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Levee Decisions and Sustainability for the Sacramento-San Joaquin Delta

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ABSTRACT

California's Sacramento-San Joaquin Delta has fragile levees subject to several trends that make them increasingly prone to failure. To assess the likely extent of Delta island flooding, this study presents an economic decision analysis approach for evaluating Delta levee upgrade and repair decisions for 34 major subsided agricultural islands that make up most of the Delta's Primary Zone and include all subsided, non-urban islands. The decision analysis provides a quantitative framework to address several relevant questions about reasonable levee upgrade and repair investments. This initial analysis indicates that it is economically optimal not to upgrade levees on any of the 34 subsided Delta islands examined, mostly because levee upgrades are expensive and do not improve reliability much. If upgrades can improve reliability more, it becomes optimal to upgrade some levees. Our analysis also suggests that, accounting for 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, only four islands originally not repaired become cost-effective to repair. The decision analysis 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 decision analysis model as a working framework for islands of high priority. An inescapable conclusion of this analysis is that maintaining the current Delta landscape is unlikely to be economical from business and land use perspectives.

KEYWORDS

Levee, decision analysis, reliability, policy, Delta

INTRODUCTION: THE DELTA'S LEVEE SYSTEM

California's Sacramento-San Joaquin Delta is currently defined by its 1,770 km (1,100 miles) of levees. The Delta levee network was developed during the late 19th and early 20th centuries to reclaim more than 450,000 acres of freshwater and brackish marsh, mainly for agriculture. 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. Four drivers are increasing probabilities of levee failure and island flooding: sea level rise, subsidence, changing inflows, and earthquakes (Mount and Twiss 2005; URS Corporation and J. R. Benjamin & Associates 2009; Cayan 2008a, 2008b; Church and White 2006; Deverel 2007; IPCC 2007; Stewart and others 2005). Physically and financially, the Delta cannot easily withstand these increasing pressures (Lund and others 2007, 2008, 2010).

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Deltas around the world are having similar problems (Syvitski and others 2009).

Physically, the Delta's 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 been expanded to cope with gradual land subsidence, sea level rise, and erosion. This expansion, accomplished by adding material to the top and sides, was, until recently, not subject to modern engineering standards.

Delta levees can fail in several ways (Linsley and others 1964; Wood 1977; 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 also may 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 in 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. With continued levee degradation and increasing external forces, these failure pressures are all likely to become worse and more frequent (Mount and Twiss 2005). Without intervention, it seems likely that 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, amidst great 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 toward 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 (DRMS) Phase 1 report (URS Corporation and J. R. Benjamin & Associates 2009), and identify resource allocation decisions the State currently faces. We evaluate the economic costs of maintaining the current levee configuration in the Delta and present a simplified, yet thoughtful, decision analysis to economically optimize levee repair and upgrades for individual islands. Our conclusions about upgrade and repair policies in the Delta extend those found in earlier studies (Logan 1989). Decision analysis is broadly used as a tool for public policy makers, both as a way to understand, organize, and quantify a problem, and as a way to compare the costs and benefits of various strategies. Decision analysis is valuable because it forces the decision maker to articulate how various parameters interact with each other, and identify a realistic and holistic set of alternatives (Hobbs and others 1997; Cheng and others 2008; Lund 2009).

Failure Probabilities: Certain Future, Uncertain Timing

Delta levees are a certain to fail. 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, the state could simply maintain the current Delta policy of supporting levee maintenance and repairs, fighting floods, and repairing islands when their levees fail. However, conditions are not static in the Delta, and risks and costs are increasing.

Using data from the DRMS Phase 1 report (URS

Corporation and J. R. Benjamin & Associates 2009), we calculated the annual probability of island levee failure from either hydrologic events or earthquakes for 34 Delta islands that have subsided below mean sea level (based on analysis in Mount and Twiss 2005). Figure 1 shows the range of failure probabilities for 36 islands (including the two urbanized islands, Bethel Tract and Hotchkiss Tract) over the next 100 years. Based on current flood and seismic failure probabilities, the median Delta island has a 95% probability of failure between now and 2050 and a 99% probability of failure by 2100. This probability of failure over extended periods is especially high for western Delta islands where, based on the DRMS data, each island has a roughly 99 percent probability of at least one failure by 2050.

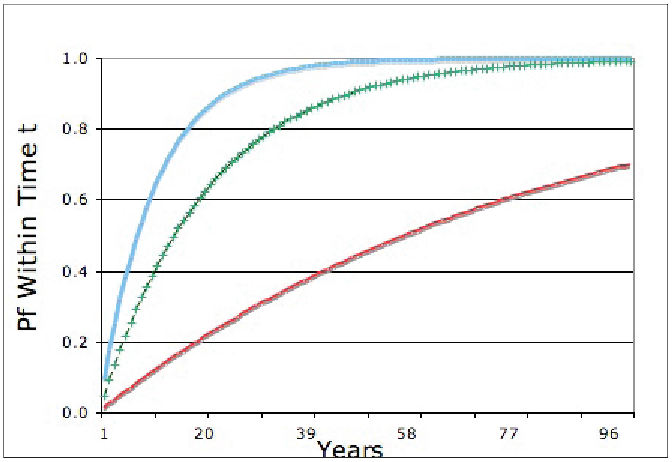

Figure 1 Maximum, median, and minimum probability of flooding from either earthquakes or floods for 36 Delta islands

These estimates are based solely on current likelihoods of failure; without major investments in levees, the probabilities of island failures will increase. Additionally, the effects of four processes—subsidence, flood inflows, sea level rise, and earthquakes—mutually re-enforce levee failure. Increasing Delta inflows and sea level rise together reduce the freeboard of the levees, increasing the frequency of levee overtopping. 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, and 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

Roughly a third of Sacramento-San Joaquin Delta levees are within federally authorized flood control projects, known as "project levees." The other two-thirds are owned and maintained by local reclamation districts on behalf of private land-owners ("non-project levees"). Most project levees are maintained by local reclamation districts with oversight and inspection from the state, following federal levee policies. This analysis focuses on non-project levees.

After 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 (DWR) set 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." These standards are summarized below in Figure 2. Levees meeting PL 84-99 standards qualify for federal aid if they are damaged by flooding. Discussions with several state and private Delta engineers indicate that most non-project Delta levees meet HMP standards, but few meet PL 84-99 standards.

Allocating Resources

Given the current fragility of the Delta levee system and the increasing risks of failure, the state will need

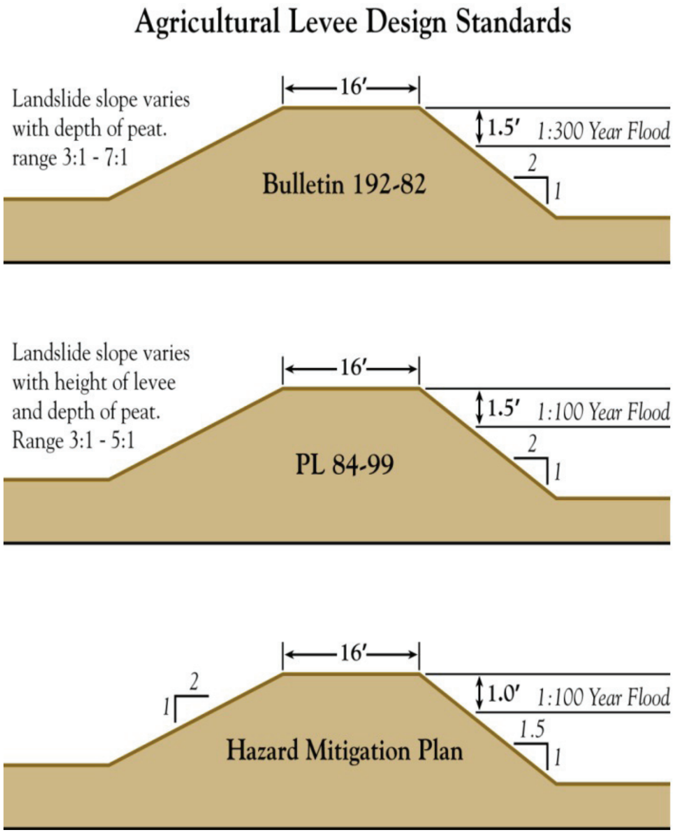

Figure 2 Comparison of state and federal levee standards

to address at least three critical policy issues.

1. Distribution of Available Resources. California voters, 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:

- Equally everywhere to mitigate flood risk throughout the 1,770 kilometers of Delta levees and the 2,735 kilometers of project levees outside of the Delta, or
- 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 historical approach has been to apply a modest level of resources broadly without prioritization, principally through the Subventions Program (averaging roughly $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 small decreases in flood risk.

2. Repair and Restoration of Islands After Levee Failure. When island levees fail, state and local entities incur considerable island repair and recovery costs. As highlighted by the Jones Tract failure in June 2004, the economic impacts and costs to repair an island will often exceed the value of the land, often by several-fold. The cost of repairing a levee breach is typically $20 million to $40 million, depending on local conditions, with roughly equal additional costs from damages to island assets and losses to the local economy (URS Corporation and J. R. Benjamin & Associates 2009). The substantial investments needed to repair an island do little to reduce the likelihood of future failures since the size of a levee breach is usually small compared to the length of levee on an island. Given the high cost of these repairs, the low values of land they restore, and that repairs do not reduce future failure rates, the state might adopt a policy of not repairing 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 after Jones Tract flooded, but it has yet to be tested.

3. 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; California Natural Resources Agency 2009). This problem is particularly acute in flood management in California in general (Galloway and others 2007) and in the Delta specifically. Climate change will require developing adaptation strategies that go beyond simply improving all Delta levees. 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.

Six combinations of levee upgrade and post-failure repair are considered, with three upgrade levels each having two post-failure repair strategies (”repair” or ”no repair”). The three upgrade actions considered are

1. No upgrade to levees
2. Upgrade to PL 84-99 standards
3. Upgrade to PL 84-99 standards plus 0.3 m (1 ft) to mitigate for expected sea level rise by mid-century (denoted upgrade PL 84-99 + 0.3 m SLR)

For each island, each upgrade policy comes with an accompanying decision of whether or not to repair that island when its levees fail (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 + 0.3 m SLR	Repair
6	PL 84-99 + 0.3 m SLR	No Repair

We begin with a summary of the decision analysis framework and method, and then describe how this analytical framework can be applied to the Delta’s levees. We exclude heavily urbanized islands from the decision analysis results. Levee upgrades for urbanized islands will be subject to Federal Emergency Management Agency (FEMA) 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, weighed by probabilities, for several alternatives. Most levee or dike investments aim to reduce net flood damages (damages plus levee costs). This presents a dilemma for the decision-maker because the value of his or her investment is in part a function of an uncertain future. Decision analysis provides a logical framework for cost-benefit comparisons of decisions options with uncertainty about their outcomes (Hobbs and others 1997; Cheng and others 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 including probabilistic reliability analysis in 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, depending on several other stochastic variables such as storm events, underlying soils, river discharge, and location of an initial breach (Wood 1977; 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 common for decision analyses to adopt failure probabilities determined by a separate effort (Van Dantzig 1956; Eijgenraam 2006). In this analysis, we use the current failure probabilities for Delta levees provided in the DRMS Phase 1 report (URS Corporation and J. R. Benjamin & Associates 2009), and then, as sensitivity analysis, explore how results change for lower failure probabilities.

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 and others 2002; USACE 1996, 1999a, 1999b). These risk-based performance values are typically attained by summing the net cost or benefit of future events multiplied by their probability of occurrence. 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 generally in the United States in a body of economic decision theory work (Pratt and others 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; Bouma and others 2005; Woodall and Lund 2009).

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 and others 1972; USACE 1999a; Aven and Kørte 2002; Voortman and others 2002; Cheng and others 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. For cases where economic consequences are small relative to the overall wealth of the society or decision-maker, risk-aversion should be negligible, and expected-value calculations are appropriate (Arrow and Lind 1970). The structure of decision options and outcomes is often represented in a decision tree.

The framework for organizing the sequence of decisions necessary for levee investments appears 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

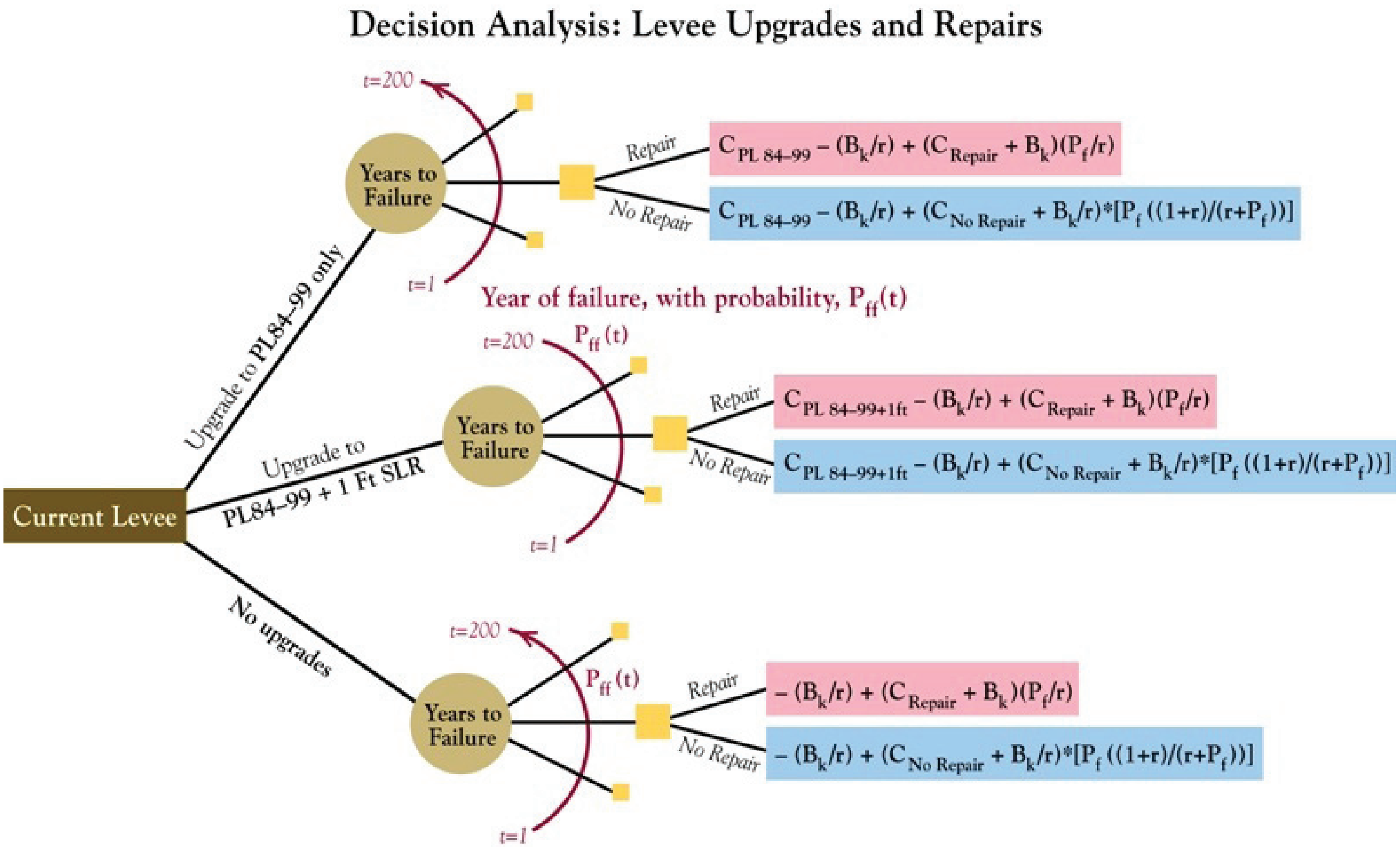

Figure 3 Island levee decision analysis tree for assessing whether to upgrade levees and to restore islands following flooding. $P_{ff}(t)$ = probability of first failure at time t, P_f = current probability of failure, r = discount rate, B_k = one year of island profits.

the future. In this way, a decision analysis facilitates the logical structuring and comparison of alternatives under uncertainty.

The LDAM presented here applies these ideas. As mentioned earlier, the state has three initial options for Delta levees: (1) no upgrade to levees, (2) upgrade to PL 84-99 standards, or (3) upgrade to PL 84-99 standards plus 0.3 m (1 ft) to mitigate for expected sea level rise by mid-century. Regardless of which direction is taken now, in some (uncertain) future year the state will need to decide whether to repair an island when its levee fails. This formulation is a variant of a classic decision tree: the node of uncertainty does not split off into different uncertain events with varying probabilities, but rather into different uncertain time-frames 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 backward dynamic programming (Hobbs and others 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. More complex, non-stationary decision analysis problems, such as long-term adaptation of levees to climate change, can be optimized using dynamic programming (Zhu and others 2007).

Decision to Repair after Failure

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

Cost of Repairing an Island when it fails 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 again and 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 a property value corrected for failure rate) are subtracted from these costs. In mathematical terms:

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

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, $[(C_{Repair} + B_k)(P_f/r)]$ 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).

Cost of Not Repairing an Island when it fails is the sum of the cost of rebuilding or re-locating 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 (repair or no repair) can be identified. 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 (Suddeth and others 2008).

Decision to Repair or Not 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.

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:

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

The first cost term will not exist in the "no upgrade" case. In the case of an enhanced upgrade to mitigate for 0.3 m (1 ft) 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 when an island fails (presented above) is that there is no current cost of repairing the island today (because it has not yet failed), so that $(C_{Repair} + B_k)$ 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, and the repair and damage costs of a failure event. Friedenfelds (1981) provides a useful formula for 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:

$$W = C + W\sum_{i=1}^{\infty} P_f\left(1-P_f\right)^{i}\left(1+r\right)$$

or

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

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:

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

Note that

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

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.

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:

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

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.

$(C_{No\ repair})*[P_f * [(1 + r)/(r + P_f)]]$ 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:

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

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 and others 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 upgrade, (2) upgrade to PL 84-99 standards or (3) upgrade to PL 84-99 + 0.3 m (1ft) sea level rise. 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.

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 prudent for some Delta islands.

Parameter Values

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 employs values from various data sources. Refinements of cost valuations for Delta islands would enhance the resolution of the model. These initial results 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.

Property Value

The analysis summed annual crop productivity with island assets as a minimum measure of property value, presented in Table 2. The assets estimate, taken from the DRMS Phase 1 report (URS Corporation and J. R. Benjamin & Associates 2009), contained buildings, equipment, and infrastructure such as roads and rail lines. Land values were extracted from data and agricultural production modeling assembled in Lund and others (2007) in which crop acreage on each island was identified as either high or low value, and assigned the appropriate multiplier for annual profit yield per acre. The nominal property values here are not market values and assume island reliability. These property values were then increased in several steps to a maximum value triple that of the crop and asset

Table 2 Land and asset values

Island Name	Land Value (Lund and others 2007)	Asset Value (URS Corp. and 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	$4,437,580	$124,671,000	$129,308,580
Wright-Elmwood Tract	$26,166,120	$15,967,000	$42,133,120

estimate. This was done to account for uncertainty in input data, crop changes over time, and potential additional values (cultural, habitat, etc.) unaccounted for in crop and assets data.

Repair Costs

An average cost of $25 million dollars was assumed to repair a levee breach, plus an additional $0.34 per cubic meter to pump water from the island. These numbers are based on interviews with engineers familiar with the Delta who estimated that the typical levee breach repair costs $20 to 30 million, recorded costs of the Jones Tract Failure, and the DRMS Phase 1 report (URS and J. R. Benjamin & Associates 2009 2009).

PL 84-99 Upgrade Costs

Three estimates for upgrade costs were evaluated. Initial 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 conversations with levee engineers and DWR engineers. This cost is close to that cited by DRMS for upgrades. We were also provided higher and lower estimates, of $2.48 million dollars per kilometer and $0.53 million dollars per kilometer, respectively. These other two costs also were evaluated in subsequent model runs. In all cases we noted which islands have already partially undergone PL 84-99 upgrades, and subtracted the appropriate amount from their estimated upgrade costs.

PL 84-99 Upgrade + 1 ft Sea Level Rise Costs

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 0.3 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 levee 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 biases the model toward this enhanced upgrade because it does not account for additional subsidence commonly following placement of fill on levees. Depending upon local conditions, subsidence can significantly increase the volume of fill needed to raise levee elevations.

Cost of No Repair

We assumed the two biggest costs of not repairing an island after failure to be the cost of rebuilding or diverting infrastructure and the cost of upgrading surrounding islands. 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). 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).

Costs of reinforcing surrounding islands were calculated with these assumptions:

1. The approximate length of levee upgrades needed for these surrounding islands should equal roughly half the circumference of the failed island (geometrically).
2. The surrounding levees need to be raised 0.3 m (1 ft) to account for this increased exposure.
3. Cost of these upgrades should thus equal half the cost of materials for raising the levee of the failed

island by 0.3 m (obtained from earlier calculations of PL 84-99 + 0.3 m SLR costs).

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

As with several other inputs, we allowed for the possibility of higher costs than those estimated with the above procedure. These initial numbers were taken as a minimum value, and were increased systematically by 10% increments to test results against a wider range of potential costs for not repairing an agricultural island.

Failure 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 without upgrades, we use the Levee Optimization Assessment from the DRMS Phase 1 report (URS Corporation and J. R. Benjamin & Associates 2009). The report evaluated risk to individual Delta levees from three events: sunny-day failures, flooding, and seismic activity. In this analysis, we ignore the smaller risk from sunny-day failures, and instead calculate the annual probability of levee breaches from floods or earthquakes. After assigning islands to one of several "vulnerability classes," DRMS calculations of annual failure probabilities for each class involved three steps:

1. Creating a "levee response function" to represent the levee's ability to withstand either hydrostatic (floods) or ground acceleration (seismic) forces
2. Creating a conditional probability of failure function to relate the conditional probability of a levee breach to a given exit gradient internal to the levee (for flooding) or the loss of freeboard (slumping from seismic ground accelerations)
3. The development of a "levee fragility function" to relate the probability of failure to channel water surface elevations or earthquake magnitudes. These functions were developed using a mixture of geotechnical models, expert elicitation, and Monte Carlo simulations.

The DRMS report went through several revisions in response to comments from CALFED's Independent Review Panel (IRP). In its final assessment of the report, the IRP generally found the analysis much improved and reliable for planning purposes, except for a few caveats.

The IRP stressed several points for the analysis of seismic and flood risk (CALFED IRP 2008). First, the IRP felt the DRMS report may have over-estimated failure from earthquake ground accelerations. The IRP points out that the frequencies predicted by the DRMS Phase 1 Report for earthquakes are significantly higher than the historical record suggests, and even for the seismically active period of 1850 through 1906, earthquakes of similar magnitude hitting the Delta region today would not necessarily cause the widespread failure suggested by the DRMS Phase 1 Report assessment. However, in a separate study, the U.S. Geological Survey (USGS) predicts a 30% chance of a 6.8 to 7.0 magnitude earthquake in the region within the next 30 years (Brocher and others 2008). This USGS study may help substantiate the higher frequencies predicted by the DRMS Phase 1 Report. Second, because the fragility curves relating levee failure to channel stage are steep, and some error occurs in predicting stage for specific sloughs and channels, it was thought that the risk from flood events may have been overstated for some islands, and understated for others. However, it was also noted that estimated seepage rates may have been low, which would tend to bias the models towards lower failure probabilities.

In this study we also attempted to assess how well PL 84-99 upgrades improved 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 rough rule that this upgrade reduces the levee failure rates by an average of approximately 10% 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 from earthquakes.

Because of concerns about the DRMS report and the necessarily coarse assessment of upgrade effectiveness, and also to test the economics against a wide range of uncertain futures, we took the DRMS probabilities of failure with a 10% decrease from upgrades as maximum values for this analysis. After we ran the model with these higher failure probabilities, we reduced them incrementally, first without upgrade and then via different upgrade options, to what we considered the lowest failure probability expected from agricultural levees in the Delta: 0.01 per year, or what is required under the Federal Emergency Management Act for urban levees. While this may be an optimistic and perhaps unrealistic lower bound, it serves to test the sensitivity of our results while also distinguishing those islands that may remain economically unsustainable even under very favorable conditions.

Discount Rate

Discount rate estimation is a routine concern in economic evaluation studies. A 5% annual real (inflation-corrected) discount rate is assumed for the base calculations. Discount rates between 3% and 7% were examined in sensitivity analysis.

Uncertainty

This analysis is used to organize and explore several uncertainties. These include: (1) pre-upgrade failure probabilities, (2) failure probability reduction with levee upgrades, (3) costs of not repairing islands, and (4) island economic production value. More generally, uncertainties can be grouped into three categories: (1) physical uncertainties, (2) parameter uncertainties, and (3) structural uncertainties with regards to the model itself (Tebbens and others 2008; Ramsey 2009). For this analysis, physical uncertainties for Delta levees and the effectiveness of various upgrade efforts are the most easily quantified, and are explicitly factored into the decision analysis. Parameter uncertainty refers to values used for inputs such as island assets and repair costs. These are accounted for by exploring different scenarios in which key inputs are varied. Structural uncertainty is difficult to quantify because it refers to the conceptual framing or formulation of the decision analysis itself, which relies on the logical formulation of the problem. Alternative logical formulations, such as expanding the problem to include dynamics and climate change (Zhu and others 2007), might be explored in later work at some cost of model comprehensibility for public policy purposes. For this analysis, structural (and other forms) uncertainty are addressed by using an "indeterminate" category for the repair decision in the base case, where the absolute net benefit (or cost) of repair is not large enough for this initial analysis to be persuasive.

RESULTS

Results are presented for a base case and sensitivity analyses regarding probabilities of failure, effectiveness of upgrades, property values, and costs of not repairing islands.

Base Case

The base case used DRMS failure probabilities with a 10% decrease from upgrades, property values reflecting only crop production and assets, and medium upgrade costs. The 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. 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 five 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 differed by less than a factor of two (Figure 4 and Table 3). Figure 4 also highlights islands that, in a separate analysis (Fleenor and others 2008), have been identified as critical for export water quality. Since Delta water exports were

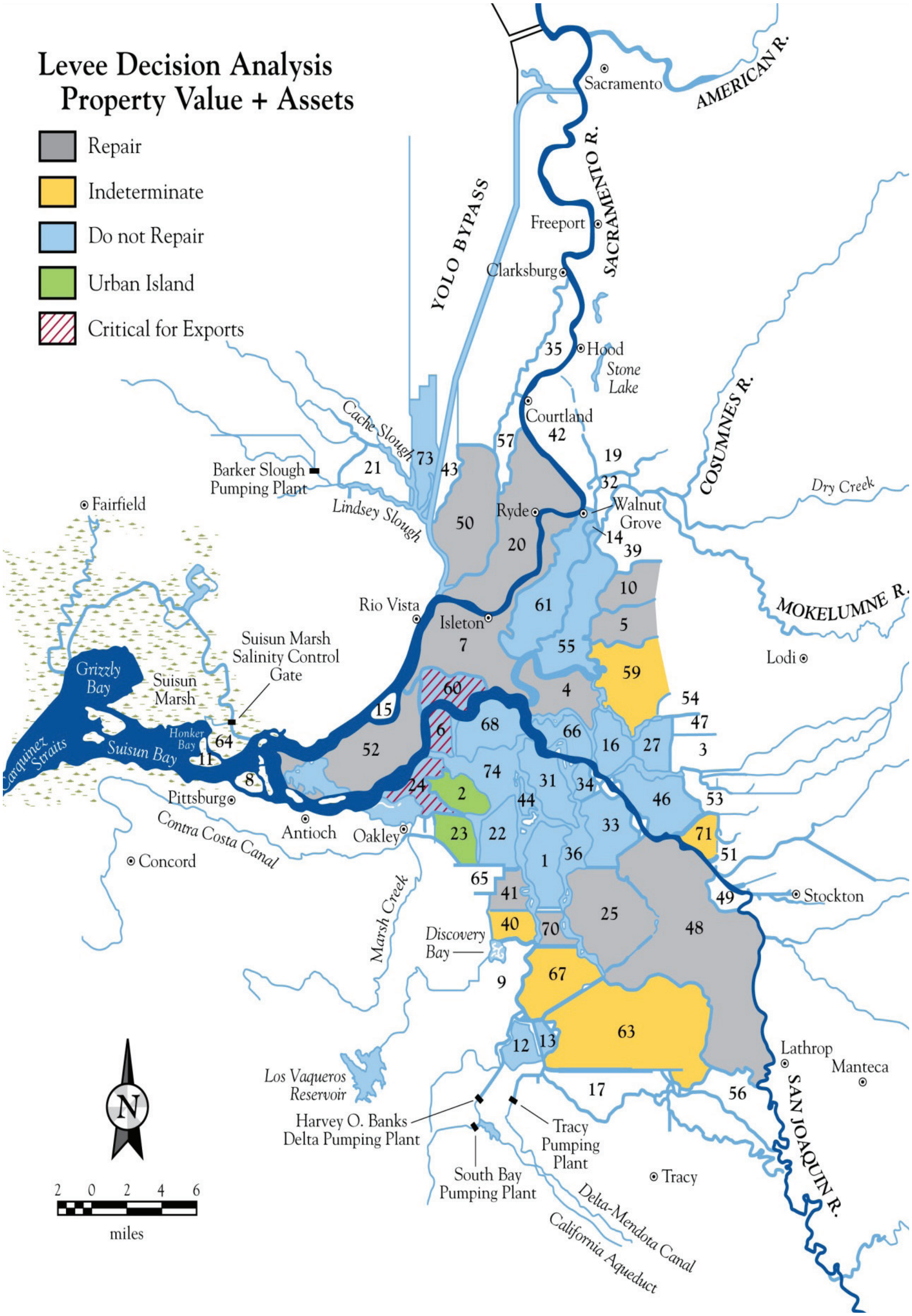

Figure 4 Base case repair decisions

Table 3 Summary of LDAM base case results for 34 subsided Delta islands

		Repair Costs, No Upgrade		Expected Present Cost of Upgrade Strategy			Decision Summary		
# on Map	Island Name	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	3.02	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 Island	$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	$44,204,857	$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	.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 Tract	$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	-$1,875,929,756	-$602,031,629	-$360,532,435			

*Ryer Island has already been upgraded

not factored into this analysis, results for these five western islands may be unrealistic given the State Water Project and Federal Central Valley Projects' current reliance on lower-salinity water in the Delta for pumping. Under current state and federal project operations, it is likely that those islands would all be repaired.

Additional Analysis Exploring a Broader Range of Input Values

All analyses have uncertainties. Because this analysis includes the simplifying assumption that failure probabilities do not increase with time, results could be viewed as optimistic. On the other hand, our costs for not repairing an island are conservative in their estimation of infrastructure replacement costs. To explore a broader range of arguable reality, we can explore the sensitivity of decisions to changes in such parameter estimates. For this analysis, we varied failure probability, upgrade costs, the costs of not funding repair, property value estimates, and discount rate to assess potential changes in the foregoing conclusions. For these sensitivity analyses, the "indeterminate" category was eliminated.

Decreased Failure Probabilities and Varying Upgrade Costs

The failure probability of an island's levees acts together with upgrade costs to influence the estimation of the net present value of upgrades and repairs. Since these probability and cost estimates are imperfect and are likely to change as we understand more, we evaluated their effect on model results. First we focused on the repair decision, and found the number of islands repaired after lowering current failure probabilities (without levee upgrades). All islands were first set to the same annual probability of failure of 0.04 (higher than DRMS estimates for some islands, and lower for others), and decreased by increments of 0.005 to the urban FEMA standard of 0.01 (lower than the DRMS estimate for all of the 34 islands analyzed). When probabilities of failure were decreased from 0.04 to 0.01, and upgrade decisions were taken into account, only two additional islands were repaired. These results, summarized in Figure 5, reflect the relative importance of property values and repair costs in the repair decision. Second, we sought to find the number of islands 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: The worst case being high upgrade costs for small increases in levee reliability, and the 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

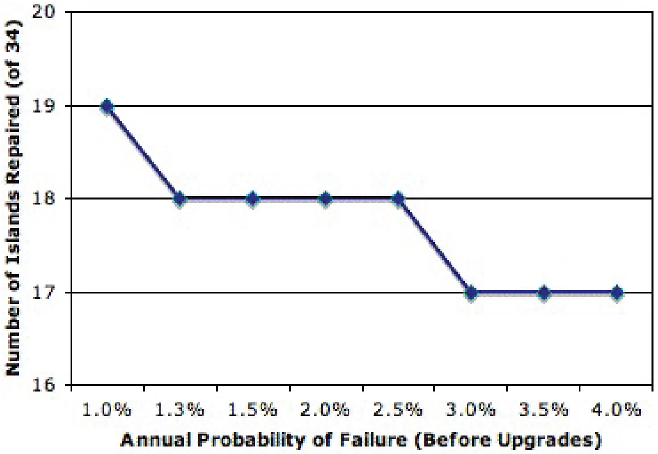

Figure 5 Effect of decreasing pre-upgrade failure probabilities on the economic repair decision

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 6.

Increasing Property Values and "Do Not Repair" Costs

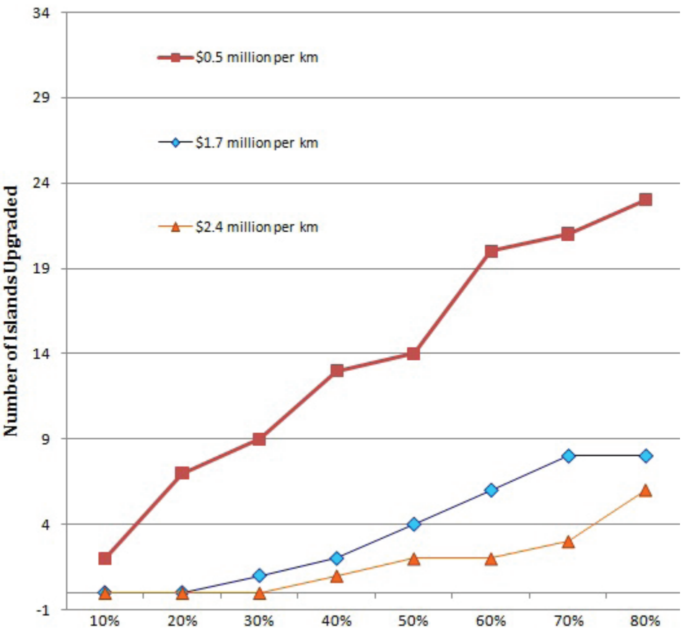

Figure 6 Effect of decreasing levee failure probabilities and upgrade costs on economic decision to upgrade islands

Because we only replace lost roads and rail lines in the case of no repairs, some other infrastructure replacement costs may not have been represented in the base case for a few islands. In addition, we did not consider potential additional costs of mitigating increased levee under-seepage that would occur on some islands adjacent to flooded islands. Finally, property values in the base case only account for crop production and on-island assets. Increases in all of these numbers could change a repair decision from "do not repair" to "repair." We first experimented with increasing "do not repair" costs by 10%. With 100% increases in the cost of not repairing an island, only five additional islands are repaired (summarized in Figure 7). This result demonstrates the relative importance of island property and asset values in evaluating whether to repair an island.

To evaluate the effect of property values in isolation from "do not repair" costs, we increased property values and assessed their 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 8.

We finally looked at a more extreme case for both property values and "do not repair" costs, tripling both of them at the same time: 9 of 34 islands were

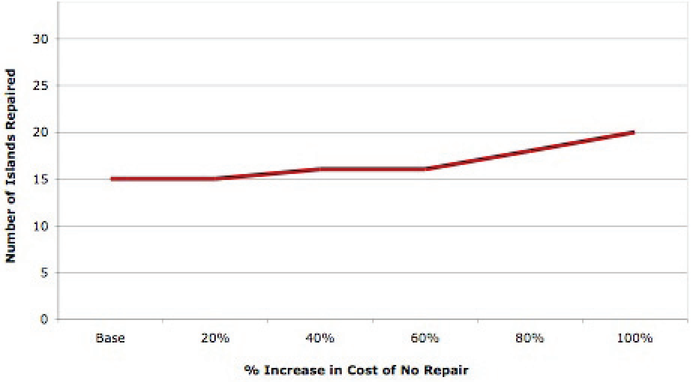

Figure 7 Islands repaired with increased costs of no repair

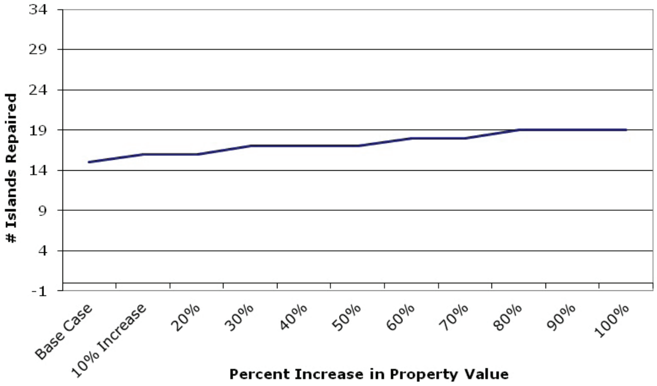

Figure 8 Effect of increasing property values on decision to repair islands after levee failure

not repaired by the model. These results are displayed in Figure 9.

Discount Rate

Discount rates were varied to see if results were sensitive to financial or social opportunity cost rates (a measure likely to depend on the decision-maker). For a high real annual discount rate of 7%, 16 islands were repaired. For the low discount rate of 3%, 14 islands were repaired. The upgrade decision responded to changes in discount rate in the opposite direction. One island (aside from Ryer, which is already at PL 84-99 standards) was upgraded with the low discount rate of 3%, with no islands upgraded for the base case of 5% and the higher discount rate. Less discounting of future costs and benefits encourages upgrades, but overall reduces the number of islands repaired.

Combining Optimistic Values

Unreasonably combining the most optimistic value for each parameter from the repair perspective (high discount rate, low initial probability of failure, low upgrade costs, tripled property value, and tripled ”do not repair” cost), 30 islands of 34 are repaired and still no islands are upgraded. Unreasonably combining the most optimistic value of each parameter from the upgrade perspective (low discount rate, initial base case failure probabilities with reduction to 1% annual failure probability from upgrades, low upgrade costs, tripled ”do not repair” costs and tripled property values), 28 islands are repaired and 24 islands are upgraded.

Results Summary

For all cases, we obtain a range of economic and risk-based upgrade and repair decisions. Results suggest that, of the 34 subsided islands analyzed, somewhere between 11 and 25 islands economically justify repair after a levee breach, and 0 to 23 islands justify current upgrades to PL 84-99 standards. For an unrealistic scenario in which *all* parameter values are altered to favor repair (within reasonable values) the number of islands repaired jumps to 30 of 34, and for a similarly unrealistic scenario for upgrades, the maximum number upgraded increases from 23 to 24. Even with unreasonably optimistic assumptions, it is uneconomical to upgrade all levees or to repair all islands.

The results of this analysis are similar to earlier work on upgrade and repair policy in the Delta. Logan (1990) 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 not using decision analysis or optimizing for individual islands. Instead, he pre-determined 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 than DWR’s plan to upgrade the entire levee system. It did not make economic sense from a state-wide perspective to upgrade all Delta islands. These results are similar to ours, indicating much better economic value for a policy of limited and prioritized upgrades and repairs for Delta levees.

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, allowing some islands to flood following failure might degrade Delta water quality for agricultural and urban uses (Lund and others 2008). Based on hydrodynamic modeling results, 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 and oth-

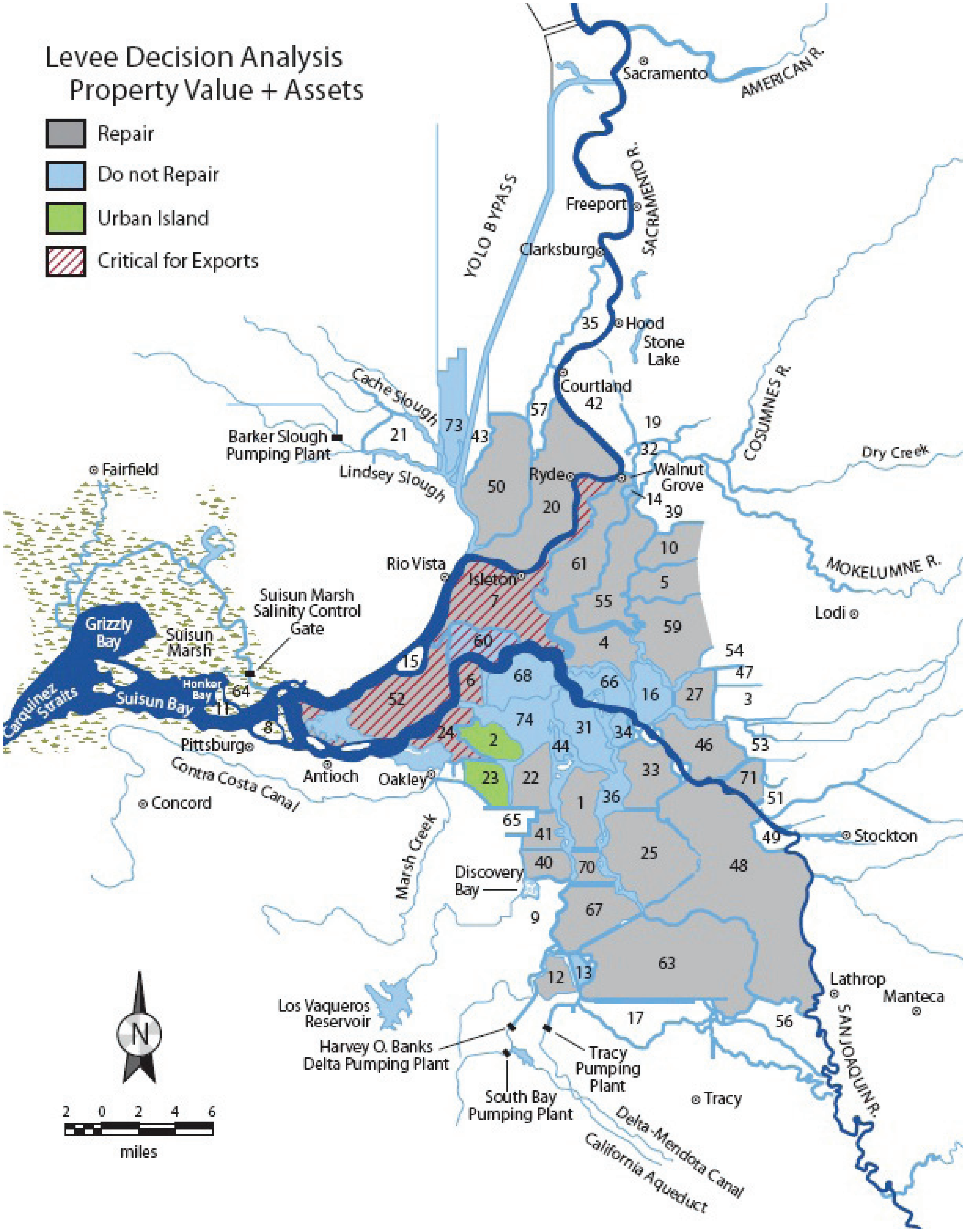

Figure 9 Repair decision using maximum property values and "do not repair" costs

ers 2008). It appears that other islands, in contrast, could be pre-flooded without harming water quality. A new state Delta levee policy would need to address how to mitigate effects for affected land-owners. Additionally, this model does not explicitly 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, as our sensitivity analyses demonstrate.

The second main limitation is that the model does not yet incorporate future risk conditions. Since failure probabilities seem to be increasing due to subsidence, changing inflows, sea level rise and seismicity, the analysis presented here seems increasingly biased to favor upgrading and repairing islands with time. This limitation could be accommodated by a non-stationary dynamic programming formulation for each island (Zhu and others 2007), at some loss of simplicity and comprehensibility of the analysis.

Third, we computed the cost of not repairing an island, 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 island. In other words, we did not calculate alternate lower "do not repair" costs where island flooding had been prepared for, either by previously moving or hardening infrastructure or by deciding to abandon particular groups of islands that might 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 account for 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 decision-making. 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

Linked human and natural systems that lack resiliency tend to undergo abrupt changes to new, irreversible regime states (Mount and Twiss 2005; Lund and others 2008, 2010). 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, as a result of overtopping, seepage or collapse during earthquakes. These risks are likely to increase in the future, raising the likelihood of fundamental change. This common problem for deltas worldwide (Syvitski and others 2009) is exacerbated by California's susceptibility to earthquakes.

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 not to be cost-effective to upgrade all levees in the Delta to PL 84-99 standards or higher, based on the value of their land and built assets alone. In addition, it is not economically viable to repair between 4 and 23 islands (of 34 subsided non-urban islands examined) once they have flooded (Figure 4 and Table 3). We assume these islands will, with time, probably be abandoned by their owners, either before or after a levee failure. Conversely, some islands have sufficiently high value, either because of their land value and assets or the costs of replacing key infrastructure, to warrant repair investments after levee failure, at least for a time. Heavily urbanized islands require a more detailed analysis, and were not included in this assessment. The many islands that have not subsided below sea level, which we did not analyze, are likely to be sustainable for 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. This new Delta will have little in common with the Delta of the early 1800s, since subsided island flooding will replace what was historically a freshwater tidal marsh—with open water more than 4.5 m deep in many places. The consequences of this transition are unknown, but will require those who manage the Delta to adapt to a new, evolving system with significant management challenges.

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REFERENCES

Ang AH-S, Tang WH. 1975. Probability Concepts in Engineering Planning and Design, Vol. 1, Basic Principles. New York (NY): John Wiley & Sons.

Arrow K, Lind RC. 1970. Uncertainty and the Evaluation of Public Investment Decisions. American Economic Review 60(3):364-78.

Aven T, Kørte J. 2003. On the use of risk and decision analysis to support decision-making. Reliability Engineering and System Safety 79:289-299.

Bouma JJ, Francois D, Troch P. 2005. Risk assessment and water management. Environmental Modeling and Software 20:141-151.

Brocher TM, Boatwright J, Lienkaemper JJ, Prentice CS, Schwartz DP, Bundock H. 2008. The Hayward Fault — is it due for a repeat of the powerful 1868 earthquake? USGS Fact Sheet, U.S. Dept. of the Interior.

[CALFED IRP] CALFED Independent Review Panel. 2008. Review of the Delta Risk Management Strategy Phase 1 Report (Draft 4). Available from: http://calwater.ca.gov/science/drms/drms_irp.html.

Cayan DR, Bromirski PD, Hayhoe K, Tyree M, Dettinger MD, Flick RE. 2008a. Climate change projections of sea level extremes along the California coast. Climatic Change 87(1):S57–S73.

Cayan DR, Maurer EP, Dettinger MD, Tyree M, Hayoe K. 2008b. Climate change scenarios for the California region. Climatic Change 87(1):S21–S42.

Cheng C, Hsu N, Wei C. 2008. Decision-tree analysis on optimal release of reservoir storage under typhoon warnings. Natural Hazards 44:65-84.

Church JA, White NJ. 2006. Twentieth century acceleration in sea level rise. Geophysical Research Letters 33:(LO1602).

Davis DR, Kisiel CC, Duckstein L. 1972. Bayesian decision theory applied to design in hydrology. Water Resources Research 8(1):33-41.

Deverel S. 2007. Technical Memorandum Delta Risk Management Strategy (DRMS) Topical Area: Subsidence. Available from: http://www.drms.water.ca.gov/Updated2007/.

Eijgenraam CJJ. 2006. Optimal safety standards for dike-ring areas. Discussion paper. Netherlands: CPB Netherlands Bureau for Economic Policy Analysis.

Finch M. 1985. Earthquake damage in the Sacramento-San Joaquin Delta. California Geology (February):39-44.

Fleenor WE, Hanak E, Lund JR, Mount JR. 2008. Delta hydrodynamics and water salinity with future conditions. Appendix C. In: Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. Comparing futures for the Sacramento San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/content/pubs/other/708EHR_appendixC.pdf.

Florsheim JL, Dettinger MD. 2007. Climate and floods still govern California levee breaks. Geophysical Research Letters 34:L22403.

Galloway GE, Boland JJ, Burby RJ, Groves CB, Longville SL, Link LE, Mount JF, Opperman J, Seed RB, Sills GL, Smyth JJ, Stork R, Thomas EA. 2007. A California challenge—flooding in the Central Valley. California Department of Water Resources. Independent Review Panel Report. Available from: http://www.water.ca.gov/news/newsreleases/2008/101507challenge.pdf.

Hobbs BF, Chao PT, Venkatesh BN. 1997. Using decision analysis to include climate change in water resources decision making. Climatic Change 37:177-202.

[IPCC] Intergovernmental Panel on Climate Change. 2007. Climate change 2007—impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Available from: http://www.ipcc.ch/ipccreports/ar4-wg2.htm.

Linsley RK, Franzini JB, Freyberg DL, Tchobanoglous G. 1992. Water resources engineering, 4th ed. U.S.: Irwin/McGraw-Hill. 768 p.

Logan SH. 1989. An economic analysis of flood control policy in the Sacramento-San Joaquin Delta. California Water Resources Center Report. University of California.

Logan SH. 1990. Simulating costs of flooding under alternative policies for the Sacramento-San Joaquin River Delta. Water Resources Research 26(5):799-809.

Luers AL, Moser SC. 2006. Preparing for the impacts of climate change in California: opportunities and constraints for adaptation. California Climate Change Center Report 500-2005-198-SF. Available from: http://www.energy.ca.gov/2005publications/CEC-500-2005-198/CEC-500-2005-198-SF.PDF

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. 2007. Envisioning futures for the Sacramento-San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/main/publication.asp?i=671

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. 2008. Comparing futures for the Sacramento-San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/content/pubs/report/R_708EHR.pdf.

Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. 2010. Comparing futures for the Sacramento-San Joaquin Delta. Berkeley (CA): University of California Press.

Maguire LA. 2004. What can decision analysis do for invasive species management? Risk Analysis 24(4):859-868.

Moss E, Eller M. 2007. Estimating the probability of failure and associated risk of the California Bay Delta Levee System. ASCE Geotechnical Special Publication, GSP 170 (Special Issue on Probabilistic Applications in Geotechnical Engineering).

Mount JF, Twiss R. 2005. Subsidence, sea level rise, seismicity in the Sacramento-San Joaquin Delta. San Francisco Estuary and Watershed Science [Internet]. Available from: http://www.escholarship.org/uc/item/4k44725p.

Pratt JW, Raiffa H, Schlaifer R. 1964. The foundations of decision under uncertainty: An elementary exposition. American Statistical Association Journal June 1964:353-375.

Ramsey MH. 2009. Uncertainty in the assessment of hazard, exposure, and risk. Environmental and Geochemical Health 31:205-217.

Stewart I, Cayan DR, Dettinger MD. 2005. Changes in snowmelt runoff timing in western North America under a ‘business as usual’ climate change scenario. Climate Change 62:217-232.

Suddeth R, Mount J, Lund J. 2008. Levee decisions and sustainability for the Sacramento-San Joaquin Delta. Appendix B. In: Lund J, Hanak E, Fleenor W, Bennett W, Howitt R, Mount J, Moyle P. Comparing futures for the Sacramento-San Joaquin Delta. San Francisco (CA): Public Policy Institute of California. Available from: http://www.ppic.org/content/pubs/other/708EHR_appendixB.pdf.

Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Day J, Vörösmarty C, Saito Y, Giosan L, Nicholls RJ. 2009. Sinking deltas due to human activities. Nature Geoscience (2):681-686. Available from: http://www.nature.com/ngeo/journal/v2/n10/full/ngeo629.html.

Tebbens RJD, Pallansch MA, Kew OM, Sutter RW, Aylward RB, Watkins M, Gary H, Alexander J, Jafari H, Cochi SL, Thompson KM. 2008. Uncertainty and sensitivity analyses of a decision analytic model for posteradication polio risk management. Risk Analysis 28(4):855-876.

Torres RA, Abrahamson NA, Brovold FN, Harder LF, Marachi ND, Neudeck CH, O'Leary LM, Ramsbotham M, Seed RB. 2000. Seismic vulnerability of the Sacramento-San Joaquin Delta levees. Report of the Levees and Channels Technical Team, Seismic Vulnerability Sub-Team. Sacramento (CA): CALFED Bay-Delta Program.

URS Corporation, J. R. Benjamin & Associates. 2009. Delta Risk Management Strategy (DRMS) Phase 1 Risk Analysis Report. Prepared for the California Department of Water Resources.

[USACE] U.S. Army Corps of Engineers. 1996. Engineering and design – risk-based analysis for flood damage reduction studies. Department of the Army. Manual No. 1110-2-1619.

[USACE] U.S. Army Corps of Engineers. 1999a. Tools for risk-based economic analysis. Department of the Army, Institute for Water Resources. IWR Report 98-R-2.

[USACE] U.S. Army Corps of Engineers. 1999b. An overview of probabilistic analysis for geotechnical engineering problems. Department of the Army. Engineering Technical Letter 1110-2-556.

Van Dantzig D. 1956. Economic decision problems for flood prevention. Econometrica 24:276-287.

Van Manen SE, Brinkhuis M. 2005. Quantitative flood risk assessment for polders. Reliability Engineering and System Safety 90:229-237.

Voortman HG, van Gelder PHAJM, Vrijling JK. 2002. Risk-based design of large-scale flood defense systems. Cardiff 28th International Conference on Coastal Engineering July 2002:2373-2385.

Woodall DL, Lund JR. 2009. Dutch flood policy innovations for California. Journal of Contemporary Water Research and Education (141):1-16. Available from: [http://cee.engr.ucdavis.edu/faculty/lund/papers/Woodall2009.pdf.](http://cee.engr.ucdavis.edu/faculty/lund/papers/Woodall2009.pdf)

Wood E. 1977. An analysis of flood levee reliability. Water Resources Research 13(3):665-67.