Valuing marginal changes in the quality of an environmental asset

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Selected paper prepared for presentation at the American Agricultural Economics Association Annual Meeting, Denver, Colorado, August 1-4, 2004

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Abstract

We present a model that extends the replacement cost theory to cases where benefits are restored for multiple years. Our theoretical framework derives a functional relationship between investments expenditures and environmental benefits. By extending the investment framework, we model reservoir benefits as a function of marginal changes in soil erosion.

Introduction

In order to value soil conservation's impact on the environmental benefits of reservoirs, we extend the replacement cost theory to cases where benefits are restored for multiple years. More importantly, our theoretical framework provides a means of valuing marginal changes in the amenities due to marginal changes in soil conservation. In this paper, we provide the theoretical framework that, first, shows how benefits can be calculated from observations on investment expenditures and, second, how marginal benefits can be calculated from marginal changes in conservation. Our application assumes that dredging is the investment expenditure (replacement cost).

Prior Research

Prior research has estimated the economic impact of soil erosion changes for a single reservoir, for the whole US, and for multi-State regions. Although objectives of earlier studies differ from ours, they have similarities and provide a comparison for the approach we propose.

The Lee and Guntermann (1976) estimate erosion costs for a single reservoir. To do so, they estimate a fate-and-transport model and an economic model. In the fate-and-transport model, sedimentation is a function of the erosion rate, the size of the reservoir's watershed, the sediment delivery ratio, and the trap efficiency of the reservoir. Should data on dredging costs not be available, Lee and Guntermann (1976) suggest estimating the annual cost of sediment as the difference in the amortized construction costs where costs are amortized under two scenarios. The first assumes no sediment thus amortizes construction costs over an infinite time horizon. The second amortizes costs across the expected life of the reservoir when there is sedimentation. The difference in these two scenarios, they postulate, represents the cost of sediment.

Ribaudo and Hellerstein (1992) extend the theoretical framework of Lee and Guntermann differentiating the sediment cost function with respect to a change in the rate of erosion. Their result shows that marginal changes in erosion will result in marginal changes in the life of the reservoir (N). Since marginal increases in N increase the years of reservoir services, the total damages from erosion are reduced.

Clark and others (1986) attempt to estimate damages to U.S. reservoirs due to erosion from all sources and from agriculture alone. Their estimate is base on the total of three types of sediment-related costs. The first is based on annual reservoir construction expenditures; the second is based on total annual dredging expenditures; the third is based on the discounted present value of the future cost of replacing lost storage. The total of these costs, they postulate, represents the cost of sediment's impact on reservoirs.

Crowder (1987) estimates the per-ton cost of agricultural erosion for each of the 10 U. S Department of Agriculture's (USDA) Farm Production Regions (FPR) of the contiguous States. To do this, Crowder first allocates the total annual cost of reservoir sedimentation—the estimate of Clark and others (1986)—across FPR based on regional sedimentation rates. Regional sedimentation rates are a sum of the sedimentation rate for all reservoirs within a region. Reservoir sedimentation rates are based on reservoir characteristics (Dendy and Champion, 1978). Data on reservoir characteristics and locations are from the U. S. Dept. of Interior (1983).

The framework of Lee and Guntermann (1976) bases the cost of sediment on costs of dredging, amortized construction costs, and damages due to sediment accumulation. The conceptual approach of Clark and others (1986) recognizes benefits of reservoirs' and the effect of sediment on costs. However, neither approach provides a theoretical framework that develops a relationship between environmental benefits (i.e., values of reservoirs amenities) and sedimentation.

Theory

Reservoirs are assets that provide services across many years. All reservoirs are subject to sedimentation. Sedimentation reduces storage capacity and, thus, economic and environmental services. Coarse sediment settles in the upper or delta reaches. Fine sediment settles throughout the reservoir but accumulates most rapidly in the deepest channels of the reservoir (Strand and Pemberton, 1982). The coarse sediment decreases the reservoir's flood control, power production, and similar benefits. Fine sediment in shallower waters provides a nutrient rich medium for rapid plant growth and thus can affect recreational, ecological, and other amenities (Peterson, 1979). Fine sediment can also decrease the reservoir's flood control, power production, and similar benefits.

A reduction in sedimentation will marginally reduce the rate of loss of reservoir services. For example, if sediment inflow were to be halted for one year, then sediment levels in subsequent years would be less than expected. With less reservoir sediment, reservoir services would be greater. The marginal value of a one-year halt in sediment inflow is the present value of the gain in reservoir services.

Direct estimation of the value of reservoir services requires one to estimate the demand for each reservoir service. To overcome associated data limitations, we use an indirect method of benefit estimation—the replacement cost approach.[1]

Dredging as a Replacement Cost

The replacement cost theory is built on the assumption that the value of lost amenities, or environmental services, is greater than or equal to the "replacement cost", or the dollar amount that would be required to recover the lost amenities (Lew, 2001). This indirect method of benefit estimation is used in assessing damages from oil spills and other environmental incidents where many environmental amenities are affected.

[1] Indirect methods are commonly applied in situations where a variety of environmental amenities might be affected (Winpenny, 1991; McNeely, 1988).

The replacement cost method has been used to value habitats, such as wetlands (Lew, 2001). In these applications, the replacement value of the wetland habitat is approximated by the amount that would be required to construct or restore a wetland habitat. In our analysis, dredging restores reservoir services. Thus, based on the replacement cost theory, dredging costs are assumed to represent the minimum value of the restored services.

Our goal is to assess the marginal benefits of a change in soil conservation policy. Therefore, we develop a marginal benefit model that incorporates the relationship between reservoir benefits and soil erosion. The benefit model relates the effect of soil erosion to future levels of reservoir services. That is, the marginal benefit function is dependent on the level of soil conservation (erosion) and the remaining life of the reservoir. In our application, the marginal benefit function represents the change in the level of future reservoir benefits given a one-year change in erosion. The economic parameters of the marginal benefit function are derived from the relationship between reservoir benefits and dredging costs, following the replacement cost approach. With an empirical application of these models, we are able to assess the marginal benefits of a change in soil conservation policy.

The Marginal Benefit of Conservation

We define $f(SED_j, Z)$ as the (net) value of the annual environmental amenities (benefits) provided by a reservoir, given SED_j and Z. SED_j is the quantity of sediment in the reservoir after j years of sediment accumulation and Z is a vector of other variables affecting the value of a reservoir's services. We assume that, as j increases, SED_j increases ($\partial SED_j/\partial j > 0$).[2] As SED_j increases, $f(SED_j,Z)$ decreases ($(\partial f(SED_j,Z)/\partial SED_j)<0$). At time 0 (t=0) when there is no sediment in the reservoir ($SED_j=0$), $f(SED_j,Z)$ is at its maximum. After sediment accumulates for T years, annual reservoir benefits will equal zero ($f(SED_T,Z)=0$).

The total value of the expected environmental services is the discounted sum of the remaining future benefits. The present value of a reservoir's benefits is at its maximum when the reservoir has no sediment (e.g., j=0). Thus, for a newly dredged reservoir, the expected total economic benefit (in present value terms), BEN_0, is:

$$BEN_0 = \int_0^T f(SED_t, Z)e^{-rt}dt \qquad (1)$$

where r is the social discount rate.

As years pass, the level of sediment in the reservoir increases, the remaining life of the reservoir decreases, hence the remaining reservoir benefits decrease. After n years, the level of sediment is SED_n, the remaining service life of the reservoir is T-n years, and the present value of the remaining benefits, BEN_n, is:

$$BEN_n = \int_0^{T-n} f(SED_{n+t}, Z)e^{-r(t)}dt. \qquad (2)$$

Should a soil conservation policy cause an unexpected one-time reduction in sedimentation, then the sediment levels in the remaining life of the reservoir will be lower than expected and environmental services will be higher than expected. Should the conservation policy be

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[2] We assume that the expected rate of sedimentation ($\partial SED_j/\partial j$) is constant over time. Thus, SED_j is the product of the sedimentation rate and j.

implemented n years after the reservoir has been dredged, then the value of the environmental gain, or marginal benefit (MB_n), of the policy, is:

$$MB_n = \frac{dBEN_n}{dSED_n} = \int_0^{T-n} \left(\frac{\partial f(SED_{n+t}, Z)}{\partial SED_n} \right) e^{-r(t)} dt. \qquad (3)$$

In other words, the environmental gain from a one-ton reduction in sedimentation in the current year (MB_n) will depend on the amount of sediment in the reservoir (SED_n) and the remaining life of the reservoir (T-n).[3]

To illustrate the above relationships, assume that f(*) is a linear function of SED_j: $f(*)=\alpha_0+\beta SED_j$. Because increases in sediment decrease benefits, $\beta<0$. The linear specification is not unreasonable because capacity losses occur in both the upstream, shallower end of the reservoir—due to the settling of coarse materials—and in all other areas where the finer sediment accumulates (Lyons, 1996; USDA, SCS, 1975; Strand and Pemberton, 1982). However, f(*) need not be linear—the conceptual framework supporting the theoretical models outlined here is applicable to all specifications of f(*).

Soil conservation this year (and just this year) will reduce the year's sedimentation. As a result, sediment levels will be less than expected in the subsequent T-n years. Substituting our specification of f(*) into equation 3, the present value of environmental services due to a reduction in sedimentation is:

$$MB_n = \frac{dBen_n}{dSED_n} = \frac{\beta}{r}\left(1 - e^{-r(T-n)}\right). \qquad (4)$$

Equation 4 is the marginal benefit of a one-unit reduction in sediment in a reservoir that has n years of sediment (SED_n). The function represents the present value of the lower sediment levels for T-n years. Thus the marginal benefit of the conservation action (MB_n) can be derived from estimates of β, r, and T. Estimates of these parameters—thus an estimate of MB_n—can be derived from the cost-benefit tradeoffs relevant to conservation investment decisions.

Benefits, Costs and Optimal Dredging

Commonly, reservoirs are dredged before losing 40 percent of their capacity (Lohnes and Austin, 1984; Hanson and Stefan, 1984). We assume that a reservoir is dredged in order to maximize social welfare. Thus, based on this assumption and the replacement cost theory, the marginal benefits of dredging are at least as great as marginal costs at the time a reservoir is dredged.

In the problem at hand, we model both benefits and costs as a function of the quantity of sediment dredged. Total benefits restored by dredging equals the quantity of benefits that have been lost. Because benefits are lost as dredging is delayed, the benefit restored by dredging increases as dredging is delayed. The marginal benefit of delaying dredging is the change in total benefits restored when dredging is delayed one year.

[3] We have assumed that $(\partial T/\partial SED_n)e^{-rT}$ is insignificant. If the change in SED_n were large enough, the change in T could be significant. However, given the long life of reservoirs, e^{-rT} is likely to be small and, consequently, would make $(\partial T/\partial SED_n)e^{-rT}$ insignificant.

As dredging is delayed, sediment accumulates and, as a result, the total cost of dredging increases. The marginal cost of dredging is the change in total costs when dredging is delayed one year. [4]

Total and marginal returns to dredging Dredging in year D is assumed to leave no sediment (SED_0) so that reservoir benefits are restored to the level provided when there is no sediment in the reservoir, $f(SED_0,Z)$. Had the reservoir not been dredged, the value of services would have been $f(SED_D,Z)$ where SED_D is the quantity of sediment dredged given D years of sediment accumulation. Thus the net increase in environmental benefits in the first year after dredging is $f(SED_0,Z)-f((SED_D+SED_0),Z)$. After t years, the net annual gain in benefits is $f(SED_t,Z)-f((SED_D+SED_t),Z)$.

The return to (or benefits of) dredging (RET) is the DPV of the all gains in benefits:

$$RET = \int_0^T \left(f(SED_t, Z) - f((SED_D + SED_t, Z))\right)e^{-rt}\,dt. \tag{5}$$

The marginal increase in RET due to one-year delaying in dredging, based on equation 5, is:

$$MR_D = \frac{\partial RET}{\partial SED_D}\frac{\partial SED_D}{\partial D} = \frac{\partial\left(\int_0^T f(SED_t, Z)e^{-rt}\,dt - \int_0^{T-D} f((SED_D + SED_t), Z)e^{-rt}\,dt\right)}{\partial D} \tag{6}$$

where $\partial SED_D/\partial D$ is the amount of sediment that accumulates due to a marginal (i.e., one year) change in D.[5] Note that after sediment accumulates for T-D years, $SED_D+SED_{T-D}=SED_T$ so that $f((SED_D+SED_{T-D}),Z)$ falls to zero. Thus, $f((SED_D+SED_t),Z)$ only needs to be summed across T-D years. Also, because the integral of $f(SED_t,Z)$ is independent of D, it is not affected by changes in D.[6]

By applying the same linear specification of f(*) to equation 6 and simplifying, we find that:

$$MR_D = -\frac{\beta}{r}\left(1 - e^{-r(T-D)}\right)\frac{\partial SED_{T-D}}{\partial D}. \tag{7}$$

In other words, a delay in dredging increases the amount of sediment that needs to be dredged ($\partial SED_{T-D}/\partial D$) and thus increases the return to dredging (MR_D). MR_D contains the economic parameter β which, based on the replacement cost approach, can be derived from dredging costs.

Total and Marginal Investment Costs Costs also increase with delays in dredging. Total cost is expressed as the product of per-unit costs (PUC) and the total quantity dredged or:

$$CST_D = PUC * SED_D. \tag{8}$$

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[4] Given a positive discount rate, delaying by a year does reduce the present value of the benefits from dredging. However, this delay also reduces the present value of the cost of dredging. Thus, subtle issues of the timing of benefits, such as the large (and undiscounted) value of dredging this year need not be explicitly accounted for.
[5] Basically, $\partial SED_D/\partial D$ is the rate of sediment accumulation.
[6] In some cases, it may be necessary to include both the opportunity cost of delaying future environmental benefits and the economic benefit of delaying current investment costs when estimating the optimal time to invest. In this case, dredging is relatively infrequent so that DPV of returns to future dredging projects are relatively insignificant. Thus the decision to dredge is essentially independent of subsequent dredging decisions.

The PUC for a single reservoir is a function of SED_D, the quantity of sediment dredged, when there are economies or diseconomies of scale. PUCs are likely to vary across reservoirs due to differences in reservoir characteristics.

The marginal cost of a change in the dredging date is:

$$MC_D = PUC * \frac{\partial SED_D}{\partial D} + \frac{\partial PUC}{\partial SED_D}\frac{\partial SED_D}{\partial D} SED_D . \tag{9}$$

The first term represents the cost change due to the change in the quantity dredged. The second term represents the scale effects.

As discussed earlier, the replacement cost approach provides a means of estimating environmental benefits as a function of costs. When replacement costs are a capital investment, then benefits can be approximated from the investment efficiency condition (MC_{D*}=MR_{D*} where D* is the optimal time to dredge) so that:

$$PUC * \frac{\partial SED_{D*}}{\partial D*} + \frac{\partial PUC}{\partial SED_{D*}}\frac{\partial SED_{D*}}{\partial D*} SED_{D*} = \frac{\beta}{r}\left(1 - e^{-r(T-D*)}\right)\frac{\partial SED_{T-D*}}{\partial D*} \tag{10}$$

or

$$PUC + \frac{\partial PUC}{\partial SED_{D*}} SED_{D*} = \frac{\beta}{r}\left(1 - e^{-r(T-D*)}\right). \tag{11}$$

Equation 11 provides a means of estimating β which can then be used to estimate MB_n in equation 4—the benefit of a marginal change in soil conservation.

Solving for β:

$$\beta = \frac{PUC + \frac{\partial PUC}{\partial SED_{D*}} SED_{D*}}{\frac{(1 - e^{-r(T-D*)})}{r}} \tag{12}$$

and substituting this relationship for β into the marginal benefit function (equation 4), we have:

$$MB_n = \frac{PUC + \frac{\partial PUC}{\partial SED_{D*}} SED_{D*}}{(1 - e^{-r(T-D*)})}\left(1 - e^{-r(T-n)}\right). \tag{13}$$

Equation 13 is the marginal benefit of a one-unit reduction in sediment in a reservoir that has n years of sediment (SED_n). Equation 13 includes the benefits of less sediment in future years resulting from a reduction in sedimentation in the current year,

Summary

The valuation approach developed here is an extension of the replacement cost theory. The replacement cost theory is built upon the assumption that the cost of replacing a good is justified by the benefits that are restored. Thus costs can serve as an indirect measure of the value of the restored benefits. The replacement cost model is especially helpful when it allows the analyst to avoid direct estimation of a variety of benefits. Direct estimation of the multiple benefits of reservoirs—flood control, power generation, recreational opportunities, etc.—would require estimates of the supply and demand for each of these services.

Our approach extends the replacement cost theory to cases where benefits are restored for multiple years. The framework assumes that expenditures are justified by future benefits. More importantly, our theoretical framework provides a means of valuing marginal changes in the amenities due to marginal changes in conservation. This framework is applicable to valuing the marginal benefits of reducing the adverse impacts of sediment, pesticides, and other effluents on any public or private assets.

Our application assumes that dredging is the replacement cost. Our theoretical model provides a conceptual framework for modeling the soil conservation benefits as a function of the expect value of future reservoir benefits. We have assumed that the loss in reservoir services is linearly related to sedimentation.

In a separate paper we use this theoretical model to examine empirically how changes in soil erosion, due to soil conservation, affect the benefit from US reservoirs. We find that the level of soil erosion in 1997 preserved $139 million in reservoir benefits relative to the 1982 level of erosion.

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