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水庫永續經營管理策略之研究

The Optimal Strategy of Sustainable Reservoir Management from a Long-term Perspective

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本論文係林馥苡君（R02521312）在國立臺灣大學土木工程學系碩士班完成之碩士學位論文，於民國 104 年 7 月 14 日承下列考試委員審查通過及口試及格，特此證明

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中文摘要

因降雨時空分布不均和可用水資源有限等問題，水庫建用以調蓄水資源，滿足農業灌溉、工業用水、民生需求等目的，水庫壩體阻斷自然輸砂機制致使大量泥砂沉積，淤砂不僅減少水庫蓄水空間，也縮短水庫營運壽命且危害壩體安全，成為一大隱憂。面對此等難題，泥砂清淤為工程上經常使用的手段，然而計畫性的清淤成效不如預期，淤砂速度始終快於清砂效能，嚴重的淤砂會迫使許多水庫面臨退役的問題，影響水庫永續利用的規劃。在某個特定時間，應當重新評斷壩體的續存問題，其中拆壩也是需考慮的選項之一，以往研究多半關心拆壩後對環境所造成的影響，然而拆除壩體的同時，河川可以在短期內得迅速移除庫內淤積泥砂，恢復自然條件。

在未來，若是水庫廢棄無法再生利用，旱季時造成供水不足，成為社會的重要問題。若視水庫相當於一種社會資源，在技術可行下，資源再生也將成為一種解決方式，本研究基於原壩址可以拆除後再重新興建的假設上，嘗試將清淤規劃結合壩體的再生進行探討，透過最佳化工具和經濟分析，在長期水庫效益最大化的前提下，基於資源理論的觀點，建構模式以模擬不同條件下短期或長期的水庫操作，分析清淤時間點和清淤量之決策等，最終，評估是否將水庫視為可更新資源或不可更新資源利用，相較於不可更新資源，研究須探討庫容的再生對模式的影響。本研究期望努力的最後，能夠提供水庫操作者具備永續性且有效的水庫淤砂處理的政策原則及方案擬定概念。

關鍵字：水庫清淤、可更新水庫之經營規劃、經濟分析

ABSTRACT

Reservoir management faces a crucial challenge from watershed sedimentation, which can significantly influence the sustainability of reservoirs. To maximize value of reservoirs and extend its lifespan, strategies of more effective and sustainable reservoir operation are always desired. For this purpose, sediment removal schemes such as dredging and flushing are usually considered; otherwise, dam decommissioning is also widely discussed. The issues raised after dam decommissioning are should we rebuild it, remove it, or just deposit the dam as it is. In the previous studies, retrofitting dam and sediment removal issues are discussed separately in the aspect of reservoir benefit estimation. However, it is very likely that sediment management might be related to dam removal problem. Using an economic analysis and an optimization, this study established a model to explore the log-term reservoir management regarding sediment removal and dam removal, thereby identifying whether operate reservoirs as renewable resources or non-renewable resources at the end of reservoir's life. As a renewable resource, lifespan of reservoir could be extended indefinitely in contrast to as a non-renewable resource. As a consequence, we expect a better strategy can be proposed for sustainable management of reservoirs.

Keywords: Sediment removal, reservoir renewal, economic analysis

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Chapter 1 Introduction

1.1 Background

People build reservoirs to store water resources on the purpose of satisfying the needs of agricultural, municipal and industrial uses, hydropower and other aims. While rivers are intercepted by hydraulic structures built to store water, sediment are also trapped then cannot be transported to downstream by water flow. Watershed sedimentation would decrease the reservoir capacity, increase risk of dam safety, shorten the lifespan of reservoir and reduce social welfare. Recently, more and more reservoirs worldwide face the end of lifespan attributed to sediment accumulation mostly. This growing problem imposes crucial challenges on reservoir management and significantly influences the sustainability of reservoirs; therefore, sediment removal is under the consideration of sustainable sediment management. With the state of the art, sediment removal approaches include hydraulic (flushing, hydrosuction and sluicing) and mechanical (dredging and excavation) schemes.

Once a reservoir is completely filled by sediment, theoretically the economic life of project is ending. It is time to consider decommissioning of a dam by evaluating the benefit of operation and salvage value of the reservoir. After retiring the dam, it remains uncertain whether we should rebuild, remove it or even leave it alone. Moreover, due to the limitation of new sites of dam construction, especially land use like Taiwan, both sediment removal and dam retirement issues should be carefully examined from a sustainable perspective before coming the end of reservoir's life.

1.2 Research motivations

Engineers are concerned with how to determine an effective strategy of sediment management to maximize the reservoir benefit and prolong its life for storing water. In previous studies, dam retirement and sediment removal are discussed separately in the aspect of reservoir value estimation. It is very likely that sediment management might be related to dam removal issue. Regardless of consequences to downstream and nature, dam removal is an approach that assists people to remove sediment and saves maintenance cost of aged infrastructures. In addition, regarding extreme hydrologic events, it is worth questioning the myth that removing sediment continually to extend storage life may achieve the economic benefits as expected.

For example, in 2009, Typhoon Morakot struck southern Taiwan and caused severe damage. The sediment which came with extreme rainfall had reduced the capability of Zengwun reservoir (see Figure 1.1). Those sediment occupied more than fifteen percent of original storage capacity (Water Resources Agency in Taiwan, 2010). Consequently, it would spend lots of time and money to deal with such significant sludge. Another remarkable example is Baihe reservoir located at Tainan city in southern Taiwan. Sediment inflow from watersheds and Typhoon Morakot almost occupied half of original capacity, thereby influencing the function for agricultural water supply due to the loss of capacity (WRA, 2012). Merely depending on sediment removal mechanism to manage sedimentation seems not a desirable plan to correspond economic demand.

Besides, most available sediment removal methods are inefficient. Sediment accumulation problem keeps getting worse on reservoirs in service worldwide. For instance, Wushe reservoir in Taiwan, as shown in Figure 1.2, has worked fifty-five years for generating electric power since 1960. According to the latest records (WRA, 2012), the remaining usable capacity left only less than forty percent of original capacity. Despite these reservoirs (above cases) are expected to live as longer as possible, the actual problems often go beyond our control. As a result, this study attempted to investigate the combination of dam removal and other measures as one of strategies of sediment management. We tried to make capacity renewable but non-sustainable to increase benefit from reservoir management by rebuilding dams.

Figure 1.1. Sediment releasing during Typhoon Morakot at Zengwun reservoir

Figure 1.2. Sediment accumulation in Wushe reservoir (徐嬋娟 攝)

1.3 Framework of study

Several challenges of sediment management remain to be overcome such as how to avoid sediment accumulating, choose appropriate removal methods and decide the programs of capacity rehabilitation. This study treated reservoirs as renewable resources rather than exhausted one. So we particularly focused on time paths of sediment removal and benefit along with dam rebuilding. Using an economic analysis with optimization approach, this research developed a model to simulate a long-term reservoir management regarding sediment removal and dam removal, thereby identifying whether operate reservoirs as renewable resources or non-renewable resources at the end of lifespan. As a renewable resource, lifespan in a broad sense can be extended infinitely in contrast to a non-renewable resource. In brief, we expected that employing the concept of resources to address sedimentation may propose a better strategy for policy-makers, enable reservoir operation to attain more profit and be able to respond to future change.

1.4 Outline of this work

This study was discussed with five chapters including introduction, literature review, methodology, results and commentaries and conclusion. Figure 1.3 indicates outline of our work.

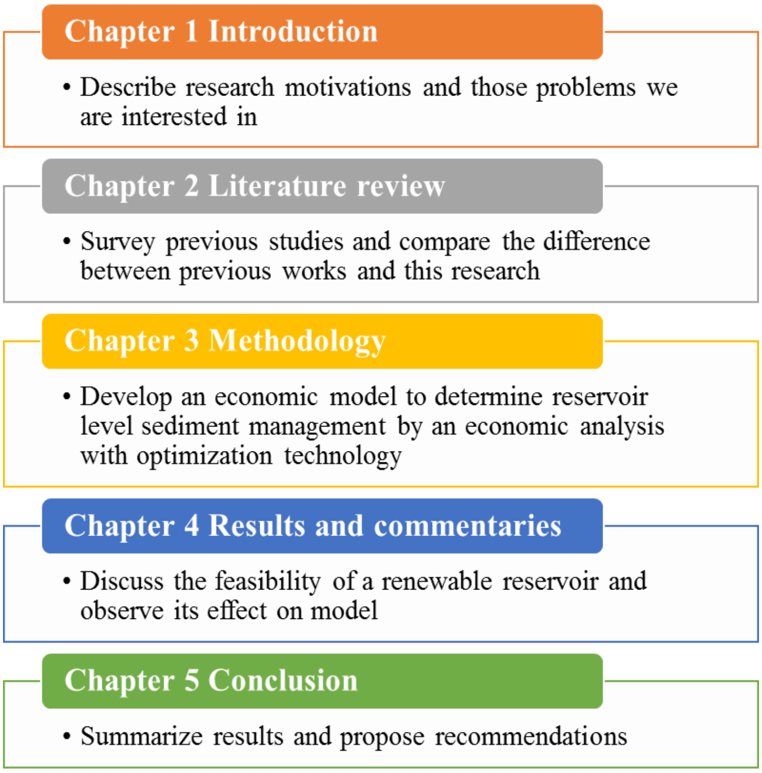

Figure 1.3. Outline of this study

Chapter 2 Literature Review

2.1 The prevalence of reservoir sediment problems

2.1.1 Influence of sedimentation on reservoir

Facing insufficient water resources, people build reservoirs to store water but also trap sediment. Recently, more and more reservoirs face the difficulties in their operation as a consequence of serious sedimentation. The sediment trapped in reservoirs would decrease effective capacity, diminish the function and also shorten the lifespan of reservoir. Based on previous study, about 0.5-1.0% of global water storage is lost annually due to sedimentation (White, 2001). Sedimentation gradually diminishes the value of existing dams and imposes economic loss to our society. Although the process of sediment depositing is slow, the accumulated amount of loss capacity over time is significant (Kawashima, 2007). Without an effective strategy of reservoir sediment management, reservoirs would eventually need to be retired soon or later. In addition, the economic cost of replacing dams might be substantial (Palmieri et al., 2001), thereby preserving reservoir capacity becoming a high priority. Such problem can be considerably deferred if sedimentation is minimized.

2.1.2 Managing sedimentation

In the past, many studies paid effort on reservoir sediment management (George et al., 2014). This issue has been extensively discussed on watershed or reservoir level. Lee et al. (2011) presented an optimal control model of integrated watershed management in the presence of a dam including upstream soil conservation, reservoir level sediment removal and downstream damage control. Watershed management can mitigate sediment impact to downstream structures but not enhance more capacity for water storage while sedimentation proceeds to occur (Kawashima, 2007). As a result, this study mainly discusses reservoir level sediment management from a long-term perspective.

2.2 Feasible sediment management strategies

2.2.1 Available sediment removal approaches

To prevent sediment problem deteriorating and prolong longevity of projects, sediment removal methods are needed. Hydraulic and mechanical removal methods such as sluicing, flashing, hydrosuction (Huffaker and Hotchkiss, 2006), dredging, excavation and other ways are usually considered. However, performance of these available methods do not achieve the goal as expected. For example, cost of hydraulic removal methods is lower than mechanical methods. It is mostly implemented during flood season, so without adequate precipitation there would be no surplus water for sediment releasing. On the other hand, mechanical removal methods are independent of weather, but it takes much more time to complete given tasks. Hence, it is very important to determine a feasible sediment removal program to effectively utilize these methods in order to enhance storage capacity economically.

2.2.2 Management composition

To answer the difficult question, the economic analysis may be an appropriate estimation approach. Using an economic analysis, sediment management could be clearly analyzed and quantified with respect to their values. It appears that dealing with siltation matters is similar to the concept of different water resource infrastructures such as pipes maintenance (Kleiner et al., 1998). A Reservoir could be recognized as the behalf of water distribution system and every loss capacity could be regarded as an old pipe. What engineers are mostly concerned is that programs a time path of replacing and chooses numbers of retired object. Dorfman (1969) extended the optimal control theory with an economic interpretation which helps operators or systems optimize their decision-makings by analytical way. Sediment removal program is one of beneficiaries.

2.2.3 Difference between this study and previous researches

Because the work of dam construction is costly, in general, engineers attempt to operate reservoir as long as possible. Hydraulic infrastructures used to be designed and operated for a time long enough. Based on reasonable assumptions, some researchers suggested that storage capacity can be conserved sustainably relying on their management strategies and effective sediment removal methods (Kawashima et al., 2003 and Kawashima, 2007). Aimed at environmental condition, these theories are subjected to:

$$\bar{X} \geq M \tag{2.1}$$

where

$\bar{X}$ maximum capability of sediment removal (m^3/yr)

M annual trapped sediment (m^3/yr)

Under this constraint, sediment problem could be successfully controlled and not fill the capacity of reservoir. The core of these theses tends to discuss difference between time paths of management strategy before the end of lifespan. They used analytical or numerical methods to respond questions including when removal tasks should be implemented and how many sediment should be removed. Particularly, contribution from papers is able to identify whether annually sediment removal plans gain more profit in contrast to cyclical removal program. Based on their assumptions, these study indicated that storage capacity can be preserved at certain level to maximize total value of reservoir by decided time path (see Figure 2.1).

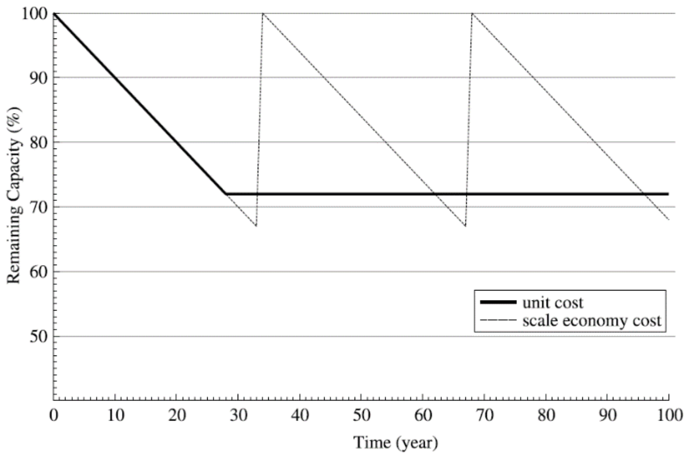

Figure 2.1. The time path of remaining capacity for dredging (Kawashima, 2007)

Despite it seems theoretically possible to extend lifespan of a reservoir infinitely, the fact of sedimentation has always exceeded our anticipation. According to the reality, this study is restricted to:

$$\bar{X} \leq M \tag{2.2}$$

Once the storage capacity becomes empty, there may be no enough water resource to meet people's demand under population growth. Later, the issue of dam decommissioning would be inevitably raised again. Clearly, the practicing that conserving capacity over a lasting but still finite period of time should be challenged. Many studies have addressed sediment management regarding salvage value and identified the optimal timing of dam retirement (Lee, 2011 and Palmieri, 2001), though, little is known about future treatment of a reservoir after dam decommissioning. It is not easy to make choices for policy-makers at the end of lifespan.

2.3 A new perspective of reservoir sediment management

Dam removal is one of the options among the measures of dam decommissioning. Most people are interested in the influence of dam removal on environment. From other points of view, while dam is deconstructed, trapped sediment could be removed in large amount by water flow (Pizzuto, 2002, Shuman, 1995 and Simons and Simons, 1991). It is likely that the consequence of dam removal coincides with our expectation for solving sediment problems. In addition, the implication of the meaning of sustainability should not be merely applied to extend a lifespan of an object. The meaning of sustainability probably imply that provides an opportunity to revive those are going to be silted up.

In the aspect of resource theory (Harris, J. M. (2006). *Environmental and natural resource economics: A contemporary approach*., Tietenberg, T., & Lewis, L. (2009). *Environmental & natural resource economics*., and Ward, F. A. (2006). *Environmental and natural resource economics*.), some resources can be considered as renewable but some others may not. How about reservoirs? If reservoirs are non-renewable resources, they would be abandoned at the end of lifespan. On the other hand, storage capacity could be reproduced again and again by repeating dam reconstruction. There is no single lifespan but many short lifespans gather to become a long time path of sustainable lifespan.

This approach evaluates accumulated benefit over time instead of benefit from each cycle. Although the cost of dam reconstruction is considerable, it might be temporary loss for society but beneficial from a long-term perspective. If sedimentation continually happens, our future will cover with the worry that profound sediment accumulation makes the end of reservoir's life come more quickly than usual. In comparison with construction cost and impact of water crisis, issue of dam rebuilding is much more acceptable. Referring a resource theory to determine a sediment removal strategy may open a new sight.

Chapter 3 Methodology

3.1 Research purposes

Reservoir sediment accumulation is an unflavored natural process and a problem to reservoirs we need to face. In previous studies, conserving capacity of reservoir has extensively been discussed for achieving sustainability. As a result, considering resource management, this study attempted to treat reservoirs as renewable resources for the sake of: (1) maximizing reservoir management benefit, (2) promoting the efficiency of sediment removal.

Using an optimization technique and an economic analysis, we established a numerical model to simulate the process of sedimentation at reservoir level, thereby optimizing sediment removal schemes. MATLAB was used for computation in this study. By this way, we could propose a potential sustainable strategy of reservoir for future policy making.

3.2 Evaluating value of reservoir

3.2.1 An economic model

Analyzing sediment problems, this model applied an economic analysis to illustrate the practice of reservoir sediment management. Assumed that dam managers generate reservoir benefit to satisfy people's demand through supplying water which is subjected to annual change of storage capacity. Benefit of generating electric power is not included in this model. Capacity of reservoir is governed by sedimentation inflow and discharge which includes both hydraulic and mechanical sediment removal measures (see Figure 3.1). Initial cost of dam construction, annual benefit of reservoir operation, cost of sediment removal and operation and maintenance cost (OMC) of reservoirs are all considered. We defined the objective function (Ψ) to accumulate annual net benefit of reservoir management until the end of lifespan as below. Initial construction cost (C_2) could be excluded for a working reservoir. For consistency, each parameter in this model is expressed in present value. Lifespan (T), a period of reservoir's life, is influenced by water inflow and capability of sediment removal. Factor, γ, is a discount rate.

$$\Psi(T) = -C_2 + \sum_{t=1}^{t=T} \left(B(t) - C_1(t) - C_{OMC}(t) \right) \cdot (1+\gamma)^{-t} \tag{3.1}$$

$B(t)$ is a production function of revenue related to water inflow and reservoir capacity. Sediment removal cost, $C_1(t)$, is in proportion to amount of sediment removal. Regarding motions of sediment removal and sedimentation (M_t), total benefit of the objective function varies with both sediment removal (X_t) and reservoir capacity (K_t).

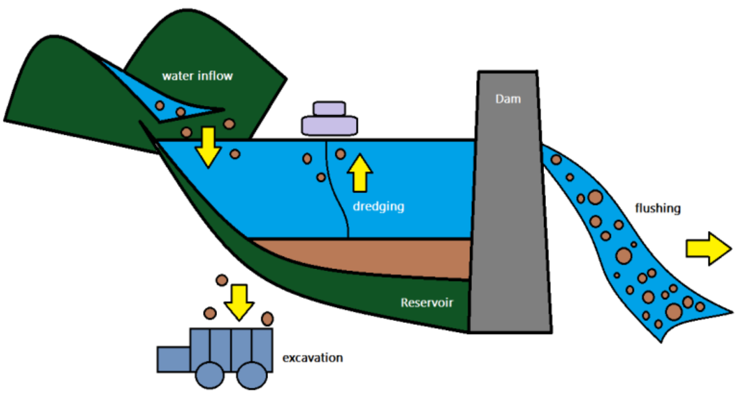

Figure 3.1. Sediment removal methods

Maximize $\Psi(T)$

which is subjected to

$$K_{t+1} = K_t - M_t + X_t \tag{3.2}$$

$$K_t \in \{0, K_0\},\ \ X_t \in \{0, \bar{X}\} \tag{3.3}$$

$$\bar{X}_t \le M_t \tag{3.4}$$

This model optimized choices of arranging time paths of variables X_t and K_t to attain maximum reservoir benefit. Symbol t is a time step. K_0 represents the initial capacity of reservoir, $\bar{X}_t$ is the maximum capability of sediment removal and M_t represents annual sediment inflow which reduces capacity. According to reality, we assumed that sediment removal cannot be able to fully discharge sediment inflow; therefore, sediment accumulation remains to happen at any moment. In addition, sediment removal in this study only manages annual incoming sediment to reservoir instead of impounded sediment in reservoir.

Attributed to the Equation (3.4), this is a finite optimal control problem that reservoir's capacity could not be indefinitely maintained at certain level because sediment income is in excess of removal. If a reservoir is required to be decommissioned, salvage value should be taken into consideration at time T. Salvage value could be positive or negative depending on whether the cost of dam reconstruction is set to be sufficiently high. It can be only estimated at the end of lifespan. In addition, although we could anticipate a fate of reservoir management, this model did not discuss the outcome for hydraulic structure after retiring dam. We left this question for further study in the future. Considering a salvage value, the objective function is regarded as

$$\Psi(T) = -C_2 + \sum_{t=1}^{t=T}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V(T)\cdot(1+\gamma)^{-T} \quad (3.5)$$

According to idea of Lee's study (2011), a terminal time (T^*) for dam retirement can be identified from the viewpoint of economic analysis. This terminal time of retirement can be evaluated as either the decay curve of marginal benefit of reservoir intersects the its increasing curve of marginal cost, as shown in Equation (3.6.1) and Figure 3.2, or the gradient of the objective function (Ψ) is equal to zero in Equation (3.6.2) and Figure 3.3.

$$MB_t - MC_t = 0 \qquad t = T^* \quad (3.6.1)$$

or

$$\frac{\partial \Psi}{\partial T} = 0 \qquad T = T^* \quad (3.6.2)$$

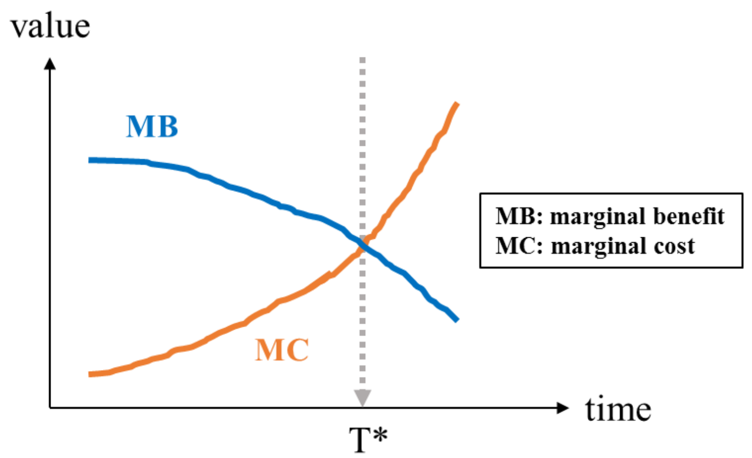

Figure 3.2. Curve of marginal benefit intersects curve of marginal cost

It seems that despite the value of the objective function keeps positive, the performance of reservoir begins to go down from the time T^* in Figure 3.3. Many reasons can lead to this consequence such as increasing cost of annual dam maintenance or decreasing benefit due to continually losing effective reservoir capacity.

The theoretical terminal time might be shorter or equal to lifespan of reservoir ($T^* \leq T$) depending on trade-off between benefit and cost. It could not be known before dam constructing but calculated by computer simulation. Other considerations such as ecological remonstration and dam safety would also make the terminal time different from original expectation. However, these conditions are not included in the framework of this model. By the way, Time step of numerical model is in annual while every parameter is also estimated in the price as annual-average.

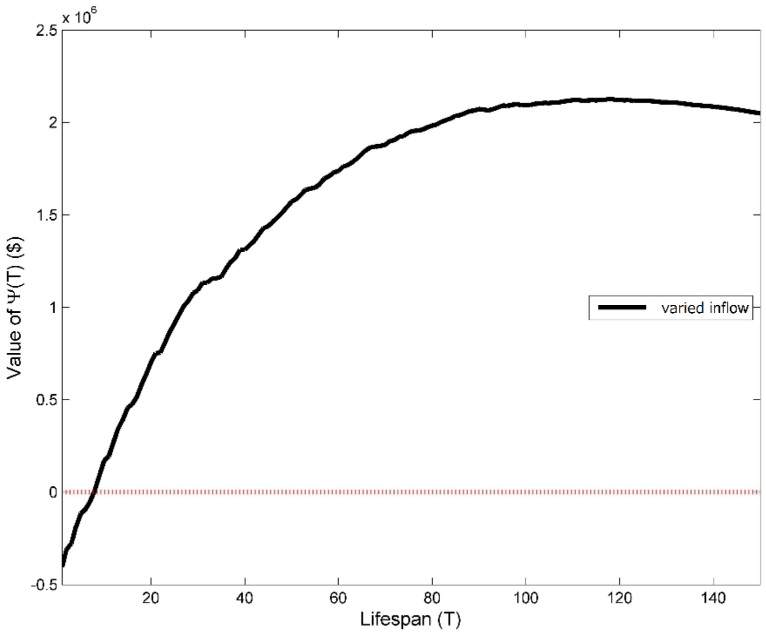

Figure 3.3. The objective function with varied inflow without concept of the reservoir renewal

3.2.2 Reservoir sediment management regarding dam removal

For policy-makers, they might abandon a dam or remove a dam for river rehabilitation or even rebuild a dam to restore reservoir capacity when dam is to be decommissioned. Considering these options, the objective function would be reformed slightly with some extra costs.

If a dam is removed, a deconstruction cost (C_3) is added to the Equation (3.5).

$$\Psi(T) = -C_2 + \sum_{t=1}^{t=T}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V(T)\cdot(1+\gamma)^{-T} - C_3\cdot(1+\gamma)^{-T} \quad (3.7)$$

Dam removal is discussed regarding its substantial expense and aftereffects on different sectors; however, it is also able to remove those sediment which accumulate in reservoirs is not successfully released by other sediment removal measures. To solve the problem of severe siltation, it is likely that dam removal may advance the efficiency of sediment management. Focused on this advantage, reservoirs could be defined as renewable resources.

As a renewable reservoir, capacity renewal is repeated over time; therefore, the lifespan of reservoir might not last forever but the reservoir itself is renewable. Lifespan of every cycle spreads on a long time stream and connects with each other. Although dam construction cost is considerable, future worth along with revival of reservoir capacity should not be ignored.

Gathering net benefit of each cycle, this study defined the new objective function (Ω) and analyzed its consequences, thereby comparing new strategy of reservoir sediment management with traditional practices. Particularly, lifespan here becomes a new controlled variable. It is highly relevant to times of dam reconstruction (n) on a fixed length of observing time stream. In other words, sediment removal schedule would be no longer dominated by remaining capacity as before. Assumed that next execution of reservoir renewal would be incurred by previous dam reconstruction cost (C_4). The objective function of each cycle regarding rebuilding dams is:

$$\Psi(T) = -C_2 + \sum_{t=1}^{t=T}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V(T)\cdot(1+\gamma)^{-T} \\ -C_3\cdot(1+\gamma)^{-T} - C_4\cdot(1+\gamma)^{-T} \quad (3.8)$$

Indeed, the work of dam retrofitting brings nature or society burden, so this model added a factor λ which is a social preference rate from economic viewpoint describes people's favor to strategy of renewable reservoir ($0 \le \lambda \le 1$). It means that people might tend not to support this policy in the future when value of λ is lower than one. As value of λ is very low, people are likely careless of the future influence.

Let the accumulated cycle benefit be defined as:

$$\Omega_n = -C_2 + \sum_{i=1}^{i=n}\Psi_i(T_i) = -C_2 + \Psi_1(T_1) + \Psi_2(T_2) + \Psi_3(T_3) + ... + \Psi_n(T_n) \quad (3.9)$$

i cycle number

n times of dam reconstruction

The Equation (3.9) is also subjected to the Equation (3.2), (3.3) and (3.4). Initial cost of dam construction only occurs at the beginning so the function of $\Psi_i(T_i)$ in Ω_n is without the term of C_2. Except the first cycle ($i=1$), λ would discount annual net benefit from reservoir along with cycle number (i). After dam removal, it will take several years to rebuild a new dam. Next cycle would be deferred few years (s) and then restart to serve people on the same dam site. Insert λ and the Equation (3.8) into the Equation (3.9) that

Maximize Ω_n

$$\Omega_n = -C_2 + \sum_{t=1}^{t=T_1}\left(B(t)-C_1(t)-C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V_1(T_1)\cdot(1+\gamma)^{-T_1} \tag{3.10}$$

$$-C_3\cdot(1+\gamma)^{-T_1} - C_4\cdot(1+\gamma)^{-T_1} + \sum_{t=1+T_1+s}^{t=T_1+s+T_2}\lambda\left(B(t)-C_1(t)-C_{OMC}(t)\right)\cdot(1+\gamma)^{-t}$$

$$+V_2(T_2)\cdot(1+\gamma)^{-(T_1+s+T_2)} - C_3\cdot(1+\gamma)^{-(T_1+s+T_2)} - C_4\cdot(1+\gamma)^{-(T_1+s+T_2)} + \dots$$

$$+\sum_{t=1+T_1+\dots+T_{n-1}+s(n-1)}^{t=T_1+\dots+T_n+s(n-1)}\lambda^{n-1}\left(B(t)-C(t)-C_{OMC}(t)\right)\cdot(1+\gamma)^{-t}$$

s reconstruction period

No matter the deconstruction cost or the reconstruction cost, they both occur at the end of reservoir's life. Furthermore, no one knows what will happen after the last cycle (assumed time of nT is far away from now); therefore, we did not add a salvage value, a dam deconstruction cost and a dam reconstruction cost to the function of Ψ_n while calculating the function of Ω_n from $i=1$ to $i=n$. After maximizing the objective function of Ω_n, we might obtained a sustainable policy for reservoir management along with both sediment removal and dam removal. We expected to investigate different time paths of sediment removal and be able to answer the questions we raised at the beginning from results.

In the Equation (3.10), lifespan of reservoir varies with cycle number of dam rebuilding. To simplify our model, let each cycle shares the same lifespan as shown in the Equation (3.11). Figure 3.4 depicts change of reservoir capacity for long time and shows a decline trend on net benefit due to social preference rate, λ.

Maximize Ω_n

$$\Omega_n(T) = -C_2 + \sum_{i=1}^{i=n} \Psi_i(T) = -C_2 + \Psi_1(T) + \Psi_2(T) + \Psi_3(T) + ... + \Psi_n(T) \tag{3.11}$$

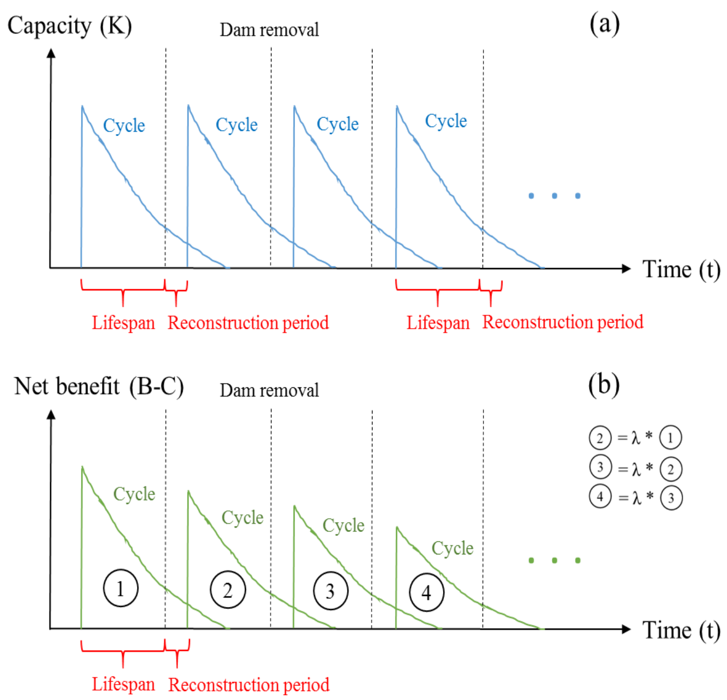

Figure 3.4. (a) Time path of repeated capacity rehabilitation. (b) Time path of net benefit as $0 \le \lambda < 1$.

Insert $\Psi_i(T)$ into $\Omega_n(T)$ and then extend it.

$$
\begin{aligned}
\Omega_n = & -C_2 + \sum_{t=1}^{t=T}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V_1(T)\cdot(1+\gamma)^{-T} \\
& - C_3\cdot(1+\gamma)^{-T} - C_4\cdot(1+\gamma)^{-T} + \sum_{t=1+T+s}^{t=T+s+T}\lambda\cdot\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} \\
& + V_2(T)\cdot(1+\gamma)^{-(T+s+T)} - C_3\cdot(1+\gamma)^{-(T+s+T)} - C_4\cdot(1+\gamma)^{-(T+s+T)} + \ldots \\
& + \sum_{t=1+T(n-1)+s(n-1)}^{t=nT+s(n-1)}\lambda^{n-1}\cdot\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t}
\end{aligned}
\tag{3.12}
$$

Let $T' = T + s$, and insert T' into the Equation (3.12),

$$
\begin{aligned}
\Omega_n = & -C_2 + \sum_{t=1}^{t=T}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} + V_1(T)\cdot(1+\gamma)^{-T} \\
& - C_3\cdot(1+\gamma)^{-T} - C_4\cdot(1+\gamma)^{-T} + \sum_{t=1+T'}^{t=T+T'}\lambda\cdot\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t} \\
& + V_2(T)\cdot(1+\gamma)^{-(T+T')} - C_3\cdot(1+\gamma)^{-(T+T')} - C_4\cdot(1+\gamma)^{-(T+T')} + \ldots \\
& + \sum_{t=1+(n-1)T'}^{t=T+(n-1)T'}\lambda^{n-1}\cdot\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t}
\end{aligned}
\tag{3.13}
$$

and

$$
n = \frac{L}{T+s} = \frac{L}{T'}
$$

L length of decision time horizon

3.2.3 The objective function in analytical form

Observing the objective function of repeating dam reconstruction in the Equation (3.11), it seems likely a progression. Fortunately, with some simple simplifications we could analyze it as a geometric progression regardless of the initial dam construction cost. Assumed that

$$
\frac{\Psi_{i+1}}{\Psi_i} = q_T
\tag{3.14}
$$

The factor q_T represents the effect of discounted rate (γ) which is

$$q_T = (1+\gamma)^{-(T+s)} = (1+\gamma)^{-T'}$$

Insert q_T into the Equation (3.11):

$$\Omega_n(T) = -C_2 + \Psi_1(T) + \Psi_1(T)\cdot q_T + \Psi_1(T)\cdot {q_T}^2 + \ldots + \Psi_1(T)\cdot {q_T}^{n-1} \tag{3.15}$$

The objective function of $\Psi_i(T)$ comprises a net benefit during lifespan and a total cost at the end of reservoir's life:

$$\Psi_i(T) = W_i(T) - \hat{C}_i(T) \tag{3.16}$$

where

$$W_i(T) = \sum_{t=1+(i-1)T'}^{t=T+(i-1)T'} \lambda^{i-1}\left(B(t) - C_1(t) - C_{OMC}(t)\right)\cdot(1+\gamma)^{-t}$$

$$\hat{C}_i(T) = -V_i(T)\cdot(1+\gamma)^{-[T+(i-1)T']} + C_3\cdot(1+\gamma)^{-[T+(i-1)T']} + C_4\cdot(1+\gamma)^{-[T+(i-1)T']}$$

Inserted $W_i(T)$ and $\hat{C}_i(T)$ into the function of $\Omega_n(T)$:

$$\begin{aligned}\Omega_n(T) = -C_2 + [&W_1(T) - \hat{C}_1(T) + W_2(T) - \hat{C}_2(T) + W_3(T) - \hat{C}_3(T) \\ &+ W_4(T) - \hat{C}_4(T) + \ldots + W_{n-1}(T) - \hat{C}_{n-1}(T) + W_n(T)]\end{aligned} \tag{3.17}$$

Actually the function W_i would not be proportioned to the next one (W_{i+1}) due to varied water inflow (I_t) but we inputted uniform water inflow into our model to adjust this little defect. We attempted to transform the Equation (3.17) into:

Let $W_{i+1} = W_i \cdot q_T$ and $\hat{C}_{i+1} = \hat{C}_i \cdot q_T$, then

$$\begin{aligned}\Omega_n(T) = -C_2 &+ \left[W_1(T) - \hat{C}_1(T)\right] + \left[W_1(T) - \hat{C}_1(T)\right]\cdot q_T \\ &+ \left[W_1(T) - \hat{C}_1(T)\right]\cdot {q_T}^2 + \left[W_1(T) - \hat{C}_1(T)\right]\cdot {q_T}^3 \\ &+ \ldots + \left[W_1(T) - \hat{C}_1(T)\right]\cdot {q_T}^{n-2} + W_n(T) - \hat{C}_n(T) \\ &+ \hat{C}_n(T)\end{aligned} \tag{3.18}$$

There is a social preference rate λ hiding in the $W_i(T)$, so we should discuss the function of $\Omega_n(T)$ from two aspects.

If n is finite,

$$\Omega_n(T) = -C_2 + \hat{C}_n(T) + \frac{\Psi_1 \cdot (1-{q_T}^n)}{1-q_T} \quad \text{as} \quad \lambda = 1 \tag{3.19.1}$$

$$\Omega_n(T) = -C_2 + \left\{ W_1\left[1-(\lambda \cdot q_T)^n\right] \Big/ 1-(\lambda \cdot q_T) \right\} - \left[\hat{C}_1(1-{q_T}^{n-1}) \Big/ 1-q_T \right] \tag{3.19.2}$$

as $0 \le \lambda < 1$

If n is infinite,

$$\Omega_n(T) = -C_2 + \frac{\Psi_1}{1-q_T} \quad \text{as} \quad \lambda = 1 \tag{3.20.1}$$

$$\Omega_n(T) = -C_2 + \frac{W_1(T)}{1-(\lambda \cdot q_T)} - \frac{\hat{C}_1(T)}{1-q_T} \quad \text{as} \quad 0 \le \lambda < 1 \tag{3.20.2}$$

where

$$\hat{C}_n(T) = \hat{C}_1(T) \cdot {q_T}^{n-1}$$

$$\Psi_1(T) = W_1(T) - \hat{C}_1(T)$$

and $\lim_{n \to \infty} {q_T}^n \simeq 0$

In this study, we both employed an analytical method and a numerical method to figure that how long we retrofit a reservoir could maximize our objective function. Obviously, lifespan T attracted our attention and probably caused a significant impact in our study. We would discuss this finding in the chapter 4.

3.3 Model procedure

Figure 3.5 illustrates procedure of computer simulation. Assumed that there is a virtual reservoir with an arbitrary but sufficiently large initial capacity (capacity would not be too small to be quickly filled with sediment). Inputted a time series of water inflow and decided the length of decision time horizon. It is worth to mention that this model focused on change of reservoir capacity instead of water storage; therefore, we did not adopt any function of storage-yield-reliability.

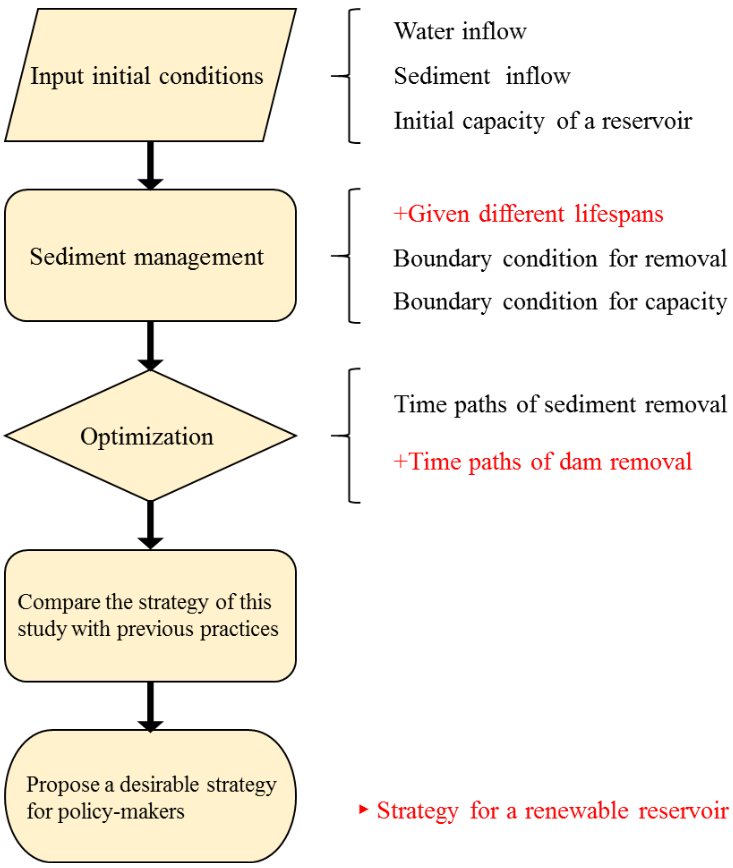

Figure 3.5. Framework of numerical model

Observing real history reservoir inflow records (WRA, 1971–2013), we roughly assumed that our volume size of reservoir is likely related to discharge of annual stream flow. Water flow from watersheds or rivers carry sediment into reservoir, hence, annual sedimentation is merely set to be proportional to stream flow. But maximum capability of sediment removal would not be able to evacuate annual sediment inflow, lifespan of reservoir is regarded as finite.

3.3.1 Benefit function

As for idea for formulating benefit from reservoir, this model recommended the Cobb-Douglas production function. It is a functional form of productivity and widely used to represent relationship between two or more inputs. Applying the Cobb-Douglas function, we had addressed issues of revenue production very well. Inflow and capacity were inputs of revenue production function. Because benefit of reservoir comes from water supply, the revenue production function is related to water price.

$$B(t) = P_W I_t^{\alpha} K_t^{\beta} \tag{3.21}$$

where

K_t is reservoir capacity,

I_t is water inflow, and

P_w is the price of unit water

We defined a condition of $\alpha + \beta > 1$ that means incremental capitals for increasing yield may give impetus to benefit generating of reservoir, and conservatively expected that a half of water inflow is usable and eighty percent of capacity is effective in our study.

3.3.2 Cost functions

The major expense on reservoir (dam) itself is caused by annual structure maintenance and sediment removal. Cost for OMC is known as an increasing function of time. As the age of structure is getting older, the maintenance cost is getting higher. A cost function of sediment removal is the total of hydraulic removal cost and mechanical removal cost. In this study, we recognized that using water to release sediment is a loss for reservoir management so that cost of hydraulic removal is a function of water price multiplying removed sediment. The rest cost of sediment removal is charged by mechanical removal schemes. In fact, cost of mechanical sediment removal is related to labor pay and consumption of electricity for sediment removing facilities. It is not easy to estimate a precise price of unit mechanical removal. As a result, this study assumed revenue from selling sediment is able to balance (is equivalent to) the cost of mechanical removal. Large amount of removed sediment leads to high cost of mechanical removal. Cost parameters are displayed as below:

$C_{11}(t)$ hydraulic removal cost

$C_{12}(t)$ mechanical removal cost

$C_{OMC}(t)$ annual operation and maintenance cost (OMC)

According to available government publications (WRA, 2013 and Taiwan Water Corporation, 2007), in Taiwan, average water price is about 10 NT dollars per cubic meter and mean sediment price per cubic meter is almost 500 NT dollars (strike price). The price of unit sediment is much higher than water price; therefore, reservoir managers usually prefer hydraulic methods to releasing sediments. However, performance of hydraulic sediment releasing is restricted to water storage. Engineers cannot freely release water as much as they want. To advance efficiency of sediment removal, mechanical removal methods are in charge of the rest impounded sediment.

3.3.3 Salvage value

In addition, this model did not seriously discuss whether salvage value should be positive or negative. After all, samples of successful dam removal are not adequate for this study to estimate a reliable value. We merely suggested that salvage value would be affected by the choice of dam removal. If a dam is deconstructed, its salvage value might be brought by river rehabilitation (V_a) and other factors; otherwise, salvage value is measured by benefit of recreation activities on a retired reservoir (V_b).

This model is explicated from a general concept and based on previous studies and engineer's practices. It still remains unclear whether assumptions of this model such as economic meaning for parameters or process of benefit generating are able to fully correspond with reality condition. However, the major of our research is to verify a feasibility for reservoir renewal instead of investigating the truth. Hence, if our model are approximately identical to future trend, it is acceptable.

3.4 Analytical solution for identifying the optimal lifespan

The difference of this study is that we renewed capacity through dam removal to determine a sustainable reservoir management strategy. Besides capacity and sediment removed, reservoir lifespan is another control variable in this model. Inputting different lifespans (how long we should remove a dam and rehabilitate a reservoir), we may overview how the objective function and time paths of sediment removal changed with lifespan.

Apart from numerical model, we could also study influence of lifespan from an analytical perspective. In the section 3.2.3, we obtained an analytical form of the objective function $\Omega_n(T)$ which is a function of lifespan. Generally, a local minimum or a maximum of function exists when its first-order differential equation is equal to zero. Therefore, we aimed at partial differential equation of the objective function to discover the point (lifespan) that satisfies the condition of $\frac{\partial \Omega(T)}{\partial T} = 0$.

Calculate the function of differentiating the Equation (3.19.1) to lifespan, we can obtain that:

$$\frac{\partial \Omega(T)}{\partial T} = 0 \rightarrow \frac{\partial\left(-C_2 + \hat{C}_1(T) \cdot {q_T}^{n-1} + S_n(T)\right)}{\partial T} = 0$$
$$\rightarrow \frac{\partial}{\partial T}\left(\hat{C}_1(T) \cdot {q_T}^{n-1} + S_n(T)\right) = 0 \tag{3.22}$$

where

$$\frac{\partial}{\partial T}\left(\hat{C}_1(T)\cdot q_T{}^{n-1}\right)=\frac{\partial \hat{C}_1(T)}{\partial T}\cdot q_T{}^{n-1}+\hat{C}_1(T)\cdot\frac{\partial q_T{}^{n-1}}{\partial T} \tag{3.23.1}$$

$$=-\hat{C}_1(T)\cdot q_T{}^{n-1}+\hat{C}_1(T)\cdot q_T{}^{n-1}$$

$$=0$$

and

$$\frac{\partial S_n(T)}{\partial T}=\frac{\partial}{\partial T}\left[\frac{\Psi_1(T)\cdot(1-q_T{}^n)}{1-q_T}\right] \tag{3.23.2}$$

$$=\frac{\left\{\frac{\partial\left[\Psi_1(T)\cdot(1-q_T{}^n)\right]}{\partial T}\cdot\left(1-q_T\right)-\Psi_1(T)\cdot(1-q_T{}^n)\cdot\frac{\partial\left(1-q_T\right)}{\partial T}\right\}}{\left(1-q_T\right)^2}$$

$$=\frac{\left(\frac{\partial W_1(T)}{\partial T}+\hat{C}_1(T)\right)\cdot(1-q_T{}^n)\cdot\left(1-q_T\right)-\Psi_1(1-q_T{}^n)\cdot q_T}{\left(1-q_T\right)^2}$$

Therefore,

$$\frac{\partial\Omega_n(T)}{\partial T}=0\rightarrow\frac{\left(\frac{\partial W_1(T)}{\partial T}+\hat{C}_1(T)\right)\cdot(1-q_T{}^n)\cdot\left(1-q_T\right)-\Psi_1(1-q_T{}^n)\cdot q_T}{\left(1-q_T\right)^2}=0 \tag{3.24}$$

Differentiated the Equation (3.20.1) to lifespan, and then

$$\frac{\partial\Omega(T)}{\partial T}=0\rightarrow\frac{\left(\frac{\partial W_1(T)}{\partial T}+\hat{C}_1(T)\right)\cdot\left(1-q_T\right)-\Psi_1\cdot q_T}{\left(1-q_T\right)^2}=0 \tag{3.25}$$

due to $q_T{}^n=\left[(1+\gamma)^{-T'}\right]^n\Big|_{n\rightarrow\infty}\simeq 0$

On the other hand, we differentiated the Equation (3.19.2) to lifespan that:

$$\frac{\partial\Omega(T)}{\partial T}=0\rightarrow \tag{3.26}$$

$$\frac{\partial}{\partial T}\left\{-C_2+\left[W_1(T)\cdot\left(1-\left(\lambda\cdot q_T\right)^n\right)\Big/1-\left(\lambda\cdot q_T\right)\right]-\left[\hat{C}_1(T)\cdot(1-q_T{}^{n-1})\Big/1-q_T\right]\right\}=0$$

$$\rightarrow \frac{\partial}{\partial T}\left[W_1(T)\cdot\left(1-\left(\lambda\cdot q_T\right)^n\right) \Big/ 1-\left(\lambda\cdot q_T\right) \right] - \frac{\partial}{\partial T}\left[\hat{C}_1(T)\cdot(1-q_T{}^{n-1}) \Big/ 1-q_T \right] = 0$$

where

$$\frac{\partial}{\partial T}\left\{ W_1(T)\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right] \Big/ 1-\left(\lambda\cdot q_T\right) \right\} \tag{3.27.1}$$

$$= \frac{ \dfrac{\partial W_1(T)\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right]}{\partial T}\cdot\left[1-\left(\lambda\cdot q_T\right)\right] - W_1(T)\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right]\cdot\dfrac{\partial\left[1-\left(\lambda\cdot q_T\right)\right]}{\partial T} }{ \left[1-\left(\lambda\cdot q_T\right)\right]^2 }$$

$$= \frac{ \left\{ \dfrac{\partial W_1(T)}{\partial T}\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right] + W_1(T)\cdot t\left(T'\right)^{-2}\lambda^n q_T{}^n \right\}\cdot\left[1-\left(\lambda\cdot q_T\right)\right] - W_1(T)\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right]\cdot\lambda\cdot q_T }{ \left[1-\left(\lambda\cdot q_T\right)\right]^2 }$$

and

$$\frac{\partial}{\partial T}\left[\hat{C}_1(T)\cdot(1-q_T{}^{n-1}) \Big/ 1-q_T \right] \tag{3.27.2}$$

$$= \frac{ \dfrac{\partial \hat{C}_1(T)\cdot(1-q_T{}^{n-1})}{\partial T}\cdot\left(1-q_T\right) - \hat{C}_1(T)\cdot(1-q_T{}^{n-1})\cdot\dfrac{\partial\left(1-q_T\right)}{\partial T} }{ \left(1-q_T\right)^2 }$$

$$= \frac{ -\hat{C}_1(T) + \hat{C}_1(T)\cdot q_T - \hat{C}_1(T)\cdot q_T + \hat{C}_1(T)\cdot q_T{}^n }{ \left(1-q_T\right)^2 }$$

$$= \frac{ -\hat{C}_1(T) + \hat{C}_1(T)\cdot q_T{}^n }{ \left(1-q_T\right)^2 }$$

Therefore,

$$\frac{\partial \Omega(T)}{\partial T} = 0 \rightarrow \tag{3.28}$$

$$\frac{ \left\{ \dfrac{\partial W_1(T)}{\partial T}\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right] + W_1(T)\cdot t\left(T'\right)^{-2}\lambda^n q_T{}^n \right\}\cdot\left[1-\left(\lambda\cdot q_T\right)\right] - W_1(T)\cdot\left[1-\left(\lambda\cdot q_T\right)^n\right]\cdot\lambda\cdot q_T }{ \left[1-\left(\lambda\cdot q_T\right)\right]^2 } - \frac{ -\hat{C}_1(T) + \hat{C}_1(T)\cdot q_T{}^n }{ \left(1-q_T\right)^2 } = 0$$

If time is infinite (n is infinite), the Equation (3.28) becomes to:

$$\frac{\partial \Omega(T)}{\partial T}=0 \rightarrow \frac{\frac{\partial W_1(T)}{\partial T}\cdot\left[1-\left(\lambda\cdot q_T\right)\right]-W_1(T)\cdot\lambda\cdot q_T}{\left[1-\left(\lambda\cdot q_T\right)\right]^2}+\frac{\hat{C}_1(T)}{\left(1-q_T\right)^2}=0 \tag{3.29}$$

We knew that the differential rule holds since our function is continuous. However, the objective function of $W_i(T)$ is not a continuous function. In order to adjust this defect, we fixed a continuous curve from numerical results to substitute the function of $W_i(T)$. Because the function of the curve is continuous and differential, calculation of $\frac{\partial \Omega(T)}{\partial T}$ would be feasible.

3.5 Sensitivity analysis

A sensitivity analysis was performed on key parameters of the economic model to investigate their effects on simulation results and examine whether our model is consistent with research incentives and economic rationality.

According to different characteristics of parameter, these parameters were classified into three groups waiting for testing. The first one is related to time including length of decision time horizon and lifespan. Changing length of reservoir operating period would significantly react on final results. Second, variation of cost and discounted rate are deserved to mention. Except the price of unit water and unit sediment, dam construction cost is assumed to be high enough in contrast to the reservoir revenue in first year. Thus, we wondered whether a lower cost for construction work would encourage the policy of reservoir renewal. The last group is about ability of sediment removal. It is believed that promoting capability of sediment removal could extend reservoir's life and change time paths of removal works. These tests are displayed in comparison with baseline policy in the chapter 4. Table 3.1 shows all parameters associated with our model and the setting of baseline test.

Table 3.1. Parameter list

Parameter	Name	Unit	Formula	Baseline value
$K(t)$	Capacity	m^3/yr	$K_{t+1} = K_t - M_t + X_t$	$K_0 = 1000$
$I(t)$	Inflow	m^3/yr		
$M(t)$	Sedimentation	m^3/yr	$M(t) = \varphi_1 \cdot I(t)$	$\varphi_1 = 0.03$
$X(t)$	Sediment removal	m^3/yr	$0 \le X(t) \le \bar{X}(t)$ $\bar{X}(t) \le M(t)$	
$\bar{X}(t)$	Capability of sediment removal	m^3/yr	$\bar{X}(t) = aM(t) + bM(t)$	$a = 0.5$ $b = 0.3$
$B(t)$	Water supply benefit	NT $/yr	$B(t) = P_W I_t^{\alpha} K_t^{\beta}$	$\alpha = 0.5$ $\beta = 0.8$
$C_1(t)$	Sediment removal cost	NT $/yr	$C_1(t) = C_{11}(t) + C_{12}(t)$	
$C_{11}(t)$	Hydraulic removal cost	NT $/yr	$C_{11}(t) = P_W \cdot X_t$	$P_W = 10(\$/m^3)$
$C_{12}(t)$	Mechanical removal cost	NT $/yr	$C_{12}(t) = P_S \cdot X_t$	$P_S = 500(\$/m^3)$
$C_{OMC}(t)$	Operation and maintenance cost of a dam	NT $/yr	$C_{OMC}(t) = C_2 \cdot i \cdot (t)^j$	$i = 0.01$ $j = 0.3$
C_2	Initial dam construction cost	NT $		$C_2 = 500000(\$)$
C_3	Deconstruction cost of dam	NT $		$C_3 = 250000(\$)$
C_4	Reconstruction cost of dam	NT $		$C_4 = 500000(\$)$
$V(T)$	Salvage value	NT $/yr	$V(T) = V_a(T) + V_b(T)$	
t	Time	yr		
T	Lifespan	yr		
L	Length of decision time horizon	yr		
s	Reconstruction period	yr		$s = 5(yr)$
γ, λ	Discounted rate			$\gamma = 0.01$, $\lambda = 0.8$

Chapter 4 Results and commentaries

This study tries to propose a new strategy for sustainable reservoir management using optimization process. In this chapter, we displayed different types of case study to illustrate the characteristics of the model and also discussed the results from both analytical and numerical solutions. In addition, based on this framework, we expected that our model should be able to answer questions such as how the decision of dam removal influenced a sediment management program and the possibility of reservoir renewal.

4.1 Reservoir management without dam reconstruction

4.1.1 Inflow condition

The objective function is defined as $\Psi(T)$ in the Equation (3.1). We used uniform inflow and varied inflow as initial conditions to simulate reservoir management. As shown in Figure 4.1, the objective function are estimated from the first year to the end of reservoir's life. It should be noted that lifespan of reservoir is relative to discharge of sediment inflow. If sediment inflow is rising or capability of sediment removal is reduced, the lifespan would be shortened. As can be seen, with the setup of the model, the curves of net utility with respect to how long the reservoir is operated (the lifespan) are concave. This consequence is consistent with our expectation of decreasing marginal utility to real reservoir operation. As time goes by, the benefit from remaining capacity is being reduced and it may not be able to balance the cost of reservoir management; therefore, the total value of reservoir is decreasing. Figure 4.2 shows reduction of reservoir profit with uniform inflow condition in temporal.

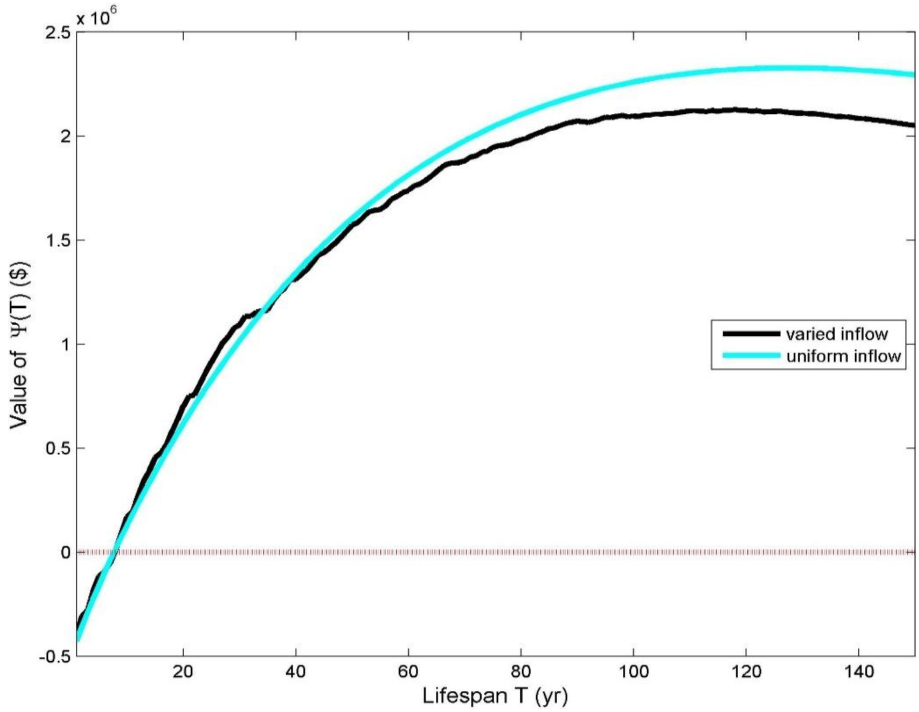

Figure 4.1. Results of the objective function with different inflow conditions

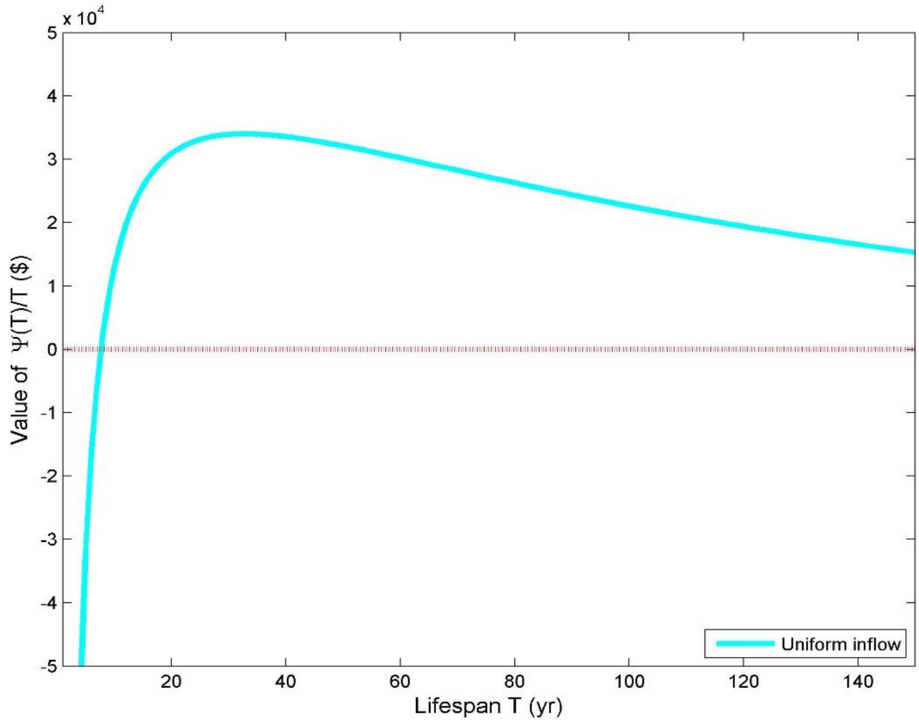

Figure 4.2. Average of the objective function with respect to lifespan

Due to substantial initial construction cost of dam, net benefit of reservoir management would be negative during the beginning. In the previous chapter, we had discussed that we could estimate a terminal time for dam retirement while gradient of the objective function is equal to zero, which is implying first order necessary condition. As can be seen in the Figure 4.1, the lifespans for each flow condition are of 128 years and 118 years respectively. They are recognized as T^* of uniform inflow and varied inflow. Due to model boundary conditions in the Equation (3.4), our reservoir would face retirement issue at the end of reservoir's life. As a result, salvage value (V) should be considered in the objective function. We can clearly observe the decreasing utility of reservoir management from the Figure 4.2.

Figure 4.3 shows the benefit of the objective function with and without salvage value. Considering the dam removal as a means of sediment removal, we made the salvage value be positive, which is beneficial for renewing capacity and dam reconstruction. In some conditions, salvage value might be negative due to unflavored consequence of dam removal. Actually, the difference between results of the simulation case in Figure 4.3 is not distinct; therefore, we used a partial enlarged figure to depict our consequences.

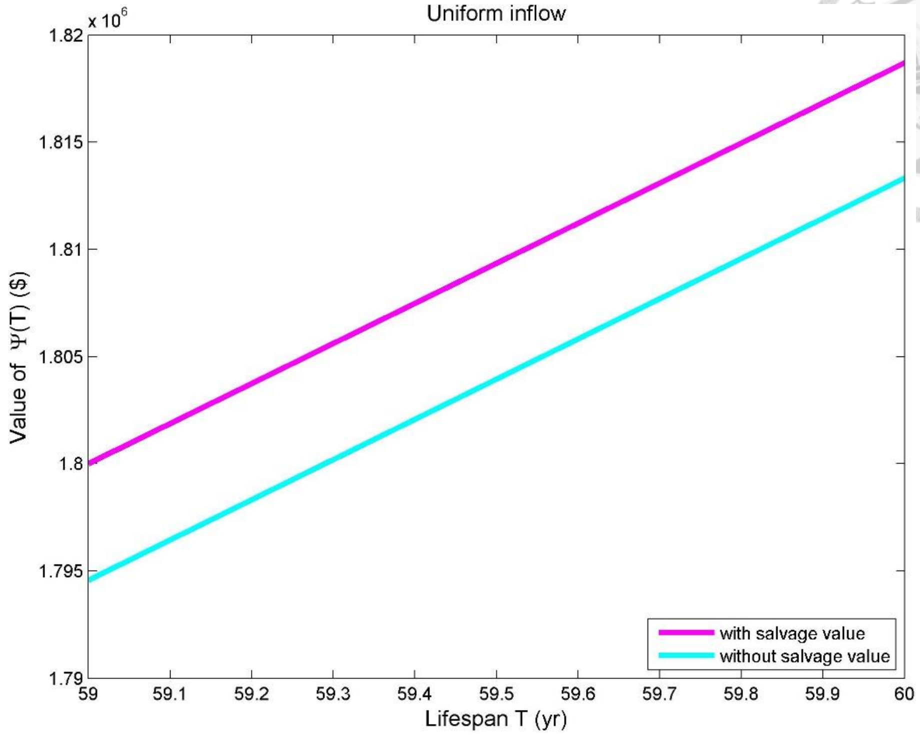

Figure 4.3. Comparing the original objective function without salvage value with the objective function regarding salvage value (partial enlarged drawing)

In contrast to uniform inflow, inflow to reservoir in real world varies year by year. We can find that the consequences of varied inflow in general are similar but a little different from the results of uniform inflow. Comparing the results under uniform and varied flow condition, we can know the influence of hydrological variability in reservoir operation.

In the Figure 4.1, the black curve decays faster than the light blue curve. It appears that if water inflow is time-uniform, theoretically terminal time of dam retirement would occur in the later year in contrast to time-varied inflow. Also, uniform flow seems to average extreme events in varied inflow, so its net benefit would be relatively advanced, especially, in a long lifespan. Besides, the curve of varied inflow is not as smooth as uniform flow condition but keep fluctuating over time. In this study, the objective function would be influenced by inflow discharge; therefore, simulation process would consider inflow variation to manage sedimentation through optimization. However, uniform inflow could more easily demonstrate the stationary of external influence in trade-off between cost and benefit or sedimentation and sediment removal.

In addition, Figure 4.4 illustrates performance of the objective function regarding sediment removal in contrast to the objective function without sediment removal. Obviously, without sediment removal, profit from reservoir management would be profoundly reduced and its lifespan would be shortened. This result is evidently supports that sediment removal is needed.

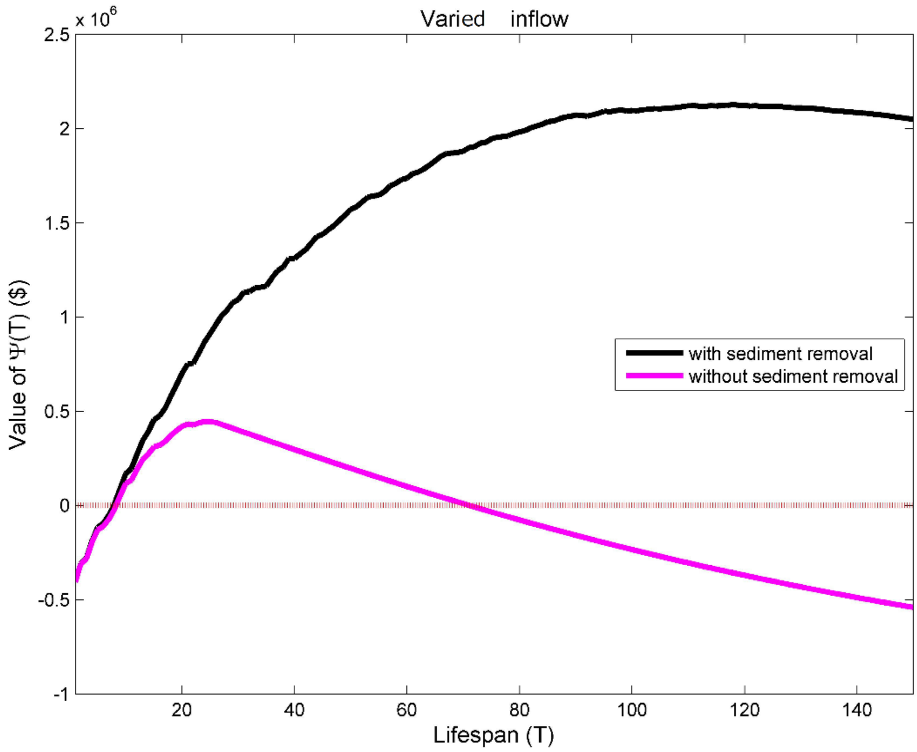

Figure 4.4. Performance of the objective function with sediment removal in contrast to the objective function without sediment removal

4.1.2 Time paths of sediment removal

During optimization, lifespan of reservoir could influence time paths of sediment removal. There are two remarkable findings. First, a long lifespan must result in more sediment removed at each moment for remaining capacity and extend reservoir's life in contrast to a short lifespan. Second, if the life of reservoir is getting close to its end, our results show that sediment removed would fall quickly to zero. It is because of decreasing marginal revenue of sediment removal.

Assuming water inflow is uniform, sediment inflow, which is determined as certain ratio of water discharge, is also uniform. We knew that benefit of reservoir operation is a function of its capacity, so benefit of a large capacity would be more than that of a small capacity. To explain the second finding, we expressed a net benefit (NB) of reservoir at each moment as below.

While $M_t = M_{t+1}$, $C_{OMC}(t) < C_{OMC}(t+1)$ and $K_t > K_{t+1}$, then

$$K_{t+1} = K_t - M_t + X_t$$

$$NB_t = B(K_t) - C_1(X_t) - C_{OMC}(t) \tag{4.1}$$

$$NB_{t+1} = B(K_{t+1}) - C_1(X_{t+1}) - C_{OMC}(t+1)$$

As $X_t = X_{t+1}$, hence

$$NB_t > NB_{t+1} \tag{4.2}$$

However,

if $X'_{t+1} < X_{t+1}$

$NB'_{t+1} = B(K_{t+1}) - C_1(X'_{t+1}) - C_{OMC}(t+1)$

then $NB'_{t+1} > NB_{t+1}$ (4.3)

Figure 4.5 perfectly depicts the marginal effect of sediment removal. There is a positive correlation between cost of sediment removal and sediment removed in contrast to relation of net benefit from reservoir and sediment removed. As can be seen, value of point A is higher than point B on the line of decision 1. If sediment removed is fixed, net benefit at $t+1$ would be less than net benefit at t due to continually decreasing reservoir capacity. However, reducing sediment removed at $t+1$ (on decision 2) would increase net benefit of $t+1$ (point B'). As a consequence, decreasing amount of sediment removal on the end of time path is reasonable and economical. Moreover, for policy-makers, it is not necessary to keep removing sediment for a soon retired reservoir.

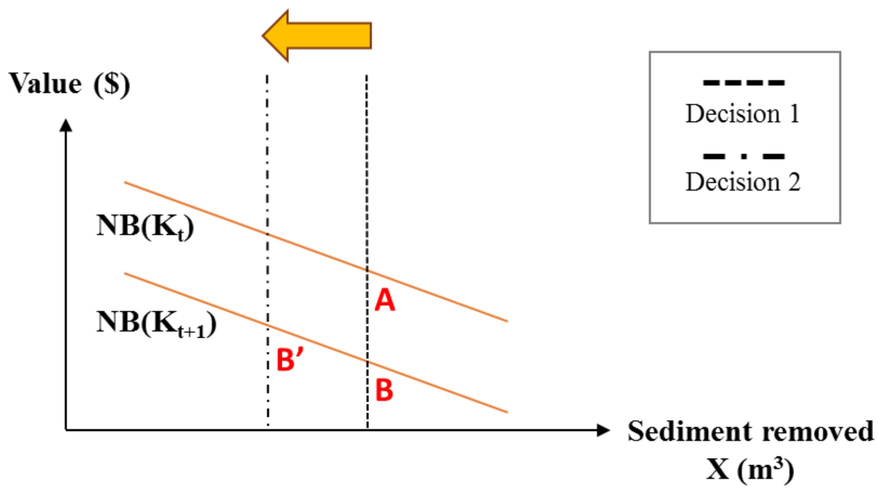

Figure 4.5. Marginal effect of sediment removal

4.1.3 Sensitivity analysis of the function of $\Psi(T)$

Process of optimization would be affected not only by water inflow but also other parameters such as capability of sediment removal and discount rate. Table 4.1 shows some cases we were interested in.

Table 4.1. List of sensitivity analysis of $\Psi(T)$

Parameter	Time discounted rate	Capability of sediment removal
Symbol	$(1+\gamma)^{-t}$	$\bar{X}_t = aM_t + bM_t$
Baseline	γ=0.01	a=0.5, b=0.3
	γ=0.005	a=0.3, b=0.5
	γ=0.03	a=0.7, b=0.1
Case 1	γ=0.01	a=0.5, b=0.3
	γ=0.005	a=0.3, b=0.5
	γ=0.03	a=0.7, b=0.1
Case 2	γ=0.01	a=0.5, b=0.3
	γ=0.005	a=0.3, b=0.5
	γ=0.03	a=0.7, b=0.1
Case 3	γ=0.01	a=0.5, b=0.3
	γ=0.005	a=0.3, b=0.5
	γ=0.03	a=0.7, b=0.1
Case 4	γ=0.01	a=0.5, b=0.3
	γ=0.005	a=0.3, b=0.5
	γ=0.03	a=0.7, b=0.1

Take numerical solutions of uniform inflow for examples. In Table 4.1, symbol a stands for capability of hydraulic sediment removal and b stands for capability of mechanical sediment removal. Figure 4.6 illustrates that objective function is dependent on capability of sediment removal. As can be seen, sum of a and b remains the same in each case. In contrast to baseline result, increasing percent of hydraulic sediment removal would improve benefit from reservoir. However, increasing capability of mechanical sediment removal causes reduction on management profit. It is likely that difference between price of unit hydraulic removal ($10/m^3) and mechanical removal

($500/m^3) makes curve of the objective function shift up and down. Benefit difference between each cases would be expanded by a long lifespan. Furthermore, advancing capability of sediment removal would also increase benefit from management. Although total cost becomes higher, there is more conserved capacity for generating revenue of water supply (Order of benefit production function is higher than that of cost function).

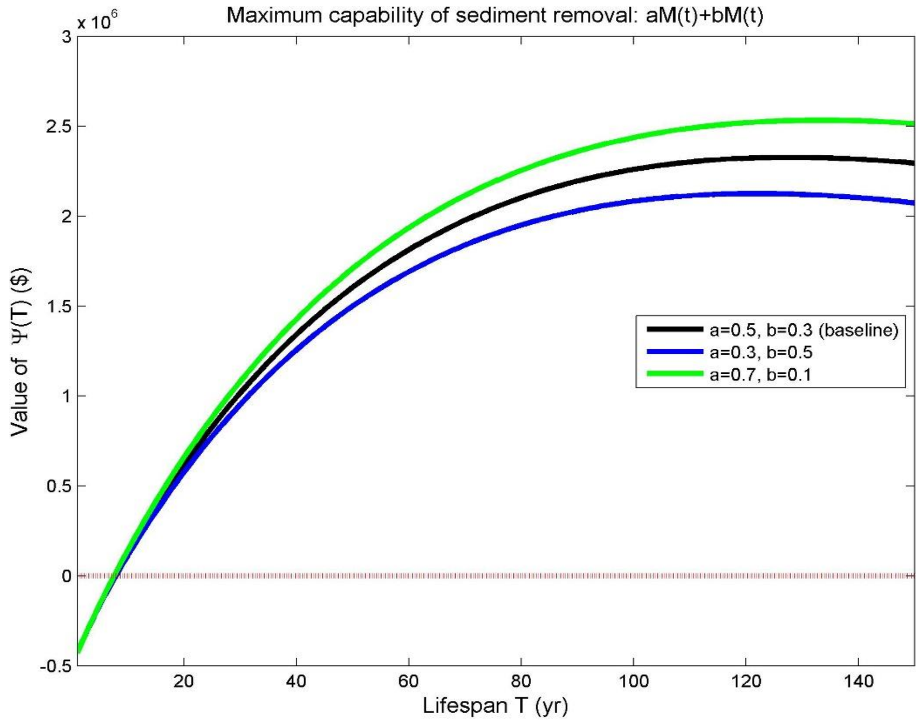

Figure 4.6. Sensitivity analysis for capability of sediment removal (Uniform inflow)

Figure 4.7 displays the effect of discount rate γ on reservoir sediment management. A higher discount rate would lead to more cost down for future price from a present value perspective. As can be seen, results of the objective function of a lower discount rate is lifted and much close to hump-shape. On the other hand, a higher discount rate makes results varies smoothly after its curve maximum. It is likely not economical to operate reservoir as longer as possible while time discount rate is sufficiently high. There is a drop on green line between $T = 100\ yr$ and $T = 120\ yr$. It was resulted from a numerical calculating error. Calculating process stopped at this point (lifespan) before it had evaluated an optimal solution of the objective function due to the setting of iteration times in MATLAB. If we modify the times of iteration, this drop would be eliminated.

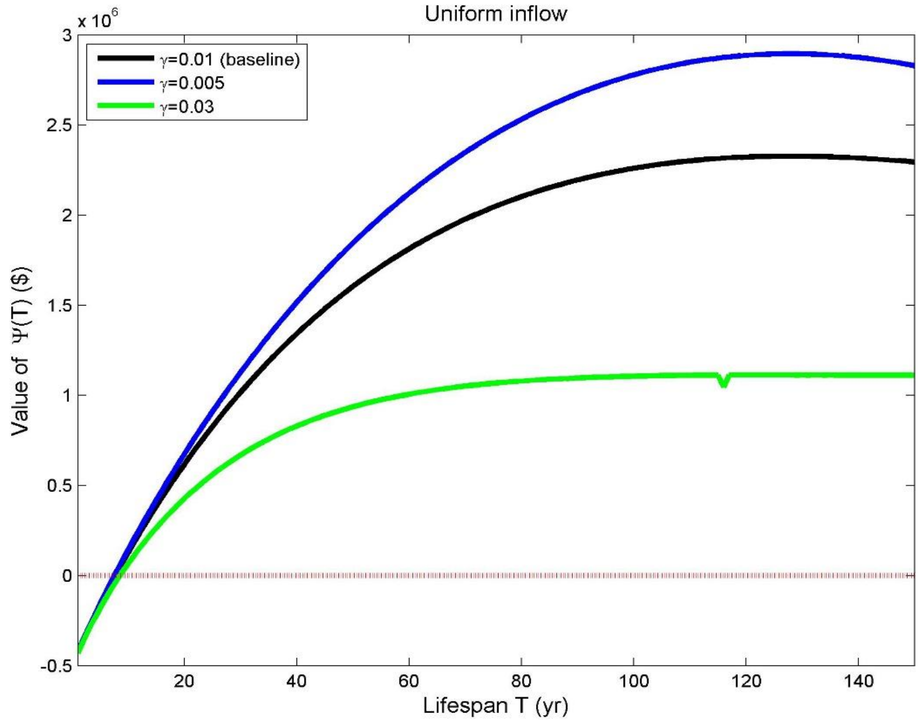

Figure 4.7. Sensitivity analysis for time discount rate (Uniform flow)

4.2 Reservoir management with dam reconstruction

This study applied dam removal to manage impounded sediment in reservoir. As a renewable resource, reservoir could be repeatedly operated instead managed until the end of its life. We attempted to verify our statements from different operating periods. In our baseline results of $\Psi(T)$, lifespan of reservoir would not exceed 150 years. Therefore, we set upper bound of lifespan to be 150 years.

4.2.1 Reservoir management from a short-term perspective

The objective function is defined as Ω_n in the Equation (3.13). Assumed the length of decision time horizon is the same as longest lifespan in Figure 4.1. We inputted uniform inflow to mitigate the effect of hydrologic conditions on model and also determined different lifespans of reservoir for dam removal. Regarding five years dam reconstruction period, lifespans were defined as ten years, fifteen years, twenty-five years, thirty years, fifty years, seventy-five years and one hundred and fifty years. We decided that these lifespans (T') are factors of length of decision time horizon. Why we could not arbitrarily determine lifespan is that we tried to avoid remainder of times (n) of dam reconstruction influencing our results.

As shown in Figure 4.8, it is a consequence of different social preference rates of λ. Maximums of these curves all respond to lifespan of 75 years. No matter value of λ is, lifespan of 75 years is likely the optimal choice for reservoir rehabilitation in 150 years. As can be seen, some values of the objective function are negative. It appears that some lifespans are not recommended for repeating dam rebuilding. In addition, a low lambda value would discount more benefit from reservoir; therefore, times of dam reconstruction appears to influence results of reservoir management.

The most important thing is that we have to prove whether the policy of this study is effective. It is said that removing sediment continually to remain capacity seems more economical and acceptable for present project practices. Therefore, we compared our results with prevailing practice of $\Psi(T)$.

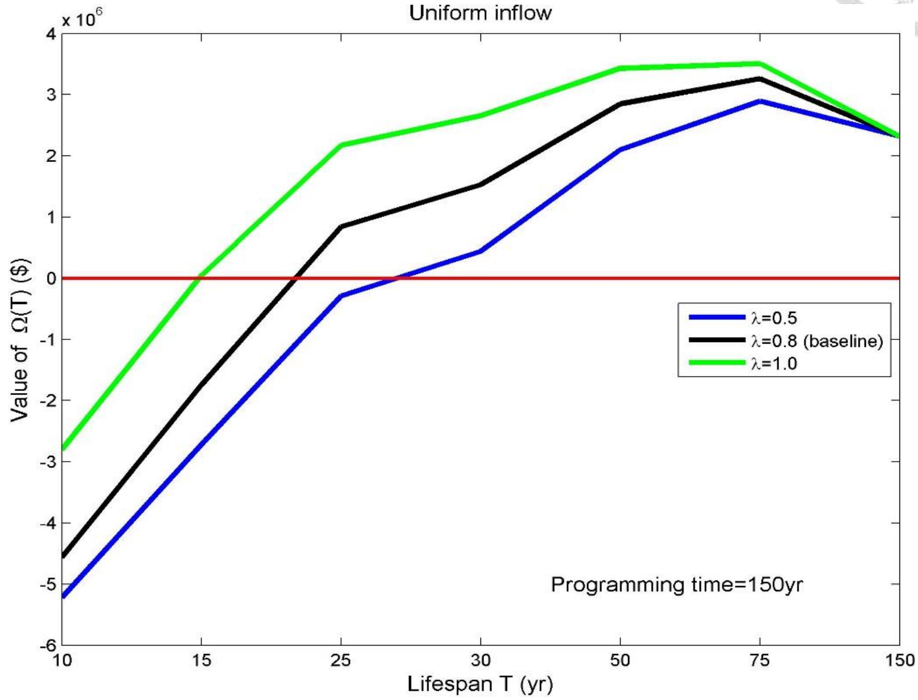

Figure 4.8. Performances of the objective function with different social preference rates of λ (From a short-term perspective)

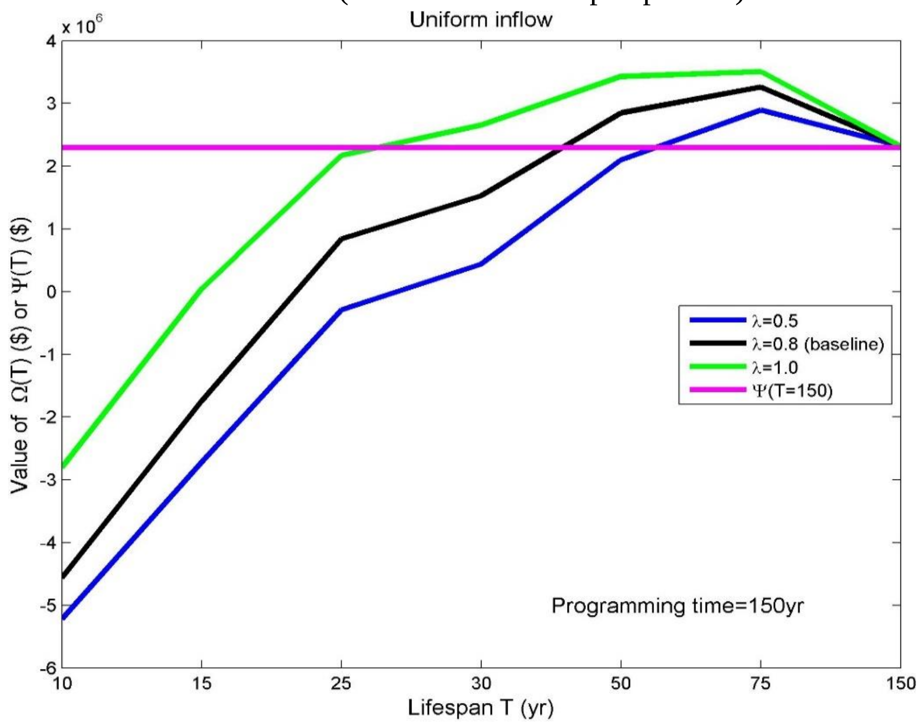

Figure 4.9. Comparing reservoir management strategy of this study with traditional practice

In Figure 4.9, magenta line is regarded as a standard, which symbolizes a prevailing engineering strategy of sediment management, is continually but only implementing sediment removal in 150 years. It seems that some lifespans could make reservoir management performs better than prevailing practice. Based on these evidences, we can boldly confirmed that the strategy of renewable reservoir may be feasible with respect to specified lifespans. There are some case study of sensitivity analysis as below.

Discount rate of γ is used for future price being discounted to present. According to the objective function of the Equation (3.15), while

$$q_T = (1+\gamma_1)^{-T'} > q_T = (1+\gamma_2)^{-T'} \qquad \text{as} \quad \gamma_1 < \gamma_2$$

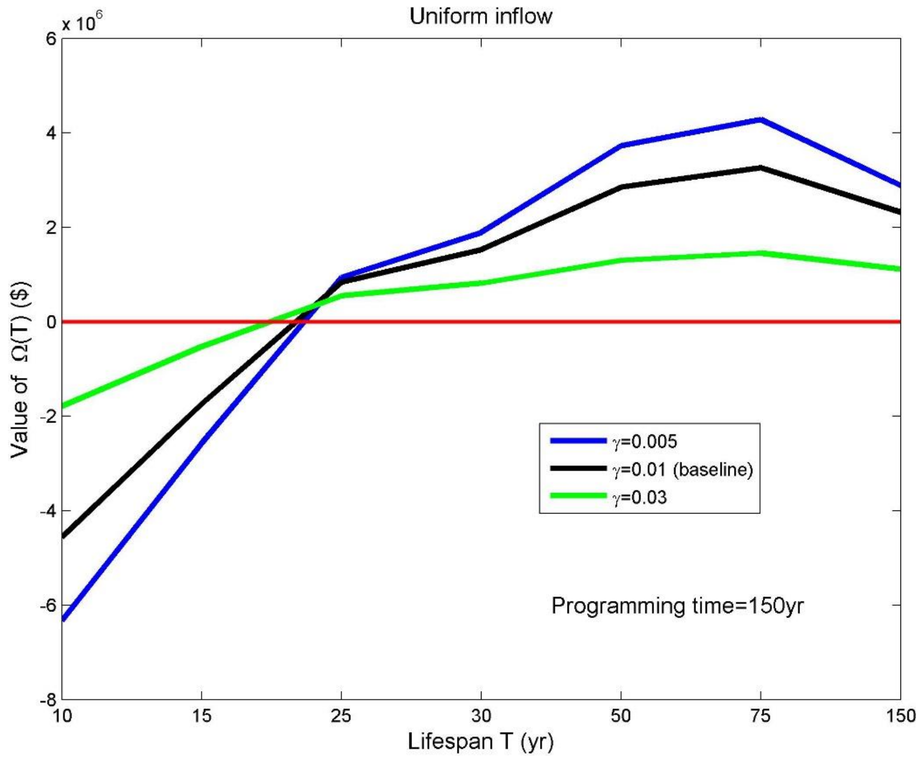

Figure 4.10. Sensitivity analysis of discount rate of γ (L=150 yr)

A lower discount rate would relatively advance absolute value of the objective function but not changed the position of curve maximum. Therefore, result curves seem to be reduced and rotated of zero point in contrast to baseline (see Figure 4.10). On the other hand, results of a higher discount rate reveal different message in contrast to results of lower discount rate. In the chapter 3, we had defined a cost of dam deconstruction and a cost of dam reconstruction as a pay of reservoir rehabilitation and a key for starting a new life of reservoir. We attempted to enhance or decrease cost in order to overview its influences on model. In Figure 4.11 we found that high cost (ten times of baseline) considerably cut down value of the objective function. It seems that if cost of dam removal is very substantial, reservoir management strategy of this study is not recommended.

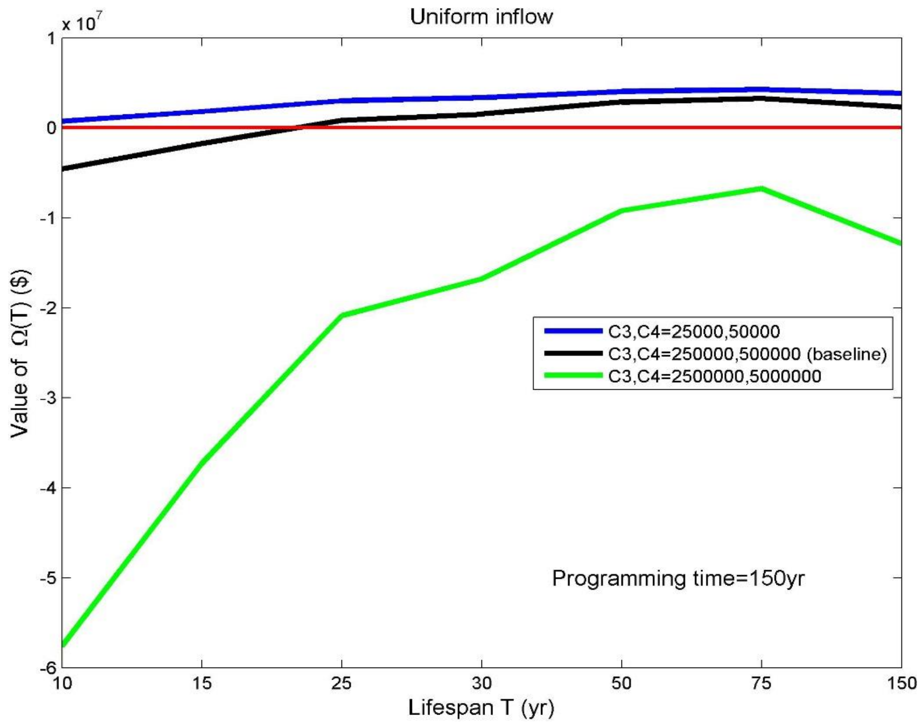

Figure 4.11. Sensitivity analysis of dam construction cost (L=150 yr)

Moreover, difference between baseline results and low cost results is not as remarkable as difference between baseline results and high cost results in Figure 4.11. We could explained this finding by the Equation (3.16) and the Equation (3.17) that:

$\Psi(T) = W(T) - \hat{C}(T)$ and $W(T) = W_A(T) = W_B(T)$

$\Psi(T) < \Psi_A(T)$ as $\hat{C}(T) > \hat{C}_A(T)$

$\Psi(T) > \Psi_B(T)$ as $\hat{C}(T) < \hat{C}_B(T)$

However,

$\Delta\Psi_A = \Psi(T) - \Psi_A(T) = 0.9\hat{C}(T)$ as $\hat{C}_A(T) / \hat{C}(T) = 0.1$

$\Delta\Psi_B = \Psi_B(T) - \Psi(T) = 9\hat{C}(T)$ as $\hat{C}_B(T) / \hat{C}(T) = 10$

As a result, $\Delta\Psi_B > \Delta\Psi_A$ (4.4)

4.2.2 Reservoir management from a long-term perspective

Assumed the length of decision time horizon is twice longer than longest lifespan in Figure 4.1 ($L = 300\ yr$). Inputted uniform inflow and determined lifespans for capacity rehabilitation. Regarding five years dam reconstruction period, lifespans were defined as ten years, twenty years, thirty years, fifty years, sixty years, seventy-five years, hundred years and one hundred and fifty years. Each lifespan is a factor of decision time horizon.

Figure 4.12 shows numerical results of different social preference rates of λ from a long-term perspective. As can be seen, a low lambda value results in a low value of the objective function. However, the optimal lifespan changes along with lambda value. We found that lifespan of each λ is 75 years, 100 years and 150 years respectively.

In the previous chapter, we knew that times of dam reconstruction is positively related to length of decision time horizon. In other word, the effect of social preference rate (λ) is more significant for the objective function of Ψ_i when cycle number (i) is getting high. In order to balance this effect, model tended to accumulate benefit from the objective function of Ψ_i in a longer lifespan in contrast to results in Figure 4.8. As a result, we boldly concluded that as length of decision time horizon(L) gets longer, optimal lifespan would tend to be longer under the condition of $0 \leq \lambda < 1$. We would prove this statement again in the chapter 4.3.

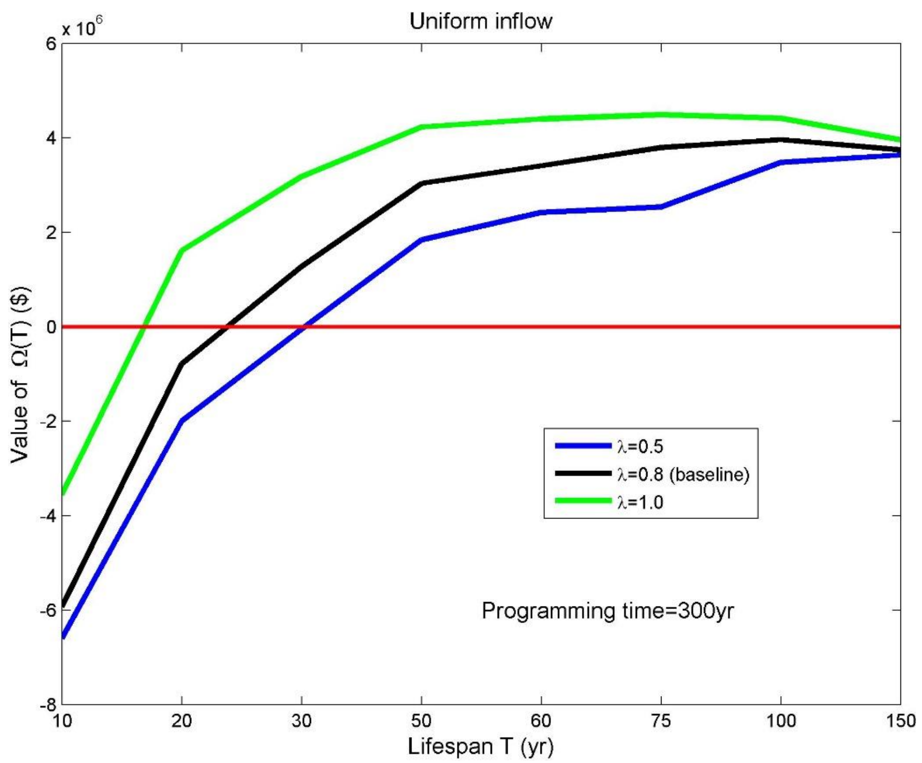

Figure 4.12. Performances of the objective function with different social preference rates of λ (From a long-term perspective)

Figure 4.13 displays results of sensitivity analysis of discount rate of γ from a long-term perspective. We found that features of this graph are very consistent with results of short-term perspective that ends of these curves would be relatively pulled up or pulled down because of the effect of gamma value. This discount rate also makes curve of results be clockwise or counterclockwise rotated in contrast to baseline.

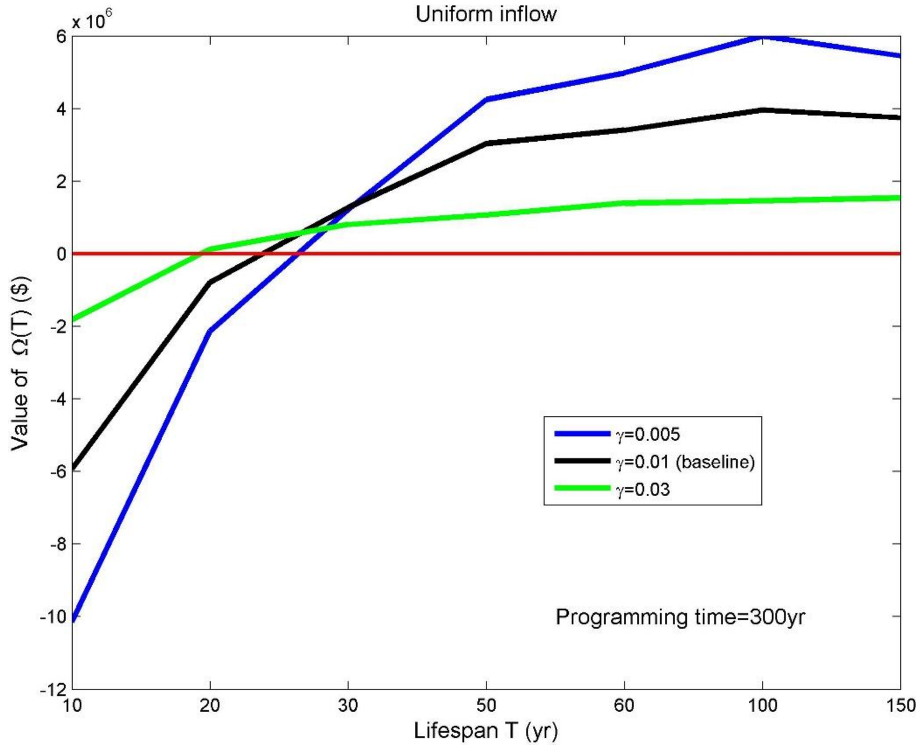

Figure 4.13. Sensitivity analysis of discounted rate of γ (L=300 yr)

Likewise, sensitivity analysis of dam construction cost from a long-term perspective in Figure 4.14 reveals that cost of dam construction directly influences the feasibility of reservoir management regarding dam removal issue. Despite dam removal seems to provide an attractive strategy for sediment management, unflavored cost of dam construction really discourage policy-makers to practice this method. By the way, the reservoir's life of this case is shorter than decision time horizon, so we did not present a comparison between reservoir management policies.

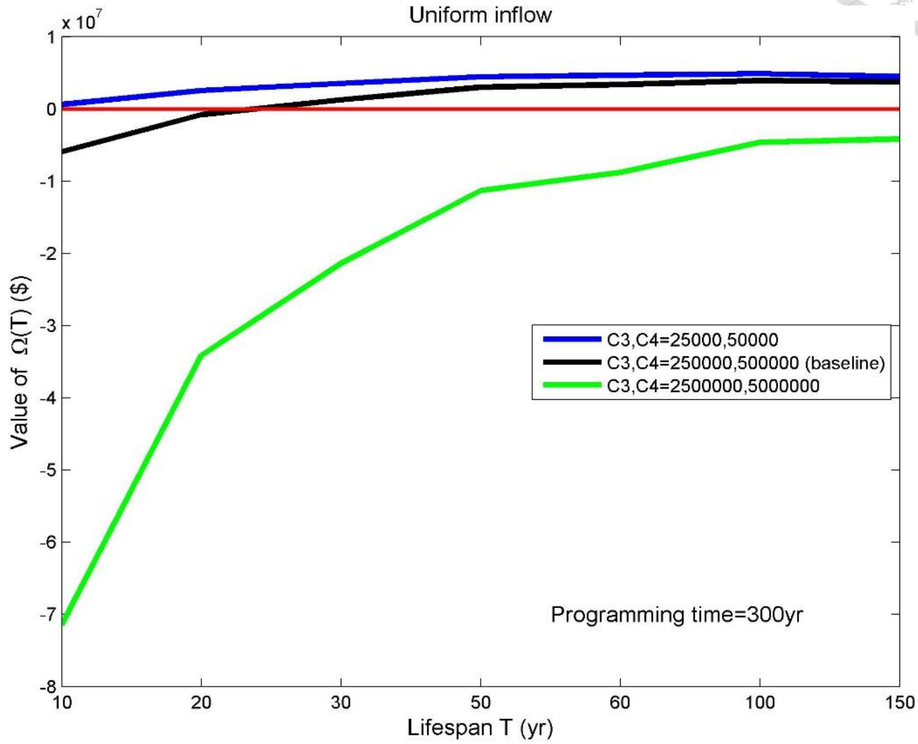

Figure 4.14. Sensitivity analysis of dam construction cost (L=300 yr)

4.2.3 Time paths of sediment removal

Time paths of sediment management regarding dam removal reveal that not only sediment removed would decrease over time but also sum of sediment removed in each cycle reduce along with increasing cycle number. This finding is discussed as below.

Annotations of the Equation (3.16) shows that

$$W_i > W_{i+1} \qquad \text{as} \quad 0 \le \lambda < 1$$

Net benefit of reservoir at each moment could be expressed as

$$NB(t) = B(K_t) - C_1(X_t) - C_{OMC}(t)$$

Due to the social preference rate of λ, we may get

$$NB_i(t) > NB_{i+1}(t) \qquad \text{as} \quad NB_{i+1}(t) = \lambda \cdot NB_i(t) \tag{4.5}$$

However,

$$NB_{i+1}(t) < NB'_{i+1}(t) \qquad \text{as} \quad X_t > X'_t \tag{4.6}$$

As a result, model tended to allocate less amount of sediment removal or even optionally implement annual removing program in next cycle. Figure 4.15 illustrates the image of decision making on sediment removal. As can be seen, value of point C is higher than pint D attributed to value of λ. Benefit of $NB_{i+1}(t)$ increases when point D shifts to point D'; therefore, sum of sediment removed would be reduced cycle after cycle. Another evident is that result of remaining capacity at the end of lifespan in each cycle is getting small as i increases, which supports our explanation above.

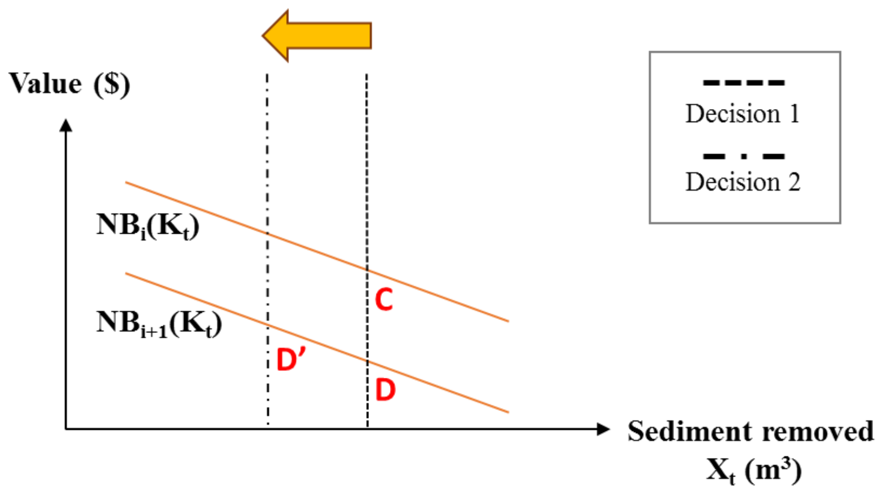

Figure 4.15. Marginal effect of sum of sediment removal

4.2.4 The effect of decision time horizon on model

Factors of 150 are not the same as factors of 300, so we chose common divisors of 150 and 300 to show comparison between numerical results of different lengths of decision time horizon. According to the consequences in Figure 4.1, $\Psi(T)$ would keep positive before coming the end of reservoir's life; therefore, length of decision time horizon simply enhance accumulation effect of the function of $\Omega_n(T)$ in Figure 4.16 ($\Omega_n(T)$ increases along with L). However, $\Psi_i(T)$ could be negative in other case before the end of reservoir's life. Extending decision time horizon might bring negative effect on model results. This kind of extreme condition may happen since sedimentation is very tremendous.

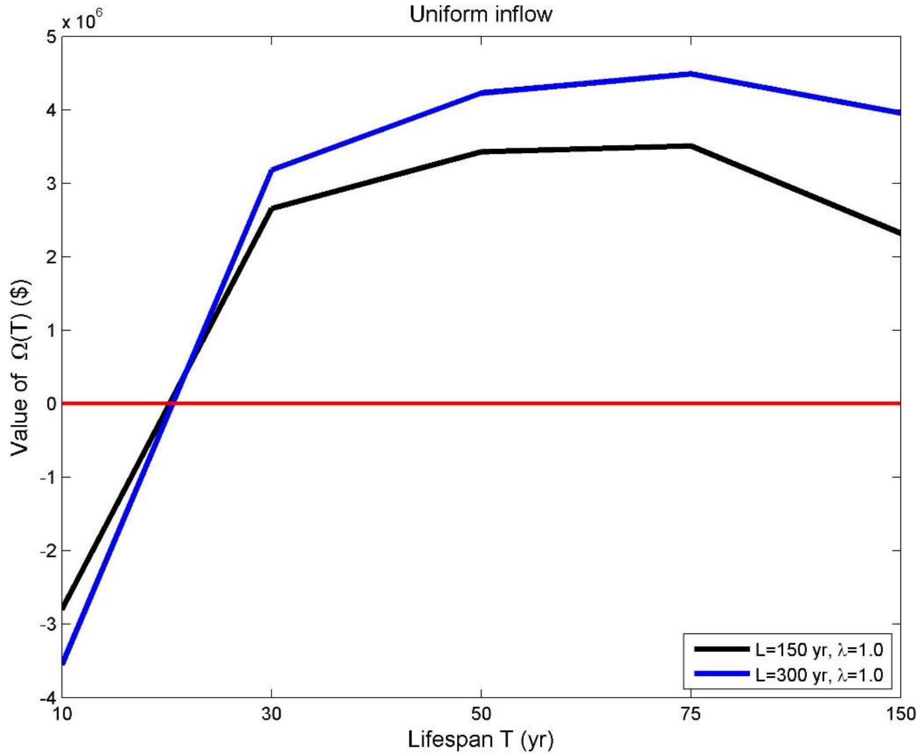

Figure 4.16. The effect of decision time horizon on model

4.3 Comparing analytical solutions with numerical solutions

An optimal lifespan for reservoir renewal could be determined by numerical scheme or analytical scheme. In the chapter 3, we had derived the objective functions of the Equation (3.15) come from a simplified idea. Since $q_T = \frac{\Psi_i}{\Psi_{i+1}} = \frac{\Psi_{i+1}}{\Psi_{i+2}} = ... = \frac{\Psi_{n-1}}{\Psi_n}$ holds, we analyzed the Equation (3.11) as a geometric progression. Obviously, it seems that only uniform inflow satisfies this condition while reservoir capacity is regular rehabilitated by fixed lifespan. Using a geometric progression rule, we determined the Equation (3.19.1) and the Equation (3.19.2) and attempted to differentiate these two functions by lifespan, thereby identifying the optimal solutions of the objective functions.

We found that the Equation (3.24) is dependent of lifespan instead of length of decision time horizon because the term of $(1-q_T{}^n)$ would be eliminated. The term of $q_T{}^n$ represents the effect of L that:

$$q_T{}^n = (1+\gamma)^{-T'\times\frac{L}{T'}} = (1+\gamma)^{-L} \qquad \text{as} \quad n = \frac{L}{T'} \tag{4.7}$$

On the other hand, the term of $q_T{}^n$ was kept in the Equation (3.28); therefore, solutions of the Equation (3.28) would be influenced by length of decision time horizon.

Evaluating the function of $\frac{\partial\Omega(T)}{\partial T}$, we supposed that there was a solution (lifespan) satisfying $\frac{\partial\Omega(T)}{\partial T} = 0$ from lifespan of one year to 150 years. Analytical solutions are displayed in Table 4.2. In this table, optimal lifespans of analytical solutions appear to be prolonged along with decreasing value of λ or increasing L. Under the condition of

$\lambda < 1$, the optimal lifespan would be correspondingly extended to increase value of $\Psi_i(T)$ because a lower λ value results in more discount for reservoir benefit and a length of decision time horizon would also intensify the effect of λ^{i-1}. However, while λ is equal to one, solutions (lifespans) are independent of length of decision time horizon due to elimination of $q_T{}^n$. Besides, analytical solutions are likely sensitive to L only when lambda value is sufficiently low.

As can be seen, results of analytical method seems be underestimated in contrast to numerical results. It is because evaluating process of analytical solutions are not affected by decreasing marginal effect. Moreover, optimal lifespans of $\lambda = 1$ seem to be correlated with the terms of $\Psi_1(T)$ and $\frac{\partial W_1(T)}{\partial T}$ in the Equation (3.24). We found that Figure 4.2 can illustrate the effect of these term. The lifespan with respect to maximum in the Figure 4.2 which is among 20 years and 40 years, is very close to analytical solutions of $\lambda = 1$.

On the other hand, optimization of numerical model is calculated considering whole domain instead of single cycle. Marginal effect on numerical model would also influence decision-making of optimizing. These possibilities might leads to a difference between analytical solution and numerical solution.

Table 4.2. Solutions of optimal lifespan

Analytical solution				**Numerical solution**			
L\ λ	**λ=1.0**	**λ=0.8**	**λ=0.5**	**L\ λ**	**λ=1.0**	**λ=0.8**	**λ=0.5**
L=150	**24~25 yr**	**45~46 yr**	**94~95 yr**	**L=150**	**75 yr**	**75 yr**	**75 yr**
L=300	**24~25 yr**	**48~49 yr**	**108~109 yr**	**L=300**	**75 yr**	**100 yr**	**150 yr**
L=600	**24~25 yr**	**49~50 yr**	**114~115 yr**	**L=600**	**60 yr**	**150 yr**	**150 yr**

Chapter 5 Conclusion

In brief, this study attempted to apply dam removal as a means to increase the efficiency of sediment removal for solving problems of severe sediment accumulation in reservoir. By this way, capacity rehabilitation along with dam reconstruction could achieve the sustainability of reservoir management. We expected our study is able to improve present engineering practices from an economic viewpoint. Based on results, we summarized important features of this study and proposed recommendations for future.

5.1 Summary

Based on results, variation of sediment removal program results from its decreasing marginal utility, which is mainly incurred by lifespan of reservoir, times of dam reconstruction and trade-off between sedimentation and removal capability. In Figure 4.9, it shows that this study could propose a more economical strategy of sustainable reservoir management by dam removal and capacity rehabilitation with respect to specified lifespans in contrast to present engineering practice. However, if cost of dam retrofitting is sufficiently high, management policy of reservoir renewal is neither feasible nor recommended.

In the previous chapter, we used Lee's study to estimate a terminal time for reservoir retirement by performance of reservoir management regardless of dam removal. However, the optimal lifespan of renewable reservoir policy is different from Lee's study. Analyzing the numerical solutions and analytical solutions, we found that optimal lifespan is influenced by social preference rate (λ) and length of decision time horizon (L). Optimal lifespan is longer since λ is lower or L is longer. Nevertheless, if a reservoir is planned to be operated for a long time while value of λ is very low, there may be no optimal solution of numerical model before coming the end of reservoir's life. Except solutions of $\lambda = 1$, it appears that applying a geometric progression to derive analytical solutions of optimal lifespan could likely respond to numerical model.

5.2 Limitations and recommendations

In fact, water inflow is time-varied. Using a fixed lifespan to simulate sediment management seems not appropriate. Lifespan of every cycle should be different lengths. In contrast to the Equation (3.13), although it might take a lot of time on computer calculating, the Equation (3.10) is much more reasonable to formulate sustainable reservoir management under the condition of varied inflow. Besides, feasibility of this model is not related to dam size. Also, our economic model does not discuss risk of dam removal and alternatives for water conservation during dam reconstruction. Under different considerations, this study could be revised differently to correspond policy-maker's expectation.

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