Decision Analysis of Delta Strategies
Technical Appendix J

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July 2008

Description

This document is an appendix to the Public Policy Institute of California report, *Comparing Futures for the Sacramento-San Joaquin Delta*, prepared by a team of researchers from the Center for Watershed Sciences (University of California, Davis) and the Public Policy Institute of California.

Supported with funding from Stephen D. Bechtel, Jr. and the David and Lucile Packard Foundation

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Contents

Summary

This appendix provides a simplified analysis of the four strategic decisions available for managing water exports from the Sacramento-San Joaquin Delta: (1) continue pumping exports through the Delta (the current policy), (2) divert water upstream and convey it around the Delta through a peripheral canal, (3) combine the current through-Delta pumping strategy with a peripheral canal (so-called "dual conveyance" or "dual facility"), and (4) end exports altogether. The analysis considers two main criteria for performance, consistent with the Delta Vision Blue Ribbon Task Force's two co-equal objectives for the Delta: environmental sustainability and reliable water supply. Specifically, we consider these objectives in terms of the probability of maintaining viable populations of desirable Delta fish species (the environmental goal) and the consequences of different export alternatives for statewide water-related economic costs (the water supply goal). Our focus is on outcomes for the middle of this century (e.g., 2050). This is a sufficiently long horizon to incorporate effects of natural forces acting on the Delta, such as sea level rise, and yet close enough in time to be relevant to today's decisions about major infrastructure investments.

Our purpose is to quantify the performance of the strategic Delta export alternatives within the ranges which can be technically and scientifically justified. To this end, the decision analysis incorporates major capital and operating costs and the probabilities that each alternative might fail (or work less effectively) because of inherent risks, such as poor fish species performance following adoption of a peripheral canal or extensive failures of Delta islands following a decision to continue through-Delta exports (Figure J.S1). To account for the remaining complexities and uncertainties, we employ a range of estimates for costs and probabilities of various outcomes. This formulation provides a framework which is relatively simple to understand, yet complex enough to represent a broad range of factors that could affect the relative performance of Delta export alternatives.

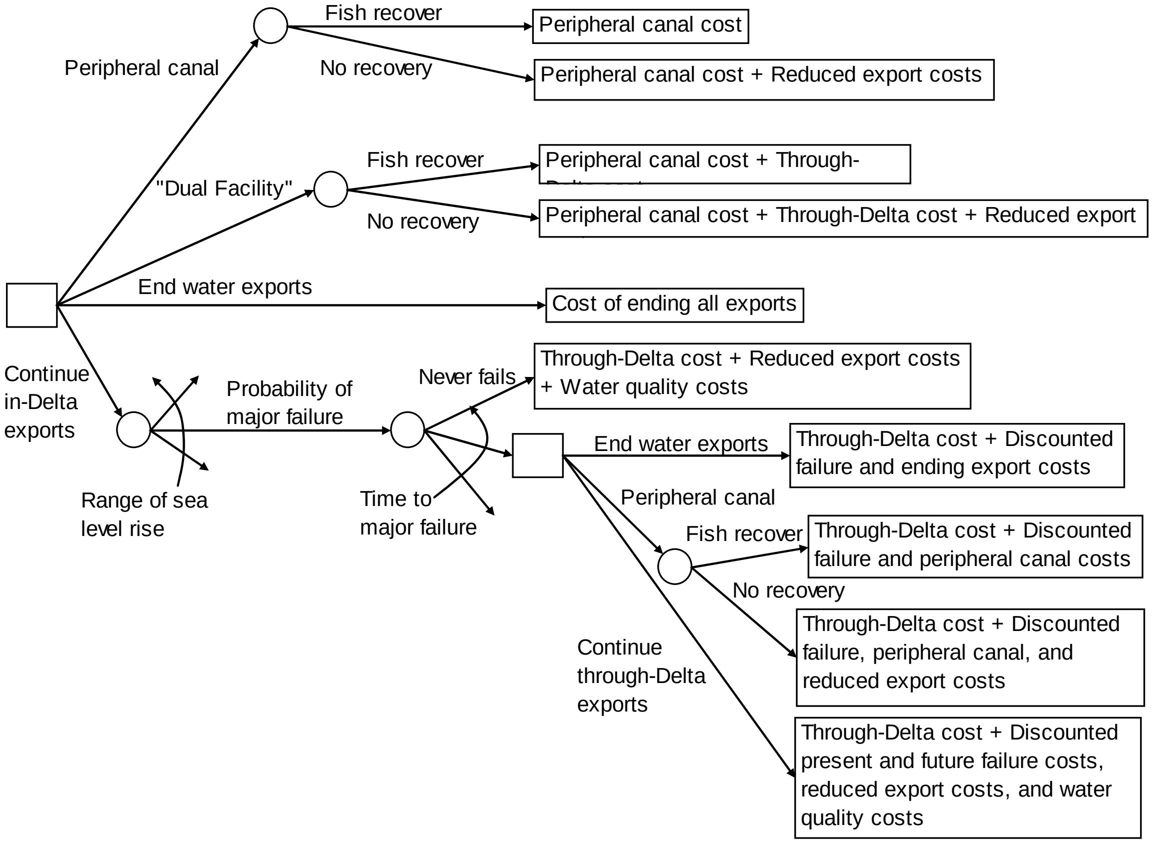


Figure J.S1 - Decision Tree for Strategic Long-Term Delta Export Decision from Statewide Economic Perspective

The performance of each alternative is estimated using answers to 16 questions, covering the cost and outcome probability estimates for various aspects of the problem. These questions and our recommended ranges of answers appear in Table J.S1. We provide technical and scientific reasoning to justify these parameter ranges, based on the work of others, new work done as part of this effort, and our own professional judgment. These answers are entered into a spreadsheet which performs economic and probability calculations to generate overall estimates of statewide economic costs and fish population viability for each alternative in 2050 (Table J.S2, Figures J.S2 and J.S3).

Table J.S1 - Ranges of Costs and Outcomes Recommended by the Authors

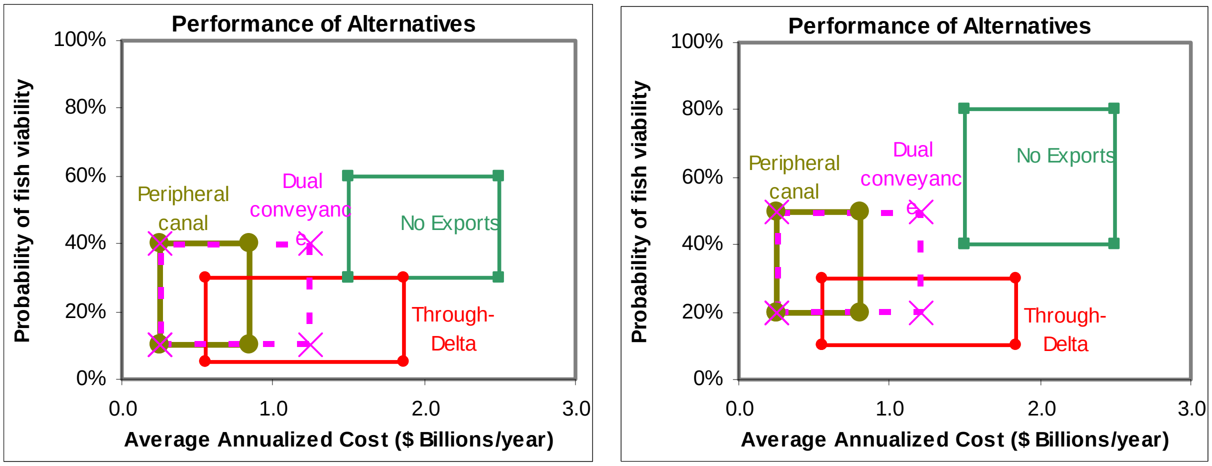
Question	Low Value	High Value
Sea level rise (ft)		
1) How much will sea level rise by 2050?	0.5	1.5
Probability of extensive Delta failure (annual failure probability in parentheses) (%)		
2) With the minimum sea level rise?	34 (1)	88 (5)
3) With the maximum sea level rise?	57 (2)	95 (7)
Population viability in 2050 for delta smelt (Chinook salmon in parentheses) (%)		
4) What is the probability of viable fish populations with continued through-Delta pumping?	5 (10)	30 (30)
5) What is the probability of viable fish populations with no Delta exports?	30 (40)	60 (80)
6) What is the probability of viable fish populations with a peripheral canal?	10 (20)	40 (50)
7) What is the probability of viable fish populations with dual conveyance?	10 (20)	40 (50)
8) By what proportion would exports be reduced for fish protection with continued through-Delta pumping?	25	40
9) If the fish continue to decline, by what proportion would peripheral canal water exports be reduced?	.25	40
Economic and financial costs ($ billion)		
10) What is the construction cost of a peripheral canal?	4.75	9.75
11) What is the additional drinking and agricultural water quality cost from using Delta water?	0.3/year	1.0/year
12) What is the annualized cost of ending Delta exports?	1.5/year	2.5/year
13) What is the annualized cost to maintain continued through-Delta pumping?	0.15/year	0.4/year
14) What is the cost to water users of a sudden extensive failure of Delta levees?	7.8	15.7
15) What is the average cost to repair an extensive Delta levee failure for water supply?	0.2	2.5
16) What exponent relates export reduction to economic cost?*	2	3

NOTES: * With a value of one, economic cost is proportional to the reduction in exports. With larger values, economic costs are less than proportional to export reductions.

Fish population viability estimates are undertaken for two key Delta species. For the delta smelt, viability is defined as achieving sufficient recovery to avoid Endangered Species Act restrictions on water exports. For fall run Chinook salmon, it is defined as maintaining adequate populations to support commercial and recreational fisheries.

Table J.S2 - Annual Costs and Fish Population Viability Under Delta Export Alternatives, 2050

Alternative	Average Cost ($ billion/year)	Likelihood of Viable Populations (%)	
		Delta Smelt Population	Fall-Run Chinook Salmon Fishery
Continuing through-Delta exports	0.55–1.86	5–30	10–30
Peripheral canal	0.25–0.85	10–40	20–50
Dual conveyance	0.25–1.25	10–40	20–50
No exports	1.50–2.50	30–60	40–80



(a) Delta smelt (b) Fall-run Chinook salmon fishery

Figure J.S2 - Range of Costs and Fish Population Viability for Delta Export Alternatives, 2050

Several conclusions seem well-supported for a reasonable range of estimates of costs and risks:

1. Ending Delta exports almost certainly has both the highest costs and the highest probability of supporting viable populations of desirable fishes.

2. Continuing through-Delta exports probably has the lowest potential for maintaining viable populations of desirable fish, and has potentially high costs and risks. The driving factors in the high costs are water quality costs (which are experienced every year), through -Delta capital and operating costs, and the costs of catastrophic levee failures and additional investments following such a failure.

3. We anticipate little difference in the environmental performance of dual conveyance and a peripheral canal. However, costs have the potential to be substantially greater

for a dual conveyance strategy if this alternative results in significant investments to improve through-Delta pumping in tandem with construction of a canal. Differences in costs and performance would be largely determined by the details of their implementation.

4. Both dual conveyance and a peripheral canal are likely to be superior to continuing through-Delta pumping for meeting the two co-equal goals of environmental sustainability and water supply. The chances of these superior outcomes are on the order of at least 60 to 70 percent from both statewide economic and fish viability perspectives (Table J.S3).

5. Some statewide economic savings from dual conveyance or a peripheral canal might be used to support investments in habitat and resource management, thereby bringing the viability of desirable fish populations closer to (and perhaps even exceeding) their prospects under the "no export" alternative. From several hundred million to over a billion dollars per year of economic savings should be available for such purposes, relative to the next best alternative. Financial savings are particularly likely if a peripheral canal or a low-cost dual conveyance strategy is selected. Some of the key savings result from water quality benefits of diverting water upstream of the Delta, which reduces urban water treatment costs and improves the profitability of southern Central Valley agriculture.

Table J.S3 - Probabilities That Each Export Alternative is Superior to Others, With Delta Smelt Viability as the Environmental Objective (%)

Alternatives	Delta Smelt	Statewide Cost	Both Objectives
Through-Delta better than peripheral canal	27	6	1
Through-Delta better than dual conveyance	27	19	5
Through-Delta better than no exports	0	95	0
Peripheral canal better than no exports	6	100	6
Peripheral canal better than through-Delta	73	94	69
Dual conveyance better than no exports	6	100	6
Dual conveyance better than through-Delta	73	81	60
No Exports better than peripheral canal	94	0	0
No Exports better than through-Delta	100	5	5

6. The selection of a long-term approach for managing water exports will not eliminate controversies regarding the Delta or water management in California. However, selection of a peripheral canal or dual conveyance approach could considerably reduce economic costs to California while improving the viability of Delta and related fisheries. Many implementation details remain to be made after a strategic policy has been established. As discussed in Appendix G, many implementation decisions can only be made after new facilities are in place.

Acknowledgments

We thank Steve Kasower of the University of California, Santa Cruz, for posing the initial question which led to this analysis, “Would the exporters still favor a peripheral canal if they understood that its failure to restore the fish would reduce exports through such a canal?” This question on a chance meeting on an airplane from Denver to Sacramento led to this decision analysis of the larger questions of the Delta addressed here.

We also thank the many people we have talked with recently and over the years who have provided us with ideas and materials to help develop the understanding of the problem presented here. Many of those who helped most directly are listed in the acknowledgements to the main report. We thank Andrew Draper, Armin Munévar, and Stacy Tanaka for helpful reviews of an earlier draft. We alone are responsible for any remaining errors. Research publications reflect the views of the authors and do not necessarily reflect the views of the staff, officers, or Board of Directors of the Public Policy Institute of California.

Introduction

This appendix develops a decision analysis to examine long-term strategic water export management alternatives from the Delta. The strategic options examined include: (1) continue pumping exports through the Delta (the current policy), (2) divert water upstream and convey it around the Delta through a peripheral canal, (3) combine the current through-Delta pumping strategy with a peripheral canal (so-called "dual conveyance" or "dual facility"), and (4) end exports altogether. The analysis considers two main criteria for performance, consistent with the Delta Vision Blue Ribbon Task Force's two co-equal objectives for the Delta: ecosystem revitalization and adequate water supply (Isenberg et al., 2008).[1] Here, ecosystem revitalization is measured by the yardstick of viability of desirable Delta fish populations and water supply adequacy by the yardstick of economic costs of water supply and quality.[2] Our focus is on outcomes for the middle of this century (e.g., 2050). This is a sufficiently long horizon to incorporate effects of natural forces acting on the Delta, such as sea level rise, and yet close enough in time to be relevant to today's decisions about major infrastructure investments.

We begin with a description of the basic methods involved in decision analysis, using as an illustration the decision to purchase a car. We then discuss how a decision analytical framework could be applied to the choice of export management alternatives for the Delta. The remainder of the appendix presents a simplified decision analysis for this problem. The underlying calculations are available in an accompanying MS-Excel spreadsheet, which users can modify to explore the implications of different assumptions about costs, ecosystem responses, and the impacts of climate change.

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[1] It is worth noting that the term "ecosystem health" should be used advisedly for the Delta. As discussed in Appendix D and elsewhere, the Delta is changing constantly and a "healthy" Delta is very much in the eye of the beholder. Here, we interpret the term to refer to a Delta that supports populations of desirable species, especially those listed under the federal and state Endangered Species Acts.

[2] "Desirable" fish species are fish that are important for making decisions about ecosystem function. They have at least two of the following attributes: They (a) are listed as threatened or endangered, or proposed for listing, under state or federal Endangered Species Acts; (b) support an important sport or commercial fishery; (c) are endemic or native; and (d) depend on the estuary to complete their life cycle, either by living there or migrating through it. (See Appendix D and chapter 5 in the main report.)

1. An Introduction to Decision Analysis

Decision analysis is a method of formalizing the evaluation and comparison of decision options when faced with uncertainty and multiple objectives. Although some aspects of this approach date to the early 1800s, decision analysis as practiced today was largely an outgrowth of the development of operations research during World War II. Today, decision analysis methods are taught widely in business and engineering schools and commonly taught in economics and political science (De Neufville 1990; ReVelle et al. 1997; Lund 2007). These methods are widely employed for business and engineering problem-solving.

The fundamental framework of decision analysis is the structuring of the decision problem as a "decision tree" (Figure J.1). A decision tree is a logical representation of the sequence of decisions to be made, along with the uncertainties in outcomes arising after each decision and the outcomes of a chain of decisions and uncertainties. In decision trees, the first decisions are on the left-hand side, with later decisions and outcomes to the right. Decision points are represented by boxes, representing choices among options. Chance events are represented by circles, representing possible outcomes and their probabilities or likelihood. Overall outcome values for each chain of decisions and uncertainties are given on the extreme right side of the tree. These outcome values are used to assess the expected costs of the first decision options, taking into account the likelihood of different outcomes. In this way, a decision analysis facilitates the logical comparison of alternatives under uncertainty.

The decision problem of purchasing a car is represented in Figure J.1. The initial decision options are to buy a new car, buy a used car, or lease a car. The uncertainty in this case is the risk of breakdown and resulting repair costs. Each initial option has a different probability of breaking down. The leased car is assumed to be perfectly reliable (because it would be replaced free of charge if it broke down), and the new car has a relatively low probability of breaking down. The used car has a higher probability of breaking down, given its age. If the used car breaks down, the consumer will want to consider additional options besides spending money on repairs, including purchasing a new car or leasing. This explicit way of representing the decisions and how they are related to uncertainties and potential subsequent decisions allows us to represent the logic of the problem, as well as the variety of decision options, uncertainties, and costs.

Typically, each decision is evaluated by its expected cost, which is the average of costs for different outcomes, weighted by their probability of occurring. This is usually the optimal way to summarize uncertain costs as long as they are not catastrophic relative to the decision-maker's wealth (Arrow and Lind 1970).[3] The cost of the initial decision to buy a new car would

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[3] Arrow and Lind (1970) examined this problem for federal government spending, where even risks of a few billion dollars are small compared with annual budgets on the order of trillions of dollars. In the presence of potentially catastrophic risk – which could wipe out the assets of the decision-making entity – it can make sense to more heavily weight high cost events, and to make decisions which provide an element of insurance against such events. Although some of the outcomes examined for the Delta would entail high costs, of multiple billions of dollars, these are not catastrophic in relation to the size of the California economy. Accordingly, this average expected cost approach is appropriate for a decision analysis of Delta water management alternatives.

be the sum of: (a) the cost of the new car times the probability of it not breaking down, plus (b) the cost of the new car plus repair costs times the probability of the car breaking down. This is equivalent to the cost of the new car plus the probability of breakdown times the cost of repairs.

The used car decision is more difficult to evaluate, as it involves an additional set of options if the car breaks down. These second tier decisions are sometimes known as "recourse" options. If the car breaks down, the consumer is assumed to select the least expensive recourse option and to use this cost to calculate the expected cost of the initial decision to purchase a used car. The final comparison the consumer makes is between the certain costs of leasing and the expected costs of a new car and a used car (both of which are subject to repair cost uncertainties). To make fair comparisons, the values need to be expressed in equivalent units, e.g. annualized costs.

For this example we have simplified the problem by omitting the option of purchasing a second used car, in effect assuming that the cost of a replacement used car exceeds the cost of repairing the existing car. All decision analysis involves some simplifying assumptions. However, reasonable simplifications usually do not affect the ordering of decisions. Often ranges of decision costs and outcome probabilities are used to help eliminate inferior decisions, to identify the range of conditions over which each decision would be preferred, and to help identify decisions which are more likely to be optimal.

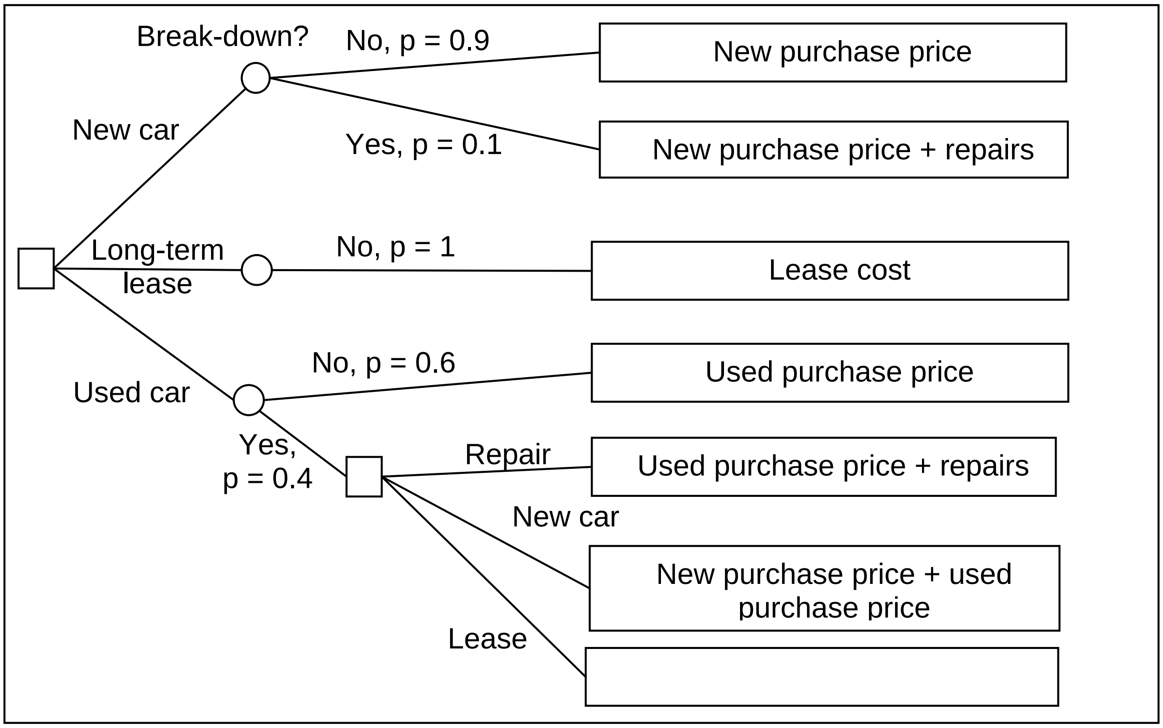

Figure J.1 - Decision Tree for Purchasing a Car

The estimation of costs can differ, depending on who is paying. For example the costs in the car decision differ from the perspective of each spouse and the kids. The purchasing spouse might see the costs of breakdown differently from the driving spouse who waits for the tow-truck and is delayed for an appointment. The driving kids might pay no purchase price at all, and not evaluate the car in terms of its financial costs, caring only for sportiness or ease of driving. So each member of the family could conceivably recommend a different car purchase option, with a policy decision being required ultimately.

The purpose of decision analysis is to structure and summarize the major aspects of a decision so that options can be evaluated systematically. Although the outcome of a decision analysis is not perfect, it is explicitly reasoned, replicable, and can be subjected to further scrutiny or elaboration. In this way, decision analysis provides a logical framework for discussing and resolving many aspects of a problem.

2. Decision Analysis Views of Delta Water Export Strategies

California faces difficult short and long-term decisions regarding the Delta and water management more generally, involving literally millions of decision options throughout a complex system. Detailed analysis of the full set of options and their associated uncertainties could not be accomplished within any reasonable time frame (and would be difficult to understand). However, it is possible to select some major decisions and to employ ranges of values for costs and uncertainties to represent how they are likely to perform.

Here, we look at the long-term strategic decision to a) continue within the current option of through-Delta pumping, b) divert water exports upstream of the Delta (peripheral canal), c) employ a combination of these two alternatives ("dual conveyance"), or d) cease exporting altogether. This decision tree appears in Figure J.2. Key uncertainties that are incorporated into the tree include the likelihood of recovery of desirable fish species, the range of future sea level rise, and associated probabilities of extensive Delta levee failure, all of which could affect levels of water exports.

Although this tree could be made much more elaborate, this simplified approach seems more insightful for the current policy discussions and decisions. The accompanying MS-Excel spreadsheet employs this representation and explores economic and fish viability outcomes for a range of assumptions about costs and probabilities.

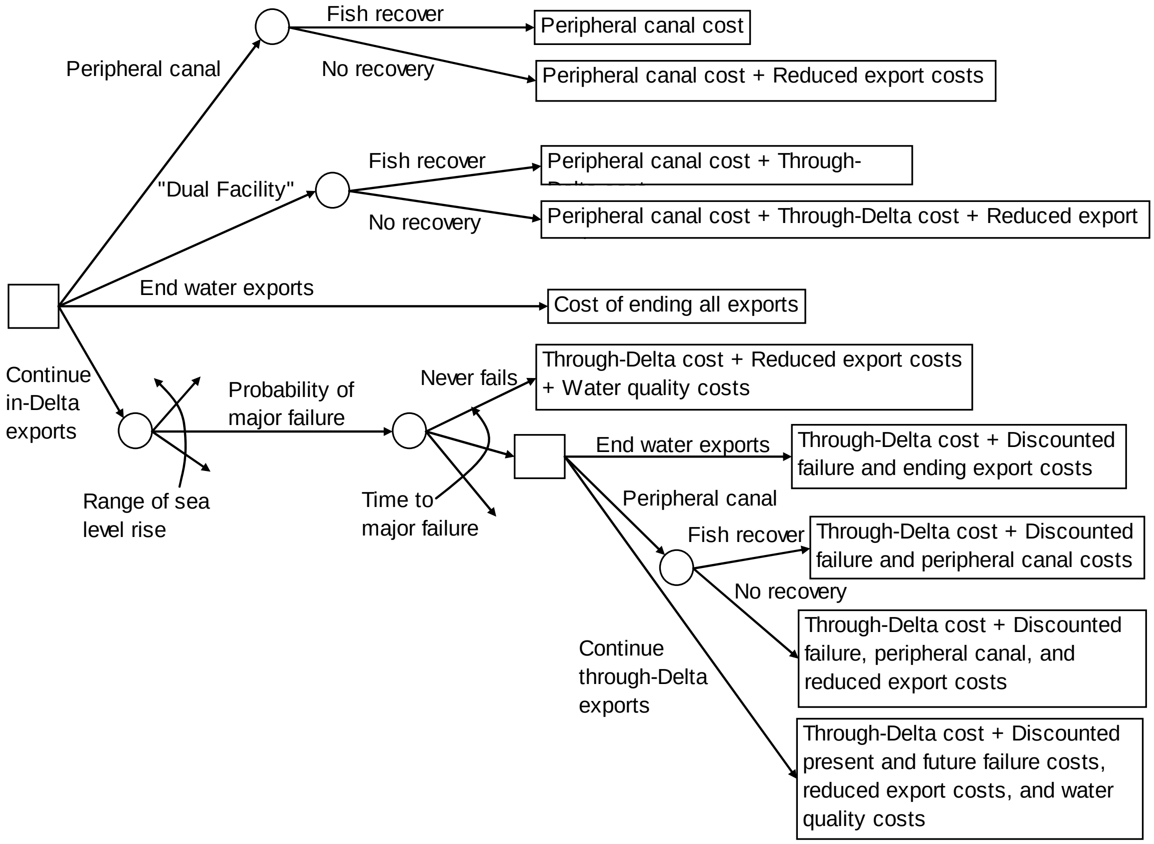

Figure J.2 - Decision Tree for Strategic Long-Term Delta Export Decision from Statewide Economic Perspective

This tree permits an evaluation of the costs of different alternatives from the perspective of water supply and quality, given the constraints of maintaining viable fish populations. The simplest decision to evaluate is the option of ending Delta exports. This would entail a significant cost on users of water exports, although it would presumably also avoid some treatment costs for water from the Delta (included in the through-Delta export option).

For the peripheral canal, costs are evaluated under two scenarios. In the best case scenario, the fish recover and net costs include only costs for constructing and operating the canal. However, if fish populations do not improve sufficiently, canal exports would likely be reduced, resulting in additional costs for alternative sources or water shortages.

Continuing to export water through the Delta is the most complex decision option. Here, the long-term probability of extensive Delta levee failure due to a major flood or earthquake, which could disrupt or end through-Delta pumping, is allowed to vary with the level of sea level rise. If the Delta levee system does not collapse, there are costs for normal operations (notably, substantial investments to maintain levees), additional costs for drinking water treatment (compared with treating Sacramento river water), losses from decreased crop yields south of the Delta due to poor water quality, and costs for reductions in exports to reduce the harm of through-Delta pumping to the fish, as illustrated by the recent decision by Judge Wanger to reduce exports to favor delta smelt.

If there is an extensive failure of Delta levees, there are three recourse decision options: (i) ending Delta exports for good, (ii) constructing a peripheral canal, or (iii) repairing the damages and continuing to export water through the Delta. These recourse decisions involve the same costs and uncertainties as if they were undertaken originally, in addition to the costs arising from the initial decision. An extensive failure of levees in the Delta is also assumed to entail significant transition costs, with substantial shortages until water users are able to put in place supply alternatives or restore through-Delta pumping ("failure costs" in Figure J.2). These failure costs and costs incurred thereafter are discounted to reflect the likely time between the present and the time of extensive failure.

Figure J.3 presents a different view of the costs of these decisions, from the perspective of ecosystem objectives. Although one might include other criteria, here we have limited representation to the probability of maintaining viable populations of desirable fish species. Because this probability is likely to vary across fish species, we conduct such analysis separately for anadromous and resident Delta species, using Chinook salmon and delta smelt as examples for each group. For this exercise, we drew on direct evaluations of fish viability (Appendices D and E). However, a more formal analysis as outlined by Figure J.3 should be useful for evaluating and designing many aspects of fish recovery programs.

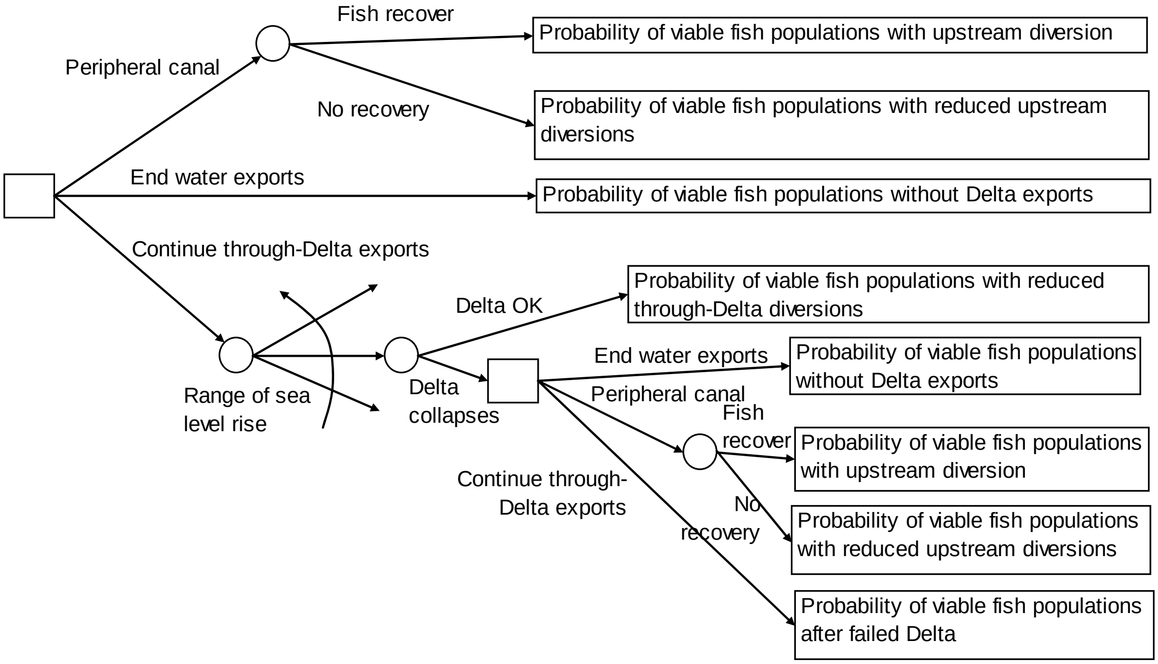

Figure J.3 - Strategic Delta export decisions from the perspective of fish population viability

Many other decision analysis perspectives are possible, and will be relevant for different stakeholders. Southern California urban water users have somewhat different views of the costs of these decisions (and might have additional public health concerns regarding water quality). For some Bay Area water users, which rely nearly 100 percent on Delta supplies, the water supply and quality costs of Delta decisions are likely to weigh more heavily than for other urban export users. Farmers in the southern Central Valley, relying to varying degrees on Delta exports and with varying capacities to store and trade water, will have different perspectives still. Various Delta farmers will have different perspectives on long-term management of Delta water exports, depending on their effects on the quality of water for agricultural uses and the commitment of others to maintain agricultural levees and islands in the Delta. Figure J.4 illustrates a simplified perspective of farmers in the southern Delta, for whom San Joaquin River salinity becomes a greater concern under any alternative except the status quo without Delta failure (Appendix C). For urban and agricultural water users north of the Delta, a key issue will be how the different alternatives affect the regulatory environment for upstream diversions. In particular, export cutbacks are likely to limit the degree of water marketing opportunities between the north and south (Appendix F).

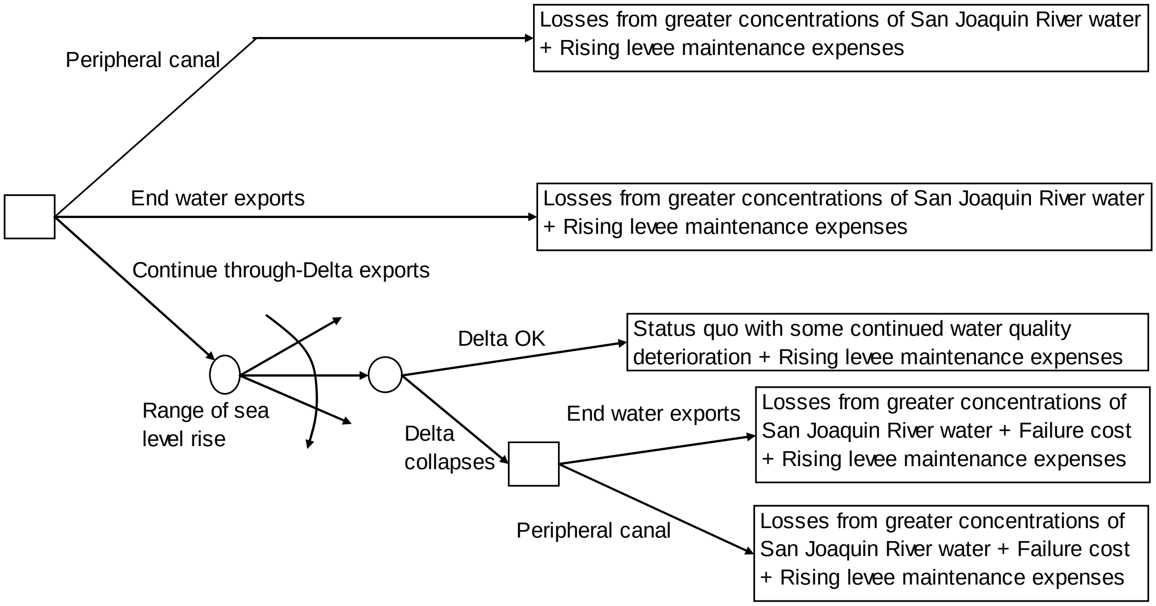

Figure J.4 - Strategic Delta export decisions from the perspective of farmers in the southern Delta

3. Calculating a Decision Analysis: Guide to the Spreadsheet

The accompanying MS-Excel spreadsheet examines the strategic decision options outlined in Figure J.2. This section provides an overview of the spreadsheets in the workbook and reviews some of the major assumptions made.

Spreadsheet Guide

The basic inputs to the analysis are the answers to sixteen questions, each of which has a range of high and low answers. These answers are entered into the spreadsheet, which performs economic and probability calculations to generate overall estimates of statewide economic costs and fish population viability for each alternative in 2050.

The spreadsheet file includes eight worksheets:

- The "Inputs" sheet contains the 16 questions with our best estimates of answers for the case with delta smelt viability as the environmental objective (the "inputs") and a figure summarizing the results. These answers can be modified by the user, to generate different results.

- The "Results" sheet summarizes the economic and fishery performance for each alternative (based on the answers in the "Inputs" sheet), in tabular and graphical form.

- The "Intermediate Calculations" sheet contains more involved calculations regarding how reductions in exports affect the economic losses to regions using water exports if the peripheral canal fails to achieve fish viability and if through-Delta pumping is reduced. It also calculates the expected cost of the decision to continue exclusively with through-Delta exports.

- The "Performance Plot Calculations" sheet contains some simple calculations and plotting information for the economic and fishery results (the basic results of which are reproduced in the "Results" worksheet). It also contains some calculations to estimate the probability of each alternative being superior to the other alternatives with respect to fish and statewide economic objectives, separately and together.

- Two worksheets of input data sets, "Delta Smelt Inputs" and "Salmon Inputs" present our best estimates of answers to the 16 questions in the "Inputs" sheet. These worksheets are included for reference purposes, and can be pasted into the "Inputs" sheet to obtain the results reported here. We describe the basis for our estimates below.

- "Variable List" - a list of variable names, for those interested in delving into the calculations.

- "State Economics Decision Tree" - the decision tree diagram for the economic objective, the framework for the economic calculations (reproduced here as Figure J.2).

The "Inputs" worksheet allows users to modify the answers to the 16 questions, and the spreadsheet automatically recalculates the economic and environmental performance indicators for the new inputs. (As an aid, the worksheet also includes a box on the upper-right corner to convert present value costs to annualized costs.)

If you have reason to change any of our suggested ranges, please go ahead and do so, to see for yourself how they would alter the expected economic and fish performance of each alternative. You might wish to explore the problem by varying the ranges of costs and probabilities. Would more precise (or different) information on selected questions make the decision easier or harder? How much additional cost or change in fish population viability would be required to change the ordering of these strategic alternatives? Below we provide some indication of the impact of changes in the range of answers, as part of the sensitivity analysis.

Some Major Assumptions

In addition to the actual numbers provided as answers to the 16 questions, the analysis has underlying assumptions on four key issues: (i) the relationship between water exports and economic costs, (ii) the range of failure events, (iii) the cost of continuing through-Delta exports (a function of the relationship between sea level rise, earthquakes, and the probability of catastrophic failure of Delta levees), and (iv) costs for a dual conveyance scheme.

Relationship between water exports and economic costs

The spreadsheet assumes a fairly simple relationship between water export reductions and economic costs, relative to a baseline of a fairly full level of exports (the roughly 6 million acre-feet (af) per year levels exported until very recently). This relationship is expressed in equation 1:

$$CRX = CNoX * (XP)^n$$

where CRX is the annualized cost of reduced exports, CNoX is the annualized costs of eliminating exports entirely, XP is the proportion of water export reduction (ranging from zero to one), and n is a scaling parameter. If n equals one, a 25 percent reduction in exports costs 25 percent of the cost of ending exports altogether. This seems unlikely, given the presence of water markets, which make it possible for users with higher economic values to purchase some water from users with lower valued uses, thereby lessening the overall cost per acre-foot of export reductions. Having n less than 1 is even less likely, because it implies that export volume cuts would fall disproportionately on higher value uses. It is therefore likely that n is greater than 1. If n equals 2, a 50 percent reduction in exports translates to an economic cost one-quarter as large as the cost of ending Delta exports.

The parameter n can be adjusted (question 16) based on the expected economic costs of long-term water shortages from ending exports to areas south and west of the Delta. This relationship is illustrated in Figure J.5 below. A similar plot is made on the "Intermediate Calculations" sheet) for the high and low values of n entered by the user.

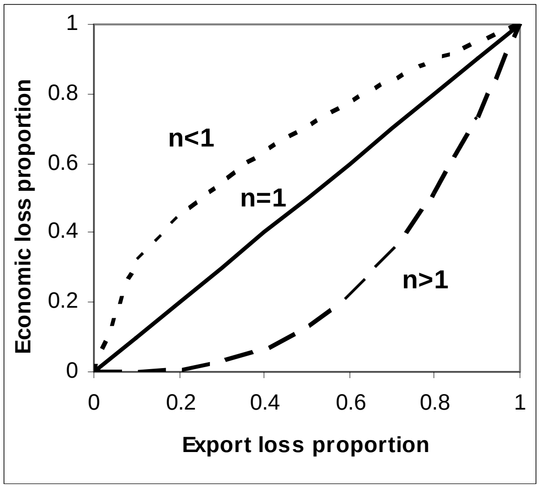

Figure J.5 - Effects of parameter n relating export economic loss to export volume loss

Range of failure events

This decision analysis is highly simplified in considering only one type of levee failure event, an extensive failure of Delta levees. In reality, there are likely to be many more, smaller failure events, each of which would impose costs and risks. Characterizing these additional smaller events or even looking at a gradation of severity for larger events would add rigor to this analysis, but would probably detract from its ability to be understood. By focusing on only sufficiently large events, we neglect these additional costs and risks, which would increase the cost of continuing through-Delta exports and dual conveyance strategies.

Costs of continuing through-Delta exports

The calculation of the expected cost of continuing through-Delta pumping is the most intricate calculation in the spreadsheet. It begins with a probability distribution of a future extensive failure of the levees that are essential for maintaining Delta exports. Using the high and low estimates of extensive failure of Delta islands due to flooding or earthquakes by the year 2050 (questions 2 and 3) as upper and lower bounds, we assume a uniform probability distribution for sea level rise (P(SLR)). In other words, each sea level rise rate between the high and low estimate is equally probable and rates outside the range are not considered. The ranges are laid out in the "Intermediate Calculations" worksheet.

For each rate of sea level rise, there is a probability of extensive Delta levee failure because of hydrostatic pressure on the levees, overtopping, seismic risk, foundation failure, and other factors. Estimates of the probability of extensive levee failure (high and low value range) with the lower and higher bounds of sea level rise are entered by the user (questions 2 and 3). The probability of extensive levee failure is then assumed to be a linear function of these high and low values for each level of risk ("Probability of Delta failure" on the "Intermediate Calculations" worksheet). This is how sea level rise enters these calculations.

The cost of recourse after extensive levee failure is the least-cost alternative of all recourse options (peripheral canal vs. no exports vs. continued through-Delta exports). These recourse costs and failure costs are discounted, with the timing of failure uncertain and a function of sea level rise. For each rate of sea level rise, with its associated extensive failure probability, the expected value of the discount factor is calculated. These expected discounted costs are then averaged across all the rates of sea level rise (failure probabilities). The total cost of continued through-Delta exports is the sum of initial and continuing costs of through-Delta exports, plus additional costs incurred at the time of extensive system failure. When extensive failure is followed by a peripheral canal or the end of exports, additional benefits for water quality and reduced exports also are included. These summed values provide the range of expected economic costs of continued through-Delta pumping. This calculation is summarized in equation 2:

$$E(TC_{in\Delta}) = C_{in\Delta} + C_{EXreduction} + C_{WQ} + \\ Min\left\{\begin{array}{l} \displaystyle\int_{SLRlow}^{SLRhigh} P(SLR)\left[\begin{array}{l}(C_{failure} - C_{WQ} - C_{EXreduction}) + \\ Min(C_{NoExports}, C_{PC} + E(C_{redEx}))\end{array}\right] DF_{sf}(P_f(SLR), r) dSLR, \\ \displaystyle\int_{SLRlow}^{SLRhigh} P(SLR)\left[(C_{failure} + C_{Repair}) DF_{isf}(P_f(SLR), r)\right] dSLR \end{array}\right\} \tag{2}$$

where, $E(TC_{in\Delta})$ is the expected total cost of continuing through-Delta exports, $C_{in\Delta}$ is the direct construction and operating cost of continuing through-Delta exports, $C_{EXreduction}$ is the cost of Delta export reduction with continued through-Delta exports, C_{WQ} is the additional cost of drinking water treatment and reduced agricultural revenues arising from lower water quality with through-Delta exports, SLR_{high} is the high estimate of sea level rise, SLR_{low} is the low estimate of sea level rise, P(SLR) is the (uniform) probability of each sea level rise rate, $P_f(SLR)$ is the annual probability of an extensive Delta levee failure with the constant sea level rise rate SLR, $C_{failure}$ is the cost of an extensive Delta levee failure event, C_{Repair} is the cost of repairing Delta levees to restore through-Delta exports after an extensive failure (a recourse option). C_{PC} is the cost of a peripheral canal (another recourse option), $C_{NoExport}$ is the cost of ending exports (a third recourse option), C_{redEx} is the economic cost of reduced Delta exports through a peripheral canal, and $E(C_{RedEx})$ is the expected cost of export reductions from a peripheral canal implemented as a recourse option.

All costs are annualized after conversion into present values. $DF_{sf}(P_f,r)$ is the expected value of the discount factor accounting for discounting the costs of events following a single failure at an uncertain time in the future, given the annual failure probability P_f and discount rate r. If exports are ended or a peripheral canal is built after a major Delta failure, these future costs and benefits are discounted based on the uncertain time of failure. $DF_{isf}(P_f,r)$ is the expected value discount factor for a series of failure and repair events into the indefinite future and is used to assess the possibility of indefinite maintenance of water exports from within the Delta. The derivations for these expected value discount factors appear in

Addendum J.1. These calculations assume that failure probabilities are constant and do not worsen with time. In practice, the likelihood of failure will probably increase as a result of external forces (e.g., earthquake risk, sea level rise, higher winter flood flows as a result of climate warming) and continued land subsidence (Appendix B).

Dual conveyance facility costs

The costs for dual conveyance can be quite varied. Theoretically, the costs for dual conveyance could be slightly lower than the cost of a pure peripheral canal alternative, if dual conveyance consists of a small peripheral canal and the existing through-Delta conveyance system. At the other end of the spectrum, the costs could be considerably higher than a peripheral canal if they include major through-Delta channel and intake modifications, perhaps approximating a second canal through the Delta. Depending on the level of resilience to earthquakes and sea level rise sought for the through-Delta component, this could amount to more than twice the cost of a peripheral canal solution.[4] In addition to differences in facilities costs, there are potential cost differences for water supply reliability and quality.

Our cost estimates for dual conveyance sum the costs of a peripheral canal and maintaining or improving the system for through-Delta pumping. They also include the minimum of the average economic losses from reduced exports from these two alternatives, because some reductions in exports are likely if fish species do not recover.[5] We make the simplifying assumption that dual conveyance generates no additional water quality costs relative to a pure peripheral canal. As discussed below, this somewhat underestimates the costs of dual conveyance, particularly with sea level rise, because the through-Delta share of exports will be of lower quality than the share that is diverted upstream of the Delta (Appendix C).\\

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[4] For example preliminary estimates for a dual facility prepared for the Bay Delta Conservation Plan range from $5.4 billion for an eastern alignment peripheral canal with $1.2 billion of additional through-Delta investments to over $17 billion for a more expensive canal along the western Delta and nearly $10 billion of upgrades to the through-Delta conveyance (Department of Water Resources, 2008).

[5] This formulation does not matter for our estimates of likely export reductions, which are identical for the through-Delta alternative and a peripheral canal, but they could make a difference with other estimates.

4. Recommended Probability, Outcome, and Cost Ranges

Table J.1 includes our recommended ranges of answers to the 16 questions posed on the "Inputs" sheet. These responses are sufficient to evaluate the strategic export alternative decision from both a statewide economic perspective and that of Delta fish populations (as presented in Figures J.2 and J.3). The answers are based on our synthesis of a wide range of information sources, including material presented in the technical appendices for this study, other published work relevant to the Delta, our conversations with numerous parties, and our own experience and professional judgment.

Table J.1 - Ranges of Costs and Outcomes Recommended by the Authors

Question	Low Value	High Value
Sea level rise (ft)		
1) How much will sea level rise by 2050?	0.5	1.5
Probability of extensive Delta failure (annual failure probability in parentheses) (%)		
2) With the minimum sea level rise?	34 (1)	88 (5)
3) With the maximum sea level rise?	57 (2)	95 (7)
Population viability in 2050 for delta smelt (Chinook salmon in parentheses) (%)		
4) What is the probability of viable fish populations with continued through-Delta pumping?	5 (10)	30 (30)
5) What is the probability of viable fish populations with no Delta exports?	30 (40)	60 (80)
6) What is the probability of viable fish populations with a peripheral canal?	10 (20)	40 (50)
7) What is the probability of viable fish populations with dual conveyance?	10 (20)	40 (50)
8) By what proportion would exports be reduced for fish protection with continued through-Delta pumping?	25	40
9) If the fish continue to decline, by what proportion would peripheral canal water exports be reduced?	.25	40
Economic and financial costs ($ billion)		
10) What is the construction cost of a peripheral canal?	4.75	9.75
11) What is the additional drinking and agricultural water quality cost from using Delta water?	0.3/year	1.0/year
12) What is the annualized cost of ending Delta exports?	1.5/year	2.5/year
13) What is the annualized cost to maintain continued through-Delta pumping?	0.15/year	0.4/year
14) What is the cost to water users of a sudden extensive failure of Delta levees?	7.8	15.7
15) What is the average cost to repair an extensive Delta levee failure for water supply?	0.2	2.5
16) What exponent relates export reduction to economic cost?*	2	3

Sea Level Rise

1. *How much will sea level rise by 2050?*

The sea has been slowly rising since the last ice age. Indeed, the Delta is a product of sea level rise over the last 12,000 years (Atwater et al., 1979; Drexler et al 2007). Warming temperatures are increasing sea level rise globally in two ways. First, a warming atmosphere causes the ocean to warm, which expands the volume required to contain a given mass of water (a process known as "thermal expansion"). Second, warmer temperatures melt continental ice sheets and glaciers, adding water to the ocean that previously has been stored in these reservoirs of ice ("ice discharge"). In California, records suggest a past rate of sea level rise of 10-20 cm (4 to 8 inches) per century, which is similar to the global estimate (Cayan et al. 2006). The rate of global sea level rise has accelerated in recent years (Bindoff et al., 2007), and projections suggest the potential for substantially greater sea level rise over this century.

According to the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC), the combined effects of thermal expansion and ice discharge could result in sea level rise in the range of 28-71 cm (11 to 28 inches) by 2100, depending on the greenhouse gas emissions scenario (Meehl et al., 2007). Another recent study suggests a larger range, with 20-40 cm (8 to 16 inches) of sea level rise by 2050 and 50-140 cm (20 to 55 inches) by 2100 (Rahmstorf, 2007). These projections themselves are uncertain and sea level rise greater than 1.2 m (4 feet) by 2100 cannot be ruled out.

Drawing on this research, the CALFED Independent Science Board has recommended that the Delta Vision effort use mid-range values for sea level rise of 8-16 inches by 2050 and 28-39 inches by 2100 for planning purposes (Mount, 2007). We use figures similar to these as our lower (0.5 ft) and higher (1.5 ft) bounds for sea level rise for 2050 (although it is the failure probability ranges associated with sea level rise, rather than direct sea level rise, which drive our calculations).

Probability of Extensive Delta Levee Failure

What is the probability of extensive levee failure in the Delta? This would be a failure extensive enough to disrupt water supply from Delta intakes, causing the kinds of damage and repair costs and recourse decision-making considered in later questions. Such failure could occur from a major earthquake or flood and would probably include several or many islands. It would create an abrupt transition to a new Delta configuration characterized by large bodies of open water.

However, not all islands are equally important to water supply (Appendix C). Flooding of islands in the northern, eastern, and southern Delta might have small effects on water supply if it occurs in a planned manner and at times of the year when river flows are high. Flooding of the western islands, close to the Bay's brackish water, would have the greatest effect. For purposes of this decision analysis, we consider extensive levee failure as a flooding of the western islands.

The probability of simultaneous or sequential permanent flooding of the islands is linked to the four factors that affect levee stability: subsidence, changing inflows, sea level rise, and earthquakes. Subsidence, inflows, and sea level rise act together to decrease levee stability. Of these, sea level rise is the most significant for the western islands (Appendix B). The other major risk factor is earthquakes. Recent reports highlight the importance of the poor foundations of western island levees and their general proximity to several earthquake faults (Mount and Twiss, 2005). The Draft Delta Risk Management Strategy (DRMS) report (URS and J.R. Benjamin and Associates, 2007) notes that the seismic risk for western islands is exceptionally high, with annual failure probabilities as high as 1-in-20 (5% per year) for each island.

The likelihood of failures depends on the interaction of: (1) sea level rise, (2) accumulations of stress on earthquake faults and the resulting location and intensity of earthquakes, and (3) the performance of levees and their foundations under these stresses. This complexity, and uncertainty, is compounded by the dearth of information about levee construction and foundations. Until the DRMS study is completed and can provide more precision on risk, it is prudent to consider a broad range of values for potential failure.

As an interim estimate, we used draft DRMS estimates of flooding due to high water or earthquakes to calculate a range of values for annual risk of flooding for 36 Delta islands (Appendix B). This range captures the highest risk islands and the lowest risk islands. We then calculated the probability of failure of these islands over time. The plot of failure probability versus length of exposure defines an envelope that captures the highest and lowest risks of failure, while still accounting for the cumulative risk associated with both failure mechanisms.

If some of the large, highly-subsided, and vulnerable islands in the interior of the Delta were preemptively converted to open water, this could reduce their potential to contribute to failure of Delta water supplies in a major earthquake. Such preemptive island failures could both lower the probability of a large disrupting event and reduce the size of a resulting "big gulp." We have assumed this is not done.

2. *With the minimum sea level rise, what is the probability of extensive Delta levee failure by 2050?*

We confined our assessment to the western five islands that appear to be most critical to maintaining water supply, both for exports and in-Delta uses. To establish a low range value, we assumed that all five islands would receive substantial upgrades to make them resist earthquakes or be more easily repaired following an earthquake. According to draft DRMS Phase 1 documents, the costs range from $3.6 to $5.2 billion for such upgrades. We assumed this construction would reduce both seismic risk and risk due to low rates of sea level rise or modest increases in inflows, creating a level of protection for all five islands (not each individual island) approximately equal to an urban standard of 1 percent annual probability of failure, or 34 percent cumulative probability of failure by 2050. This method recognizes that the western islands all have approximately equal probability of failure due to earthquakes or floods and that a single earthquake or very large flood is likely to cause a sufficient number of these islands to fail simultaneously to disrupt water supplies.

For the high range of failure with minimal sea level rise, inflows, and earthquakes, we used something less than the median level of combined annual flood and seismic failure probability outlined in Appendix B: 5 percent annual probability of failure, for a cumulative probability of failure of 88 percent by 2050. These values are well below the estimated current annual risk of failure of the western islands suggested by the DRMS study, and represent the upper bounds of an optimistic view of failure likelihood.

3. *With the maximum sea level rise, what is the probability of extensive Delta levee failure by 2050?*

Here we used the range of failure probabilities outlined in Appendix B for the entire Delta. That is, the best possible failure probability under rapid rates of sea level rise, high seismic risk and increasing inflows is approximated by the island with least current combined risk of failure from flooding and earthquakes at 2 percent per year, for a cumulative probability of failure of 57 percent by 2050. For the high end of risk, we used the current estimated combined flood and earthquake annual failure probability of the western Delta islands of approximately 7 percent per year, or a cumulative probability of failure of 95 percent by 2050 (J.R. Benjamin and Associates, 2007).

These estimates are based on *current* probabilities of failure. Even this high end number may not capture the increase in risk with time (Appendix B).

Fish Population Viability in 2050

4. *What is the probability of viable fish populations with continued through-Delta pumping?*
5. *What is the probability of viable fish populations with no Delta exports?*
6. *What is the probability of viable fish populations with a peripheral canal?*
7. *What is the probability of viable fish populations with dual conveyances?*

There is no broadly accepted method for estimating the probability that Delta fish populations will remain viable under different water management scenarios in the future, and many factors affect population viability. Nevertheless, a considerable body of scientific knowledge now exists on the role of water operations in the declines faced by the key pelagic species in the Delta – the native delta smelt and longfin smelt, and the non-native striped bass (e.g. Bennett 2006; Feyrer et al. 2007). Water operations are also recognized to affect the health of the salmon runs that migrate through the Delta on their way to and from the ocean (Moyle 2002, Kimmerer 2007). Here, we rely on expert judgment to assess the ranges of viability.

For this exercise, we estimated the probability of fish population viability for two key Delta species that have fairly different requirements. For the delta smelt, viability is defined as achieving sufficient recovery to avoid Endangered Species Act restrictions on water exports. For fall run Chinook salmon, it is defined as maintaining adequate populations to support commercial and recreational fisheries. While delta smelt can actually be driven to extinction by water management, fall run Chinook salmon (the principal run) are likely to persist in small numbers under most scenarios, but the valuable recreational and commercial fishery for them may disappear.

In addition to our team's own biologists, we sought input on these questions from a sizable group of experts on the Delta ecosystem. The results of this survey are provided in Appendix E, and they are quite consistent with our own judgments (Appendix D).

There is a general consensus of opinion among these experts that through-Delta pumping is detrimental to the populations of delta smelt and longfin smelt, and perhaps also to young-of-year striped bass. A peripheral canal could improve conditions for these fish, by limiting entrainment and other harmful consequences of through-Delta pumping, such as reverse flows on the Old and Middle rivers, which affect fish movement into unsuitable areas of the Delta. Dual conveyance, which maintains some through-Delta pumping, lies somewhere in between. By contrast, for salmon, the experts' views reflect concerns that intakes on the Sacramento River (as would occur with a peripheral canal or dual conveyance) would likely be harmful if the facilities were not operated carefully. These intakes could also harm striped bass which spawn in the river upstream of likely intake locations, by entraining larvae. Through-Delta exports also are seen as likely to harm salmon through both entrainment and confusion of downstream migrating juveniles. However, experts concur strongly that ending Delta exports would considerably improve the chances of viability for all four fish species. By contrast, they anticipate that future conditions in the Delta, with sea level rise and temperature increases, may be detrimental to all four fish species under all four export management alternatives. Their responses also suggest that the ranges of likelihood of fish viability for any alternative are often greater than differences between alternatives.

Our own rankings of fish population viability under different export alternatives largely coincide with those from the expert survey. However, an important difference concerns the likely outcomes for salmon with a peripheral canal, which we believe could be better than with continued through-Delta exports. We recognize that a peripheral canal will need to be designed and operated to minimize entrainment and other potentially negative effects. We assume that solving these problems will be part of the price of a peripheral canal solution. A major reason why a peripheral canal could improve conditions for Sacramento River salmon is that it would allow Sacramento River water to flow straight through the Delta, without diversions into the central and southern Delta. For San Joaquin salmon, ending through-Delta exports would allow salmon to avoid entrainment and high predation rates associated with the pumps. Likewise, with through-Delta pumping, juvenile salmon will most likely continue to suffer considerable mortality from being carried to less desirable places within the Delta (e.g, the central Delta) and by increasing predation by resident fishes, as their movement through the Delta is slowed or as they are brought into the vicinity of the pumping plants.

Another difference between our rankings and those from the expert survey concerns the relative performance of a pure peripheral canal and dual conveyance. Although dual conveyance is potentially a more flexible water management tool from a fish perspective, we do not believe that it will make a significant difference in the long run for either the pelagic organisms, such as delta smelt, or for anadromous fish, such as the Chinook salmon. Our main reason is that the dual facility would have to be operated at both ends on very short time scales (hours or days), based on knowledge of the presence or absence of desirable fish. While this might be possible, the history of water project operations suggests that such a rapid and flexible operation to favor fish is highly unlikely. Thus, dual conveyance may suffer from the disadvantages of both the peripheral canal and through-Delta pumping.

8. *By what proportion would exports be reduced for fish protection with continued through-Delta pumping?*

With continued through-Delta pumping, we estimate that the exports are likely to be reduced in the long term by between 25 and 40 percent. This is slightly higher than the anticipated reductions resulting from the recent federal court (Wanger) decision, which limits reverse flows on Old and Middle rivers to protect delta smelt.[6] The Department of Water Resources has estimated that this decision would result in export cuts of 22 to 30 percent in an average water year for State Water Project customers (Department of Water Resources, 2007). We anticipate that the US Fish and Wildlife Service's new biological opinion for delta smelt, due in late 2008, will maintain similar restrictions. Our estimate of higher potential cutbacks, of up to 40 percent on average, reflects the possibility of additional restrictions. In particular, longfin smelt was listed as a "candidate species" under the California Endangered Species Act in February 2008. In April 2008, Judge Wanger ruled that the biological opinion for the coordinated operations of the Central Valley Project, State Water Project, and the Operational Criteria and Plan (OCAP) is invalid for several listed anadromous fishes (winter and spring-run Chinook salmon and steelhead), likely resulting in additional remedies and restrictions on water exports.

9. *If the fish continue to decline, by what proportion would peripheral canal water exports be reduced?*

We assume that initially, a peripheral canal would be able to operate without the types of reductions currently being imposed on through-Delta exports, because the canal avoids the problems of entrainment of delta smelt and longfin smelt at the southern Delta pumps. However, if desirable fish species continue to decline despite this change in intakes, water exports from a canal are likely to be reduced. We estimate that these reductions would be similar to the 25 to 40 percent cutbacks currently imposed on through-Delta pumping.

This estimate is based on several factors. First, delta smelt, longfin smelt, and Chinook salmon all depend on freshwater inflow to the Estuary for rearing and (for the smelt) spawning during the late winter and spring (as reflected in water quality regulations to maintain the salinity gradient, X2, at the mouth of the Delta from February through June). Second, the period of highest vulnerability (February through June) is also when outflows are likely to be highest, with the most water available for upstream diversions. Third, more freshwater flows and reduced pumping also may be needed in the fall to provide habitat for delta smelt in upper Suisun Bay and the Delta. Thus, if the fish do not recover, windows of opportunity for use of a peripheral canal are likely to diminish and to be confined to months when water is least available.

It is unclear how the likely range of export reductions would differ between a peripheral canal and dual conveyance. The greater operational flexibility might reduce the size of export reductions, but the cutbacks also could be very similar to those of a peripheral canal, because the periods when more through-Delta pumping could occur are also times when effects on fish are likely to be greatest. The spreadsheet calculations assume that the cutbacks for a dual facility would take the average value of cutbacks for through-Delta and peripheral canal alternatives.

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[6] Natural Resources Defense Council, et al. v. Kempthorne, Findings of Fact and Conclusions of Law Re Interim Remedies Re: Delta Smelt ESA Remand and Reconsultation, United States District Court, Eastern District of California, 1:05-cv-1207 OWW GSA (2007).

Economic and Financial Costs

Our cost estimates all assume similar levels of investment in environmental improvements to those of the recent past. By increasing environmental investments to much higher levels, we expect that each export management alternative could be improved in terms of fish population viability, albeit at some additional economic cost. The particular ecosystem investments might vary in content, cost, and effectiveness for different alternatives.

10. What is the construction cost of a peripheral canal?

The construction costs of a peripheral canal include the costs of building the canal itself and the necessary environmental mitigation devices, such as fish screens or bank filtration. We do not include additional habitat investment costs for fish and the Delta ecosystem, as these are assumed to be similar for all alternatives. Some financial compensation for Delta farmers might be included for this alternative. However, because many of these agricultural islands are expected to fail under any alternative, this compensation might be roughly similar for all alternatives. Consequently, we do not include these potential costs.

Our range of costs for a peripheral canal is $4.75 billion to $9.75 billion. We base this range on the following inputs. For the canal itself, we use estimates developed in 2006 by the Metropolitan Water District of Southern California (MWDSC). A canal on the eastern side of the Delta was estimated to cost on the order of $4 billion, with small variations depending on whether the canal was routed entirely in the primary zone of the Delta or partly in the secondary zone. A western alignment, drawing water from the Sacramento Deep Water Ship Channel and including some portion with deep tunneling, ran on the order of $7.5 billion. We inflate these cost estimates by 20 to 30 percent to allow for cost overruns.

The estimates include fish screens, investments for seismic safety (for a 200-year seismic event), and resilience to at least three feet of sea level rise. (The western alignment would be resilient to higher levels of sea level rise, given the greater ease of moving intakes further upstream). Estimates for both alignments also include the costs of building an additional forebay, consistent with the maintenance of dual conveyance, at roughly $0.1 billion. This cost could be eliminated for a pure peripheral canal.

11. What is the additional drinking and agricultural water quality cost from using Delta water?

As detailed in Appendices H and I, the water quality costs and public health risks of continuing to use waters pumped from the Delta are significant for urban water users in the San Francisco Bay Area and Southern California and for long-term agricultural production in the southern Central Valley. Our numerical estimates, based on many treatment plants and a wide range of agricultural lands, should be considered as preliminary, but sufficient to demonstrate that the costs and risks are large.

Currently, the total additional water treatment cost of continuing to take drinking water from the Delta is on the order of $20 to $60 per acre-foot, and this cost is likely to rise to $100 to $500 per acre-foot as Delta waters become more saline with sea level rise (Appendix H). With roughly 2 million acre-feet (maf) of future export water demand for urban water use, the total additional urban drinking water treatment cost for continued through-Delta pumping as opposed to upstream diversion is $0.2 to $1 billion per year.

Greater net Delta outflows from reduced exports or upstream diversions might be used to counteract the effects of sea level rise on water quality for urban uses; this would require roughly 0.5 maf per year of additional net outflows for one foot of sea level rise without island failures (Appendix C). At a market price of $100 to $200 per acre-foot, this would have an economic cost of about $50 million to $100 million per year for this additional outflow. Adding this to the additional treatment cost with current export water quality and a future 2 maf per year of urban water use provides an urban water quality cost range of $0.1 billion to $0.25 billion per year. These costs would probably be higher with tightening drinking water standards and western island failures.

Reductions in water exports as a result of actions to support fish recovery might provide urban water quality benefits as a by-product, depending on how such export reductions are managed. Retaining through-Delta exports would tend to prevent some urban water quality benefits of reduced exports, since presumably export reductions optimal for fish (particularly with variability) might not always translate into increased outflows to improve drinking water quality. The costs of reduced export quantity for fish recovery purposes are included in the cost calculations that use responses to questions 8, 12, and 16. These effects might be studied further to offer additional refinement.

Overall, we anticipate that additional drinking water treatment costs from Delta water would fall in the range of $0.1 to $0.7 billion per year, possibly continuing as low as they are today (if combined with increased Delta outflows) or much higher with additional salinity intrusion and tighter drinking water standards. Both higher and lower values are possible, but seem unlikely to us.

The long term costs of Delta salinity for southern Central Valley cropping and animal production (relative to using Sacramento River water) appears to be an additional $0.2 billion to $0.3 billion per year, although these estimates are still quite preliminary. It was surprising to us that the agricultural salinity losses were so large, comparable to additional urban water treatment costs (Appendix I).

Combining drinking water and agricultural water quality costs, the range of total water quality costs from through-Delta exports as opposed to upstream diversions is on the order of $0.3 billion to $1.0 billion per year.

12. What is the annualized cost of ending Delta exports?

CALVIN model results indicate that the cost of a well-planned and thoughtful end to water exports from the Delta would average roughly $1.5 billion per year (Appendix F). This is probably an optimistic (low) estimate, because it comes from an optimization model which assumes that water users have perfect hydrologic foresight and no difficulties reaching agreements to transfer and exchange water. Although smart managers generally make good decisions, it can take some time to discover and implement the best operations under a new regime. However, there are also reasons why CALVIN estimates may miss some opportunities for cost savings. For example, the model can err when it is not aware of less expensive options that water users may be able to develop. Some have argued that the current CALVIN model does not make enough opportunities available for water conservation, which might lower costs.

When additional water transfers from the Tulare Basin to Southern California cities are prohibited (in an additional CALVIN model run), the costs of ending exports increases about $700 million per year, mostly from increased operating costs in Southern California, but also increased water scarcity cost in that region, counteracted a bit by lower scarcity costs in the Tulare Basin. Total costs of ending exports without allowing additional water transfers from the Tulare Basin to Southern California are $2.2 billion per year (about $370/af).

For a low cost estimate for ending exports, we use the CALVIN estimate of $1.5 billion/year. For a high cost of ending exports, we use $2.5 billion per year. This includes the cost estimate of ending exports without allowing additional transfers from the Tulare Basin plus and adds an additional $300 million per year for good measure. These estimates result in an average cost of roughly $250 to $420 per acre-foot of foregone exports.

13. What is the annualized cost of maintaining continued through-Delta pumping?

Currently, levee maintenance costs in the Delta are subsidized up to 75 percent by the state's Subventions Program. Recent applications for support by Delta reclamation districts indicate a general maintenance cost of $15,000 to $25,000 per mile, or $16.5 to $27.5 million dollars per year for the 1,100 miles of Delta levees (and $1.4 to $2.4 million dollars per year for the western five islands critical to water supply).

To continue to operate the Delta as a water supply structure will also require upgrading the western islands to resist earthquakes. DRMS Phase 2 estimates the cost of upgrading eight western islands to resist an earthquake with a recurrence interval of 300 years (annual probability of 0.3 percent) is on the order of $8.1 billion. Here we use a slightly lower range of $3 to $5 billion, because we consider only five islands to be critical (based on the modeling results presented in Appendix C). The annualized cost of this investment, at a 5 percent discount rate, would range from $150 million to $250 million. These costs seem necessary for prolonged use of Delta intakes for water exports.[7]

Another potentially important cost for maintaining through-Delta pumping is the additional carriage water needed to keep the Delta fresh enough to support exports. With sea level rise this amount will increase. For 1 foot of sea level rise, the average increase may be on the order of 400,000 – 500,000 acre-feet per year, with considerable variation across years (Appendix C). If exports are valued at $100 to $200 per acre-foot, this cost ranges up to $50 million to $100 million per year.[8] Its cost could be as low as zero if Delta management for fish

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[7] There also will be costs for repairing levees on other Delta islands. We do not include these costs in our estimates here, as they appear unnecessary for water supply. Rather, these costs should be viewed as an element of land and infrastructure policy in the Delta. We estimate annualized repair costs for the subset of islands for which economic activity and infrastructure investments justify these expenditures on the order of $45 million per year (Appendix B).

[8] The per-acre-foot cost would increase as the volume of carriage water increases, because higher volumes of cutbacks necessitate reductions in higher valued water uses to meet outflow requirements (Appendix F).

provides these greater outflows, through the export reductions accounted for elsewhere, also provides this water quality benefit for water export users. We omit these costs in our estimates of maintaining through-Delta pumping, because we have already accounted for the costs of declining water quality with sea level rise (question 11). However, for small increases in required Delta outflow, it might well be less expensive to reduce exports than increase treatment costs.

Summing the costs of annual Delta levee maintenance and seismic upgrades of the five western islands gives a range of annualized costs by 2050 of approximately $165 to $280 million per year to maintain the Delta as a viable source of fresh water for pumping.[9]

As an alternative to the approach outlined here of fortifying the western islands, some proposals and cost estimates have been made for fortifying Middle River levees for seismic resistance, at a cost of roughly $500 million. This seems to be an interim measure, perhaps also useful for longer-term dual conveyance operations. Other estimates emerging from the Bay Delta Conservation Plan's examination of dual conveyance include from $1 billion to $10 billion in capital cost for modifying channels within the Delta to create and maintain a fortified through-Delta canal (Department of Water Resources, 2008). If viewed as an alternative to the reinforcement of western islands examined above, this through-Delta reinforcement would result in a much wider range of annualized costs, from a low of $67 million to a high of $528 million, without maintenance costs.

Overall, the lowest costs seem to be about $150 million per year for inexpensive Delta improvements with increased carriage water, and adding $30 million per year for maintenance costs. The highest costs would be about $400 million per year for maintaining the western islands and increasing carriage water, with $80 million per year for Delta improvements and other expenses.

14. What is the cost to water users of a sudden extensive failure of Delta levees?

An "extensive" failure of the Delta would involve failure of a sufficient number of islands critical to water exports during a single event, ending exports to water users outside of the Delta for up to two years. DRMS Phase 1 calculated the economic costs and impacts of an event of this type. DRMS examined three different conditions during this event – wet spring, average summer, dry fall—and calculated the economic costs of emergency response and repair, infrastructure repair, lost use of structures and services, agricultural losses and recreation within the Delta. They estimated that roughly 80 percent of the total statewide economic costs would be from disruption to water users, with the balance resulting from the inability to use some infrastructure. The range of economic costs to water users is $7.8 billion to $15.7 billion, depending upon conditions during failure and the length of time it takes to restore water deliveries. The additional costs to repair levees and islands to restore water exports are addressed separately in the following question. Preemptive failure of interior islands might reduce the water supply consequences of an extensive levee failure, but this approach has not been studied significantly.

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[9] Low estimate: $16.5 million annual levee maintenance plus $150 million annualized costs of western island reinforcement. High estimate: $27.5 million annual levee maintenance plus $250 million annualized costs of western island reinforcement.

15. What is the average cost to repair an extensive Delta levee failure for water supply?

The cost of repairing an extensive set of Delta levee failures depends on two key factors: 1) the level of prior investments made to prepare and mitigate potential levee failures; and 2) the magnitude and distribution of individual levee failures following a major flood or earthquake event. Spokespersons for DWR and URS (the lead firm conducting the DRMS study) have stated publicly that an extensive earthquake event in the Delta under present conditions would cost $30 billion to $60 billion in repairs and economic impacts from lost water withdrawals and disruption to key infrastructure.

For this analysis, we estimated a range of values for an event which would lead to flooding of five western islands critical to water supply. For the lower end cost, we assume the levees have already been upgraded to seismically repairable levels and that there is only a single breach in each island. Based on the DRMS estimates of damage and repair costs for a "Mean Higher High Water" flood of these five islands, the total low-end cost would be approximately $184 million.

High end costs are more difficult to estimate and depend principally upon the length of levees to be rebuilt. If a major earthquake struck the western Delta before seismic upgrades of levees had been completed, multiple levee failures would likely occur on each island, requiring extensive repairs taking several years. (Then again, repairs may not be possible given the domino effect of levee failure once a few large islands are flooded). The DRMS study evaluated the repair costs of a variety of failure scenarios, although none precisely match the simultaneous loss of all five western islands. Here we use one DRMS scenario, which envisions the loss of three major islands with significant damage to four additional islands, to approximate the high-end range of the costs of repairing the five western islands at $2.5 billion. There would clearly be additional costs to repair other islands damaged during the same event, particularly those with important transportation or other infrastructure, but these costs are outside the scope of our inquiry. [10]

16. What exponent relates export reduction to economic cost?

Figure J.6 shows the relationship between the additional economic costs of reducing exports and the proportion of water export quantity reduction for several constants of proportionality as well as results from the CALVIN model, which was used to estimate statewide economic costs for export reductions of 0 percent, 19 percent, 59 percent, and 100 percent (Appendix F).

From these results, it appears that a constant of proportionality (n in equation 1) between 2 and 3 is reasonable. Any economically efficient allocation of water exports – even at highly reduced levels of exports - will result in the constant of proportionality greater than 1. A non-linear regression of the CALVIN results obtained a value of n = 2.91.

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[10] Estimates of island repair costs for ten and 30 island failures are $6.3 and $14 billion, respectively (URS and J.R. Benjamin and Associates, 2007).

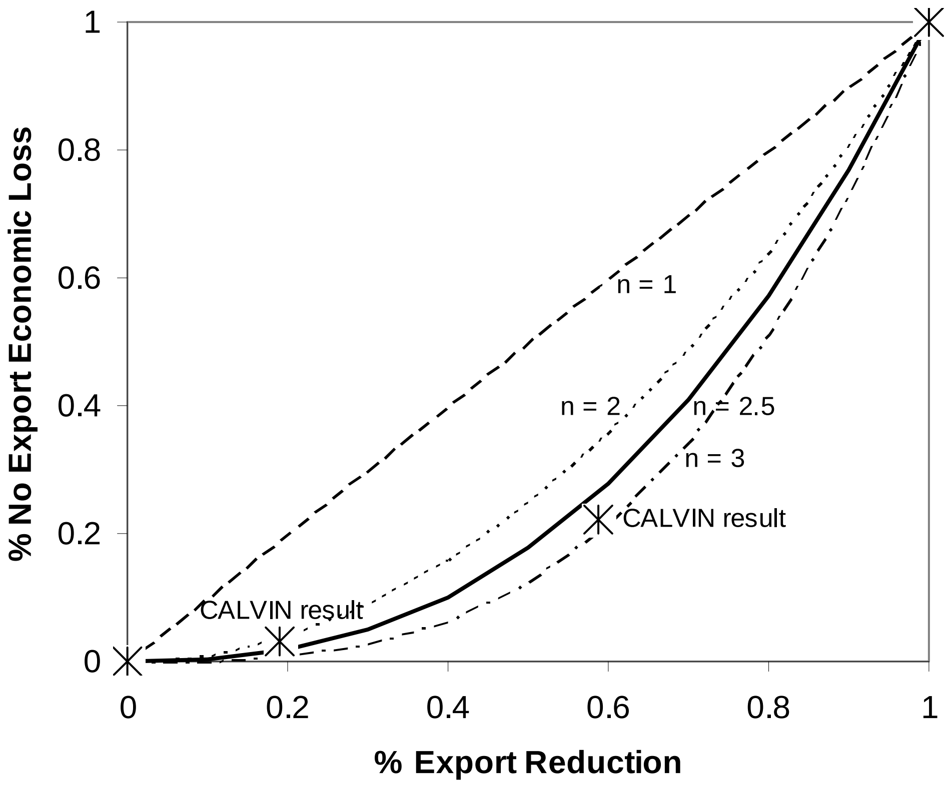


Figure J.6 - Relationship between proportion of economic loss from reducing exports and proportion of export reduction from recent levels with CALVIN results

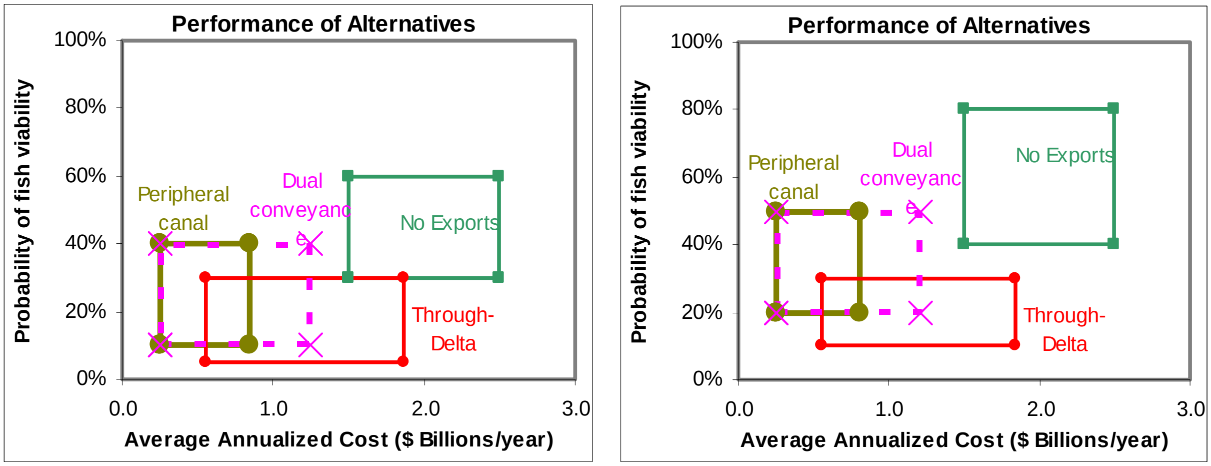
5. Summary of Results

Results are prepared for three objectives: (1) statewide economic costs, (2) the probability of viable delta smelt populations (sufficiently healthy to remove ESA restrictions on water exports), and (3) the probability of a viable fall run Chinook salmon fishery. These results illustrate the use of the spreadsheet to compare the performance of the four strategic alternatives with more than one environmental objective. This is done by varying the fish viability probabilities for different spreadsheet "runs."

Table J.2 summarizes the performance of the four strategic alternatives, given the ranges of inputs shown in Table J.1 and justified in the discussion above. Figure J.7 depicts these results in multi-objective graphics. There is clearly uncertainty in the ranges of environmental and economic performance for each strategic Delta alternative. For ending exports, costs are likely to range from $1.5 billion per year to $2.5 billion per year, with the probability of viable delta smelt populations ranging from 30 percent to 60 percent. While this represents considerable uncertainty, these results offer some insights for comparing these strategic alternatives.

Table J.2 - Estimated range of annual economic cost and fish viability for Delta export alternatives, 2050

	Low Estimate	**High Estimate**
Continuing through-Delta exports		
Average annualized cost ($ billions/year)	0.55	1.86
Probability of viable delta smelt population (%)	5	30
Probability of viable Chinook salmon fishery (%)	10	30
Peripheral canal		
Average annualized cost ($ billions/year)	0.25	0.85
Probability of viable delta smelt population (%)	10	40
Probability of viable Chinook salmon fishery (%)	20	50
Dual conveyance		
Average annualized cost ($ billions/year)	0.25	1.25
Probability of viable delta smelt population (%)	10	40
Probability of viable Chinook salmon fishery (%)	20	50
Ending Delta exports		
Average annualized cost ($ billions/year)	1.50	2.50
Probability of viable delta smelt population (%)	30	60
Probability of viable Chinook salmon fishery (%)	40	80



(a) Delta smelt (b) Fall-run Chinook salmon fishery

Figure J.7 - Range of costs and fish population viability for Delta export alternatives, 2050

The results reveal some clear distinctions along both the environmental and economic criteria. The no exports alternative presents some of the best potential outcomes for fish, but also the highest likely costs to the economy, given the need to reduce water use and draw on more costly sources. Continuing through-Delta exports has an intermediate range of economic costs and the lowest range of likely outcomes for both fish species. The peripheral canal, followed by dual conveyance, has the lowest range of costs, and these alternatives present medium-range opportunities for fish (Figure J.7).

However, given the levels of overlap among alternatives for both fish and economic outcomes, the question arises: How likely is it that each alternative will outperform the others? If the likelihood of performance is assumed to be spread evenly and independently over the ranges in Figure J.7, we can calculate the probability that each alternative performs better than any other alternative for any single objective or combination of objectives (fish viability and statewide economic cost). Results of these calculations appear in Table J.3, with delta smelt viability as the environmental objective (Addendum J.2 contains details on the method).

"No exports" appears to be strongly superior to the other alternatives for the fish (probabilities of 94 to 100 percent). These numbers are reversed for economic performance (where ending exports has a 5 percent chance of outperforming through-Delta exports, and no chance of outperforming a peripheral canal or dual conveyance). Even though there is significant overlap between the ranges for the peripheral canal/dual conveyance alternatives and the through-Delta alternative, the through-Delta alternative is clearly inferior when considered over the entire range of potential outcomes. It has a 73 percent chance of performing less well for the fish and a 94 percent change of performing less well from the standpoint of statewide economic costs. Taking both objectives together, the odds of through-Delta performing better than a peripheral canal round up to 2 in 100.

Table J.3 - Probabilities That Each Export Alternative is Superior to Others, With Delta Smelt Viability as the Environmental Objective (%)

Alternatives	Delta Smelt	Statewide Cost	Both Objectives*
Through-Delta better than peripheral canal	27	6	1
Through-Delta better than dual conveyance	27	19	5
Through-Delta better than no exports	0	95	0
Peripheral canal better than no exports	6	100	6
Peripheral canal better than through-Delta	73	94	69
Dual conveyance better than no exports	6	100	6
Dual conveyance better than through-Delta	73	81	60
No Exports better than peripheral canal	94	0	0
No Exports better than through-Delta	100	5	5

Notes: * If probabilities of performance are independent, then the probability of superiority for both objectives is the product of superiority on the individual objectives.

6. Limitations

The greatest limitation of this analysis is that it simplifies the dynamics of costs, benefits, and uncertainties, thereby largely avoiding the question of exactly *when* a strategic decision should be made. A more elaborate analysis could examine the optimal timing of a decision to switch from through-Delta to peripheral conveyance, taking into account evolving costs and risks of Delta collapse and the associated costs of maintaining the levees in sufficient shape to protect the pumps from seawater intrusion.

Here, the problem was simplified so that failure probabilities and through-Delta salinities do not increase with time. In reality, increasing failure probabilities and increasing sea levels will worsen the prospects for through-Delta exports. As a result, our assumptions tilt the analysis in favor of continued use of through-Delta exports. We have chosen to frame the problem in a more analytical way than is common for discussions of Delta policy, but still streamlined enough to be interpreted and employed by those familiar with the Delta, drawing on the estimation of common-sense parameters.

This analysis also excludes costs and potential co-benefits of different export alternatives with other Delta objectives, such as urban settlement, maintenance of infrastructure, or recreation. Additional human health risks from poorer water quality are not quantified in economic terms. Such objectives could be incorporated into an expanded decision analysis, with some additional questions and calculations.

For the through-Delta alternative, the additional water quality costs of using lower quality Delta water are not reduced when export volumes are reduced. If this aspect were added to the calculations, the cost reduction would occur at the rate for agriculture, because urban users can be expected to maintain most of their exports. Similarly, the analysis assumes that dual conveyance entirely avoids the water quality costs of using Delta water, whereas in reality there would be some blending. These additional water quality costs could be added to the cost calculations, but the outcome would not be a simple linear combination of the costs of water from the two intakes. For example, if a third of dual conveyance exports were from through-Delta pumping, it is not necessarily the case that a third of the water quality costs should apply. If the blended water quality falls below a treatability threshold, it might avoid most of the additional water treatment costs of Delta water. Agricultural salinity costs for blended water also have some nonlinearity.

The future of the Delta has many sources of risk and uncertainty. Many short-term factors could quickly change conditions, while others could have profound consequences over the longer term. Some of these are summarized in Table J.4. In our ranges of costs and probability values we have explicitly considered some of these factors, and have tried to implicitly consider others.

Table J.4 - Some factors affecting short and longer term reliability of Delta solutions

Floods*	Sea level rise
Earthquakes*	Climate warming
Geotechnical failures*	Land subsidence
Mechanical failures*	Urbanization
Endangered species regulatory actions*	Water demand growth
New invasive species*	

Note: * indicates factors which could be important in the short-term, as well as over the longer term.

7. Sensitivity Analysis

To guard against the dangers of putting too much weight on a single number, we purposefully chose ranges for each key input to this decision analysis. The Delta is a complex and changing place; the only certainty about exact numbers in the Delta is that they are usually wrong. But recognizing this uncertainty is very different from implying that we know nothing. Indeed, we probably have a good understanding of many issues. It is clear that the delta smelt population is small, less than hundreds of thousands. It is clear that a peripheral canal would cost more than $1 billion and less than $20 billion to build. It is clear that the economic costs of ending Delta exports would exceed a billion dollars per year. Although reasonable people are likely to judge a range of costs and outcomes differently, some values can be ruled out. For a decision analysis, the important question is not whether the numbers used are highly accurate, but rather, by how much must they be changed to alter the ordering of alternatives on the two objectives of economic cost and sustaining viable fish populations.

For our set of parameter values, costs behave in a counter-intuitive way for changing probabilities of extensive levee failures in the Delta. As the probabilities of extensive levee failure increase, the costs of a through-Delta alternative actually decrease. This result arises because after failure, the least-cost decision is not to repair and restore the system to continue through-Delta pumping, but to construct a peripheral canal, which is considerably cheaper. If, instead of allowing a switch to a peripheral canal, we force a policy of continued through-Delta pumping after each extensive levee failure, this increases the costs of this alternative beyond levels shown here.

To provide a sense of the key drivers of costs, Table J.5 shows the shares of major cost components for the low and high-cost scenarios for each alternative. As an illustration, the low-end cost of the through-Delta alternative ($0.55 billion/year) is driven mostly by the additional water quality costs of using Delta water (42%) and the operating and annualized capital costs of maintaining Delta intakes and levees (27%). After failure, the through-Delta solution would be replaced by a peripheral canal (the least-cost alternative). Because failure in this low-cost scenario occurs far in the future (mean time to failure is 71 years), the costs of failure and replacement facilities are relatively low, accounting for only 27 percent of total costs.[11] These costs are considerably higher in the high-cost scenario, where the mean time to failure is only 18 years.

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[11] After failure, the higher water quality costs of the through-Delta alternative are also deducted.

Table J.5 – Major components of costs for export alternatives (%)

Alternative	Major Components of Low Cost Estimate	Major Components of High Cost Estimate
Continued through-Delta exports	Water quality: 42 Through-Delta operations: 27 Reduced exports: 4 Failure: 17 Replacement facilities: 10	Water quality: 24 Through-Delta operations: 21 Reduced exports: 17 Failure: 24 Replacement facilities: 15
Peripheral canal	Facilities: 94 Reduced exports: 6	Facilities: 58 Reduced exports: 42
Dual conveyance	Facilities: 94 Reduced exports: 6	Facilities: 71 Reduced exports: 29
No exports	Water scarcity and operations: 100	Water scarcity and operations: 100

Notes: Costs based on delta smelt viability estimates. Totals may not sum to 100 due to rounding.

It is a practical impossibility to perform complete sensitivity analysis for any complex model, even one as simple as the one here. However, the availability of this spreadsheet might lead people looking at these issues from different perspectives to explore many particular sets of conditions. Our explorations of different ranges of costs, probabilities, and rates indicate that our major qualitative conclusions are quite robust with reasonable ranges.

Conclusions

This report presents a formal performance-based analysis of the strategic decision of water export alternatives for the Delta. Four strategic options are considered: (1) continuing through-Delta pumping, (2) diverting exports from an upstream location (peripheral canal), combining the first two options (dual conveyance), and (4) ending Delta exports altogether. While any analysis involves some simplifications, several conclusions seem well-supported for a reasonable range of estimates of costs and risks:

1. Ending Delta exports almost certainly has both the highest costs and the highest probability of supporting viable populations of desirable fishes.

2. Continuing through-Delta exports probably has the lowest potential for maintaining viable desirable fish populations, and has potentially very high costs and risks. The driving factors in the high costs are water quality costs (which are experienced every year), through-Delta capital and operating costs, and the costs of a catastrophic levee failure and additional investments needed following such a failure.

3. We anticipate little difference in the environmental performance of dual conveyance and a peripheral canal. However, costs have the potential to be substantially greater for a dual conveyance strategy if it results in significant investments to improve through-Delta pumping in parallel with a new canal. Differences in costs and performance would be largely determined by the details of implementation.

4. Both dual conveyance and a peripheral canal are likely to be superior to continuing exports through the Delta for meeting the two co-equal goals of environmental sustainability and water supply. The chances of these superior outcomes are on the order of 60 percent for dual conveyance and 70 percent for a peripheral canal for both statewide economic and fish viability objectives.

5. Some statewide economic savings from dual conveyance or a peripheral canal might be used to support investments in habitat and resource management, thereby bringing the viability of desirable fish populations closer to (and perhaps even exceeding) their prospects under the "no export" alternative. From several hundred million to over a billion dollars per year of economic savings should be available for such purposes, relative to the next best alternative. Financial savings are particularly likely if a peripheral canal or a low-cost dual conveyance strategy is selected. Some of the key savings result from water quality benefits of diverting water upstream of the Delta, which reduces water treatment costs and improves the profitability of southern Central Valley agriculture.

6. The selection of a long-term approach for managing water exports will not eliminate controversies regarding the Delta or water management in California. However, selection of a peripheral canal or dual conveyance approach could considerably reduce economic costs to California while improving the viability of fish species that depend on the Delta. Many implementation details will need to be worked out once a strategic policy has been established. As discussed in Appendix G, many implementation decisions can only be made after new facilities are in place.

There are considerable uncertainties regarding the management of water and the Delta, and such uncertainties will probably continue into the indefinite future. Formal methods have been well developed for decades to compare decisions under such conditions of uncertainty. We apply such methods here and find that there is also considerable and unexpected certainty to guide the strategic decision of how to export water from the Delta assuming two co-equal objectives of water-related economic costs and fish population viability.

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Addendum J1. Derivation of Discount

This addendum contains derivations for discount factors used in the decision analysis of Delta solutions. The first derivation is for the expected value of the discount factor for the costs of a single failure occurring at some uncertain time in the future, such as those costs associated with abandoning an island once it fails. The second derivation is for the expected value of the discount factor for an infinite series of costs associated with an infinite series of future failures, such as those associated with repairing islands into the indefinite future. The real annual discount rate is r and the annual probability of failure is P_f. Both rates are assumed to be constant over time.

Expected Discount Factor for a Single Failure Occurring at an Uncertain Future Time

The expected value of the discount factor for a failure cost occurring at an uncertain future time is:

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

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

Using geometric series expansions, this reduces to:

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

which is used in the spreadsheet.

A continuous derivation which comes to a very similar result begins with the definition:

$$DF_{sf} = \int_0^{\infty} P_f (1-P_f)^t (1+r)^{-t} \, dt \, .$$

Because $\int b^u du = b^u / \ln(b)$, letting u = t and b = (1-Pf)/(1+r), yields:

$$DF_{sf} = \frac{-P_f}{\ln\left[(1-P_f)/(1+r)\right]} = \frac{-P_f}{\ln(1-P_f) - \ln(1+r)}$$

To annualize this cost over an indefinite period into the future, one multiplies this present value cost by the discount rate r.

Expected Discount Factor for an Infinite Series of Future Failures Occurring at an Uncertain Future Times

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

As the time between failures (t) increases, the present value cost decrease both because failures are becoming less frequent and because of the increased effects of discounting. For Freidenfeld's derivation, the infinite series begins with a failure in the present.

When the time of failure is uncertain and represented by a probability distribution, this becomes:

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

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

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

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

since this part is an infinite geometric series. This allows the entire expression to be simplified to $W' = C\, P_f/r$. Or, $DF_{isf} = P_f/r$ for the present value. 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.

Addendum J2. Probabilities of Superior Performance

If the boxed areas in Figure J.7 represents evenly distributed likelihood of cost and environmental performance for each alternative, then we can calculate the probability of each alternative having superior performance for each objective, separately and together. This indicates the probability of Pareto-optimality for each alternative (Cohon 1978). Others have explored similar ideas in application to multi-objective optimization (Teich 2001; Fieldsend and Everson 2005) and surgical decisions (Hudgins 1994).

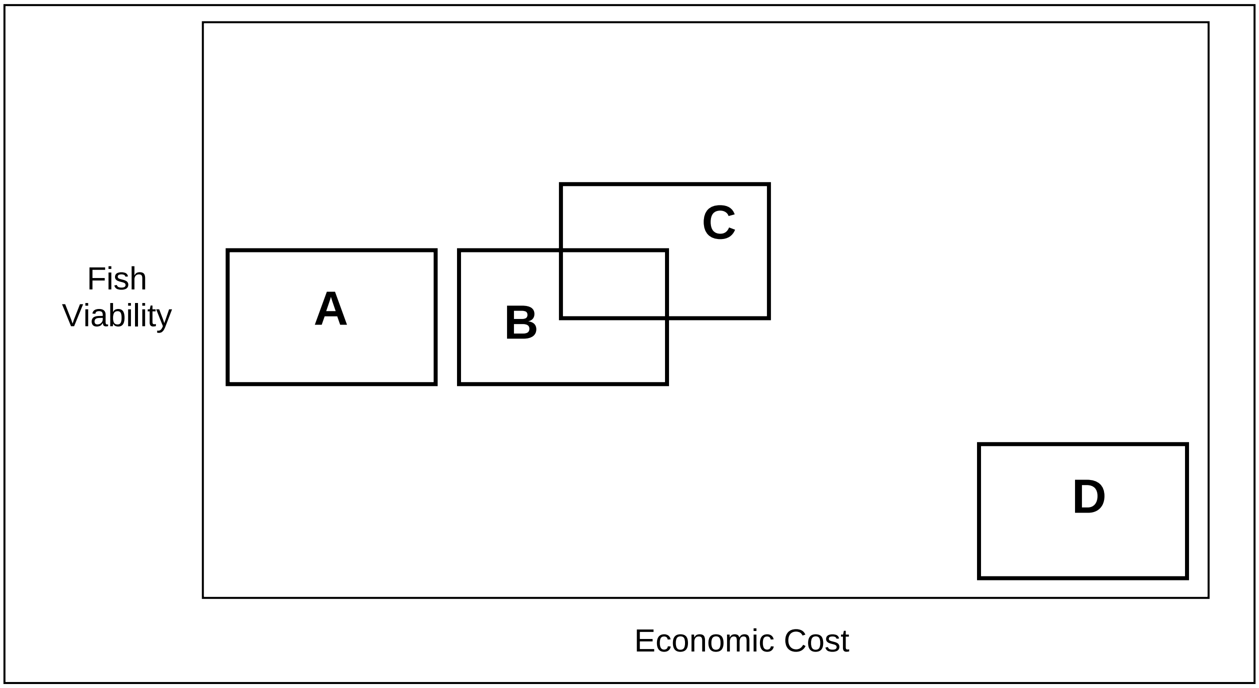

Figure J2.1 - Performance and Superiority

Figure J2.1 can be used to illustrate this concept. For this case, alternative D is clearly inferior to alternatives A, B, and C, never having a possibility of performing better than A, B, or C on either fish or economic objective. Let P(AsB) be the probability that alternative A is superior to alternative B. Then, from Figure J2.2, P(AsD) = P(BsD) = P(CsD) = 1 for either objective and for both objectives taken together.

Alternative A is always superior to B in terms of cost. Half the time A will be superior to B in terms of fish viability, with an equal probability that B will be superior to A for fish. Overall, there is a 50% chance that A is superior to B for both fish and cost.

If C overlaps area B by 25%, as shown with the southwest corner of C at the centroid of B, there is a 87.5% chance that C is better for fish than B (or A) (=0.5 + 0.5(0.5+0.25)), with a 12.5% chance that B (or A) is better for fish (=0.5*0.5*0.5). For cost, there is a 87.5% chance that B is superior to C, and 12.5% chance that C is better than B. Overall, there is a 10.9% chance that B is superior to C for <u>both</u> objectives, and a 10.9% chance that C is superior to B for <u>both</u>

objectives. C will never be superior to A for both objectives, but there is a 12.5% chance that A is superior to C for both objectives. For the remaining probability, each alternative would be better on a different objective, indicating a performance trade-off requiring a value judgment. These calculations are more fully explained in the following section.

Assuming that performance is equally likely over the entire region and not more concentrated near the middle of each area probably means that these calculations are, for the overlapping comparisons, somewhat skewed for overlaps of corners far from the centroid of an alternative's performance region.

A More Formal Derivation

Given two alternatives, each with uncertain and probabilistic performance on two objectives, what is the probability that the actual (point) performance of each alternative will be superior (non-dominated or Pareto-optimal) relative to the other? Consider the problem as in Figure J2.2, with the assumption that more of Z1 is inferior and more of Z2 is superior, so ideal performance is in the Northwest corner of the diagram.

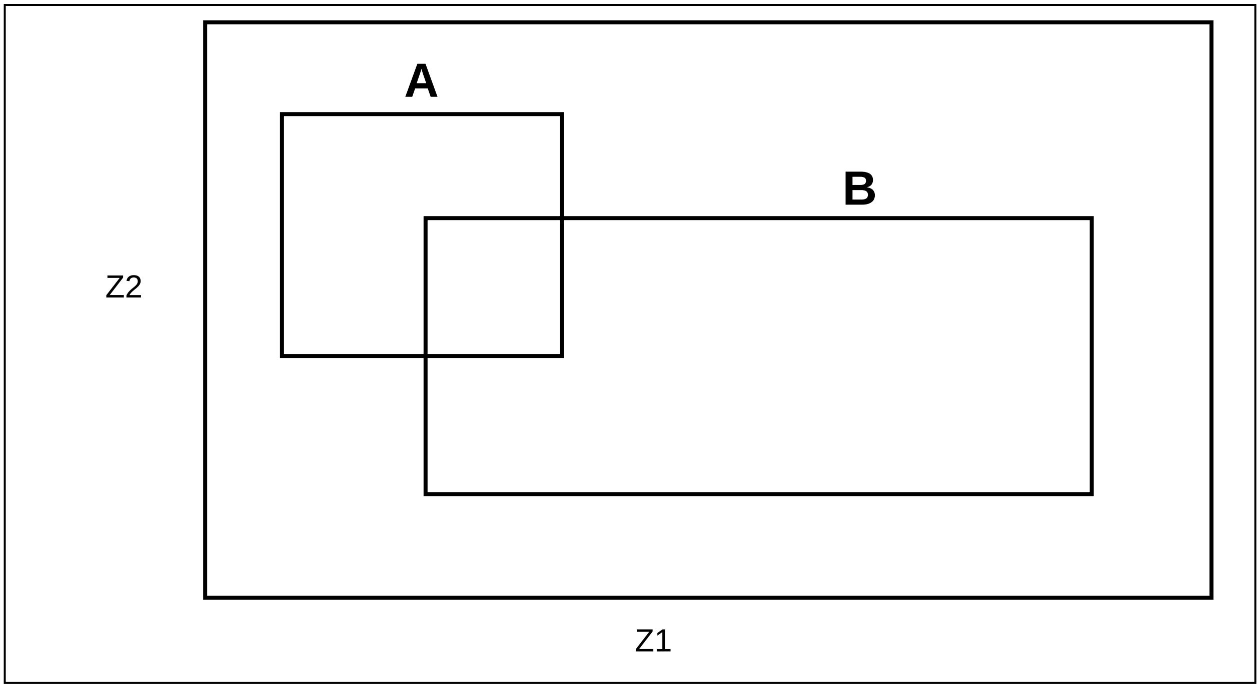

Figure J2.2 - Performance and Superiority for Two Overlapping Alternatives

Let actual performance of alternatives A and B be points in this multi-objective space, but our knowledge of their future performance is only given by probability distributions $P_A(Z1, Z2)$ and $P_B(Z1, Z2)$. What is the probability that alternative A will be superior to B in terms of each objective and what is the probability that the performance of A will be superior to B for both objectives (i.e., B is a dominated solution)?

Let P(AsB) be the probability that A is superior to B for both objectives, and let PZi(AsB) be the probability that A is superior to B with respect to objective i.

To define overall probabilistic dominance or superiority of A over B,

$$P(AsB) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(P_A(Z_1, Z_2)\int_{Z_1}^{\infty}\int_{-\infty}^{Z_2} P_B(z_1, z_2)dz_2dz_1 \right)dZ_1dZ_2,$$

where the probabilistic performance of each alternative is independent. If the probabilistic performance of alternative B is a joint probability with alternative A, then

$$P(AsB) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(P_A(Z_1, Z_2)\int_{Z_1}^{\infty}\int_{-\infty}^{Z_2} P_B(z_1, z_2 \mid A(Z_1, Z_2))dz_2dz_1 \right)dZ_1dZ_2,$$

where $P_B(z_1, z_2 \mid A(Z_1, Z_2))$ is the probability distribution of B's performance given A's performance at Z_1, Z_2.

For a single objective, the probability that A is superior to B is

$$PZ1(AsB) = \int_{-\infty}^{\infty}\left(P_A(Z_1)\int_{Z_1}^{\infty} P_B(z_1)dz_1 \right)dZ_1$$

for independent probabilistic performance, where less of objective Z1 is better. Where more of objective Z2 is better,

$$PZ2(AsB) = \int_{-\infty}^{\infty}\left(P_A(Z_2)\int_{-\infty}^{Z_2} P_B(z_2)dz_2 \right)dZ_2$$

This should apply to any two alternatives in a two-dimensional performance space. Higher dimensional objective spaces can be incorporated with the suitable additional integrals.

Consider special conditions where the point performance of A and B are independent probability distributions, each of which is uniform between different ranges of performance on each objective, with some overlap of these distributions as in Figure J2.2. Overlapping and partially overlapping sub-areas of each distribution can be defined as in Figure J2.3.

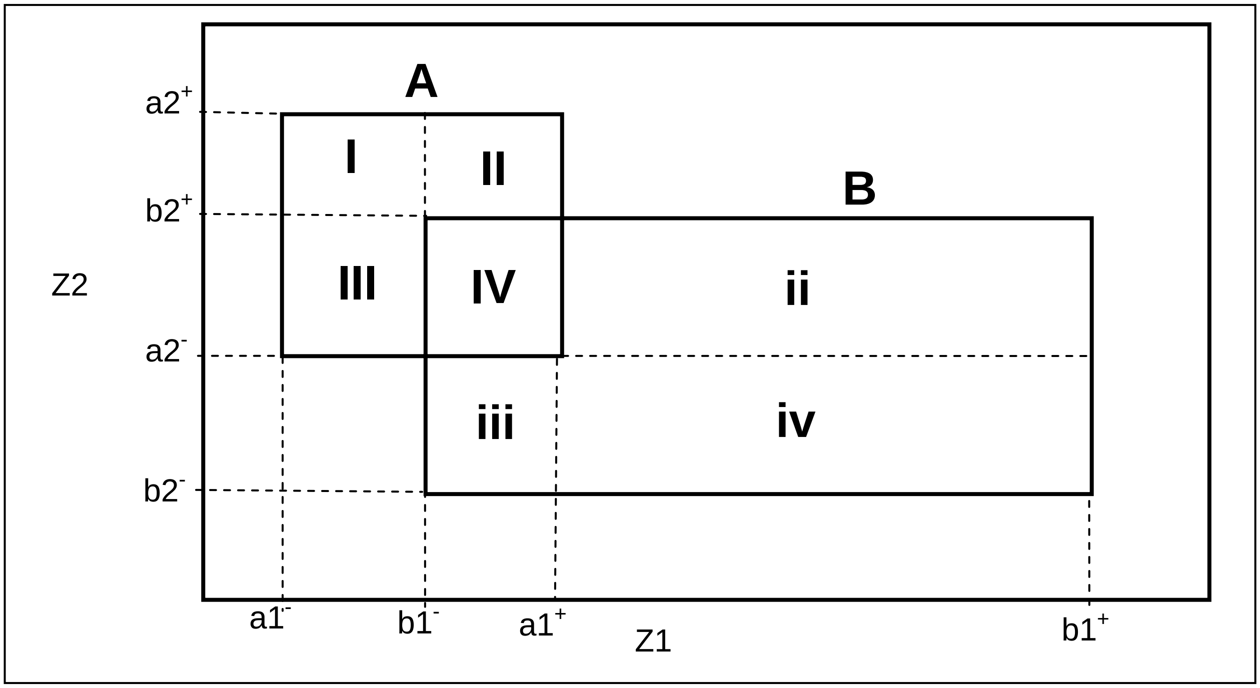

Figure J2.3 - Performance and Superiority for Two Overlapping Objectives - Detailed

$$P(AsB)=\frac{I}{A}1+\frac{II}{A}\left(\frac{ii+iv}{B}+0.5\frac{IV+iii}{B}\right)+\frac{III}{A}\left(\frac{iii+iv}{B}+0.5\frac{IV+ii}{B}\right)+\frac{IV}{A}\left(\frac{iv}{B}+0.5\frac{ii+iii}{B}+0.25\frac{IV}{B}\right)$$

where A is the total area of A, B is the total area of B, each Roman number represents a different quadrant area, as shown in Figure J2.3. If A falls in area I, there is 100% chance that A is superior to B for both objectives. If A falls in area II, there is 100% chance of A being superior for both objectives if B falls in areas ii or iv, and a 50% chance of A being superior if B falls in areas IV or iii. If both A and B fall in area IV, there is a 25% chance of A being superior to B and an identical chance of B being superior to A for both objectives. With complete overlap for both objectives, there is a 25% change of dominance. With an overlap for one objective, there is a 50% chance of dominance for that objective. When there is no overlap for any individual objective dimension, one solution will completely dominate the other.

The area-based equation above can be expanded to the coordinate-based equation:

$$P(AsB) = \frac{(a2^{+} - b2^{+})(b1^{-} - a1^{-})}{A} +$$

$$\frac{(a2^{+} - b2^{+})(a1^{+} - b1^{-})}{AB}\left((b2^{+} - a2^{-})(b1^{+} - a1^{+}) + (a2^{-} - b2^{-})(b1^{+} - a1^{+}) + \frac{(b2^{+} - a2^{-})(a1^{+} - b1^{-}) + (a2^{-} - b2^{-})(a1^{+} - b1^{-})}{2} \right)$$

$$+ \frac{(b2^{+} - a2^{-})(b1^{-} - a1^{-})}{AB}\left((a2^{-} - b2^{-})(a1^{+} - b1^{-}) + (a2^{-} - b2^{-})(b1^{+} - a1^{+}) + \frac{(b2^{+} - a2^{-})(a1^{+} - b1^{-}) + (b2^{+} - a2^{-})(b1^{+} - a1^{+})}{2} \right)$$

$$+ \frac{(b2^{+} - a2^{-})(a1^{+} - b1^{-})}{AB}\left((a2^{-} - b2^{-})(b1^{+} - a1^{+}) + \frac{(a2^{-} - b2^{-})(b1^{+} - a1^{+}) + (a2^{-} - b2^{-})(a1^{+} - b1^{-})}{2} \right)$$

$$+0.25\frac{\left((b2^{+} - a2^{-})(a1^{+} - b1^{-}) \right)^{2}}{AB}$$

If terms are given values of zero when they become negative, this equation should be generalizable without foreknowledge of the geometric arrangement of alternatives in objective space. The calculations are much simpler when the alternatives overlap on only one objective, or if they do not overlap at all. Where probabilities of performance are independent, the product of the probabilities of dominance for each single objective is the probability that an alternative is superior for all objectives.

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