Chapter 5

Hysteresis, Uncertainty, and Economic Valuation

I. INTRODUCTION

The purpose of this chapter is to investigate some issues that arise when one attempts to conduct a benefit evaluation for the control of pollution in an aquatic ecosystem. Obviously, the extent of the benefits depends on the nature of the ecosystem's response to control. We are concerned with two aspects of ecosystem behavior in particular. The first is the phenomenon known as "hysteresis", as discussed in chapter 3. Recall that this is the notion that a damaged ecosystem may not respond immediately to a cessation in pollution discharges and, when it does respond, may not exactly retrace the trajectory of its decline. Indeed, because of some irrecoverable losses from the system, it may never return to its original state. The second aspect of ecosystem behavior we focus on is the stochasticity of natural phenomena which, as emphasized in chapter 4, implies that the ecosystem response is inherently uncertain.

Both the uncertainty and the dynamic constraints on ecosystem behavior need to be taken into account in evaluating the benefits of control and in the related decision on whether, or when, to control. Recovery dynamics, for example, may favor doing nothing, as in the case where the system is so far gone that recovery is impossible, or they may favor early action precisely to forestall more damaging, long-lasting consequences.

When uncertainty is factored into the analysis, an additional consideration arises which is sometimes overlooked. The temporal resolution of uncertainty--

the possibility of acquiring better information about the future consequences of controlling or continuing pollution--adds an extra element to the decision calculus. Regardless of whether the decisionmaker exhibits risk aversion or risk neutrality, if further information is forthcoming, there is a premium on those initial actions which preserve future flexibility and a discount on those which reduce flexibility and preclude the exploitation of the additional information at a later date. In the present context, this could be information about either the dynamics of ecosystem behavior or the social valuation of ecosystem products. If we control pollution now and, subsequently, learn that the ecosystem was not at a threshold of irreversible damage, we can always resume pollution later; but if we do not control now and then observe irreversible changes in the ecosystem, we cannot undo them by controlling later. Similarly, if we control now and then learn that future generations place a low value on ecosystem services, we can resume pollution; but if we do not control now and the ecosystem is irreversibly damaged, it is too late to act if we subsequently discover that future generations place a high value on the ecosystem. In each case there is an asymmetry in our ability to exploit future information and a premium associated with the action that preserves flexibility.

This flexibility premium has been recognized in the environmental valuation literature under the name of "quasi option value" (Arrow and Fisher [1974]) or "option value" (Henry [1974]).[1] Within the context of an irreversible land development decision where the future benefits of preservation in an undeveloped state are uncertain, these authors show that, when a decisionmaker ignores the possibility of acquiring further information about the future value of undeveloped land, he inevitably understates the net benefit of preservation over development and prejudices the decision somewhat in favor of immediate development.

The present work extends these results in several ways. First, we consider a decision framework where the irreversibility is associated with not taking action now (i.e., not controlling): In effect, we are dealing with the sin of omission rather than commission. More importantly, we consider a multiperiod decision problem, rather than the two-period problem of previous work. This change is important not merely because it is a step in the direction of greater realism--most practical policy issues involve a sequence of decision points--but also because it enables us to investigate some questions that are obscured within a two-period framework.

Suppose continued stress on a system is certain to trigger irreversible changes, beyond some critical point or period, but we do not know the period. Is there an analog to the two-period option value? Or suppose the critical period is known, but the damaging consequences are delayed as with certain kinds of health impacts. How does this affect the control decision? Still another issue we can consider in a multiperiod setting is the distinction between ordinary lags and irreversibility. Irreversible environmental degradation may be regarded as an extreme form of a lagged recovery in which the lag period is infinite (or, at any rate, longer than the effective planning horizon). What about less extreme lags where, if pollution continues beyond a certain point, the ecosystem is disabled for a certain (finite) period of time but then recovers: Do the option value arguments still apply?

Uncertainty, or more precisely the nature of learning, is necessarily treated differently in a multiperiod setting. In the two-period models, uncertainty is assumed completely resolved by the start of the second period. By contrast, we assume that the decisionmaker acquires some, but not all of the information over the first period, more over the second, more still over the third, and so on. Partial, not perfect, information at any time is accordingly part of the structure of our model.

The chapter is organized as follows: In the next section we develop a model to evaluate pollution control, taking account of both the relevant physical constraints and the uncertainties. The model is used in sections III and IV to study the implications of various interesting combinations of recovery dynamics and uncertainties, of the sort just noted. Conclusions are offered in section V.

II. A FRAMEWORK FOR BENEFIT EVALUATION AND DECISION

We model the decision on whether or not to control pollution from the point of view of an environmental authority concerned with the net present value (benefits minus costs) of control, The optimal control is defined as the choice that maximizes this value. The important constraints are those that emerge from the discussion of the preceding section: (1) Beyond some point in time, failure to control is not readily reversible; and (2) the benefits of control are uncertain due to a lack of knowledge about the timing and nature of ecosystem recovery and the willingness of individuals to pay for the goods and services it can produce.

Though recovery is a continuous process, evaluation and control take place in a discrete setting. Thus, we assume that a decision to control pollution can be made in each period t = 1, 2, 3, ... The outcome of the decision can be represented by a sequence $X_1, X_2, X_3, \ldots$ where $X_t = 1$ corresponds to building a treatment plant, say, and $X_t = 0$ corresponds to not building. Note that we are considering a binary choice, neglecting intermediate levels of control. The results we obtain can be extended to the case of continuous control, but this is somewhat beside the point and comes at a substantial cost in complexity.

Associated with the choice of X_t is a set of benefits and costs. The capital and operating costs of the control facility in period t are denoted by C_t, and the benefits are denoted B_t; the net benefits are $NB_t \equiv B_t - C_t$. In the most general model, the benefits and costs accruing during any time period depend not only on the current pollution control decision, X_t, but also on all previous decisions, $X_1, \ldots, X_{t-1}$.

An essential feature mentioned above is that the benefits and costs of ecosystem recovery are uncertain. Thus, we write the overall net benefit function as

$$NB(X_1,X_2,X_3, \ldots; \theta) = NB_1(X_1; \theta) + \beta\, NB_2(X_1,X_2; \theta) + \beta^2 NB_3(X_1,X_2,X_3; \theta) + \ldots$$

where

$$NB_t(X_1, \ldots X_t; \theta) \equiv B_t(X_1, \ldots, X_t; \theta) - C_t(X_1, \ldots, X_t; \theta).$$

Here β is a one-period discount factor, and θ is a random variable (or vector of random variables) representing the present uncertainty concerning the future consequences of pollution control.

With regard to the cost functions, it seems reasonable to assume that, with probability 1,

$$C_t(0, \ldots 0; \theta) = 0$$

and

$$C_t(X_1, \ldots X_{t-1}, 1; \theta) \geq C_t(X_1, \ldots, X_{t-1}, 0; \theta).$$

That is to say, pollution control is costly. Finally, in order to keep the decision problem simple while still making it interesting, we focus on a three-period model. This is significantly more general than the two-period models which have been used in irreversibility literature so far (for example, Arrow and Fisher [1974], Henry [1974], Epstein [1980]). With minimal notational clutter, it permits us to consider scenarios involving a variety of types of irreversibility, which is our primary objective in this paper.

Given this structure, the social decision problem is to maximize the discounted present value of expected net benefits:

(1) $$\max_{X_1, X_2, X_3} E\{NB(X_1, X_2, X_3; \theta)\}.$$

Two aspects of this problem need to be addressed, both pertaining to the treatment of uncertainty. First, what about attitudes toward risk? Should one assume risk aversion on the part of the social decisionmaker and, therefore, include a risk-premium term when taking the expectation in (1), or should one assume risk neutrality following the arguments, for example, of Samuelson [1964] or Arrow and Lind [1970]? Although it clearly makes a difference in practice, the question of risk aversion is not fundamental to the results that we will obtain: They are qualitatively independent of any assumption about risk preferences. The second aspect of modeling uncertainty in a dynamic setting is its behavior over time. Uncertainty means a lack of information; yet, it is likely that this situation changes--that information is acquired over time. Our analysis is largely concerned with the consequences of a failure on the part of the decisionmaker to take this prospect into account. We will show how this affects the social decision and how conventional benefit-cost analysis must be adjusted to incorporate this consideration.

Suppose, first, that the decisionmaker does not have to commit himself in the first period to an entire intertemporal control strategy; he can postpone the choice of X_2 to t = 2 and the choice of X_3 to t = 3. Suppose, moreover, that in each time period (except t = 3), he recognizes that further information about the future consequences of control will become available which he can exploit in making these future decisions. Define

(2a) $$\hat{V}_3(X_3 | X_1, X_2) \equiv E_3\{NB_3(X_1, X_2, X_3; \theta)\}$$

(2b) $$\hat{V}_2(X_2 | X_1) \equiv E_2\{NB_2(X_1, X_2; \theta) + \max_{X_3} \beta \hat{V}_3(X_3 | X_1, X_2)\}$$

$$\hat{V}_1(X_1) \equiv E_1\{NB_1(X_1;\ \theta) + \max_{X_2} \hat{V}_2(X_2|X_1)\}. \tag{2c}$$

where Et {*} denotes an expectation with respect to the information set available at time t--i.e. , E_1 is the expectation with respect to the decisionmaker's prior distribution for θ, E_2 is the expectation with respect to his posterior distribution in t = 2 which is updated in a Bayesian reamer on the basis of the information obtained by the beginning of the second period, etc. One point must be emphasized: We assume that the acquisition of information does not depend on the choice of X_t; it emerges either with the passage of time (e.g., as period 2 approaches, one can make a more accurate assessment about the social value of environmental quality in the second period) or as the result of a separate research program on ecosystem dynamics.[2]

Following the Backwards Induction Principle of dynamic programming, in the third period the decisionmaker selects

$$\hat{X}_3 \equiv \arg\max \hat{V}_3(X_3|X_1, X_2), \tag{3a}$$

in the second he selects

$$\hat{X}_2 \equiv \arg\max \hat{V}_2(X_2|X_1), \tag{3b}$$

and in the first he selects

$$\hat{X}_1 \equiv \arg\max \hat{V}_1(X_1). \tag{3c}$$

In each case we are assuming that, however $X_1, \ldots, X_{t-1}$ are chosen, X_t is chosen optimally in the light of these previous decisions. Where it is necessary to emphasize this dependence, we shall write X_t as an explicit function of the previous choice variables--e.g. , $\hat{X}_2 = \hat{X}_2(X_1)$. In the terminology of stochastic control theory, $(\hat{X}_1, \hat{X}_2, \hat{X}_3)$ represents a closed-loop policy: At each decision point, both current information and all future anticipated information are considered in choosing a control.

We wish to contrast this with a policy in which the prospect of future information is disregarded. There are two ways to model this. One is to assume that, although the decisionmaker is still free to postpone his choice of X_2 and X_3 until the second and third periods , respectively, in each period he ignores the possibility of future learning and deals with uncertainty about future consequences by replacing random variables with his current estimate of their mean. Define

$$V_3^*(X_3 | X_1, X_2) \equiv E_3\{NB_3(X_1, X_2, X_3; \theta)\} \tag{4a}$$

$$V_2^*(X_2 | X_1) \equiv \max_{X_3} E_2\{NB_2(X_1, X_2; \theta) + \beta\ NB_3(X_1, X_2, X_3; \theta)\} \tag{4b}$$

$$V_1^*(X_1) \equiv \max_{X_2, X_3} E_1\{NB_1(X_1; \theta) + \beta\ NB_2(X_1, X_2; \theta) + \beta^2\ NB_3(X_1, X_2, X_3; \theta)\}. \tag{4c}$$

In the third period, the decisionmaker selects

$$X_3^* \equiv \arg\max V_3^*(X_3 | X_1, X_2), \tag{5a}$$

in the second he selects

$$X_2^* \equiv \arg\max V_2^*(X_2 | X_1), \tag{5b}$$

and in the first he selects

$$X_1^* \equiv \arg\max V_1^*(X_1). \tag{5c}$$

In the terminology of stochastic control theory, this is an open-loop feedback policy: As new information becomes available, the decisionmaker incorporates it in his choice of a control; but he assumes that no further information will become available.

The other approach to modeling the disregard of future information is to assume that the decisionmaker does not wait (or camot wait) until the second and third periods to choose X_2 and X_3 but, instead, chooses them in the first period along with X_1. This decision, denoted $(X_1^{**}, X_2^{**}, X_3^{**})$, is the solution to

$$(6) \qquad \max_{X_1,X_2,X_3} E_1\{NB_1(X_1;\theta) + \beta NB_2(X_1,X_2;\theta) + \beta^2 NB_3(X_1,X_2,X_3;\theta)\}.$$

This is known as an open-loop control where all decisions are made simultaneously on the basis of the information available at the beginning of the initial period. Comparing (5) and (6), it is clear that $X_1^* = X_1^{**}$, but in general, $X_2^{**} \neq X_2^*$ and $X_3^{**} \neq X_3^*$--there is no difference between the open-loop and open-loop feedack controls in the first period but in subsequent periods they differ. Thus our discussion belowof the relation between $\hat{X}_1$ and X_1^* also applies to X_1^{**}, but it does not apply to relations in t = 2 and t = 3. Since, in a three-period model, unlike a two-period model, the choice of X_2 is of substantive interest, the sharp distinction between open-loop and open-loop feedback policies is one of the benefits that we gain by switching to a multi-period setting. It will become clear below that, for our purposes, useful results can be obtained by comparing the closed-loop policy with the open-loop feedback policy.

We can pursue this comparison in two ways. We can ask a policy question: How do $\hat{X}_t$ and X_t^* differ? In particular, under what circumstances is it true that $\hat{X}_t \geq X_t^*$ (i.e., the case for intervening to control pollution is strengthened when the prospect of further information is recognized)? Or we can ask a benefit evaluation question: How do $\hat{V}_t(\cdot)$ and $V_t^*(\cdot)$ differ? What correction is required when expected benefits are estimated by replacing uncertain future quantities with a current estimate of their expected value?

Given the constraint that $X_t = 0$ or 1, these questions can be answered by observing that, from (2)-(4),

$$\text{(7a)} \qquad \hat{X}_1 \geq (\leq)\ X_1^* \qquad \text{as} \qquad OV_1 \geq (\leq)\ 0$$

and, for any given X_1,

$$\text{(7b)} \qquad \hat{X}_2(X_1) \geq (\leq)\ X_2^*(X_1) \qquad \text{as} \qquad OV_2(X_1) \geq (\leq)\ 0$$

where

$$\text{(8a)} \qquad OV_1 \equiv [\hat{V}_1(1) - \hat{V}_1(0)] - [V_1^*(1) - V_1^*(0)]$$

$$\text{(8b)} \qquad = [\hat{V}_1(1) - V_1^*(1)] - [\hat{V}_1(0) - V_1^*(0)];$$

and, given X_1,

$$\text{(9a)} \qquad OV_2(X_1) \equiv [\hat{V}_2(1|X_1) - \hat{V}_2(0|X_1)] - [V_2^*(1|X_1) - V_2^*(0|X_1)]$$

$$\text{(9b)} \qquad = [\hat{V}_2(1|X_1) - V_2^*(1|X_1)] - [\hat{V}_2(0|X_1) - V_2^*(0|X_1)].$$

The quantities OV_1 and $OV_2(X_1)$ are the correction factors required when the prospect of future information is disregarded and benefits are measured in terms of $V_t^*(\cdot)$ instead of $\hat{V}_t(\cdot)$; they are multiperiod generalizations of the Arrow-Fisher-Henry concept of option value.

To interpret them, consider (8b) and (9b) and observe that the term $[\hat{V}_t(X_t) - V_t^*(X_t)]$ canbe cast in the form of

$$\text{(10)} \qquad \hat{V}_t(\cdot) - V_t^*(\cdot) = E_t\{\max_{X_{t+1},\ldots} F_t(\cdot;\theta)\} - \max_{X_{t+1},\ldots} E_t\{F_t(\cdot;\theta)\}.$$

This is a measure of the value of information acquired after the beginning of period t that can be exploited in the subsequent choice of $X_{t+1}, X_{t+2}, \ldots$ conditional on the choice of X_t in period t. Thus, in (8b), $[\hat{V}_1(1) - V_1^*(1)]$ is the expected value of the information that might be acquired in time to influence the second- and third-period choices conditional on controlling pollution in the first period, while $[\hat{V}_1(0) - V_1^*(0)]$ is the expected value of subsequent information conditional on not controlling pollution in the first period. The correction factor OV_1 is simply the difference between these two conditional values of information; similarly, for OV_2. Thus, if $OV_t > 0$, the value of information associated with setting $X_t = 1$ exceeds that associated with a decision to set $X_t = 0$ and the case for controlling pollution in period t is strengthened when the prospect of future information is considered. Conversely, if $OV_t < 0$, the case for pollution control is weakened.

However, without placing further structure on the model, it is impossible to determine which outcome is the more likely. From the convexity of the maximum operator and Jensen's Inequality applied to (10), it follows that $\hat{V}_t(\cdot) - V_t^*(\cdot) > 0$. Thus, each component of OV_t is nonnegative; but this tells us nothing about the sign of their difference. In the following sections we consider some alternative model structures embodying features of ecosystem dynamics discussed in section II and explore their effect on OV_t and their implications for pollution control policy.

III. CRITICAL PERIOD IRREVERSIBILITY

Suppose that, at some point in the evolution of the ecosystem, if the policymaker does not intervene and control pollution at that time, it could never be optimal for him to control pollution subsequently. We shall call a time period with this property a "critical" period. Whether such a phenomenon exists and what factors bring it about depends on the specifics of the ecosystem structure. In the context of the three-period model, suppose that, while it might pay to introduce controls after pollution has continued unchecked for one more period, it could never pay to introduce controls after pollution has continued unchecked for two more periods in a row. More formally, we assume that, with probability 1,

$$(11) \qquad E_t\{NB_3(0, 0, 1; \theta)\} \leq E_t\{NB_3(0, 0, 0; \theta)\} \qquad t = 2, 3.$$

Thus, if pollution is not controlled in the first period ($X_1 = 0$), the second period becomes critical.

From (2a,b) and (4b), when $X_1 = 0$, we have

$$(12a) \quad \hat{V}_2(0|0) = E_2\{NB_2(0, 0; \theta) + \beta \max [E_3 NB_3(0, 0, 1; \theta), E_3 NB_3(0, 0, 0; \theta)]\}.$$

$$(12b) \quad V_2^*(0|0) = E_2 NB_2(0, 0; \theta) + \beta \max [E_2 NB_3(0, 0, 1; \theta), E_2 NB_3(0, 0, 0; \theta)].$$

Applying (11) yields

$$(13a) \qquad \hat{V}_2(0|0) = E_2 NB_2(0, 0; \theta) + \beta E_2\{E_3 NB_3(0, 0, 0; \theta)\}.$$

$$(13b) \qquad V_2^*(0|0) = E_2 NB_2(0, 0; \theta) + \beta E_2 NB_3(0, 0, 0; \theta).$$

However, by the Total Probability Theorem, $E_t\{h(\theta)\} = E_t\{E_{t+1}\, h(\theta)\}$ for any function of a random variable, $h(\theta)$. Therefore, we obtain the key result that

$$\hat{V}_2(0|0) - V_2^*(0|0) = 0 . \tag{14}$$

Because the second period is critical when $X_1 = 0$, it follows that, if the decisionmaker does not control pollution in that period, he anticipates that he will never choose to control it subsequently. Since the anticipated future decisions are exactly the same under both the closed-loop and open-loop feedback policies, the expected future benefits are identical under both policies. In effect, any subsequent information is expected to have no economic value because it is not anticipated to have any effect on future decisions; hence, (14). Substituting this into (9) yields

$$OV_2(0) = \hat{V}_2(1|0) - V_2^*(1|0) \geq 0. \tag{15}$$

From (7b), this implies that $\hat{X}_2(0) \geq X_2^*(0)$. That is, if pollution is not controlled in the first period, we have a situation where, once the potential for the acquisition of future information is recognized, the case for controlling pollution in the second period is strengthened, and there is a positive flexibilitypremium associated with setting $X_2 = 1$.

The key to this analysis is equation (11) which embodies our particular assumption that the second period is critical when $X_1 = 0$. Without imposing any additional restrictions, it is impossible to determine the signs of OV_1 or $OV_2(1)$. For example, from (11), one <u>cannot</u> infer that $\hat{V}_2(0|1) = V_2^*(0|1)$. Therefore, the indeterminacy concerning the relation between $\hat{X}_1$ and X_1^*, or $\hat{X}_2(1)$ and $X_2^*(1)$, remains.

Generalizing from this particular example, a period is critical whenever an equation analogous to (11) holds, i.e., whenever the situation is such that, if the decisionmaker does not control in that period, with probability 1 he anticipates that it would never pay to control in future periods regardless of the information subsequently acquired. By construction, when a period t is critical, we have $\hat{V}_t(0|\cdot) = V^*_t(0|\cdot)$ which implies that $OV_t(\cdot) \geq 0$ and $\hat{X}_t(\cdot) \geq X^*_t(\cdot)$.

It may be useful to compare our notion of a critical period with the concept of irreversibility employed by Arrow and Fisher [1974] and by Henry [1974] which, in the present context, would be represented by a constraint of the form

$$X_1 = 0 \rightarrow X_2 \geq X_3. \tag{16}$$

Our assumption (11) implies (16) but is somewhat broader and illuminates the two crucial ingredients required to extend their results to more general settings. First, what is irreversible is the *policy*, not the fate of any particular biotic components. The ecosystem dynamics may be such that, if '$_2$ = 0, the lake trout become extinct without this necessarily implying (11) as long as the trout are sufficiently unimportant relative to the decisionmaker's other objectives. The truth or falsity of (11) depends on values as well as biology. Second, what is at issue is *economic* rather than *technical* irreversibility. The technology may be such that the decision on X_2 is physically reversible in later periods (e.g., setting $X_2 = 0$ corresponds to permitting the construction of a steel mill on the edge of a lake which could subsequently be converted to a nonpolluting bowling alley); the question is whether it could ever *pay* to reverse the current decision. Moreover, what matters is the present *anticipation* of whether it could ever pay to reverse that decision. Our assumption (11) does not preclude the possibility that, ex post, at the end of period 3, it might actually turn out that it would have been optimal to choose $X_3 = 1$ even with $X_2 = 0$. What is required is that, ex ante, this choice is always deemed implausible. Thus, we can admit the possibility that

$$NB_3(0, 0, 1; \theta) > NB_3(0, 0, 0; \theta)$$

for some realizations of e as long as the prior density on θ and the subsequent updated posterior densities are sufficiently bounded to ensure that the expected benefits satisfy the inequality in (11).

IV. DELAYED AND TEMPORARY IRREVERSIBILITY

In this section we consider two forms of irreversibility which are weaker than the critical-period concept introduced above and yield somewhat different results. First, we consider what might be called "delayed" irreversibility: If pollution is not controlled, the consequences are (economically) irreversible, but the irreversibility sets in only after a lag. Thus, if pollution is permitted to continue now, there is an intermediate period during which it may or may not be optimal to impose controls; but, after this intermediate period, it can never pay to control. Within the framework of our three-period model, we identify "now" with period 1, the intermediate period during which it may or may not be optimal to control with period 2 , and the subsequent future with period 3. The assumption of delayed irreversibility is capturedby combining (11) together with the assumption that

(17) $$E_t\{NB_3(0, 1, 1; \theta)\} \leq E_t\{NB_3(0, 1, 0; \theta)\} \quad t = 2, 3$$

with probability 1. The question to be addressed is how this type of irreversibility affects the pollution-control decision in period 1.

Substituting (11) and (17) into (2c) and (4c) yields the following expressions for $\hat{V}_1(0)$ and $V_1^*(0)$:

$$\hat{V}_1(0) = E_1 NB_1(0;\theta) + \beta E_1\{\max[E_2 NB_2(0, 0; \theta) + \beta E_2 NB_3(0, 0, 0; \theta),$$

(18a)

$$E_2 NB_2(0, 1; \theta) + \beta E_2 NB_3(0, 1, 0; \theta)]\}$$

$$V_1^*(0) = E_1 NB_1(0; \theta) + \beta \max [E_1 NB_2(0, 0; \theta) + \beta E_1 NB_3(0, 0, 0; \theta),$$

(18b)

$$E_1 NB_2(0, 1; \theta) + \beta E_1 NB_3(0, 1, 0; \theta)].$$

By inspection, it can be seen that, while $\hat{V}_1(0) - V_1^*(0) > 0$, it is <u>not</u> true in general that $\hat{V}_1(0) = V_1^*(0)$. Since it can also be shown that $\hat{V}_1(1) - V_1^*(1) \geq 0$, from (8a,b), this is a situation where the sign of ΔV_1 and the relation between $\hat{X}_1$ and X_1^* are indeterminate.

Observe that the formula for $\hat{V}_1(0)$ in (18a) involves information acquired between the first and second periods but not that acquired between the second and third periods--the expectation $E_3\{\cdot\}$ does not appear. The latter information has no economic value when $X_1 = 0$ because the irreversibility has set in by then, but the former does have some value because it can be exploited during the intermediate period (t = 2) where there is still some flexibility. Of course, if $X_1 = 1$, there is sufficient flexibility to exploit <u>both</u> sets of information. But this fact, by itself, does not guarantee that the overall value of information associated with setting $X_1 = 1$ necessarily exceeds that associated with setting $X_1 = 0$. The point is that, with delayed irreversibility, the first period is not critical because, if one does not control, then it is <u>not</u> true that it can never be optimal to control subsequently; it may still be optimal to control during the intervening period before the irreversibility sets in. Thus, with delayed irreversibility, the introduction of future learning into the decision calculus need not tilt the balance in favor of immediate control.

We now examine what might be called "temporary" irreversibility as opposed to the "permanent" irreversibility considered so far. We consider two scenarios. In the first we suppose that, if pollution is not controlled in any period, the consequences are temporarily irreversible and are felt in the following period but not necessarily thereafter. In effect, the system has a one-period memory with

(19) $$E_t\{NB_2(0, 1; 9)\} \le E_t\{NB_2(0, o; e)\}$$

(20a) $$NB_3(X_2, X_3; \theta) \equiv NB_3(0, X_2, X_3; \theta) = NB_3(1, X_2, X_3; \theta)$$

(20b) $$E_t\{NB_3(0, 1; \theta)\} \le E_t\{NB_3(0, O; \theta)\}.$$

In this case Vi(0) and $V_1^*(0)$ are given by

(21a) $$\hat{V}_1(0) = E_1 NB_1(0; \theta) + \beta E_1 \Big\{ \max\Big(E_2 NB_2(0, 1; \theta) + \beta E_2 \max[E_3 NB_3(1, O; 13), E_3 NB_3(1, 1; \theta)], E_2 NB_2(0, O; \theta) + \beta E_2 NB_3(0, O; \theta)\Big) \Big\},$$

(21b) $$V_1^*(0) = E_1 NB_1(0; e) + \beta \max\{E_1 NB_2(0, 1; 6) + \beta \max[E_1 NB_3(1, O; e), E_1 NB_3(1, 1; e)], E_1 NB_2(0, o; e) + \beta E_1 NB_3(0, 0; e)]\}.$$

It follows that, while $\hat{V}_1(0) - V_1^*(0) \geq 0$, it is not true in general that $\hat{V}_1(0) = V_1^*(0)$. Thus, with this type of temporary irreversibility, the sign of OV_1 and the relation between $\hat{X}_1$ and X_1^* are indeterminate.

We now change the scenario by assuming that, if pollution is not controlled in the first period, the consequences are temporarily irreversible in the second period but the third period is entirely independent of what has happened previously, i.e., the system makes a fresh start and has no memory in the third period. Thus, we retain (19) while assuming that the third-period benefit functions satisfy the restrictions

$$\begin{aligned} NB_3(X_3;\ \theta) \equiv NB_3(1,\ 1,\ X_3;\ \theta) &= NB_3(1,\ 0,\ X_3;\ \theta) \\ &= NB_3(0,\ 1,\ X_3;\ \theta) = NB_3(0,\ 0,\ X_3;\ \theta). \end{aligned} \tag{22}$$

The new formulas for $\hat{V}_1(0)$ and $V_1^*(0)$ are

$$\begin{aligned} \hat{V}_1(0) = {} & E_1 NB_1(0;\ \theta) + \beta\ E_1 NB_2(0,\ 0;\ \theta) \\ & + \beta^2\ E_1\ \{\max\ [E_3\ NB_3(0;\ \theta),\ E_3\ NB_3(1;\ \theta)]\} \end{aligned} \tag{23a}$$

$$\begin{aligned} V_1^*(0) = {} & E_1\ NB_1(0;\ \theta) + \beta\ \ E_1\ NB_2(0,\ 0;\ \theta) \\ & + \beta^2 \max\ [E_1\ NB_3(0;\ \theta),\ E_1\ NB_3(1;\ \theta)]. \end{aligned} \tag{23b}$$

Similarly, substitution of (19) and (22) into (2c) and (4c) yields the following formulas for $\hat{V}_1(1)$ and $V_1^*(1)$:

$$\hat{V}_1(1) = E_1\, NB_1(1; \theta) + \beta\, E_1\, \{\max\, [E_2\, NB_2(1, 0; \theta),\, E_2\, NB_2(1, 1; \theta)]\}$$

(24a)

$$+ \beta^2 E_1\, \{\max\, [E_3\, NB_3(0; \theta),\, E_3\, NB_3(1; \theta)]\}$$

$$V_1^*(1) = E_1\, NB_1(1; \theta) + \beta \max\, [E_1\, NB_2(1, 0; \theta),\, E_1\, NB_2(1, 1; \theta)]$$

(24b)

$$+ \beta^2 \max\, [E_1\, NB_3(0; \theta),\, E_1\, NB_3(1; \theta)].$$

In this case, although it is still true that $[\hat{V}_1(1) - V_1^*(1)] \geq 0$ and $[\hat{V}_1(0) - V_1^*(0)] \geq 0$, we <u>can</u> determine the sign of OV_1 since application of (8) yields

$$OV_1 = \beta\, E_1\, \{\max\, [E_2\, NB_2(1, 0; \theta),\, E_2\, NB_2(1, 1; \theta)]\}$$

(25)

$$- \beta \max[E_1\, NB_2(1, 0; \theta),\, E_1\, NB_2(1, 1; \theta)] \geq 0.$$

It follows, therefore, that $\hat{X}_1 \geq X_1^*$.

In the first scenario, based on (19) and (20a,b), if one fails to control in the first period, it may nevertheless be optimal to control in the second, despite the irreversibility embodied in (19), because second-period decisions influence third-period outcomes. Thus, when $X_1 = 0$, information acquired between the first and second periods still has some economic value because it may shed light on third-period outcomes and can, therefore, affect the second-period decision. When $X_1 = 1$, information acquired between the first and second periods also has an economic value. Consequently, the net effect of incorporating future learning into benefit estimation is ambiguous: it may strengthen or weaken the case for initial control.

By contrast, in the second scenario, based on (19) and (22), the second-period decision cannot affect third-period outcomes at all because of the total lack of memory between these two periods. Therefore, the temporary irreversibility in (19) ensures that it is never optimal to control in the second period when one has not also controlled in the first. As a result, the information acquired between the first and second periods has some value when $'_1$ = 1 but none when $X_1 = 0$. Moreover, because the system makes a fresh start in the third period, the information acquired between the second and third periods is equally valuable regardless of whether $X_t = 0$ or 1, t = 1, 2. Hence, the case for initial control is unambiguously strengthened when one recognizes the possibility of future learning.

While it is clear that the first scenario of temporary irreversibility is incompatible with the concept of a critical period, the second scenario can still be related to that concept, albeit in a somewhat unusual reamer. Uncle r the second scenario, if the decisionmaker decides not to control in the first period, he anticipates that it could never be optimal for him to reverse this decision during the subsequent interval lasting until the system's memory is "reset." Once that has occurred, all future decisions are entirely independent of prior events. Thus, there is a sense in which the first period is "locally" critical.

V. CONCLUSIONS

It has long been recognized that the selection of an optimal pollution control or other environmental policy is highly dependent on the treatment of time and uncertainty in the benefit cost calculus. A delay in ecosystem recovery, for example, may reduce the present value of the benefits from control; but if the recovery lags caused by continuing pollution are growing faster than the discount rate, this would tilt the balance in favor of early control, as shown in a somewhat different context by Krutilla and Fisher (1975). Similarly, depending upon one's view of the degree of risk aversion appropriate for public policy decisions, the presence of uncertainty may require an adjustment to the expected monetary benefits and costs of control. Since there may be uncertainty about the consequences of both control and no control, this could cut either way.

While not denying the importance of these issues for empirical policy analysis, in this chapter we have focused on a different aspect of benefit evaluation involving flexibility, the temporal resolution of uncertainty, and the value of information. In a dynamic system, information about the consequences of previous actions may arrive over time, and this prospect must be taken into consideration when one makes policy decisions. Future observations have no economic value, however, if (1) they are entirely uninformative in the sense that the prior and posterior distributions coincide or (2) they are informative but they cannot affect subsequent decisions because the policymaker lacks freedom of action. Thus, flexibility is a necessary ingredient for information to have economic value. This must be borne in mind when one contemplates an action with irreversible consequences, because the resulting lack of flexibility nullifies the value of any subsequent information.

In many pollution control issues this may be a relevant consideration because the ecological consequences of a failure to control may be irreversible. Actually, we have shown that what is crucial is economic irreversibilitv. That is to say, if in some time period the decisionmaker anticipates that, unless he controls then, it would never pay to control in the future, regardless of the subsequent information, a decision not to control then would effectively eliminate future flexibility. In that case, there is a positive flexibility premium associated with a decision to control: When future learning is taken into account, the balance is tilted in favor of control. We have termed this a critical-period irreversibility. In other cases, however, the issue is less clear cut. For example, it may happen that the irreversible consequences are delayed in their onset or are only temporary in their effects. In such cases, we show that the conditional value of future information when one fails to control now is not necessarily zero; conceivably it may exceed the value of information associated with a decision to control. The prospect of future learning then has an ambiguous effect--it may strengthen or weaken the case for control. Our intuition is that the value of information conditional on control will ordinarily exceed the value of information conditional on no control but this is an empirical issue to be resolved through specific case studies. Such an application is the focus of our current research and will be reported separately.

FOOTNOTES

[1]The term “option value” has also been used in connection with a different concept related to risk version in an atemporal setting. Major references include Schmalensee [1972], Bohm [1975], Graham [1981], Bishop [1982], Smith [1983], and Freeman [1984].

[2]Obviously, if the control decision itself generates information, this may alter the balance of the argument. If, by not controlling now, one generates potentially useful information which can be exploited in future decisions (for example, because the major uncertainty concerns the consequences of not controlling), this would weaken the case for control. If, on the other hand, one generates useful information by controlling now (because the major uncertainty concerns the consequences of control), this would strengthen the case for control. In the absence of a specific case study, it is difficult to say a priori whether or not there is dependent learning and, if there is, which form it takes. For this reason we have focused on the case of independent learning. For a further discussion of this issue see Fisher and Hanemann [1985].

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