The Economics of Environmental Preservation: A Theoretical and Empirical Analysis

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Concern over the adequacy of nature's endowments has been reflected in economic literature at least from the time of Malthus. For Malthus, the natural environment was essentially a source of increasingly scarce resources to sustain economic activity. Recent theoretical contributions in this framework have sought to develop programs for the optimal intertemporal consumption of fixed and renewable natural resource stocks.[1] Some evidence, on the other hand, suggests that technological progress has so broadened the resource base that the scarcity foreseen by Malthus and assumed, for example, in the stationary utility function postulated by Plourde, has not in fact been realized.[2] Yet, though the statistical evidence is that the direct costs of production from natural resources have fallen (relatively) over time, it seems likely that some of the environmental costs have risen.

It is desirable to distinguish two kinds of environmental costs. One is pollution, concerning which there is a relatively large and growing literature,[3] which we do not address in this paper. The other is the transformation and loss of whole environments as would result, for example, from clear cutting a redwood forest, or developing a hydroelectric project in the Grand Canyon. Surely there are important economic issues here, yet although there is a vast literature dating back to the 1930's on benefit-cost criteria for water resource projects, economists have said virtually nothing about the environmental opportunity costs of these projects. Where reference is made to the despoliation of natural environments, note is made only in passing to "extra-economic" considerations.[4] Similarly in the texts on land economics no mention is made of the economic issues involved in the allocation of wildlands and scenic resources, nor do the costs of land development include the opportunity returns foregone as a result of destroying natural areas.

More recently Krutilla has argued that private market allocations are likely to preserve less than the socially optimal

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1 See for example, studies by Vernon Smith, Charles Plourde, Oscar Burt and Ronald Cummings.

2 See the studies by Neal Potter and Francis Christy, and Harold Barnett and Chandler Morse.

3 For a summary of this literature, see E. J. Mishan.

4 See for example, *Proposed Practices for Economic Analysis of River Basin Projects*, p. 44, Krutilla and Otto Eckstein, p. 265, Roland McKean, p. 61, and Maynard Hufschmidt, Krutilla, and Julius Margolis, pp. 52–53.

amount of natural environments. Moreover, he concludes that the optimal amount is likely to be increasing over time—a particularly serious problem in view of the irreversibility of many environmental transformations.

In this paper we extend Krutilla's discussion in two ways. First, in Sections I and II we develop a model for the allocation of natural environments between preservation and development. Then, in Section III, we apply the model to a currently debated issue: Should the Hells Canyon of the Snake River, the deepest gorge on the North American continent, be preserved in its current state for wilderness recreation and other activities,[5] or further developed as a hydroelectric facility?

I

Before proceeding with the discussion of allocation between preservation and development, we observe that a natural area may have not just one, but several uses in each state. For the development alternative, we abstract from this problem by assuming allocation to the highest valued use or combination of uses via the market, or some appropriate mix of market, government intervention and bargaining.[6] Similarly for an area reserved from development, we make the same assumption; i.e., the area is used optimally for recreation.[7] Our objective at this stage, then, is to formulate a model for guiding choice between the two broad alternatives of preservation and development.

We begin in this section with a rather general model for the optimum use of natural environments. In succeeding sections a more specific methodology will be developed and used to evaluate the Hells Canyon alternatives.

As a defensible definition of optimum use we propose that use which maximizes the present value of net social returns, or benefits, from an area. In symbols, we wish to maximize

$$(1)\qquad \int_0^\infty e^{-\rho t}[B^P(P(t), t) + B^D(D(t), t) - I(t)]dt$$

where B^P and B^D are expected net social benefits (benefits minus costs) at time t, from P units of preserved area, and D units of developed; I is the "social overhead" capital investment cost at time t of transforming from preserved into developed; and ρ is the social discount rate. Note that the opportunity costs of development, the benefits B^P from preservation, generally ignored in benefit-cost calculations, here enter explicitly into the expression to be maximized.

There are several constraints, imposed by nature and past development, on the maximization of (1). We recognize, first, that the amount of any given area developed, residually determines the amount preserved. In symbols,

$$(2)\qquad P + D = L$$

where L is the fixed amount of land in the area.[8] Second, current and future choice is

[5] For a discussion of some of the uses of a preserved natural environment, including some suggestions as to how benefits might be evaluated, see Krutilla.

[6] At least two types of externality, pollution and crowding, are likely to be significant in the commercial exploitation of a natural area, making an efficient allocation in general unattainable in the absence of some form of government intervention or private bargaining to internalize. For a summary discussion of the general externality problem, see Mishan. For an interesting treatment of the crowding problem in particular, see Smith.

[7] The problem is that beyond some point, expanding recreation activity can result in congestion disutility to recreationists, or ecological damage, or both. For a detailed discussion, see Fisher and Krutilla.

[8] For sufficient flexibility in application, we think of D as the number of units affected by the development activity, adjusted perhaps for the character of the activity.

constrained by the results of past choices. In symbols,

(3) $P(0) = P_0$ and, $D(0) = D_0$,

i.e., initial values for preserved and developed portions of the area are given. The dynamic and irreversibility constraints are:

(4) $D = \sigma I$,

where σ is a positive constant of transformation with dimensions area/money,[9] and

(5) $I \geq 0$

Clearly, were the converse true, i.e., were the transformation reversible, much of the conflict between preservation and development would vanish. It seems to us that it is precisely because the losses of certain natural environments would be losses virtually in perpetuity that they are significant.

Finally, we assume concave benefit functions B^P and B^D, so that returns to increasing preservation or development are positive but diminishing; in symbols,

(6) $\overset{P}{B}_P, \overset{D}{B}_D > 0$ and, $\overset{P}{B}_{PP}, \overset{D}{B}_{DD} < 0$

It is conceivable that initial stages of water resource development may be characterized by increasing returns. This will not in general be true of river systems in advanced stages of development, such as the Columbia River system, of which the Hells Canyon reach of the Snake River is a part. Accordingly, while the larger High Mountain Sheep project is more profitable than the smaller Pleasant Valley-Low Mountain Sheep, any increase in scale beyond High Mountain Sheep runs into severely diminishing returns, as the higher pool reduces the existing developed head upstream. Moreover, though this anticipates the analysis just a bit, what really matters is the behavior of development benefits *net* of opportunity costs. And the marginal opportunity costs of development, the benefits from preservation, are *increasing* as *development* increases.[10]

We now proceed with a control-theoretic solution of this problem in the general case, in which no restrictions are placed on the time paths of the benefit functions.[11] The Hamiltonian is

(7) $$H = e^{-\rho t}[B^P(P, t) + B^D(D, t) - I(t)] + p(t)\sigma I(t)$$

where the first term on the right-hand side, $e^{-\rho t}[B^P(P, t)+B^D(D, t)-I(t)]$, is the (discounted) flow of net benefits at time t, and $p(t)$ is the (discounted) shadow price (value of future benefits) of development. Setting $q(t)=p(t)\sigma - e^{-\rho t}$, H can be simplified to

(8) $$H = e^{-\rho t}[B^P(P, t) + B^D(D, t)] + q(t)I(t)$$

Note the relationship of q to p. If technology or demand relationships are changing, then p and hence q will be affected.

Applying the maximum principle of Pontryagin, et al., I is chosen to maximize H subject to the irreversibility restriction (5):

(9) $$H \text{ is maximized by } \begin{array}{ll} I = 0 & q < 0 \\ I \geq 0 & q = 0 \end{array}$$

For $q>0$, investment would have to be infinite over an interval. Quite apart from its impracticality, this possibility can be ruled out because it leads to a contradic-

[9] In specifying the constraint in this fashion we are assuming "constant returns" to increasing investment. This seems at least as plausible, in the general case, as either increasing or decreasing returns, as would be implied by some more complicated functional form for the relationship between investment and development.

[10] This follows from the other half of equation (6), namely that $B^P_P>0$ and $BP^P_{PP}<0$.

[11] Problems similar in form to (1)-(6) have recently been studied by Arrow and Kurz and by Arrow. In the remainder of this section we draw heavily on their work.

tion. Obviously, past development could not have been optimal; more should have been invested earlier.

Since, from (2) P and D are not independent, H can also be written

$$H = e^{-\rho t}[B^P(L - D, t) + B^D(D, t)] + q(t)I(t) \tag{10}$$

Again applying the maximum principle,

$$P = -\frac{\partial H_{\max}}{\partial D} = -e^{-\rho t}(-B_P^P + B_D^D) \tag{11}$$

Since equation (9) is written in q, not p, let us write

$$\begin{aligned}\dot{q} &= \sigma P + \rho e^{-\rho t} \\ &= \sigma e^{-\rho t}(B_P^P - B_D^D) + \rho e^{-\rho t} \\ &= e^{-\rho t}[\rho - \sigma(B_D^D - B_P^P)],\end{aligned} \tag{12}$$

and,

$$q(t_1) - q(t_0) = \int_{t_0}^{t_1} e^{-\rho t}[\rho - \sigma(B_D^D - B_P^P)]dt \tag{13}$$

From (9), the optimal development path is a sequence of intervals satisfying alternately the conditions $q(t)=0$ and $q(t)<0$. Following Kenneth Arrow, define intervals in which $q(t)=0$ as free intervals, intervals in which $q(t)<0$ as blocked (no investment) intervals. In a free interval, $\dot{q}=0$, so

$$\rho = \sigma(B_D^D - B_P^P) \tag{14}$$

Assume, however unrealistically, that investment were costlessly reversible, except for prior interest charges. This would be equivalent to renting the area for this period, at a rate equal to the rate of interest. As in the related capital accumulation problem, optimal investment policy would then have the myopic property

$$\frac{\rho}{\sigma} = B_D^D(D^*, t) - B_P^P(P^*, t), \tag{15}$$

or

$$B_D^D(D^*, t) = \frac{\rho}{\sigma} + B_P^P(P^*, t),$$

which may be interpreted to mean that optimal investment policy equates the marginal benefits from development B_D^D to the sum of direct and marginal opportunity costs $(\rho/\sigma + B_P^P)$ at any point in time.

Combining (14) and (15), we have

$$D(t) = D^*(t) \text{ on a free interval} \tag{16}$$

Again, following Arrow, define a rising segment of $D^*(t)$ as a riser. Then, since $D(t)$ is increasing on a free interval, $D^*(t)$ is increasing, and a free interval lies within a single riser.

On a blocked interval (t_0, t_1), $0<t_0<t_1<\infty$, it follows that $D(t_0)=D^*(t_0)$ and $q(t_0)=0$, since t_0 is also the end of a free interval. Since $I=0$, $D(t)$ is constant, so $D(t)=D^*(t_0)$, $t_0 \leq t \leq t_1$. Similarly, since t_1 is the start of a free interval, $D(t) = D^*(t_1)$, $t_0 \leq t \leq t_1$ and $q(t_1)=0$. Summarizing, on a blocked interval (t_0, t_1), $0<t_0<t_1<\infty$,

$$D^*(t_0) = D^*(t_1), \tag{17}$$

$$\int_{t_0}^{t_1} e^{-\rho t} r[D^*(t_0), t]dt = 0 \tag{18}$$

where

$$r(D, t) = \rho - \sigma[B_D^D(D, t) - B_P^P(P, t)],$$

$$\int_{t_0}^{t} e^{-\rho t} r[D^*(t_0), t]dt < 0,\ t_0 < t < t_1, \tag{19}$$

and

$$\int_{t}^{t_1} e^{-\rho t} r[D^*(t_0), t]dt > 0,\ t_0 < t < t_1 \tag{20}$$

Equations (18)–(20) can be given economic interpretations. Holding $D(t) = D^*(t_0)$, net marginal benefits $(B_D^D - B_P^P)$ first exceed (constant) marginal costs, since we do not invest, or push development, to the point $(D^*(t))$ at which they are equal. As short-run optimal development $(D^*(t))$ begins to fall, however, beyond some point there is too much development, i.e., $D(t) = D^*(t_0) > D^*(t)$. From this point, marginal benefits are less than marginal costs. Equation (18) then says that over the full interval (t_0, t_1) the sum of (discounted) marginal costs just equals the sum of (discounted) marginal benefits. Equation (19) says that, over an interval starting at t_0 and ending at any time t short of t_1, marginal benefits exceed marginal costs. Equation (20) is, of course, not independent of (18) and (19), and says that, over an interval starting at any time t beyond t_0 and ending at t_1, marginal benefits are less than marginal costs.

Myopic (D^*) and "corrected" (D) optimal development paths are shown in Figure 1. Note that at a point such as

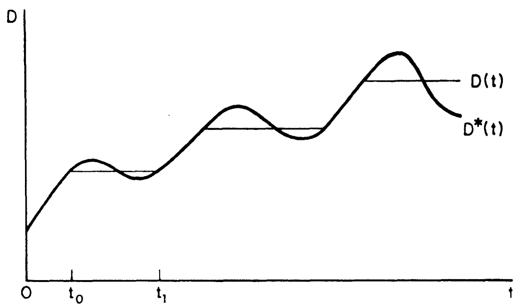

FIGURE 1

t_0 at which D^* is rising, if it will be falling in the relatively near future, then the present value of benefits may be sufficiently low for $q<0$, and investment should cease (equation (9))—until t_1 (equation (17)). We should observe, then, an alternating sequence of rising segments and plateaus in the path of optimal growth over time of the stock of developed land. The divergence of this corrected path from the myopic is a crucially important result. It says that it will in general be optimal to refrain from development even when indicated by a comparison of current benefits and costs if, in the relatively near future, "undevelopment" or disinvestment, which are impossible, would be indicated.[12]

II

In the foregoing analysis no restrictions were placed on the patterns of time variation of the benefit functions. But when we come to consider the Hells Canyon project, and quite probably other similar proposals, both theoretical and empirical considerations suggest that benefits from development are likely to be decreasing, whereas benefits from preservation are likely to be increasing. The former, at least, may seem implausible. After all, shouldn't the demands of a growing economy increase the benefits from development of a natural area such as a hydroelectric power site? In this section we first explore this question, and the related one concerning the time pattern of benefits from preservation, then go on to show how the suggested restrictions affect optimal policy.

The traditional measure of the benefits of a hydroelectric power project, at any point in time, is simply the difference in costs between the most economic alternative source and the hydro project. This assumes, of course, that the amount of power provided by the project will be provided in any event, so that gross benefits are equal and the net benefit of the project is the saving in costs.[13] However, over the relatively long life of a hydro

[12] This result was anticipated by Krutilla, who noted " . . . our problem is akin to the dynamic programming problem which requires a present action (which may violate conventional benefit-cost criteria) to be compatible with the attainment of future states of affairs" (p. 785).

[13] For a fuller discussion of this point, see Peter Steiner.

project, costs of the (best) alternative source of energy will be decreasing as plants embodying new technologies replace the shorter-lived obsolete plants in the alternative system. This means that the benefits from developing the hydro project are correspondingly decreasing over the life of the project. In the traditional benefit-cost analysis this adjustment is not made. Benefits are calculated as of the construction date, implicitly assuming that the technology of alternative sources is fixed over the entire life of the project. For purposes of discussion in this section, a simplified process of technical change and replacement involving some constant rate of decrease of benefits is considered. The implications of a more complicated and realistic process are derived in the Appendix, and applied in our computations in the next section.

Benefits from not developing, on the other hand, appear to be increasing over time. The benefit from a nonpriced service such as wilderness recreation in the Hells Canyon, at any point in time, is the aggregate consumer surplus or area under the aggregate demand curve for the service. Much evidence suggests that demand for wilderness recreation in general, and for the Hells Canyon area in particular, is growing rapidly. This growth is due perhaps to growing population and per capita income, with the extra income used by consumers in part to "purchase" more leisure for themselves. Rising education levels, which seem to be associated with increasing preferences for taking this leisure in a natural environment doubtless also account for the rapidly growing demands.[14] Growth in demand can be broken down into two components: a quantity and a price shift. The effect of population growth, for example, given unchanging distributions of preferences and income, would be to increase the quantity demanded by the same percentage at any given "price," or willingness-to-pay.

On the other hand, for any fixed quantity, assuming growth of incomes, a set of conditions which will guarantee an increase in price to occur can be summarized as follows: if (a) present services of the environmental resource have no good substitutes among produced goods, (b) income and initial price elasticities of demand for such services are larger than for produced goods in general, and (c) the fraction of the budget spent on the environmental services in fixed supply is smaller than for produced goods in general, then the relative "price" or value of the environmental services in fixed supply will increase over time relative to the price of the produced goods at those levels of use short of the point at which congestion externalities occur.[15] Additionally, changes in consumer preferences clearly can affect both the quantity and the price shift parameters.

Suppose, now, that the demand for wilderness recreation in the Hells Canyon is expanding at some rate in the quantity dimension, due perhaps to changes in population and preferences, and at some other rate in the price dimension, due perhaps to changes in income and technology. Then total benefits will be increasing at a rate equal to the sum of these rates, assuming a linear imputed demand function.[16]

[14] For an illustration of the rapid growth in wilderness recreation, see the figures for National Forest wilderness, wild and primitive area recreation, reported by Irving Hoch.

[15] These conditions can be derived from the Hicks–Allen two-good general equilibrium model. Details can be furnished by the authors on request.

[16] Let P_t = the vertical intercept at time t
Q_t = the horizontal intercept at time t
r_y = rate of growth in willingness to pay (vertical shift)
γ = rate of growth in quantity (horizontal shift)
B_t = benefits at time t

Then

It is easily seen that as benefits from preservation increase relative to benefits from development, the optimal short-run level of development $D^*(t)$ decreases.[17]

We can now show, in the analytical framework of the preceding section, the effect of this trend on optimal policy. If $D^*(t)$ is monotone decreasing, then there is in effect an infinite blocked interval. Development is either frozen at the initial level $D(0)$, or jumps, at $t=0$, to some higher level $\overline{D}$, and is then frozen. If there is some initial investment, obviously $q(0)=0$. Also, $\lim_{t\to\infty} q(t)=0$, because

$$(21)\quad -e^{-\rho t} \leq q(t) = \sigma p(t) - e^{-\rho t} \leq 0,$$

and

$$(22)\quad \lim_{t\to\infty} - e^{-\rho t} = 0$$

On the blocked interval $(0, \infty)$ then, $D(t)=\overline{D}$, with

$$(23)\quad D(0) \leq \overline{D},$$

$$(24)\quad \int_0^\infty e^{-\rho t} r(\overline{D}, t)dt \geq 0$$

(but the strict inequality cannot hold in both) and

$$(25)\quad \int_t^\infty e^{-\rho t} r(\overline{D}, t)dt > 0 \quad .0 < t < \infty$$

For the projected development in the Hells Canyon, the interpretation of the analytical results is that it should be undertaken immediately, if at all. In symbols, if

$$(26)\quad \int_0^\infty [B^P(L - \overline{D}, t) + B^D(\overline{D}, t) - I(t)]e^{-\rho t}dt > \int_0^\infty [B^P(L - D(0), t) - I(t)]e^{-\rho t}dt,$$

where $\overline{D} > D(0)$, then some initial development, to a level of $\overline{D}$, will be optimal. If the inequality is reversed, then no further development beyond $D(0)$ should be undertaken. In the next section, a partial and approximate evaluation of these present value integrals is attempted, with $\overline{D}$ corresponding to the most profitable level of development, the High Mountain Sheep project.

Before proceeding with the evaluation, a few qualifying remarks about the analytical results may be made. First, although a particular program, in this case nondevelopment, may be indicated given current anticipations, it can be revised (in the direction of further development) at any time following the emergence of new and unanticipated relationships in the econ-

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(a) $$B_t = (1/2)P_tQ_t = 1/2\ (P_0e^{r_y t})(Q_0e^{\gamma t}) = 1/2\ P_0Q_0e^{(r_y+\gamma)t}$$

The increment over an infinitesimal period is

(b) $$\frac{dB_t}{dt} = 1/2P_0Q_0e^{(r_y+\gamma)t}(r_y + \gamma),$$

and the percent rate of increase is

(c) $$\frac{\frac{dB_t}{dt}}{B_t} = \frac{1/2P_0Q_0e^{(r_y+\gamma)t}(r_y+\gamma)}{1/2P_0Q_0e^{(r_y+\gamma)t}} = r_y + \gamma$$

[17] Ignoring investment, total benefits at any time t from an area of size L, where $L=P+D$, and benefits B^P from the preserved area P are increasing relative to benefits B^D from developed area D at a rate of α', are

(a) $$B = B^P(P, t)e^{\alpha' t} + B^D(D, t) = B^P(L - D, t)e^{\alpha' t} + B^D(D, t)$$

Optimal D, D^*, is found by differentiating with respect to D and setting equal to zero.

(b) $$\frac{\partial B}{\partial D} = -B^P_P e^{\alpha' t} + B^D_D = 0$$

or

$$B^D_D = B^P_P e^{\alpha' t}$$

As t increases, $e^{\alpha' t}$ increases, so that B^P_P (the marginal benefits of preservation) must be decreasing, implying that P^* is increasing—and D^* decreasing.

omy, as for example, a reversal of the historic decline in energy costs. Or, though a particular level of development, corresponding say to High Mountain Sheep in the Hells Canyon, may be optimal for the purposes of power generation, a more intensive level may be indicated by the inclusion of another purpose, for example, flat water recreation. In fact, this is not now true for development in the Hells Canyon, because the separable costs of high density recreation facilities would exceed their benefits.[18]

Second, the somewhat abstract nature of the development measure D might be noted. D can increase, for example, by developing additional sites along the river, the construction of facilities to accommodate larger numbers of flat water recreation seekers, the penetration by roads of virgin sections, etc.

Third, to what extent, if any, has the case for preservation been overstated by the absolute restriction on reversibility, and can the restriction be relaxed? Our view, as stated earlier, is that the irreversibility of development is fundamental to the problem. This does not, however, mean that it must be absolute. Two kinds of reversal are possible, or at least conceivable. One is the restoration of an area by a program of direct investment. This would seem to have little relevance, however, for the sorts of phenomena with which we are mainly concerned: an extinct species or ecological community that cannot be resurrected, a flooded canyon that cannot be replicated, an old-growth redwood forest that cannot be restored, etc.[19]

The other kind of reversal is the natural reversion to the wild, which, though also seemingly of little relevance to our main concerns, is easily fit into the analytical framework. Suppose some (constant, though this is not necessary) nonzero rate of reversion, δ. Then $D'(\mathrm{t}) = D(\mathrm{t})\ e^{-\delta \mathrm{t}}$, where $D'(\mathrm{t})$ is development subject to reversion. It is not clear how much additional flexibility this gives to investment policy. Even in situations in which δ is significantly different from zero, it may be much smaller than the desired rate of decrease as determined by changing technology and demand and unconstrained by nature.

III

In this section we present estimates of the costs and benefits associated with the alternatives for Hells Canyon. There are various services which the canyon can provide if preserved in its natural state. The value of some have become measurable through recent advances in economic analysis, for example, outdoor recreation, while the value of others are still intractable to economic measurement, for example, preservation of rare scientific research materials. Since we cannot measure the benefits in toto, we ask, rather, what would the present value of preserving the area need to be to equal or exceed the present value of the developmental alternative. Owing to the inverse relationship between π and α_{t} (see below) the initial year's preservation benefit may need to be only very modest in comparison with the development benefit. This is illustrated in simplified, discrete form in equation (27) below.

$$b_p^m = \sum_{\mathrm{t}=1}^{\mathrm{T}} \frac{b_0/(1+\pi)^{\mathrm{t}}}{(1+i)^{\mathrm{t}}} \div \sum_{\mathrm{t}=1}^{\mathrm{T}'} \frac{\$1(1+\alpha_{\mathrm{t}})^{\mathrm{t}}}{(1+i)^{\mathrm{t}}} \tag{27}$$

where:

b_p^m = the minimum initial year's benefit

[18] See testimony of Krutilla, *FPC* hearings, R-5840 and R-6494-6499.

[19] This is not to deny its relevance in some contexts, as shown for example in the clean-up and revegetation of certain former coal mining areas.

required to make the present value of benefits from preserving the area equal to the present value of the development benefits,

b_0 = the initial year's development benefit,

π = the simplified representation of technological change for the development alternative and is defined in the Appendix

T = the relevant terminal year for the development alternative,

T′ = the relevant terminal year for the preservation alternative,

i = the discount rate,

α_t = the percent rate of growth in annual benefits as described in footnote 16.

This is the required initial year's benefit from preservation which makes the two alternatives equivalent and relation (26) an equality.

The terminal years for each choice, T and T′, are determined by the years in which the discounted annual benefit falls to zero. They need not and probably would not be the same. Any change in the relative annual values of the incompatible alternatives would result in different relevant time horizons.[20] For convenience in computation, we select T and T′ as the years in which the increment to the present value of net benefits of each alternative falls to \$0.01 per \$1.00 of initial year's benefits.

Now π in the numerator of equation (27) is derived from our technical change model (see the Appendix). The value of π depends on a) investment per unit of thermal capacity, b) cost per kilowatt hour of thermal energy, and c) the rate of advance in technical efficiency. We have relied on construction cost data provided by Federal Power Commission (*FPC*) staff witnesses;[21] taken energy costs to be increasing from 0.98 mills per kilowatt hour in the early stage to 1.28 mills per kilowatt hour in the later period of analysis owing to projected increases in cost of processing nuclear materials;[22] and selected rates of technological progress of 3 to 5 percent, believed to bracket the relevant range.[23] Using such data in our technological change model we find that gross hydroelectric benefits will be overstated between 5 and 11 percent when technological change is not introduced into the analysis.[24] While the difference in *gross* benefits may not be very large, if the two alternatives are close cost competitors, such small differences can make a large difference in *net* benefits. In short, using a medium value for all of the parameters tested results in a reduction in the net present value by approximately a half in the Hells Canyon hydroelectric evaluation.[25]

[20] Since control theory has not previously been applied in public sector benefit-cost studies, the time horizons have been selected arbitrarily.

[21] See testimony of *FPC* witness Joseph J. A. Jessell, *FPC* hearings, and Exhibit No. R-54-B.

[22] See testimony of *FPC* witness I. Paul Chavez, "In the Matter of . . . , " and Exhibit No. R-107-B.

[23] The rate of technological change was computed from data presented in the biennial reports of *Electrical World* over a period representing a consistent method of reporting, 1950–68. It must be acknowledged that the model used for computational purposes is applicable to the period of the past, dominated by use of fossil fuels and not specifically relevant to the yet unspecified changes in technology of the future, doubtless to be tied closely to nuclear reactors. The argument, however, is that while the relevant models would differ, the effects of technological change on costs of generation will be of the same or greater order of magnitude and should not be ignored. (See testimony of Krutilla, *FPC* hearings, R-5838.) Although, as noted earlier, at least some of the reduction in costs may be balanced by a rise in environmental pollution from the more efficient fossil fuel plants, estimated costs of dealing with the thermal pollution from a nuclear plant *are* included in our calculations (though not the possible but unknown costs of radioactive waste disposal).

[24] See Table 1, Exhibit R-670, *FPC* hearings, for the complete range of values resulting from the computational model given in the Appendix.

[25] See testimony of John V. Krutilla, *FPC* hearings, R-5842-3 and Exhibit Nos. R-669 and R-671.

In our discussion of benefits from preservation in the last section, especially in footnote 16, we took α_t to be constant. This is plausible, however, only so long as the capacity of the area for recreation activity is not reached. If demand for the wilderness recreation services of the area is growing, congestion externalities eventually will arise. That is, a point will be reached beyond which use of the area by one more individual per unit time will result in a diminution of the utility obtained by others using the area. For purposes of this analysis, this point is taken as the "carrying capacity" of the area. If the benefits of additional use exceeded the congestion costs, total benefits could be increased by relaxing this constraint.[26] But we seek here to define a quantity of constant quality services, the value of which will be a lower bound for preservation benefits. Counting from the base year, let k be the year in which use of the area reaches capacity, m the year in which γ falls to the rate of growth of population, and d the rate of decay of γ.

Beyond some point, then, annual benefits do not grow at a uniform rate over time but depend upon the values taken by γ, r_y, k, d, and m. The particular values taken, i.e., γ of 10 percent and k of 20 years, with alternative assumptions for purposes of sensitivity analyses, were chosen for reasons given elsewhere.[27] A discount rate of 9 percent with alternatives of 8 and 10 percent was the result of independent study.[28] The selection of the value of m for 50 years, with alternative assumptions of 40 and 60, was governed by both the rate of growth of general demand for wilderness or primitive area recreation, and the estimated "saturation level" for such recreational participation for the population as a whole. Finally, the range of values for r_y was taken from what we know about the conventional income elasticity of demand[29] as related to the special case of a unique resource in fixed supply and growth in per capita income over the past two or three decades.[30]

To contrast the results of our analysis with traditional benefit-cost analysis, consider the computed initial year's preservation benefit (Table 1) corresponding to i of 9 percent, r of 0.04, γ of 10 percent and k of 20 years, m of 50 years and r_y of 0.05; namely, \$80,122. This sum compares with the sum of \$2.9 million, which represents the "levelized" annual benefit from the hydro-electric development, when neither adjustments for technological progress have been made in hydroelectric power value computations, nor any site value (i.e., present value of opportunity benefits foreclosed by altering the present use of Hells Canyon) is imputed to costs. Typically then, the question would be raised whether or not the preservation value is equal to or greater than the \$2.9 million annual benefits from development.

Let us now consider the readily quantifiable opportunity benefits which would be foreclosed by development of the canyon. These are based on studies conducted by the Oregon and Idaho fish and game commissions in cooperation with the U.S. Forest Service and monitored by an observer representing the applicants for the *FPC* license. Presented in summarized form they appear in Table 2.[31]

While systematic demand studies of the several different recreational activities were not conducted in connection with the imputed values, given what is known about prices paid for fishing and hunting rights where such rights are vested in

[26] For a detailed discussion of this and other considerations in determining the capacity of a natural area for recreation activity, see Fisher and Krutilla.

[27] See testimony of John V. Krutilla, *FPC* hearings, R-5859-73.

[28] See Eckstein and Arnold Harberger, and also James Seagraves.

[29] See Cicchetti, Joseph Seneca and Paul Davidson.

[30] See footnote 15.

[31] See testimony of John V. Krutilla, *FPC* hearings, R-5877-, Table 3 R-5878-9, R-5880-4.

TABLE 1—INITIAL YEAR'S PRESERVATION BENEFITS, b_p^m, (GROWING AT THE RATE α_t) REQUIRED IN ORDER TO HAVE PRESENT VALUE EQUAL TO DEVELOPMENT

r_y		γ=7.5 Percent k=25 years	γ=10 Percent k=20 years	γ=12.5 Percent k=15 years
	i=8 Percent,	m=50 years,	r=0.04,	$PVC_{1\ldots T}$ = $18,540,000
0.04		$138,276	$109,149	$106,613
0.05		87,568	70,363	70,731
0.06		48,143	39,674	41,292
	i=9 Percent,	m=50 years,	r=0.04,	$PVC_{1\ldots T}$ = $13,809,000
0.04		$147,422	$115,008	$109,691
0.05		101,447	80,122	78,336
0.06		64,300	51,700	52,210
	i=10 Percent,	m=50 years,	r=0.04,	$PVC_{1\ldots T}$ = $ 9,861,000
0.04		$142,335	$110,240	$103,030
0.05		103,626	80,888	77,232
0.06		71,369	56,397	55,194

Sources: Exhibit No. R-671, R-672, *FPC* hearings, and Transcript R-5869-5873.
Where:

i=discount rate
r_y=annual rate of growth in price for a given quantity
γ=annual rate of growth of quantity demanded at given price
k=number of years following initial year upon which carrying capacity constraint becomes effective
m=number of years after initial year upon which γ falls to rate of growth of population
$PVC_{1\ldots T}$=present value of development (adjusted)
r=annual rate of technological progress in the development case

private parties, we feel our estimates are rather conservative.[32]

[32] See also William Brown, Ajmer Singh and Emery Castle; Stephen Mathews and Gardiner Brown; and Peter Pearse for more systematic evaluation of the Oregon and Washington Steelhead-Salmon Fisheries and other big game resource values, and the estimated willingness to pay. On the basis of all the evidence available to us the imputation of values in the Hells Canyon case appear to be most conservative. It should be noted, however, that two assumptions are made in order that the values appearing in Table 2 represent net benefits, consistent with the benefits estimated for the hydro development. One assumption is that there are no adequate substitutes of like quality, i.e., other primitive scenic areas are either congested or being rationed, conditions which are widely encountered in national parks and over much of the wilderness system. Secondly, it is assumed that the demand unsatisfied by virtue of the transformation of the Hells Canyon would impinge on the margin in other sectors of the economy characterized by free entry and feasibility of augmenting supplies, i.e., incremental costs will equal incremental benefits.

Considering the estimates one might argue, for example, that the preservation benefits shown are roughly only a third ($.9 to $2.9 million) as large as would be

TABLE 2—ESTIMATED INITIAL YEAR'S QUANTIFIABLE PRESERVATION BENEFITS

Recreation Activity	Visitor Days Initial Year	Unit Value	Imputed Benefits
Streamside Use			
Angling	84,000	$ 5.00	$420,000
Canyon Area Hunting			
Big game	7,000	25.00	175,000
Upland bird	1,000	10.00	10,000
Increased value of remaining hunting experience	29,000	10.00	290,000
Total Quantifiable Opportunity Benefits			$895,000

required in comparisons based on traditional analysis of similar cases. By introducing the differential incidence of technological progress on, and growth in demand for, the mutually exclusive alternative uses of the Hells Canyon, we reach quite a different conclusion. The initial year's preservation benefit, subject to reevaluation on the basis of sensitivity tests, appears to be an order of magnitude ($900,000 to $80,000) larger than it needs to be to have a present value equaling or exceeding the present value of the development alternative. Thus we get results significantly different from traditional analysis.

What about the sensitivity of these conclusions to the particular values the variables used in our two simulation models are given? Sensitivity tests can be performed with the data contained in Table 1, along with additional information available from computer runs performed. Some of these checks are displayed in Table 3.

TABLE 3—SENSIVITIY OF ESTIMATED INITIAL YEAR'S REQUIRED PRESERVATION BENEFITS TO CHANGES IN VALUE OF VARIABLES AND PARAMETERS (at $i=9$ percent)

Variable	Variation in Variable From	To	Percent Change	Percent Change in Preservation Benefit
r_y	0.04	0.05	25	39–49
r	0.04	0.05	25	25
k[a] (years)	20	25	25	30–40
γ (percent)	10	12.5	25	-4 to $+7$
m (years)	40	50	25	3

[a] The 25 percent change in years before carrying capacity is reached translates into a 40 percent change in carrying capacity at the growth rate of 10 percent used here.

Given the estimated user days and imputed value per user day, the conclusion regarding the relative economic merit of the two alternatives is not sensitive within a reasonable range, to the particular values chosen for the variables and parameters used in the computation models.

There is need, however, for another set of tests when geometric growth rates are being used. We might regard these as "plausibility analyses." For example, the ratio of the implicit price to the projected per capita income in the terminal year was examined and found to equal $2.5\text{x}10^{-3}$. At today's per capita income level this is comparable to a user fee of approximately $10.00. Similarly, the ratio of the terminal year's preservation benefit to the *GNP* in the terminal year is found to be $4.0\text{x}10^{-7}$. This value compares with a ratio of the total revenue of the applicants in 1968 to *GNP* of $5.0\text{x}10^{-4}$. The year at which the growth rate in quantity of wilderness-type outdoor recreation services demanded falls to the rate of growth of the population must also be checked to ensure that the implicit population participation rate is something one would regard as plausible. Such tests were performed in order to avoid problems which otherwise would stem from use of unbounded estimates. We found our assumed initial rate of 10 percent, appropriately damped over time, was a realistic value.

Finally, since the readily observed initial year's benefits appear to be in excess of the minimum which would be required to have their present value exceed the present value of development, the computation is concluded at this point. Note, however, that since the analysis relies implicitly on the price compensating measure of consumer surplus, the resulting estimate of preservation value would be for this reason, as well as the restricted carrying capacity, a lower bound. Moreover, in seeking maximum expected benefits, we have implicitly assumed a neutral attitude toward risk. In fact, some preliminary findings as to the effect of uncertainty on optimal environmental policy suggest that there may be a kind of risk premium, or other adjustment, in the direction of reducing benefits from development relative to preservation.[33]

IV

In Section I of this study we propose a model for the allocation of natural environments between preservation and development, and show that it will in general be optimal to refrain from some development indicated by current benefits and costs if, in the relatively near future, "undevelopment," which is impossible, would be indicated. In Section II we show that if, as in the case of the proposed development in the Hells Canyon, benefits from development are decreasing over time relative to benefits from preservation, it will be optimal to proceed with the development immediately, if at all.[34] In Section III we consider this question in detail for the case of the Hells Canyon, and show that it will not, in fact, be optimal to undertake even the most profitable development project there. Rather the area is likely to yield greater benefits if left in its natural state.

Appendix

Over the first 30-year period, taken as the useful life of a thermal facility, let PVC_t represent the present value of annual costs per kilowatt of the thermal alternative in year t:

$$PVC_1 = C_1 + E(8760F)$$

$$PVC_2 = \left\{C_1 + [E8760(F - k)] + \frac{E}{(1 + r)}(8760k)\right\}\left(\frac{1}{(1 + i)}\right)$$

$$\vdots$$

$$PVC_n = \left\{C_1 + E[8760(F - (n - 1)k)] + \frac{E}{(1 + r)^{n-1}}[8760(n - 1)k]\right\} \cdot \left(\frac{1}{1 + i}\right)^{n-1} \quad \text{for } 1 < n < 30$$

where

C_1 = Capacity Cost/KW/yr during first 30-year perlod

E = Energy Cost/KWh

F = The plant factor; (.90)

k = a constant representing the time decay of the plant factor (.03)

i = the discount rate

r = the annual rate of technological progress

Writing out the nth term yields:

$$PVC_n = \frac{C_I}{(1 + i)^{n-1}} + \frac{8760EF}{(1 + i)^{n-1}} - \frac{8760Ek(n - 1)}{(1 + i)^{n-1}} + \frac{8760Ek(n - 1)}{[(1 + r)(1 + i)]^{n-1}}$$

These terms can be summed individually using standard formulas for geometric progressions and then factored to form:

$$PVC_{1,\ldots,30} = \sum_{n=1}^{30} PVC_n = (C_I + 8760EF) \cdot \left[\frac{1 - a^{30}}{1 - a}\right] - \frac{8760Ek}{i} \cdot \left\{\frac{1 - a^{29}}{1 - a} - 29a^{29}\right\} + \frac{8760Ek}{(1 + r)(1 + i) - 1}\left\{\frac{1 - b^{29}}{1 - b} - 29b^{29}\right\}$$

where

$$a = \left(\frac{1}{1 + i}\right)$$

$$b = \frac{1}{(1 + r)(1 + i)}$$

[33] See Cicchetti and A. Myrick Freeman, and Fisher. This is an important question and one which bears on the design of optimal policies for pollution control as well, but further consideration is beyond the scope of this paper.

[34] This is consistent with the obvious differences in views held by members of affluent societies and less developed countries on these and related environmental issues.

Over years 31, . . . , T the cost expressions are similar except that we are dealing with only T−30 additional years and all terms thus get discounted by a factor of $(1/1+i)^{30}$. Hence, using similar formulas for the sum of geometric series the present value of annual costs per kilowatt from this later period is determined to be:

$$PVC_{31,\ldots,T} = \sum_{p=31}^{T} PVC_p = \left(\frac{1}{1+i}\right)^{30} \cdot \Bigg\{ (C_{II} + 8760E'F)\left[\frac{1 - a^{(T-30)}}{1-a}\right] - \frac{8760E'k}{i}\left[\frac{1 - a^{(T-31)}}{1-a} - 19a^{(T-31)}\right] + \frac{8760E'k}{(1+r)(1+i)-1} \left[\frac{1 - b^{(T-31)}}{1-b} - 19b^{(T-31)}\right]\Bigg\}$$

where

$$C_{II} = \frac{C_I}{(1+r)^{30}}$$

$$E' = \frac{E}{(1+r)^{30}}$$

The overall present value is:

$$PVC_{1,\ldots,T} = PVC_1 + \ldots + PVC_{30} + PVC_{31} + \ldots + PVC_T$$

Traditional analyses are based essentially on the model given below.

$$K = \sum_{n=1}^{T} \frac{[C_I + E(8760F)]}{(1+i)^{n-1}}$$

or, which is equivalent,

$$= [C_I + E(8760F)]\left[\frac{1 - a^T}{1-a}\right]$$

We can therefore determine a relationship between the traditional measure of development benefit (K) and the measure outlined in this appendix ($PVC_{1,\ldots,T}$) in order to define the simplified measure of technological change (π) utilized in the text above.

$$\frac{K}{PVC_{1,\ldots,T}} = \sum_{t=1}^{T} \frac{b_0}{(1+i)^t} \div \sum_{t=1}^{T} \frac{b_0/(1+\pi)^t}{(1+i)^t} = T \Big/ \sum_{t=1}^{T} \frac{1}{(1+\pi)_t}$$

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