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Optimal Dam Construction under Climate Change Uncertainty and Anticipated Learning

Author
Cameron-Loyd, Patricia Jane

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by

Patricia Jane Cameron-Loyd

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Committee in charge:

Professor Larry Karp, Chair
Professor David Sunding
Associate Professor Catherine Wolfram

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Abstract

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Public capital-investment projects are typically evaluated using standard net-present-value (NPV) analysis. Projects with large, up-front investments, such as dams or energy plants, often are irreversible and have uncertain future benefits. If we expect to reduce uncertainty about these future flows over time, introducing the option to delay the project may increase project value and lead to different decisions. This dissertation evaluates a pending California water storage and conveyance project that would increase the capacity of an existing dam, the value of which depends upon the future climate state. The research uses a dynamic optimization program with two stochastic state variables to analyze decision making. One state variable is the belief about the future climate state, and the other is the level of green-house-gas (GHG) stocks, both of which change in a random manner. The analysis allows for the possibility of learning more about the true state of the future climate as time goes on. The results differ substantially from those of the policy makers involved in the empirical project.

To my wonderful children, Gemma, Phil and Casey, who took care of themselves when I was too busy to make them a good dinner or to take them on a nice day trip, and who were always there to give me hugs, kisses and encouragement.

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1 Introduction

This research uses a specific Northern California dam expansion project to examine how the anticipation of future information about climate change should be used when evaluating large infrastructure projects. The Los Vaqueros Dam Expansion Project would increase the storage and conveyance capacity of an existing dam. The Bureau of Reclamation evaluated this project using a standard cost-benefit analysis, in which they compare the net present value (NPV) of the future net benefit streams with the current value of the investment. (Bureau of Reclamation (BOR), 2006). The value of the future benefit stream depends (among other things) on the future distribution of precipitation in California. The BOR analysis assumes that historical distribution of precipitation will continue into the future.

There is extensive evidence that human-influenced climate change is occurring. The 2007 Fourth International Panel on Climate Change Assessment (IPCC, 2007, pg 2) finds that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level." The magnitude of future climate change is thought to be primarily dependent upon the path of annual emissions, and resultant atmospheric stock, of greenhouse gases (GHGs). The IPCC Assessment cites multiple models for the future paths of GHG emissions and stocks.

The effect of climate change on the precipitation distributions in California, and hence the value of dam projects, is uncertain in terms of both timing and direction, even at known GHG levels. Different prominent models predict either dryer or wetter futures for California with increasing GHGs. In this research, I use two widely accepted general circulation models (GCMs) to predict future precipitation distributions. My maintained hypothesis is that the future climate is either becoming increasingly wet or increasingly dry, and can be accurately predicted by one of these two GCMs. I model future climate as a distribution of precipitation. There are many other aspects of climate that could be considered in this kind of research, such as timing of precipitation and the effect of rising temperature on precipitation in the form of snow and on annual snowpack levels, but I choose annual precipitation distribution in order to calibrate exactly with the BOR analysis. In this way I can isolate the effects of climate change and anticipated learning on decision making.

The planner does not know which of these two possible precipitation futures is true, but has a belief about it that I model as the planner's subjective probability that the true future climate is wetter. As the planner observes precipitation realizations each period, he updates his belief about the true climate state using Bayesian learning. Because the planner anticipates the ability to learn about the true nature of the future climate, he can anticipate learning more about the true value of the dam.

Dam projects are typically evaluated using current information to compare the net present benefit of constructing the dam now or of never constructing it. The real choice, however, is whether we construct the dam now or wait until the next period, at which time we will again be faced with the choice of construction or further delay. The ability to begin construction in the future, if we delay construction today, is worth something. The value of this possibility is known as the “option value”. Studies that fail to take into account this option value understate the benefit of delaying construction and are therefore biased in favor of early construction. The option value arises because we anticipate obtaining better information in the future about the value of the dam.

I develop a dynamic programming model of decision making, where the decision is either to build this year or wait one year and decide again to either build or delay. The model depends on two stochastic state variables. One is the subjective belief that the true climate is wet. Because the precipitation (the learning signal about the true climate scenario) is random, this state variable is updated in a stochastic manner. The second state variable is the GHG stock level, which grows stochastically due to exogenous variability.

I find the optimal decision given the two state variables. That is, given that we know the current GHG level and we have a subjective belief about the true climate future, I determine whether we should decide to build today or not. The BOR analysis determines that the optimal decision is to build the dam. My research concludes that given certain parameters there is value to delaying the project unless our belief that the future climate is the wetter one is low. Unless the policy makers have a high level of confidence in a dryer future, they should delay building until they learn more about the true climate, contrary to the BOR recommendation.

The World Commission on Dams (WCD) (2000) reports that the decision-making framework on dams has traditionally been a simple cost-benefit analysis and excludes consideration of uncertainty with regard to future benefits of the dam. A dam, once built, is an irreversible investment, as it cannot be repurposed. Arrow and Fisher (1974) show that when we make an irreversible decision to develop an environment and the benefit is uncertain, assuming risk-neutrality, simply replacing known values with expectations does not capture the loss of the benefits in perpetuity of the affected environment. Hence, the benefits of such an investment are overstated. In order to preserve these potential benefits, less development should occur than implied through traditional cost-benefit analysis. They combine the notion of irreversibility with the assumption that a realization in one period will affect the expectations in the next. Their model allows for the reduction of uncertainty in the second period, allowing for a revision of decision-making (compressing all future periods into the single second period.) Irreversibility under these circumstances acts upon investment decisions in a manner similar to risk aversion. The key to their model is that development is irreversible, while preservation (or the potential for future development) is not. Their quasi-option value measures the value of information that is gained by learning during delay and the ability to react to that information.

Dixit and Pindyck (1994) develop the concept of real option theory and use dynamic optimization over multiple periods to improve decision making under irreversibility, uncertainty and learning. There is an extensive literature in economics on real options in a general setting. A smaller literature (Kolstad (1996), Ulph and Ulph (1997), Gollier et.al. (2000) and Karp and Zhang (2006)) studies the effect of anticipated learning in the context of climate change. Several of these papers find that the anticipation of future learning about climate change tends to decrease current efforts to reduce carbon emissions.

When uncertainty and learning are involved in decision-making, the expected speed of learning can affect the analysis. Kelly and Kolstad (1999) apply Bayesian learning to estimate the amount of time required to resolve uncertainties about climate change effects. They find that learning can take far longer than might be expected intuitively, arriving too late to affect decisions. Their analysis involves active learning, where the decision makers may influence the change that is learned about. Their theory also applies in cases of passive (exogenous) learning, as in this paper.

As part of my analysis I examine how the rate of expected learning depends on the initial subjective belief about the future of climate change, and how that rate of learning changes as the rate of information delivery changes. When the GHG stock changes at a faster rate, the stochastic weather realizations change at a faster rate, delivering more useful information sooner. In some cases, the anticipation of more rapid learning has a positive effect on the option to delay. I also examine how learning, and thus the option value, is affected when GHG stock changes are stochastic.

Forsyth (2000) and Conrad and Kotani (2005) evaluate decision-making in a forest, and in the Alaska National Wildlife Refuge, respectively. In both cases, the key state variable is the random price, which affects the value of the project. Michailidis and Mattas (2005) apply real option theory in valuing a dam investment. They demonstrate that adding the management flexibility to delay, later expand or abandon a dam project improves analysis of project profitability when compared to a traditional NPV approach. Their underlying future asset value, based on price, follows a random distribution over discrete periods.

My research differs from these studies in that one of my state variables is the subjective belief about how a particular system will evolve in the future. Thus, the key learning is not simply about the realization of a random variable. Instead the planner understands that he will learn about a dynamic process over time, in this case about the evolving distribution of precipitation or climate state.

The practical result of this work is to demonstrate the application of better decision-making tools than those currently employed, using information and beliefs about climate change, leading to the possibility of better decisions concerning major hydrological projects. The techniques employed are applicable to assessing other types of long-term capital projects using beliefs about climate change or other fundamental types of change.

In the next chapter I develop the model of decision-making and make recommendations on whether to build a dam today or to delay, depending on the decision maker's belief about the climate future. In chapter three I perform sensitivity analyses, varying several key parameters to determine the degree to which small changes in these parameters affect those recommendations. In the final chapter I discuss the strengths and weaknesses of cost-benefit analysis methods when deciding to build a major dam project.

2 A Model of Dam Construction Decision Making under Climate Change Uncertainty and Anticipated Learning

The policy maker needs to decide whether to build a dam today or to delay for one period and decide again as he learns more about the true value of the dam, which is dependent upon the distribution of precipitation. I assume that the actual weather pattern will follow one of two possible climate scenarios: $i = 1, 2$, where $i = 1$ describes an increasingly wet climate scenario, and $i = 2$ describes an increasingly dry scenario. The policy maker does not know which of these two scenarios is the true future climate, but has a belief about the true climate future. The policy maker's belief is his subjective probability that the true climate is the increasingly wet one, p.

The two possible future climate states are both modeled as a weather distribution j which describes five types of precipitation levels (driest, very dry, below normal, above normal and wet) such that when $j = 1$ a driest type precipitation occurs (under 16 annual inches) and when $j = 5$ a wettest type year occurs (over 23 annual inches.) The likelihood of a type j precipitation year occurring in a given year y assuming that the true climate state is $i = 1, 2$ is designated by f_{ijy}. Thus, as y increases, and if $i = 1$ (the wetter scenario) the probability of a driest weather type $j = 1$ occurring will decline.

I want to decide whether to add storage that is expected to produce annual benefits dependent on the annual precipitation type and, because of price increases, is dependent on the year $z(j,t)$. The benefit will occur for T years, after which there will be no benefit. The benefits are in real dollars and are expected to change with time as this analysis assumes annual real price increases of variable water benefit at a constant rate of r. The decision to build the dam is irreversible due to political and practical constraints. Construction will be completed in τ years from the point of decision, year y, and will cost k. (Construction is expected to be delayed τ years from the decision point due to the need to acquire congressional approval and funding, and for project design.) The capital investment k is incurred at the beginning of the "base" year, $y+\tau$, and the stream of annual benefits begins to be accrued at the end of that year. The future benefits are discounted using an annual discount factor of β. All costs and fixed benefits are calculated using real price levels corresponding to the earliest possible decision year, $y = 1$, while prices associated with variable benefits increase annually at a rate r. The expected value of the project at base year $y + \tau$ if decided upon in year y when the true climate future is i is:

$$w_{iy} = \left(\sum_{t=y+\tau}^{T+y+\tau-1} \beta^{t-\tau} \sum_{j=1}^{J} f_{ijt} z(j,t) \right) - \beta^{y-1} k. \tag{1}$$

The subjective probability that the wetter climate future is the true effect of climate change ($i = 1$) is p. Define the expected present value of the future benefits of the additional storage given the current beliefs about climate change as:

$$v(p, y) = p w_{1y} + (1-p) w_{2y}. \tag{2}$$

If our only choice is to decide at the earliest possible decision point ($y = 1$), the problem is a simple NPV calculation (where the superscript N stands for the "naive" solution):

$$J^N(p, 1) = \max\{v(p, 1), 0\} \tag{3}$$

We have the option to wait until some period in the future to build the dam. As time goes on, we observe j, the precipitation that occurs at each annual observation. Using Bayes' model of learning we update our belief about the true climate state.

For example, if we observe a sequence of very wet years, our belief that the true climate is wet, p, will increase over time. Thus, the realization of j affects how the belief about the true climate is updated.

The choice today is to either decide to build the dam or to wait one period and decide again. To determine the optimal action, where j is observed in year y, I calculate the expected value of the project by solving the dynamic programming equation

$$J(p,y) = \max E_{p'|p}\{v(p,y), J(p',y')\} \tag{4}$$

$$\text{subject to } p'(j,p,y) = \frac{pf_{1jy}}{pf_{1jy} + (1-p)f_{2jy}} \tag{5}$$

$$\text{subject to } y' = y + 1. \tag{6}$$

The subjective probability that $i = 1$ is represented by p, and p' denotes the value of p in the next period, such that $p' = p'(j,p,y)$ as shown in Equation 5, and j, the type of precipitation year, is an exogenous variable that will occur with probability f_{ijy}. Thus, the subjective probability distribution of p' is

$$\begin{aligned} \Pr\left(p' = \frac{pf_{1jy}}{pf_{1jy} + (1-p)f_{2jy}}\right) &= F_{pjy} && (7) \\ where\ F_{pjy} &= pf_{1jy} + (1-p)f_{2jy} && (8) \\ for\ j &\in \{1, 2, ..., \bar{j}). \end{aligned}$$

2.1 Empirical Application and Data

The empirical evaluation is based on the proposed addition of storage and delivery capacity to the Los Vaqueros reservoir system in Northern California (BOR, 2006) operated by the Contra Costa Water District (CCWD). It is an offstream reservoir, with an intake and pumping station on the Delta. Currently the reservoir's primary purpose is to store water when Delta water quality is good, return water to the Delta when quality is bad, and to provide storage for emergencies, including drought or major fire.

The primary purpose of the proposed new storage and conveyance system is to transfer water from the wetter, lower-demand north to the low-volume, high-demand south. The value of the project is in two parts: fixed benefits (b) and variable benefits ($\pi(j)(1+r)^y * q(j)$), from which annual fixed costs (c) are deducted. Thus,

$$z(j, y) = \pi(j)(1+r)^y * q(j) + b - \beta^{-.5}c. \tag{9}$$

2.1.1 Parameters and variables

Table 1 summarizes all of the key variables and parameters, except for prices and quantities, which are covered in the next section, and, where applicable, show the values used in the Bureau of Reclamation (BOR, 2006) analysis. Because my analysis only considers the effects of climate change and anticipated learning on decision making, I calibrate my model to the BOR analysis, and use all of their parameter values.

Label	**Definition**	**Value**
i	Possible future climate distributions.	1=wet, 2=dry
j	Precipitation year types from driest to wettest.	1 to 5
y	Index of years.	1 = 2006
f_{ijy}	Prob. of weather type j occurring in y if true climate is i.	
T	Years for which the project has a positive annual benefit.	100
$z(j, y)$	Expected annual benefit in year y with weather-type j.	
β	Annual discount rate applied to annual benefits	1/1.05125
	at year's end and to costs mid-year.	
τ	Years between dam building decision and completion.	10
k	Present value of one-time project capital cost at $y + \tau$.	$\$596,889,000$
w_{iy}	Exp. NPV of project decided in year y if climate is i.	
p	Subjective probability that $i = 1$.	
$v(p, y)$	Expected present value of project given climate belief.	
$q(j)$	Additional acre feet used in weather type year j.	See Table 2
$\pi(j)$	Acre foot water price dependent on weather j in year y.	See Table 2
b	Fixed annual benefits from increased water and fishery	$\$12,240.000$
	quality, and emergency water supplies from project.	
c	Fixed annual operating costs.	$\$3,546,100$
r	Annual expected price increase for variable benefits	0.1%

Table 1: Variables list with values taken directly from Bureau of Reclamation analysis.

All costs and benefits are in real 2006 dollars; variable benefit prices increase at an annual rate of r. In order to calibrate to the BOR analysis, nominal price and cost changes due to inflation are assumed to affect all other categories equally, and are excluded from the analysis.

2.1.2 Expected prices and quantities

Under the BOR analysis the variable benefits that depend on precipitation each year make up between 63% and 78% of the total benefit of the project, depending on the price increase level. The purpose of the variable benefit is to provide additional water supply and transport capacity to move water from north of the Delta to south of the Delta as provided for by the Environmental Water Account (EWA) program. This water is then stored and is available to replace water supplies that were originally designated for, but not delivered to, south of the Delta water districts (primarily for agriculture). The curtailments occur under various programs, including the Central Valley Improvement Act (CVPIA), the State Water Resources Control Board (SWRCB) Water Right Decision 1641, certain CALFED programs, and the Vernalis Adaptive Management Plan (VAMP). These programs are meant to counter the decline of fish species in the Delta due to loss of habitat, water quality degradation and water resource development.

The BOR uses the CALFED Common Assumptions Economic Workgroup (CAEWG) methodology for pricing water. The BOR uses average maximum prices incurred in past years for EWA spot market purchases during each weather-year type, along with the historical distribution of year types, to project future prices, as shown in Table 2. All prices are in 2006 dollars. Each of 83 years of precipitation data from 1920 to 2002 is assigned a type of year depending on the total annual precipitation inches to derive the historical distribution. I use these distribution types for the categories of the variable j in my model. The BOR's expected price for EWA water is \$215 per acre foot using historical data for prices and precipitation.

Year Type	j	**Precipitation**	**Hist.**	**'06 Prices (π)**	**Yield (q)**	**\$\$(mm)**
		inches	**Dist.**	**\$/acre foot**	**acre ft/yr**	**Benefit**
Driest	1	$P < 16.2$	.192	340	55,700	19.0
Dry/Critical	2	$16.2 < P < 20$	.188	284	99,400	28.3
Below Normal	3	$20 < P < 22$	.192	201	112,700	22.7
Above Normal	4	$22 < P < 25$	.140	182	118,900	21.7
Wet	5	$P > 25$	.288	160	121,500	19.5
Exp. Value				215	104,200	22.0

Table 2: Interim maximum CAEWG EWA purchase prices and expected deliveries.

Table 2 shows project yield estimates as a function of historical precipitation year type. New storage and conveyance is meant to smooth out the supply of water going to the South Bay Aqueduct for storage purposes. In wet years there is an abundance of water to transfer through the new facility and conveyance to south of the Delta storage. The yield declines in drier years because restrictions on water transfers increase. The BOR uses an average yield of 104,200 annual acre feet in its estimates.

The BOR's expected value of benefits is calculated using the expected value of price times the expected value of yield. Let f_{jh} be the historical probability that a weather-type j level of precipitation will occur. The BOR calculates benefits (assuming the price increase $r = 0$) as

$$\text{Expected variable benefit} = E[\pi] * E[q] = \sum_{j=1}^{5} f_{jh}\pi(j) * \sum_{j=1}^{5} f_{jh}q(j).$$

The correct calculation is

$$\text{Expected variable benefit} = E[\pi * q] = \sum_{j=1}^{5} f_{jh}\pi(j)q(j).$$

The BOR calculation overstates the benefits. We know this from the fact that $Cov(\pi, q) = E[\pi * q] - E[\pi] * E[q]$. Because π and q are not independent random variables, $Cov(\pi, q) \neq 0$. Because the values of π in Table 2 decrease while the values of q increase with an increase in j, I expect a negative covariance, and this is verified when the covariance is calculated. While in all other areas I have calibrated my results to the BOR analysis, this error cannot be carried through my analysis without compromising the results.

2.1.3 Possible future climate distributions

I introduce potential climate change in the analysis. The model for future climate projections used by the National Weather Service (NWS) includes twelve climate scenarios. According to Zhu, et.al. (2003), the model has considerable empirical validity and has withstood years of scrutiny. It has been used to model general hydrology impacts (Miller, et.al., 2003) and water supply management in California, (Zhu, et.al., 2005). The scenarios include both increases and decreases in anticipated precipitation. I use six of these scenarios, applying two general circulation models (GCMs.) The Hadley Centre's HadCM2 Run 1 (HadCM) projects a relatively warmer, wetter California, while the National Center for Atmospheric Research's Parallel Climate Model Run B06.06 (PCM) projects a relatively dryer and cooler scenario. Both models assume a 1% annual increase in GHG emissions and project for three future periods: 2010-2039, 2050-2079 and 2080-2099, as shown in Table 3 :

Model	Period	Temperature Change (Mean) Degrees Celsius	Precipitation Percentage Change (Mean)
HadCM	2010-'39	1.4	26
HadCM	2050-'79	2.4	32
HadCM	2080-'99	3.3	62
PCM	2010-'39	0.4	- 2
PCM	2050-'79	1.5	-12
PCM	2080-'99	2.3	-26

Table 3: Projected 100-year changes in precipitation and in temperature under the Hadley Climate Model and the Parallel Climate Model.

I apply these projected changes by changing the 83 historical observations of yearly California precipitation inches by the appropriate percentage and categorizing the results into the five weather-year types used by the BOR, resulting in two different future precipitation patterns. For example, over the historical 83 years, there were 16 years for which the annual precipitation was fewer than16 inches, ranging from 9.2 inches to 15.8, qualifying as a driest type year. Since 16 is 19.2% of the 83 years, the historical likelihood of a driest type year occurring is 19.2%. I apply the expected 26% mean increase under the HadCM model that will occur in the period 2010-'39 to each of these 16 precipitation amounts, and come up with an adjusted range of 11.6 inches to 19.9 inches, of which only two observations are less than 16 inches. Two observations out of 83 imply that in the 2010-2039 period, the mean percentage of years that will be driest occur with a likelihood of 2.4%. Table 4 gives the resulting conditional probabilities that describe the likelihood that a given year's precipitation will be at a particular level given that the true future climate is accurately predicted by the HadCM or the PCM model. (The headings 2025, 2065 and 2090 refer to the mean year of the projection, for example the header "2025" represents the period 2010-'39.)

Climate Model	Historical $i=0$	HadCM $i=1$			PCM $i=2$		
Period	All	2025	2065	2090	2025	2065	2090
Driest	.192	.024	.024	.012	.313	.361	.506
Dry/Critical	.188	.048	.012	.012	.229	.181	.181
Below Normal	.192	.254	.254	.012	.181	.229	.169
Above Normal	.140	.096	.108	.072	.108	.084	.084
Wet	.288	.578	.602	.892	.169	.145	.060

Table 4: Conditional precipitation distribution under possible future climate models

Figure 1 shows that, in the period 2010-2039, under the PCM the climate is expected to be drier than historical patterns, and the HadCM predicts wetter than historical climate. Table 4 shows these effects increase over time.

Because climate changes gradually, I assume a piecewise linear transition from historical precipitation levels to future predicted mean precipitation levels. For example, Figure 2 shows how the probability of a driest type year occurring changes over time under the predictions of the Parallel Climate Model.

2.1.4 Expected learning time

With Bayesian learning we can estimate when uncertainties about climate change will be approximately resolved (Kelly and Kolstad, 1999).[1] If learning occurs slowly, the opportunity to make a productive decision may pass while we gather more information. If learning is rapid, the option value is initially high and falls as we learn. Therefore, it is useful to estimate how quickly learning occurs. Because learning increases as the climate reveals itself over time, we can estimate the expected learning path for each climate scenario and any value of p, the initial subjective belief. If the true climate is i, we can find the expected value of the next period's belief p' as:

$$E(p'|p,i,y) = \sum_{j=1}^{5} \frac{pf_{1jy}}{pf_{1jy} + (1-p)f_{2jy}} f_{ijy} \tag{10}$$

---

[1] For example, if there are two possible future scenarios, approximate resolution of uncertainty occurs when the probability of one of those future scenarios occurring approaches one.

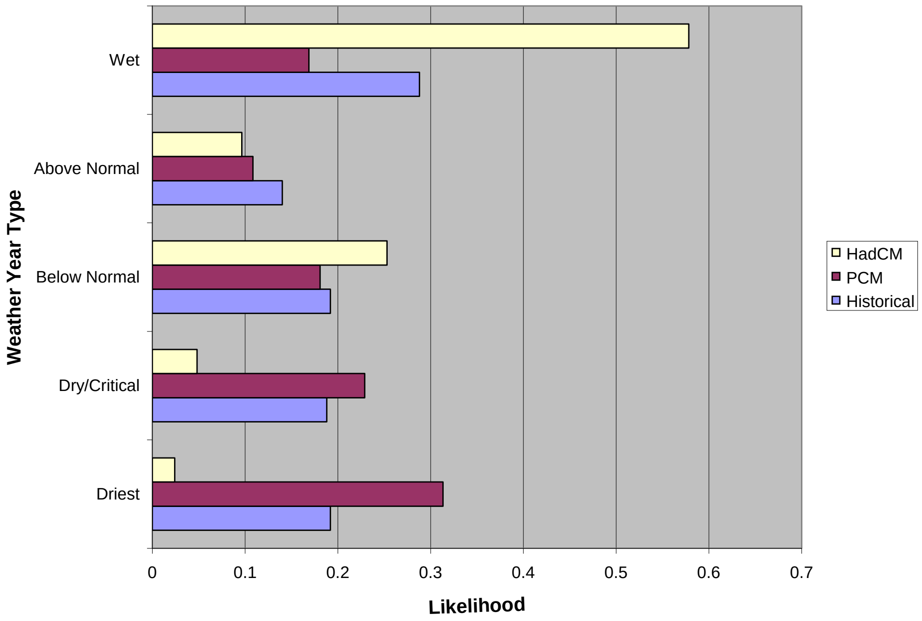

Figure 1: Projected mean probability distribution of two precipitation models for 2010-2039 compared to historical precipitation.

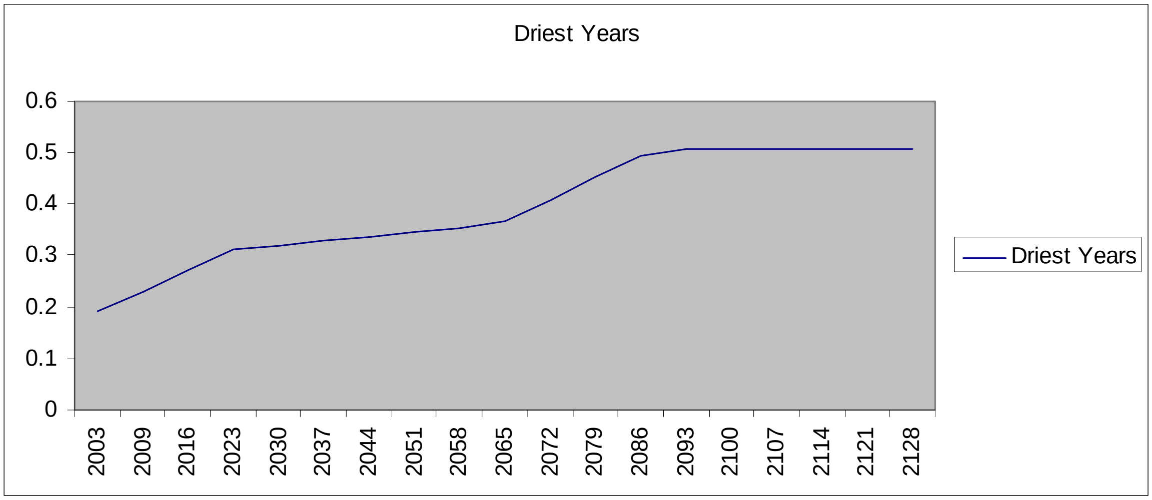

Figure 2: Changing probability of a driest type year under the Parallel Climate Model

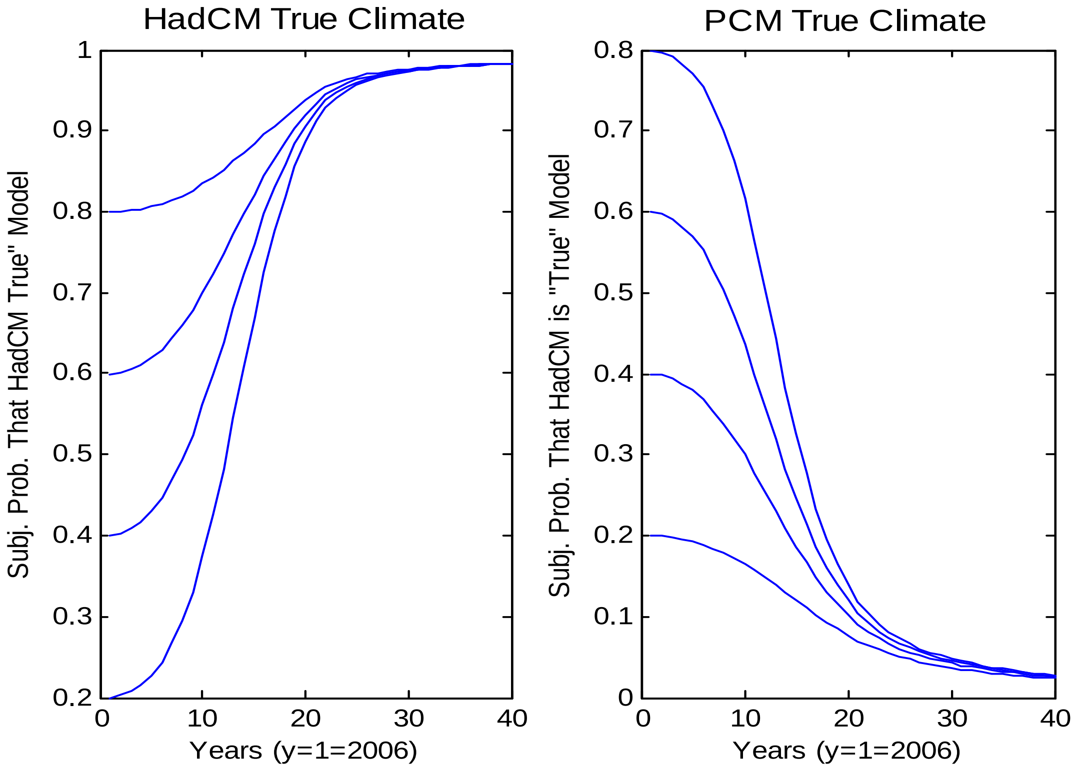

Figure 3: Expected p at each year (learning path) if PCM or HadCM predicts the future climate accurately.

Figure 3 shows that after about 30 years, there is an estimated 95% certainty about the true climate state for a large range of our initial belief. Thus, I put a 30-year cap on the possible delay in decision-making, because after 30 years no substantial learning can occur, rendering delay worthless.

2.2 Initial Problem Solution

I frame the problem as finite over thirty years because, as Figure 3 demonstrates, after about 30 years from $y = 1$ there is an estimated 95% certainty about the true climate state in most cases of our initial belief. After $y = 30$ there is little opportunity to learn, thus no benefit to delaying the decision and at $y = 31$ the option to build the storage has expired. Therefore $v(p, 31) = 0$ for all p.

If the delay were limited to only one or two years, a closed-form solution is easily found. However, expanding the problem over a full thirty years of possible delay becomes intractable because the number of possible paths that p can take is 5^{30}. Therefore, I use interpolation estimation to approximate a solution to the problem. The general solution method is derived from Miranda and Fackler (2002.)

I use numerical interpolation methods to estimate the bi-variate function[2]:

$$\begin{aligned} J(p,y) &= \max\{v(p,y), E_{p'|p}\beta J(p',y')\} && (11) \\ \text{subject to } p\acute{}(j,p,y) &= \frac{pf_{1jy}}{pf_{1jy}+(1-p)f_{2jy}} && (12) \\ y' &= y+1. && (13) \end{aligned}$$

where

$$\Pr\left(p\acute{} = \frac{pf_{1jy}}{pf_{1jy}+(1-p)f_{2jy}}\right) = F_{pjy} \tag{14}$$

To estimate the function $v(p,y)$, I first define a set of interpolation nodes:

$p \in (0,1)$ over $n_1 = 30$ unevenly spaced breakpoints. For derivation of breakpoints, see Miranda and Fackler 2002, page 129.

$y = 1, 2, ..., \bar{Y}$, where for the initial problem $\bar{Y} = 30 = n_2$.

Given these two state variables, there are a total of $N = \Pi_{i=1}^{2} n_i = 900$ nodes.

Next, I define an $N = 900$-degree function basis using cubic splines as basis functions. I develop an N by N interpolation matrix using the function basis and nodes and derive $\Phi(p,y)$, a tensor product of the univariate interpolation matrices for the set of N known linearly independent basis functions. For a detailed description of the derivation of $\Phi(p,y)$, see Miranda and Fackler (2002), especially page 131.

I first evaluate $v(p,y)$ at the N selected interpolation nodes, and then derive a curve-fitting estimation function by approximating the solution to the value function $v(p,y)$:

$$\hat{v}(p,y) = C\Phi(p,y) \tag{15}$$

where C = basis coefficients which are to be determined. To find basis coefficients, C, I solve the linear equation:

$$\begin{aligned} C\Phi(p,y) &= V(p,y). \\ C &= V/\Phi, \end{aligned}$$

---

[2] See Equation 8 for definition of F_{pjy}.

where $V(p, y)$ is a solution matrix of explicit function values over the 900 interpolation nodes. Once I solve for C, I can estimate the value function for any p, y using Equation 15.

The finite Bellman Equation 11 is solved using backward induction. The solution to $v(p, 31) = 0$ for all nodes, because the option to delay building the dam expires in year 30 when no more learning can occur. I estimate the solution for $v(p, 30)$:

$$\hat{v}(p, 30) = C\Phi(p, 30). \tag{16}$$

I now estimate the expected solution to the dynamic programming equation assuming the decision is made in year 29:

$$J(p, 29) = \max[v(p, 29), E_{p'|p}\{\hat{v}(p', 30) = C\Phi(p', 30)\}] \tag{17}$$

Once I have an estimated solution for Equation 17, I solve Bellman Equation for the prior year:

$$J(p, 28) = \max[v(p, 28), E_{p'|p}J(p', 29)\}].$$

I continue the backward induction process until I estimate $J(p, 1)$, which maximizes the problem for all nodes when year $y = 1$. The option value is the estimated value of the ability to delay

$$OptionValue = J(p, 1) - v(p, 1).$$

Figure 4 shows the solution for decision-making in Year 1.

We are better off proceeding with the project without delay only if we believe with a probability of under .08 that the true climate will follow the wet climate model – thus it is valuable to wait to learn more about the climate before proceeding over most of the belief space.

2.3 Variable Growth of Greenhouse Gas Levels

The HadCM and the PCM both assume that greenhouse gas stocks are increasing at a steady 1.3% rate every year, as have I so far in this paper. The solution to this problem might differ if GHG growth is at a different rate or is random. To evaluate these cases, I assume that there is a direct relationship between the GHG level and the precipitation distribution under a wet or dry climate type.

Let

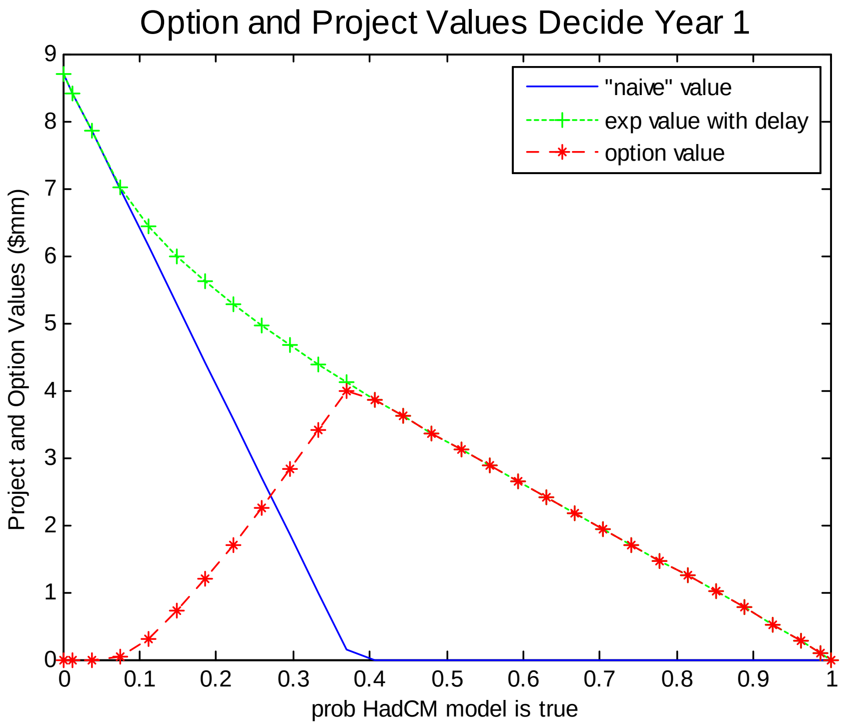

Figure 4: Option and project expected values in year 1 given the ability to delay for up to 30 years.

g be the annual percentage growth rate of GHG, and

G be the GHG level, such that

$G|y, g$ is the GHG level in year y given a GHG growth rate of g.

As a normalization, I set $G = 1$ as of the beginning of year 2003 in order to calibrate with the HadCM and PCM scenarios. I previously assigned the value $y = 1$ to the first possible decision year of 2006. Thus, $G|_{y=1,g=.013} = 1.013^3$. The distribution of weather types under either the wet (HadCM) or dry (PCM) climate models for the year 2006 can be associated with a GHG level of 1.0395. Similarly, the distribution of weather types for the year 2009 can be associated with a $G|_{y=4,g=.013} = 1.013^6$, or $G = 1.0806$. Assuming $g = .013$, simplify the notation to $G_y = 1.013^{y+2}$.

Recall that f_{ijy} is the conditional probability of observing signal j (precipitation type) in the year y given the true climate state is i. If the climate pattern depends on the GHG level regardless of the year in which it occurs, we can replace the former relationship between climate distributions and time with climate distributions conditional upon GHG levels – that is map f_{ijy} to $f_{ijG.}$

The inverse of the relationship $G = 1.013^{y+2}$ is

$$\begin{aligned} y+2 &= \log_{1.013} G \\ y &= \log_{1.013} G - 2 \\ y &= \frac{\ln G}{\ln 1.013} - 2 \end{aligned} \tag{18}$$

With this transformation I map f_{ijy} to $f_{ijG.}$ Restating the weather distribution from f_{ijy} to f_{ijG} allows for analysis when deterministic GHG growth is at a rate other than 1.3%.

I first explore how the results change when the deterministic growth rate varies from 1.3% annually. Secondly I consider what happens when GHG levels grow stochastically. In that case we might expect more uncertainty to increase the option value of waiting.

2.3.1 Deterministic GHG growth

Suppose that GHG levels are increasing at a steady and predictable rate, g per period (year). There is an option to make a decision in year 2006 when $y = 1$, and $G|y, g = (1+g)^{y+2} = (1+g)^3$. I restate the problem as a function of the GHG level G by replacing the time variable y with the transformation $y = \frac{\ln G}{\ln 1.013} - 2$. As before, the capital investment k is incurred at the beginning of the base year, τ years after the decision when $G_{\tau+y} = (1+g)^{\tau+y+2}$. The benefits begin at the end of the base year and accrue over time at the end of each year. The future benefits are discounted using an annual discount factor of β. All costs and benefits are calculated using real price levels corresponding to the earliest possible decision year, when $G_{y=1,g} = (1+g)^3$, except for the variable benefits which are increased at an annual rate of r. The expected value of the project at base GHG level $G|y+\tau, g$ if decided upon when GHG levels $= G|y, g$ and the true climate future is i is**:**

$$\begin{aligned} w_{iG} &= \left(\sum_{t=\frac{\ln G}{\ln 1.013}-2+\tau}^{T+\frac{\ln G}{\ln 1.013}+\tau-3} \sum_{j=1}^{J} \beta^{t-\tau} f_{ijG(t)} z(j,t) \right) - \beta^{\frac{\ln G}{\ln 1.013}-3} k && (19) \\ where\ G(t) &= (1+g)^{t+2} && (20) \end{aligned}$$

Let p be the subjective probability that $i = 1$ (the wetter HadCM reflects the true climate state). Define the expected present value of the future benefits of the additional storage given the current belief about climate change, GHG level and expected growth in GHG level g, as:

$$v(p, G) = p w_{1G} + (1-p) w_{2G}. \qquad (21)$$

Restate the value function as a function of our belief in the probability of a wet climate state being true, p, and of greenhouse gas levels G, where GHG levels grow at a rate g.

$$J(p, G) = \max[E_{p\rceil p}\{v(p, G), J(p', G')\}] \qquad (22)$$

$$\text{subject to } p'(p, j, G) = \frac{p f_{1jG}}{p f_{1jG} + (1-p) f_{2jG}}$$

$$\text{subject to } G' = G * (1+g)$$

where

$$\Pr\left(p' = \frac{p f_{1jG}}{p f_{1jG} + (1-p) f_{2jG}} \right) = F_{pjG.}$$

Expected learning time with variable growth rate. When we assumed that g=.013, we found that after approximately 30 years there would be a high certainty about the true climate state, such that the option value after 30 years approaches 0. If GHG levels grow at a faster rate learning should occur more quickly. For example, if the true climate is dry, and GHG levels grow faster, we are likely to observe more dry years sooner – thus we will update our belief more quickly to reflect the true state of nature. To illustrate, I restate Equation 10 to be a function of the GHG level

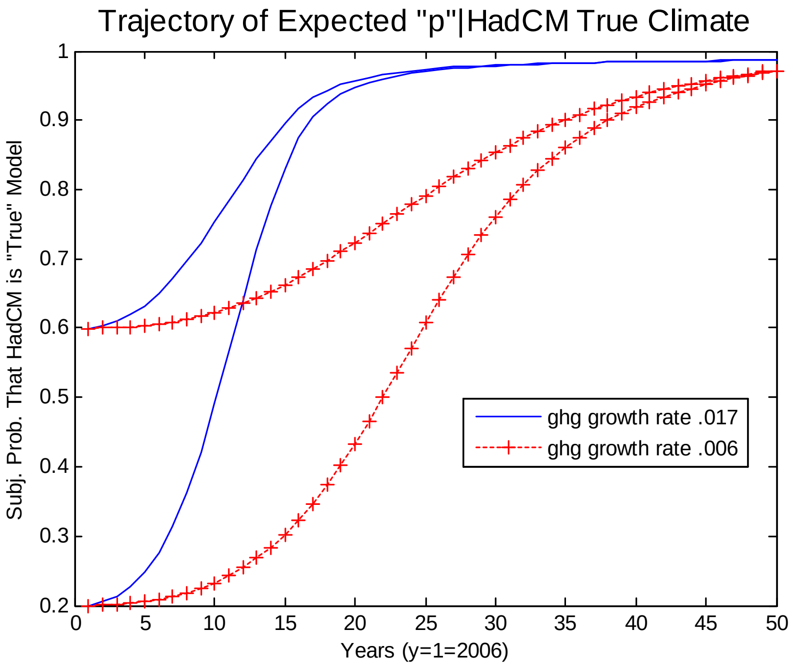

Figure 5: Learning path when Hadley Climate Model (wet) is true given initial p=.2 or .6, and g=.017 (blue) or .006. (red).

G rather than of the period y in Equation 23 using the transformation Equation 18.

$$E(p'|p, i, G) = \sum_{j=1}^{5} \frac{p f_{1jG}}{p f_{1jG} + (1-p) f_{2jG}} f_{ijG} \tag{23}$$

If the growth rate parameter $g = .017$ per year, learning occurs faster, as observed by comparing Figure 5 to Figure 3. After 20 years, rather than 30, there is a very high certainty about the climate state regardless of our original belief.

Conversely, Figure 5 shows learning is expected to occur over a longer period should GHG levels increase by a slower .006 per year, such that we would need at least 40 years to obtain relative certainty about the true climate state. (A similar result is found if the true climate state is the Parallel (dry) Climate Model.)

Solution for deterministic GHG growth Setting $g = .017$, I solve Equation 22.

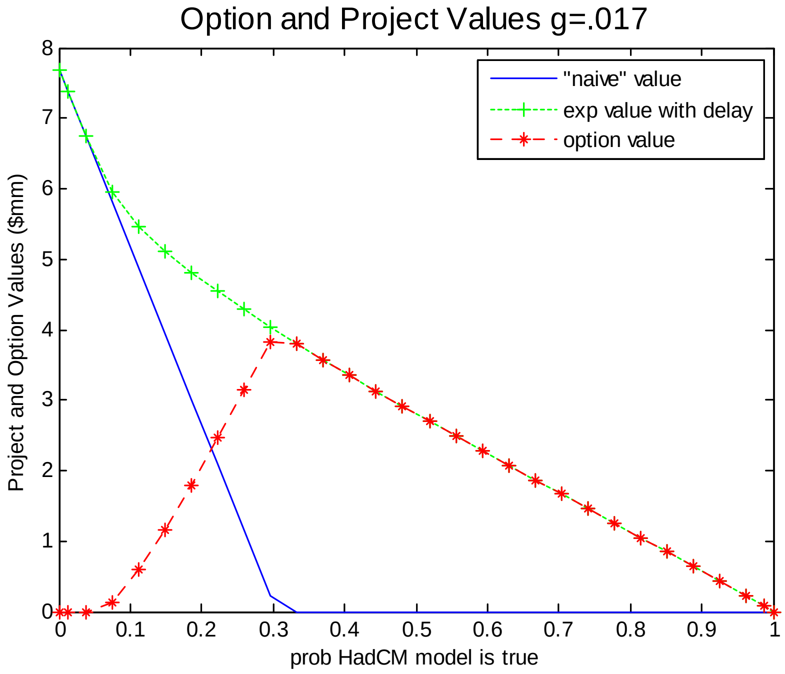

Figure 6: Option and project value when GHG level growth is .017 per year. Solved over a 40-year horizon.

With a faster GHG growth rate, the range of values for p over which there is a positive option value to delay increases slightly from greater than .08 shown in Figure 4 to greater than .05 as shown in Figure 6. The intuition about this increase in range is that when learning occurs more quickly, the value of waiting before making a decision is more likely to be positive.[3]

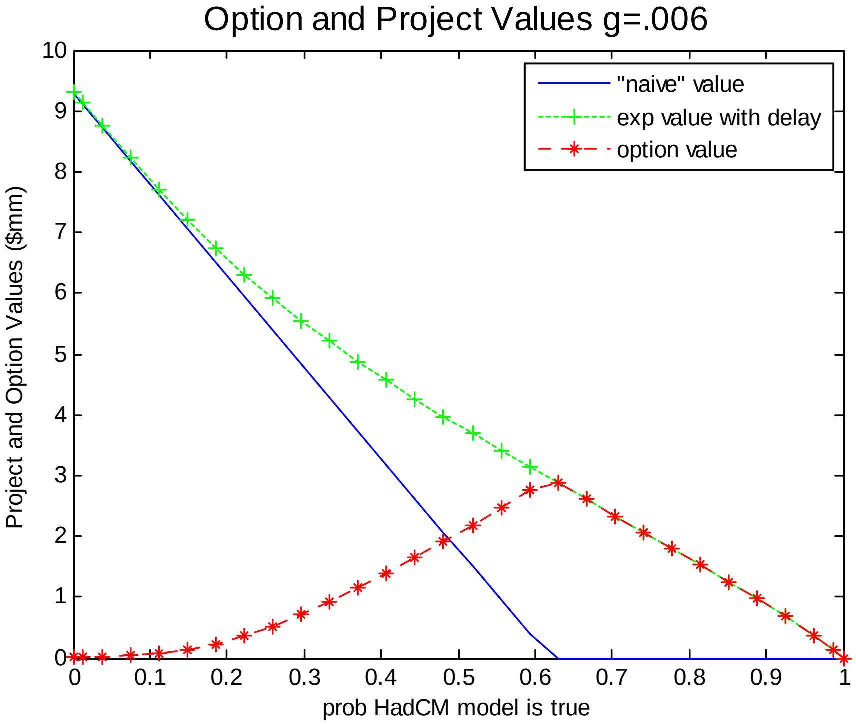

Figure 7: Expected project and option values when annual GHG growth rate is .006.

Figure 7 shows that if $g = .006$ and there were no option to delay the project, it would proceed if the likelihood that the future climate is wet is less than .63. The range over which there is a positive option to delay decreases slightly to greater than about 0.1.

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[3] To assure a consistent answer, I solve the problem over 40 years for both $g = .017$ and for $g = .06$. However, as expected, when $g = .017$ and I solve the problem over 20 years (the period by which there is a high certainty as to the correct climate state) the solution is virtually unchanged. Solving Equation 11 for $g = .013$ over 40 years also results in a solution that is virtually unchanged from the original 30-year solution shown in Figure 5.

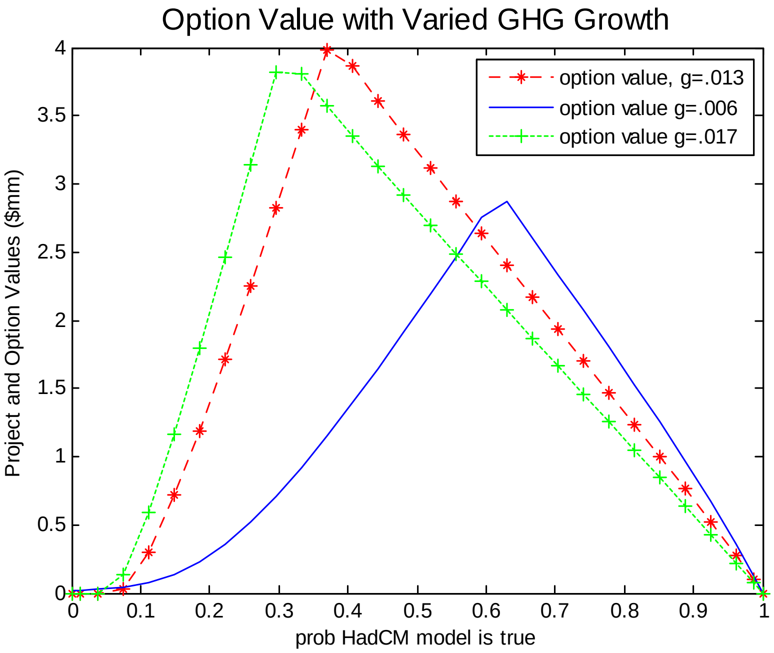

Figure 8: Option values dependent on constant GHG-level growth rate.

Figure 8 compares the option values depending on the three deterministic growth rates I have used as examples. The maximum option values of the graphs shift to the right as the projected GHG-level growth rate is reduced. This shift occurs because as the GHG growth rate is reduced, the value of p (the probability that the true climate is wetter) under which the project would proceed given no ability to delay increases. The option value to delay the project is maximized in each case at this critical value of p.

There are two effects at work. The first is that the naive value for the project, that is the value of the project when there is no chance to delay, decreases for all p when GHG growth increases. Under the wet scenario the effects of climate change are detrimental to project value, while under the dry scenario project value increases with GHG growth. The inverse relationship between GHG growth rate and naive project value for all p occurs because detrimental effects under the wet scenario increase faster with GHG level growth than the beneficial effects increase under the dry scenario. For the second effect, observe that if these three graphs were stacked such that the apex occurred at the same value of p for all graphs, the option value to delay for the slowest growth scenario would be less over much of the range of p. An intuition for this result is that as changing information is received more slowly, the usefulness of the information may pass before it can be used in decision-making.

2.3.2 Stochastic GHG growth

So far I have assumed that the GHG levels grow at a constant, deterministic rate. I now consider the problem in which the annual growth rate is stochastic, but has a known distribution. Throughout this section each expected precipitation distribution depends on the GHG level.

The problem can be restated as:

$$\begin{aligned} J(p,G,y) &= \max\{E[v(p,G,y)], E_{G'|G}E_{p'|p}J(p',G',y')\}] \\ \text{subject to } G'(G,g,e) &= G*(1+(g+e)), \quad e \sim \textit{some} \text{ distribution} \\ \text{subject to } y' &= y+1 \end{aligned} \tag{24}$$

and subject to the transition and probability distribution from Equation 22 for p'.

With stochastic GHG-level growth, we must determine the expected value of the project as a function of p, the beginning GHG level G, and the decision year y.

$$E[v(p,G,y)] = pE[w_{1Gy}] + (1-p)E[w_{2Gy}]. \tag{25}$$

The expected value of the project given climate i and beginning GHG level G decided upon in year y can be written using a Bellman Equation

$$\begin{aligned} E[w_{iGy}] &= E[V_i(G,y)] - \beta^{y-1}k \\ &\quad where \\ E[V_i(G,y)] &= \sum_{j=1}^{J} f_{ijG} * z(j, y+\tau) + E_{G'|G}[V_i(G',y')] \\ \text{subject to } G'(G,g,e) &= G*(1+(g+e)), \quad e \sim some \text{ distribution} \\ \text{subject to } y' &= y+1. \end{aligned}$$

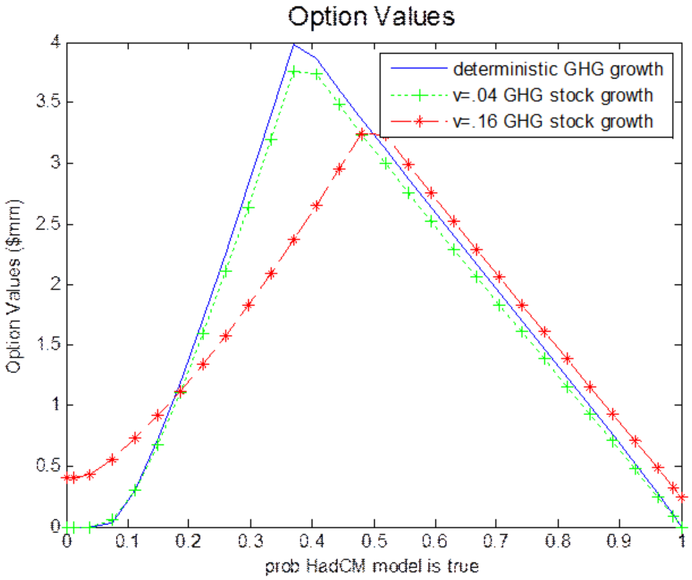

Figure 9: Option values when GHG stock changes are stochastic, with normal distributions and variances of .04 and .16.

Figure 9 shows the solution to Equation 24 when e follows a normal distribution with mean $= 0$, and the variance in GHG growth is either .04 or .16, as compared to the results when the variance $= 0$. The mean growth rate over time in all cases remains $g = .013$. In the case of the smaller variance, the option value is reduced over much of the range of p. This result may appear counterintuitive, as most models have found that greater stochasticity leads to higher option values. Why does the addition of stochastic GHG growth reduce the value with delay in some cases? The intuition for this result is that the stochasticity in the GHG level slows our learning.

When we observe precipitation realizations, our estimation of the future changes in precipitation is based not only upon the expected precipitation distribution changes given our belief about the true climate state, but also on the random speed at which the precipitation distribution will change. Thus, with GHG stochasticity we cannot anticipate learning as quickly in the future as we can without. As previously shown, when learning is anticipated to occur more slowly, the option value of delay diminishes in some cases.

With greater stochasticity in GHG growth (variance = .16) in Figure 9, there is still a range of p for which the option value is reduced, but for the highest and lowest values of p the option value increases. In these cases perhaps the risk associated with the extreme randomness of the GHG growth outweighs the effect of the slower learning.

2.4 Discussion

This chapter demonstrates empirically how the anticipated observation of information about climate change can be incorporated in the analysis of a major infrastructure project. I show that with uncertainty and the prospect of learning, under some circumstances the option to delay a major project has a positive and quantifiable value. If learning is expected to occur slowly, in some cases the opportunity to make a productive decision may pass while we gather more information and the option value of delay is reduced.

It is relatively easy to solve the option value of delay over one or two periods, assuming two known projections of value and a finite, discrete distribution of signals. Over longer periods, or with more complex problems, numerical methods can be employed. I apply function estimation by interpolation methods, using cubic spline functions, to approximate a solution to the option valuation problem.

Using the parameters in my example, while the expected value of a project may decrease with faster GHG growth, the option value to delay increases in some cases as learning is more rapid. The addition of stochasticity in a climate change state variable can decrease the expected value of a delayed project. We might expect a second stochastic element to increase the option value as it increases uncertainty, but by slowing learning the option value can diminish. The determination of when the range of beliefs with a positive option value to delay is increased due to the stochasticity of the GHG growth depends on the parameter values and the distribution of GHG growth stochasticity, and can have a minor or a major effect on the decision.

By applying the relevant theory to an empirical question, my results differ substantially from when a planner simply follows the common NPV approach. This analysis suggests questions a planner should ask and, where possible, incorporate in the analysis, for example:

1) What uncertainties exist with respect to the potential value of the project?

2) Under which of these scenarios does the value of the project change more rapidly, and is that change positive or negative?

3) Is there a way to quantify a possible distribution of values and probabilities resulting from these uncertainties?

4) Will there be measurable information forthcoming that will allow us to learn and update our belief about these distributions?

5) Will this information come quickly enough for the option to delay to have a positive value?

This chapter demonstrates empirically how an analysis taking into account these questions can be done, and if enough information about parameter values is available, methods to improve decision-making with the objective of improving expected results of major capital projects.

Future theoretical work could explore the general circumstances under which option values increase or decrease when stochasticity affects the transition of more than one state variable, particularly when the transition of one stochastic variable (learning) is dependent upon the other stochastic variable. It may address the question as to how to determine when increased uncertainty outweighs slower learning. In addition, more practical empirical studies could be performed to improve the methodology of valuing projects that possess the option to delay and for which there exists some likely distributions of positive and negative outcomes that are scientifically justified.

3 Sensitivity Analysis

In Chapter 2, I analyze a specific water storage project, the Los Vaqueros Dam Expansion Project, and conclude that given the anticipation of learning about the effects of climate change there is a positive option value to delay the project under some circumstances. I also find that the option value is reduced in some cases when greenhouse gas (GHG) level growth stochasticity is added to the problem. I assume specific parameters in reaching these conclusions, most of which are provided from the original Bureau of Reclamation (2006) analysis. In this chapter I vary some of the key parameters and analyze the effect on the conclusions from Chapter 2.

In conducting a project evaluation it is important to consider possible changes to parameter values, as there are uncertainties associated with future benefit and cost flows, especially for long-term projects. Sensitivity analysis allows the decision maker to understand the effect if an uncertain parameter changes from its expected value. If a small change in a parameter value leads to a large change in project value, efforts to manage the parameter value should be implemented. If a parameter value can vary widely resulting in potential project value change, the effect of this variation must be considered.

In this chapter I analyze changes in the discount rate, projected prices, capital investment, project benefit lifespan and rate of GHG-level growth. For each variable I answer the following three questions: 1) Above or below what parameter value does the project have a zero (or negative) value? 2) What is the range of parameter values for which the project would be done if there were no option to delay? 3) What is the range of parameter values for which there is a positive option to delay? I assume in each of these cases that GHG-growth is deterministic, but conclude this chapter by reviewing how varying GHG growth stochasticity affects my base case results.

3.1 Restatement of Problem and Base Case

Recall that the problem I solve is:

$$J(p,G) = \max[E_{p'|p}\{v(p,G), J(p',G')\}] \tag{26}$$

$$\text{subject to } p'(p,j,G) = \frac{pf_{1jG}}{pf_{1jG} + (1-p)f_{2jG}}$$

$$\text{subject to } G'(G,g,e) = G * (1 + (g+e)), \quad e \sim \textit{some} \text{ distribution} \tag{27}$$

where the probability distribution of p' is

$$\Pr\left(p' = \frac{pf_{1jG}}{pf_{1jG} + (1-p)f_{2jG}}\right) = F_{pjG}$$

and

$$v(p,G) = pw_{1G} + (1-p)w_{2G} \tag{28}$$

given that

$$\begin{aligned} w_{iG} &= \left(\sum_{t=\frac{\ln G}{\ln 1.013}-2+\tau}^{T+\frac{\ln G}{\ln 1.013}+\tau-3} \sum_{j=1}^{J} \beta^{t-\tau} f_{ijG(t)} z(j,t) \right) - \beta^{\frac{\ln G}{\ln 1.013}-3} k \qquad (29) \\ where\ G(t) &= (1+(g+e))^{t+2},\ e \sim some \text{ distribution.} \qquad (30) \end{aligned}$$

Equation 26 is the Bellman equation that solves for the value of the project given the optimal decision on when to build the dam. Equation 28 is the value of the project given a beginning GHG level, G, and a belief that the likelihood that a wet climate future will occur is p. Equation 29 is the expected profit for a project given a beginning GHG level G and a known climate future i, where $i = 1$ represents a wet climate future (the Hadley Centre Model, HadCM) and $i = 2$ represents a dry climate future (the Parallel Climate Model, PCM.) The option value of delaying the project is calculated as

$$OptionValue = J(p, G) - v(p, G)$$

where $v(p, G)$ is the expected value of the project when the decision is made at GHG level G, and there is no possibility of delay, what I call the naive project value. For the base case I assume G is the GHG level in the year 2006. For a full description of the problem and definitions of the parameters and values used, refer to Chapter 2.

Figure 10 shows the project and option values under the base case scenario. Under the naive solution, the project has a positive value when $p < .38$, and would not be pursued otherwise. With the option to delay, the project has a positive expected value for all p, and a positive option value if $p > .08$, with a peak option value of about \$4 million if $p = .38$.

3.2 Parameters to be Varied and Sensitivity Analysis

Table 5 describes the parameters that will be varied in this sensitivity analysis and their values under the base case. For each variable, I calculate the range over which the project would never be done, the range over which the project would be done if there were no option to delay (the naive solution) and the range over which there is a positive value to delay. These calculations vary depending on our belief that the true climate is wet as expressed by the probability p. I note the corner solutions at $p = 1$ because when we are certain the future climate is wet, the relevant project and option values are more likely to be zero than for other values of p.

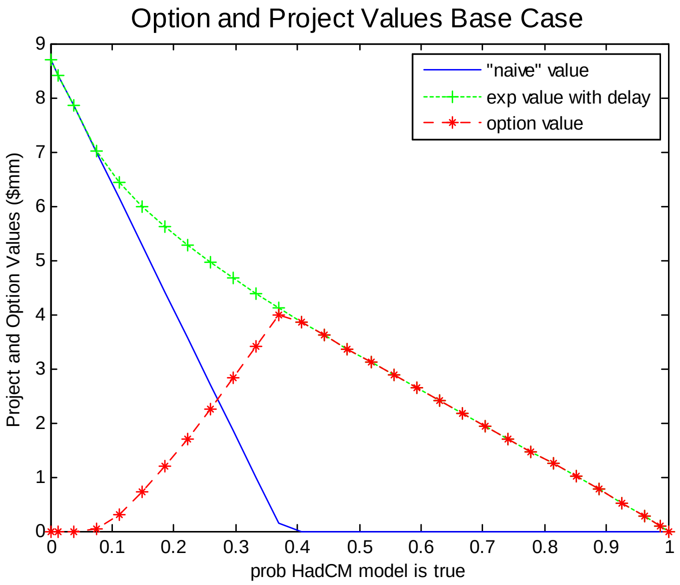

Figure 10: Base case option and project value.

Label	**Definition**	**Value**
d	Annual discount rate applied to benefits at year's end,	5.125%
	and to costs mid-year.	
k	Present value of one-time capital cost of the	$\$596,889,000$
	project at $y + \tau = 2016$.	
r	Annual expected price increase for variable benefits.	0.1%
T	Lifespan (years) of project benefits.	100
g	Annual growth in GHG level.	1.3%

Table 5: Parameters and values used in baseline analysis.

3.2.1 Change in discount rate

The BOR analysis uses the federal discount rate of .05125 in its calculations. As the discount rate increases the project value decreases, until at $d = .0528$ the project would never be done for all values of p. This represents less than a 3% increase in the variable from the base case value.

Discnt. Rate (d) Range	*some* p	*all* p ($p \neq 1$)	$p = 1$
Project never done	$d > .0528$	$d > .0528$	$d > .0503$
Positive naive proj. value	$d < .052$	$d < .0499$	$d < .0499$
Positive option value	$.0499 < d < .0528$	$.052 < d < .0528$	$.0499 < d < .0503$

Table 6: Key parameter ranges for discount rate variable.

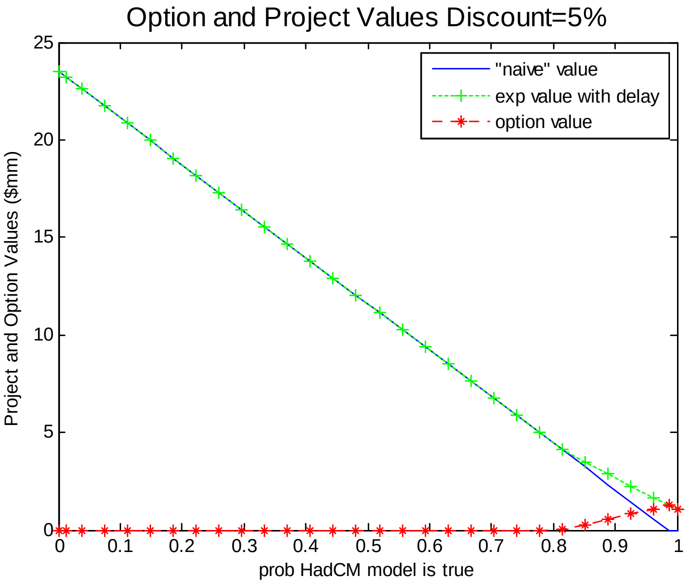

Figure 11: Project and option value when discount rate is 5%.

Figures 11 and 12 show the results for high and low discount rates under which the project has a positive value when the decision cannot be delayed, the naive project value. Given the option to delay, when the discount rate is 5% (Figure 11) the option value is positive only when $p > .81$. Thus the project should be done in year one over all but about 20% of the range of values for p and should be delayed with a

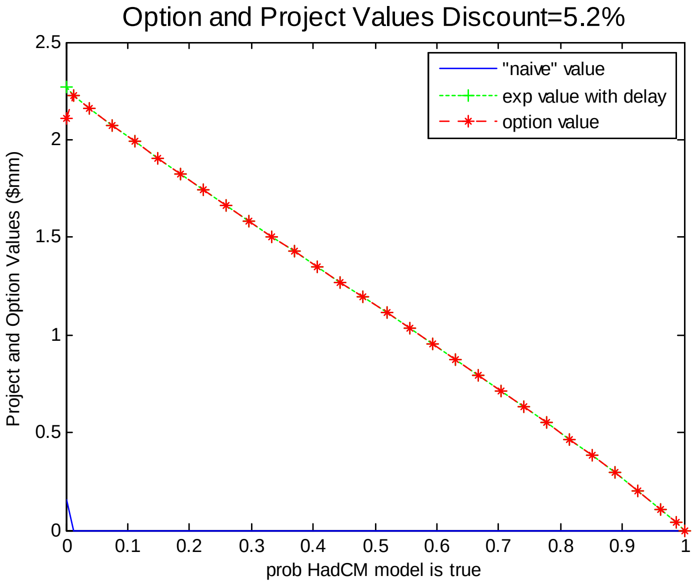

Figure 12: Option and project value with a 5.2% discount rate.

positive option value otherwise. With the option to delay, the project has a positive value for all values of p. When the discount rate is less than about 4.99%, the project has a positive value regardless of when it is begun, and that value increases as the discount rate decreases. For a discount rate of 5.2% (Figure 12), the project would have a positive value without the option to delay only for very small values of p, but for almost all p there is a positive expected value of the project with the ability to delay.

Table 6 shows that given the base case levels for all other parameters, there is a narrow range in the discount rate for which there is a positive option to delay: between .0499 and .0528. The project should be done today if $d < .0499$, a decrease of less than 3% from the base case value of $d = .05125$, no matter what our belief about the climate future. When the discount rate equals zero, the project has a value in excess of $2.6 billion irrespective of the value of p.

3.2.2 Price increase rate change

The annual price increase used in the base case is 0.1%. Table 7 shows that there must be some price increase, at least .00028 annually, for the project to be done at

Price Incr. (r) **Range**	*some* p	*all* p ($p \neq 1$)	$p = 1$
Project never done	$r < .00032$	$r < .00028$	$r < .00145$
Pos. naive proj. value	$r > .00032$	$r > .00215$	$r > .00215$
Positive option value	$.00028 < r < .0038$	$.00032 < r < .0038$	$.00145 < r < .0038$

Table 7: Key parameter ranges for price increase variable.

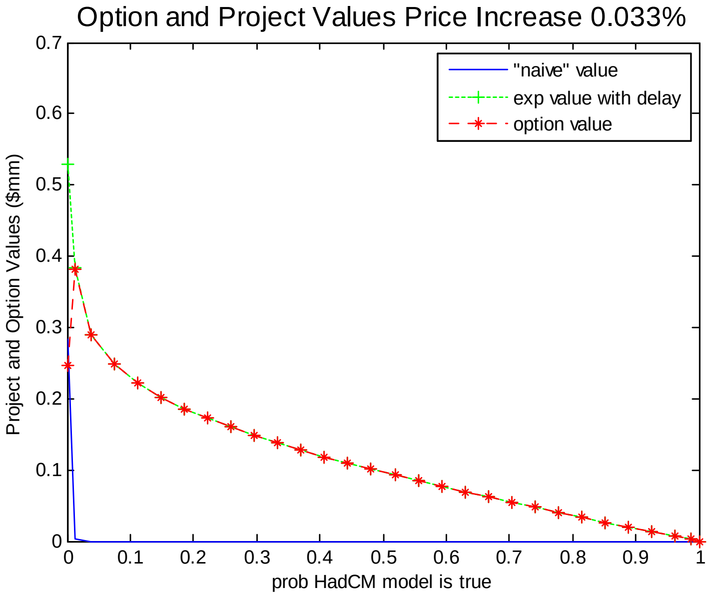

Figure 13: Option and project values when the annual price increases .033%.

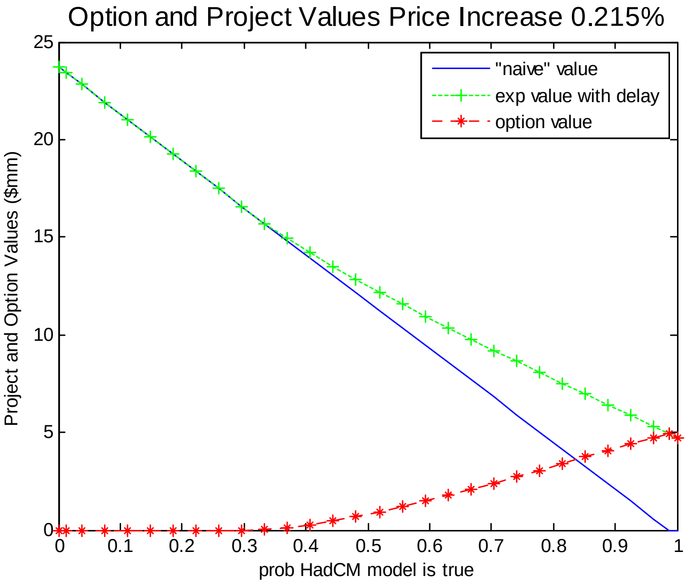

Figure 14: Option and project value with a 0.00215 annual price increase.

all. As price increases faster, the project value increases. At an annual price increase of 4%, the highest price considered in the BOR analysis, project profits are between \$1.4 and \$1.5 billion.

Figures 13 and 14 show low and high annual price increases under which the project has a positive value when the project cannot be delayed. When the price increase is .033% (Figure 13) the naive project value is positive only when $p < .01$ and the project should be done in decision year one only when there is an very small likelihood that the wet climate state is true. Figure 14 shows that once the price increase is greater than about .215% there is a positive project value for all p when there is no possibility for delay – however, there is a positive option value to delay when $p > .4$. When the price increase is greater than .38% for all p the option value to delay equal 0, and the project should always be decided upon in year 1. These conclusions are very sensitive to price fluctuation as small price increase changes from the base case can lead to a different decision.

3.2.3 Change in project capital cost

Table 8 shows that given the parameters in the problem, the project capital cost would need to only increase by about 3% to \$614.5 million from the base case level

Capital Cost (k) **Range** (\$$mm$)	*some* p	*all* p ($p \neq 1$)	$p = 1$
Project never done	$k > 614.5$	$k > 614.5$	$k > 586$
Positive naive project value	$k < 605$	$k < 583$	$k < 583$
Positive option value	$581 < k < 614.5$	$599 < k < 614.5$	$581 < k < 586$

Table 8: Key parameter ranges for capital cost variable.

of \$596.9 million to be unprofitable under any belief about the future climate. The project value decreases as the capital cost increases. The range for which there is a positive option value for some p is small: between \$581 and \$614.5 million. Project and option values are sensitive to small changes in capital cost.

3.2.4 Change in benefits lifetime

Project Life (T) **Range**	*some* p	*all* p ($p \neq 1$)	$p = 1$
Project never done	$T < 68$	$T < 68$	*all* T
Positive naive project value	$T > 78$	N/A	$Never$
Positive option value	$T > 68$	$68 < T < 93$	$Never$

Table 9: Key parameter ranges for benefits lifetime variable.

Table 9 shows that the project delivers positive value independent of the value of p for project life of 68 years or more, except when $p = 1$. As the project life increases, so does the expected value. When $p = 1$, there is never a positive project value independent of the life of the project.

Figure 15 shows that if there were no option to delay the project, it should be done for some values of p as long as project life is greater than 78 years. However, even when the benefit lifetime is very long, under the base case parameter values the project will never be done for the highest values of p. (See Figure 17.)

Figure 16 shows there is a positive option to delay for all p as long as $68 < T < 93$. As the project life increases, the range of values for p for which there is a positive option value decreases but does not disappear until well past the project's useful life, as shown in Figure 17.

3.2.5 Deterministic GHG level growth change

Table 10 shows that holding the other parameters constant the project is expected to deliver a positive value for all values of g, except at the corner solutions when

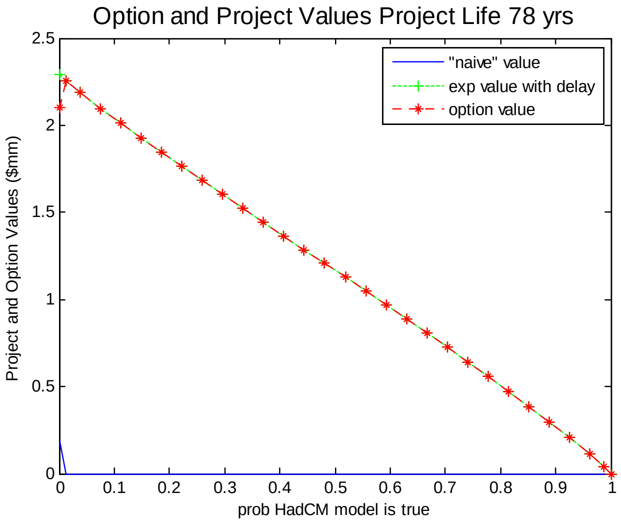

Figure 15: Project and option values when project life is 78 years.

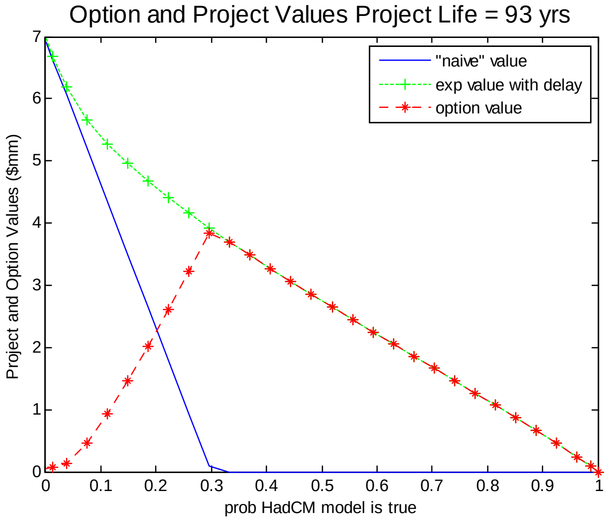

Figure 16: Option and project values when project life is 93 years.

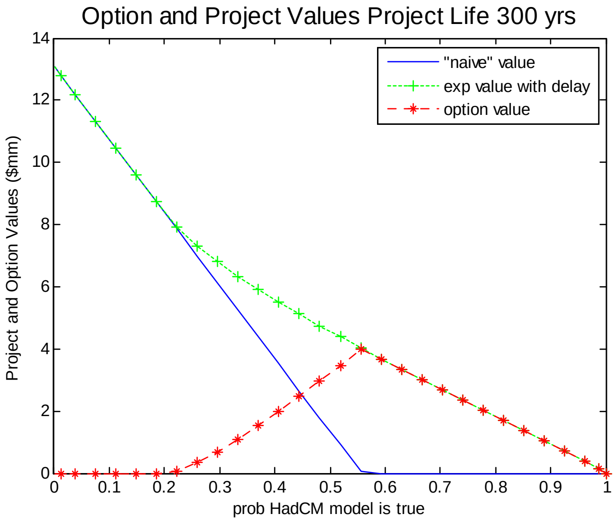

Figure 17: Project and option values if project life is 300 years.

GHG Level Growth (g) **Range**	*some* p	*all* p $(p \neq 0, 1)$	$p = 1$
Project never done	N/A	N/A	$g > .0045$
Positive naive project value	$g < .03$	$g < .0032$	$g < .0032$
Positive option value	$g > 0$	$g > .025$	$g < .0045$

Table 10: Key parameter ranges for GHG-level growth variable.

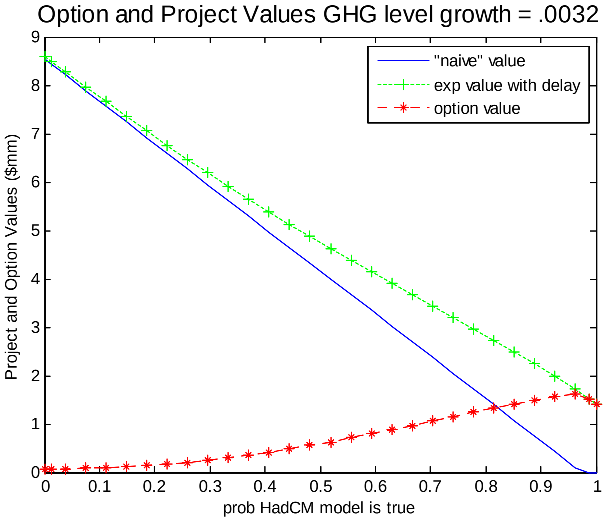

Figure 18: Option and project values when GHG annual growth is .0032.

$p = 1$ or $p = 0$. In the former case, the project will only be done if the GHG-level growth rate is under .0045 annually. In the case where $p = 0$ there is a positive naive project value until the GHG growth rate reaches .03.

Figure 18 shows that if there is no option to delay in year 1, the project will always be done when g is less than about .0032. As GHG growth rates increase, the project becomes less likely to be approved in year 1 until the naive project will never be approved if growth is greater than 3%.

There is a positive option to delay the project for at least some values of p as long as there is a positive growth in GHG levels. There is never a positive option value to delay when $p = 0$. As GHG level growth increases, option values increase for all values of p except $0, 1$. The solution is less sensitive to small changes in GHG growth rates than it is for small changes in other parameter values.

3.3 Stochasticity in GHG-level Growth

As described in Chapter 2, Figure 19 shows the option values to the problem when e follows a normal distribution with mean $= 0$, and the variance in GHG growth is either .04 or .16, as compared to the results when the variance $= 0$. The variable e is the stochasticity in the growth rate, g, to the GHG level, as used in Equations 27 and 30. The mean growth rate over time in all cases remains $g = .013$. In the case of the

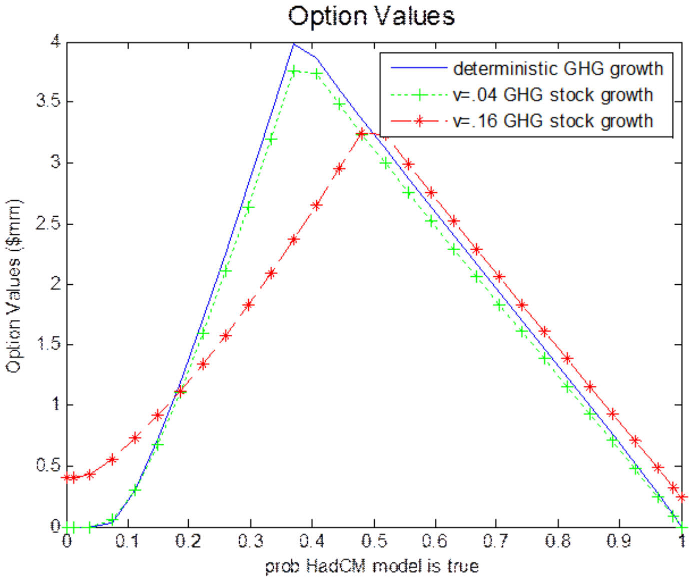

Figure 19: Option values when GHG stock changes are stochastic, where e is distributed normally with mean = 0 and variances of .04 and .16.

smaller variance, the option value is reduced over much of the range of p. As stated in Chapter 2, this result may appear counterintuitive, as most models have found that greater stochasticity leads to higher option values. The intuition for this result is that the stochasticity in the GHG level slows our learning. When we observe precipitation realizations, our estimation of the future changes in precipitation is based not only upon the expected precipitation distribution changes given our belief about the true climate state, but also on the random speed at which the precipitation distribution will change. Thus, with GHG stochasticity we cannot anticipate learning as quickly in the future as we can without. As previously shown, when learning is anticipated to occur more slowly, the option value of delay diminishes in some cases.

With greater stochasticity in GHG growth in Figure 19, (when the variance = .16) there is still a range of p for which the option value is reduced, but for the highest and lowest values of p the option value increases. In these cases perhaps the risk associated with the extreme randomness of the GHG growth outweighs the effect of the slower learning.

As a percentage of the base-case value of $g = .013$, the smaller of these two variances, .04, is more than 300% or the original parameter value. This large variance results in a relatively small change in option value for all p, as shown in Figure 19, suggesting that the problem results are relatively insensitive to GHG stochasticity.

3.4 Discussion

This chapter examines the sensitivity of the conclusions from Chapter 2 to changes in several key parameters. I find that in the case of discount rates and capital costs, the project values are very sensitive to small upward parameter value changes. Project values are also sensitive to a small decrease in expected price increases. The project value is less sensitive to changes in the total life of the project, to GHG-level growth and to stochasticity in that growth. Future work might consider how sensitive the project is to stopping the project once it has begun, for example due to budget cuts or input shortage. The results may vary depending on the probability of such a stoppage occurring.

4 Cost-Benefit Analysis and Decision Making

Dam building dates to antiquity, with the earliest recorded dam dating from 2900 BC, a 15 meter masonry structure across the Nile River in Egypt. The oldest dam still in existence is a rockfill dam built in modern Syria in 1300 BC. Dams benefitted the ancients in providing flood control and reservoirs for consistent human and animal water consumption and for irrigation. During the Industrial Revolution the construction of dams increased to fulfill the need for water power. (Encyclopedia Britannica, 1994). From the 20th century dams provided energy in the form of electricity. Today there are more than 800,000 dams worldwide, of which over 45,000 are taller than a five-story building. (World Commission on Dams (WCD), 2000).

Leading analysts foresee growing competition for water demand in agriculture, industry and for drinking water. Each of these uses drain water from natural systems. Populations in water-stressed countries continue to grow, such that by 2025 there are projected to be a total of 3.5 billion people living in water-stressed areas. Electricity demand continues to rise, while in 2000 one-third of the earth's population lacked electricity. Water for nature is an essential consideration, as freshwater species are increasingly threatened and wetlands continue to be lost, reducing goods and services produced by aquatic ecosystems upon which many societies depend.

The contributions of dams to human development are important and significant, and dams produce considerable benefits for humankind. However, the costs, particularly in environmental and social terms, often have been excessive and unnecessary. Displacement of populations, downstream sacrifices, environmental destruction and excessive taxpayer contribution have sometimes outweighed the dam benefits. Taking into account all such costs, even when the net benefits are positive, distribution of benefits and costs are often inequitable, especially when compared to viable alternatives. Bringing together all affected stakeholders may improve equity and result in positive resolution of competing interests and conflict. In addition, it may allow for the early dismissal of unfavorable projects so that evaluation can focus on the most desirable projects.(WCD, 2000)

In analyzing whether to build a dam, there are several questions that must be answered:

1) Is it economically viable? That is, does the economic benefit outweigh the economic cost? Economic benefits and costs must not only include the actual prices of the marketable benefits and inputs used in construction and management of the dam, but also the values of nonmarket benefits and costs and externalities (generally costs) created by the dam production.

2) Are there alternatives that offer the same level of net benefit, but minimize social and environmental costs? Are there better economic investments available for public funds and resources?

3) Is it socially equitable? Who will suffer due to resettlement, loss of livelihood, loss of local communities and cultures and the transfer of water rights. If the dam is not socially equitable, how and to what extent will the losers be compensated by the winners?

4) Is it environmentally sustainable? How will environmental resources be depleted, degraded or improved due to the dam? What is the environmental trend over the life of the dam? For example will increased silting cause reduced benefits or increased costs over time?

We can categorize the benefits of a dam into five categories: flood control, on-demand irrigation, human water consumption, recreation and energy generation. However, assessing the value of any of these benefits is not simple. (Hanley and Splash, 1993).

Quantifying the costs associated with dams is also complex. There are easily quantifiable costs, such as that of construction, annual maintenance and operations. There are less easily quantifiable costs, both to human and ecological systems. Humans may be impacted by forced relocation, resulting in cultural harm, or even annihilation of some cultural systems. Ecosystems may be impacted by the flooding of areas, resulting in species habitat and other benefits of biodiversity destroyed forever. Otherwise abundant rivers can be choked, leading to less productive fisheries, degradation of riparian wildlife, changes in temperature of the rivers and growth of weeds. Anadromous fish species once supported by rivers that are diverted to the point that they no longer reach the ocean are endangered or decimated.

As with many capital projects, a dam reallocates the benefits from one set of constituents to another. As stated by the World Commission on Dams (2000):

> Dams fundamentally alter rivers and the use of a natural resource, frequently entailing a reallocation of benefits from local riparian users to new groups of beneficiaries at a regional or national level. At the heart of the dams debate are issues of equity, governance, justice and power – issues that underlie the many intractable problems faced by humanity

A most comprehensive and useful method for dam-building evaluation would be to calculate the overall benefits to society, calculate the overall costs and finally allocate the net benefits and costs across winners and losers in society. It would consider how to reallocate some of the net benefits of winners to the losers. Since benefits and costs will occur over a long term, often a century or more, a complete analysis should take into account the uncertainty associated with future pay-off and cost streams – issues like changing future real prices for operations; changing demand for usage of the energy, recreation or water benefits; variances in weather patterns that result in stochastic annual value; and changes in long-term climate that may affect the value proposition of the project. It would recognize that decision makers value the present differently than the future. and thus apply an appropriate discount rate to future expected benefits and costs. Finally, the analysis should consider the risk associated with catastrophic events such as earthquakes or flooding which "tops" the dam.

Cost-benefit analysis (CBA) and it's close cousin, Cost-effectiveness analysis (CEA) are two well-recognized economic analysis methods. Yet, there are disagreements over the correct approaches for implementing these methods. Two extreme views of CBA follow, the first from Hall (1964, pg 173):

> We have begun to grope our way towards a practical concept of economic planning which may prove in a few year's time to be as revolutionary in its policy implications as was the Keynesian revolution in economics thirty years ago. It also originated, many years ago, with a Cambridge economist: Keynes' contemporary Pigou. It is the concept that we can actually add up the social costs and benefits, in money terms, by asking what value people would themselves put on them. We can then express them as a rate of return on capital, as an ordinary capitalist would, and so determine our investment rationally, from the point of view of the community as a whole, just as the capitalist can now do from his private point of view.

But the practical implementation of such an evaluation system is fraught with problems. An alternate view expressed by Smithies (1955, pp 344-5) is:

> The foregoing discussion leads to two major conclusions: First judgment plays such an important role in the estimation of benefit-cost ratios that little significance can be attached to the precise numerical results obtained...Second, competition is likely to drive the agencies towards increasingly optimistic estimates; and far from resolving the organisational difficulties, computation of benefit-cost ratios may in fact make them worse.

These two perspectives show that a CBA can either be considered as the ideal, infallible method of assessing the value of a project or an unreliable waste of time and effort. (Prest and Turvey, 1965)

Other methods to assess the impact of policies include Environmental Impact Assessments (EIAs), scenario analysis, and risk-effectiveness analysis. These three methods tend to focus more on the physical information about environmental impacts than on the pure financial costs and rewards. (Hanley and Splash, 1993).

In the next section I will focus on CBA and discuss its usefulness and weaknesses. I will give a history of the method, describe its implementation, and elaborate on areas of controversy. In the following section I will briefly discuss Environmental Impact Assessments (EIAs) and how they add to the analysis of dam projects. I will conclude by discussing recommendations to improve dam analysis.

4.1 Cost-Benefit Analysis

Cost-benefit analysis describes the basic financial structure used to compare the benefits and costs of any large project. I use this section to describe how a CBA is developed for a dam project, largely drawn from Hanley and Splash (1993). As will be explained, there are several aspects of CBA that are difficult to quantify. I enumerate some of them in the last part of this section, and discuss some approaches that can be taken to address these issues.

4.1.1 Brief history

In 1808, Robert Gallatin, the U.S. Secretary of the Treasury, recommended that water-related projects be evaluated by comparing benefits to their costs. The Bureau of Land Management, created in 1902, was charged with performing economic analysis of irrigation projects. The Flood Control Act of 1936 provided that benefits for flood control projects must exceed costs. Continuing improvements to evaluation techniques occurred, with primary focus on supply-side efficiency in providing a private good from public projects. Quality management and optimal computer-aided operations were incorporated in project analysis, as discussed in Kneese (1964). The addition of recreation benefits began to be considered, with the early development of the travel cost method (Clawson and Knetsch, 1966) to measure the benefits of environmental improvement in relation to outdoor recreation. Beginning with the early 1970s, the effect of projects on public goods such as wildlife, air quality, human health and aesthetics gained consideration, and newer methods to measure these intangible benefits in addition to the travel cost method, such as contingent valuation and hedonics, began to be considered. In the 1970s and '80s, the importance of nonuse values, that is value of ecosystems or wildlife that does not directly affect human well-being, gained recognition, as examined by Krutilla (1967.) In 1981, Presidential Order 12291 enforced the need for assessment of environmental benefits of proposed legislation. In recent years it has become apparent that implementation of CBA is particularly challenging with relation to long-term effects including irreversibilities, risk and uncertainty. While research continues to consider how these effects might be incorporated in CBA, practical application of such research is slow. (Hanley and Splash,1993).

4.1.2 Steps to analysis

These steps are drawn largely from Hanley and Splash (1993).

Definition of project This step delineates the reallocation of resources and the population of gainers and losers to be considered. For a dam, water resources are typically contained in a reservoir, preventing the water from proceeding downstream. Typical gainers when a dam is built are recreational users of lakes, energy producers, agriculture, household users who want to increase the quality or reliability of water availability, and communities that are negatively affected by downstream flooding. The reservoir may create a new lake that can be used for increased recreation. The water from the dam may be diverted to be used for irrigation and household use. The dam may prevent damaging floods from occurring. The dam may house an energy plant that will create electricity. The losers could be those who must relocate to make room for a newly flooded area, riparian users of a river with newly restricted flows, riparian ecosystems and fisheries. The new reservoir may flood land that has other uses, including residential property or sensitive ecosystems. In some cases large communities or ecosystems are completely submerged under new reservoirs. Depending on how much the downstream flow is curtailed, riparian water users may lose access to a water and/or energy sources. Downstream wildlife and ecosystems will be affected by changes in flow timing and amount of release, resulting in changes in water temperature, the ability of anadromous fish to procreate, and the ability of river systems to absorb toxins.

Identification of project impacts This step delineates a list of resource, employment, price, traffic, property value, and other impacts that will result from the project. It should consider additionality and displacement. Additional impacts are net of other positive impacts that might have occurred without the project. For example, without a dam, riparian irrigation may be available. With the dam, the riparian farmers may receive similar irrigation water allocations from the new dam, but this water cannot be considered additional because it was available to the riparian farmer before the dam construction. Displacement refers to other economically viable enterprises that will be replaced by the project. For example, a new water storage facility may replace land that could be used for agriculture. Or if a reservoir is built that creates a recreational opportunity for fishing and other water sports, the additional value must be calculated to take into consideration the loss of sport and fishery associated with the river that has been curtailed. Also, the reservoir may lead to lakeside developments that are valuable for developers and taxpayers, but the value of property owned by communities in the flooded area that is lost must be subtracted.

Determination of economically relevant impacts As stated by Hanley and Splash (1993, pg 9) :

> The aim of CBA is to select projects which add to the total of social utility, by increasing the value of consumables and nice views by more than any associated depletion in the levels of other utility-generating goods.

What counts is the maximization of the social welfare function that is derived by the utility over goods that vary from theater tickets to bananas, nice views and clean air. That is, the benefits are a combination of marketable and nonmarketable goods. CBA is concerned with determining the most efficient projects from a list of alternatives which maximize social welfare. Positive impacts, or benefits, are increases in the quantity or quality of goods that generate positive utility, or decreases in their prices. Costs are counted as decreases in quantity or quality of such goods, or increases in price. The shadow cost of a non-renewable resource must also be considered — that is the cost of preserving a resource for potential use in the future.

Quantifiable benefits include increasing quantity and quality of consumable goods that have a market price. Quantifiable costs include the costs of production for such goods. Transfer payments should be excluded from such an analysis. There are benefits and costs that are difficult to quantify using market price, but still generate positive utility, such as clean air or water, unobstructed views and wildlife preservation, and the shadow cost of non-renewable resources. These may be highly economically relevant to a CBA, but require methods of nonmarket valuation in order to be adequately accounted for – discussed later in this paper.

Physical quantification of relevant impacts We examine the physical flows of the costs and benefits, including timing. For a dam, we might first consider how long the dam will last. With regard to benefits, we consider timing and quantities. Benefits might include irrigation flows, residential water flows, recreational benefits and the timing and amount of energy the dam is expected to produce. Costs include the inputs to building and maintaining the dam, including the amount of resources such as labor and materials. In addition, costs might include the reduction of fish populations. The estimation of environmental impacts generally necessitate an environmental impact report (EIR.) Calculations of cost and benefit quantities must take into account uncertainties. While the amount of labor and materials may be relatively easy to predict, the effect on fisheries may be very difficult to predict. Whenever possible, planners can attach probability distributions to uncertain events to arrive at an expected value of a quantity.

Monetary valuation of relevant effects In order to express costs and benefits in common units, the CBA uses money as a convenient device for common valuation. Prices of materials and labor are generated by markets to reflect relative values, and also their current relative scarcity. To complete the CBA, it is necessary to i) predict future prices for value flows, ii) correct market prices where necessary and iii) calculate prices for nonmarket valued goods. The prices used in the CBA should be real prices, but should reflect the relative changes in resource price, such as how relative prices for cement versus steel may vary in the future. Under scenarios ii) and iii), market prices may not reflect the true value of a good (that is marginal cost may not equal price) due to imperfect competition, government intervention in a market, or the absence of a market. In the case of imperfect competition (monopoly or oligopoly), the producer's marginal cost at the current production quantity reflects the true cost to society of an additional unit, not market price. Where there is government intervention, such as farm subsidies or import taxes, market prices do not reflect the true cost or benefit to society of an additional unit. In the case of farm output, producer subsidy equivalents can be calculated and used as the price estimate of the good.

If no market exists for a good, such as for clean air, clean water or biodiversity, techniques such as contingent valuation, the travel cost method, hedonic pricing, avoided cost and dose-response approaches can be used to estimate marginal social cost or marginal social benefit. The valuation of nonmarket goods is a hotly contested field, and is covered in more detail later in this paper. However, it is generally agreed that modern CBA must take environmental costs into account to be thorough. From Randall (1986, pg 193)

> No longer can it be claimed that there are overwhelming economic arguments for the development option, while the benefits of the preservation option are confined to sentiments and emotions existing only in the woolly head of environmentalists.

Discounting of cost and benefit flows The value of a good consumed today may differ from the value of that good consumed in the future; for example one may prefer to consume a hamburger today than wait until the following week to consume that same hamburger, even though the price of that hamburger doesn't change over time. I may prefer to pay a debt of \$100 one year from now rather than today. In order to account for this time preference, monetary flows over time are converted to a measure of their present value by applying a discount rate to future flows. The higher the discount rate, the more the investor prefers the present to the future. The choice of discount rate can be controversial. One approach is to use a discount rate that reflects the return on investment one would expect to receive should one invest in a project with similar risk. However, with respect to natural resources such as clean air and clean water, one can argue that the future value, that is the value of clean air to our descendants, should not be discounted. By applying a discount rate of only 3% per year, the value of clean air in ten years would be worth only 75% of its value today. Some would argue that this does not reflect the true value today of the future benefit. The discount rate is addressed again later in this paper.

Applying the net present value test This test asks whether the net present value gains exceed the net present value costs. If so, the project can be said to represent an efficient shift in resource allocation that improves social welfare. The calculation of the NPV can be expressed as:

$$NPV = \sum_{t=0}^{T} B_t(1+i)^{-t} + \sum_{t=0}^{T} C_t(1+i)^{-t}$$

where B_t represents the benefit in time period t, i is the discount rate, C_t is the cost incurred in time period t, and T is the life of the project. This simple analysis does not take into account uncertainty. In order to do so, a probability distribution can be applied to uncertain benefits and costs in order to calculate an expected NPV for the project. However, in the case of irreversibility and expected learning, this method may not result in the optimum decision. This is discussed further later in this paper.

While the expected NPV test may provide a reasonable estimation of overall social welfare change with the project when there is no anticipation of learning about uncertainties over time, it does not give any indication of the allocation of benefits and costs between winners and losers. One option to address this failing is to weight impacts according to income, thereby taking into account the fact that willingness to pay (WTP) will differ depending on the wealth of those affected. For example, if the impact affecting a low-income group is -\$1 million, and a high-income group would receive a \$2 million impact, the net impact to society is \$1 million and the project would be acceptable. But perhaps the low-income group would starve if they paid

$1 million, but the high-income group could easily borrow $2 million at low interest rates. To remedy this issue, the low-income group's loss could be weighted higher, say at 75%, leading to a net impact of -$.25 million, and the project would not be done. Re-weighting the impacts according to income or some other factor is rarely practiced at the public agency level. This kind of inequity demonstrates why CBA is rarely the sole input to decisions affecting different groups.

Sensitivity analysis This test explores how the NPV of a project changes should a single input in the calculations change. This kind of analysis is helpful as a way to address the fact that some future flows of benefits or costs are uncertain. For example, with respect to a dam, future weather patterns are unknown and may affect the water available for storage, irrigation and electricity generation. The real price of benefit flows or the costs may change. A small increase in the discount rate may cause the project value to be negative. The true life span of the project may be more or less than that used in the base NPV analysis, and if too short the project NPV may no longer be positive. The key parameters to be analyzed should be those quantities and qualities that are uncertain and that could either vary considerably or could have a large affect on the project given a small variance.

4.1.3 Problem areas using CBA

In this section I address several difficulties in deriving an accurate net present value analysis using CBA, most of which have already been mentioned.

1) The valuation of nonmarket goods such as habitat, clean air, views or ecosystems.

2) Ecosystem complexity. Can society predict the full cost of destruction of a rain forest, including lost species, lost plant life that could have been used for medicinal purposes, value of plant carbon capture, effect on neighboring ecosystems, etc.?

3) The choice of discount rate. How should we value what is permanently lost to future generations, and would they approve our placing less value on their benefits than on ours?

4) Industrial capture. Since CBA is often performed by institutions that will benefit from the projects that they are analyzing, can we rely on their objective assessments of benefits, costs and risks?

5) Uncertainty and irreversibility with anticipated learning. How will these be accounted for in a CBA?

6) Allocation issues. Will the gainers compensate the losers?

Nonmarket valuation Market prices do not always reflect the value of goods. If one were on a desert island and could choose between a day's worth of fresh water or a large amount of gold, one would choose the good that has a market value close to $0. While not traded in a marketplace, air, water and land quality and availability for use have value. Our health and our ability to enjoy our environment, through having clear views or enjoying recreation, are also amenities that are not readily evaluated through markets. The quality of each of these goods can change due to choices made by society, but cannot be decided upon unilaterally by individuals.

Nonmarket costs or benefits can affect humans in a variety of ways. Focusing on pollution costs, in some cases pollutants to water, air and land may affect human health or wealth directly and equally. For example, all of the residents of Los Angeles county experience the negative effects of air pollution. In other cases, different users of a given nonmarket good may not experience the same level of such good. For example, people who live close to trash dumps incur more costs in terms of health risks and a negative environment than those who live further away. Other instances of pollution may affect far away ecosystems that may indirectly affect humans (the melting of the arctic ice sheets that leads to rising sea levels) or may never directly affect humans (the garbage left in space from orbiters and satellites.)

Economists attempt to maximize a social welfare function that describes the aggregate well-being of individuals. Individual preferences are described by their willingness to pay for gains or accept payment for losses of goods, including nonmarket goods. The compensating surplus for an environmental good is the maximum amount a person would pay to not give up an improvement to that good – or willingness to pay (WTP). For example, if there is a creek that is polluted, how much will each person who lives along that creek pay in order to clean it up? The equivalent surplus is the minimum sum of money a person needs in order to forego the improvement, or willingness to accept (WTA). For example, if the government has already planned to improve the creek water quality, WTA measures how much money each resident would be willing to accept in order forego such improvement. Each measure assumes that an environmental good could be substituted for by some amount of money. The decision about which measurement to use depends on the type of problem.

Whether economists are measuring WTP or WTA, they need some way other than market prices to assess values for nonmarket goods. There are two types of methods used to estimate such values: stated preferences and revealed preferences. Revealed preference methods rely on how actual purchases of market valued goods reflect the value of nonmarket goods. Stated preference methods rely primarily on survey data in which responders place monetary values on nonmarket goods.

Revealed preference methods allow researchers to infer values of nonmarket goods through the prices paid for market goods that include nonmarket amenities. Revealed preference methods draw statistical inferences on values from actual choices people make within markets. Although we do not explicitly purchase nonmarket goods, we do purchase other goods for which demand is related to nonmarket goods. For example, we may choose to recreate where there is clear air, clean water, forests, fish and other environmental amenities. Or, we may choose to buy a home that has access to park areas, lakes or attractive views. Prices of homes or recreational areas may be higher when such amenities are available compared to when they are not. There are four commonly used revealed preference methods: travel cost, hedonics, defensive behavior and damage costs. Travel costs are used to estimate values for recreational usage changes when environmental quality changes. Hedonic models analyze how home or other property prices change when they are close or far from environmental amenities. Defensive behavior models analyze what people are willing to pay to reduce risk of exposure to disamenities such as pollution. The damage cost method measures the costs associated with environmental contamination. (Boyle, 2003)

Stated preference methods use carefully worded surveys to rank preferences monetarily or ordinally. Some skepticism exists for stated preference methods because of a concern that people will not or cannot answer valuation questions truthfully. Stated preference methods can be used where there is no linkage between market and nonmarket goods, an advantage over revealed preference methods. This advantage is particularly useful in the case of nonuse amenities, such as wilderness or species preservation. There are three methods for stated preference valuation: attribute-based methods, paired comparison and contingent valuation. The contingent valuation method was designed to measure monetary value, generally of a single good. Survey takers may be asked "How much would you be willing to pay to remove the sludge from the creek near your property?" The criticism is that survey takers may not actually pay that amount if required to do so. The other two methods were originally designed for ordered preferences, but have since been adapted for monetary valuation. The paired comparison method asks survey takers to compare values of numerous goods, and by including money as one good results in monetary valuation. The attribute-based method compares the value of similar goods that differ in the level of certain assets to be valued. Once again, by including monetary cost of an attribute, monetary valuation can be achieved. (Brown, 2003)

Ecosystem complexity CBA of a project that reduces or enhances ecosystem complexity must attempt to quantify the value of ecosystem services that benefit humans. Ecosystem complexity provides a challenge in benefit evaluation. Fisher, et.al. (2008) suggest three criteria to be used to evaluate the human benefit for ecosystem services. 1) The marginal benefit of increasing or decreasing a protected ecosystem area or species should be quantified and considered in a CBA. For example, the pollination services provided by a small forest next to a coffee plantation from the birds and insects should be weighed against the increased production from arable land that would result from the forest's destruction. If the contribution of the pollinators is reduced along with the forest, the marginal benefit could be negative. 2) The safe minimum standard of ecosystem or structure is that below which the ecosystem will change nonlinearly and perhaps irrecoverably. There is a high level of uncertainty about where the minimum quantity of ecosystem structure and process (including diversity, populations, interactions, etc.) exists. For example, the otter population decline in the Aleutians led to an increase in the sea urchin biomass, resulting in a collapse of the otherwise healthy kelp system. 3) There is a demand for ecosystem services that is not reflected in market prices. See the above discussion on nonmarket valuation. Fisher et.al. (2008) conduct a thorough review of literature addressing the economic benefit of environmental services. They point to many studies that note that the market under-provides ecosystem services. Ecosystem attributes that only indirectly benefit humans may have value as a nonuse good, but their benefits may be difficult to quantify.

Discount rate Howarth and Norgaard (1993) investigate the relationship between intergenerational asset transfers and the choice of the discount rate for use in cost-benefit analysis in a model of a competitive overlapping generations economy constrained by a socially managed exhaustible resource. They find that if the discount rate is set equal to the market rate of interest, and there are no distortions in capital markets and that all agents hold perfect foresight, cost-benefit techniques will result in a Pareto efficient resource allocation. But since the path of the interest rate depends on the level of intergenerational transfers, cost-benefit techniques do not ensure a socially desirable distribution of welfare between generations; a social optimum will result only if intergenerational transfers are properly chosen and enforced. In general, there will be an under distribution of assets from the current to future generations. Their conclusion is that CBA is at best a partial criterion to policy formulation that should be used only in conjunction with ethical principles that define the proper distribution of welfare between present and future generations.

Ackerman (2009) comments on the conclusion of The Stern Review, released in 2006 by a team headed by Sir Nicolas Stern who reviewed the economics of climate change at the request of the British government. Ackerman points out there are two components to the discount rate in economic theory. One component is the rate of pure time preference which would apply if all incomes remain the same across generations. The second is a growth-related rate that assumes the future will be richer than the present. While Stern endorses the idea of a growth-related rate, he argues that the time-preference rate should be close to zero, because the value of a good to future generations should not be less than the value of the same good today. If there is a growth rate of 1.3%, under Stern's application, that would be close to an appropriate discount rate. Ackerman points out that other economists infer both a higher growth rate and a time-preference rate, leading to discount rates of as high as 6%. Ackerman's view is that economics can "see" into the future much more with a low discount rate, and becomes myopic with a high one.

Regulatory capture Levine and Forrence (1990) define regulatory capture as the process through which special interests affect state intervention in any of its forms, including taxes, subsidies, monetary or foreign policy, or legislation involving intellectual property. Regulatory capture is the process through which regulated industries or monopolies manipulate government agencies that are supposed to control them. (Dal Bo, 2006). Stigler (1971) observed that regulation is generally acquired by the industry and is designed and operated primarily for its benefit. He also observed that natural monopolies are not the only recipients of regulation, but that large industries that could benefit from regulation were also likely to be subject to regulation. Peltzman (1976) developed a model of politician behavior that showed that monopolies such as utilities will attract regulation by the politician in order to create political gains for him. The politician will be careful to incur only moderate political losses with the producer in exchange for large political gains from consumers.

Even when regulations are developed for the public good, regulators may not fulfill their responsibilities in exchange for bribes, promises of campaign contributions, or for tacit or explicit promises of future lucrative employment. This last effect is referred to as the "revolving doors" phenomenon, in which personnel move back and forth between industry and regulator jobs. Dal Bo postulates that regulatory capture can be very costly to society. He suggests that reducing the likelihood of regulatory capture is difficult, as proposed solutions such as above-market wages and monitoring to induce regulator performance appear limited compared to the stakes involved. For a comprehensive review of regulatory capture literature, see Dal Bo (2006).

Uncertainty, irreversibility and anticipated learning The World Commission on Dams (WCD) (2000) reports that the decision-making framework on dams has traditionally been a simple cost-benefit analysis and excludes consideration of uncertainty with regard to future benefits of the dam. I have mentioned two methods to address the concept of uncertainty in a major infrastructure analysis. The first is using a sensitivity analysis in which key parameters are varied to determine the impact on project results, allowing for decision makers to pay extra attention to the most sensitive parameters by of reducing uncertainty or monitoring performance such that project risks are reduced. The second method is to apply a probability distribution to uncertain parameter values and calculate their expected values.

However, as pointed out in Chapter 1, a dam, once built, is an irreversible investment, as it cannot be repurposed for another use. Arrow and Fisher (1974) show that when uncertainty is introduced into making an irreversible decision, assuming risk-neutrality, simply replacing known values with expectations does not capture the loss in perpetuity of the benefits of the affected environment, and hence overstates the benefit values. In order to preserve these potential benefits less development should occur than implied through traditional cost-benefit analysis. They combine the notion of irreversibility with the assumption that a realization in one period will affect the expectations in the next. The key to their model is that development is irreversible, while preservation (or the potential for future development) is not. See Chapter 1 for a thorough discussion of major project construction under uncertainty, irreversibility and anticipated learning.

While there is a considerable literature demonstrating the advantage of applying option theory to valuing irreversible projects when learning is anticipated, practically speaking such application is rarely practiced. This dissertation presents one example of how to incorporate uncertainty and anticipated learning when making a decision about a large-scale, irreversible project.

Allocation issues and other social costs. In Section 2.2.7 I suggested that a weighted NPV could be used to more equitably analyze allocations of benefits and costs. However, in many cases this is an inadequate method of measuring the total social costs incurred in major dam construction when areas are inhabited with large human populations. The WCD (2000) estimates that 40-80 million people have been forced to leave their homes because they have been flooded by dam projects – sometimes leading to an increase in illness and starvation. Displaced people often lose access to fisheries and forests that had provided them with a livelihood. The still water in reservoirs resulting from dams have sometimes become toxic due to flourishing bacteria; thus, the World Health Organization has recommended that health impact assessments be performed before dams are built. These kinds of effects are not adequately accounted for in traditional CBA. I have not found evidence that most displaced peoples, or those people who lose downstream amenities, are adequately compensated such that there is no loss in their utility in aggregate or individually.

4.2 Environmental Impact Analysis

From the foregoing discussion, it is apparent that while CBA is an important element in decision-making for dam projects, it is imperfect or controversial in terms of many valuation questions, and remains inadequate to give a comprehensive assessment of the effects of introducing a dam. Therefore, some kind of non-financial assessment must complement the CBA, such as an Environmental Impact Analysis (EIA). As stated by the London Department of the Environment (1991, pg 1):

> A government's policies can affect the environment from street corner to stratosphere. Yet environmental costs and benefits have not always been well integrated into government policy assessments, and sometimes they have been forgotten entirely. Proper consideration of these effects will improve the quality of policy making.

The National Environmental Policy Act (NEPA) of 1969 required EIA of proposed actions that may impact environmental quality. EIA is required if the proponent is public, if the proposed action occurs on public lands, if the action is publicly funded or funded by a development bank, or if a specified government approval requirement triggers the EIA requirement. Its basic elements have been replicated in over 100 countries. From Lawrence (2004), EIA is a systematic process of determining and managing potential and real impacts from proposed or existing human activities that affect the environment. Covered environmental effects include physical, chemical, ecological, cultural, human health, social, economic and interrelationship effects. The focus of EIA is generally not financial or economic, but its conclusions should be based on science – either physical or social. The objective of EIA is to incorporate environmental information and interpretations into planning and decision making. It is also a means to facilitate public, professional and scientific involvement in decision making. It is not to be dominated by technical, cost and economic considerations, but instead to address broader environmental objectives such a sustainability. It is a subjective process that ideally allows for participation from all interested and affected parties to an action that affects them and the environment. Given the limitations of CBA, even with the best attempts to objectively evaluate impacts in monetary terms, a well-rounded approach to decision-making with respect to a major project such as a dam is limited without an EIA or something similar.

4.3 Discussion

A thorough and well performed CBA is an important tool in deciding whether to build a large infrastructure project such as a dam. Financial investors and governments must have some guidelines in decision-making, and a CBA is a necessary first step for them and for other beneficiaries of a dam. However, there is great difficulty in assessing the true value of some of the benefits and costs associated with such projects. When a project involves uncertainty and irreversibility, as most dam projects do, sensitivity and expectation analysis should be performed, and option value theory can be useful when there is an anticipation of learning about uncertainty. CBA has not proven to be effective in adequately dealing with inequitable distribution of benefits, and generally does not include an exhaustive compilation of impacts on ecosystems and affected communities. Empirical evidence shows that CBAs often overestimate the return on investment of such projects when reviewed in hindsight. For example, the WCD (2000) found that half of the 52 irrigation dams studied failed to irrigate the targeted amount of land. The Grand Coulee Dam on the Columbia River in Washington State irrigated only half the land it was supposed to.

While CBA methodology may be well understood, implementation appears to need much improvement. CBA is an important tool in analysis of new dam projects, and the methodologies are continually being improved. However, no matter how well performed, it has limited ability to fully describe the impacts of major dam projects, and should be accompanied by a non-financial analysis such as an environmental impact analysis.

Some recommendations by the WCD (2000) to improve the analysis of dam projects are:

1) Consider the rights and risks of peoples affected by the dams, not just the investors.

2) Perform a comprehensive options assessment that will clearly consider alternatives to dam construction.

3) Maximize the operations of existing dams for efficiency and to improve environmental and restoration programs.

4) Sustain rivers and livelihoods of communities affected by dams, and mitigate damage to downstream ecosystems.

5) Share benefits from the dam with people who are negatively affected by its

construction.

6) Ensure that operators, governments and regulators comply with their obligations.

7) Emphasize sharing of rivers to ensure peace and security.

In addition to these recommendations, comprehensive analysis of how the results of dam projects have not agreed with the CBA estimates should be performed in order to understand the causes of underperformance. It is important to learn whether underperformance is the result of poor forecasting techniques or regulatory capture, and to investigate ways to prevent it.

While these are issues to be considered when building dams, especially in the industrialized world, it is important to remember that as of 2000 energy starved countries such as China had tapped only about 10% of their potential hydroelectric power, while industrialized countries had utilized 75% of their potential. (WCD, 2000) For industrialized nations to oppose development of dams in developing nations under these circumstances is not realistic. Perhaps new developments can proceed in a more thoughtful and equitable manner than previously.

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