Levee Decision Analysis for Sustainability of the Sacramento-San Joaquin Delta, California

Robyn Suddeth¹, Jeffrey F. Mount², and Jay R. Lund³

Instructor Notes

Summary and Background

The Sacramento-San Joaquin Delta landscape is defined by its 1100 miles of levees. Today, this fragile levee system supports agriculture, maintains water diversions from the Delta, and protects transportation corridors, energy infrastructure, and Delta towns. These levees, however, are subject to several physical realities that make them increasingly prone to failure. As sea level rise, seismicity, subsidence, and changing inflows all act to increase the rate and consequences of failures, state planners face the challenge of preparing for and responding to future Delta flooding. This case 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 optimally prioritize levee upgrade efforts in the Delta? Model inputs include property values for each island, the failure probability of each island, levee upgrade costs, and the effectiveness of upgrades at reducing failure probabilities. From these and several other inputs, the future expected costs of three different upgrade options are calculated for a subset of non-urban, subsided islands: 1) no upgrade, 2) upgrade to current federal standards (PL 84-99), and 3) upgrade beyond federal standards to accommodate one foot of sea level rise. An accompanying decision of whether or not to fund the repair of an island when its levees fail is also assessed. Students will apply the LDAM procedure and perform sensitivity analyses on a few inputs to suggest how results might change if, for example, particular islands were assigned greater land values or lower probabilities of failure.

Learning Objectives

Through this case study, students will

1. Gain an understanding of factors contributing to flooding hazards;
2. Become familiar with policies for flood risk management, flood recovery, and climate change adaptation;
3. Learn how the framework of decision analysis can be useful in solving planning problems involving significant uncertainties;
4. Gain experience conducting sensitivity analysis and an appreciation of its importance when input data are uncertain.

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Prerequisite Course(s):

Hydrology, Engineering Economics.

Type of Activity

The instructor should introduce the background material during class and should consider an assigned reading of related material (e.g., Logan, 1990; Mount and Twiss, 2005), along with a homework problem on decision analysis, prior to students completing the case study. The study consists of students interpreting input data provided in a spreadsheet, applying the data to a decision analysis model that is fully described herein, and conducting a limited sensitivity analysis on specified model inputs. Optionally, sensitivity analysis of different model inputs could be assigned to different students, working individually or in teams of two, followed by classroom presentation of students’ results and conclusions.

Level of Effort by Instructor

It is suggested that the instructor allocate one 50-minute class period to the introduction of decision analysis (e.g., ReVelle et al., 2003). A second class period should be spent on flood risk analysis (Ford, 1996; Mays, 2005) and government policies related to flood risk reduction and disaster recovery (see Galloway et al., 2007 and other references cited herein). The case study itself may be introduced at the end of the second class period, or in a third class period in which more information specific to the Sacramento-San Joaquin Delta is presented. An instructor who is not familiar with this topic may require an additional 4-6 hours for review and understanding of this material and related literature.

Level of Effort by Individual Student

Students should be expected to spend 2-4 hours reviewing and understanding this material, along with related literature distributed by the instructor. Students may spend an additional 2-3 hours completing the Levee Decision Analysis assignment.

Software Required

No specialized software is required. Case study data is provided in a Microsoft Excel spreadsheet, which may also be a convenient tool for computations.

Suggested Assessment Methods

The result of the first analysis suggested in the case study should be similar to that shown in Table (i). Assessment should involve written or verbal response to related evaluation-level questions. The instructor may choose to ask one or more of the following:

- Based on the results of your sensitivity analyses (±/− 20% in input parameters), which uncertainties have the greatest overall impact on optimal decisions?
• Identify one island for which the optimal decision is relatively insensitive to uncertainties in the data, and one island for which the optimal decision is particularly sensitive to data uncertainties. Can you identify any general characteristics of islands which seem to affect solution sensitivity?
• In your opinion, will human activities at the local (island), regional (state), or global level have the greatest impact on the future of the Delta? Explain, and cite at least one reference to support your opinion.
• How could the decision analysis model be extended to estimate the value of mitigating climate change (say, by reducing emissions), rather than simply adapting to it?
• What are some of the main caveats of this decision analysis? (What would you tell a decision maker who is planning to use this model to guide actual policy decisions?)

Table (i). Sample LDAM results.

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>1</td>
<td>Bacon Island</td>
<td>No</td>
<td>no</td>
<td>-$3,976,850</td>
<td>No</td>
<td>no</td>
<td>-$22,894,511</td>
</tr>
<tr>
<td>Central</td>
<td>4</td>
<td>Bouldin Island</td>
<td>No</td>
<td>yes</td>
<td>$63,420,402</td>
<td>No</td>
<td>yes</td>
<td>$39,807,517</td>
</tr>
<tr>
<td>Central</td>
<td>16</td>
<td>Empire Tract</td>
<td>No</td>
<td>no</td>
<td>-$2,344,364</td>
<td>No</td>
<td>maybe</td>
<td>-$6,561,594</td>
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<tr>
<td>Central</td>
<td>31</td>
<td>Mandeville Island</td>
<td>No</td>
<td>no</td>
<td>-$1,375,500</td>
<td>No</td>
<td>no</td>
<td>-$3,418,183</td>
</tr>
<tr>
<td>Central</td>
<td>33</td>
<td>McDonald Tract</td>
<td>No</td>
<td>no</td>
<td>-$7,195,452</td>
<td>No</td>
<td>maybe</td>
<td>-$24,527,166</td>
</tr>
</tbody>
</table>
Case Study

Introduction

The Sacramento-San Joaquin Delta currently is defined by its 1100 miles of levees \(^4\) (Figure 1). 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, principally to support agriculture and waterfowl habitat. By the mid- and late 20th century, these same levees became integral to local, state and federal efforts to export water from the Delta. By restricting the volume of the tides moving in and out of the Delta, the narrow leveed channels, along with managed inflows, outflows, and exports, keep most salts from the Delta’s core.

Four processes are acting on the Delta’s levees to fundamentally change the levee system. Land subsidence, changing inflows, sea level rise, and earthquakes are acting or will act separately and together to shift the Delta from a system of narrow, leveed channels surrounding deeply subsided islands, to a system with large bodies of open water. This transition will occur mainly through levee failures.

Delta levees fail in many ways. The levees are prone to overtopping and erosion during storms, principally when high winds create large waves at high tides. Levees also fail due to seepage. The elevation difference between the water surface in the channel and the floor of the subsided island causes water to flow both through and under the levee. Seepage is common for most levees and does not normally lead to failure. However, when water pressure gradients are great, seepage can erode material within and under the levee, causing sand boils on the levee interior, eventually leading to collapse. Rodents, particularly beavers, can exacerbate this problem. Poor foundations or levee construction materials can lead to slumping, cracking or sagging of levees that allows water to flow through and over the levee, leading to its failure. And finally, levees can fail during earthquakes as shaking causes either the foundation or embankments to lose cohesion, deform, or collapse.

The levee failure mechanisms described above have one thing in common: the forces that cause these failures are all increasing or will worsen in the future. This stems from both the natural degradation of levees with time and the progressive changes in physical forces acting on them, as summarized in Table 1. For this reason, it is prudent to assume that, without intervention, levee failures will increase in the future.

In this case study, students will gain an understanding of the risk of levee failures and economic costs of maintaining levees in the Delta and perform a simplified decision analysis for economically optimizing levee repairs and upgrades. The analysis will focus on a subset of 34 major subsided Delta islands that make up most of the Delta’s Primary Zone. A spreadsheet including source data, equations and calculations for the Levee Decision Analysis Model (LDAM) presented here is provided as an accompaniment to this text.

\(^4\) Delta levees are not levees, \textit{per se}. Outside of the Delta, a typical levee holds back water only during floods. A Delta levee is actually a dike, similar to those protecting the Dutch, with high water always against them. However, since dikes in the Delta are widely referred to as “levees,” we continue that convention.
Figure 1. Project (federal) and non-project (local) levees of the Delta, 2006.
Table 1. Summary of forces causing levee failures.

<table>
<thead>
<tr>
<th>Force</th>
<th>Historical Cause(s)</th>
<th>Current State and Future Projections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land subsidence</td>
<td>Caused principally by oxidation of the Delta’s organic-rich peat soils from draining the soils for farming, although soil erosion and compaction also have occurred (Deverel, 2007).</td>
<td>Average elevations of islands commonly 15 feet or more below sea level, with localized island elevations more than 25 feet below sea level. Projected to continue at current rate if land use remains the same (Mount and Twiss, 2005).</td>
</tr>
<tr>
<td>Changing inflows</td>
<td>Seasonal inflows to the Delta, particularly during winter floods, show considerable variability (Knowles, 2002). Flows are now confined to a narrow network of channels, rather than being spread over a broad tidal marsh.</td>
<td>By confining flows, the levee network increases water surface elevations and hydraulic gradients within the levees. Warming climate will shift runoff events toward the winter, with an earlier spring, and potentially higher intensity of winter floods (Stewart et al. 2005; Barnett et al. 2008).</td>
</tr>
<tr>
<td>Sea level rise</td>
<td>Over decades or more, sea level rise is due to increases in ocean mass (due to contraction of continental glaciers and ice sheets) and volume (due to thermal expansion). At the annual to decadal scale, sea level responds to long-term lunar cycles and warming or cooling due to Pacific climate disturbances, such as El Niño (Church and White, 2006).</td>
<td>Sea level rise has affected the Delta over the last century, with a sea level change of nearly +20 cm from 1900 to 2000. (Rahmstorf, 2007). Projections in sea level rise by 2100 range from 20-40 cm (IPCC, 2007) to roughly 70-100 cm (Rahmstorf, 2007), with approximately one-third of that rise occurring by 2050.</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>The Delta lies within a region known worldwide for its high risk of earthquakes. Historically, Delta levees have been damaged by earthquakes (Finch, 1985). However, since the 1906 San Francisco earthquake, there has not been an earthquake of sufficiently large magnitude to test the levee system.</td>
<td>Ground accelerations from earthquakes with 20- to 100-year recurrence intervals (annual probability of occurrence of 1-5%) may be sufficient to cause multi-island flooding (Torres et al. 2000, J.R. Benjamin &amp; Assoc. 2007). The probability of a major earthquake in the region increases with time as stress builds on Bay Area fault systems.</td>
</tr>
</tbody>
</table>

**Certain Future, Uncertain Timing**

The failure of Delta levees in the future is 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 are increasing.
To illustrate the magnitude of this problem, consider the level of risk for today’s conditions, irrespective of worsening future conditions. Using data from the draft Delta Risk Management Strategy Phase 1 report (Benjamin and Associates, 2007), we calculated the annual probability of island failure from either hydrologic events or earthquakes for 35 islands of the Delta that have subsided below mean sea level (based on analysis in Mount and Twiss, 2005). Then, using this information we calculated the probability that any given island will fail over a given period of time. For example, an island with an annual probability of failure of 1 percent has a probability of 40 percent that it will fail sometime in the next 50 years and 64 percent that it will fail sometime in the next 100 years.

In Figure 2, we present the range of failure probabilities for 36 islands (including the two urbanized islands) over the next 100 years. Based on current flood and seismic risk factors summarized in Table 1, the median probability of failure for a Delta island is 95% between now and 2050 and 99% by 2100. This risk of failure over extended periods is especially high for the western islands of the Delta, where each island has a roughly 99% probability of at least one failure by 2050.

![Figure 2. Probability of flooding from either earthquakes or floods with length of exposure for 36 significant Delta islands. Source: Author calculations, using data reported in “Draft DRMS Phase 1 Risk Analysis” (J.R. Benjamin and Associates, 2007). (For annual failure probabilities for individual islands see accompanying spreadsheet.)](image)

These estimates are based solely on current likelihoods of failure. But as discussed above, the probabilities of island failures will increase in the future 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 both increase the
risk 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 much of the Delta landscape toward extensive bodies of open water.

**Policy Issues and Challenges**

State and federal policy and funding for improving, repairing, restoring or abandoning levees will play a key role in determining future Delta landscapes. Approximately two-thirds of the 1100 miles 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 of the levees in this latter category are maintained by local reclamation districts with oversight and inspection from the state. Following significant floods in the Delta in 1986, the state was compelled by the federal government to 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.” Levees meeting PL 84-99 standards qualify for federal aid following damage due to flooding.

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. All project levees are assumed to meet PL 84-99 standards. Both HMP and PL 84-99 standards are tied to the 100-year flood water surface elevation as calculated following the 1986 floods. The hydrology used to set these standards has not been updated since. Given the number of large inflow events in the Delta during the past 20 years, updated calculations will undoubtedly produce a higher 100-year flood elevation than the figures used at present. However, completing and adopting this new hydrology as a benchmark would require setting new elevation standards for the Delta. This, in turn, could result in a requirement that all levees be raised to higher standards – a very costly undertaking.

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:

1. **Distribution of Available Resources.** In 2006, the voters of California 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 1100 miles of Delta levees and the 1700 miles 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, typically $6 million per year, to help
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.

(2) 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 just 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, investments 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 is appropriate for the state to adopt a policy of not restoring all islands that fail and to prioritize repairs.

(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). 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 together. Inevitably, this issue will be addressed with elements of the two policy challenges described above: selective investments in levee upgrades and repair of islands that flood.

Decision Analysis Framework and Methodology

To address the three policy issues concerning future levee investments and repairs, we developed the Levee Decision Analysis Model (LDAM). This model supports an economic comparison of three strategic options for levee management:

(1) No Upgrades
(2) Upgrades to PL 84-99 standards
(3) Upgrades to PL 84-99 standards plus 1 foot to mitigate for expected sea level rise by mid-century (denoted Upgrade PL 84-99 + 1ft SLR)

For each island, each of these strategic policies regarding whether and how to upgrade comes with an accompanying decision of whether or not to repair that island when its levees fail, leading to a total of six policy options (Table 2). We exclude heavily urbanized islands from the decision analysis, since 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. We also assume, based on discussions with many state, federal, and private engineers, that upgrades to the PL84-99 standards improve levee performance by an average of approximately 10 percent for failures from levee overtopping, through-seepage and under-seepage. These upgrades, which occur principally on the surface of the levee, do little to improve levee foundations and the risk of failure due to earthquakes.
LDAM builds on extensive previous work formalizing assessments of costs, damages, and probabilities of failure, and incorporating probability into economic cost calculations for optimal flood protection design (e.g., Van Dantzig, 1956; USACE, 1996; Voortman, et al., 2002). Decision analysis is a logical method to guide benefit-cost comparisons of available decision options when there is uncertainty about their outcomes (Lund 2007). The framework for the sequence of decisions necessary to optimize levee investments is presented in Figure 2 as a decision tree. In this decision tree, decision points among options (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-hand side of the tree and are used to assess the expected costs of the decision options. In this way, a decision analysis facilitates the logical structuring and comparison of alternatives under uncertainty.

![Decision Tree](image)

**Figure 2. Island levee decision analysis tree for assessing whether to upgrade levees and to restore islands following flooding. (Mathematical expressions of outcomes are described below.)**

Decision analyses are calculated working backwards. Values are estimated for choices occurring furthest into the future for each 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.
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 one foot 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 chance node 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.

### Table 2. Levee Decision Analysis Model (LDAM) Policy Options

<table>
<thead>
<tr>
<th>Option Number</th>
<th>Current Upgrade Policy</th>
<th>Future Repair Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Upgrade</td>
<td>Repair</td>
</tr>
<tr>
<td>2</td>
<td>No Upgrade</td>
<td>No Repair</td>
</tr>
<tr>
<td>3</td>
<td>PL 84-99</td>
<td>Repair</td>
</tr>
<tr>
<td>4</td>
<td>PL 84-99</td>
<td>No Repair</td>
</tr>
<tr>
<td>5</td>
<td>PL 84-99 + 1ft SLR</td>
<td>Repair</td>
</tr>
<tr>
<td>6</td>
<td>PL 84-99 + 1ft SLR</td>
<td>No Repair</td>
</tr>
</tbody>
</table>

### Cost Estimation

Cost estimates for each of the policy options are derived as follows. 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.

1) *Cost of Repair After Failure, No Upgrade* – Cost of repair 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, plus those same costs occurring over and over again further into the future each time the island fails. This future cost 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:

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

where \(C_{\text{Repair}}\) 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 \((C_{\text{Repair}})\) 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, and the fourth term \((B_k/r)\) is the present value of future island profits. (For the derivation of the infinite series of future repair costs, see the accompanying spreadsheet file.)
2) **Cost of Not Repairing an Island, No Upgrade** – The cost at the time of failure, assuming that no entity is willing to fund repair, 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 tides. In mathematical terms:

\[
\text{Cost}_{\text{Abandon}} = \text{Cost to Reinforce Downwind Islands} + \text{Cost of Lost Infrastructure}
\]  

The net present expected cost of upgrading surrounding islands and rebuilding infrastructure, minus the profit made from the island until the time of failure, is given by:

\[
\text{NPV Cost} = - \left( \frac{B_k}{r} \right) + \left( \text{CA}_{\text{Abandon}} \right) \left[ \frac{P_f \cdot [(1+r)/(r + P_f)]}{r} \right]
\]  

where:

- \( \text{CA}_{\text{Abandon}} \) is the present expected cost of upgrading surrounding islands and rebuilding infrastructure (roads, houses, railroads), and
- \( \left( \frac{B_k}{r} \right) - \left( \frac{B_k}{r} \right) \left[ \frac{P_f \cdot [(1+r)/(r + P_f)]}{r} \right] \) is the present expected value of the profit made on the island until time of failure.

Equation (3) is obtained by subtracting the present expected profits made before failure from the total present expected cost of abandoning the island. (The formulas expressing these present values are derived in the accompanying spreadsheet file.)

This logic is easily extended to the costs of repair or no repair for levees that have previously been upgraded.

3) **Cost of Repair After Failure, with Upgrade** – This 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:

\[
\text{NPV Cost} = \text{Upgrade Cost} - \left( \frac{B_k}{r} \right) + \left( \text{C}_{\text{Repair}} + B_k \right) \left( \frac{P_f}{r} \right)
\]  

In the case of an enhanced upgrade to mitigate for one foot of sea level rise, the upgrade cost will include the cost of that additional fortification. The only significant change in Equation (4) compared to Equation (1) is that there is no current cost of repairing the island today (because it has not yet failed), so that \( \left( \text{C}_{\text{Repair}} + B_k \right) \) only appears once and is multiplied by \( \left( \frac{P_f}{r} \right) \). The cost of current upgrades is incorporated to allow comparison of the three strategies.

4) **Cost of Not Repairing an Island, with Upgrade** – This 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:

\[
\text{NPV Cost} = \text{Upgrade Cost} - \left( \frac{B_k}{r} \right) + \left( \text{CA}_{\text{Abandon}} \right) \left[ \frac{P_f \cdot [(1+r)/(r + P_f)]}{r} \right]
\]  

which is identical to Equation (3) except for the additional upgrade cost.
With the formulas in Equations (1)-(5), probability acts to weight the relative costs of repair or no repair between the three strategic options. 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.

Additional information about costs (upgrade, repair, and abandonment costs; property values; profits), as well as failure probabilities with and without upgrades, are provided in the accompanying spreadsheet.

**LDAM Assignment**

Apply the above analysis to estimate the present value of the three upgrade strategy options for each island for which data is provided in the accompanying spreadsheet. 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.” Summarize your results in a table.

Next, conduct a limited sensitivity analysis to determine the effects of input data uncertainties on your results. Using your first set of results as a baseline:

- Failure probabilities and upgrade costs are imprecise and may have been estimated conservatively. How many additional islands should be upgraded if failure probabilities are reduced by 20%, 50%, and 80%?
- How many additional islands should be upgraded if failure probabilities are reduced by 50% and upgrade costs are reduced by 20%, 50%, and 80%?
- Because only replacement costs of lost roads and rail lines are considered in the model in the case of “no repairs,” total infrastructure replacement costs may be underestimated. What are the effects of increasing “no repair” (abandonment) costs by 20%, 50%, and 80%?
- Assume property values increase by 20%, 50%, and 80%. What are the effects on the decision of repairing or abandoning islands?

There may be additional questions posed by your instructor.
References


Intergovernmental Panel on Climate Change (IPCC), 2007, Climate Change 2007—Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Available at: [http://www.ipcc.ch/ipccreports/ar4-wg2.htm](http://www.ipcc.ch/ipccreports/ar4-wg2.htm)


