as an assessment of the actual annual likelihoods of water supply disruption. The lack of existing comprehensive data, complexity of this issue, and associated uncertainties do not allow for establishing more familiar final units of analysis (e.g., lives, acres, dollars); however, as described below, flooded island volumes and associated influence factors provide key physically based parameters upon which the risk *score* is based.

3.4.1 Calculating Water Supply Disruption Risk Score

The EAW from a particular island flooding can be defined in the classic probability-consequence framing:

$$EAW_i = p_{flood_i} \times p_{disruption_i} \qquad (3\text{-}13)$$

Where p_{flood_i} is the probability of a flood on island i associated with a levee breach or failure. The consequence in this case is a conditional probability—the probability of a disruption to water supply given island flooding, written as $p_{disruption_i}$.

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[3] For instance, while most studies on water supply reliability focus on Delta water exports (which account for approximately 85 percent of water use), the same factors that influence water quality for exports influence water quality for in-Delta use; therefore, potential disruption of one may act as a proxy for potential disruption of both.

There are no existing data that specifically identify values for $p_{disruption_i}$. This relationship is determined based on how particular islands or groups of islands may affect water supply reliability. The risk of water supply disruption considers both: 1) potential islands and groups of islands throughout the Delta that provide a buffer against salinity intrusion, and 2) those specific islands and associated levees located along the through-conveyance corridor.

Several studies note that flooded volume is a useful proxy for water supply disruption (DWR 2013b, 2014d, and DRMS); however, they also point out that disruption and flooded volume are not always directly linked. There are other important island characteristics, in addition to volume, that may affect water supply reliability, including:

1. Proximity of the island or tract to the through-conveyance corridor.
2. Salinity effects at the pumping stations for users south of the Delta.
3. Islands containing or supporting critical in-Delta and Suisun Marsh water supply infrastructure.

To capture these interactions, the actual flooded volume is scaled by an "influence factor" $\alpha_{T,i}$ that captures island $i's$ characteristics of proximity, salinity effects, and water supply infrastructure. This results in an effective flooded volume (EFV) score.

$$EFV_i = \alpha_{T,i} \times (TrueFloodedVolume_i) \qquad (3\text{-}14)$$

The true flooded volume is calculated using mean higher high water (MHHW) elevations from the DRMS (DWR 2009e). MHHW is used because it represents long-term salinity intrusion. Water levels may be significantly higher at the time of the breach, but those are generally short-term river events, and there is likely an abundance of freshwater to keep salinity low if the failure occurs during a high river stage.

Next, the total influence factor $\alpha_{T,i}$ is determined. As shown in equation 3-15, the total influence factor is the sum of the individual influence factors if flooding of islands increases salinity. Each influence factor has a maximum of 0.333, so the highest total influence factor is 1.0. However, some island flooding has the potential to decrease salinity, which is a desirable outcome. In these cases, the total influence factor consists of only the salinity effect. The minimum salinity effect is -0.333, and so the lowest total influence factor is -0.333.

$$\alpha_{T,i} = \begin{cases} \alpha_{Proximity_i} + \alpha_{Salinity_i} + \alpha_{Infrastructure_i}; & \alpha_{Salinity_i} \geq 0 \\ \alpha_{Salinity_i} & ; \quad \alpha_{Salinity_i} < 0 \end{cases} \qquad (3\text{-}15)$$

To calculate the proximity influence factor $\alpha_{Proximity_i}$, the distance is calculated from the closest edge of each island or tract to the closest branch of the through-conveyance corridor, as presented in Appendix D, figure D6 of the Delta Protection Commission (DPC) Economic Sustainability Plan DPC 2012). The closest third of islands are assigned a proximity influence factor of 0.333, the next closest third of islands a proximity influence factor of 0.167, and the farthest third of islands a proximity influence factor of 0.

The salinity effect influence factor $\alpha_{Salinity_i}$ is calculated based on previous system-wide modeling studies of salinity levels at Clifton Court Forebay following the simulated failure of different islands or sets of islands. This is based primarily on the DWR report titled *Draft Long-term Salinity Impacts from Permanently Flooding*

Delta Islands (DWR 2013b), though this report ("draft Delta salinity report") is supported by other similar studies, like the Public Policy Institute of California (PPIC) report titled *Delta Hydrodynamics and Water Salinity with Future Conditions* (PPIC 2008).

The draft Delta salinity report documents the effects on salinity of the failure of 19 individual islands and seven island groups as a percent change in the salinity measured at Clifton Court Forebay. The relative effect of each island is determined based on the individual island effect from the DWR modeling study for the 19 islands the report considered. For additional islands included in the seven island groups, their relative effect is determined based on their contribution to the overall group effect, dividing the group effects among their constituent islands by multiplying the total group effect by the fraction of the group flooded volume made up by each island. Combining individual and group effects risks double counting the effect of islands whose effects are large enough to control their group effect, so group effects were only used to cover islands not studied individually.

The absolute value of the effects is scaled to the range (0, 0.333) and then multiplied by the sign to reach a final salinity effect influence factor in the range (-0.333, 0.333). A negative influence factor is an important condition because it captures the effects of modeled flooded islands where salinity effects were negative, resulting in improved water quality. For islands with a negative salinity effect influence factor, the total influence factor is equal to the negative salinity effect influence factor alone, not the sum of all influence factors.

The critical water supply infrastructure influence factor $\alpha_{Infrastructure_i}$ reflects those islands or tracts that contain or support important in-Delta water supply infrastructure facilities (e.g., EBMUD aqueducts, Contra Costa Water District intake facilities, North Bay Aqueduct intake facilities, other DWR facilities). Those islands are assigned a high influence value (0.333). Islands with in-Delta water supply infrastructure were determined using geographic information systems data (referenced in TM 2.1) on conveyance and pump stations locations, and Suisun Marsh water quality mitigation projects data provided by DWR.

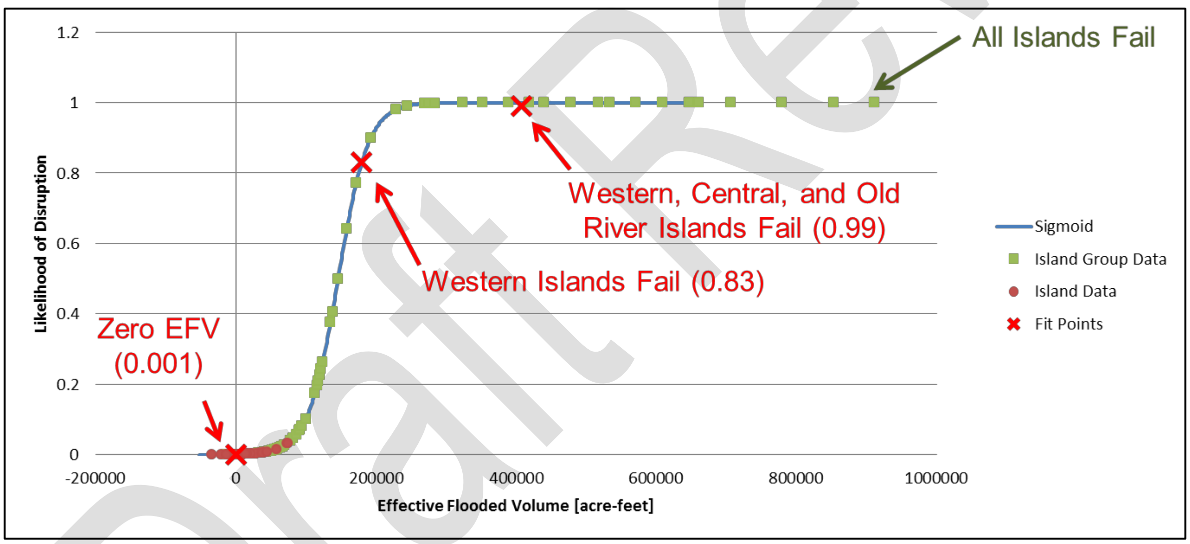
For illustration, consider the EFV of Twitchell Island. Twitchell Island has a flooded volume at MHHW of about 46.5 thousand acre-feet (TAF). It is close to the conveyance corridor (1.7 miles), so it has a proximity influence factor of 0.333. It was studied as an individual island, and its salinity effects are high (it provides an individual effect of +6 percent), which puts it in the 89th percentile of islands. Scaling from the range (0.0, 1.0) to the range (0, 0.333) gives a high salinity effect influence factor (0.89 * 0.333 = 0.296). The island does not contain any significant water supply infrastructure, so it has a critical water supply infrastructure influence factor of zero. The total influence factor is the sum of these (0.333 + 0.296 + 0 = 0.629), and the EFV is the product of the true flooded volume and the total influence factor (46.5 * 0.629 = 29.25 TAF).

Having assigned influence factors and resulting EFVs to each island or tract, a function is developed that maps EFV to a probability of disruption, called a *disruption curve*. The relationship between EFV and the probability of disruption is represented by a sigmoid function as shown below (Kucharavy and De Guio 2012). One advantage of this function is that it maps total EFV to probability of disruption, so understanding the effect of multiple islands flooding is straightforward: it is the disruption from the sum of the EFVs of the individual islands.

To develop the sigmoid disruption curve, three data points are fit via a least-squares method. The first point at zero EFV was selected and assigned a disruption probability of 0.001. This accounts for uncertainty in the method, because islands / tracts assigned zero EFV may have a small change of affecting water supply due to potential unknowns. The second point was selected at an EFV equal to the sum of the seven Western Delta Group islands / tracts from the DWR draft Delta salinity report (DWR 2013b): Sherman, Twitchell, Bradford, Jersey, Bethel, Hotchkiss, and Holland islands / tracts. The sum of their effects on salinity at Clifton Court Forebay and that of the group as a whole is 83 percent, so they were assigned a disruption probability of 0.83.

The third point was selected based on what is believed would cause a certain disruption: the failure of the Western Delta Group, the Central Delta Group, and the Old River Group from the DWR draft Delta salinity report (DWR 2013b), which would open a large, direct path from San Francisco Bay to the pumping stations at Clifton Court Forebay. To indicate an almost certain water supply disruption failure, the total EFV of these islands / tracts was assigned a disruption probability of 0.99. The curve resulting from a least-squares fit to these parameters is shown on Figure 3-1 and the distribution parameters are given in Table 3-1.

Figure 3-1. Sigmoid Disruption Curve for Expected Annual Water Supply Disruption Risk Score



Notes: The Disruption Curve is a sigmoid curve mapping EFV to disruption probability. The points used to define the curve are marked in red.

Table 3-1. Sigmoid Curve Parameters

Parameter	Value	Description
L	1.0	Asymptotic maximum (maximum disruption probability)
x_0	145919	Inflection point (highest growth rate of disruption probability)
k	$4.70x10^{-5}$	Shape parameter (steepness and curvature of disruption relationship)

With these two components of EFV and a disruption function, the EAW for a single island, *i*, can be calculated as:

$$EAW_i = p_{flood_i} \times disruption(EFV_i) \quad (3\text{-}16)$$

where p_{flood_i} is the annual probability of island flooding calculated earlier and *disruption* (EFV_i) is the disruption curve mapping EFV to the likelihood of water supply disruption (see Table 3-1).

Calculating the Delta-wide risk of disruption is summative, analogous to calculating Delta-wide EAD (Section 3.3). A probability density function p_{delta} is computed for the annual effective flood volume for the entire Delta by convolving the individual p_{flood_i} distributions.[4] The expected annual water supply disruption risk score EAW_{delta} for the entire Delta is:

$$EAW_{delta} = \sum_n [disruption(EFV = n) \times p_{delta}(EFV = n)] \quad (3\text{-}17)$$

over all values of *n.*

3.4.2 Water Supply Disruption Risk Score Over Time

The water supply metric has been developed to represent current baseline conditions. To support baseline future projections, some basic assumptions have been made to account for potential changes to the metric that would occur at years 2030 and 2050. Basic assumptions include the following:

- Island flooded volumes will change or increase as SLR results in higher water surface elevations.
- Salinity influences will become more critical as the position of X2[5] moves eastward with SLR.
- The general effects associated with the implementation and operation of the BDCP proposed project and associated upstream Sacramento River water supply diversions would decrease the likelihood of water

[4] This approach assumes that the probability distribution functions (PDF) for flooding of each island can be treated independently at this point. There are (at least) two ways in which they would not be independent. First, many of the conditions that cause levee failures (e.g., high water in the Delta, seismic activity) will affect multiple islands simultaneously. This joint likelihood is already included in the stage-recurrence curves that affect all islands. Secondly, the breach of a levee on one island may create hydrodynamic conditions that induce a break on another island; however, this chain of dependencies is not well understood and is not part of the existing data available for this project.

[5] X2 is used as a measure of salinity in the Delta, and it is defined as the position of the two practical salinity units (psu) bottom salinity value, measured along the axis of the estuary in kilometers from the Golden Gate Bridge. It is assumed that the eastward movement of X2, as a percent, increases the salinity effect by an equal percent.

supply disruption associated with flooding of Delta islands due to a reduced dependence on through-Delta conveyance (California Department of Water Resources and U.S. Bureau of Reclamation 2013).

The future likelihood of water supply disruption can be considered in terms of the four factors that drive the water supply metric (flooded volume, proximity to the through-conveyance corridor, salinity distribution effects, and in-Delta water supply infrastructure). There are two primary future drivers that would influence these factors: SLR and BDCP. These changes to the water supply metric are considered under conditions at years 2030 and 2050, and the changes are divided into the case with BDCP and the case without BDCP.

If the BDCP proposed project is not constructed and operated, the likelihood of water supply disruption will be similar to present conditions, though SLR will exacerbate the likelihood of disruption. Rising mean sea levels could increase saltwater intrusions into the Delta, which would reduce water supply deliveries and decrease annual Delta exports. In-Delta infrastructure may change, but this is subject to high uncertainty and cannot be predicted with given information. Under the assumption that there will either be no changes or the changes will offset one another (e.g., a new pumping plant will replace an older one), it is assumed that the infrastructure influence factor will remain the same. The through-conveyance corridor is unlikely to move, so the proximity influence factor will remain the same.

Because the previous modeling reports used to estimate salinity effects do not include SLR, changes in salinity effects are estimated using estimated changes in X2 associated with future SLR scenarios. The movement of X2 will be interpolated from the SLR modeling results of Fleenor and Bombardelli (2013). These results are supported and corroborated by studies performed by others, including the U.S. Bureau of Reclamation (U.S. Bureau of Reclamation 2008, 2011), the BDCP (California Department of Water Resources, and U.S. Bureau of Reclamation 2013), Brown et al. (2013), and Moyle et al. (2010). SLR will alter flooded volumes, so these will be recalculated with higher MHHW levels based on the California SLR estimates. In potential cases where SLR leads to MHHW levels above current levee crest elevations, it is assumed that the levees are raised to MHHW to hold back the tide, so the islands are flooded to MHHW.

If BDCP is implemented and the conveyance operated as a dual-conveyance facility as proposed, it is estimated that on average 50 percent of the water currently passing through the pumps at Clifton Court Forebay will be diverted at the proposed Sacramento River intakes through tunnels beneath the Delta. This will add some new infrastructure to the Delta, but changes to in-Delta supply infrastructure remain uncertain, as described above, so the in-Delta infrastructure influence factor will remain the same. The through-conveyance corridor is unlikely to move, but only 50 percent of the water pumped south will pass through the Clifton Court Forebay pumps, so the present-day proximity influence factor will be multiplied by 0.5. As above, the salinity effect will be scaled based on eastward movement of X2; however, because only 50 percent of the water pumped south will pass through the Clifton Court Forebay pumps, the scaled salinity influence factor will be multiplied by 0.5, as well. BDCP will not affect SLR, so flooded volumes will be altered by SLR in the same way as described above.

3.4.3 Data Sources

Calculating EAW requires data on volumes of water that would inundate each island in the event of a flood. This is available from the DRMS Salinity Impacts section (DWR 2009e). It also requires a determination of islands' relative contribution to water supply disruption. Several studies were used to make these judgments: the DPC Economic Sustainability Plan (DPC 2012), the DWR draft Delta salinity report (DWR 2013b), the

PPIC *Delta Hydraulics and Water Salinity With Future Conditions* (Public Policy Institute of California 2008). The relationship between the flooding of an island and likelihood of water supply disruption is not well understood and so will be treated as a key uncertainty in our analysis.

3.4.4 Caveats for Expected Annual Water Supply Disruption Risk Score

This metric does not include the economic and social consequences of water supply disruption, given the deep uncertainties and difficulties associated with calculating such impacts. This metric also considers each Delta island and its associated levees as one unit whereby a breach event results in the filling of the island. Precise levee breach locations and the size/magnitude of potential breaches are not specified. Salinity is applied as the primary water quality parameter influencing potential water supply disruption risks; other potential water quality contaminants that may be discharged following island flooding have not been considered due to lack of sufficient data available to support this level of detail. Given the availability and scope of previous hydrodynamic studies of the Delta, the understanding of potential disruptions including the duration or the severity of disruption is limited. Most importantly, there are no existing standard calculations on which this metric can be based. The proposed calculations attempt to map flood risks to disruption consequences in a straightforward and transparent way.

3.5 Expected Annual Change in Habitat

According to the Delta Plan, "achieving the coequal goal of protecting, restoring, and enhancing the Delta ecosystem" means successfully establishing a resilient, functioning estuary and surrounding terrestrial landscape capable of supporting viable populations of native resident and migratory species with diverse and biologically appropriate habitats, functional corridors, and ecosystem processes (Council 2013). The elements that create ecosystem value are complex. For decision makers and stakeholders to understand and trade off the impact of projects on the ecosystem, the ecosystem metric must be relatively simple and understandable and still capture the essential elements of ecosystem value. The effect on ecosystems will be measured by the quantity and quality of habitat maintained, created, or lost.

The EACH is the amount of habitat that would be lost or gained on average annually due to permanent island flooding. This metric captures expected habitat benefits analogous to EAD used in the flood risk analysis. It is similar to the expected annual habitat metric developed for the Central Valley Flood Protection Plan Conservation Strategy (DWR 2014c), described in Matella and Jagt (2013). This metric is only relevant when flooded islands are not recovered; if islands are recovered, then we assume that the original habitat will also be restored. Note that flooding need not be a negative outcome – flooding can have positive effects such as the creation of tidal wetland.

As with other metrics, we will measure the effect of each investment on habitat at the beginning (Year 2012), middle (Year 2030), and end (Year 2050) of the planning horizon. This is explained in Section 3.5.2, Habitat Metrics over Time.

Habitat types include a range of natural communities, such as tidal marsh and riparian, and agricultural communities that can provide foraging habitat for certain wildlife species ("wildlife-friendly agriculture"). These habitat types will be quantified both inside and outside the levees. Twenty habitat types are tracked consistent with the Delta Plan Environmental Impact Report: seven agricultural community types and 12 natural community types, and developed land (Table 3-2). To help summarize the effects of levee investments on habitat, the amount of habitat is aggregated into five classes of quality. Recognizing that habitat value is highly species-specific and not all habitat types provide the same ecosystem value, habitat types will be assigned a corresponding habitat quality rating. Habitat types will be characterized as providing low, moderate, high, or very high quality habitat, and acres will be reported by habitat quality.

Table 3-2 provides initial habitat quality ratings based on importance to recovering species, historical losses, and priorities from existing conservation plans. For example, tidal marsh was once the most abundant type of habitat in the Delta and Suisun Marsh (Atwater and Belknap 1980; The Bay Institute 1998; Whipple et al. 2012). Tidal marshes (Herbold et al. 2014) and seasonally inundated floodplains (Opperman 2012; Sommer et al. 2014) are highly productive systems that provide rearing habitat and food web subsidies for native fishes. In recognition of their value for biodiversity and recovering species, numerous conservation plans place high value on protecting and restoring tidal marsh, seasonal wetland, and riparian habitats, for example the Delta Plan (Council 2013); Ecosystem Restoration Program Conservation Strategy (Ecosystem Restoration Progam 2014); BDCP (California Department of Water Resources and U.S. Bureau of Reclamation 2013); Central Valley Flood System Conservation Strategy - Draft (DWR 2015); and Central Valley Habitat Venture (Central Valley Joint Venture 2006; Riparian Habitat Joint Venture 2004).

Depending on the crop and cultivation practices, wildlife-friendly agriculture can benefit certain terrestrial species. For example, Swainson's Hawk is closely associated with agricultural lands as foraging habitat (Estep 1989, 2009; Woodbridge 1998). Alfalfa provides high-value foraging opportunities for Swainson's Hawk, while orchards and vineyards provide minimal habitat value (Estep 1989, 2009; Woodbridge 1998. Rice provides habitat for Giant Garter Snake during summer (U.S. Fish and Wildlife Service 1999). Grain crop stubble that is flooded in winter supports migratory waterfowl (Central Valley Joint Venture 2006) and sandhill cranes (Littlefield 2008). Agriculture will be assigned a habitat quality ranking between none (vineyards and orchards) and moderate (wildlife-friendly agriculture).

Open water habitat will be quantified, but not rated by quality. The quality of open water habitat can vary depending on conditions not readily apparent from existing datasets, species-specific habitat preferences, and differing opinions on food web relationships. The extent of open water habitat has increased greatly and replaced historical extents of tidal marsh, which is one factor in the decline of native fishes (San Francisco Estuary Institute-Aquatic Science Center 2014). Some scientists hypothesize that restoring deep open water would benefit native pelagic fish species such as delta smelt and longfin smelt (Moyle and Bennett 2008; Moyle et al. 2010), while others find little evidence that flooded islands support these species (Grimaldo et al. 2009). Shallow subtidal habitat favors non-native invasive fishes and submerged aquatic vegetation (SAV) (Moyle et al. 2012). Invertebrate production from SAV in the littoral (nearshore) zone, however, can provide food for fish in adjoining open water, such as juvenile Chinook salmon (Grimaldo et al. 2009).

Habitat quality is to some extent subjective and will vary by stakeholder. The decision-support model is set up so that habitat quality values can be adjusted and aggregated according to stakeholder preferences.

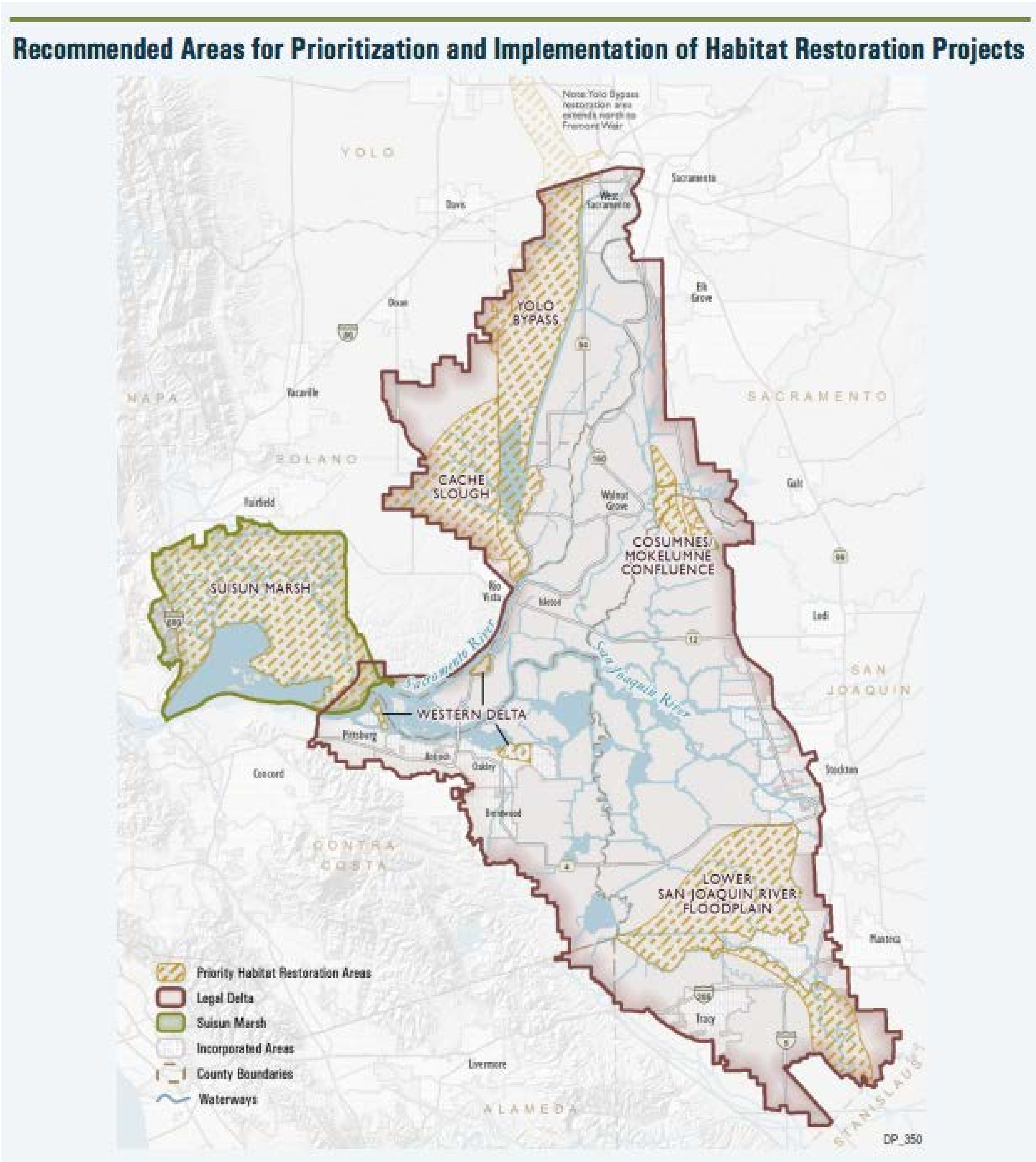
Table 3-2. Existing Habitat Types

Community	Habitat Categories (Delta Plan)	Habitat Quality Value	Notes
Natural	Alkaline seasonal wetland	Moderate	• Rare plants
	Grassland	Moderate	• Swainson's Hawk (Estep 1989; Woodbridge 1998)
	Vernal pools	High	• Vernal pool plants, invertebrates, California tiger salamander
	Disturbed vernal pools	Moderate	
	Managed wetland	High	• Waterfowl (Central Valley Joint Venture 2006; Council 2013) • Giant Garter Snake (U.S. Fish and Wildlife Service 1999)
	Marsh (nontidal)	High	• Giant Garter Snake (U.S. Fish and Wildlife Service 1999) • Waterfowl (Central Valley Joint Venture 2006) • Seasonally inundated floodplain native fishes including migrating juvenile Chinook salmon (Sommer et al. 2014)
	Marsh (tidal)	Very High	• Native fishes, migratory salmonids, and aquatic foodweb support (Herbold et al. 2014; Howe et al. 2014)
	Open water (nontidal)	Varies	• Shallow subtidal habitat could favor non-native invasive fishes and submerged aquatic vegetation (Moyle et al. 2012). • Deep open water could benefit native pelagic fish species (Moyle and Bennett 2008; Moyle et al. 2010), but depends on location (Grimaldo et al. 2009).
	Open water (tidal)	Varies	
	Riparian scrub	Very High	• Riparian birds (Riparian Habitat Joint Venture 2004) • Shaded riverine aquatic habitat for salmonids (Ecosystem Restoration Progam 2014; DWR 2014a)
	Riparian forest / woodland	Very High	
	Riparian invasives	Moderate	
Agricultural	Alfalfa	Moderate	• Swainson's Hawk (Estep 1989; Woodbridge 1998) • Sandhill Crane (Littlefield 2008)
	Irrigated pasture	Moderate	
	Other agricultural lands	Low	
	Other cultivated crops	Low	
	Rice	Moderate	• Giant Garter Snake (U.S. Fish and Wildlife Service 1999) • Wintering waterfowl (Central Valley Joint Venture 2006) • Sandhill Crane (Littlefield 2008)
	Orchard	None	• Swainson's Hawk (Estep 1989; Woodbridge 1998) • Sandhill Crane (Littlefield 2008)
	Vineyard	None	
Developed	Developed	None	

In addition, two other subcategories of habitat that would be lost or gained annually are reported. First, the change in the amount of habitat within locations prioritized for restoration in the Delta Plan is quantified. This will be determined using the information on Figure 4-8 of the Delta Plan (Figure 3-2). Opportunities for habitat restoration are constrained by elevation. Deeply subsided Delta lands offer few opportunities to recover native ecosystem forms and functions, but may be important to protect for seasonal wetlands and wildlife-friendly agriculture (Council 2013). These deeply subsided lands may have value as deep water habitat, although the benefits of increasing deep water habitat in the delta ecosystem have not been established (Ecosystem Restoration Progam 2014).The most promising restoration opportunities for intertidal and floodplain habitats are found in the areas adjacent to river corridors and less-subsided islands along the Delta's perimeter.

Second, the change in amount of habitat that is near fish migratory corridors will be quantified, with the aim of focusing on maintaining functional corridors that connect priority native fishes with favorable habitats while minimizing movement into unfavorable or high-risk habitats (Moyle et al. 2012). Juvenile salmon entering the interior Delta have lower survival than those migrating within the mainstem Sacramento River (Newman 2008; Perry et al. 2012) and San Joaquin River (Newman 2008), due to risk of entrainment at South Delta export facilities and longer migration routes that increase exposure to predation. Overall, survival is very low on all routes and uncertainty exists regarding the best way to improve survival of outmigrating juvenile salmon, especially from the San Joaquin River. To protect the integrity of the corridor along better-survival routes, islands along the mainstem Sacramento and San Joaquin rivers where a breach would potentially divert fish toward the central or south Delta are included.

Figure 3-2. Priority Habitat Restoration Areas from the Delta Plan



Source: Figure 4-8 of the Delta Plan (Council 2013)

3.5.1 *Calculating Expected Annual Habitat Change*

EACH is the amount and quality of habitat that would be lost or gained on average annually to floods if an island is not reclaimed. It is analogous to EAALL, but it is possible for flooding to increase habitat, such as by creating tidal wetland or seasonal floodplain.

EACHx is defined in the classic probability-consequence framing:

$$EACHx_i = p_{flood_i} \times floodchange_{xi} \quad (3\text{-}21)$$

where p_{flood_i} is the probability of a flood on island i associated with an unreclaimed levee breach. $floodchange_{xi}$ is the net change in habitat x if island i were to flood.

Potential habitat types that would form on a permanently flooded island will be characterized by the seven habitat types shown in the Delta Plan, with expected habitats based on elevation (Table 3-2) – subtidal, intertidal, transitional, seasonal floodplain, upland, and developed. Habitat types will be estimated within the formerly leveed island.

The expected annual change in habitat for the entire Delta is:

$$EACHx = \sum_i EACHx_i \quad (3\text{-}22)$$

The change in habitat is summarized according to the acres of habitat of different quality that are created or destroyed. Table 3-3 provides initial habitat quality ratings.

Table 3-3. Potential Habitat Types and Quality Values of Permanently-Flooded Islands

Flooded Island Habitat Type	Habitat Quality	Notes
Developed	None	Developed areas would persist on flooded islands if on high elevation or protected by internal levees.
Uplands	Moderate	Includes grasslands and perennial dune scrub. Approximate elevation: above transitional habitat and seasonal floodplain
Seasonal Floodplain	Very High	Restoring access and winter/spring inundation to floodplains is highly desirable to create seasonal wetlands that are nurseries for native fishes, and riparian habitat at upper edges (Opperman 2012; Sommer et al. 2014). Elevation varies, above transitional habitat within river corridors.
Transitional habitat	High	Transitional areas provide an interface between intertidal and adjacent seasonal floodplain or uplands. With sea level rise, some transitional habitat will convert to intertidal. Approximate elevation: EHW up to 7 to 9.5 feet above EHW.
Intertidal	Very High	Returning tidal exchange to areas in this tidal range is highly desirable to create very high value habitat for fishes, aquatic food web support

Flooded Island Habitat Type	Habitat Quality	Notes
		(Herbold et al. 2014). Approximate elevation: MLLW to EHW.
Subtidal	Varies	Conversion to shallow subtidal open water habitat would favor non-native invasive species such as Brazilian waterweed (*Egeria*), warmwater fishes (Moyle et al. 2012). Conversion to deeper open water could benefit native pelagic fish species (Moyle and Bennett 2008; Moyle et al. 2010). Approximate elevation: below MLLW.

Source: Adapted from DFG 2011, as presented in Council (2013).

Note: Elevations in NAVD88. EHW = extreme high water; MLLW = mean lower low water.

3.5.2 Habitat Metrics Over Time

For future conditions, habitats that are subject to tidal inundation, not leveed, will be estimated based on land elevations relative to the tidal frame. Habitat types and their associated elevation ranges relative to the tides are shown in Table 3-3. Tidal elevations will be updated at each time step (Current, 2030, and 2050) by adding projected SLR to existing tidal elevations. Tidal elevations will be applied by region throughout the Delta and Suisun Marsh. For example, tidal elevations will differ between Suisun Marsh, the north Delta, and other parts of the Delta. Habitats within the levees are assumed not to change over time. Currently leveed areas that become flooded will be progressed into the future.

3.5.3 Data Sources

Calculating EACH requires data on potential flooded habitats, which will be calculated in the geographical information system (GIS) based on relative land and tide elevations, using methods similar to those shown in the Delta Plan, Figure 3-2. Elevations are from an ICF International (ICF) dataset that merges the 2007 DWR LiDAR with a raster created for the DRMS project. Tidal elevations will be provided either from California Department of Fish and Game 2011 (as cited in the Delta Plan; Council 2013) or from BDCP tidal elevation analysis (ESA 2012).

3.5.4 Limitations

There are many characteristics that describe ecosystem function, such as biodiversity, habitat structure, water quality, and population dynamics. These characteristics are complex and hard to measure, particularly into the future. While the amount and quality of habitat serve as useful indicators, they do not capture all important effects and indicators of ecosystem function. The metrics themselves require the application of judgment regarding level of detail in habitat types to track, how to value habitat quality, and how to estimate habitat evolution over time. Following an unreclaimed levee breach, erosion of habitats downwind of any large open water areas can be expected. This erosion of habitat is not captured in the metrics because of the additional complexity it would introduce. Salinity is acknowledged as an important habitat parameter affecting vegetation communities, native fish species, and other species of interest. Salinity changes that would occur with any unreclaimed breaches and how these changes would affect habitat types and quality are also not captured in the metrics, again due to the desire to keep the metrics relatively simple. Finally, the potential suitability of any resulting subtidal habitat for fish species depends on many factors that are not captured simply by elevation and depth. Key unknowns about the nature of the new open water habitat are: (1) the characteristics of the physical and chemical habitat created, such as depth, turbidity, flow, and salinity; (2) how productive this new habitat is likely to be in terms of algae, copepods, and other organisms that support food webs leading to fish; and (3) how susceptible it will be to invasions by harmful alien species such as overbite clam, Brazilian waterweed, and Asian clam (Moyle and Bennett 2008).

4. DLIS PLANNING TOOL

4.1 Objective of the Planning Tool

The flood risks facing the Delta are complex and varied. The possible investments are numerous, and they will affect Delta risks differently (flood damages, water supply reliability, and ecosystem function). Alternative views about the importance of different types of risks will affect how one might prioritize investments. Lastly, uncertainty about future risks could lead to ambiguity about the best investment prioritization.

The Planning Tool is being developed to support Council decision-making about levee investments. The Planning Tool is still under development and, when complete, it will help the Council understand the range of possible risks facing the Delta, such as which islands are at highest risk for flood damage and which islands most threaten the State's water supply. It will allow the Council and interested stakeholders to develop their own prioritizations of islands based on risk and prioritizations of investments based on the estimated cost effectiveness of those investments. Through these explorations of priorities, the Council and stakeholders will learn more about where there are common views of Delta risks and opportunities for achieving multiple risk reduction benefits.

The ranking of individual investments by risk alone cannot identify the best investments to advance State interests. First, a balance of risk reduction across metrics and regions of the Delta may be desired. The top ranked investments, for example, may disproportionally reduce risk with respect to flood damage, but not with respect to water supply or habitat. Second, some investments may be mutually exclusive, such as two different approaches for upgrading the levees on the same island. Third, other constraints on the State's investment strategy, such as total funding, could lead to a choice of smaller, lower-ranked projects if funding is not sufficient to include a higher-ranked but more expensive investment.

The Planning Tool helps address these issues by developing portfolios of levee investments that would best meet State goals under different implementation constraints, such as funding levels. The Planning Tool will help the Council to compare the outcomes of different portfolios and key trade-offs among them.

The decision analytic approach supported by the Planning Tool is grounded in decision theory. At its core, the Planning Tool is designed to support a deliberation with analysis process by which quantitative analysis is used not to provide a single answer but rather to frame and illuminate key policy trade-offs (National Research Council 2009). The Planning Tool builds on the Planning Tool developed for the Louisiana Coastal Protection Agency's 2012 Coastal Master Plan (Groves and Knopman 2012; Groves and Sharon 2013).

4.2 Overview of the Planning Tool

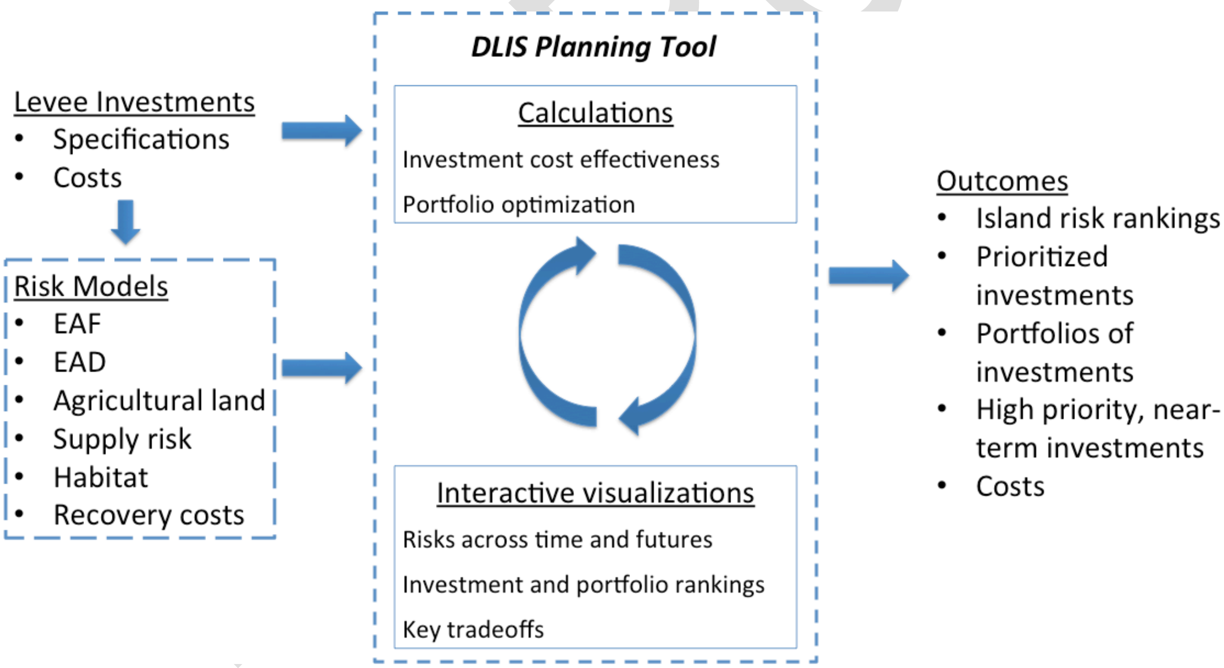
The Planning Tool (1) assimilates and summarizes information about baseline risks to the Delta over time; (2) showcases the effects of different levee investments on those risks and comparisons of investments based on cost effectiveness; (3) develops portfolios of levee investments; (4) summarizes the key trade-offs among the portfolios; and (5) identifies the near-term levee investments that are most robust and most consistent with State interests.

The Planning Tool takes asset and risk information for each island and tract with and without levee investments. The Planning Tool allows users to specify weights for different performance metrics, such as EAD reduction or habitat area, and then rank investments. The Planning Tool also enables the user to specify budgets and other planning constraints to guide the development of different investment portfolios.

The Planning Tool performs some basic calculations to summarize risk information and compare levee investments. Furthermore, it uses a sophisticated optimization engine to develop portfolios of investments that best achieve the State's goals given different planning constraints.

The output of the Planning Tool is a series of interactive visualizations in which the user can specify information of interest (e.g., risks with respect to a particular performance metric or time period), set metric weights for island rank and investment rankings, define portfolios of levee investments, and explore different trade-offs across the portfolios. Figure 4-1 summarizes the inputs, calculations, and outputs of the Planning Tool.

Figure 4-1. Overview of Planning Tool



The Planning Tool visualizations are made available on interactive websites (Figure 4-2). Different versions of the Planning Tool will be developed to support internal analysis by the Council, review by technical stakeholders, and review by the general public.

Figure 4-2. Planning Tool Welcome Screen

4.3 Theoretical Basis of the Planning Tool

The Planning Tool supports deliberations by summarizing information about baseline risks and the effects of different investments on that risk, and then identifying portfolios of investments that reflect State interests given user-specified preferences over the different performance metrics and assumptions about future risks. Such an exploratory modeling approach is suited for long-term policy questions in which uncertainty is significant, there are a variety of views on desirable outcomes, and there is disagreement about how the system will respond to future stressors (Lempert et al. 2003). The Planning Tool seeks to define portfolios that maximize State goals while satisfying a wide range of constraints.

To develop optimal investment portfolios, the Planning Tool defines a simple objective function based on a small set of weighted risk performance metrics, according to multi-criteria decision analysis (MCDA) methods (Keeney and Raiffa 1993; Lahdelma et al. 2000; Kiker et al. 2005; Linkov et al. 2006). Then the Planning Tool uses a standard mixed-integer programming (MIP) approach (Schrijver 1998) to solve the constrained optimization problem of maximizing the objective function subject to funding and other implementation constraints. Importantly, the analysis seeks to use a simple and easily understood objective function made up of only a few key performance metrics. Following Romero (1991), the Planning Tool will include only some of the metrics in the objective function. The others will be used as constraints. For example, the Planning Tool might be specified to include EAD, EAW, and EACH for a high value category, and then set as constraints that EAF cannot be higher than a specific level for each island.

4.4 Key Functions of the Planning Tool

The Planning Tool performs a variety of functions, but, at its core, it does three things: (1) summarizes and visualizes risks without levee investments; (2) compares individual investments based on cost effectiveness of risk reduction; and (3) develops and compares portfolios of investments.

4.4.1 Calculation and Visualization of Risks without Investment

To support the visualization of Delta risks, the Planning Tool presents shaded maps showing different island attribute information. Figure 4-3, for example, shows the minimum island elevation relative to mean sea level. Figure 4-4 shows results of an assessment of the levee condition for each island.

Figure 4-3. Island Attributes Visualization Showing Minimum Island Elevation

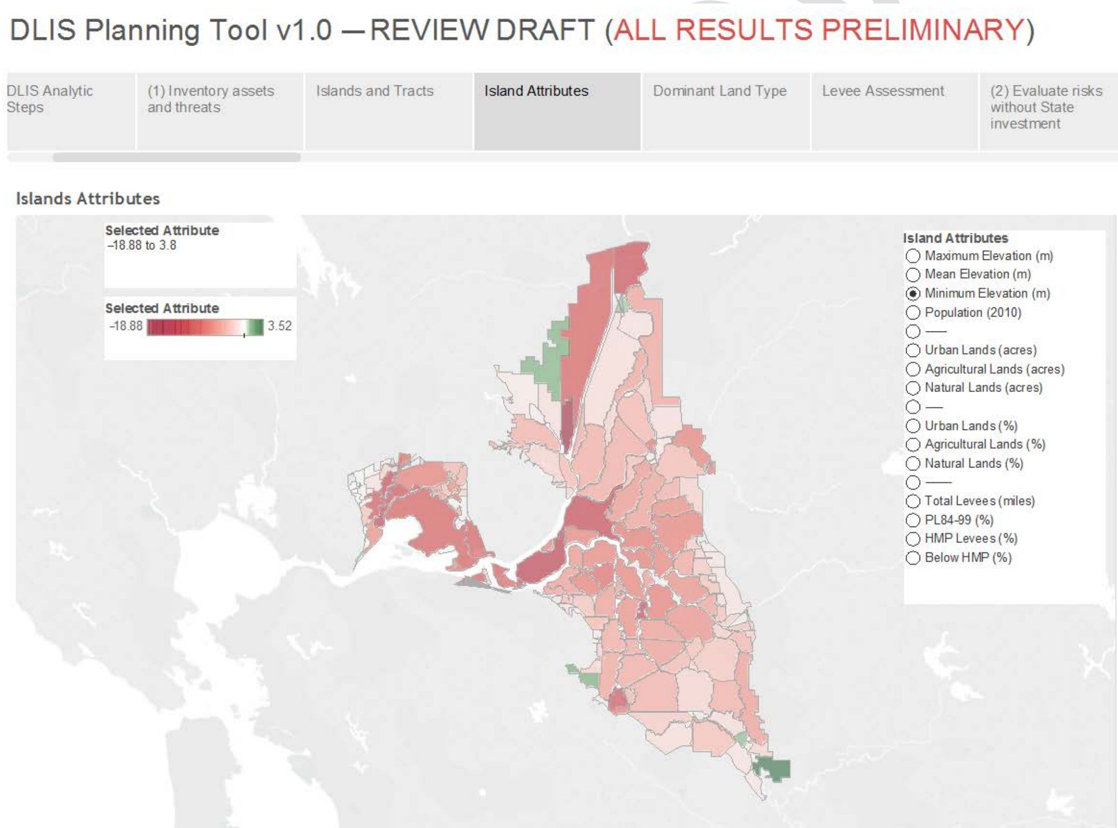
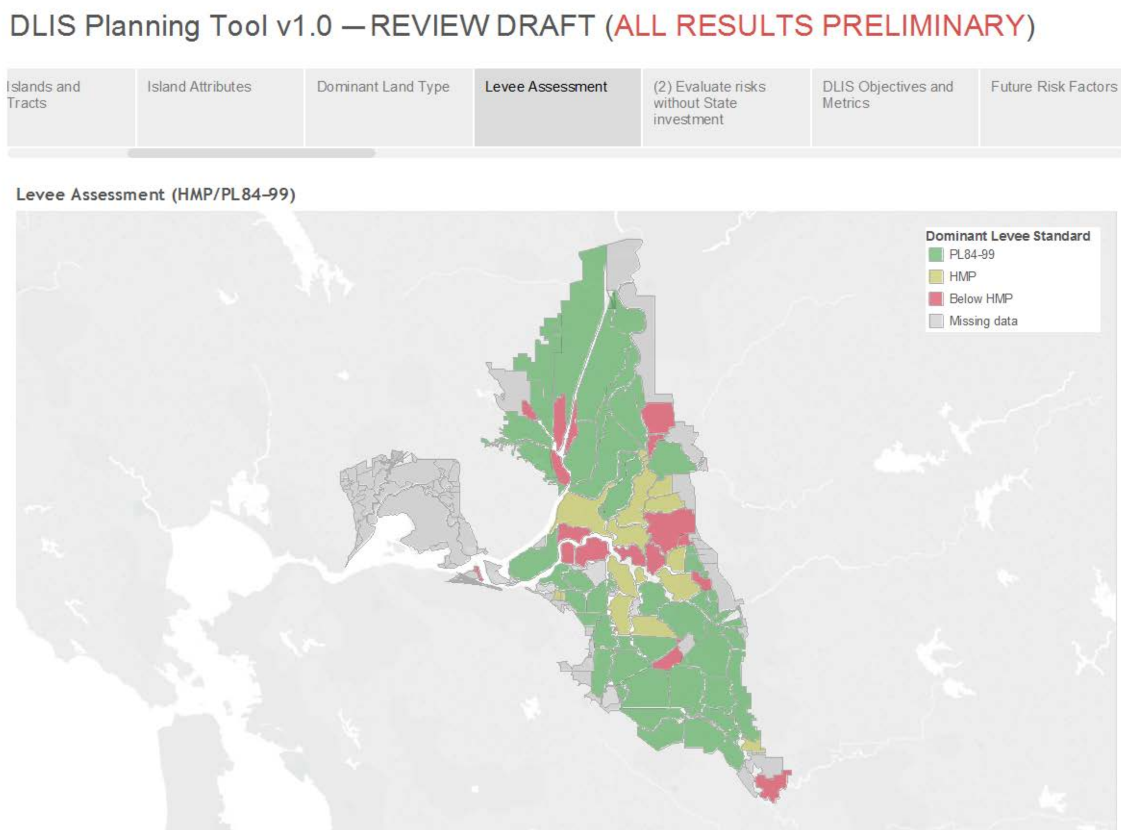


Figure 4-4: Visualization Showing the Dominant Levee Type Standard for an Assessment of Levee Condition



The Planning Tool allows the user to specify different performance metrics, maps, and lists showing risk for different time periods and future. For example, the Planning Tool will show the risk results for EAD on each island.

Islands and tracts across the Delta face different risks. An aggregate risk score helps identify islands that are high risk with respect to multiple metrics. As there is no consensus among stakeholders about the relative importance of different risks, the Planning Tool can help different users understand the risks based on their preferences by calculating weighted risk scores based on *user-specified* weightings of the metrics. First, the risk scores for an island or tract, *i*, for each metric, *m*, are adjusted to a common scale. The scaled risk scores are then combined using a set of weights specified by the user within the Planning Tool for each island or tract:

$$\text{aggregate risk score}_i = \frac{\sum_m(\text{scaled risk score}_{i,m} \times \text{weight}_m)}{\sum_m(\text{weight}_m)} \quad (4\text{-}1)$$

Through visual exploration, users can better understand the different Delta risks over time and which islands or tracts are most vulnerable. Using the aggregate risk score for each island, the Planning Tool can develop a single ranking of high risk islands. When the analysis is complete, the Planning Tool can show island risks based on the individual risk metrics and an aggregate risk score considering all risks and relative weights.

4.4.2 Comparison of Individual Levee Investments

The Planning Tool compares levee investments based on their cost-scaled effect with respect to each metric. To calculate the cost-scaled effect, or cost effectiveness, of a levee investment, *p*, the Planning Tool first calculates an investment effect score for each metric, *m*. The investment effect score is the net change to the metric across all islands, *i*, due to the levee investment. In other words, it is the difference between the risk with and without the investment, summed over all islands:

$$\text{investment effect score}_{p,m} = \sum_i \left(risk\ score_{p,i,m}^{investment} - risk\ score_{i,m}^{base} \right) \tag{4-2}$$

The cost effectiveness score is then calculated by dividing the investment effect score by the project cost in present dollars*:*

$$\text{cost effectiveness score}_{p,m} = \frac{\text{investment effect score}_{p,m}}{project\ cost_p} \tag{4-3}$$

Using the cost effectiveness score, the Planning Tool can rank investments based on each individual metric.

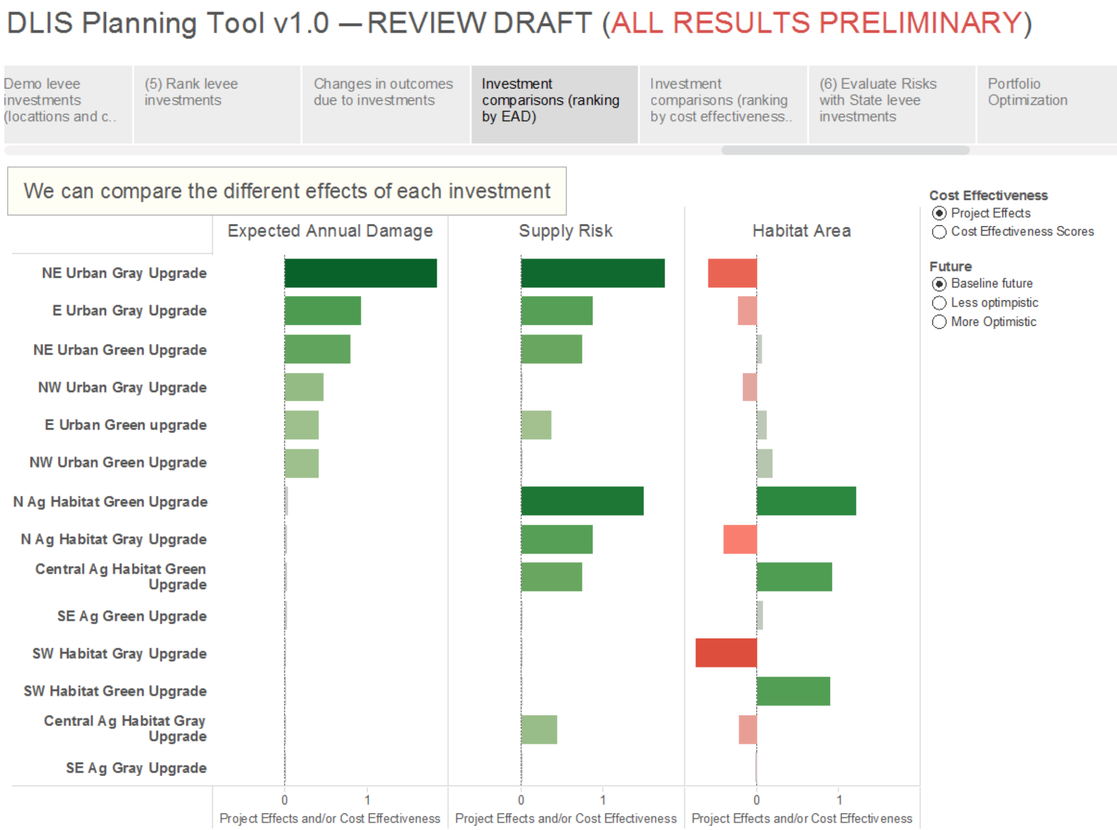
Different investments will affect different types of risks, and thus rankings of investments are significantly different depending on which performance metrics are considered. Therefore, the Planning Tool calculates an aggregate cost effectiveness score for each investment to allow a single ranking of investments, based on user-specified weightings of the metrics.

First, the cost effectiveness scores for each metric are adjusted to a common scale. Next, the scaled cost effectiveness scores for an investment, *p*, are combined using a set of weights specified within the Planning Tool:

$$\text{aggregate cost effectiveness score}_p = \frac{\sum_m \left(\text{scaled cost effectiveness score}_{p,m} \times \text{weight}_m \right)}{\sum_m \left(\text{weight}_m \right)} \tag{4-4}$$

The weighted scaled cost-effectiveness scores for each investment can then be compared and used to rank the projects. The Planning Tool has not yet assimilated information on investments or portfolios. The review version of the Planning Tool includes some sample visualizations of investment rankings for a fictitious set of islands and investments. See, for example, Figure 4-5.

Figure 4-5. Example Visualization Comparing Levee Investments (demo results using fictitious data)



4.4.3 Development and Comparison of Levee Investment Portfolios

The Planning Tool develops different levee investment portfolios using an optimization algorithm that seeks to select the combination of levee investments that maximizes an objective function representing the State's interests for a particular set of constraints and future. A unique portfolio of investments is identified for each user-specified set of risk metric weights and implementation constraints and, for each future, representing uncertain assumptions about future risk factors.

Specifically, the Planning Tool uses an optimization calculation to identify the set of investments that together leads to the highest State benefit. State benefit is represented by an objective function set to be the sum of the weighted scaled cost-effectiveness score (equation 4-4) for all investments in the portfolio:

Maximize:

$$\sum_p \left(\text{aggregate cost effectiveness score}_p\right) \tag{4-5}$$

such that the total cost of each included investment does not exceed a specified total budget:

$$\sum_p (\text{project cost}_p) \leq \text{specified total budget.} \qquad (4\text{-}6)$$

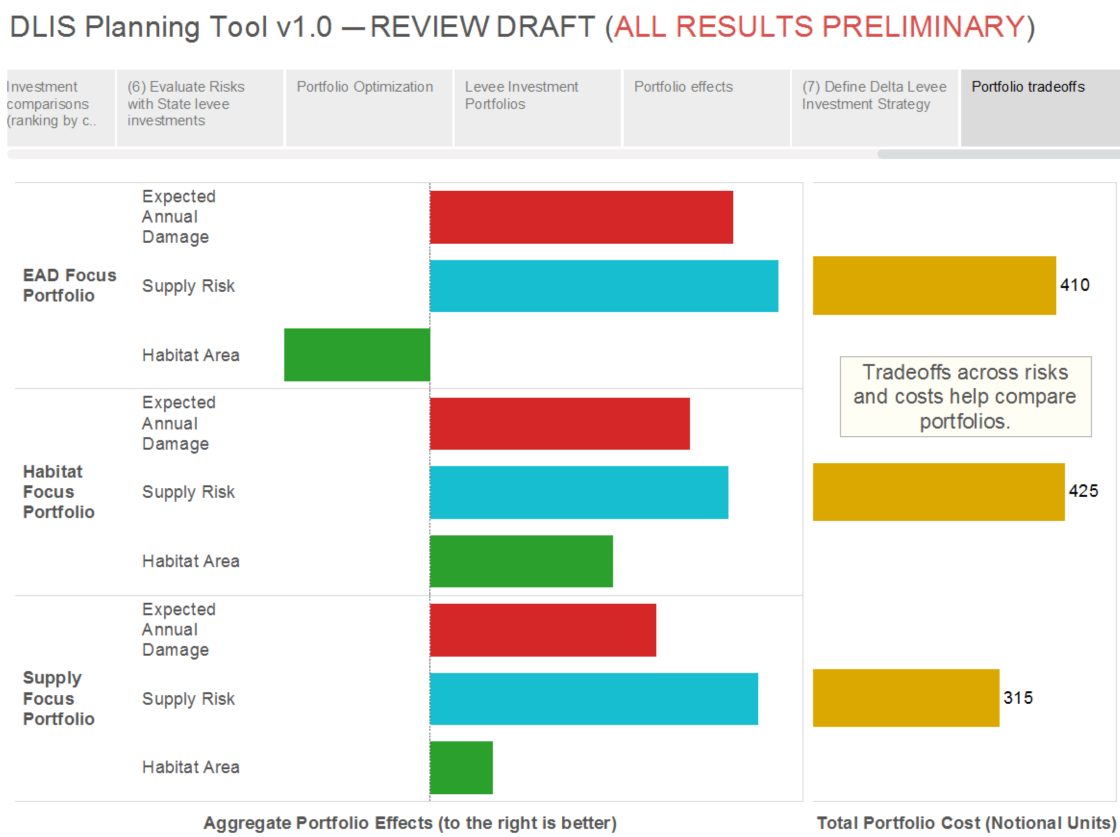
The Planning Tool can address other constraints as well, including:

- Mutually exclusive investments—only one of a set of investments that target the same locations can be selected.
- Performance minimums—some risks, such as EAF, could be specified to be required to be reduced beyond a tolerable risk threshold.

The Planning Tool will be used functionally to develop a large set of portfolios representing the optimal investment strategies under different futures, for different weights over metrics, and for different budgets. The Planning Tool will then present visualizations that compare the included investments across the portfolios. This shows those investments that are frequently included, which can be interpreted as high priority, robust options. The Planning Tool will also show how risks change over the islands and tracts under the implementation of the different portfolios. Lastly, the Planning Tool will show trade-offs graphs summarizing how performance varies across the metrics for the different portfolios.

Figure 4-6 shows a simple example of some key trade-offs from the demonstration analysis included in the Planning Tool. This type of visualization can help the Council and stakeholders explore opportunities to improve portfolios to balance and maximize risk reduction benefits.

Figure 4-6. Example Visualization Showing Trade-offs among Portfolios (demo results using fictitious data)



4.5 Components of the Planning Tool

The Planning Tool comprises four key components:

- SQLite Planning Tool database
- R-based risk models
- GAMS-based optimization engine
- Tableau-based visualization software

4.5.1 SQLite Planning Tool Database

All data used for the Planning Tool visualizations are stored in a structured SQLite database. SQLite is an open source platform with the key feature of storing a database as a single file, allowing for easy sharing and archiving. Scripts are used to import data into the database from comma separated value files (.csv). The final report will include an appendix that documents the structure and content of the Planning Tool database.

4.5.2 R-based Risk Models

The risk models described in Section 3 are all implemented in R, an open source statistical programming language. The risk models read in data about islands and tracts, risks and hazards, and levee fragility from .csv files and a Microsoft Access database developed as part of Tasks 2.1 and 2.2.

The risk models calculate risks with and without investments for each performance metric, time period, and future. They export these results into the SQLite Planning Tool database.

4.5.3 GAMS-based Optimization Engine

The Planning Tool calculates optimal portfolios using optimization in the GAMS computer programming language. GAMS accesses all input data from the SQLite Planning Tool database and returns all portfolio results back to the same database.

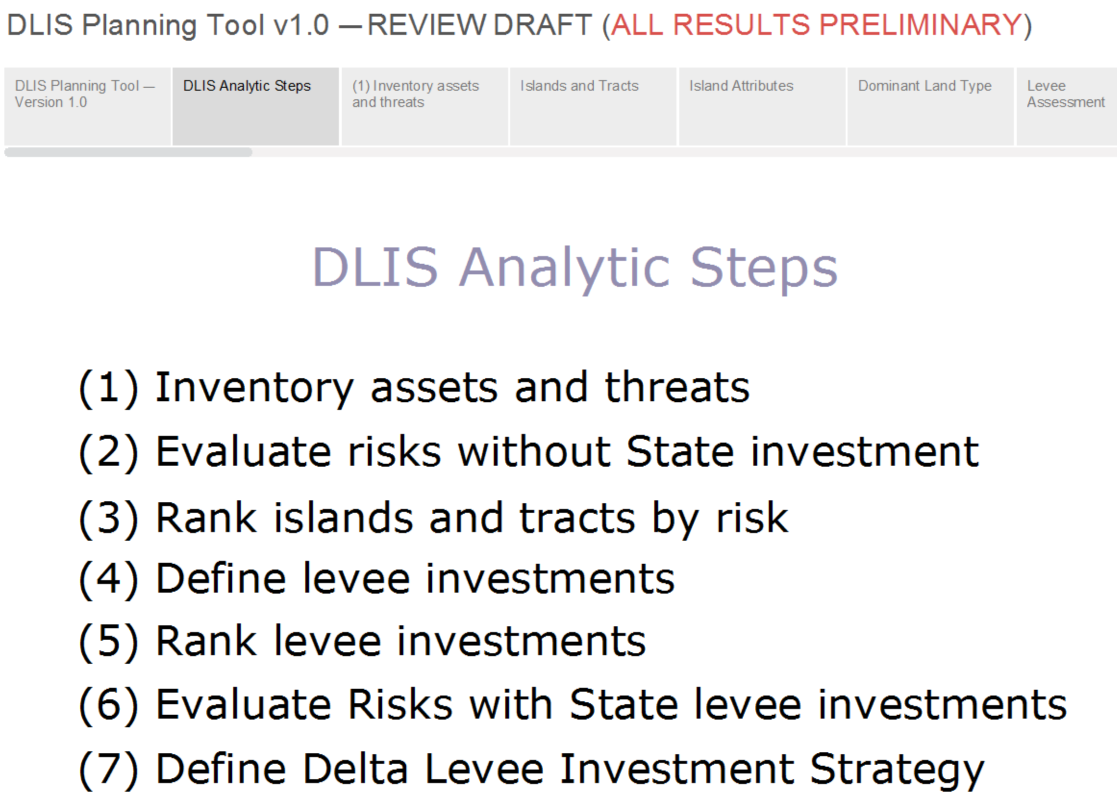
4.5.4 Tableau-based Visualization Software

Interactive visualizations are developed using the Tableau Desktop software (version 8.3) and made available to the Council, DWR, stakeholders, and the public by posting them to custom-built websites using the Tableau Public offering. Under the direction of the Council staff, visualizations can be updated as necessary, ensuring that the most appropriate results are shared at any given time. This allows any user with the credentials to access the website to interact with the results and export snapshots of visualizations. To protect the integrity of the data and analysis, the underlying Tableau workbook is not available for download to the website users.

4.6 Planning Tool Structure and Status

The Planning Tool visualizations are organized around the following key steps of the analysis, as shown on Figure 4-7.

Figure 4-7. Key Analytic Steps Supported by the Planning Tool



At the time of this report's writing, data compilation, development of risk models, and development of the Planning Tool are underway. Therefore, the current version of the Planning Tool uses, in some cases, incomplete, preliminary, and / or fictitious data. Specifically, fictitious data were developed for an early demonstration of the Planning Tool (denoted "demo" in the Planning Tool). Updated data are being added regularly. However, at this time, none of the visualizations should be construed as indicative of the outcomes of the forthcoming analysis.

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