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Sediment Management in Flood Control Dams

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Abstract: Reservoir sedimentation reduces economic value and longevity of flood control dams. Periodic sediment removal allows extension of reservoir life. An optimal control model is developed to evaluate alternative sediment management strategies for flood control dams. An illustrative empirical analysis shows that sustainable management is economically desirable for a wide range of parameter values.

Key Words: flood control, sedimentation, dams, cost-benefit analysis.

JEL Codes: Q25, Q27

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I. Introduction

Each year millions of dollars worth of property and other valuables are lost due to floods. A dam can prevent or reduce downstream flood damage by temporarily storing a large part of the storm runoff. Reservoir sedimentation leads to decrease in storage capacity, which in turn can significantly impair the ability of a dam to perform this function. Also, sedimentation might cause structural damage and increase maintenance cost of operating the dam and/or lead to costly decommissioning at an earlier date. Periodic sediment removal, using techniques such as flushing, hydrosuction, or mechanical dredging, can play an important role in extending the useful life of dams.

This paper presents an optimal control model that helps determine the desirable timing and extent of sediment removal from a flood control dam. Sediment removal is expensive, but it needs to be compared against other alternatives. The model extends the work of Palmieri, Shah, and Dinar (2001) who consider flushing a reservoir that serves irrigation or hydropower purposes only. The problem we address is conceptually more complex because of the fact that floods are probabilistic events. We also believe it is an important practical problem that has hitherto been ignored in the economics literature.

The paper is organized as follows. Section II provides background information and reviews the literature on sedimentation and flood control dams. Section III discusses our general model. Section IV presents the results of an illustrative case study that uses data from a flood control dam in Connecticut. Section V concludes the paper.

II. Background and Literature Review

In the United States, about 7 percent of the land is in floodplains. The most common cause of flooding is high rate of runoff from heavy and prolonged rain. Floods cause enormous economics losses, both directly and indirectly. In 1981, the estimated direct damage from flooding in the United States averaged around \$2.2 billion annually and was expected to increase (WRC, 1981).

About 25 percent of dams in the U.S. have been built primarily for flood control purposes. The first flood prevention dam under the Flood Control Act was constructed in 1938. Since then, more than 10,000 dams have been added under small watershed programs. Earlier dams were built with a 50-year life span, which meant that the lakes were expected to fill with sediment in 50 years. Later dams were built for a 100-year life span. As of now, a vast majority of these dams are reaching or have already past their expected life span. In many cases, sedimentation is significantly affecting reservoir ability to hold floodwater. As a result, we are now facing with a decision whether to rehabilitate or retire these dams.

A recent study by United Nations Environment Program (2001) indicates that worldwide reservoir storage lost because of mud and silt is about 1 percent annually. In 1999, the World Bank organized a workshop of experts in the field of reservoir sediment management. Following the workshop, research concentrated on building on the work of Palmieri, Shah, and Dinar (2001) by developing software that has the ability to identify economically optimal sediment management strategies that are also technically feasible. This computer program, however, only takes into consideration two types of benefits from storage, namely, irrigation and hydroelectricity. Flood control benefits have yet to be incorporated, despite the fact that flooding

causes enormous damage to both property and life, and many flood control dams are losing their ability to prevent flooding due to sedimentation. The purpose of the current paper is to start filling this gap in the literature.

One of the challenges is to develop a functional relationship for flood damages. Several approaches have been proposed for estimating residential flood damages. One of the most widely used is the depth-damage function. This function describes the relationship between the level (height) of floodwater and the damage to the building structures and content. The damage is usually measured as a percentage of total value of building structures and content (Davis, 1992). This is the basic approach that we will be adapting for use in our study.

III. Model and Methodology

In our model, a dam provides two types of services: non-flood control (agriculture, hydroelectricity, recreation, etc.) and flood control. The ability of the dam to provide these services decreases as remaining reservoir capacity goes down due to sedimentation. Capacity recovery through sediment removal is often possible, but the process is expensive and may be constrained by technical feasibility. For the sake of simplification, we consider only flushing as a sediment removal technique. Other operation and maintenance costs are also accounted, as is an initial construction cost for new dams. Our problem is to choose a reservoir level sediment management policy such that total discounted net benefits of the dam are maximized.

The above is a dynamic optimization problem, for which an optimal control formulation is specified later in this section. We begin, however, with a discussion of some of the key components of the net benefit function, namely: (1) Non-flood Control Benefits (2) Flood

Control Benefits (3) Sediment Removal Costs.

(1) Non-flood Control Benefits

We assume that there is an annual output of services from stored water, i.e., reservoir yield that represents water available for use in irrigation and/or hydropower. For simplification, the price of water obtained for these services is taken as a constant, P_1 , which is then multiplied by reservoir yield to obtain annual non-flood control benefits.

Reservoir yield is a function of available storage and it decreases over time as the reservoir storage is lost due to sedimentation. In this paper, we use Gould's Gamma method for estimating yield as described in Morris and Fan (1997, pp. 3.20-3.22).

The relationship between storage level, yield, and reliability is

$$S_t = \{Z_p^2/[4(1-D)]-d\}C_v^2$$

Where S_t = storage volume express as hydrological size

C_v = coefficient of variation of annual flows ($C_v = S_d/MAR$)

Z_p = standardized normal variate at p%

D = withdrawal rate as ratio of the mean annual discharge rate (yield)

d = correction factor

MAR = mean annual runoff

Value of d and Z_p will depend on the probability of failure and is given in table 3.5 in Morris and Fan (1997). Reservoir yield (W_t) is equal $D*MAR$, after substitute for W_t we get reservoir yield as a function of storage and mean annual runoff as follow:

$$W_t = (4*MAR*S_t - Z_p^2S_d^2+4dS_d^2)/4(d/MAR)S_d^2 + S_t)$$

Where Z_p , S_t , and d are describe as above and,

W_t is reservoir yield at time t

S_d is standard deviation of the mean annual runoff

Using one percent probability of failure the above equation can be rewritten as

$$W_t = (4 * \text{MAR} * S_t - (5.4289)S_d^2 + (6)S_d^2) / 4(1.5/\text{MAR})S_d^2 + S_t$$

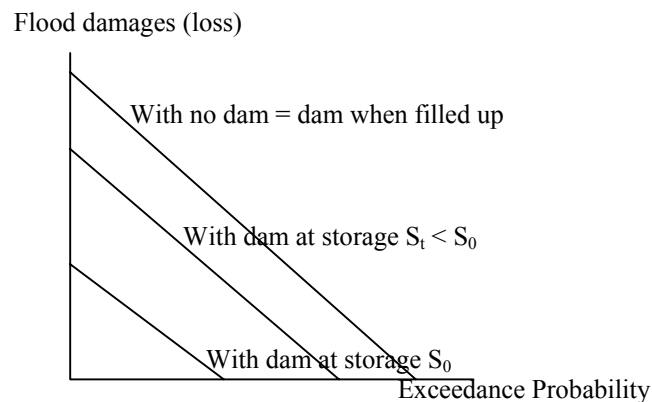
This is the function we use to estimate value of non-flood control benefits in this study.

Assuming that all other variables are given, this reservoir yield is a function only of only reservoir storage. As a result, we are able to write this reservoir yield as $W(S_t)$.

(2) Flood Control Benefits

We postulate flood control benefits as the difference between expected damages when there is no dam and when the dam exists. Dams may be viewed as limiting flood damages by reducing the likelihood of floods or reducing the damages due to a flood of given magnitude. It follows that flood control benefits may be taken as the difference between the area under the damage probability curve without dam and the same curve with dam. This is represented in Figure 1.

Figure 1²



² Note that this is only a representation. The actual function is not necessarily a straight line.

While the damage probability curve without dam will not change over time, the damages probability curve with dam will move outward as sedimentation occurs, which will reduce flood control benefits. This change will continue until the dam is completely silted, at which point damage probability curves with dam and without dam will coincide and flood control benefits will be zero.

Estimation of flood damages is a complex task since many factors both qualitative as well as quantitative are involved. In general, flood damage can be grouped into two major categories namely, economic damage and social damage. Economic damage is a loss that can be valued in an economical way (or in monetary value) such as properties, crops, services, etc. Social damage is a qualitative impact of flood on human's life such as anxiety, panic, inconvenience and disruption of social activities. This social damage is hard to represent by monetary value or estimate in some quantitative form without using a nonmarket valuation procedure. In this study only economic damages due to flood are considered. Loss of human life is also excluded from our flood damage estimate for the same reason. Thus, "flood damages" throughout this paper refer to easily economic damages only.

Flood damages are a function of characteristics of flood which include flood depth, duration, and velocity. Among them, flood depth is considered the critical factor that determines the damages. Depth-damage function is widely used to represent this relationship. This function differs differently among land use patterns (e.g. residential, agriculture, industry, services) and location. For any flood plain, determination of expected flood damages requires knowledge of three component terms: i) magnitude and probability of floods, ii) depth-damage function, and iii) value of all property and land used in the flood plain. We now discuss these components individually.

i) Magnitude and probability of floods

In our simplified approach, a flood occurs when the peak flow coming into a reservoir is larger than the capacity of reservoir. In this case, the difference between the peak flow level and the reservoir capacity defines the magnitude of the flood. The flood causes damages that depend on its magnitude. The probability of a flood of given magnitude is equal to the probability of the corresponding peak flow level.

Using historical peak flow data at each dam we can construct the distribution of peak flow. Under the assumption that distribution of peak flow does not change over time, one can get the probability of each exceed peak flow using a proper density function.

ii) Depth-damage function

Depth of water in the floodplain determines damage. The depth-damage function for 'building type' land is distinct from the depth-damage function for 'agricultural type' land. The former relates damages to the percentage of the structural or content value that will be destroyed by a certain flood depth and has two parts - one for structure and another for content. For agriculture type land, the depth-damages depend on proportion of flood-free gross return³. This function is not only a function of depth but also the time (of the year) of flood as well as duration of flood. Damage to infrastructures and services consist of direct cost, which is the cost of repair and reconstruct the infrastructure, and indirect cost of disruption of services. Several functional form of depth-damage function has been discussed and appeared in the literature including Dutta (1998), Davis (1992), and Kiefer (1996).

A typical residential depth-damage function can be represented as

$$Y = \alpha + \beta_1 X + \beta_2 X^2 + \beta_3 X^3 + u$$

³ More details can be found in Dutta (1999), p.113.

where Y is the percent damage to structure or content, α is a constant that represent the percent damage when flood height is 0, that is the percent damage at the first floor level and X is the depth of flood

To estimate the depth-damage function , one can use several types of data such as, historical flood data, survey data of potential losses in properties, or specialist assessments of the potential losses. The U.S. Army Corp of Engineers has developed various depth-damage functions for both residential and non-residential structures. However, as we have stated earlier, the depth-damage function is a location specific. In other words, the depth-damage function for one location may not be suitable for another.

iii) Value of Structures and Land

In order to get a total monetary value of flood damage for any flood magnitude we need to multiply the percentage damage of both structure and contents that we get from depth damage function to the total value of structure and contents. This total value can be estimate using actual survey data or using secondary spatial data with a median house price as a representative value. Unfortunately, this type of data is not always readily available.

Expected flood damage at any given flood magnitude is its probability times total damages. Using annual historical peak flow data, we can get the annual expected flood damage as a summation of expected flood damage of each magnitude. And we can obtain flood control benefit for reservoir at storage level S_t as the difference between expected annual flood damage without dam and expected annual flood damage with the dam at remaining storage S_t .

It is suggested in the literature that the average annual flood protection benefits should be computed from at least three flood events.⁴ When a dam exists, sediment accumulation in the

⁴ Parker (1987) and Green (2000).

reservoir reduces storage and increases the probability of flood at each magnitude. Thus, annual expected annual flood damage increases over time. On the other hand, expected annual damage without dam will not change. As a result, flood control benefits, as defined above, decrease over time as sedimentation increases. Figure 2 and 3 below show the relationship between reservoir storage, expected flood damage, and flood control benefits. Sediment removal will increase reservoir storage and thus increase both the flood control benefit as well as other benefits.

Figure 2

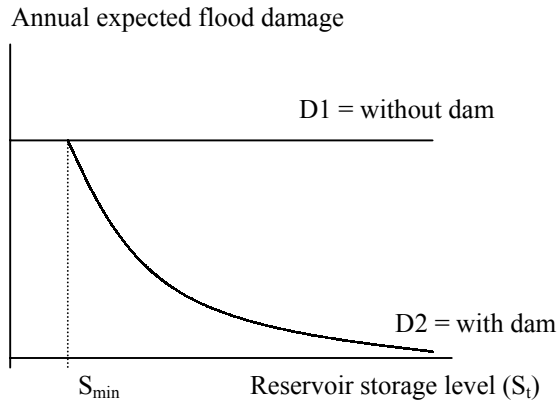
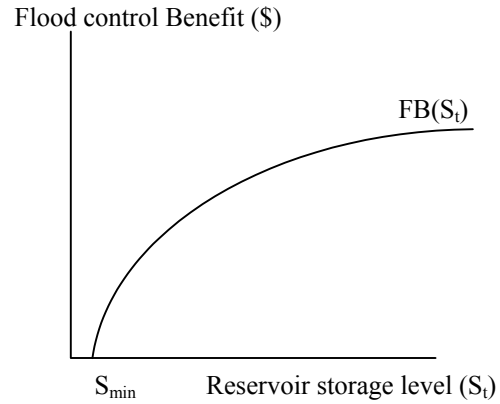


Figure 3



3) Sediment Removal Costs

Although there are several methods of sediment removal, we only consider only flushing. This method uses the power of water to flush the sediment deposited downstream (Morris and Fan, 1997). The amount of sediment removed will depend on several technical parameters and sediment characteristics. This water used in flushing can be written as:

$$Y_t = g(X_t^{(1/1.3)})$$

Where Y_t is water used in flushing,

X_t is amount of sediment removed, and

g is the inverse flushing efficiency ratio which is equal to

$$g = ((12.8^{0.6}) / (P * SB^{1.2}) * T^{0.3})^{(1/1.3)} * (9.82 * sg)^{(1/1.3)}$$

P = sediment type coefficient,

SB = slope of reservoir bed,
 T = Time duration of flushing, and
 sg = Specific gravity of sediment.

In addition to the opportunity cost of water used in flushing, the cost of sediment removal may include other fixed cost that can be accommodated in the model.

Social Planner Problem

Given the above discussion of the components of the net benefit function, we are now in a position to formulate our social planner problem. We seek to determine the sediment management strategy that maximizes the net present value of discounted lifetime net benefit. In mathematical terms, annual sediment removed, X, and lifetime T are to be chosen to

$$\text{Max } Z = \int_0^T [\text{OB}_t(S_{1t}) + \text{FB}_t(S_{2t}) - C_O - C_S(X)]e^{-rt} + SVe^{-rt} - C$$

Subject to

$$dS_{1t}/dt = -\alpha(M-X)$$

$$dS_{2t}/dt = -(1-\alpha)(M-X)$$

$$S_0 = S_{10} + S_{20}, S_0 \geq S_{10} \geq 0$$

$$S_t = S_{1t} + S_{2t} = S_0 - (M-X)t$$

Where $\text{FB}_t(S_{2t})$ is flood control benefits,

OB_t is other benefits (i.e., non-flood control benefits),

S_0 is initial storage capacity,

α is the flood control priority parameter,

S_{10} is the initial reservoir storage allocated for non-flood control purposes,

S_{20} is the initial reservoir storage allocate for flood control purpose,

S_t is remaining storage at time t ,

r is the discount rate,

C_0 is annual operating cost,

C is construction cost,

C_S is cost of removing sediment, and

SV is salvage value of the dam.

The flood control priority parameter, α , determines how much of the net incoming sediment will be allocated for the flood control pool and how much will be allocated for the other purposes pool. When α equal to one, all sediment deposited is allocated to the other purpose pool, thus maintaining the flood control storage. This indicates that the management's priority is given to flood control purpose. When α is zero all sediment will be allocated to flood control pool and the management's priority is for other purposes.

The following assumptions are used in the base case model in this study.

1. The entire flood control storage is available at the beginning of each flooding season.
2. There is no uncertainty in the incoming sediment.
3. Distribution of peak flow is not change over time.
4. Annual operating cost is constant at C_0 and is independent of sediment level in the reservoir.
5. Amount of sediment removed is constant at X for every removal.
6. There is no externality associated with the sediment removal.
7. Discount rate is 7 %.

IV. Application

Data and Empirical Specification

We apply our model to a small flood control dam in northern Connecticut. Much of the data needed are available, but some important pieces of information are missing, for which best guess values are used. Thus our present exercise is for illustrative purposes only.

One of the key data limitations is lack of historical flood records and damages. In view of this problem, we developed a general functional form from data for typical depth damage function provided in Davis (1992). We use this data to estimate a depth-damage function. Employing synthetic data on probability distribution of floods and total value of structures in the area to calculate total flood damages, we then alter this probability as it would have changed with declining reservoir storage. After several repeated calculations we conclude that the following functional form is most appropriate for the Flood Control Benefit (FB) function:

$$FB(S_{2t}) = \gamma(S_{2t} - S_{\min})^{1/2}$$

Where γ is a benefit coefficient that will depend on the land use, depth-damage function, and distribution of peak flow for each flood plain. Given the same size of dam γ will be higher for higher mean of peak flow, or value of each land use. S_{\min} is the minimum storage level for flood control benefit. That is the storage level in which annual expected flood damage is equal to annual expected flood damage without dam. Assuming S_{\min} is zero, we estimated the FB function for our case as⁵

$$FB(S_{2t}) = 17.64(S_{2t})^{1/2}$$

⁵ Estimation details are available upon request.

We consider three alternative reservoir management strategies, namely, sustainable, nonsustainable and run-of-river. Sustainable management occurs when sediment is removed periodically in a way reservoir storage will maintain at the same level forever (at least theoretically). Nonsustainable management is the strategy where we do not practice any sediment removal and the dam structure is retired when the reservoir is silted to the optimal degree. In the run of river case, there is also no sediment removal, but the dam structure is maintained after it is silted up and continues to provide limited benefits.

A computer program written in Excel is used to run the base case model explained in the previous section. The following specific forms and parameter values are used.

$$\text{Flood control benefit } FB(S_{2t}) = 17.64(S_t^{0.5})$$

$$\text{Other purpose benefit } OB(S_{1t}) = P_1 * W_t$$

$$OB(S_{1t}) = P_1 * (4 * MAR * S_t - Zp^2 S_d^2 + 4d S_d^2) / 4(d/MAR) S_d^2 + S_t$$

Where P_1 = unit value of reservoir yield, assume to be 1.

Construction cost: We assume that construction cost can be calculated as

$$C = cS_0$$

$$\text{Where } c = \text{cost per unit of storage} = 3.5 - 0.53 \text{LN}(S_0/1000000)$$

Operating cost: We assume operating cost to be a proportion of the construction cost.

$$C_o = \varphi C$$

Where φ is assumed to be 5% .

Cost of sediment removal: Cost of removal sediment amount $X = C_s(X)$ where

$$C_s(X) = F + P_2 (g(X_t^{(1/1.3)}))$$

Where F is fixed cost of sediment removal per event, assumed to be 5,000

P_2 is the unit value of water used for removing sediment, assumed to be 0.1.

Salvage value is taken to be zero.

Base Case Results

Net present value for sustainable management, nonsustainable, and run-of-river strategies are \$5,926,285.298, \$4,543,559.224, and \$4,495,841.760 respectively. With sustainable management net present value of dam increases by 30 percent and life of the dam increases from 60 years to over 300 years. Net present value of run-of-river strategy is less than nonsustainable because the dam is relatively small and non-storage benefits are less than the cost of maintaining the structure of the dams. Thus if sustainable management is not possible, under the given physical characteristics and cost involved, one should retire and remove dams structure after the optimal life of the dam is reached.

Figure 4.

Percent of sediment that can be removed

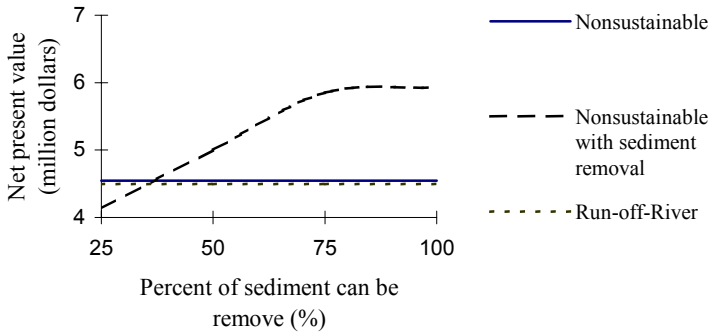


Figure 5.

Flood Control Priority Parameter

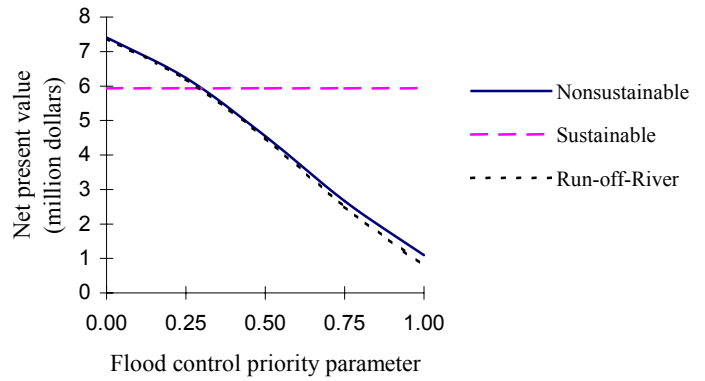


Figure 6.

Annual incoming sediment

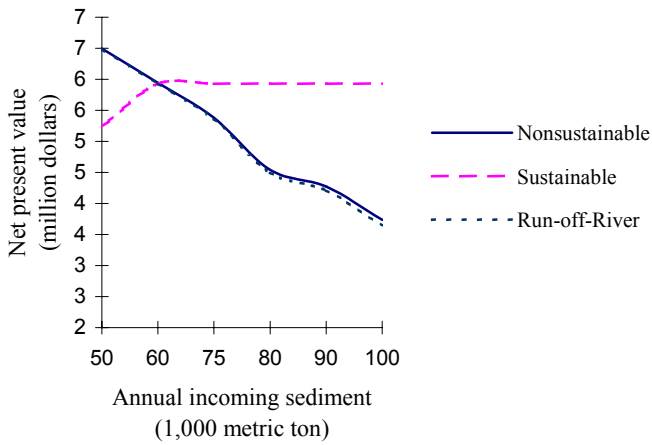


Figure 7.

Fixed cost of sediment removal

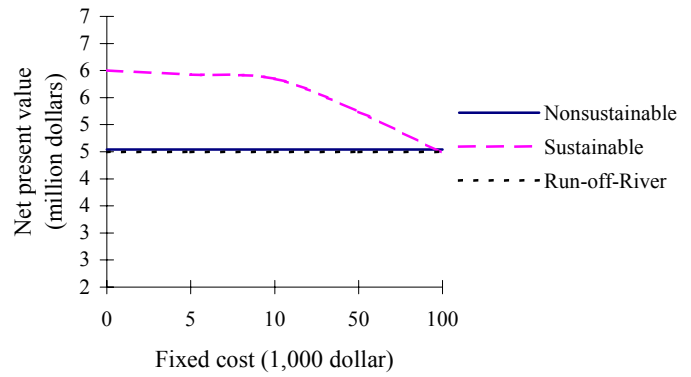


Figure 8.

Interest Rate

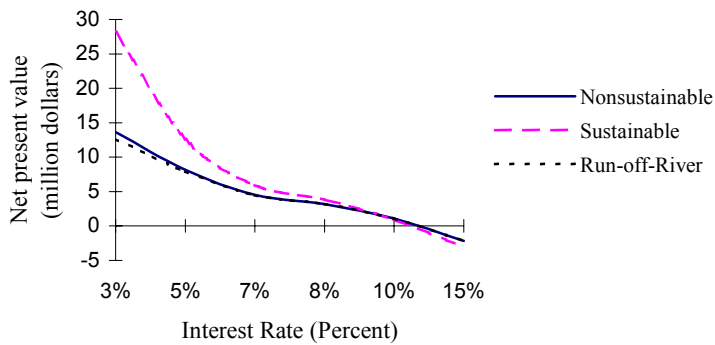


Figure 9.

Mean annual runoff

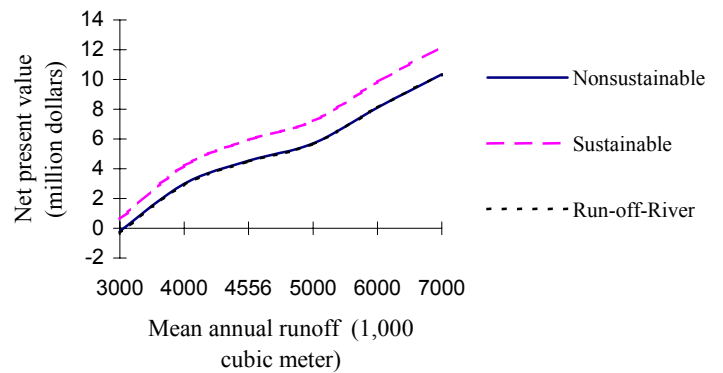


Figure 10.

Unit value of water use to remove sediment

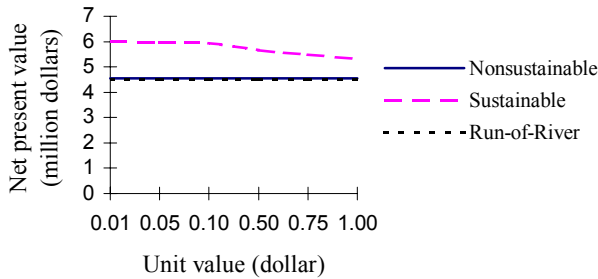


Figure 11.

Unit value of reservoir yield

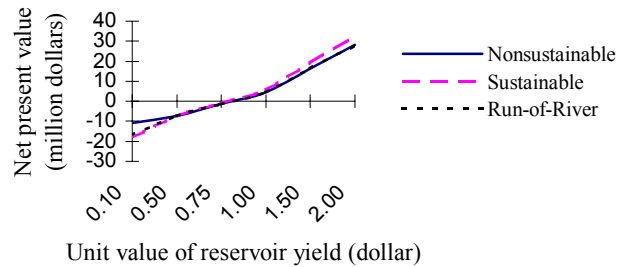


Figure 12

Flood control benefit coefficient

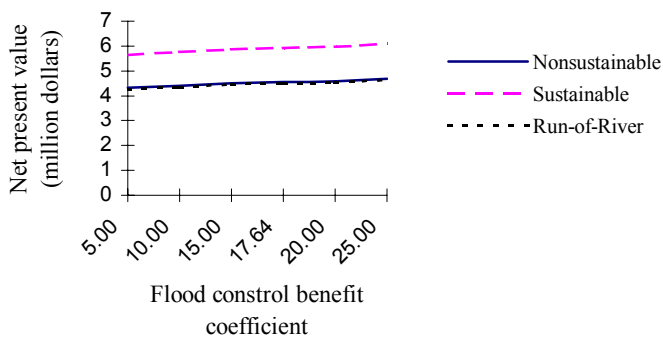
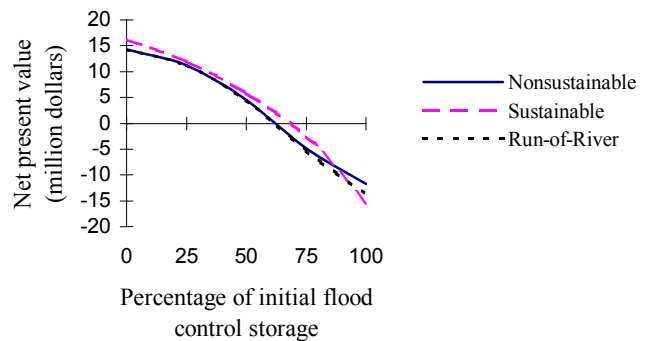


Figure 13

Percentage of initial flood control storage



Sensitivity Analysis

The base case model was modified to further investigate the sensitivity of the results to changes in various economic and technical parameters such as incoming sediment, percentage of incoming sediment that can be removed, unit price of reservoir yield, and interest rate. Figures 4 to 13 shows the net present value of each management strategy when these key parameters are changed.

Although most of the time sustainable management is still preferred, this is not always the case. Generally, sustainable management is dominant for the range parameter values used when changes are made in mean annual runoff, flood control benefit coefficient, and the unit value of water used in removing sediment. For all other sensitivity exercises, nonsustainable management may be preferred in some range of parameters.

Concerning the case of partial removal reported in Figure 4, when the percentage of the sediment that can be removed is less than 36, it is not worth practicing sediment removal. On the other hand, if the percentage that can be removed is higher, then the strategy is desirable and reservoir life is extended. For example, reservoir life will be extended from 60 years if we do not remove any sediment to 109 years if we can remove 50 percent of the incoming sediment. Reservoir life will increase further to 145 years if we can remove 75 percent of the incoming sediment. Net present value of the dam will increase from \$4,543,559 to \$5,001,880, and 5,851,150 respectively in these cases.

When annual incoming sediment is low we should not practice sediment removal because the high fixed cost of sediment removal relative to the amount of sediment we can removed makes it less economical than no removal. Thus nonsustainable management is preferred in such cases..

Nonsustainable is also preferred if the interest rate is higher than 8.5 percent. This is because high interest rate makes the present value of future benefit become much smaller, which reduces the value of extending the life of the reservoir.

Similarly, if the fixed cost of removing sediment is increased above \$100,000 per event, we should no longer practice sediment removal and just let the dam silt up. This is because at

this point the cost is too high as compared to the benefit of removal. Similarly, the sustainable policy is dominated by the nonsustainable policy if the flood control priority parameter is above 0.25.

V. Summary and Conclusion

Loss of reservoir capacity due to sedimentation is a major concern for many flood control dams. Policy makers need to take into account sedimentation and its management costs when evaluating and ranking proposed dams. Also, sediment management in existing dams needs to be given careful consideration with a view towards extending the useful life of these projects. This paper presents an optimal control model of sediment management in multipurpose dams that have flood control as a main function. The model is applicable to new as well as existing dams.

Results of an illustrative application show that, for a wide range of parameter values sustainable management of dams is a preferred policy. It can increase discounted net benefits by almost one-third over the nonsustainable outcome that involves no sediment removal. Partial sediment removal may also be more desirable than the latter strategy if technical constraints do not allow full removal and a sustainable outcome.

Although the numerical example presented is based partly on synthetic data and the model is quite simplified (e.g., only one sediment removal technique is allowed), our general approach can be extended quite easily to serve as a basis for policy relevant work in this field.

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