Levee Decisions and Sustainability for the Sacramento-San Joaquin Delta

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Abstract

The Sacramento-San Joaquin Delta's fragile levees are subject to several physical realities that make them increasingly prone to failure. State planners face the challenge of preparing for future Delta flooding. This study presents an economic method for approaching the evaluation of Delta island levee upgrades and repairs. A Levee Decision Analysis Model (LDAM) is applied to the question: How should the state economically prioritize levee upgrade and repair efforts in the Delta? We focus on 34 major agricultural islands that make up most of the Delta's Primary Zone and include all non-urban subsided islands. This initial analysis indicates that it is economically optimal to *not* upgrade all 34 Delta islands examined, mostly because levee upgrades are expensive, but produce little improvement in levee reliability. When we assume increased effectiveness of upgrades, it becomes optimal to upgrade some islands. Other islands are never optimally upgraded, even under the most optimistic scenario. Our analysis also suggests that from an economic perspective, taking into account land and asset values, it is not cost effective to repair between 18 and 23 of these islands when they fail. When property values for all islands were doubled in a sensitivity analysis, only four islands of those originally not repaired become cost effective to repair. The LDAM model presented here is a useful approach for Delta policy-makers. It provides a quantitative framework for addressing several relevant questions regarding reasonable levee upgrade and repair investments. These initial results may act as a springboard for discussion, and the LDAM model as a working framework for developing an optimal strategy. An important and inescapable conclusion of this analysis is that maintaining the current Delta landscape is unlikely to be economical from a business or land use perspective.

Introduction: The Delta's Levee System

The Sacramento-San Joaquin Delta currently is defined by its 1770 km (1100 miles) of levees. The Delta levee network was developed during the late 19th and early 20th century to reclaim more than 450,000 acres of freshwater and brackish marsh, mainly to support agriculture and waterfowl habitat. By the mid- and late 20th century, these levees became integral to local, state and federal efforts to export water for urban and agricultural use. Today, four drivers are acting to increase the risks of levee failure and island flooding: sea level rise, subsidence, changing inflows, and earthquakes (Mount and Twiss, 2005, Jack R. Benjamin and Associates, 2009). For physical and financial reasons, the Delta cannot easily adjust or respond to these increasing pressures (Lund et al., 2007, 2008).

Physically, the levee network is rigid and brittle. Most levees were poorly constructed on weak, seismically unstable foundations. They are the descendents of originally small, private structures that have expanded over time to cope with gradual land subsidence, sea level rise, and erosion. This expansion, accomplished by episodically adding material to the top and sides, was, until recently, not subject to modern engineering standards.

There are several failure mechanisms for Delta levees (summarized in: Linsley et al 1964, Wood 1997, Mount and Twiss, 2005, Moss and Eller 2007). Most commonly, levees fail from slumping, rupturing, erosion or overtopping during storm events or when high winds create large waves at high tides. Levees may also fail on a relatively calm day from internal degradation that has occurred over time with seepage, or from slumping and cracking that allows water to flow through and over the levee. Seepage is common on most levees and usually does not lead to failure, but when water pressure gradients are great, seepage can erode material within and under the levee, causing sand boils on the levee interior that eventually lead to collapse. Poor foundations, weak construction materials, and rodents all exacerbate these problems. Finally, a levee can fail during earthquakes. Shaking causes the foundation or embankments to lose cohesion, deform, and collapse. All of these failure mechanisms have one thing in common: the forces in the Delta that cause them are increasing or will worsen in the future (Mount and Twiss, 2005). This stems from both the degradation of levees with time and the increasing physical forces acting on them. For this reason, it seems likely that, without intervention, levee failures will increase in the future.

The levees are under growing financial pressure as well, often competing with other public interests in the Delta and elsewhere for funds, and a growing concern for the region's declining ecosystem and native species. The fragile levee system depends largely on the willingness of landowners and state and federal governments to invest in upgrading the levees or repairing them when they fail. With 166 levee failures over the past 100 years, that willingness to pay has kept all but three major islands intact. However, the roughly $90 million cost of the 2004 Jones Tract failure highlighted the high costs of levee failures and caused some state planners to question the economic viability of funding repairs and upgrades, especially when this money might be applied towards other public benefits or focused on prioritized islands (L. Harder, Senate Hearing May 2006)

Acting together, these physical and financial drivers or constraints are likely to shift the Delta from its current configuration of narrow channels and subsided islands towards a system with several additional bodies of open water. In this analysis, we first present current estimates of failure probabilities for Delta levees, based principally on the recently released Delta Risk Management Strategy Report (Jack R. Benjamin and Associates, 2009), and identify resource allocation decisions currently facing the state. We evaluate the economic costs of maintaining the current levee configuration in the Delta and present a simplified decision analysis for economically optimizing levee repair and upgrades for individual islands.

Our conclusions regarding upgrade and repair policies in the Delta extend those found in earlier studies (Logan, 1989).

Failure Probabilities: Certain Future, Uncertain Timing

Failures of Delta levees in the future are a certainty and a fundamental fact of Delta life. For more than 100 years federal and state governments and Delta landowners have adapted to this reality. If the past were a reliable predictor of the future, it could be argued that the state could simply maintain the current Delta policy of supporting levee maintenance and repairs, fighting floods, and restoring islands when their levees fail. However, conditions are not static in the Delta, and risks and costs are increasing.

Using data from the draft Delta Risk Management Strategy Phase 1 report (Jack R. Benjamin and Associates, 2009), we calculated the annual probability of island failure from *either* hydrologic events or earthquakes for 34 islands of the Delta that have subsided below mean sea level (based on analysis in Mount and Twiss, 2005). In Figure 1 we present the range of failure probabilities for 34 islands (including the two urbanized islands, Bethel Tract and Hotchkiss Tract) over the next 100 years. Based on current flood and seismic risk factors, the median Delta island has a 95 percent probability of failure between now and 2050 and a 99 percent probability of failure by 2100. This risk of failure over extended periods is especially high for the western islands of the Delta where, based on the DRMS data, each island has a roughly 99 percent probability of at least one failure by 2050.

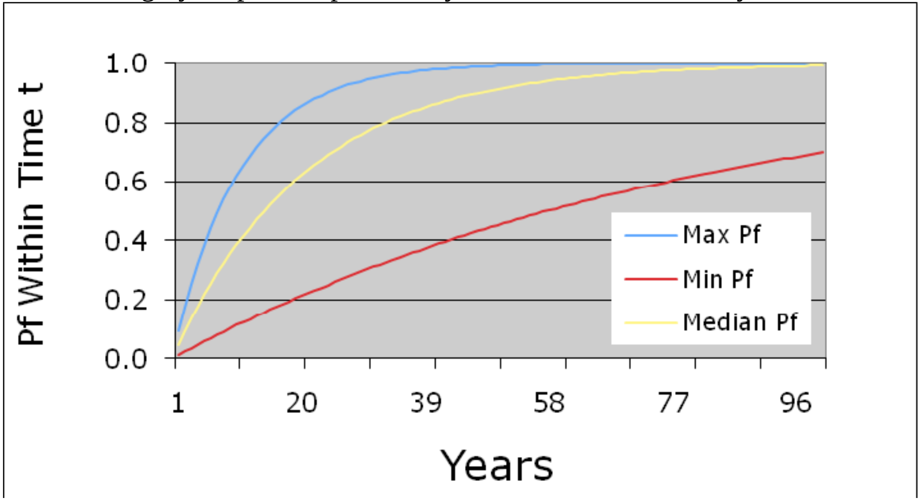

Figure 1. Probability of flooding from either earthquakes or floods for 34 Delta islands

These estimates are based solely on current likelihoods of failure. But as discussed above, the probabilities of island failures will increase without major investments in levees. Additionally, the effects of subsidence, flood inflows, sea level rise, and earthquakes on levee failure are mutually re-enforcing. Subsidence, sea level rise, and increasing inflows act together to increase the relative difference in elevation between island interiors and surrounding water surfaces. All three factors increase hydraulic gradients within the levees, increasing through-seepage and under-seepage failures. Increasing Delta inflows and sea level rise together reduce the freeboard of the levees, increasing the frequency of levee overtopping. All three amplify the effects of poor levee construction and foundation conditions to increase the likelihood of levee failure during earthquakes. And all four processes increase the frequency and consequence of island failures, while increasing the costs of repair and upgrades.

Without substantial and sustained levee investments, levee failures will transform some Delta islands to extensive bodies of open water. State and federal policy and funding for improving, repairing, restoring or abandoning levees will play a key role in determining future Delta landscapes.

Current Levee Policy and Policy Challenges

Approximately two-thirds of Delta levees are owned and maintained by local reclamation districts on behalf of private landowners (“non-project levees”); the other third are within federally authorized flood control projects. Known as “project levees,” most levees in this latter category are maintained by local reclamation districts with oversight and inspection from the state, following Federal levee policies. This discussion focuses on non-project levees. Following significant floods in the Delta in 1986, the state set new standards for Delta levees to reduce the frequency of island flooding. The Sacramento District of the Army Corps of Engineers and the California Department of Water Resources set two standards for levee crown height and width and levee slopes for agricultural levees. The State Hazard Mitigation Plan (HMP) standard was viewed as an intermediate standard, with the long-term goal of upgrading to a higher federal standard, termed “PL 84-99.” Both of these standards are summarized below in Figure 2. Levees meeting PL 84-99 standards qualify for federal aid following damage due to flooding.

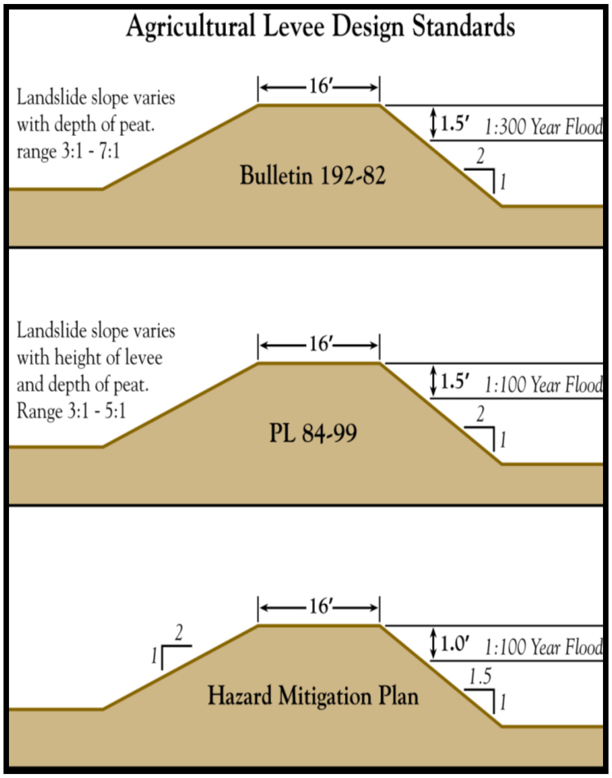

Figure 2. Comparison of State and Federal Levee Standards

Discussions with several state and private Delta engineers indicate that most non-project Delta levees meet HMP standards, but relatively few meet PL 84-99 standards. We made an effort to assess the effectiveness of PL 84-99 upgrades in improving levee performance. That is, to assess the amount such an upgrade would reduce a levee’s annual failure probability. We contacted many state, federal and private engineers and asked their opinion of the reduced annual failure probability achieved through upgrading levees from the HMP to the PL 84-99 standard. All engineers noted that local differences in levee and foundation conditions lead to high variability in the value of improvements, but we were able to adopt a general rule that this upgrade reduces the levee failure rates by an average of approximately 10 percent for failures from levee overtopping, through-seepage and under-seepage. These upgrades, which occur mainly on the surface of the levee, do little to improve levee foundations and the risk of failure due to earthquakes.

Allocating Resources

Given the current fragility of the Delta levee system and the increasing levels of risk of failure, at least three critical policy issues will need to be addressed by the state. These include:

Distribution of Available Resources. The voters of California, by passing Proposition 1E and Proposition 84 in 2006, allocated more than $3 billion in state bond funds to support levee improvements in the Central Valley (including the Delta). These funds and any future state and federal funds can be distributed in two ways: 1) equally everywhere to mitigate flood risk throughout the 1770 kilometers of Delta levees and the 2735 kilometers of project levees outside of the Delta, or 2) concentrated at specific locations to meet broader state objectives such as water supply, ecosystem restoration, transportation, and recreation, or to reduce the economic impacts of levee failures. In the Delta, the state's historic approach has been to apply a modest level of resources broadly without prioritization, principally through the Subventions Program (typically $6 million per year), which helps fund levee maintenance. However, as shown below, the costs of upgrading all Delta levees to even minimal current standards would require extraordinary increases in state contributions, with only nominal decreases in flood risk.

Repair and Restoration of Islands Following Failure. When island levees fail, state and local entities are faced with considerable repair and recovery costs. As highlighted by the Jones Tract failure in June 2004, the economic impacts and costs of repair of an island will often exceed the value of the land, frequently by several-fold. The cost of repairing a breach in a levee is typically between $20 million and $40 million, with roughly equal costs from damages to island assets and losses to the local economy (URS, 2007a). Additionally, the substantial investments needed to repair an island do little to reduce the likelihood of future levee failures since the size of a levee breach is often small compared to the total length of levee on an island. Given the high cost of these repairs, the low values of land they restore, and the fact that repairs do not reduce future failures, it may be appropriate for the state to adopt a policy of not restoring all islands that fail and to prioritize repairs, particularly when multiple island failures occur in a single storm or earthquake. California's Department of Water Resources (DWR) announced such a policy following the flooding of Jones Tract, but it has yet to be tested.

Levee Upgrades and Climate Adaptation. California is recognized as a national leader in climate change mitigation policies. However, to date, the state does not have well-defined policies regarding climate change adaptation (Luers and Moser 2006). This problem is particularly acute in flood management in California in general (Galloway et al. 2007) and in the Delta specifically. Climate change will require developing adaptation strategies that go beyond simply making all levees in the Delta better. This issue can be partly addressed with elements of the two policy challenges described above: selective investments in levee upgrades and repair of islands that flood.

Methods: Evaluation of Levee Policy Decisions

To address the three policy issues concerning future levee investments and repairs – how to distribute funds, whether investments to repair islands are worth the cost, and how to adapt levee policies to climate change - we developed the Levee Decision Analysis Model (LDAM). This model supports a comparison of strategic options for levee management from an economic perspective.

Three upgrade policies are compared:

1. No Upgrades

2. Upgrades to PL 84-99 standards

3. Upgrades to PL 84-99 standards plus 0.3048 meters (one foot) to mitigate for expected sea level rise by mid-century (denoted Upgrade PL 84-99 + 0.3048m SLR)

For each island, each upgrade policy comes with an accompanying decision of whether or not to repair that island when its levees fail. We begin with a summary of the decision analysis process and method, and then describe how this analytical framework can be applied to Delta levees. We exclude heavily urbanized islands from the decision analysis results. Levee upgrades for those islands will be subject to Federal Emergency Management Agency National Flood Insurance Program standards that are not accommodated well in this initial decision analysis.

Decision Analysis: Framework and Methodology

Formal analysis of levee and other flood control decisions requires a comparison of costs and benefits for several alternatives. For most levee or dike investments, the aim is a reduction in flood damages. This presents a dilemma for the decision maker because the value of his/her investment is in part a function of an uncertain future. Decision analysis provides a logical framework for benefit-cost comparisons of decision options when there is uncertainty about their outcomes (Hobbs et al. 1997, Cheng et al. 2008, Lund 2009). All decision analyses require a probability model and a “value” model (Maguire 2004). For flood structure analyses, the probable effectiveness of a levee or dike investment is factored into its economic evaluation by incorporating probabilistic reliability analysis into the economic decision theory framework.

Reliability analysis developed independently from decision analysis. Assessing the probability of structural failure for a levee or dike is a complicated geotechnical endeavor, dependent upon several other stochastic variables such as storm events, underlying soils, river discharge, and location of an initial breach (Wood 1997, Moss and Eller 2007). Many studies focus almost exclusively on determining the appropriate probability distribution for flood events or a structural failure (Ang and Tang 1975, Van Manen and Brinkhuis 2005). Given the complexity of reliability analysis, it is not uncommon for decision analyses to adopt failure probabilities determined by a separate effort (Van Dantzig 1956, Eijgenraam 2006). In this analysis, we adopt current probabilities of failure for Delta levees provided in the Phase 1 Delta Risk Management Strategy (DRMS) Report (JR Benjamin and Associates, 2009).

Some studies bridge the gap between reliability and cost-benefit analysis by assessing the “risk” or “expected value” for a given levee height, width or other characteristic (Voortman et. al 2002, USACE 1996, USACE 1999). These values are typically attained by multiplying the net cost or benefit of future events by their probability of occurrence within a time frame of interest. Probabilistic weighting for the value of a current decision was pioneered in the Netherlands in Van Dantzig’s 1956 assessment of optimal dike heights, and in a more general sense in the United States in a body of economic decision theory work (Pratt et. al, 1964; Raiffa, 1968). Reliability-based design uses these calculations to determine flood protection investments based upon a pre-accepted probability of failure (van Manen and Brinkhuis 2005, J.J. Bouma et. al 2005, Progar 2008).

Decision analysis brings risk or expected benefit calculations into a broader decision framework to allow comparison of several alternatives, as well as to incorporate a sequence of possible future decisions and/or events. Decision analysis is common in work on optimal flood protection design (Davis et al. 1972, USACE 1999, Aven and Korte 2002, Voortman et al. 2002, Cheng et al. 2008). An expected value is derived for each alternative, which provides the expected benefits (or costs) of a project given an amount of uncertainty in its future performance. Alternative decision sequences are often represented in a decision tree.

The framework for the sequence of decisions necessary to optimize levee investments is presented in Figure 3. Decision points among options (in our case to upgrade levees, and to repair or abandon levees), are represented by boxes. Chance events and their outcome probabilities, such as levee failures, are represented by circles. The outcome values for each chain of decisions and events appear at the right side of the tree and are used to assess the expected costs of the decision options. The tree branches out into the future. In this way, a decision analysis facilitates the logical structuring and comparison of alternatives under uncertainty.

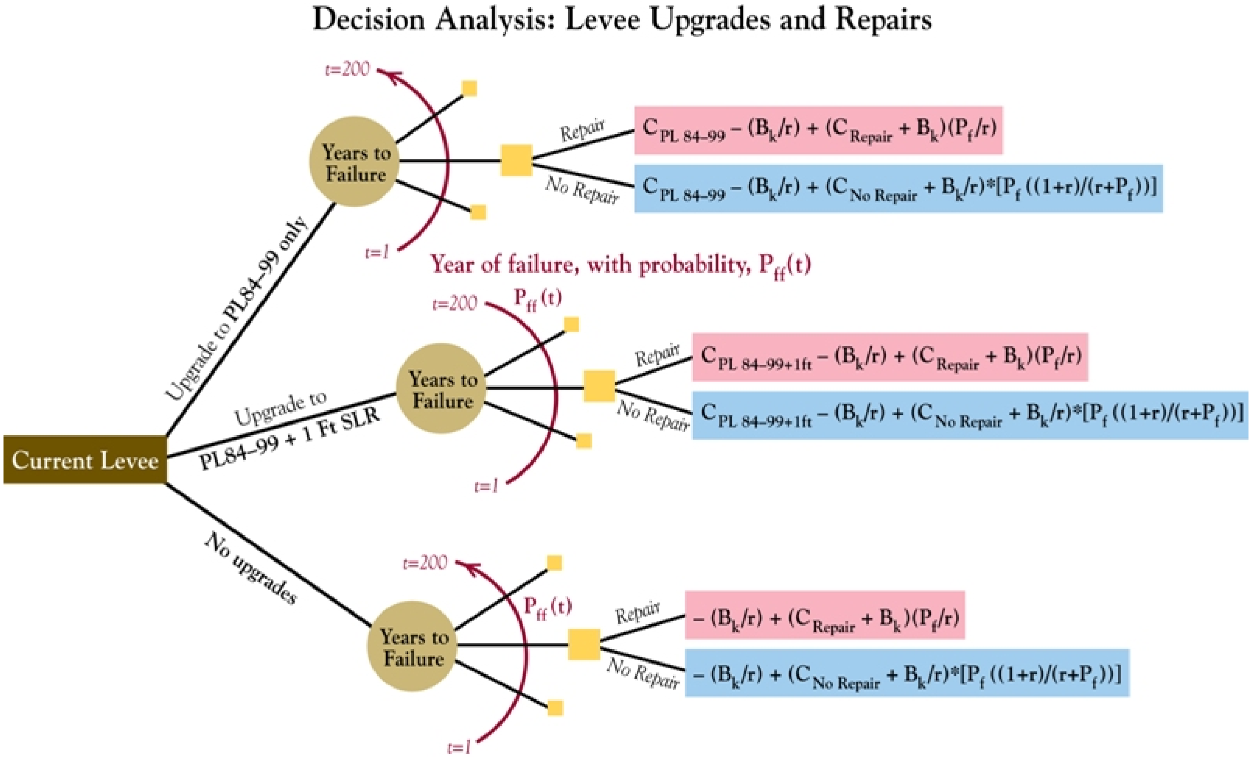

Figure 3. Island levee decision analysis tree for assessing whether to upgrade levees and to restore islands following flooding.
$P_{ff}(t)$ = probability of first failure at time t, P_f = current probability of failure

The Levee Decision Analysis Model presented here is another application of these ideas. For Delta levees, there are three initial strategic options: 1) do not invest in upgrades, 2) invest in PL 84-99 upgrades, or 3) invest in PL 84-99 upgrades plus 0.3048 meters additional levee crown height to mitigate for near-term sea level rise. Regardless of which direction is taken now, in some (uncertain) future year there will be a decision whether to repair an island when the levee fails. In this sense, this analysis is a variant of a classic decision tree in that the node of uncertainty does not split off into different uncertain events with varying probabilities, but rather into different uncertain timeframes in which one event will occur. In other words, like life insurance, uncertainty revolves around *when* failure will occur, not *if* failure will occur.

Because the present value of a current upgrade decision depends on the possible future flood and repair events that follow, it must be calculated by working backwards. This procedure is called "folding back" in some analyses, and has been compared to backwards dynamic programming (Hobbs et al. 1997). Values are estimated for repair choices occurring furthest into the future for each upgrade strategy, and then the costs of those choices are weighted by an outcome probability and assigned to the present value of that strategy. In other words, the first step in the analysis is to look at the choices remaining *after* an initial policy has been employed (for which costs are sunk) and a future uncertain event has occurred.

Funding or Not Funding Repair after Failure

The first step is to look to a point in the future after an island has failed, and determine if the economic value of the failed island justifies the costs of repair. The costs of each choice for an individual island are discussed below.

1. **Cost of Repair** at time of failure is a function of the materials and engineering costs of fixing and re-enforcing breached levees, pumping out the island, and the lost profits from one year of lost agricultural production on the island (assuming annual crops), plus those same costs occurring over and over again further into the future each time the island fails. This second future cost term is represented by an infinite series of future costs for repairing the island each (probabilistic) time it fails again. The present value benefits of all future profits of the island (here, assumed equivalent to its property value) are subtracted from these costs. In mathematical terms:

$$\text{Cost} = C_{\text{Repair}} + B_k + (C_{\text{Repair}} + B_k)(P_f/r) - (B_k/r)$$

   Where C_{Repair} is the average cost of repairing a failure, B_k is one year of island profits, r is the inflation-corrected interest (discount) rate, and P_f is the probability of island failure in any given year. The first term (C_{Repair}) is the cost of repairing the first failure. The second term, B_k, is the loss of one year's farm profit from island failure. The third term, $[(C_{\text{Repair}} + B_k)(P_f/r)]$ is the present value cost of all future failures (derived under "Present Cost of Repair" below), and the fourth term $[(B_k/r)]$ is the present value of island profits (a negative cost).

2. **The Cost of Not Repairing an Island** at the time of failure, is the sum of the cost of rebuilding or diverting existing infrastructure (such as highways, towns and railroads) and the cost of fortifying nearby islands that would be newly vulnerable to wind and waves from newly open water. In mathematical terms:

$$\text{Cost of No Repair} = \text{Cost to Reinforce Downwind Islands} + \text{Cost of Lost Infrastructure}$$

   Once the cost of no repair and the cost of repair for each island have been estimated, the least expensive (or most profitable) action can be identified (repair or not repair). The cost of this action is brought back to the present time and assigned a present value. This is where probabilities and discount rates are important for the analysis. Because the costs of funding or not funding repair are summed over an infinite range of potential times to failure, formulas are derived to express these present values.

Repair or No Repair after Failure with Upgrades

This logic can now be extended to the costs of repair or no repair for levees that have been upgraded.

1. **Present Cost of Repair** is the present value of all present and future repair costs, plus the cost of upgrades, minus the present value of all future profits. Mathematically:

$$\text{Cost} = \text{Upgrade Cost} - (B_k/r) + (C_{\text{Repair}} + B_k)(P_f/r)$$

The first cost term will not exist in the “no upgrade” case. In the case of an enhanced upgrade to mitigate for 0.3048 meters of sea level rise, it will include the cost of that additional fortification. The only significant change in this formula from that of repair costs at the time of failure presented above is that there is no current cost of repairing the island today (because it has not yet failed), so that ($C_{\text{Repair}} + B_k$) only appears once and is multiplied by (P_f/r). The cost of current upgrades is incorporated to allow comparison of the three strategies.

The derivation of the infinite series of future repair costs (third term) is as follows:

Let C be the cost of each failure episode, the repair and damage costs of a failure event. Friedenfelds (1981) provides a nice formula understanding the present value of an infinite series of future costs (W), $W = C + W(1+r)^{-t}$, which can be re-arranged algebraically to:

$$W = \frac{C}{1-(1+r)^{-t}}\,.$$

As the time between failures (t) increases, the present value cost decreases both because failures are becoming less frequent and because of the increased effects of discounting. For Freidenfeld’s derivation, the infinite series begins with a failure in the present. When the time of failure is uncertain and represented by a probability distribution, this becomes:

$$W = C + W\sum_{i=1}^{\infty} P_f(1-P_f)^i(1+r)^{-i} \text{ or } W = \frac{C}{1-\sum_{i=1}^{\infty} P_f(1-P_f)^{i-1}(1+r)^{-i}}$$

For our problem, there is no failure in the present, but the first failure occurs at some uncertain time in the future, so W’ = W – C, or:

$$W' = \frac{C}{1-\sum_{i=1}^{\infty} P_f(1-P_f)^{i-1}(1+r)^{-i}} - C\,.$$

Note that $$\sum_{i=1}^{\infty} P_f(1-P_f)^{i-1}(1+r)^{-i} = \frac{P_f}{1-P_f}\sum_{i=1}^{\infty}\left(\frac{1-P_f}{1+r}\right)^i = \frac{P_f}{r+P_f}$$

since this part is an infinite geometric series. This allows the entire expression to be simplified to W' = C P_f/r. Or, $DF_{isf} = P_f/r$ for the present value (DF = discount factor). The annualized value of these costs over an indefinite future period would be calculated by simply multiplying the cost C by the probability of failure P_f.

2. **The Present Cost of No Repair** is the cost of upgrades applied today to the island, plus the net present expected cost of upgrading surrounding islands and rebuilding infrastructure (roads, houses, railroads), minus the profit made from the island until the time of failure. In mathematical terms:

$$\text{Cost} = \text{Upgrade Cost} - (B_k/r) + (C_{\text{no repair}} + B_k/r)*[P_f * [(1+r)/(r + P_f)]]$$

Where: $(B_k/r) - (B_k/r)*[P_f * [(1+r)/(r + P_f)]]$ is the present expected value of the profit made on the island until time of failure. The profits made before failure are subtracted from the total cost of abandoning the island.

$(C_{\text{no repair}})*[P_f * [(1+r)/(r + P_f)]]$ is the present expected cost of upgrading surrounding islands and rebuilding infrastructure (roads, houses, railroads).

The expected value of the discount factor for a failure cost occurring at an uncertain future time (third term) is derived as follows:

$$DF_{sf} = \sum_{t=0}^{\infty} P_f (1-P_f)^t (1+r)^{-t} = P_f \sum_{t=0}^{\infty} \left(\frac{1-P_f}{1+r} \right)^t$$

Here the probability of failure is the same in each year, yielding a geometric probability distribution for the time of first failure. This probability distribution of the time of failure is used to weight each year's discount factor.

Using geometric series expansions, this reduces to:

$$DF_{sf} = P_f \frac{1+r}{r+P_f},$$

which is used in the above equation to weight the profits made on the island before time of failure. Our use of a geometric probability distribution here is in accordance with other engineering studies interested in the time to first failure, or the recurrence interval for a given event (Ang and Tang, 1975). Alternatively, some studies choose to use a continuous probability distribution, so that time need not be divided into intervals. The exponential distribution is similar to the geometric, and is likewise used for problems involving failure probabilities and recurrence intervals (Voortman et. al 2002, Eijgenraam 2006).

Because upgrading an island to any standard will always cost more in cash today than not upgrading the island, the net expected present value of upgrades will only be cheaper than no upgrades if the upgrade significantly reduces the probability of failure for that island. In other words, if the upgrades significantly increase protection, upgrades should have a lower expected cost than no upgrades. Otherwise, the costs of upgrading are not justified.

The above analysis can be used to estimate the present value of the three upgrade strategy options for each island. The strategy for each levee is composed of two successive decisions. The first is the level of island upgrade: 1) No upgrades, 2) PL 84-99 or 3) PL 84-99 + 1ft SLR. The second decision (which was actually analyzed first in this discussion) is what to do when that island fails: fund or not fund repairs. A complete strategy for an island might look something like this: "Upgrade to PL 84-99, Do not fund repair." The six logically available strategies for each island are summarized in Table 1.

Table 1 – Levee Decision Analysis Model (LDAM) Policy Options

Option Number	Current Upgrade Policy	Future Repair Decision
1	No Upgrade	Repair
2	No Upgrade	No Repair
3	PL 84-99	Repair
4	PL 84-99	No Repair
5	PL 84-99 + 0.3048 m SLR	Repair
6	PL 84-99 + 0.3048 m SLR	No Repair

In some cases, it might be worthwhile to add another option to the analysis. A "Prepare to Abandon" option for an island would include hardening or removing infrastructure to reduce flood damage or better survive permanent flooding. Although we did not include this option in our assessment, the results of this analysis suggest that such preparations might be a prudent approach to levee management for some Delta islands.

Assigning Costs

The results of this decision analysis depend on the values assigned to the costs and failure probabilities for each island. For instance, increasing the profitability or property value of an island makes repair more attractive. Likewise, a high cost of repair coupled with a low property value makes repair less likely.

This initial analysis was done using values from various data sources. With more time, a more thorough cost and valuation study for Delta islands would enhance the resolution of the model. These initial results should serve as a springboard for discussion, and this analysis as a working framework for developing an optimal strategy. We calculated costs using the following sources, assumptions and methods:

1. Property Value: The analysis summed two measures of property value. The first included only land values (structures and easily-transported assets were not included), and the other included an asset estimate (buildings, equipment, infrastructure such as roads and rail lines, etc). Land values were extracted from data assembled in Lund et al., 2007, and asset values were taken from the Draft Delta Risk Management Strategy Phase 1 Report (J.R. Benjamin and Associates, 2007).

2. Repair Costs: An average cost of $25 million dollars was assumed to repair a breach and pump water from the island, based on interviews with engineers familiar with the Delta who estimated that the typical levee breach repair costs $20 to 30 million. To repair the breached levee perimeter, we assumed $6.54 per cubic meter ($5 per cubic yard) for on-island replacement fill, $19.62 per cubic meter ($15 per cubic yard) for off-island fill, 20 percent per

meter engineering costs, and $16.40 per meter for replacing rip rap. These materials costs were also developed from estimates provided in interviews with Delta engineers.

3. <u>PL 84-99 Upgrade Costs:</u> These costs were calculated assuming $1.74 million dollars per kilometer of levee. This figure was based on evaluation of a range of PL 84-99 upgrade costs taken from multiple islands, including Twitchell, Sherman, Bouldin, and King, based on communication with levee engineers and DWR engineers. This value is close to that cited by DRMS for upgrades. Also, we noted which islands have already partially undergone PL 84-99 upgrades, and subtracted the appropriate amount from their estimated upgrade costs.

4. <u>PL 84-99 Upgrade + 1 ft SLR Costs:</u> These were calculated by taking the lengths of each island's levees and applying a geometric formula for increased cut volumes needed to raise the island levee 0.3048 meters (one foot), in keeping with PL 84-99 geometric standards. Levee lengths were obtained from GIS data derived from DWR, cited in Mount and Twiss (2005). Once we calculated the volume of material needed, we assigned the following costs: $13.08 per cubic meter ($10 per cubic yard) for fill and 1.4 cut cubic meters per cubic meter. These values were obtained from interviews with Delta engineers. We assigned no costs for engineers and contractors because in our analysis, we assume that such extra upgrades would occur at the same time as the PL 84-99 upgrade, for which engineering costs have already been included. This estimate is also conservative and biases the model toward this enhanced upgrade because it does not account for the common phenomenon of subsidence following placement of fill on levees. Depending upon local conditions, subsidence can significantly increase the volume of fill needed to increase levee elevations.

5. <u>Cost of No Repair:</u> We assumed the two biggest costs of not repairing an island after failure, presuming no other entity funds repair and with the exception of urban islands, will be the cost of rebuilding or diverting infrastructure and the cost of upgrading surrounding islands.

    a. Costs of rebuilding or diverting infrastructure were calculated as follows:

        i. Cost estimates for rebuilding roads, highways, or railroads are based on a simple, per mile cost obtained from the DRMS Preliminary Strategies Report Section 12, which reports an estimated cost of $45 million per mile (approximately $28 million per kilometer) of seismically resistant levee. Levees of this caliber would have to be built to support the roads or highways on top of them (these costs are conservative in that they do not include the actual cost of the road or rails themselves).

        ii. The length of roads and railroads on each island used in the assessment of seismically resistant levee needs (above) were obtained from GIS Tele Atlas StreetMap Premium data, and included only the lengths on the interior of the island without counting road length along the levees themselves. The relevant roads used were the major highways routes (4, 12, 160); other highways were grouped (mostly Highway 5 and 84).

    b. Costs of reinforcing surrounding islands were calculated with these assumptions:

        i. The approximate length of levee upgrades needed for these surrounding islands should equal roughly half the circumference of the failed island (geometrically).

ii. The surrounding levees need to be raised 0.3048 meters (1 foot) to account for this increased exposure.

iii. Cost of these upgrades should thus be equal to *half* the cost of materials for raising the levee of the failed island by 0.3048 meters (obtained from earlier calculations of PL 84-99 + 0.3048m SLR costs).

iv. A multiplier of 1.3 is assigned to account for 20 percent cost for engineers and construction management, along with 10 percent state costs for management and processing.

Assigning Probabilities

Equally as influential to the outcomes of this analysis are the probabilities of failure assigned to each island, and the change in failure probability that occurs with each potential upgrade. For our probabilities of failure in the case of no upgrades, we use the DRMS Levee Optimization Assessment (J.R. Benjamin and Associates, 2009). Based on interviews with government and private levee experts, we then assumed a 10 percent decrease in probability of failure for that island, with each level of upgrade.

Results

Our results suggested "no upgrade" as the economically optimal decision for every island, regardless of whether it would be optimal to repair the island in the future. This makes intuitive sense, because levee upgrades have a high cost for a small increase in reliability. This initial analysis also suggested that 11 islands fall in the "repair" category and 18 islands in the "no repair" category, with 5 classified as "indeterminate" (Figure 4). An island was assigned to the indeterminate category if the difference in cost between repairing and not repairing the island was less than twice the cost of the cheaper strategy. (Figure 4 and Table 3).

The results of this analysis are similar to an earlier report addressing upgrade and repair policy in the Delta. In 1989, Logan et. al studied the cost effectiveness of a proposed DWR system-wide levee upgrade plan for the Delta. The cost for upgrading all islands was compared to the costs of a policy in which islands were not upgraded and were repaired post-failure. Logan's approach differs from ours in that his analysis did not employ decision analysis and did not compare nor optimize strategy for individual islands. Instead, he predetermined the number of islands to be repaired, and then applied Monte Carlo simulations to several stochastic variables to come up with a range of possible system-wide costs for each Delta levee policy. He calculated the expected costs of three reclamation policies: repairing all islands after they fail, repairing only 13 islands, or repairing no islands. His results suggested that *any* of the three policies analyzed would be more cost-effective for the state than DWR's plan to upgrade the entire levee system. In other words, it did not make economic sense from a statewide perspective to upgrade all Delta islands. These results are similar to ours, which points to the resiliency of a limited and prioritized upgrade and repair policy for Delta levees.

Table 2 – Land and Asset Values

Island Name	Land Value (Lund et al, 2007)	Asset Value (J.R. Benjamin & Associates, 2009, Table 12-7)	Land + Asset Values
Bacon Island	$16,248,424	$34,664,000	$50,912,424
Bouldin Island	$13,040,542	$21,511,000	$34,551,542
Brack Tract	$23,205,096	$13,647,000	$36,852,096
Bradford Island	$5,518,842	$19,003,000	$24,521,842
Brannan-Andrus Island	$73,173,177	$177,734,000	$250,907,177
Canal Ranch Tract	$27,692,544	$15,622,000	$43,314,544
Coney Island	$2,438,255	$14,614,000	$17,052,255
Dead Horse Island	$862,581	$910,000	$1,772,581
Empire Tract	$9,114,605	$9,511,000	$18,625,605
Grand Island	$64,673,235	$181,275,000	$245,948,235
Holland Tract	$8,823,343	$14,669,000	$23,492,343
Jersey Island	$7,272,961	$24,238,000	$31,510,961
Jones Tract	$42,496,164	$497,784,000	$540,280,164
King Island	$12,081,613	$30,840,000	$42,921,613
Mandeville Island	$11,731,203	$5,212,000	$16,943,203
McDonald Tract	$20,591,848	$30,780,000	$51,371,848
Medford Island	$2,221,145	$7,594,000	$9,815,145
Orwood Tract	$8,893,034	$239,425,000	$248,318,034
Palm Tract	$5,346,593	$21,107,000	$26,453,593
Quimby Island	$1,565,687	$584,000	$2,149,687
Rindge Tract	$19,906,394	$18,094,000	$38,000,394
Roberts Island	$164,103,230	$538,471,000	$702,574,230
Ryer Island	$38,670,068	$55,877,000	$94,547,068
Sherman Island	$27,023,167	$110,416,000	$137,439,167
Staten Island	$26,409,675	$20,191,000	$46,600,675
Terminous Tract	$50,975,498	$80,050,000	$131,025,498
Twitchell Island	$9,023,367	$12,105,000	$21,128,367
Tyler Island	$33,202,759	$91,184,000	$124,386,759
Union Island	$80,672,567	$140,909,000	$221,581,567
Venice Island	$6,839,964	$13,308,000	$20,147,964
Victoria Island	$22,618,787	$47,053,000	$69,671,787
Webb Tract	$11,554,466	$416,000	$11,970,466
Woodward Island	$4,637,580	$124,671,000	$129,308,580
Wright-Elmwood Tract	$26,166,120	$15,967,000	$42,133,120

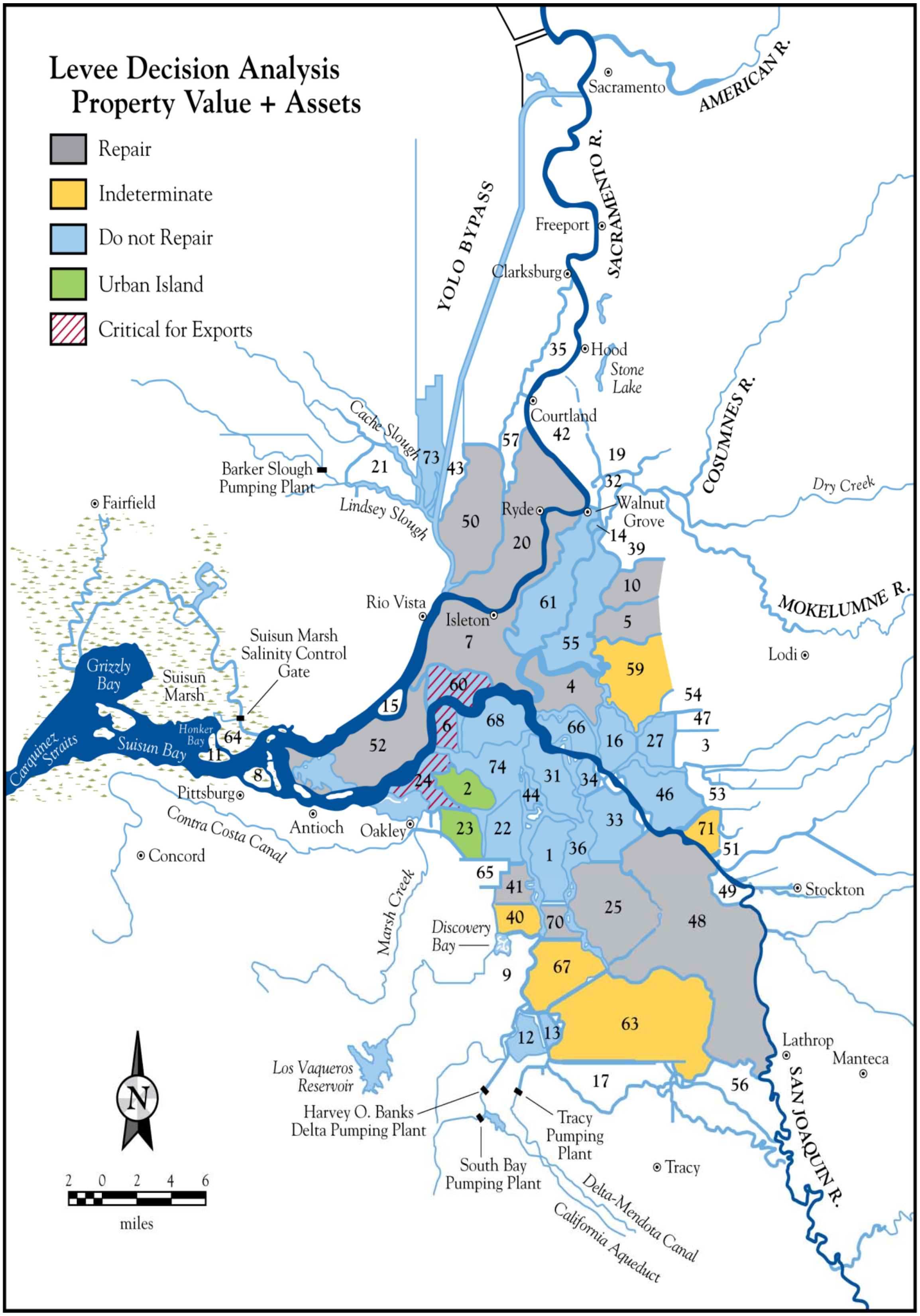

Figure 4. Repair decision using property values plus assets to calculate net present values

Table 3 – Summary of LDAM Results for 34 Delta Islands

		Repair Costs, No Upgrade		Expected Present Cost of Upgrade Strategy			Decision Summary		
# on Map	Island	Cost of Repair	Cost of No Repair	No Upgrade	PL 84-99	PL 84-99 & 1 ft SLR	Upgrade Decision	Repair Spread / Min Cost	Repair Decision
1	Bacon Island	$74,170,946	$4,930,479	-$21,432,120	$17,803,803	$24,575,354	No Upgrade	14.04	Not Repair
4	Bouldin Island	$50,701,075	$213,036,975	$6,280,319	$54,666,794	$62,447,509	No Upgrade	3.20	Repair
5	Brack Tract	$30,779,601	$290,128,755	-$152,294	$29,286,637	$33,074,630	No Upgrade	8.43	Repair
6	Bradford Island	$47,396,917	$2,547,863	-$11,211,402	$9,336,404	$13,100,248	No Upgrade	17.60	Not Repair
7	Brannan-Andrus	$143,136,217	$534,606,881	-$40,079,378	$41,055,338	$57,601,934	No Upgrade	2.73	Repair
10	Canal Ranch Tract	$21,153,000	$100,338,229	-$17,274,655	$11,419,514	$16,505,363	No Upgrade	3.74	Repair
13	Coney Island	$53,101,021	$1,888,373	-$10,712,759	$4,464,574	$7,205,908	No Upgrade	27.12	Not Repair
14	Dead Horse Island	$29,734,105	$882,166	-$1,234,006	$5,915,590	$7,251,142	No Upgrade	32.71	Not Repair
16	Empire Tract	$44,024,857	$2,580,558	-$7,540,314	$21,567,527	$25,284,449	No Upgrade	16.06	Not Repair
20	Grand Island	$161,079,249	$632,108,744	-$76,175,303	-$74,971,324	-$62,331,264	No Upgrade	2.92	Repair
22	Holland Tract	$41,054,683	$3,762,228	-$10,349,819	$20,093,890	$25,746,214	No Upgrade	9.91	Not Repair
24	Jersey Island	$41,213,403	$5,298,546	-$9,183,422	$33,460,372	$41,194,943	No Upgrade	6.78	Not Repair
25	Jones Tract	-$242,826,036	$246,264,918	-$380,607,659	-$337,110,891	-$335,040,129	No Upgrade	-2.01	Repair
27	King Island	$60,034,074	$3,112,987	-$25,106,531	-$326,670	$3,966,906	No Upgrade	18.29	Not Repair
31	Mandeville Island	$47,779,653	$4,920,445	-$4,795,895	$34,929,662	$42,230,873	No Upgrade	8.71	Not Repair
33	McDonald Tract	$63,686,312	$4,717,197	-$18,996,260	$18,683,638	$25,301,291	No Upgrade	12.50	Not Repair
34	Medford Island	$52,893,470	$2,021,808	-$3,420,891	$12,869,007	$15,837,938	No Upgrade	25.16	Not Repair
40	Orwood Tract	-$66,321,741	$2,905,255	-$159,659,980	-$141,971,477	-$142,843,340	No Upgrade	-1.04	unsure
41	Palm Tract	$31,354,174	$124,503,940	-$2,859,112	$24,994,514	$30,100,025	No Upgrade	2.97	Repair
44	Quimby Island	$38,275,617	$2,413,574	-$390,020	$19,218,792	$22,916,823	No Upgrade	14.86	Not Repair
46	Rindge Tract	$31,242,597	$5,424,936	-$16,237,862	$27,536,440	$35,570,508	No Upgrade	4.76	Not Repair
48	Roberts Island	-$542,186,742	$604,431,954	-$618,820,393	-$496,727,006	-$472,037,573	No Upgrade	-2.11	Repair
50	Ryer Island*	$8,965,794	$138,815,097	-$53,438,418	-$55,028,153	-$45,743,380	Upgrade	14.48	Repair
52	Sherman Island	$31,404,098	$297,394,598	-$27,849,519	$19,976,484	$24,327,090	No Upgrade	8.47	Repair
55	Staten Island	$36,167,863	$12,011,078	-$11,437,213	$85,466,405	$103,220,536	No Upgrade	2.01	Not Repair
59	Terminous Tract	$55,819,068	$76,856,695	-$42,335,028	$14,501,533	$21,978,974	No Upgrade	0.38	unsure
60	Twitchell Island	$55,389,976	$4,087,597	-$7,229,820	$19,024,728	$25,067,144	No Upgrade	12.55	Not Repair
61	Tyler Island	$39,086,253	$8,665,380	-$37,544,331	-$2,899,668	$8,849,897	No Upgrade	3.51	Not Repair
63	Union Island	-$62,480,954	$11,580,883	-$154,202,742	-$64,900,064	-$48,689,736	No Upgrade	-1.19	unsure
66	Venice Island	$56,168,608	$4,274,192	-$5,022,624	$29,358,610	$35,574,725	No Upgrade	12.14	Not Repair
67	Victoria Island	$77,047,296	$204,987,529	$8,325,075	$48,451,894	$54,583,650	No Upgrade	1.66	unsure
68	Webb Tract	$44,674,014	$4,443,922	-$3,546,216	$32,458,763	$39,175,373	No Upgrade	9.05	Not Repair
70	Woodward Island	-$44,449,476	$70,569,861	-$87,822,876	-$64,016,738	-$60,334,101	No Upgrade	-2.59	Repair
71	Wright-Elmwood	$4,611,486	$3,010,509	-$24,866,287	-$620,551	$3,797,641	No Upgrade	0.53	unsure
	Total for 34 islands	$513,880,476	$3,629,524,149	-$1,876,929,756	-$602,031,629	-$360,532,435			

**Ryer Island has already been upgraded*

Sensitivity Analysis

All analyses have uncertainties. Because this analysis includes the simplifying assumption that failure probabilities do not increase with time, results could be viewed as conservative. On the other hand, our costs for not repairing an island are conservative in their estimation of infrastructure replacement costs. To explore the robustness of the suggested decisions, the sensitivity of decisions to changes in such parameter estimates can be explored. For this sensitivity analysis, failure probability, upgrade costs, the costs of not funding repair, and property value estimates were varied to assess the general robustness of the foregoing conclusions. We consider these to be the most important uncertainties in this analysis.

Probabilities and Upgrade Costs

The failure probability of island levees acts together with upgrade costs to influence the estimation of net present value of upgrades and repairs. Since these probability and cost estimates are imperfect and are likely to change with improvements in understanding, we evaluated their effect on model results. The goal of this sensitivity analysis was to find the number of islands that are optimally upgraded under increasingly effective upgrade scenarios, given low, medium, or high costs for those upgrades. This brackets our understanding into a “worst-case” through “best-case” continuum, with the worst case being high upgrade costs for small increases in levee reliability, and best case being low upgrade costs resulting in significantly more reliable levees. Because our initial results using medium-range values already suggest a policy of no upgrades, we can assume that a higher upgrade cost will not change this and therefore call this our optimal policy under worst-case valuations as well. Under the best-case scenario, in which we assigned upgrade costs of $0.53 million per kilometer (versus the $1.74 million per kilometer used in the analysis above) and decreased every island’s annual post-upgrade failure probability to 0.01 (the urban standard for levees), it is optimal to upgrade 23 of the 34 islands included in this analysis. Even if levee upgrades were relatively inexpensive and were thought to dramatically decrease failure probability (highly unlikely since these upgrades do not increase resistance to earthquakes), it still does not make economic sense to upgrade 11 islands of the 34 islands under review. These results support our initial conclusion that it is not cost-effective to invest in upgrading all Delta islands to PL 84-99 standards or higher. The results of this analysis are summarized in Figure 5.

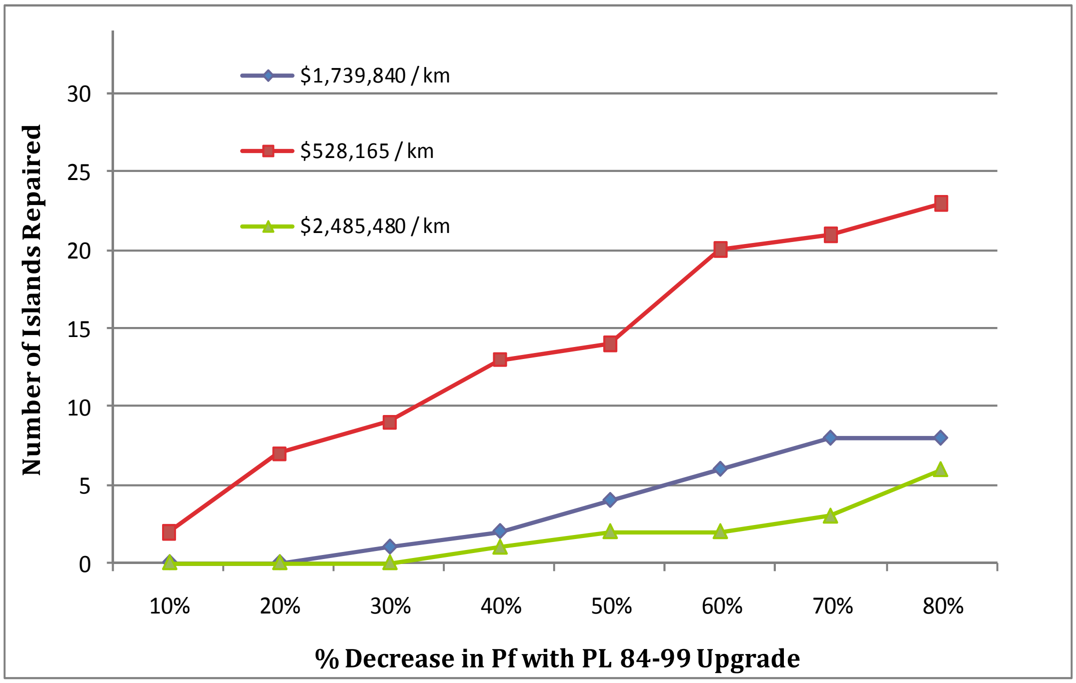

Figure 5. Effect of decreasing levee failure probabilities and upgrade costs on economic decision to upgrade islands

Do Not Repair Costs

Because we only replace lost roads and rail in the case of no repairs, some other infrastructure replacement costs may not have been represented in this initial analysis for a few islands. In addition, we did not evaluate the additional costs of mitigating increased levee underseepage that would occur on some islands adjacent to flooded islands. We experimented with increasing "no repair" costs by 10 percent increments to test the sensitivity of our results to a possible change in subsequent cost estimations. With 100 percent increases in the cost of not repairing an island, only five additional islands are repaired (Summarized in Figure 6). This result demonstrates the relative importance of island property and asset values in evaluating whether to repair an island.

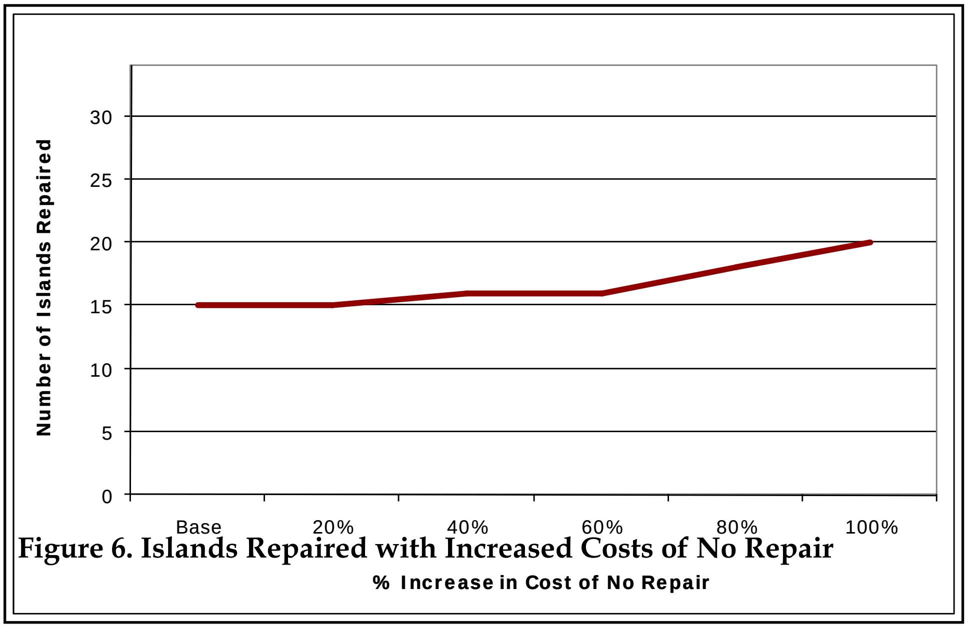

Figure 6. Islands Repaired with Increased Costs of No Repair

Property Values

To evaluate the effect of property values used in the model we increased values and assessed its effect on the "Abandon versus Repair" decision. Combined land and asset values were systematically increased by increments of 10 percent. Small increases in land and asset values had minimal effect. When values were increased by 100 percent, only four additional islands moved from the Abandon to Repair category. (The indeterminate category was ignored for this sensitivity analysis.) This modest shift in the number of islands to repair reflects the high costs of levee repairs relative to island property values, even with substantial increases in those values. These results are summarized in Figure 7.

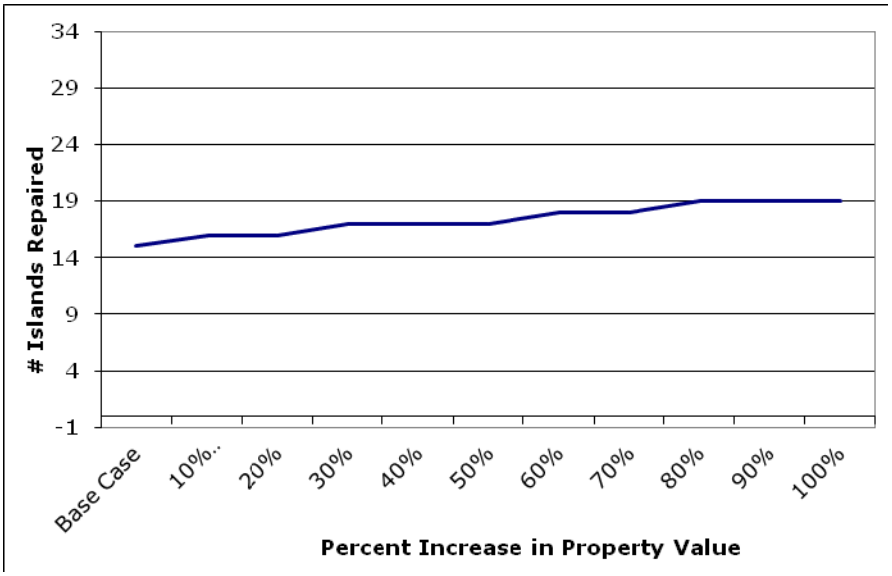

Figure 7. Effect of increasing property values on decision to repair islands following levee failure

Caveats

This economic decision analysis for levee upgrades and repairs is based solely on the value of the land and assets of an island and the likelihood of failure under current conditions. There are four main limitations to this approach. First, there are other reasons to assign higher values to specific islands. Most notably, as discussed in a recent PPIC and UC Davis report (Lund et al. 2008), allowing some islands to flood following failure will degrade Delta water quality for agricultural and urban uses. Based on the hydrodynamic modeling results presented in Chapter 4 and Appendix C of the same report, the western islands—Sherman, Twitchell, Brannan-Andrus, Jersey and Bradford—have the greatest effect on water quality and would be given higher value on this basis alone (Fleenor et al., 2008). It appears that the other islands, in contrast, could be pre-flooded without harming water quality. As discussed in the main report, the state would first need to develop a policy for mitigating any resulting impacts to affected landowners. Additionally, this model does not account for other cultural values such as legacy towns, or potential environmental costs and/or benefits, such as terrestrial sandhill crane habitat on Staten Island and potential positive habitat gains from flooded islands. However, the model can be used to experiment with the simple question of “how great must other values be” to alter a repair or upgrade decision.

The second main limitation is that the model does not yet incorporate future risk conditions. Since risk of failure is increasing due to subsidence, changing inflows, sea level rise and seismicity, the analysis presented here is biased to favor upgrading and repairing islands.

Third, the cost of not repairing an island was computed assuming that the flooding was unplanned, and that no private or public entity would be willing to fund repairs if the costs outweighed the economic value of the islands. In other words, we did not calculate alternate “no repair” costs where island flooding had been prepared for, either by previously moving or hardening infrastructure or deciding to abandon particular groups of islands that may not greatly affect the vulnerability of other nearby levees. This also biases the model in favor of repairing islands, because “no repair” costs might be lower if the state or other infrastructure owners prepare in advance for flooding.

Finally, this analysis does not take into account who pays for levee repairs and upgrades, nor the legal and political obstacles facing state-planned island flooding. The source and amount of funds available, whether federal, state or local, will have considerable influence on decisionmaking. Also, selective and well-planned island flooding in the Delta stands in stark opposition to California's current legal framework and policies for the Delta, which generally approach the Delta's levee network as a homogenous system (California Water Code Sections 12980 - 12985).

Conclusions

As noted in Chapter 2 of *Comparing Futures for the Sacramento San Joaquin Delta* (Lund et al. 2008), linked human and natural systems that lack resiliency tend to undergo abrupt changes to new, irreversible regime states. The Delta is a rigid, fragile system at high risk of undergoing just such an irreversible change. The current levee network that protects deeply subsided islands has high probabilities of failure, whether due to overtopping, seepage or collapse during earthquakes. These risks are likely to increase in the future, raising the likelihood of fundamental change.

State and federal policy and the public's willingness to pay for upgrading and/or repairing Delta levees will modulate the nature of this change. Based solely on the net benefits and costs of such upgrades for 34 subsided islands in the Delta, it appears to not be cost-effective to upgrade levees in the Delta to PL 84-99 standards or higher based on the value of their land and built assets alone. In addition, 18 islands (of 34 subsided non-urban islands examined) are not economically viable for repair once they have flooded (Figure 4 and Table 3). We assume these islands will, with time, likely be abandoned either before or following a levee failure. Conversely, 11 islands have sufficiently high value, either because of their land value and assets or the costs of replacing key infrastructure, to warrant repair investments following levee failure, at least for a time. For the remaining five islands analyzed here, the difference between costs of no repair and cost of repair is low (less than twice the property value of the island), and a decision would need to be made based on conditions at the time of failure. Heavily urbanized islands require a more detailed analysis and were not included in this assessment. The many islands, not analyzed, that are not subsided below sea level are likely to be sustainable for a many decades.

The forces acting on the Delta and the costs of mitigating those forces lead us to conclude that much of the subsided Delta, composed of a network of levees that separate subsided land from the water, is about to undergo (or may already be undergoing) a transition to a new regime state. This new state will have little in common with the Delta of the early 1800s, since island flooding will replace what was historically a freshwater tidal marsh, with open water more than 4.5 meters deep in many places. The consequences of this transition are unknown, but will require those who manage the Delta for its array of ecosystem services to adapt to a new, evolving system with significant management challenges.

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