Working Paper Series

WORKING PAPER NO. 713

WETLANDS MITIGATION BANKS: A DEVELOPER'S INVESTMENT PROBLEM

by

Linda Fernandez
and Larry Karp

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS

BERKELEY

CALIFORNIA AGRICULTURAL EXPERIMENT STATION

University of California

DEPARTMENT OF AGRICULTURAL AND RESOURCE ECONOMICS
DIVISION OF AGRICULTURE AND NATURAL RESOURCES
UNIVERSITY OF CALIFORNIA AT BERKELEY

WORKING PAPER NO. 713

WETLANDS MITIGATION BANKS: A DEVELOPER'S INVESTMENT PROBLEM

by

Linda Fernandez
and Larry Karp

California Agricultural Experiment Station
Giannini Foundation of Agricultural Economics
June, 1994

Wetlands Mitigation Banks: A Developer's Investment Problem

by

Linda Fernandez and Larry Karp

Department of Agricultural and Resource Economics, University of California, 210 Giannini Hall, Berkeley, CA 94720

JEL classification: Q20, Q25, Q24

Keywords: Wetlands mitigation banks, stochastic control, option value

contact:

Linda Fernandez
Department of Agricultural and Resource Economics
College of Natural Resources
University of California
210 Giannini Hall
Berkeley, CA 94720

Abstract

We study a land developer's decision to invest in a wetlands mitigation bank. The state at which it is optimal to "cash in" the investment in return for restoration credits increases with uncertainty. We calibrate and numerically solve a stochastic control model which describes the developer's investment problem. We study the effect of the parameters of the model on the investment trajectory and the optimal stopping state. A subsidy increases the option value of the investment and the stopping state. A small decrease in the variance of the state dynamics decreases the option value of investment and the stopping state.

I. INTRODUCTION

Wetlands provide public goods such as flood control and wildlife habitat. Since private users and owners do not capture all benefits from wetlands there is not always an incentive to preserve them. Wetlands functions such as groundwater recharge and assimilation of pollutants are not efficiently allocated as long as the price system and market do not reflect the functions' relative scarcity and value. Therefore, public resource agencies serve a role in establishing and enforcing regulations to protect the natural capital and mitigate wetland losses.

Wetlands Mitigation Banks (WMBs) are a component of recent national and state legislation to curtail loss of wetlands and regain acreage that supports wildlife habitat and other functions. The WMB program designates sites for the creation, restoration and/or enhancement of wetlands. These sites are used to offset the unavoidable losses from future development in the same watershed.

We study a land developer's investment in a WMB. The number of credits that a developer obtains per dollar of investment depends on the success of the wetlands restoration, which is stochastic. The developer is able to "cash in" credits in exchange for permission to develop other wetlands. Therefore, demand for credits in the WMB is derived from the demand for development projects. The developer minimizes the cost of stocking an inventory of degraded wetlands acreage for restoration, to be able to undertake future development projects (e.g., housing, shipping, port expansion).

The WMB program was introduced as a national policy in August 1993. There is insufficient data to estimate a complete model. We use the small amount of available data to calibrate a stochastic control model which describes the developer's investment problem. We solve the model numerically and perform sensitivity analysis. This procedure: (i) provides information on the optimal dynamics of investment; (ii) it enables us to study the qualitative effect of changes in various parameters; and (iii) it suggests the order of magnitude of changes in investment resulting from changes in parameter values. Given the paucity of data, the third type of information is particularly important. It indicates the kind of data that is most urgently needed to improve policy prescriptions. We study changes in parameter values of the restoration costs, the (stochastic) biological growth equation, and the interest rate. We show how these parameters affect the trajectory of investment, the value of the investment program, and the optimal stopping state (i.e., the state at which it is optimal to cash in the investment). For some parameter values, it does not pay the developer to invest in the WMB. In these cases, subsidies are needed to support the WMB.

Section II describes WMB policy, and Section III discusses relevant literature. The analytical model is described in Section IV. The data for the empirical application is discussed in Section V, and the model is solved in Section VI. Section VII provides concluding remarks.

II. INSTITUTIONAL BACKGROUND

WMBs are designed to assist in meeting the goal of federal Clean Water Act regulations [Section 404 (b) (1)] for promoting "no overall net loss" of wetlands (Federal Register [8]). The broadly defined goal is to maintain a steady state of physical and biological functions and human use values of wetlands. Under the regulations, land developers must offset unavoidable damage to wetlands by creating, restoring, or enhancing other wetlands. Agricultural, urban and industrial land developers are subject to this national policy. The Farm Bill's Agricultural Wetlands Reserve Program (WRP) is one component of a WMB system. Developers can purchase WRP easements from the U.S. Department of Agriculture and pay to restore wetlands (Lant [15]).

The program works in the following manner: In order to obtain permission to develop a wetlands area, a developer must have credits in a WMB in the same watershed. These credits are obtained by previous investment in the restoration of other wetlands areas (the WMB). Thus, the program encourages protection and restoration of some wetlands areas as a precondition for developing other areas.

The policy is an attempt to address the lag time and uncertainty in any restoration effort. There may be interrupted flow of wetlands services and "net loss" due to the uncertainty of ecosystem replacement. Restoration means returning an ecosystem to an approximation of its condition prior to disturbance (National Research Council [17]). This requires ensuring that the ecosystem structure and functions are operating again. The multiple biological, chemical and physical factors that affect hydrologic, vegetative, and faunal recovery of a particular wetland ecosystem make it inappropriate to assume a static, deterministic relation between input costs and resulting quantities of recovered wetlands (Castelle [5]).

The diversity of species in ecosystems such as wetlands is correlated with the size of the habitat area; larger areas devoted to restoration in a watershed have greater potential to sustain ecosystems (National Research Council [17]). WMBs are intended to create large, high quality habitats which incorporate entire ecosystems, in contrast to previous mitigation efforts which tended to be fragmented and threatened by adjacent land uses (Anderson and Rockel [1]). Restoration on large expanses of floodplain acreage may be possible through the Farm Bill's Agricultural Wetlands Reserve Program (Lant [15]).

The larger site can be used by multiple developers, who are able to take advantage of economies of scale which do not occur on smaller, fragmented sites. The multiple investors in the WMB can pool financial resources, planning and scientific expertise (Reppert [20]). Often restoration tasks on one site involve joint efforts of public resource agencies, the private sector, and non-profit environmental groups. The momentum generated may lead to a more successful restoration project with all participants informed of mitigation activities throughout the regulatory process (Griswold [10]). This involvement benefits the developer attempting to win support for a development project.

Regulatory approval of a development project depends on the level of restoration credits in the developer's WMB account. Credits are denominated in Habitat Units (HU). The number of HU's is the product of the number of species or functions per acre at a wetlands, times the number of acres. The number of HU's are used to determine the "compensation ratio", which gives the number of wetlands acres which must be replaced for each acre damaged by development (Cruickshank [6]). Requiring restoration credits might deter development projects whose size is fixed or costly to adjust.

The restoration investment can be one asset in a diversified portfolio. For some transportation development projects affecting several wetlands along a route, investing in more than one WMB may be optimal.

III. LITERATURE REVIEW

There has been little previous work in economic modeling of wetlands restoration. Several papers study the conversion of pristine wetlands to agricultural use (Stavins [22], Stavins and Jaffe [23], Van Kooten [25], Kramer and Shabman [14]). These examine impacts of federal farm support programs which promote the drainage of wetlands for farming. Heimlich [12] estimates the foregone crop revenues and restoration costs of restoring currently cropped wetlands acreage. He emphasizes the need for studies of the value of WMB credits resulting from restoration.

Fisher and Hanneman [9] use the concept of an option value to model the decision to preserve or to develop pristine wetlands. In their model, preservation is equivalent to not developing the site, and is therefore passive. A WMB involves restoration rather than merely preservation; the former requires an active investment program, which must be determined.

The physical state of wetlands before and after restoration and the market value of credits earned through a WMB is similar to an inventory. A WMB enables smoothing of the developer's response to the future development demand, since an inventory of restored wetland acreage is a means of complying with environmental regulations. Williams and Wright [26] and Ramey [19] discuss "goods in process" inventory models under certainty. Both studies address lag time involved with inventory of intermediate goods. Ramey [19] identifies inventory as a factor of production, which with other factors (capital and labor) contributes to the final product. Investment in a WMB creates an inventory of restored wetlands functions. This inventory enables the developer to respond as demand for development occurs. In any period, the current wetlands inventory is a capacity constraint on current development plans. If trading of WMB restoration credits is allowed, an individual may want to invest in a WMB when a restoration opportunity arises, even in the absence of plans for development.

Applications of stochastic control in the literature on capital theory provide guidelines for determining the level of investment and optimal stopping state in our problem. Pindyck [18] examines models where investment expenditure is a sunk cost and the future value of a project fluctuates stochastically. He studies the effect of irreversibility on the planner's choice of when to invest. Brennan and Schwartz [2] derive a rule for operating and closing a mine. The rule determines the value of the resource as a function of the current state of the mine (open or closed) and the stochastic resource price.

Brock et al. [3] show how to determine stopping times (states) in a model of an asset whose intrinsic value follows a diffusion process with instantaneous mean and variance. Using various boundary conditions, they derive comparative statics for the interest rate and instantaneous variance. Our model is similar, except that we are concerned with investment decisions as well as stopping times. In addition, due to data limitations we cannot use any of the boundary conditions that they consider, and therefore rely on a different method to solve the model.

IV. THE MODEL

The economic-ecological model for the WMB is used to determine the optimal stopping rule and path of investment. The ecological component of the model is a stochastic differential equation which describes the evolution of the wetlands habitat as a function of the current state of the habitat, investment in conservation and restoration, and a stochastic term. The economic component of the model is an optimization problem. The developer chooses the optimal level of investment activity (a control rule) as a function of the state of the wetlands quality, and decides when to "cash in" the investment. The latter decision involves exchanging investment credits for permission to proceed with a commercial development which damages some other wetlands areas. The action (cashing in) taken at the final time is called stopping. The state of wetlands quality at this point of optimal stopping (a "Markov time") is called the stopping state.

The model uses the following notation:

$z(t)$ =	Quality of wetlands habitat at time t.
$m(t)$ =	Level of discretionary spending on maintenance and restoration services (engineering, revegetation activities).
T =	Time at which developer cashes in her investment and earns restoration credits.
$K(z)$ =	Present expected discounted market value of restoration credits for z); the "intrinsic value" of z.
$C(m,z;\beta)$ =	Restoration cost function depending on level of discretionary spending, site quality, and β, a vector of other parameters (property tax, etc.)
r =	Developer's discount rate.

The state variable $z(t)$, the index of restored wetlands quality, follows a continuous stochastic process. The level of z determines the number of credits that a developer obtains from cashing in her investment. The expected present discounted value of these credits is $K(z)$. We assume that the function K (but not its argument) is fixed and deterministic. A more complete model would allow the function K to evolve stochastically, to reflect changing demand for development projects.[1] Our assumption of nonstochastic K focuses the model on the uncertainty associated with restoration efforts.

The domain of the state variable is divided into two regions, a continuation region and a stopping region. If the state is in the continuation region it is optimal to hold the asset, and to invest in restoration. If the state is in the stopping region, it is optimal to cash in the investment. The boundary separating these regions is the optimal stopping boundary, or "stopping state" (Malliaris and Brock [16]), which we denote as z^*.

The definition of quality is described in more detail in the next section. The level and speed of wetlands recovery depends on the amount of restoration maintenance and existing wetlands quality. The stochastic term captures the uncertain exogenous factors (biological, chemical, physical) which contribute to a change in wetlands. The following stochastic differential equation for z includes an ecological uncertainty component W, which evolves according to Brownian motion.

(1) $$dz = g(z,m)dt + \sigma z dW$$

where: $g(z,m)dt$ = expected trend or drift in wetlands quality; σz = the instantaneous standard deviation in site quality change; dW = increment of the stochastic Weiner process, which is normally distributed.

The value function J is the expected present value, under optimal behavior, of restoration costs, minus the value of credits obtained when the investment is cashed in. The choice variables are the investment rule $m(z)$ and stopping state z^*. The value function is

[1] For example, $K(z)$ might depend on the demand for housing in the area which evolves stochastically. In this case, the decision of whether to cash in the credits (i.e., the optimal stopping state), and of how much to invest in discretionary expenses would depend on both z and the stochastic parameters of K.

(2) $$J(z,t) \; = \; \min_{m} \left\{ E \int_{t}^{T} C(m,z;\beta) e^{-r(\tau)} d\tau \; - \; K[z(T)] e^{-rT} \right\}$$

s.t. (1), $z(0) = z_0$, $m(z) \geq 0$.

The Bellman dynamic programming equation (DPE) is:

(3) $$0 = J_t + \min_{m} (C(z,m) e^{-rt} + J_z g(z,m) + \frac{1}{2}\sigma^2 z^2 J_{zz}) \; .$$

In order to eliminate the time dependence, we use the fact that (2) is autonomous, so $J(z,t)$ has the separable form $J(z,t) = V(z)e^{-rt}$. This implies: $J_t = -rV(z)e^{-rt}$, $J_z = V_z e^{-rt}$, $J_{zz} = V_{zz}e^{-rt}$. Substituting these expressions into equation (3) gives

(3*) $$0 = \; - \; rV(Z) \; + \; \min_{m} (C(z,m) \; + \; V_z g(z,m) \; + \; \frac{1}{2}\sigma^2 z^2 V_{zz}).$$

The functions for costs and wetlands quality, C and g are assumed to be twice continuously differentiable. The first and second derivatives of the functions satisfy the following inequalities:

(4) $$C_z > 0, \; C_m > 0, \; C_{zz} \geq 0, \; C_{mm} \geq 0, \; C_{zz}C_{mm} \; - \; C_{zm}^2 \geq 0$$

(5) $$g_m > 0, \; g_{zz} \leq 0, \; g_{mm} \leq 0, \; g_{zz}g_{mm} \; - \; g_{zm}^2 \geq 0 \; .$$

Costs are increasing and convex in z and m, and the growth equation is increasing and concave in these arguments. The curvature assumptions insure that the first order condition to the DPE in (3*) gives a local minimum; the first order condition is also a necessary and sufficient condition for optimality in the deterministic version of our problem, obtained by setting $\sigma^2 = 0$. The signs of the first derivatives of C and g are easily motivated. By definition, an increase in discretionary expenditures, m, increases instantaneous costs. It is reasonable to assume that there are also non-discretionary expenditures which increase with habitat quality, so $C_z \geq 0$. Discretionary expenditures would never be undertaken unless they led to an increase in quality, so $g_m \geq 0$ for optimal m.

Assuming an interior solution, the first order necessary condition from equation (3*) yields the optimal control rule for m:

(6) $$C_m + V_z g_m = 0.$$

Equation (6) states that the marginal cost of discretionary investment equals the value of the marginal product of investment. The latter quantity equals the marginal product of discretionary investment, g_m, times the shadow price, $-V_z$.

Two boundary conditions for the DPE are:

(7) $$V(z*) = -K(z*)$$

(8) $$V_z\big|_{z*} = -K_z\big|_{z*}$$

In the continuation region, where $V(z) < -K(z)$, it pays to continue holding the asset. Since cashing in the asset is always an option, it must be the case that $V(z) \leq -K(z)$. The value matching condition in (7) states that if it is optimal to cash in, then the value of the program equals the intrinsic value of the state. Equation (8) is known as the smooth pasting condition. It states that the shadow value of the stock evaluated at the optimal stopping state equals the marginal salvage (intrinsic) value.

Substitution of $m*$, the optimal control rule, and the boundary conditions into (3*) yields the following relationship at the optimal stopping state, z^*:

$$\text{(9)} \qquad rK(z*) = -C\Big(z*,m*\big(z,K_z(z*)\big)\Big) + K_z(z*)\bigg(g\Big(z*,m*\big(z,K_z(z*)\big)\Big)\bigg) - \frac{1}{2}\sigma^2 z^2 V_{zz}(z*)$$

Equation (9) contains two unknowns, the values of z^* and $V_{zz}(z^*)$, and therefore is not sufficient to determine the value of the stopping state. In the deterministic version of this problem ($\sigma^2 = 0$), equation (9) implicitly defines z^*. In that case, the condition for cashing in the investment is the familiar requirement that the opportunity cost of holding the investment for a unit of time, rK, must equal the increase in value of the investment, $K_z g$, minus the flow cost, C, per unit of time.

When $\sigma^2 > 0$, we need one more piece of information to obtain z^*. Once z^* is known, equations (7) and (8) provide two boundary conditions for the second order ordinary differential equation (ODE) that we obtain by substituting (6) into (3*). In other words, we need one more boundary condition in order to solve the problem. The determination of this missing boundary condition is discussed in Brock et al. They consider a simpler problem, in which the control m is absent. Although their arguments can be generalized to apply to our problem, the resulting methods are not useful in the present context because of lack of data. In particular, we would need to know about the value of the program as z approaches a lower bound (some finite value, or $-\infty$). For example, if we were told that the investment were worthless for $z \leq \hat{z}$, and knew the value of $\hat{z}$, we would have the additional boundary condition $J(\hat{z}) = 0$.

In the absence of this kind of information, we use the following approach to find the missing boundary condition for our empirical application. For arbitrary stopping state z^{**} we solve the ODE (3*) using the boundary conditions (7) and (8). Denote the resulting function as $V^{z^{**}}(z)$, where the dependence on the arbitrary stopping state is indicated by the superscript. $V^{z^{**}}(z)$ gives the value of investing optimally, conditional on cashing in the asset when $z = z^{**}$. We then search over z^{**} to find the value that minimizes $V^{z^{**}}(z)$. The minimizing z^{**} is the optimal stopping state, z^*. In order for this procedure to work, the following relation must hold: For any two values of z^{**}, e.g. $z1$ and $z2$, if $V^{z}1(z_o) \leq V^{z}2(z_o)$ for some z_o, then $V^{z1}(z) \leq V^{z2}(z)$ for all z. In other words, the graphs of $V^{zi}(z)$, i= 1,2, cannot intersect. This means that when we search for the optimal stopping state, the answer does not depend on the value of z at which we evaluate the functions. We can verify by inspection that this "no-crossing condition" is satisfied in our application.

Brock et al show that the comparative statics of the stopping state, z^*, with respect to exogenous parameters, do not depend on the type of missing boundary condition. With this encouraging result in mind, it seems reasonable to look for analytic results in our model. Totally differentiating (9) with respect to z^* and σ^2, gives

(10) $$\frac{dz*}{d\sigma^2} = \frac{\frac{1}{2}V_{zz}Z^2}{-C_z + K_z(g_z - r) + gK_{zz} - \frac{1}{2}\sigma^2 V_{zzz}z^2 - \sigma^2 V_{zz}}$$

In (10) all functions are evaluated at $z = z^*$. We cannot sign this expression in general. However, we obtain some insight by considering the limiting case as $\sigma^2 \rightarrow 0$, so that the last two terms in the denominator of (10) vanish. In order to evaluate the resulting expression, it helps to consider the deterministic problem, using the Maximum Principle. The Hamiltonian for this problem is $H = C(\cdot) + \lambda g(\cdot)$, where λ is the costate variable, and $\dot{\lambda} = (r - g_z)\lambda - C_z$. (A dot over a variable indicates differentiation with respect to time.) Using this relation, and the transversality condition $\lambda = -K_z$ at the stopping state, we can rewrite (10) as

(11)
$$\frac{dz^*}{d\sigma^2} = \frac{z^2 V_{zz}}{2\left[\dot{\lambda} + K_{zz}\dot{z}\right]} = \frac{z^2}{2\dot{z}}\left[\frac{V_{zz}}{V_{zz} + K_{zz}}\right]$$

for the second equality we have used the relation $\dot{\lambda}/\dot{z} = d\lambda/dz = V_{zz}(z)$. Under the assumption that the value of z is initially small, the state approaches the stopping region from the left (if $z > z^*$ it is optimal to stop immediately), so $\dot{z} > 0$ evaluated at z^*. For the special case where K is linear, so that $K_{zz} = 0$, (11) implies that a small increase in the variance increases the stopping state. For non-linear K we can show that $sign\,\{dz^*/d\sigma^2\} = sign\,\{-V_{zz}(z^*)\}$. This is done using the fact that $V_{zz}(z^*) + K_{zz}(z^*) < 0$. This inequality is established by noting that $V(z^*-\varepsilon) + K(z^*-\varepsilon) < 0$ for $\varepsilon > 0$. For small ε, we can approximate both functions using a second order Taylor expansion. Using this approximation and (7) and (8) in our last inequality implies $V_{zz}(z^*) + K_{zz}(z^*) < 0$. We summarize these results in

Proposition 1: For values of σ^2 close to 0, a small increase in σ^2 leads to an increase in the value of the stopping state if either (i) the cash-in function K is linear, or (ii) the value function V is concave.

Brock et al. obtain analogous results for their simpler model. Their results are valid even for large values of σ^2, whereas Proposition 1 is a local result, for $\sigma^2 = 0$. However, their result is obtained for the case where both $g(\cdot)$ and $K(\cdot)$ are linear. Brennan and Schwartz [2] also show that an increase in variance increases the value of the asset. Under condition (i), we see that an increase in uncertainty increases the value of holding the investment in the WMB. The developer delays cashing in her investment. (An increase in z^* means that it is profitable to hold the asset in more states of nature.) This is also true for non-linear K, provided that the function V remains concave in the neighborhood of z^*. This is very intuitive: we know that an increase in uncertainty decreases the expected value of a concave function. In our context, where we are minimizing a functional, this decrease in expected value is an improvement.

In order to obtain sensitivity results that are valid for large ranges of parameter values, and also to determine the probable magnitude of the effects of changes in parameter values, we need to solve the problem numerically. We now turn to the empirical application.

V. MODEL CALIBRATION

In this section we explain how the index of quality, z, is determined. We then present the functional forms, and explain how we calibrated the model which is used in the following section.

Investment in restoration changes wetlands quality, which refers to specific wetlands functions. The Habitat Evaluation Procedure (HEP) is a method of quantifying the habitat (USFWS [24]). The procedure involves the estimation of the quantity of various wetlands attributes known to be important to one or more selected indicator species of flora or fauna. The species act as an indicator of overall ecosystem integrity. The species chosen might be based on their economic value (hunting, trapping, etc). The HEP produces a Habitat Suitability Index (HSI) ranging from 0-1 for each indicator species. The number of indicator species times the HSI is z. The range of z in our application is from 0-2, which means that the wetlands can support two indicator species. Non-integer values indicate the presence of contributing factors that support the indicator species.

We chose the following functional forms: $C = \alpha z^2 + m$; $dz = \beta\sqrt{m} + \rho z + \sigma z dW$; and $K = \gamma z^2/2 + \eta z$. The natural expected growth rate, i.e. the growth rate when discretionary expenditures are 0 and $dW = 0$, is ρ; β determines the effect of discretionary expenditures on growth. The justification for these functions is that they involve very few parameters. Since we rely on numerical methods to solve the model, more complicated functional forms would not be an obstacle.[2]

We obtain "estimates" of three parameters, α, β and ρ by means of calibration. We have insufficient data to obtain even rudimentary estimates of the remaining three parameters, γ, η and σ, so we assign them "reasonable" values and then do numerical sensitivity analysis.

Restoration site data from Bracut Marsh, California, for a six year period, includes expenditures for the first, third, and sixth year (CCC [4]). We allocate the cost data into categories of discretionary and non-discretionary expenditures. We think that this is a useful distinction: whether an item is discretionary or non-discretionary may have an important effect on the optimal path for aggregate investment, and on the value of an investment opportunity. In practice it may be unclear to which category an item belongs. The

[2] Note that if we define $y \equiv \sqrt{m}$, the model is equivalent to a linear-quadratic control problem. However, it makes more sense to think of instantaneous costs as being linear in discretionary expenditures, and the growth equation to be non-linear, then vice-versa. Despite this linear-quadratic structure, the value function V is not quadratic; this is because the investment program will be stopped at some state z^*. To verify this, suppose to the contrary that V were quadratic. Using a quadratic form of V in (3*) and proceeding in the usual manner to "equate coefficients" of powers of z, leads to algebraic equations for the parameters of V. Given these parameter values, the boundary conditions (7) and (8) provide two equations in one unknown, z^*. There is, in general, no value of z^* that solves both equations, since they are linearly independent.

determination is likely to be a matter of policy rather than of physical and biological laws. For example, the design of a WMB may state that certain activities must be performed when the state reaches a given level, whereas other activities can be undertaken at the investor's discretion. In that case, the former activities entail non-discretionary expenditures from the standpoint of the investor, even though all activities are discretionary from the standpoint of society (or the designer of the WMB).

For our calibration exercise, we include as discretionary expenditures: labor and depreciation of capital equipment for planting, land excavation, and hydrological engineering. Non-discretionary expenditures consist of costs of physical inputs used to establish the ecosystem habitat. These include seeds, plants, and soil material, which contribute to the vegetation associated with the indicator species for wetlands quality. (Costs are in units of thousands of dollars per acre.) We refer to the parameter estimates obtained using this allocation of costs as the "base parameters", and we use these for sensitivity studies. In order to determine the effect of this allocation of costs on our results, we also consider the extreme case in which all costs are discretionary. That is, we allocate all the costs in our data to the discretionary category, and recalculate the model parameters. We refer to these as the "alternate parameters".[3]

[3] This experiment answers the following question: Suppose that we had misunderstood how the WMB works, and that in fact, all expenditures are discretionary; given our data, how would recognition of this mistake change our parameter estimates? The experiment does *not* answer the following, more difficult question: Suppose that the WMB is re-designed to allow the investor more flexibility, in the sense that previously non-discretionary expenditures are now discretionary; what effect does this have on the model parameters? It is important to bear in mind this distinction when interpreting the sensitivity analysis of the next section.

Non-discretionary expenditures, which by definition depend on z, alter the drift term in the equation of motion. The parameter ρ incorporates both the biological/physical effect of z on the drift, and the effect of non-discretionary expenditures induced by z. Therefore, a design change in the WMB that allows investors more discretion would lead to a decrease in α and a decrease in the estimate of ρ. The decrease in α would benefit investors, but this would be partly offset by the decrease in ρ. Note that the "alternate estimate" of ρ is higher than the base estimate: our

An estimate of α is obtained by solving $\alpha\sum_{i=1}^{6} z_i^2 = N$, where N (total non-discretionary expenditures) equals the sum of total project expenses for plants, seeds, and soil inputs. The unit of measure for wetlands quality is the number of indicator species times their HSI. We have only three years of data on z, z_0, z_3 and z_6. We obtain estimates for the missing years by linear interpolation. For our sample, N = 1.68 ($1680 per acre) and $\sum_{i=1}^{6} z_i^2 = 10.09$, which results in an estimate of .16 for the parameter α.

Estimates for parameters ρ and β are obtained by using the data of z and m in the deterministic version of the state equation, obtained by setting $\sigma^2 = 0$. We solve this equation to obtain

(12) $$z_{t+3} = z_t e^{3\rho} + (e^{3\rho} - 1)\frac{\beta\sqrt{m_t}}{\rho} \quad \text{for } t = 0,3.$$

Using the following observations on z, $z_0 = 0$, $z_3 = 1$ and $z_6 = 2$ in (12) gives two equations which we solve for β and ρ. We set the value of m_t for these two equations equal to the average discretionary expenditures, in the three year period beginning at time t: for the first three years we have $m_t = 4.96$ and for the last three years $m_t = .462$. These imply estimates of $\beta = .11$ and $\rho = .18$ We have no degrees of freedom left to estimate σ^2. For our base case we arbitrarily set σ^2 equal to 1.

If we assume that all expenditures are discretionary, then by definition $\alpha = 0$. We

experiment answers the first question, but it clearly does not answer the second.

reallocate the expenses we previously defined as non-discretionary, to the discretionary category, and recalculate β and ρ, obtaining $\beta = .09$, $\rho = .183$. These are the "alternate parameters".

We do not have sufficient data to estimate γ and η. However, we think that a value of \$6000 per acre of wetlands with $z = 2$ is reasonable; this figure is based on the sales price of coastal marsh in California (Eliot and Holderman [7]). We set $\eta = 6$ and $\gamma = -3$, values which are consistent with $K(2) = 6$. These values also imply that K is maximized at $z = 2$. This means that $z^* \leq 2$, since it would never be optimal to incur a cost of holding an investment when the value of the investment cannot increase. The remaining parameter is the interest rate, r, which we set equal to .1 for the base case.

VI. RESULTS

Using the parameter values in the previous section, we solve the second order ordinary differential equation obtained by substituting (6) into (3*), and the boundary conditions (7) and (8). We search over the interval (0, 2) to find the optimal z^*, as described in Section IV. This section reports results of the base case and sensitivity studies, which are illustrated in Figures 1 - 4 and summarized in Table I.

Figure 1 shows the graphs of $-K(z)$ and two functions of $V(z)$, for the base case parameters, and with α reduced from .16 (the base case) to .08. We first discuss the base case. For these parameter values the stopping state is $z^* = 1$. For a given value of z, the difference between cashing in immediately and behaving optimally, $-K(z)-V(z)$, is the option value of the investment. For $z = .1$ the option value is 18.5% of the value of the investment.

The option value is negligible at $z = .6$, where $K = 3.06$ (50% of its maximum value).

If we assume that α represents the true social costs associated with non-discretionary restoration activities, then private decisions are socially optimal. However, in the illustration above, the investor has little incentive to restore the wetlands to a level close to the private (and social) optimum; she looses a negligible amount by stopping restoration too soon. Therefore, if the investor is uncertain about the "true model", or has bounded rationality, it is likely that adequate restoration would not occur. A subsidy on non-discretionary expenditure increases the investor's incentive to restore the wetlands. We examine the effect of a 50% subsidy by reducing the parameter α from .16 to .08. The resulting value function is graphed in Figure 1. The stopping state, z^*, increases to 2, the level that maximizes the intrinsic value $K(z)$. The subsidy causes the privately optimal stopping state to be twice the socially optimal stopping state, and increases the value of the investment program. The option value, as a percentage of the value of the program, increases to approximately 75% at $z = .1$. The option value is 26% (instead of .5% with $\alpha = .16$) for $z = .6$, and does not fall to 1% until $z = 1.5$. This subsidy has a substantial effect in increasing the investor's incentives to restore the wetlands. Failure to invest at all (i.e. cashing in when z is negligible), leads to a large loss. However, the subsidy can lead to excessive restoration (under the assumption that social costs are represented by $\alpha = .16$).

The subsidy also alters the (privately) optimal profile for discretionary investment, m(z). This function, obtained using (6), is graphed for the two values of α in Figure 2. For low values of z, the subsidy increases discretionary expenditures. For example, at $z = .1$, the subsidy increases discretionary expenditures from \$391 to \$563 per acre per year. The reason for the increase is that the subsidy makes it less costly, and therefore more attractive, to have the state reach a high level. However, for values of $z > .2$, the subsidy decreases discretionary expenditures. This is because the subsidy decreases the cost of waiting to cash in, during which time non-discretionary expenditures are incurred. This increases the investor's incentive to allow the state to increase at its natural rate, rather than as a result of discretionary expenditures.

We obtain a certainty equivalent approximation[4] of total undiscounted discretionary costs by taking the integral, from the initial state z_o to z^*, of the function $m(z)/g(z,m(z))$. We denote this integral as $D(z_o)$. To show that this equals the total undiscounted discretionary cost of driving the state from $z = z_o$ to $z = z^*$, when the decision rule $m(z)$ is used, and $\sigma^2 = 0$, we use the following relation:

$$D(z_o) = \int_0^T m(t)dt = \int_0^T \frac{m(z(t))\, dz}{dz/dt} = \int_{z_0}^{z^*} \frac{m(z)}{g(m,z)} dz \,. \tag{13}$$

The 50% subsidy in non-discretionary expenditures may cause discretionary expenditures to increase or decrease at a point in time, but aggregate discretionary expenditures fall by approximately 30%. Since the wetlands are restored to a higher level, and discretionary expenditures fall, non-discretionary expenditures must increase. In this sense, discretionary and non-discretionary expenditures are "substitutes in production". Just as is the case in a static production model, where two inputs are substitutes and one is subsidized, the subsidy

[4] The exact value of total expected discounted discretionary costs, denoted $L(z)$ can be obtained by solving the second order ODE $0 = -rL(z) + m(z) + L'(z)g(z,m(z)) + \sigma^2 z^2 L''(z)/2$, with boundary conditions $L(z^*) = 0 = L'(z^*)$.

leads to a decrease in the use of the unsubsidized input.

To summarize, the subsidy has two effects. First, it increases the option value of investment. This can be socially beneficial if private investors would not undertake restoration activities which have only a small positive expected return. However, it can be socially harmful if it leads to an excessive level of restoration. Second, the subsidy shifts discretionary investment forward in time, decreases aggregate discretionary expenditures, and increases aggregate non-discretionary expenditures (only half of which are paid by the private investor). These changes tend to lower social welfare, since they represent an inefficient allocation of inputs, both over time, and across categories of discretionary and non-discretionary expenditures. When discretionary expenditures are lower, as is the case under the subsidy for $z \in (.2, 1)$, the expected improvement in wetlands occurs more slowly. Therefore, although the subsidy would probably eventually result in a higher quality of wetlands, it is likely to cause a delay in the expected arrival time of a reaching a moderate level of quality (e.g., $z = 1$).[5]

Small changes in the variance lead to large changes in the optimal investment strategy. Figure 3 shows the graph of the value functions with $\sigma^2 = 1.0$ and $\sigma^2 = 1.1$. Consistent with Proposition 1 and results from previous literature, an increase in the variance increases the value of the investment program. The magnitude of the change is surprising. This larger variance causes an increase in the stopping state from $z^* = 1$ to $z^* = 2$. The option value, as a percentage of the value of the program, is approximately 46% at $z = .1$, but it falls to 6.7%

[5] Using the same type of equation described in footnote 4, we could calculate exactly the expected arrival time under optimal behavior. We could also calculate other measures that might be of interest, such as the expected present value of the cost of the subsidy.

at $z = .6$.

Figure 4 graphs the control rules for the two values of σ^2. For very low values of the state, discretionary investment is higher for $\sigma^2 = 1.1$, but for most values of z, it is lower with the higher variance. The measure of aggregate discretionary expenditures increases slightly, although the investment is held until a much higher level of z. With a lower variance, it does not pay the investor to wait around in the hope of getting lucky. Instead, when it is worth holding the asset she uses higher discretionary expenditures, but cashes in sooner.

Beginning with the base parameter values and increasing the interest rate from $r = .1$ to $r = .12$ decreases the stopping state from $z^* = 1$ to $z^* = .6$. The value of the program decreases considerably, as shown in Table I. The higher interest rate increases discretionary expenditures for all values of z at which the investment is held. With a higher interest rate, the investor wants to cash in quickly, if she invests at all. The investor therefore undertakes discretionary expenditures rather than relying on the natural growth rate of the state. The measure for aggregate discretionary expenditures, $D(.1)$ is approximately 75% of the base case level.

We also experimented with changes in the parameters of K(z). These led to changes in optimal behavior, in the direction expected. For example, an increase in $K(2)$ from \$6,000 per acre of coastal marsh, to \$7,000 per acre implies parameters values $\gamma = -3.5$ and $\eta = 7$. The increase in the credits makes it optimal to restore wetlands to a higher level. The stopping state is $z^* = 1.8$ instead of $z^* = 1$ as in the base case. The option value at $z = .1$ is 61% of the value of the program and does not decline to 3% until $z = 1.5$. The increased value of credits has a substantial increase in the incentive to engage in restoration.

Finally, we examined the importance of our assumption concerning which expenditures are discretionary, using the alternate parameter estimates described in the previous section. The last row of Table I presents the results. The most important parameter change is for α, which becomes 0. The effect of a decrease in α was described above in the discussion of the subsidy. The changes in optimal behavior are simply magnified here, although the interpretation is different. (In the present context, the change in α is due to correcting a "mistake" in our model, rather than to providing a subsidy.) The changes in the estimates of β and ρ work in the same direction as the change in α.

VII. CONCLUSION

We formulated a stochastic control model of investment in a Wetlands Mitigation Bank. We calibrated a simple version of the model and solved it numerically. This approach to the problem makes efficient use of the data we have, and it also suggests where we would most benefit from better data.

By assumption, non-discretionary costs increase with the quality of the wetlands. The optimal level of discretionary expenditure, on the other hand, decreases with quality. Since we expect, on average, the quality to be increasing over time, this means that most of the discretionary investment comes early in the program.

The value of delaying cashing in the investment and continuing restoration (the option value) is largest when the quality of the wetland is low. It decreases monotonically as the quality improves. The incentive is negligible even when the quality is far below the (privately and socially) optimal stopping state in the base case. Since the investor is unlikely to know exactly what this state is (due incomplete knowledge or bounded rationality, for example), this result suggests that wetlands may not be restored to their optimal level.

A subsidy on non-discretionary expenditures increases the option value and therefore encourages continued restoration, possibly to a level higher than is socially optimal. The subsidy increases initial discretionary expenditures but then decreases these expenditures for a range of wetlands quality. Therefore, the subsidy accelerates improvements in wetlands at first (for low levels of z), but then delays them. The net effect of the subsidy is to decrease aggregate discretionary expenditures. The subsidy introduces a distortion; by decreasing the amount of non-discretionary costs that the developer must pay, it decreases her willingness to incur discretionary costs. The net effect on social welfare of the subsidy may therefore be negative. This particular subsidy is a blunt instrument. A more finely tuned policy, e.g. a subsidy which changes with the state of the wetlands, would result in a smaller distortion. Of course, such a policy requires more information and is harder to administer.

The quantitative results are sensitive to parameter values, which are based on inadequate data. For example, the magnitude of the variance was important in determining both the incentives for investment, and the optimal investment path. Less uncertainty decreases the option value of investment. However, conditional on investment occurring, discretionary investment is higher with less uncertainty. A decrease in uncertainty makes it less tempting to rely on good fortune.

In order to make our model more useful, it is especially important to improve our knowledge about the index of quality, z. The dynamics of this variable need to be modelled carefully, a task which requires better data. In addition, the relation between the quality index and the value of credits, $K(z)$, has to be understood better. This requires a clear definition of the relation between the quality index and the number of credits a developer receives. It also requires that we know more about the monetary value of restored wetlands. Since WMB's are a recent innovation, the current lack of data is not surprising.

References

1. R. Anderson and M. Rockel, *Economic Valuation of Wetlands*, Discussion Paper No. 065, American Petroleum Institute, Washington, D.C. (1991).

2. M. J. Brennan and E. S. Schwartz, "Evaluating Natural Resource Investments," *Journal of Business*, **58**, 2 (1985).

3. W. A. Brock, M. Rothschild, and J. E. Stiglitz, Stochastic Capital Theory, Chapter 20 of *Joan Robinson and Modern Economic Theory*, (G. R. Feiwel, ed.), New York University Press, New York (1989).

4. California State Coastal Conservancy, *Bracut Marsh Case Study Report*, State Coastal Conservancy, Oakland (1991).

5. A. Castelle, C. Connelly, and M. Emers, *Wetland Mitigation Replacement Ratios*, Washington State Department of Ecology, Public. No. 92-09, Olympia, February (1992).

6. S. L. Cruickshank, "Air Emissions, Banking and Trading: Analysis and Implications for Wetland Mitigation Banking" draft report, American Petroleum Institute, Washington DC, October (1993).

7. W. Eliot and R. Holderman, "Pickleweed or Parking Lot?" CA Coast and Ocean, California State Coastal Conservancy, Oakland **4**, 1 (1988).

8. Federal Register, 40 CFR Part 110, *Clean Water Act Regulatory Programs: Final Rule*, August 25 (1993).

9. A. C. Fisher and W. M. Hanemann, "Option Value and the Extinction of Species," in *Advances in Applied Micro-Economics*, (V. K. Smith, ed.) JAI Press, Greenwich, (1986).

10. T. Griswold, "Messing with Mother Nature: The Quagmire of Wetlands Mitigation Banking," *California Regulatory Law Reporter* **13**, 2&3 (1993).

11. M. Guinon, *Study of Field Implementation Costs for Restoration Projects in California*, Sycamore Associates, Lafayette (1992).

12. R. Heimlich, "Costs of an Agricultural Wetland Reserve" *Land Economics* **70**, 2 (1994).

13. D. M. King, *Wetland Creation and Restoration: An Integrated Framework for Evaluating Costs, Expected Results and Compensation Ratios*, University of

Maryland, Solomons, April (1991).

14. R. A. Kramer, L. Shabman, "The Effects of Agricultural and Tax Policy Reform on the Economic Return to Wetland Drainage in the Mississippi Delta Region," *Land Economics* **69**, 3 (1993).

15. C. Lant, "Making Better Use of the Farm Bill," *National Wetlands Newsletter*, Environmental Law Institute, January (1993).

16. A. G. Malliaris, and W. A. Brock, *Stochastic Methods in Economics and Finance*, North-Holland Press, New York (1982).

17. National Research Council, *Restoration of Aquatic Ecosystems*, National Academy Press, Washington D.C. (1992).

18. R. S. Pindyck, "Irreversibility, Uncertainty, and Investment, " *Journal of Economic Literature* **29**, 3 (1991).

19. V. Ramey, "Inventories as Factors of Production and Economic Fluctuations," *American Economic Review* **79**, 3, June (1989).

20. R. Reppert, "Wetlands Mitigation Banking Concepts," IWR Report 92-WMB-1, Fort Belvoir, VA (1992).

21. L. Shabman and S. Batie, "Mitigating Damages from Coastal Wetlands Development: Policy, Economics and Financing," *Marine Resource Economics* **4**, 3 (1987).

22. R. Stavins, "Alternative Renewable Resource Strategies: A Simulation of Optimal Use," *Journal of Environmental Economics and Management* **19**, 2 (1990).

23. R. Stavins and A. Jaffe, "Unintended Impacts of Public Investment on Private Decisions: The Depletion of Forested Wetlands," *American Economic Review*, **80**, 3 (1990).

24. U.S. Fish and Wildlife Service, *Habitat Evaluation Procedures, Ecological Services Manual*, #102-ESM1, Fish and Wildlife Service, Department of the Interior, Washington, D.C. (1980).

25. C. Van Kooten, "Bioeconomic Evaluation of Government Agricultural Programs on Wetlands Conversion," *Land Economics* **69**, 1 (1993).

26. J. C. Williams, and B. D. Wright, *Storage and Commodity Markets*, Cambridge University Press, Cambridge (1991).

Table
Sensitivity Analy[illegible] Results

Parameter value	z^*	option value, $z = .1$ percentage of investment value	dollar amount	option value, $z = .6$ percentage of investment value	dollar amount	Approximate total discretionary costs, $D(.1)$
base case values	1	18.5%	$133	.5%	$7	$2,909
$\alpha = .08$	2	74.6%	$1719	26%	$1074	$2,043
$\sigma^2 = 1.1$	2	46%	$505	6.7%	$222	$2[illegible]
r = .12	0.6	6%	$41	0%	$0	$2,267
$\alpha=0, \beta=.09, \rho=.183$	2	86%	$3611	44%	$2412	$839

Figure 1. Base Case and Effect of Decreasing Non-Discretionary Cost Parameter from .16 to .08

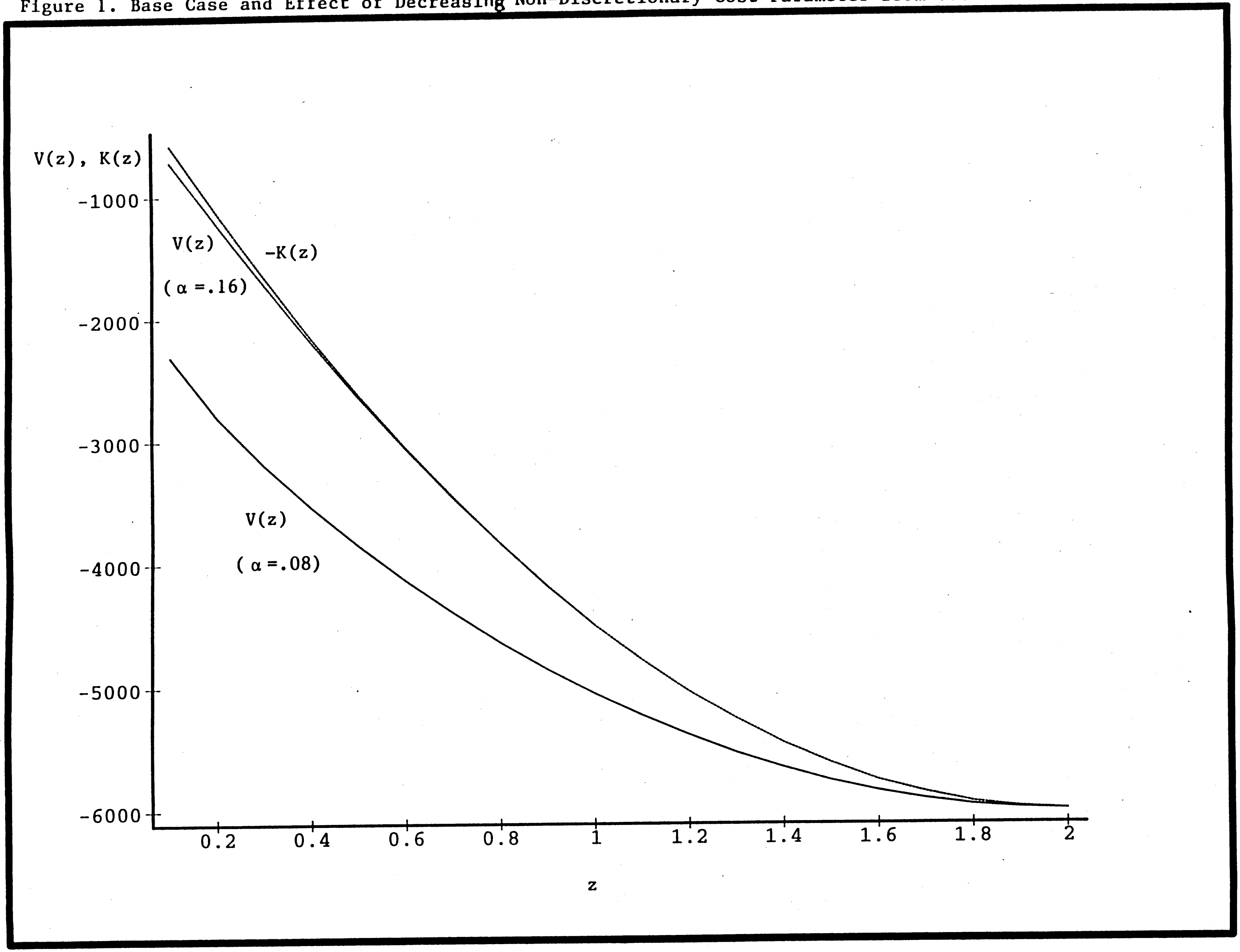

Figure 2. Control Rule m for Base Case and Decrease in Non-Discretionary Cost Parameter

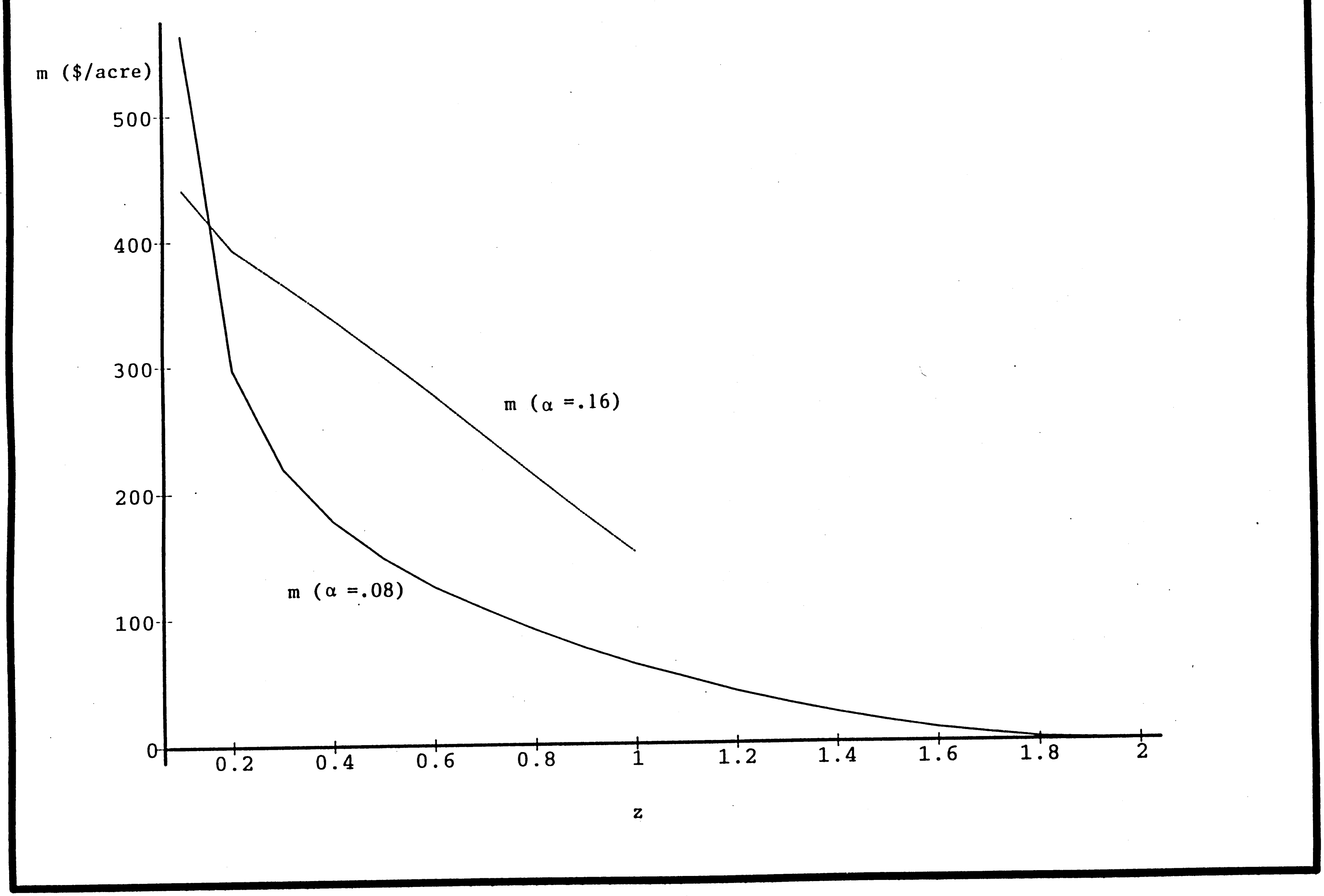

Figure 3. Base Case and Effect of Increase in Variance from 1.0 to 1.1

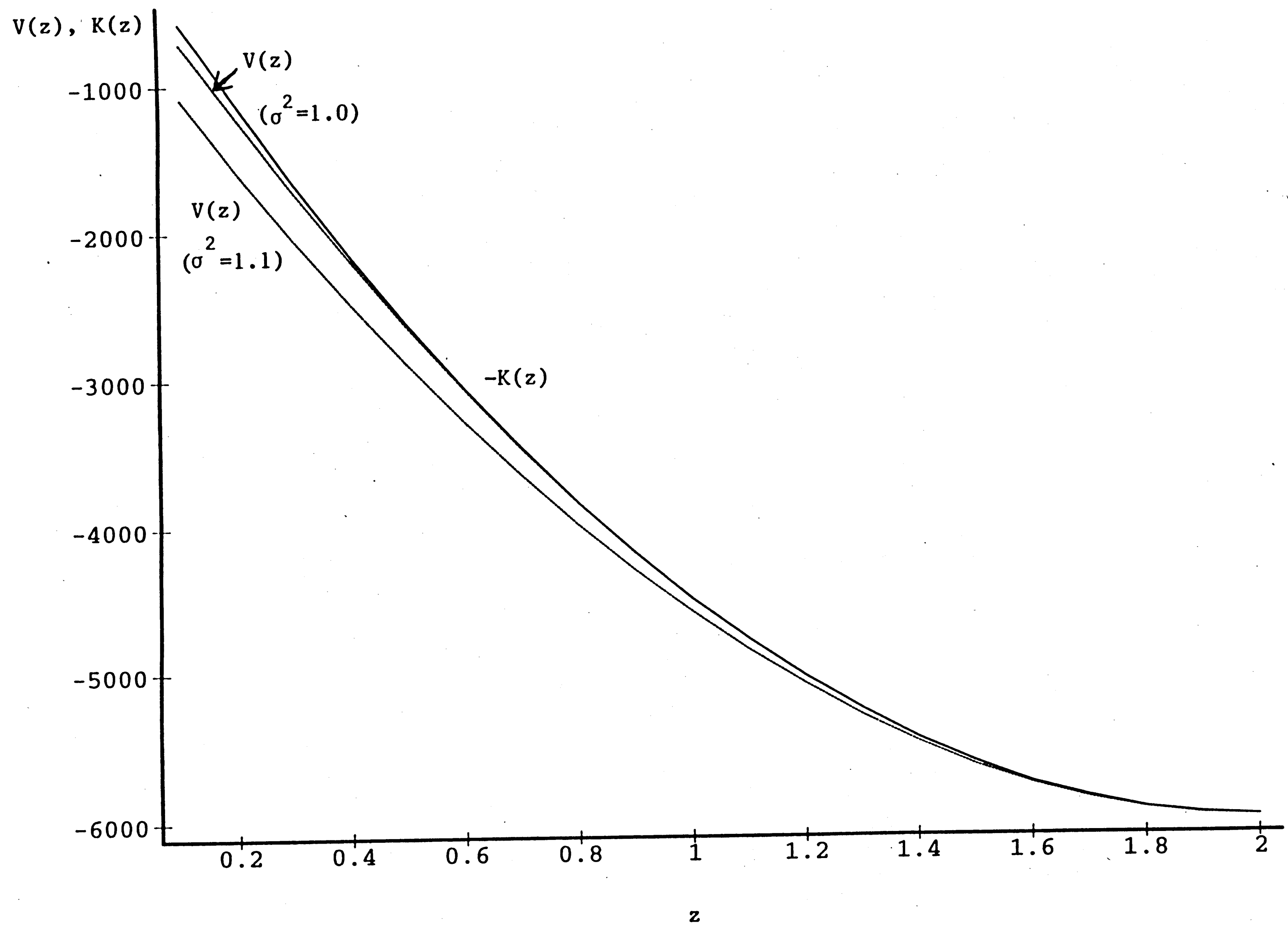

Figure 4. Control Rule m for Base Case and Increase in Variance