Reservoir Conservation

Volume I

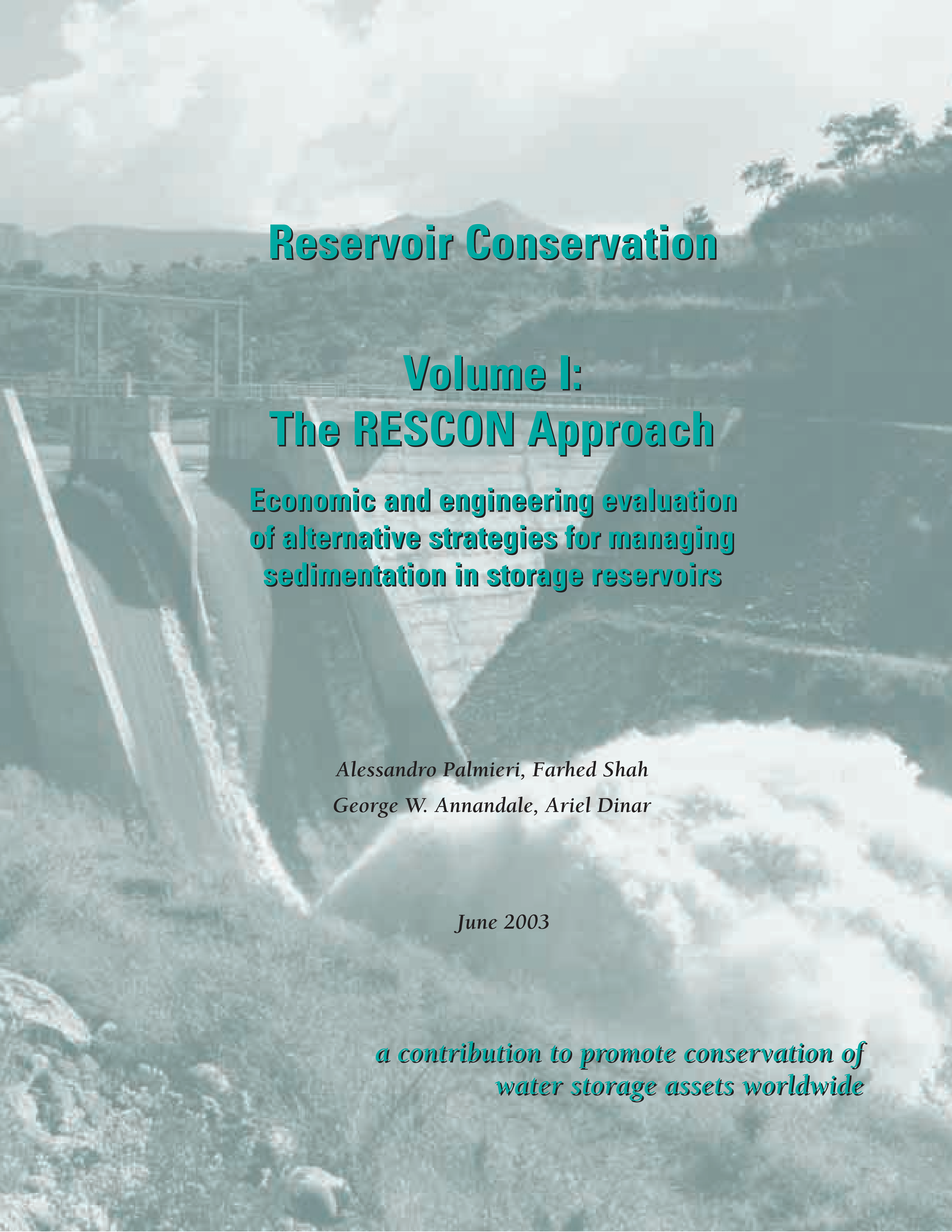
The RESCON Approach

economic and engineering evaluation of alternative strategies for managing sedimentation in storage reservoirs

Alessandro Palmieri · Farhed Shah
George W. Annandale · Ariel Dinar

June 2003

A CONTRIBUTION TO PROMOTE CONSERVATION OF WATER STORAGE ASSETS WORLDWIDE



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Cover photo by Alessandro Palmieri: *Little Beles Dam in Ethiopia's lowlands at the onset of the flood season, when erosion from the highlands in the background brings great amounts of sediments.*

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FOREWORD

Among the many sessions of the Third World Water Forum, held in Kyoto, Japan in March 2003, there was one titled “Sedimentation Management Challenges for Reservoir Sustainability”. Two main messages emerged from that session:

- Whereas the last century was concerned with reservoir development, the 21st century will need to focus on sediment management; the objective will be to convert today’s inventory of non-sustainable reservoirs into sustainable infrastructures for future generations.
- The scientific community at large should work to create solutions for conserving existing water storage facilities in order to enable their functions to be delivered for as long as possible, possibly in perpetuity.

These important messages are very much in line with the World Bank’s Water Resources Sector Strategy, which calls the institution to address management of existing infrastructure, as well as to develop much needed new priority investments for water infrastructure.

Many poor countries with climate conditions similar to those of richer ones have as little as *1/100th* as much water infrastructure capacity. This means that they are extremely vulnerable to the vicissitudes of climate variability, a vulnerability that is exacerbated by climate change. There is much that can and must be done through better management of watersheds and of water demand.

This book can help to make the reservoirs we already have sustainable and contribute to sustainable design of new surface storage facilities. It addresses the issue of reservoir sustainability from an economic angle, a perspective that has received only limited attention to date.

We hope that this initial step will encourage others to follow, both with additional research and with actions aimed at conserving water storage assets for future generations.

Ian Johnson
Vice President, Sustainable Development
World Bank

RATIONALE AND SUMMARY

Introduction

The current estimate of total reservoir storage worldwide is around 7,000 km^3 (ICOLD, 1998). This storage is used for water supply, irrigation, power generation and flood control. Concern about loss of reservoir capacity due to sedimentation was raised by Mahmood (1987) and has recently been expressed in many forums and publications. It is estimated that more than 0.5 percent of the total reservoir storage volume in the world is lost annually as a result of sedimentation (White, 2001). This translates into the need to add some 45 km^3 of storage per year worldwide. Costs would be on the order of US$13 billion per year and the associated environmental and social impacts significant. The introduction of sediment management measures in some older dams, where appropriate, and in the design of new ones could help to reduce this need for additional storage.

In December 1999 the World Bank initiated the RESCON (REServoir CONservation) research project to develop an approach to the assessment and promotion of sustainable management of reservoirs, with special emphasis on the economic evaluation of sediment management and the promotion of sustainable development. This book outlines the results of the project.

Sediment management alternatives

There are a number of well researched, practiced and well documented alternatives for managing reservoir sedimentation. This book outlines the principal methods and provides references for further information. Each reservoir site has its own constraints and not all alternatives will be suitable. This book provides some guidance as to the applicability of the various alternatives.

Sustainable development economics

Literature on sediment management in reservoirs has focused mostly on engineering aspects (Morris and Fan, 1998). A review undertaken for the project revealed that there is little, if any, published information on the economics of reservoir sedimentation and its implication for sustainable development. A framework is needed to assess the economic feasibility of sediment management strategies that would allow the life of dams to be prolonged indefinitely. Such a framework should be able to answer two related but distinct questions:

- Is the extra cost incurred in undertaking sediment management activities worthwhile in terms of extending the productive life of a dam?
- Is it economical to extend the life of a dam indefinitely?

Common engineering practice uses a “design life” approach in dam and reservoir design, which assumes that over the course of its life, a water resource project would recover investment costs through the benefits generated by the project. This approach does not take into account what happens to the project at the end of its design life and it is assumed that problems with reservoir sedimentation and eventual retirement will be addressed by future generations. The “life cycle management” approach advocated by this book instead aims at designing and managing water resource infrastructure for sustainable use. This requires the incorporation and use of sediment management facilities. For existing dams built along the concepts of the design life approach, it is recommended that the potential for converting them into sustainable projects be investigated.

Where a sustainable project cannot be achieved and the dam and reservoir will eventually need partial or total retirement, appropriate planning is needed for dealing with the resulting problem. This could be achieved by establishing a retirement fund with annual contributions made during the life of the dam to pay for any actions required at its retirement. These actions can comprise substantial plant modification (e.g., protecting the intakes and converting to a run-of-river scheme), change of purpose (e.g., recreation, farming, environment creation) and in extreme cases dam retirement using partial or complete removal of the dam. Such a fund would best be established at the start of the project and will require periodic reviews and adjustments to ensure its adequacy.

Environmental and social safeguards

In too many cases in the past, insufficient attention has been paid to the environmental and social impacts of large dam projects. This is no longer tolerable. Environmental and social issues must be accorded a status equal to, if not higher than, economic expediency. Potential environmental and social impacts and where possible potential opportunities for enhancement need to be identified early on in the project life cycle (at pre-feasibility stage) so that they can be investigated thoroughly and dealt with appropriately during project development. This book advocates the use of the "safeguards" approach to identify in broad terms the environmental and social impacts of a project so that they can be studied further in the next phase of the project evaluation procedure and mitigation actions determined.

The RESCON model

A computer model of the RESCON approach was developed as a demonstration tool. The key algorithm of the model is an economic optimization function, supported by engineering relationships that allow the quantification of basic parameters. The model helps to evaluate at the pre-feasibility-level the technical and economic feasibility of implementing the life cycle management approach. The results from the economic optimization routine identify the preferred sediment management technique for sustainable use of the water resource infrastructure. Where sustainable use cannot be achieved, the model computes the annuities required for the retirement fund.

The model is intended for use by experienced practitioners of reservoir sedimentation management. It is released as a "beta version" for further testing and improving in the field and as such it is acknowledged that it may contain errors. Users are advised to employ caution and sound engineering judgment when interpreting the results. Nonetheless, in the hands of an experienced practitioner the model should provide guidance at pre-feasibility-levels of project appraisal.

1. INTRODUCTION & OBJECTIVES

Background and Motivation

The current estimate of total reservoir storage worldwide is around 7,000 km^3. This storage is used for water supply, irrigation, power generation and flood control. Concerns about the loss of reservoir capacity due to sedimentation were raised in a World Bank publication in 1987 (Mahmood, 1987) and recently expressed in many forums and publications. Table 1.1 shows the worldwide distribution of storage, power generation and sedimentation rates.

It is estimated that between 0.5 and 1.0 percent of global water storage volume is lost annually as a result of sedimentation (White, 2001). Using an intermediate rate, this loss in storage is approximately 45 km^3 per year. If it is further assumed that the average reservoir volume is 150 million m^3, then 300 large dams should be built annually just to maintain current total worldwide storage. Nearly US$13 billion per year would be needed to replace this storage, even without taking into account the environmental and social costs associated with new dams. However, if most existing and still to be constructed reservoirs are managed in a sustainable manner, the number of new dams required to maintain reliable water and power supply could be decreased.

The "creeping" problem of sedimentation has several implications. First, the lost storage capacity has an opportunity cost in the form of replacement costs for construction of new storage if the present level of supply is to be maintained. Second, there are direct losses in the form of less hydropower production capacity available for sale, less irrigated land to produce food and reduced flood routing capacity. Third, the filled reservoirs, with no benefits to pay for their maintenance, will continue to be a liability to their owners and could become a hazard. Finally, the fully silted reservoirs will create a decommissioning problem that has both direct and indirect costs.

Dam retirement or decommissioning is emerging gradually in developed countries as a new chal-

TABLE 1.1
WORLDWIDE STORAGE, POWER AND SEDIMENTATION

Region	Number of large dams	Storage (km^3)	Total Power (GW)	Hydropower production in 1995 (TWh/yr)	Annual loss due to sedimentation (% of residual storage)
World wide	**45,571**	**6,325**	**675**	**2,643**	**0.5–1**
Europe	5,497	1,083	170	552	0.17–0.2
North America	7,205	1,845	140	658	0.2
South and Central America	1,498	1,039	120	575	0.1
North Africa	280	188	4.5	14	0.08–1.5
Sub Saharan Africa	966	575	16	48	0.23
Middle East	895	224	14.5	57	1.5
Asia (excluding China)	7,230	861	145	534	0.3–1.0
China	22,000	510	65	205	2.3

Source: Adapted from White 2001.

lenge for the engineering community. To date, only small dams have been decommissioned.[1] Decommissioning of large dams is both full of technical uncertainties and highly contentious on social grounds.

In December 1999 the World Bank initiated a research project to develop an approach to assessment and promotion of sustainable management of reservoirs. The specific objectives included development of guidelines for evaluating alternative sediment management options from an engineering perspective as well as a mathematical model to help policy makers rank the technically feasible sediment management strategies in economic terms. The project was named RESCON (RESservoir CONServation) and its outcomes are described here.

RESCON Contribution to Policy Making

National level policy makers have a long list of priorities. Management of existing reservoirs, including sediment management, very rarely rises close to the top of the list. Two actions are required to change this attitude: (i) awareness raising and (ii) development of a decision making tool that can be used at the policy level. The RESCON approach outlined in this book aims to assist policy makers in making these decisions within the framework of promoting sustainable development and intergenerational equity.

The RESCON Model

In order to assist policy makers in their decision making process, an Excel based model has been developed as part of this work. The model is described in detail in Volume II of this book. In summary, the model evaluates alternative sediment management options for a given (new or existing) dam and reports on the economically optimum option. For non-sustainable options the program calculates annual contributions to a retirement fund and takes this into consideration in the analysis.

Book Structure

The book is in a two volume format, of which this is Volume I. Following the Introduction, Chapter 2 outlines the RESCON philosophy, which represents a significant departure from the conventional design life approach towards dams. The chapter presents the key ideas underlying this approach. Chapter 3 goes on to describe the various alternatives for managing sedimentation in reservoirs and Chapter 4 covers the difficult to quantify environmental and social consequences that may be associated with these management alternatives. Chapter 5 discusses the RESCON approach and mathematical model that underlies the associated computer program and Chapter 6 provides the results of applications of the RESCON computer program to data from a set of representative dams. Sensitivity analysis is also performed on key physical and economic parameters to test the robustness of the results. The purpose of this chapter is to demonstrate the use as well as indicate possible limitations of the program.

Chapter 7 reports on results of using the RESCON approach to reservoir sedimentation management in three trial countries. Chapter 8 provides conclusions from the study and recommendations for further work. A series of annexes to the book provide further background information.

Volume II describes the computer model in detail and includes a CD-Rom with the model in Excel format.

[1] A list of 35 cases published by American Rivers et al. (1999) and relative to the US show dam height values from 1 to 26 m, with an average of less than 6 m.

2. RESERVOIR LIFE CYCLE MANAGEMENT

Introduction

The concept of intergenerational equity requires that natural resources be developed and used in a way that accounts for the interests of all members of society, including future generations. The philosophy behind intergenerational equity is that a subsequent generation should not pay (under any terms, whether they be economic, social, health or environmental costs) for the legacies of previous generations. With regard to infrastructure projects this means that future generations should not be burdened with the decommissioning of assets built to benefit their predecessors.

Application of this philosophy to dams requires a modification of the conventional "design life" approach. The design life approach assumes a finite project life and gives superficial attention (if any) to what will happen to the dam at the end of its life. This results in substantial environmental, social, economic and safety considerations being left to subsequent generations.

An alternative approach is that of "life cycle management." The ultimate goal of this approach is sustainable use, where the major functions of the dam are maintained, through good management and maintenance, in perpetuity. Where this is not achievable, decommissioning within a finite period is allowed, provided that this is funded by the establishment of an accumulating retirement fund. With this mechanism in place, all generations benefiting from the services of the dam contribute to the cost of decommissioning and intergenerational equity is maintained.

The main features of the design life and the life cycle management approaches are illustrated in Figures 2.1 and 2.2, respectively. The figures consist of three areas, depicting external environmental and societal concerns and impacts on the left and right and the project focus in the center of the diagram. The links between these areas are shown using dashed arrows, thick for dynamic relations and thin for static single links. A single static link represents an event that occurs only once and not continuously throughout the life of a project as is the case for dynamic links. The impacts generated by the facility, in the lower external boxes, can generate concerns, shown in the upper external boxes.

Design Life Approach

The design life approach (Figure 2.1) is essentially viewed as a linear process of finite duration. Once it has been decided how long the design life would be, say 50, 75 or 100 years, the project is planned, designed, constructed, operated and maintained for that period of time. Input of societal and environmental concerns is limited to the initial project conception stage (denoted by the thin dashed arrow) and the process occurs once, regardless of changes over the course of the project design life. Conventionally the economic evaluation of such projects does not account for the cost of decommissioning. Such costs are borne by future generations. This has been the practice on most, if not all, projects that have been conceived using the design life approach.

Residual concerns, such as infrastructure fatigue and reservoir sedimentation, are depicted as external effects in Figure 2.1. Solutions to the associated problems can include rehabilitation, sediment removal and in the extreme case, decommissioning. Solutions of this type, however, constitute an entirely new project that can, in principle, be designed within a life cycle framework.

The issues of infrastructure fatigue, environmental change, social needs and perspectives and regulatory policies can vary considerably over the design life of the project. However, there is no mechanism for introducing these concerns into a design life management approach, where such decisions are formalized during the project's initial planning stage. This is demonstrated in Figure 2.1 by the thin dashed line indicating a static input of societal concerns at the initiation of a design life type project.

Life Cycle Management Approach

The life cycle management approach is illustrated in Figure 2.2. The process contains the same elements as the design life approach but arranged in a circular fashion, indicating perpetual use of the infrastructure. Consequently, the opportunity exists to incorporate changing environmental and societal concerns, often associated with direct impacts of the facility. Operations and maintenance are conducted in a way that will encourage sustainable use and continuously evaluated for this purpose. When the system ages, components are replaced and refurbished as is usual in conventional systems. Reservoir sedimentation management, however, is an additional element (not shown in the figure) of an operations and maintenance program associated with the life cycle management approach. If suitably implemented, reservoir sedimentation management preserves reservoir capacity and allows perpetual use of the facility. Figure 2.2 emphasizes that the eventual decommissioning of the facility, should it be necessary, is included within the project management objectives.

The adaptation of an existing, or expired, design life project to a life cycle management approach is possible. However, there are likely to be significant economic hurdles to overcome. The general idea is that the rehabilitation, operation, or decommissioning of an existing facility will become the focus of a project, which can be managed through the use of the life cycle method in a sustainable manner. The benefits of such a project may, however, be either indirect in nature, or found in the avoidance of a negative impact associated with the prior operation of the facility.

To overcome any original design limitations, existing water resource infrastructure should be refurbished to allow reservoir sedimentation management and continued profitable operation. If this is not possible and the dam reaches the end of its life and requires decommissioning, the facility could be replaced with another dam and reservoir designed according to the life cycle management approach, allowing sustainable and perpetual use. If perpetual use is not possible, a retirement fund should be established.

FIGURE 2.1
DESIGN LIFE APPROACH

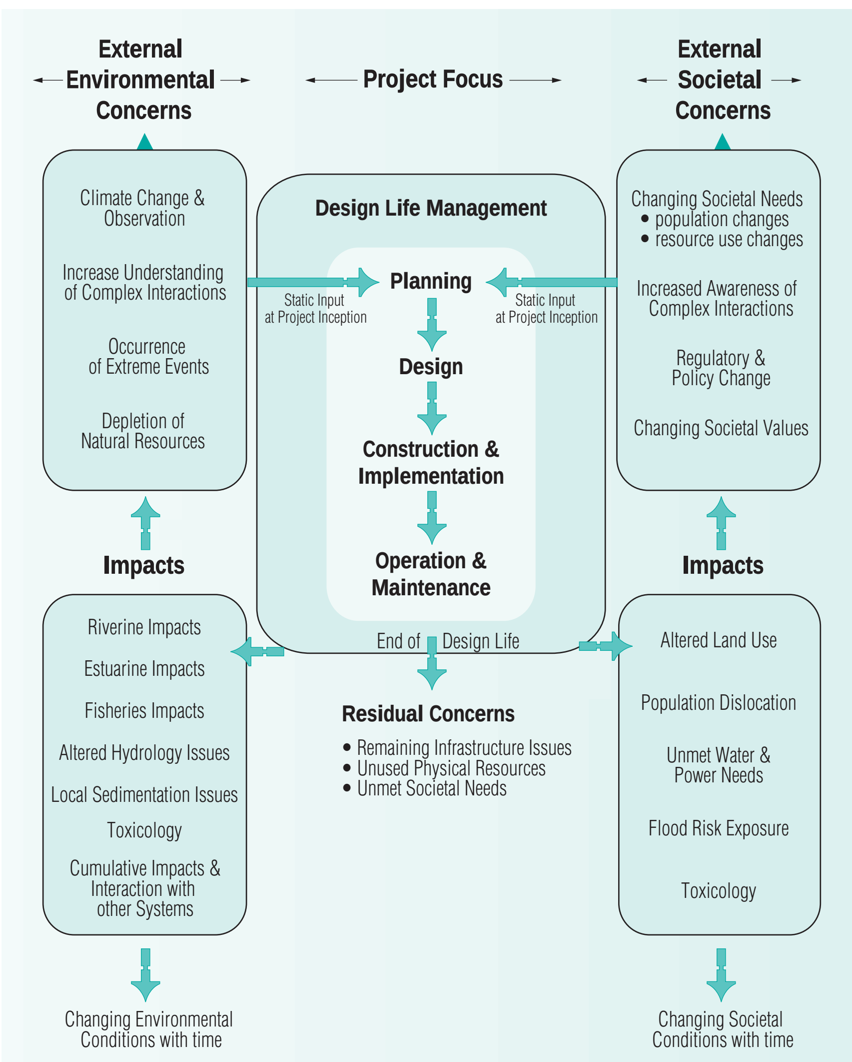
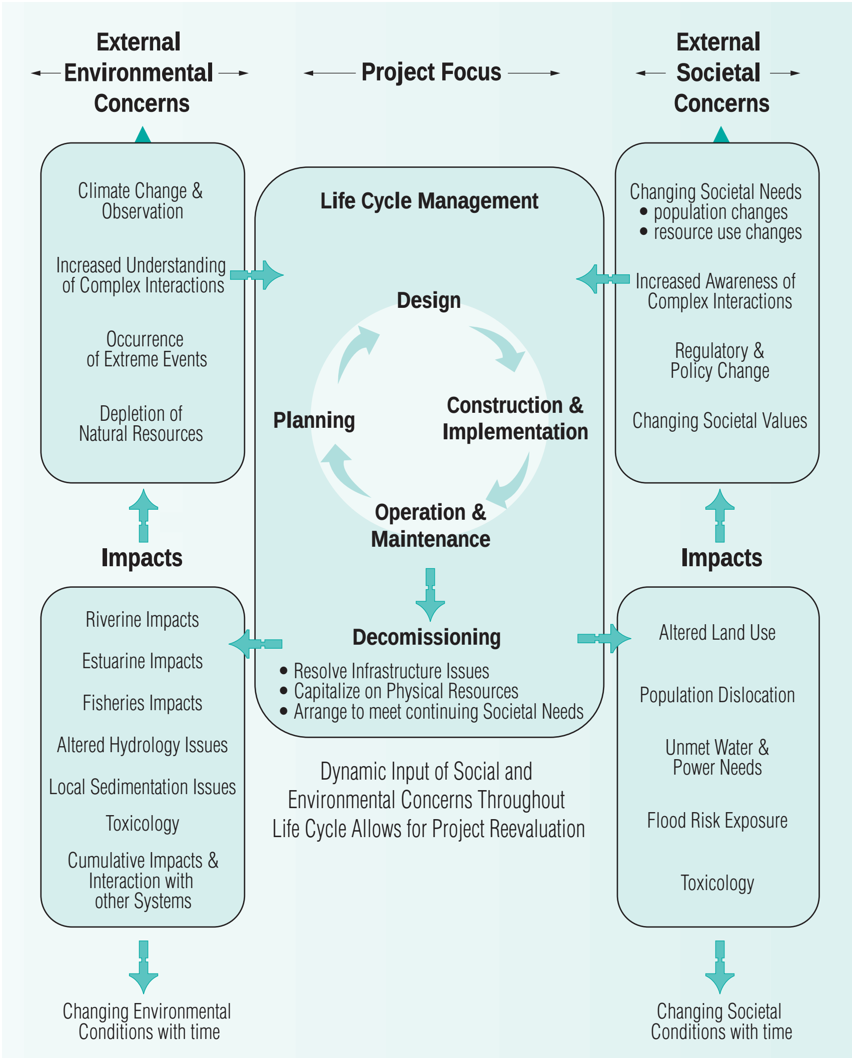


FIGURE 2.2
LIFE CYCLE MANAGEMENT APPROACH



Comparison of the Two Approaches

Several of the differences between the two approaches are quite obvious. The design life approach follows a linear time line and assumes that the project would have served its purpose at the end of its design life. Projects previously designed following this approach did not allow for decommissioning at the end of the project life and as such ignored intergenerational equity: current generations pay for the decommissioning of facilities of which earlier generations enjoyed the benefits.

In contrast, the concept of life cycle management takes intergenerational equity into account by designing, constructing, operating and maintaining the infrastructure in a way that will encourage perpetual and sustainable use. An important design element is the incorporation of reservoir sedimentation management features. If operated and maintained correctly, such facilities can be used in perpetuity, fully allowing for intergenerational equity. Current and future generations can enjoy the benefits of the facility, while spreading the cost of ownership, operations and maintenance over many generations.

The two approaches have different abilities to accommodate external concerns. External concerns are those that are considered outside of the project's purpose, but can greatly impact the approval, function and success of large infrastructure projects. In general, these external issues can be grouped into environmental and social issues, as depicted in Figures 2.1 and 2.2. While the design life approach can introduce such issues at the outset, no capability is available to incorporate any changes over the course of the project's design life. The life cycle approach implicitly allows for variation on these issues, as it is understood that project reevaluation is an eventual and intended goal for the continuing success of the project.

Another critical difference between the design life and life cycle management approaches is found in the economic evaluation of the project. When using the design life approach, economic evaluation is conducted over a finite life and the cost of decommissioning is not taken into account. Economic evaluation of a non-sustainable project following the life cycle management approach would take into account the cost of decommissioning by means of a retirement fund. This fund would receive contributions from those benefiting from the dam and would be used to decommission, thus promoting intergenerational equity. Where a project can be designed to be either sustainable or non-sustainable the economic analysis using the principles of life cycle management should tip the balance in favor of the sustainable solution.

3. RESERVOIR SEDIMENTATION MANAGEMENT

Introduction

The importance of reservoir sedimentation management is evident when one considers that the cost of replacing storage lost annually due to sediment deposition throughout the world is in the order of US$13 billion. If sedimentation can be managed successfully, as it has been in some reservoirs, the loss in reservoir storage space due to this phenomenon can be lowered significantly. The benefit of effective reservoir sedimentation management is therefore clear.

This chapter outlines the state of current knowledge in reservoir sedimentation management. Further information can be found in other publications such as Morris and Fan, 1997; Basson and Rooseboom, 1997; and White, 2001.

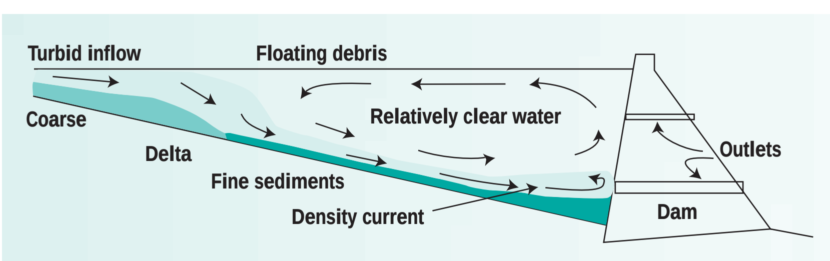
The Sedimentation Process

As sediment enters a reservoir it deposits as the flow velocity reduces. The coarser portion of the sediment load deposits in a delta at the upstream end of the reservoir and the finer portion deposits in reaches closer to the dam (Figure 3.1). The sediment profile can be described by: the topset, the foreset and the bottom set. The topset is the gently inclining portion of the delta at the upstream end of the reservoir. The foreset is the steep slope at the front of the delta. The bottom set is the flat portion in front of the delta. The intersection of the topset and foreset is termed the pivot point. As more sediment enters the reservoir, the bottom set gradually increases in thickness and the foreset moves forwards.

In some instances sediments can flow into a reservoir as a density current. This phenomenon can occur when the sediment concentration in the inflowing river is much higher than the water in the impoundment and/or there is a significant temperature difference between the incoming flow and the impounded water. Under such circumstances the density current may flow under the impounded water in the reservoir toward the dam. If the density current is not allowed to flow through the dam by means of low-level gates, a technique known as density current venting, it will curl up at the dam and its return-flow will mix with the clearer water in the reservoir. The sediment thus mixed into the clearer water will deposit with time.

Most dams have been designed with a dead storage capacity below which there are no outlets and therefore the water in this zone cannot be used. Many designers incorrectly assumed that sediments would naturally deposit in this dead storage. As described above, this is not the case and a good proportion of the sediments deposited are found in the upper reaches of the reservoir, thus reducing the live storage volume.

FIGURE 3.1
THE SEDIMENTATION PROCESS



Sedimentation has a number of consequences:

- Depletion of storage (reducing yield and flood attenuation capability)
- Abrasion of outlet structures (e.g., spillways) and mechanical equipment (e.g., turbines)

- Blockage of outlets causing interruption of benefits (e.g., irrigation releases or electricity generation) and reducing the ability of the dam to pass floods safely (e.g., by blocking emergency outlet gates)
- Increased loads on the dam.

This book concentrates on the reduction of storage caused by sedimentation. However, the other consequences listed above should also be taken into account when assessing reservoir sedimentation management alternatives.

Available Sediment Management Alternatives

It is possible to successfully manage reservoir sedimentation by using one or more of a host of well publicized techniques. The techniques can be categorized as follows:

- Reducing sediment inflows
  - watershed management
  - upstream check structures
  - reservoir bypass
  - off-channel storage
- Managing sediments within the reservoir
  - operating rules
  - tactical dredging
- Evacuation of sediments from the reservoir
  - flushing
  - sluicing
  - density current venting
  - mechanical removal (dredging, dry excavation, hydrosuction)
- Replacing lost storage
  - increased dam height
  - construction of new dam
- Decommissioning

The techniques are outlined in the following sections.

Reducing sediment inflows

Watershed Management
Soil erosion is a significant problem in many areas of the world with rates in excess of 1000 t/km^2/year not uncommon. Soil erosion reduces land fertility and in extreme cases can result in large areas becoming barren. Soil erosion is caused by many factors including: soil type, surface gradient, temperature fluctuations, rainfall and wind. Natural erosion rates can often be accelerated dramatically by human activity such as poor land management techniques, poor detailing of infrastructure and deforestation. In North America alone the economic damages associated with soil erosion are estimated to be in excess of US$16 billion per year (Osterkamp et al, 1998). It is therefore not surprising that a great deal of effort is expended globally to control and reduce soil erosion rates through watershed management techniques. Commonly practiced techniques include bunding, terracing (e.g., Figure 3.2), contour plowing and afforestation.

Where properly undertaken, watershed management has been effective in reducing soil erosion and therefore it is seen as an effective way of reducing reservoir sedimentation rates also. Unfortunately research and literature (e.g., Mahmood, 1987) on the subject do not support this belief in most cases.

Research (Hufschmidt, 1986) has shown that intensive conservation efforts spanning several decades may be needed to reduce sediment yields by 10–20 percent for catchments that exceed 1 000 km^2. Furthermore, in very large catchments conservation measures are often, from a reservoir sedimentation

FIGURE 3.2
EXAMPLE OF GOOD WATERSHED MANAGEMENT (INDUS CATCHMENT, PAKISTAN)

management point of view, considered to be ineffective because of the large time lag between implementation of erosion control measures and realization of their effect in reducing sediment discharge in rivers. The reason for this is that the sediment delivery ratio[2] of large catchments is low,[3] which means that large volumes of eroded material are stored at various locations in the watershed. See Figure 3.3. Eroded material does not immediately enter streams and rivers, but instead is washed into the streams and rivers over many successive storm events. Therefore, the effect of erosion protection measures is not immediately reflected by a similar change in sediment yield.

In some catchments, however, where sediment delivery ratios approach unity (e.g., where the eroded material is very fine and is quickly transported into the river systems) watershed management can be effective in reducing river sediment yields in relatively short time spans. This has been demonstrated in the Loess Plateau Watershed Rehabilitation Project in China (Voegele, 1997).

From a management point of view it is important to quantify the effectiveness of alternative watershed management measures in order to identify the economically optimal technique. Furthermore, the cost effectiveness of watershed management measures needs to be compared with that of other measures to reduce reservoir sedimentation rates. This is a complex subject requiring specialized studies.

The current state of knowledge on sediment transport in rivers and in catchment processes and on how the two sets of variables relate is not adequate to allow prediction of the impact of optional catchment management techniques on sediment discharge in rivers. It is recommended that managers rely on experts in the field of sediment transport and catchment management, who have appropriate expertise and experience in judging the potential impact of a variety of catchment management approaches. No simple solution exists and assessment of the potential effect of optional catchment management approaches requires detailed study of the catchments under consideration and assessment and analysis of available data and local knowledge.

Good catchment management has a large number of benefits, including benefits to agriculture, the environment, food production, forestry and water availability. The concomitant reduction in sediment yield from catchment that could result from good catchment management is an added advantage that should be included with the rest of the benefits.

Further information is provided in Annex C.

FIGURE 3.3
EXAMPLE OF CATCHMENT SEDIMENT YIELD (INDUS CATCHMENT, PAKISTAN)

Upstream check structures

Debris dams are used on mountainous streams where coarse-grained sediments occur. They are usually located on one or more tributaries upstream of a reservoir and sediments should be periodically removed. Ease of access to remove sediment from the debris dams and the potential to re-use sediments make the application of debris dams potentially feasible. In the absence of these conditions, the life of a debris dam is likely to be short and its effectiveness limited.

Care needs to be exercised in the design and construction of debris dams. In particular consideration needs to be

[2] *Sediment delivery ratio is t*he ratio between catchment erosion rates and river sediment transport rates.

[3] The sediment delivery ratio of catchments greater than 100 km^2 may be as low as 10 percent.

given to how flood flows will be handled. Often debris dams are small and are designed to be overtopped by floods. Attention must also be paid to the design of the embankment and the downstream energy dissipation measures to prevent failure due to erosion. Such failure will not only result in the release of the trapped sediments, thereby negating the benefits of the structure, but may also pose a hazard.

Reservoir bypass

The purpose of a bypass is to divert sediment laden flood flows around a reservoir. By-passing a reservoir by making use of conveyance structures is often only feasible when favorable hydrological and morphological conditions exist. Operating costs of the conveyance structures due to the high erosion rates of the sediments, as well as the benefits lost by not capturing the flood flows, must be taken into account.

An example of a successful bypass project is shown in Figure 3.4. Nagle Dam in South Africa is located in a high sediment yield catchment. Sediment deposition in the reservoir has been kept to a minimum throughout its life by use of a bypass. The dam has been designed to impound water in a long river meander. At the upstream end of the meander and reservoir, a set of floodgates has been installed that are closed when large floods occur. By closing the gates the flood is diverted past the reservoir, carrying large volumes of sediment that would otherwise have deposited in the reservoir with it. The project has been in operation for several decades with very little sediment deposition.

Off-channel storage

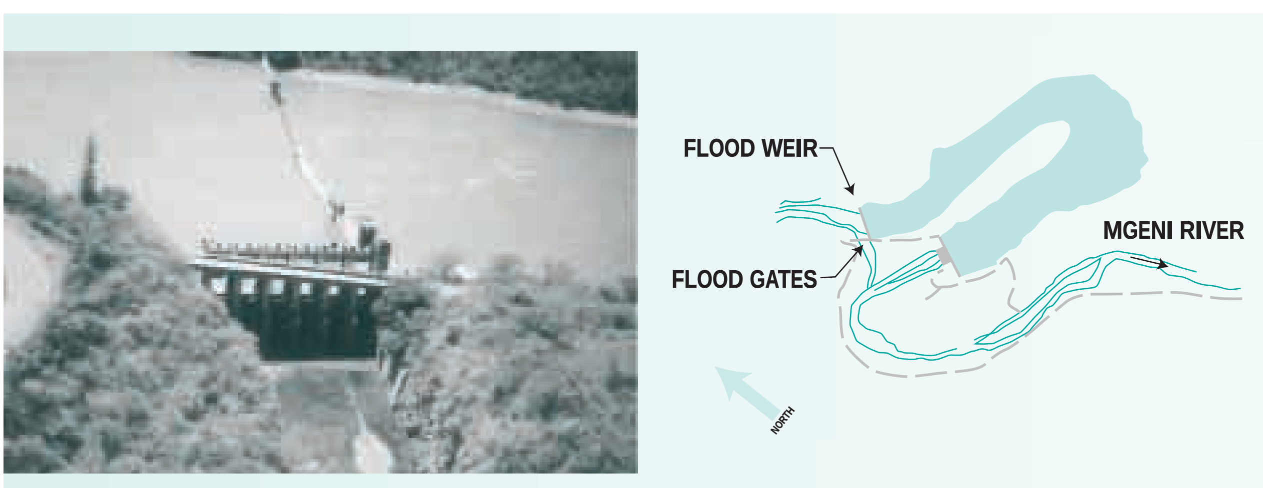
Off-channel storage reservoirs are built adjacent to the main river channel (e.g., a small tributary or on the flood plain). Water from the main river is diverted into the reservoir during times of low sediment concentrations. Although this option is not available for the management of sediments in existing reservoirs, it should be considered for new projects.

Managing Sediments within the Reservoir

The behavior of sediments within the reservoir is sensitive to reservoir water levels. If the reservoir level is kept high during the flood season, incoming sediments will tend to deposit in the upper reaches of the reservoir as the incoming flows decelerate upon entering the still water. This holds the sediments back from the dam and importantly the dam outlets. But it also means that sedimentation occurs in the live storage, leading to a loss in yield due to both the reduction in live storage and the resulting inability to draw down the reservoir to its full extent. Conversely, if the reservoir level is drawn down in advance of the flood season, the incoming flows will erode the previously deposited delta and move the sediments towards the dam. While this will increase

FIGURE 3.4

NAGLE DAM BYPASS, SOUTH AFRICA (FROM BASSON AND ROOSEBOOM, 1997)

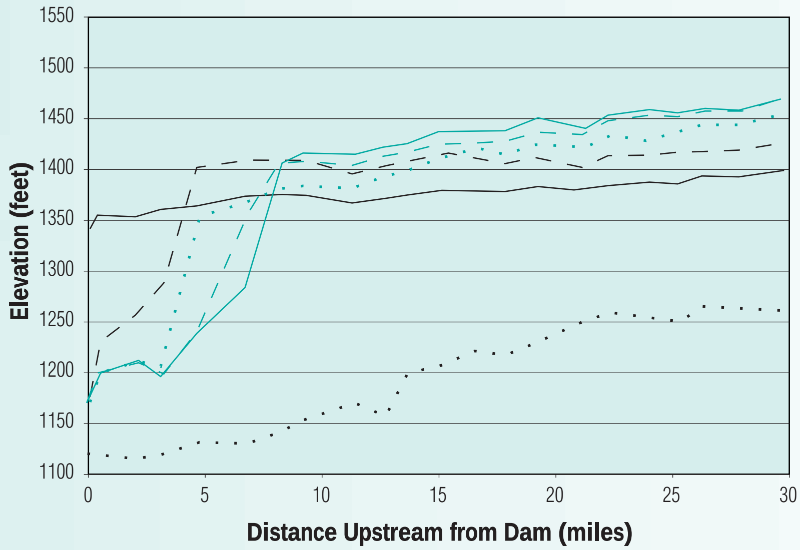


the deposition of sediments in the dead storage zone of the reservoir, thus allowing for greater yield from the live storage, it may pose a hazard to the dam outlets.

From the above, it can be seen that the selection of reservoir operating rules can control how sediment deposition occurs. Mathematical models exist to predict this. In a study undertaken for Tarbela Dam, Pakistan (WAPDA, 1998) it was shown that by modifying the operating rules of the reservoir, the accumulating sediments could be held at a safe distance away from the power house intakes. This would protect the intakes from the ingress of sediments and hence preserve the power generating capabilities of the project for a further ten years at no capital cost. Figure 3.5 shows the results of the mathematical modeling.

FIGURE 3.5

TARBELA DAM PREDICTED DELTA PROFILES AFTER 10 YEARS OF OPERATION UNDER DIFFERENT OPERATING RULES.



Source: WAPDA, 1998. "Tarbela Dam Sedimentation Management Study, Final Report."

As a reservoir fills with sediments there is a danger that the outlets from the reservoir will become blocked. This is a particular problem if the reservoir is used for hydropower production. It is however often possible to protect the dam outlets from becoming blocked with sediments using a number of techniques. These include: tactical dredging in the vicinity of the outlets and the construction of physical barriers to keep the outlets clear.

Tactical dredging is the term given to localized dredging. It is used to keep outlets clear of sediments and can be an effective means of prolonging the useful life of a reservoir which is filling up with sediments. The method is currently being used at Koka dam in Ethiopia. The dredged quantities are very small compared to the annual sediment build-up rate in the reservoir. However, the dredging has unblocked the low-level outlet and will keep the outlets to the powerhouse clear. See Figure 3.6.

FIGURE 3.6

KOKA DAM – TACTICAL DREDGING NEAR DAM OUTLETS

Evacuation of Sediments from the Reservoir

Flushing

Flushing is a technique whereby the flow velocities in a reservoir are increased to such an extent that deposited sediments are re-mobilized and transported through low-level outlets in the dam. This differs from sluicing, which is intended to move sediment coming into the reservoir from upstream through the reservoir. Flushing is implemented to remobilize sediment that has already deposited.

Two approaches to flushing exist: complete draw-down flushing and partial draw-down flushing. Complete draw-down flushing occurs when the reservoir is emptied during the flood season, resulting in the creation of river-like flow conditions in the reservoir. Partial draw-down flushing occurs when the reservoir level is drawn down only partially. In this case the sediment transport capacity in the reservoir increases, but usually only enough to allow sediment within the reservoir to be re-located, i.e., sediment is moved from upstream locations in the reservoir basin to locations further downstream and closer to the dam.

Low-level outlets for flushing operations should be close to the original river bed level and of sufficient hydraulic capacity to achieve full draw-down. The intent with flushing operations is to re-create river-like flow conditions in the reservoir. By doing so, the sediment that has deposited is re-mobilized and transported through the low-level gates to the river reach downstream from the dam. This operation is usually performed during the flood season. The low-level gates are closed towards the end of the flood season to capture clearer water for use during the dry season.

Flushing with partial draw-down may be used to move sediments from the upper reaches of a reservoir to zones closer to the dam. If this is done, studies should be completed beforehand to ensure that intake structures and other ancillary facilities are not impacted. Flushing with partial draw-down may be used to clear more live storage space and locate the sediment in a more favorable position for future complete draw-down flushing.

Further information on flushing is included in Annex D.

Sluicing

Sluicing is an operational technique by which a substantial portion of the incoming sediment load is passed through the reservoir and dam before the sediment particles can settle, thereby reducing the trap efficiency of the reservoir. This is accomplished in most cases by operating the reservoir at a lower level during the flood season in order to maintain sufficient sediment transport capacity (turbulent and colloidal) through the reservoir. Higher flow velocities and higher sediment transport capacities in the water flowing through the reservoir result from operating the reservoir at these lower levels. The increased sediment transport capacity of the water flowing through the reservoir reduces the volume of sediment that is deposited. After the flood season, the pool level in the reservoir is raised to store relatively clear water.

Effectiveness of sluicing operations depends mainly on the availability of excess runoff, on the grain size of the sediments and on reservoir morphology. In many cases sluicing and flushing are used in combination.

Density current venting

As noted earlier, density currents may develop under exceptional conditions, causing more sediment to be transported towards the dam than the relationships for turbulent suspension indicate. Such currents occur because the density of the sediment carrying water flowing into the reservoir is greater than the density of clear water impounded in a reservoir. The increased density, increased viscosity and concomitant reduction in turbulence intensity result in a coherent current with a high sediment concentration that dives underneath the clear water and moves towards the dam.

If it is known that density currents occur in a particular reservoir, installation and operation of low-level gates in the dam will make it possible to pass the sediment current through the dam for discharge downstream. By passing the density current through the low-level gates sediment that would have deposited in the reservoir is released downstream, thus reducing the possibility of storage loss. Density current venting is an attractive way of releasing sediment laden flows because, unlike flushing operations, it does not require the lowering of the reservoir level.

Mechanical removal

Mechanical removal of deposited sediment from reservoirs takes place using conventional dredging techniques, dry excavation and the hydrosuction removal system (HSRS).

Dredging

The process of excavating deposited sediments from under water is termed dredging. Dredging is a highly specialized activity which is mostly used for clearing navigation channels in ports, rivers and estuaries. However, the technology is often used in reservoirs also. See Table 3.1 for examples.

Sediment dredging is commonly used to reclaim storage lost to sediment deposits. However, conventional hydraulic dredging is often much more expensive than the cost of storage replacement and it is generally not economically viable to remove all sediment from reservoirs by means of dredging alone. With large contracts the cost of dredging can approach the cost of building a new dam.

Disposal of dredged material can constitute an environmental problem and suitable mitigating measures, which can occasionally be quite expensive, have to be found on a case by case basis. If discharged directly downstream from the dam, the high sediment concentrations generally associated with dredging can be unacceptable from an environmental point of view. However, it may be possible to reduce the sediment concentration of the water flowing in the river by releasing clean water from the reservoir concurrently with the release of dredged material. If the material is not deposited downstream of the dam, then large expanses of land fill may be required.

Although dredged material can be a liability, it can be seen as an asset also (USACE, 1985). Uses of dredged sediments include:

- ❖ Habitat development
- ❖ Agriculture and forestry—to improve marginal soils
- ❖ Construction—e.g., brick making.

Dry excavation

Dry excavation (also known as trucking) requires the lowering of the reservoir during the dry season when the reduced river flows can be adequately controlled without interference with the excavation works. The sediment is excavated and transported for disposal using traditional earth moving equipment. Excavation and disposal costs are high, and as such this technique is generally used for relatively small impoundments. Reservoirs used for flood control may be more amenable to sediment management by trucking, such as has been performed at Cogswell Dam and Reservoir in California. The sediment from this reservoir has been excavated with conventional earth moving equipment and has been used as engineered landfill in the hills adjacent to the reservoir.

Hydrosuction removal system (HSRS)

This is a variation of traditional dredging. The difference is that the hydraulic head available at the dam is used as the energy for dredging instead of

TABLE 3.1

EXAMPLES OF RESERVOIR DREDGING[1]

Country	Dam	Required dredging rate to meet inflow rate (t/yr)	Achieved dredging rate (t/yr)
Algeria	Cheurfas	No Data	3,500,000
	Sig	No Data	467,000
	Fergang	No Data	2,100,000
	Hamiz	No Data	840,000
China	Xuanwei	280,000	220,000
	Shuichaozi	1,900,000	2,120,000
	Tianjiawan	350,000	320,000
Japan	Akiba	560,000	490,000
	Sakula	4,260,000	420,000
	Miwa	950,000	320,000
Sudan	Roseires	Tactical dredging undertaken to keep outlets clear	
Switzerland	Lausanne	No Data	200,000
	Palagnedra	No Data	168,000
United States	Lake Herman	No Data	22,330
	White Tail Creek	No Data	51,100

[1] Taken from Basson & Rooseboom, 1999

pumps powered by electricity or diesel. As such, where there is sufficient head available, the operating costs are substantially lower than those of traditional dredging. Roveri (1984) promotes application of the hydrosuction removal system (HSRS) that uses the hydrostatic head at the dam to provide energy for sediment removal. The system consists of a barge that controls the flow in the suction and discharge pipe and can be used to move the suction end of the pipe around. The upstream end of the pipe is located at the sediment level in the reservoir and its downstream end is usually draped over the dam to discharge sediment and water to the downstream river. The arrangement of the pipe layout essentially creates a siphon and the suction at the upstream end of the siphon is used to evacuate sediment. The system can be used in relatively short reservoirs, not longer than approximately 3 km and also depends on the elevation of the dam and reservoir.

Replacing lost storage

Lost storage can be replaced by the construction of a new dam (upstream, downstream or on another river), or the raising of the existing dam. These options require careful engineering considerations that are beyond the scope of this book. .

Decommissioning

Reservoirs can generally be expected to experience serious operational constraints by the time half of their original capacity is lost. When dam decommissioning becomes a potential alternative, because of advanced reservoir sedimentation, it is very often a sign of overdue decision on sedimentation management

Dam decommissioning should be regarded as the last possible option. Although several dams have been decommissioned in developed countries, most of these have been small in size. There are no reported cases of the decommissioning of a dam higher than 40m. The decommissioning of large dams is problematic and needs careful consideration. The situation is exacerbated if the reservoir behind the dam is full of sediments (see Chapter 4). Guidance for the decommissioning of dams is given by the ASCE.[4]

There are other options available apart from decommissioning silted reservoirs. These include:

- In many situations it may be technically and economically feasible to continue to operate hydropower plants as run-of-river stations, albeit with increased operational and maintenance costs.
- Maintaining the dam (perhaps at a lower level) and using the now silted reservoir for: ecology enhancement, e.g., creation of wetland habitats; for farming; or recreation.

Each site will have specific opportunities for beneficial use. It is recommended that these be explored before opting for decommissioning.

Application of RESCON

The preceding sections have provided a summary of methods that can be used to manage sediment in reservoirs. These management techniques include a wide range of activities, from attempts to control the source of the problem, i.e., sediment delivery, to managing sediment flow and deposition in the reservoir, to removing deposited sediment. Should these management approaches prove ineffective, the reservoir volume can be increased by raising the dam; finally, the dam and reservoir can be decommissioned if the sedimentation problem becomes so acute that it renders them useless.

The RESCON software developed during the course of this project can be used to assess the technical and economic feasibility of applying these techniques. The software focuses on removal of deposited sediment and is capable of assessing the techniques of flushing, dry excavation (trucking), dredging, HSRS and decommissioning. Routing techniques, such as bypassing and pass-through strategies, are not represented in the software, nor is watershed management.

Recommendations on watershed management are presented in Annex C.

[4] American Society of Civil Engineers, 1997, Guidelines for the retirement of dams and hydroelectric facilities.

4. ENVIRONMENTAL AND SOCIAL SAFEGUARDS

Consequences of implementing sediment management on the downstream environment

Dams have serious environmental and social impacts which require mitigation actions. Some of the more important aspects are outlined in Annex E. Dam decommissioning and the implementation of sediment management techniques outlined in Chapter 3 also have impacts that need to be taken into consideration. This book does not purport to detail these, but merely to draw the reader's attention to some of the key aspects.

Dam decommissioning and many of the sediment management techniques that involve the release of reservoir sediments downstream need to be appraised within the framework of environmental and social impacts. Downstream impacts may include:

- Geomorphological changes to the downstream river channel
- Increases in turbidity
- Changes in flooding frequency and patterns
- Reduction of dissolved oxygen in the river
- Poisoning of the ecosystem especially where toxic sediments are released.

All of the above will have an impact on the natural environment as well as on human activity.

Sediment management can both mediate and exacerbate some of the negative effects caused by dams. Some sediment management alternatives involve moving sediments downstream. This can be environmentally positive or negative depending on the strategy used. In the San Gabriel River in southern California, United States, both facets were observed. In an upstream area studies on flow assisted sediment transport to remove sediment from behind Cogswell Dam suggested that using flow assisted sediment transport that depended on a more natural hydrograph could have beneficial effects on the native fish fauna, while sediment removal by trucking would maintain the status quo, with a temporary reduction in ecosystem services due to the escape of fine sediments into the stream reach below the dam during the cleanout operation. For Morris Dam, further downstream in the San Gabriel River system, sediments had been managed by sluicing. As a result of the sluicing (and dam management procedures governing water release) the downstream riverine habitats have been destroyed and no longer support the native aquatic fauna. It should be noted in this case that the cost of the environmental mitigation required as a condition of permitting sluicing was lower, at least in the short term, than alternative sediment management options.

A study undertaken by Zhou and Donnelly (2002) cites numerous occasions where insufficient consideration of the ecological effects of dam removal have resulted in serious impacts downstream. Impacts depend on whether sediments are suspended in the river flow or are deposited in the river bed. Released sediments may fill pools and interrupt mussel reproduction, as well as kill adult fish, mussels, and other aquatic wildlife by clogging gills and causing suffocation. Some species may be very sensitive to even small increases in turbidity. Kundell and Rasmussen, 1995 noted that occasional substantial increases in river turbidity (e.g., caused by the release of sediments from a dam) may eliminate up to 75 percent of some fish species.

Damages to the downstream ecosystem may also have wider ranging consequences on human activities. An example would be the loss of artisan fisheries in a developing country. This would not only deprive a society of its livelihood but may also destroy a way of life. Such indirect consequences need to be considered when appraising alternatives.

Where substantial changes to the water and sediment releases from a dam are being considered (such as would occur with flushing or sluicing) particular care needs to be exercised. Large increases in flows and sediment concentrations in addition to damaging the ecosystem may result in large scale geomorphological changes to the river regime. Such changes may include changes to meander patterns, scouring or infilling of river beds, deposition of sediments at manmade intakes, undermining of flood defense works and blockage of bridges or culverts. Such effects in addition to having far ranging social and economic impacts may have safety implications also. If sediment removal measures are employed from the start of a project, the impacts are likely to be less than if measures are introduced late in the project's life. If no removal is practiced and the dam is ultimately decommissioned, impacts may be severe. An example of this was observed when the Fort Edwards dam was removed in New York. The process released over 400 000 m^3 of sediment and resulted in partial blockage of the east channel of the Hudson River as well as increased risk of flooding of the town of Fort Edward. See Zhou and Donnelly, 2002.

Any method of sediment management that results in the return to a more natural hydrograph or incorporates an environmental flow requirement will probably yield positive environmental results or at least a mix of positive and negative impacts. Use of release flows for environmental reasons or sediment management may result in a short-term reduction in financial returns from the project, but will likely lead to increased sustainability and a re-distribution of the benefits of the dam.

Large reservoirs sited closely upstream of estuaries and deltas have in some cases caused widespread environmental, social and economic impacts by reducing the flow of sediments. The release of sediments from such a reservoir due to the implementation of sediment management may have positive impacts on the estuary or delta downstream.

Creative sediment management options such as watershed management directed to the upper reaches of the watershed may have direct environmental benefits. Recent studies on headwater streams throughout North America indicate that these streams exert control over nutrient exports to rivers, lakes and estuaries. Thus, restoration and preservation of small stream ecosystems could not only reduce sediment loads delivered to reservoirs, but would improve the quality of water delivered to downstream areas. This could have the additional benefit of reducing eutrophication.

The degree to which sediment management can yield positive environmental impacts is largely a function of its ability to mitigate some of the negative effects of the storage project. Combining sediment management with environmental flows to restore downstream ecosystem services will yield the greatest positive result. Environmental flows can enhance fisheries, support flood recession agriculture, stabilize riparian vegetation, maintain biodiversity, etc. Other approaches such as restoring or preserving portions of the watershed to reduce sediment yield can also have positive environmental effects.

A Safeguard Approach

In previous decades, relatively little importance was attached to the environmental and social impacts of development projects. Today much greater emphasis is placed on such considerations. Not surprisingly, sediment management plans for reservoirs are now expected to include environmental and social impact analyses.

A complete impact analysis is rarely justifiable at the pre-feasibility level due to lack of appropriate information. The intention of the RESCON approach, on the other hand, is to identify, already at pre-feasibility level, the reservoir sedimentation management techniques that will maximize economic benefits without conflicting with technical feasibility requirements and environmental/social acceptability. When conducting investigations at pre-feasibility level, it is usually necessary to employ approximate evaluation techniques and use the answers as a basis for detailed further investigation. Unfortunately, such preliminary methods have not been fully developed for assessment of aquatic environments. In other words, despite scientific progress in environmental science, no generic cause-effect relationships exist between changes in sediment flows and environmental quality that can be incorporated in a pre-feasibility level mathematical model such as RESCON.

It is expected that improved methods based on the principles of ecohydrology may become available in the future. Ecohydrology is a new concept that was postulated in 1992 during the Dublin International Conference on Water and Environment. It is defined as "the science of integrating hydro-

TABLE 4.1
SAFEGUARD RATINGS

Safeguard	Value	Descriptor	Discussion of Assignment Criteria
Natural Habitats	1	Potential Enhancement	Potential enhancement of natural ecosystems due to flushing of sediments, restoration of overbank flows, downstream movement of nutrient, *etc.*
	2	Minor Impact	Either minor permanent impacts to natural functioning ecosystems, or temporary impacts.
	3	Moderate Impact	Permanent impacts to natural ecosystems, unavoidable significant conversion or degradation of natural habitats.
	4	Significant Impact	Significant conversion or degradation of critical natural habitat.
Human Uses	1	Potential enhancement	Benefits to floodplain agriculture/grazing, downstream or coastal fisheries, preservation of beaches, *etc.*
	2	Minor Impact	Minor or temporary impacts to floodplain agriculture, downstream fisheries, *etc.*
	3	Moderate Impact	Permanent impacts to downstream fisheries, loss of agriculture/grazing, short term impacts to potable water, *etc.*
	4	Significant Impact	Significant loss of agricultural or fisheries potential, long term impacts to potable water, *etc.*
Resettlement	1	No Resettlement	No resettlement necessary.
	2	Minor Resettlement	Limited population impact, and impacted population will not suffer loss of income or assets.
	3	Moderate Resettlement	Significant numbers of individuals displaced, no social disruptive; but some potential for loss of income, assets, or means of livelihood.
	4	Significant Resettlement	Displaced population is likely to suffer loss of assets, income, and/or means of livelihood. Resistance to resettlement or cultural/social displacement as a result of resettlement.
Cultural Assets	1	None Affected	No cultural assets affected by project (assets with archaeological, paleontological, historical, religious, or unique natural values, including remains left by previous human inhabitants).
	2	Minor Impact	Cultural assets can be protected, salvaged, or translocated, without significant loss of cultural value.
	3	Moderate Impact	Minor to moderate loss of cultural assets, or significant diminution of cultural value due to salvage.
	4	Significant Impact	Significant loss of cultural assets, or devaluation of assets due to translocation.
Indigenous Peoples	1	No Impact	Indigenous peoples may derive direct, socially or culturally appropriate, benefit from the project, or indigenous peoples are not impacted by the project.
	2	Minor Impact	Temporary impacts to land or resources, owned, occupied or used by indigenous peoples.
	3	Moderate Impact	Permanent impacts to land or resources, owned, occupied or used by indigenous peoples, not recompensable in type.
	4	Significant Impact	Physical relocation of households, or permanent loss of access to resources.

(continued on next page)

TABLE 4.1
SAFEGUARD RATINGS (continued)

Safeguard	Value	Descriptor	Discussion of Assignment Criteria
Trans-boundary Impacts	1	No Issues	Project will not affect any river, lake, or body of water that forms a boundary or flows between two states. All states will be beneficiaries of the project.
	2	Minor Impacts	The project may have minor or transient impacts to one or more impact aspects of a state other than the beneficiary state.
	3	Moderate Impacts	The project may have moderate and/or permanent impacts to one or more impact aspects of a state other than the beneficiary state.
	4	Significant Impacts	The project will likely have significant impacts to one or more of the impact aspects of a state other than the beneficiary state.

logical processes with biota dynamics over varied spatial and temporal scales." Ecology as a science appeared at the end of the nineteenth century and was devoted initially to the description of the structure of ecosystems, leading to the first observations and descriptions of succession, predator/prey relationships and other phenomena that drive the dynamics of the ecosystem. However, the science lacked the predictive capability to manage aquatic systems.

As a result, two extremes have appeared in literature: over-engineered management of aquatic environments on the one hand and restrictive environmental conservation, with the general assumption that the aquatic environment should be maintained in its pristine condition, on the other. The former approach sometimes results in unsatisfactory management of the environment and the latter is unrealistic. The integration of ecology and hydrology promises to accelerate the process of moving ecology and environmental sciences from a descriptive stage to an analytical, functional, operational stage. Once this has been accomplished, the chances of successfully managing water resources in a manner that concurrently benefits humanity and the environment will be improved.

Until such methods have been developed for implementation in quantitative computer models, however, the following approach is proposed to assess social and environmental issues in relation to reservoir conservation. It is preliminary in concept and should be supplemented by more comprehensive environmental assessments as necessary. The procedure detailed below may be used for decision making at the pre-feasibility level. The results that emerge should be reviewed in detail during subsequent feasibility studies, prior to implementation of the optimal management approach.

Application of Safeguard Policies

Outlined in Table 4.1 are the relevant safeguard policies of the World Bank,[5] as they would apply to a generic reservoir conservation program. Each of the concerns mentioned in the first column have values ranging from one (1) to four (4). In all cases, the value of one (1) is assigned to no impact or to possible benefits and the value four (4) is assigned to the worst condition. The safeguards are assessed when a RESCON investigation is executed and values (1 to 4) are assigned to each concern. The final score is determined by adding the safeguard values. Decisions pertaining to the potential environmental and social feasibility of the project are based on the recommendations in Table 4.2.

The RESCON program is used to calculate the economic net present value (NPV) of each sediment management alternative and report the rankings. It

[5] For more information visit http://lnweb18.worldbank.org/ESSD/essdext.nsf/52ByDocName/SafeguardPolicies

TABLE 4.2
INTERPRETATION OF SUM OF SAFEGUARD RATINGS

Sum of Ratings	Interpretation
6	No impact and potential benefit
6 to 12, with no 3's	Minor impact
12 to 15 or at least one 3	Moderate impact
16 or higher, or at least one 4	Significant impact

also reports the highest ranked management alternative that meets the safeguards standard of acceptability. This standard is specified by the user and is based on the final score in Table 4.2.

Conclusions

In addition to technical and economic feasibility, environmental and social impacts of sediment management play pivotal roles in determining project selection. Studies of such impacts could use a normative approach, in which the monetary consequences of implementing different levels of safeguard compliance are compared with one another. If the economically and technically optimal strategy is rejected because it does not meet the safeguards standard, the RESCON program results for the case with no safeguards imposed are used to calculate the financial opportunity cost of implementing the safeguard approach. This cost is the difference between the NPVs of the environmentally and socially constrained and unconstrained alternatives.

In order to implement a normative approach, cause-effect relationships for the specific cases would be needed and typically these are not readily available. The insights provided by the safeguard rating method described in this chapter permit outlining of the terms of reference of feasibility level studies required for moving the process forward.

When selecting options for sediment management, emphasis should be placed on estimating and mitigating against the environmental and social impacts a particular option may have and on building this into the decision making process. However, as discussed above, some alternatives for managing sediments have positive impacts as well as negative ones and these need to receive attention also. Furthermore, when outlining the options an opportunity exists for identifying environmental and social enhancement measures which if possible should be included in the option.

5. RESCON APPROACH AND PROGRAM

The Need for RESCON

A decision as to whether sustainable management of dams and reservoirs should be implemented on a national or regional scale as a matter of policy is subject to considerable uncertainty. Engineering methods are available to analyze a specific project in detail, but the detail is proportional to the quantity and quality of the data used. Obtaining all the necessary data, choosing the appropriate analytical tools and making a decision requires significant amounts of time and resources. For this reason, in most situations it is impractical to execute feasibility studies on large dam and reservoir systems to determine the potential for success of such a policy.

To fill this gap, a tool is needed that can provide reasonably reliable information to decision makers as to whether sustainable management of dams and reservoirs in an existing water resource system is an achievable goal. The RESCON project aims to do so by providing a tool kit that can be used for decision making purposes at the policy level. The technique is designed to use dam and reservoir data that are readily available. Should such data not be available the approach directs users' attention to the acquisition of critical data. The RESCON approach also promotes policy makers' awareness of the importance of reservoir conservation at the national level.

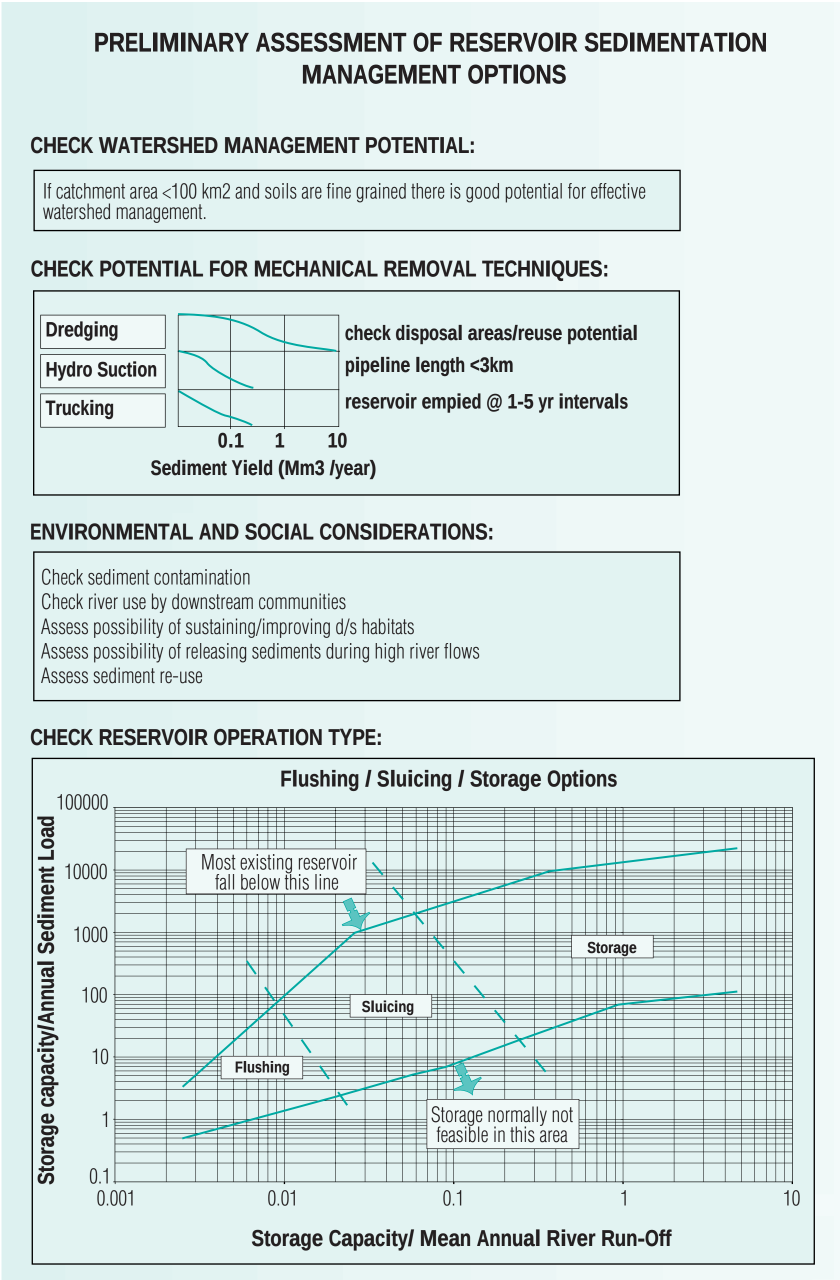
Preliminary Assessment of Management Options

Before the RESCON model is used to assess the options available for a dam or a suite of dams, it is advisable to undertake a preliminary screening following the indications shown in Figure 5.1. The results of this screening should be used to priorities the dams for RESCON analysis as well as to check on the output of the model.

There are four parts to the figure:

- *Watershed management potential.* As noted earlier, the RESCON model does not have a specific routine for assessing watershed management options. Figure 5.1 can be used as preliminary guidance as to whether further watershed management studies should be undertaken. If watershed management is a potential option then the RESCON model can be "tricked" into considering it by reducing the annual average sediment load by an appropriate amount.
- *Environmental and social considerations.* The RESCON model has a routine for assessing these. The notes given in the Figure are a reminder of some of the more important considerations.
- *Potential for mechanical removal.* The RESCON model has a routine for assessing the mechanical options. From the figure the user can quickly ascertain whether these options are likely to be technically feasible or not. For example, the hydrosuction option shows that the procedure is unlikely to be effective in controlling sedimentation if the annual inflow of sediments is greater than 100,000 m^3 per year or if the reservoir is much more than 3km long.
- *Reservoir operation diagram.* This is based on the work done by Basson and Rooseboom (1997). The diagram's entry data are: a) hydrological size of the reservoir which provides an indicator of exess water available for sediment management; b) sediment inflow relative to reservoir capacity, which provides an indicator of reservoir life span.The diagram is based on observations from many dams in the world and shows which operation model is likely to be effective.

FIGURE 5.1
PRELIMINARY ASSESSMENT OF OPTIONS



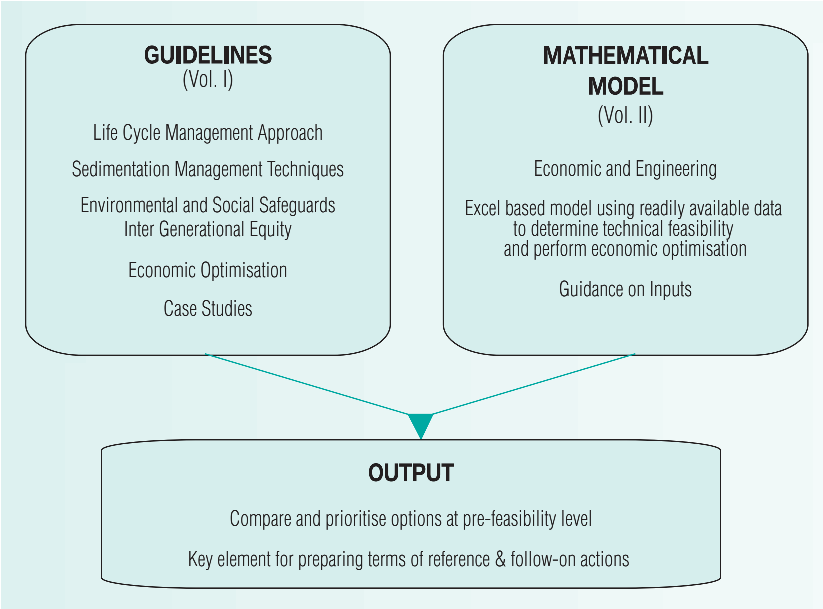
The RESCON Toolkit

Figure 5.2 summarizes the RESCON toolkit. It consists of general guidelines pertaining to sustainable management of surface water reservoirs and a preliminary mathematical model that can be used to analyze readily available data to identify preferred approaches. The model is intended to assist in prioritizing actions for sustainable reservoir management and in laying the groundwork to prepare terms of reference for more detailed feasibility studies.

The RESCON approach allows reservoir owners and operators to prioritize management decisions at the policy level, to develop and justify budgets for implementation of sediment management strategies or to justify construction of new storage, as appropriate. The typical steps in the RESCON approach can be outlined as follows.

- *Current sedimentation trends.* These allow the user to forecast the evolution of the sedimentation processes in the reservoirs examined. Associated impacts at social, environmental and economic levels can also be assessed. Comparison can be made of sedimentation rates among individual cases and identification of focal reservoirs in which storage loss is causing the highest socio-economic impacts.
- *Basis for managing reservoir sedimentation.* Reservoir sedimentation management encompasses investigation together with monitoring, as well as structural and non-structural measures (see Chapter 3).
- *Basis for prioritizing sediment management measures.* The actions required to improve sedimentation trends should be organized into separable sediment management packages. Each package contains one or more actions of structural and/or non-structural nature. By so doing, each stage of an action plan can be prioritized separately, a more rapid improvement of the sedimentation rate is likely to be achieved and stronger justification to decision makers provided.

FIGURE 5.2
THE RESCON TOOLKIT



Investigations needed to better understand reservoir sedimentation trends, or to support design work, should also be prioritized.

❖ *Reservoir Conservation Action Plan*. The scope and format of the outcomes should be adapted to meet the needs of the reservoir owner and other stakeholders. The decision making entity should be provided with a clear, concise picture of the current storage loss trends and of the improvements that the proposed action plan can introduce. A schematic view of a generic reservoir conservation action plan is shown in Figure 5.3.

The action plan, which is based primarily on available information, should be seen as a "living document" that is periodically updated. Updates should incorporate the following: (i) new information; (ii) improved estimates of input data; (iii) additional or revised evaluation or prioritization criteria; and (iv) advances in sediment management procedures.

The RESCON mathematical model

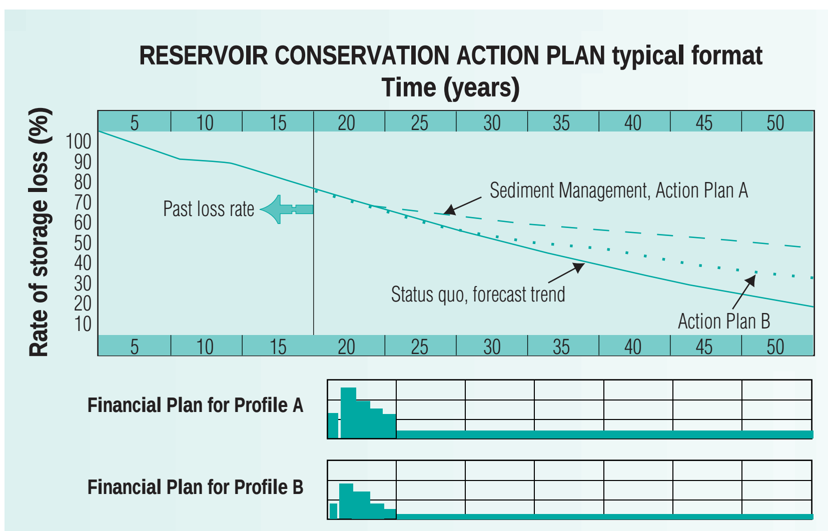
Overview

Several models have been developed for the engineering design of sediment management strategies. Few of them are suitable for application outside the specific context for which they were developed. In all cases the detailed nature of data required for such models makes them unsuitable for use at the option assessment level. They have been applied instead at the feasibility or detailed design stages of a project. In some cases, such models have been employed for the back analysis of sedimentation in existing reservoirs and to forecast future trends of the phenomenon. None of the existing models take into account economic parameters.

The following list of mathematical models is based in part on Morris and Fan (1998).

❖ GSTARS, Molinas and Yang (1986)
❖ FLUVIAL, Chang (1988)
❖ HEC-6, U.S. Army (1991)

FIGURE 5.3
SCHEMATIC RESERVOIR SEDIMENTATION MANAGEMENT ACTION PLAN



- SSIIM, Olsen, et al. (1994)
- MIKE 11-RFM, Basson and Rooseboom (1997)
- RESSASS, HR Wallingford (2001).

The RESCON model aims to provide a tool to be used at the planning stage when data are scarce and strategic decisions need to be made.

The overall aim of the RESCON model is to select a sediment management strategy that is technically feasible and also maximizes net economic benefits. The model is built on the Microsoft Excel platform. The model explicitly considers the following sediment removal techniques: (1) Flushing; (2) Hydrosuction; (3) Traditional Dredging; and (4) Trucking. In addition, the "do-nothing" alternative, (i.e., no sediment removal) where eventual decommissioning will be required, is also analyzed. The program may be used for existing dams as well as proposed dams.

Economic optimization is performed for each of the sediment removal techniques in separate subprograms and the net present value (NPV) is reported. The objective is to maximize net returns from practicing each technique. Reservoir yield, which is based on remaining reservoir capacity and the unit value of this yield are key determinants of annual revenue. The unit value of reservoir yield, or water price, depends on water use (e.g., irrigation, domestic, industrial, energy, etc.) as well as political factors. Annex F presents a range of observed water prices from various countries and sectors. Costs include annual operations and maintenance and any periodic sediment removal expenses. Revenues and costs that accrue over time are discounted prior to aggregation. The program also allows initial construction costs (for proposed dams) to be included in the NPV calculation.

Optimal control theory is used to maximize the aggregated net benefits. The solution may take two forms: (1) reservoir capacity is never fully depleted and the dam performs its primary function forever; or (2) the primary function of the dam is terminated within a finite period. Case (1) is called "sustainable" while case (2) is called "non-sustainable." The non-sustainable case (2) itself involves two possibilities: 2(a) the dam is decommissioned at an optimally determined time; and 2(b) the dam structure is maintained as a "run-of-river" project even after the reservoir is silted. Case 2(a) allows a salvage value to be collected at the terminal time. This value would normally be negative if, for example, decommissioning is required. Another point to note is that the optimal terminal time (and terminal capacity) in this case will depend on the magnitude of the salvage value. The program calculates an annual replacement fund payment which, if invested, will earn interest and accumulate to equal the costs of decommissioning at the optimal terminal time.

RESCON Model Structure

This section provides general information on the mathematical model. Further information on the detailed use of the model is presented in Volume II.

FIGURE 5.4
PROGRAM STRUCTURE

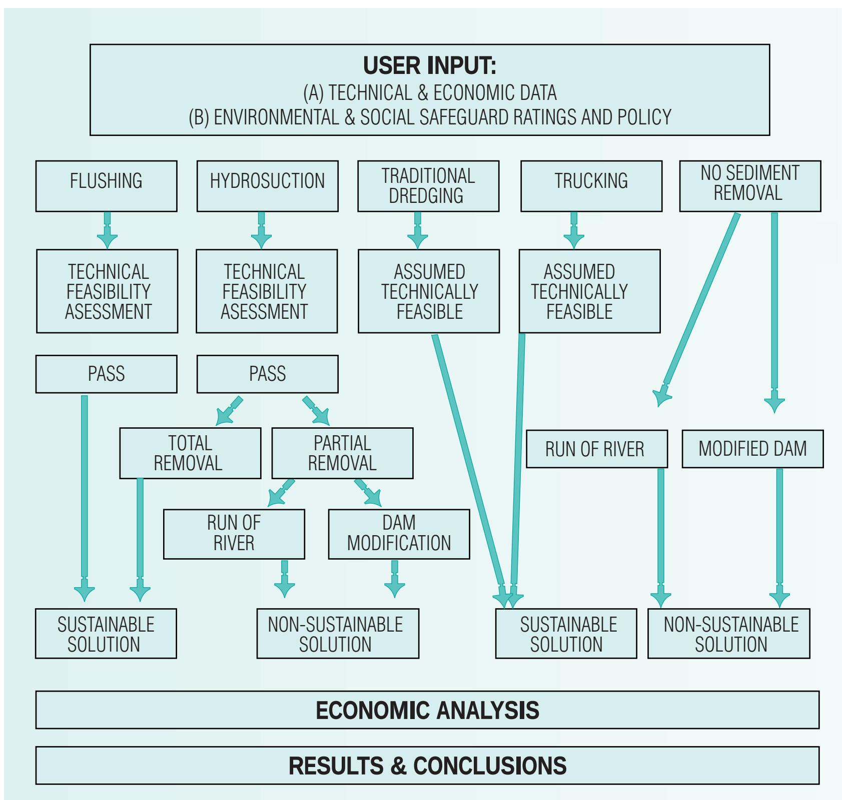


Figure 5.4 illustrates the main steps in RESCON which are described below.

- Project-specific technical and economic data are entered by the user
- The user is also prompted for environmental and social safeguards (see Chapter 4)
- The model assumes dredging and trucking are always technically feasible[6] and tests the technical feasibility of flushing and hydrosuction.
- For the baseline case of no sediment removal the model assumes two alternatives: run-of-river and eventual decommissioning.
- All options are taken through an optimization routine to find economically optimum values for each.
- The results of economic optimization are compared and ranked.

Economic Optimization Routines[7]
The general economic optimization problem is to choose a sediment removal option and the manner in which it is to be used (i.e., schedule and amount of sediment removed) so as to maximize the lifetime aggregate NPV of the project. The life of the dam is also determined optimally and could be finite or infinite. The various sediment management options are assumed to be mutually exclusive. The problem is solved in two steps.

Step 1

- The following optimization is performed for each sediment management option:

$$\text{Maximize} \sum_{t=0}^{T} NB_t \cdot d^t - C2 + V \cdot d^T$$

subject to $S_{t+1} = S_t - M + X_t$, (1)

given initial reservoir capacity, S_0 and other physical and technical constraints.

The symbols used in the above formulation are defined as:

d = discount factor—defined as 1/(1+r), where r is rate of discount[8]

C2 = initial cost of construction for proposed dam (= 0 for existing dam)

V = salvage value

T = terminal year

S_t = remaining reservoir capacity (volume) in year t

M = trapped annual incoming sediment

X_t = sediment removed in year t

NB_t stands for annual net benefits in year t. It is defined as annual revenue from the services of the dam minus costs of operations and maintenance and costs of any sediment removal that occurs during that year. Annual revenue is the product of the unit value of water and annual reservoir yield, W_t (which is based on remaining reservoir capacity S_t). The latter is calculated via Gould's Gamma function as follows (see McMahon and Mein, 1978).

$$W_t = \frac{4 \cdot S_t \cdot V_{in} - Zpr^2 \cdot sd^2 + 4 \cdot Gd \cdot sd^2}{4 \cdot \left(S_t + \frac{Gd}{V_{in}} \cdot sd^2 \right)} \tag{2}$$

where:

V_{in} = incoming flow volume (annual runoff),

sd = standard deviation of incoming flows (annual runoff),

Zpr = standard normal variate of p %,

Gd = adjustment factor to approximate the Gamma distribution (offset from the normal distribution).

The use of Gould's Gamma function proved instrumental in the development of the RESCON model. However, the user should be aware that for Wt/Vin < 0.2 the function does give unreliable results. For 0.2<Wt/Vin<0.4 the user is advised to exercise caution.

The above maximization problem may be solved using optimal control theory (Seierstad and Sydsaeter, 1987). The standard procedure is to select a time path of the control variable, X_t, to maximize a Hamiltonian function while satisfying a co-state equation, appropriate end-point conditions and all other constraints specified in the statement of the problem. The relevant Hamiltonian function is:

[6] See chapter 3 and Figure 5.1 for quick feasibility checks.
[7] The following text requires some knowledge of economics mathematics, however its understanding is not essential for using the RESCON model.
[8] The discount rate is taken to be constant over time.

$$H_t = (NB_t)(d)^t + q_t(-M + X_t) \tag{3}$$

where q_t is the co-state variable associated with S_t and has a shadow price interpretation (i.e., it measures the discounted value of a marginal increase in remaining storage capacity). It is possible to interpret H_t as a discounted net benefit function that accounts for the value of reduced reservoir capacity in the future due to current choice of X_t.

Maximization of H_t with respect to X_t requires more information about the relationship between annual net benefits, NB_t and X_t. For the sediment removal techniques under consideration, we assume that cost functions are linear in X_t but subject to technical constraints on removal. Under this assumption, the Hamiltonian function is linear in X_t. The consequence is that, depending on the technique used and the nature of physical constraints, the solution may involve annual removal (partial or complete) of incoming sediment or there may be cyclical patterns of sediment accumulation and removal. Furthermore, technical or economic optimization considerations may sometimes necessitate an initial phase that involves declining storage capacity, followed by annual removal or a cyclical but stable pattern of accumulation and removal. A detailed discussion of the solution for each individual technique is available in Volume II.

Aside from maximization of H_t and satisfaction of all the aforementioned constraints (including equations (1) and (2)), optimization also requires the co-state equation stated below to hold:

$$q_{t+1} - q_t = -\partial H_t/\partial S_t \tag{4}$$

Solutions in which at least a minimally acceptable storage capacity is maintained forever are termed *sustainable.*[9] *Non-sustainable* solutions, on the other hand, involve an end to storage related services in finite time. If the dam is to be decommissioned at time T, then determination of optimal T and optimal S_T is possible by using the following end-point condition:

$$H_T = -\partial(V\, d^T)/\partial T \tag{5}$$

Optimal S_T is typically positive, but larger negative values of the salvage value, V, are likely to reduce it. There may also be situations in which decommissioning can be avoided by operating the dam as a "run-of-river" project even after complete siltation. The NPV of a dam under such scenarios is calculated by assuming that storage related benefits end when the dam is silted, but pure "run-of-river" benefits continue to accrue indefinitely.

Step 2

- After the optimization procedure outlined above has been carried out for each technique, the next step is to compare their NPVs and that of the "no removal" strategy. The latter strategy involves setting $X_t = 0$ for all t, but the terminal time is determined optimally for the scenario in which decommissioning occurs. All applicable "run-of-river" scenarios are also included in the comparison. The highest ranked alternative is then highlighted.

  If flushing, dredging or trucking techniques are adopted, the outcome is always sustainable. Under HSRS, however, a sustainable outcome occurs only if removal of all annual incoming sediment is technically feasible. The "no sediment removal" strategy obviously leads to a non-sustainable solution. Detailed explanations and likely time paths of sediment accumulation and removal for each technique are presented in Volume II.

Intergenerational Equity and Retirement Fund

If the optimal strategy turns out to be such that expensive dam modification is required (i.e., the salvage value, V, is negative), future generations would end up paying this cost without enjoying any of the services of the dam. Such intergenerational

[9] The remaining storage capacity at which the reservoir "stabilizes" under a sustainable solution is determined optimally, subject to a lower bound specified by the dam manager. Also, sustainability does not imply desirability. The sediment management strategies are judged only in terms of NPV, subject to technical feasibility and any environmental or social constraints.

equity or fairness concerns may be addressed by setting aside some of the annual net benefits (NB) as a retirement fund for use at time T. While it is possible to construct sophisticated contribution schemes that reflect the declining services from an aging dam, RESCON proposes a less perfect but easy to calculate plan. Under this plan, a constant amount, k, is invested in each period so that the accumulated proceeds from the investment at time T are equal to – V. With optimal T calculated using equation (5) and letting m stand for the interest rate at which the retirement fund is invested, the desired value of k is given by:

$$k = -\ mV/((1+r)^{T} - 1) \qquad (6)$$

Observe that the interest rate m is allowed to differ from the discount rate r. Also, if V is not known initially with certainty, it may be necessary to adjust the amount k (up or down) as more is learnt about the true value of V. Any other unforeseen changes in parameters that impact optimal T and/or H_T may also call for appropriate modification in k. The general procedure for making this modification would be as follows. First, optimal T is re-calculated for the remaining storage capacity and new parameter values. The new value of k is then determined using equation (6), but with a revised "net" V that has been adjusted for any exogenous changes as well as all existing retirement fund savings (along with interest) which will be accumulated by the new optimal T. Of course, continued contributions to the retirement fund would be needed only as long as the appropriately adjusted "net" V is negative.

Cautionary Remarks

The RESCON model has been released as a tool for use by experienced practitioners in water resources management. The following should be noted by users:

The model always assumes dredging and trucking are technically feasible and automatically takes these two options through to the economic analysis. Clearly if the annual inflow of sediments is very large, it is unlikely to be practical to dredge or truck the required quantities. The user therefore should note the annual volumes of sediment that are being removed and make an assessment of whether they are realistic or not. (See Table 3.1 and Figure 5.1).

Even where two or more options have very close aggregate NPVs, RESCON will pick the largest one as the economically optimal solution. The program also outputs the detailed results of the analysis and the user is advised to check these.

6. EVALUATION OF RESCON MODEL

Introduction

The RESCON computer program has been applied to several case studies for purposes of validation and sensitivity analyses. These case studies represent reservoirs that have either been subjected to reservoir sedimentation management with flushing or at least have been extensively studied for such management. RESCON predictions and results have been compared to field data and research findings. Sensitivity analyses have examined the response of the RESCON program to changes in input parameters. The objective was to determine whether the results are logical and consistent with worldwide experience.

The RESCON program has been applied to the following reservoirs: Tarbela, Pakistan; Sefid-Rud, Iran; Ichari, India; Gebidem, Switzerland; Baira, India; Unazuki, Japan; and Sakuma, Japan. Details of the dams and the results of the RESCON applications are detailed below.

Description of Dams

Tarbela Dam, Pakistan

Tarbela dam was substantially completed in 1973. The dam provides almost 50 percent of the nations regulated irrigation water and over 30 percent of its electricity. The pre-impoundment capacity of the reservoir was 14,300 Mcm (million cubic meters). The mean annual runoff (MAR) at the site is 80,920 Mcm per year with a clearly defined and predictable flood season and little variation from year to year. The annual average sediment inflows to the reservoir are estimated as 200 Mt.

The quality and quantity of data available for the project are outstanding. In particular detailed bathymetric surveys of the reservoir have been undertaken annually since 1979, providing an excellent history of sedimentation in the reservoir.

The Tarbela Dam Sediment Management Study (WAPDA, 1998) commissioned by the owners used detailed reservoir sediment modeling to predict future sedimentation of the reservoir and test the feasibility of undertaking different management options. The study recommended the implementation of a three phase action plan.

Phase I: Modify reservoir operating rules to slow down the advance of the sediment delta.

Phase II: Construct protection measures for the dam outlets.

Phase III: Construct new large capacity (7,500 m^3/s) low-level outlets to flush the reservoir annually.

The study predicted that the construction and operation of the flushing device would provide a sustainable solution to the sedimentation problem at Tarbela and maintain approximately 50 percent of the original storage for many generations. The recommended action plan was shown to be economically attractive with an internal economic rate of return (EIRR) of 20 percent.

Gebidem Dam, Switzerland

Gebidem is a hydrologically small reservoir, with a capacity/inflow ratio of 2.1 percent. Sediment inflows are high due to glacial activity, with stone sizes up to 100mm and the potential to reduce the original storage by more than 4 percent per year due to sediment deposition. The reservoir has been flushed annually during the flood season, with the result that virtually the entire storage capacity has been preserved. This is attributed to the gorge-like geometry of the basin and the steep valley slope. Problems have been experienced with downstream sediment accretion, where the valley slope reduces, which were expected to be overcome by deploying greater flushing discharges.

Baira Dam, India
Baira reservoir is hydrologically very small with a capacity on the order of 0.1 percent of the mean annual runoff from the catchment. In the first 18 months of operation, almost 20 percent of the original capacity was lost due to sediment deposition, representing a sediment load at least double the average annual sediment load assumed during the design. The diversion tunnel originally used during the construction period was fitted with gates to facilitate flushing and model studies suggested that this modification would be capable of removing virtually all the deposited sediment. The first flushing operation was successful, removing over 80 percent of the deposited sediment in 40 hours and it appears that annual flushing should be effective in maintaining a large proportion of the original storage capacity, approximately 85 percent.

Ichari Dam, India
Ichari Dam is hydrologically very small, with a capacity of only 0.2 percent of the mean annual inflow. The highly variable annual sediment load has the potential to replace about 20 percent of the original storage per year. This was borne out in the first year of operation, when the storage capacity was reduced by 23 percent, increasing to a total storage loss of 60 percent after six years. The sediment sizes range from fines up to cobbles and has severely damaged the spillway roller bucket.

Although the dam includes facilities for excluding coarse sediment at the hydropower intake, there is no low-level outlet for flushing sediment from the storage impoundment. Flushing via the gated spillway has been undertaken annually since 1976 and an approximate equilibrium has been maintained since about 1980. Long-term active storage is likely to average about 35 percent of the original.

Unazuki Dam, Japan
The multipurpose Unazuki dam was completed in June 2000 on the Kurobe River, which has high sediment concentrations. The reservoir is hydrologically small, with a capacity/inflow ratio of 3 percent. The sediment inflows are around 2 Mt per year and the mean annual runoff is around 700 Mcm. The dam is fitted with low-level flushing outlets. Flushing was successfully conducted in June and July 2001 and in July 2002 to secure capacity for flood control.

Sakuma Dam, Japan
The Sakuma Dam, a hydroelectric facility, was completed in June 1956 on the high sediment yielding basin of the Tenryu River. The reservoir is hydrologically small, the original capacity being around 6 percent of the inflow. The sediment inflows are around 1.6 Mt per year and the mean annual runoff is approximately 5,000 Mcm. The dam is fitted with flushing outlets. About 35 percent of the storage capacity of the reservoir storage was lost to sedimentation by 2000. A combination of flushing, dredging and hydraulic suction techniques is currently employed to manage sediment at Sakuma.

Sefid-Rud Dam, Iran
This reservoir is hydrologically larger than the others cited above, with a capacity/inflow ratio of 35 percent. Sedimentation was a serious problem over the first seventeen years of operation, reducing the storage capacity at a mean annual rate of 2.1 percent with a total storage loss of 63 percent by 1982-1983. Flushing measures have been implemented since then to remove deposited sediment from the reservoir by first emptying the reservoir from October to February to create river-like flow conditions and then refilling it in time for the start of irrigation in May.

Lateral erosion, piping and the use of a longitudinal diversion channel have aided in recovery and maintenance of storage capacity. It is anticipated that, by creating a new diversion channel each year, a long-term storage capacity of 90 percent might be reached, compared with 75 percent by flushing alone.

Long-term Capacity

The long-term capacity (LTC) of a reservoir that is achievable with flushing can be expressed in dimensionless terms by making use of the Long-term Capacity Ratio (LTCR), which is defined as the long-term sustainable storage capacity attainable by flushing divided by the initial storage capacity of the reservoir. Of the reservoirs that have been evaluated, Gebidem, Baira, Sefid-Rud and Ichari have all been subject to field trials and long-term capacity is estimated from the field data. Although there are no prototype data for Tarbela, it has been studied extensively using mathematical models. These studies indicated that flushing could potentially be used to evacuate sediments from the reservoir. Tarbela has by far the most comprehensive data set in terms of hydrology, hydraulics, sediment inputs and sediment deposition. Unazuki and Sakuma Dams in Japan have been flushed to varying extents, but no LTCR values were reported to the RESCON team.

The LTCR values calculated with the RESCON software were compared to the estimates based on the field trials and, in the case of Tarbela, the results of the detailed modeling. The comparison of calculated and observed LTCRs is presented in Table 6.1.

TABLE 6.1
COMPARISON FOR LTCR

Reservoir	Prototype Data	RESCON Estimate
Tarbela, Pakistan	50%[a]	36%
Gebidem, Switzerland	99%	39%
Baira, India	85%	50%
Sefid-Rud, Iran	75%	8%
Ichari, India	35%	44%
Unazuki, Japan	Unknown[b]	41%
Sakuma, Japan	Unknown	72%

[a] results of detailed hydraulic modeling using RESSASS software
[b] reported to be less than 40 percent

In general, the RESCON model appears to underestimate LTCR and therefore provides a conservative estimate for planning purposes. This is probably partially due to the fact that RESCON provides the economically optimum solution which does not necessarily coincide with the maximum storage, whereas the prototypes presumably attempt to maximize storage.

The RESCON estimate of LTCR for Gebidem is significantly lower than the field value. This could be attributed to more frequent flushing operations at higher discharges than what is reported in the literature. Alternatively it could be attributed to the large sediment sizes and the narrow, steep valley of its reservoir. However, the sediment is also highly graded and its effect on flushing is uncertain.

Sefid-Rud remains an anomaly. The RESCON predictions for LTCR are very low compared with the claimed values. Atkinson (1996) independently obtained a very low value of 13 percent. The estimate of 75 percent for the actual LTCR should most probably be investigated in more detail.

Ranking of Sediment Management Techniques

The sediment management techniques evaluated by the RESCON model for technical and economic feasibility include:

- Sediment flushing
- Hydrosuction sediment removal system (HSRS)
- Dredging
- Trucking.

The economic ranking of technically feasible approaches to management of reservoir sedimentation, as estimated by RESCON, is shown in Table 6.2.

The rankings presented in Table 6.2 largely agree with experience or study findings for the corresponding projects. However, there are exceptions and care needs to be exercised when interpreting the RESCON results. In particular, RESCON does not assess the technical feasibility of dredging or trucking. Instead it assumes these are always feasible. The model does output quantities that are assumed to be dredged or trucked and the user needs to exercise judgment on the feasibility of these. For example, for Tarbela RESCON ranks dredging as the highest option with an annual dredged quantity in excess of 135 Mcm. With the largest ever attempted dredging operation in the world not exceeding 10 Mcm, it is very unlikely that this result is credible.

Experience with sediment management in Gebidem indicates that flushing is an effective technique for removing sediment from the reservoir. This agrees with the RESCON findings. Trucking and dredging are also potentially feasible from both an economic and technical point of view. It is estimated that one dredge would be required to maintain the reservoir for sustainable operation and that trucking would require approximately a year's worth of effort to remove sediment at various points in time.

RESCON indicates that flushing is the optimal method for managing sediment in Sefid-Rud. Although RESCON indicates that it should be feasible to flush sediment from the reservoir, it estimates that the LTCR is in the order of 8 percent, which implies that the flushing channel cannot cover the width of

TABLE 6.2
SUMMARY OF RESCON ECONOMICS RESULTS

Reservoir	Sustainable?	Technologies (in order of Net Present Value)
Tarbela, Pakistan	Sustainable	Dredging / Flushing / HSRS (partial removal, run of river)
Gebidem, Switzerland	Sustainable	Flushing / Dredging / Trucking/ HSRS
Baira, India	Sustainable	Flushing / HSRS (partial removal, run-of-river)
Sefid-Rud, Iran	Sustainable	Flushing / Dredging
Ichari, India	Sustainable	Dredging / Flushing
Unazuki, Japan	Sustainable	Flushing / No Removal (run-of-river and non-sustainable)
Sakuma, Japan	Sustainable	Dredging / HSRS (partial removal run-of-river and non-sustainable)

the reservoir. Experience on site confirms this finding and led to the development of a concept to create additional longitudinal channels to enhance flushing. Such features, typical of an advanced design level, are not considered by the RESCON model. Trucking and dredging are considered technically infeasible for removing sediment from the reservoir because it would require 129 years to remove the sediment at 100 truckloads per day, or 66 dredges to remove the same amount of sediment.

Baira Reservoir has been successfully flushed, which agrees with the findings of RESCON. The economically close second choice of RESCON is the HSRS technique for partial removal of sediment and continued use of the facility in the long term as a run-of-river facility. Thus, the first choice is not only more economical, but also sustainable.

The findings for the Ichari Reservoir also seem to confirm practical experience. The dam contains no low-level gates for flushing, but if the gated spillway is used for flushing the achievable long-term capacity is estimated at 35 percent, which is close to that predicted by RESCON. The economic solution from RESCON indicates that a sustainable management approach for Ichari is optimal, which compares well with the findings of the dam owners and operators. The optimal economic solution that is also technically feasible is dredging. Should dredging be implemented, it is estimated that one dredge will be required to maintain the reservoir capacity in the long term. Should the owner decide against dredging, flushing through the gated spillway will also result in a sustainable reservoir with a positive economic value that is only slightly lower than that for dredging. RESCON indicates that trucking is not feasible from a technical point of view because it would require approximately 5 years to clear sediment from the reservoir if 100 truckloads of sediment were removed from the reservoir per day.

RESCON predicted that sustainable operation via flushing would have the highest positive economic return for Unazuki Dam in Japan. No removal, with either the run-of-river or decommissioning options once the reservoir has filled with sediment, was predicted to have the next highest economic return. Because the owners have successfully flushed the reservoir twice to maintain flood control capacity, RESCON proved to be effective for Unazuki.

The Sakuma Dam in Japan was predicted by RESCON to be sustainable through individual use of all four removal techniques, with dredging producing the highest economic benefit. The owners have employed various techniques in combination to provide successful sediment management. Thus, RESCON's predictions are correct for feasibility and economic value of each alternative; however, the assessment and prediction of the NPV of using combined techniques is a more complex task and a subject for more detailed, i.e., feasibility level, analysis.

Sensitivity Analysis

The purpose of the sensitivity analysis was to check whether the model stays consistent for a wide variety of cases. The model was tested for general physical parameter sensitivity, comparison of RESCON flushing sensitivity results to a published empirical flushing sensitivity graph and sensitivity of the water yield equation used in valuation of the model. Detailed sensitivity analysis of economic parameters for the Tarbela case study was also performed. Results of all these tests are reported below.

The first set of general sensitivity tests was conducted on three existing reservoirs. The reservoirs were selected to represent narrow, medium and wide widths with respect to length. The reservoir choices were: Strontia Springs Reservoir, USA, for the narrow option; Cabora Bassa Reservoir, Mozambique, for the medium option; and Guanting Reservoir, China, for the wide option. Testing of these three reservoirs provided enough data to draw conclusions as to the sensitivity of the model to reservoir geometry.[10]

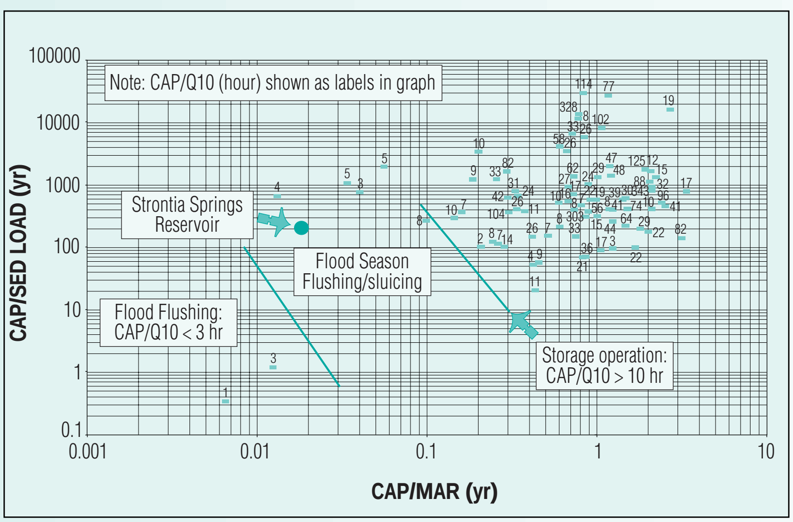
The second set of sensitivity results was generated from the general sensitivity testing by formatting the results according to Basson and Rooseboom (1997), who studied empirical data from many reservoirs and developed Figure 6.1, making use of experience and judgment to delineate ranges where flushing is considered to be technically feasible. The graph demonstrates the relationship between reservoir capacity, mean annual runoff and annual sediment load. Each data point in Figure 6.1 represents a reservoir that has been flushed and whose flushing success in terms of sediment removal has been noted. Based on their findings, they concluded that unsuccessfully flushed reservoirs fall above and to the right of the top inclined line. Successful flushing on a seasonal basis in terms of reservoir sustainability occurs in reservoirs between the two inclined lines in the centre of the graph, while reservoirs where single event-type flushing is successful fall below and to the left of the lower line.

A third set of sensitivity tests was conducted on RESCON's ability to predict water yield on seventeen reservoirs. Gould's Gamma function estimates reservoir yield as a function of the reservoir's capacity, mean annual inflow, standard deviation of that inflow and the required reliability of water supply (probability of failure to deliver yield), as shown in the Gould equation in Chapter 5. The equation typically shows that reservoir yield increases as probability of failure increases (reliability decreases). In other words, as more water is drafted from the reservoir for various uses, less is available to provide reliability for future stock.

Details of the sensitivity tests undertaken are presented in Annex J. The following sections summarize the results.

FIGURE 6.1

EMPIRICAL FLUSHING RESULTS (BASSON AND ROOSEBOOM 1997).



CAP = Reservoir Capacity, SED LOAD = Annual average sediment inflow, MAR = Mean annual runoff, Q10 = 10 year return period flow.

General Sensitivity Testing

By selecting pre-existing geometries, the number of variables that are arbitrarily varied within the expected range of possibilities are reduced because relationships for the various geometric parameters to the capacity are fixed. The geometric parameters were scaled according to the relationships taken from the geometry data available for each site.

The model outcomes from changes in the physical input parameters generally followed anticipated trends. For example, increasing widths of reservoirs for a constant value of flushing flow result in lower long-term capacity ratios; increasing the sediment

[10] The general testing was conducted by writing a Visual Basic Macro to run the RESCON model thousands of times varying one parameter at a time and recording all results in a table.

load results in more sediment being deposited in the reservoir prior to removal. Inspection of the results leads to the conclusion that the RESCON model is consistent.

A summary of results from the sensitivity analysis for RESCON as it relates to the technical feasibility of flushing was developed. Similar to Basson's and Rooseboom's Figure 6.1, Figure 6.2 relates the ratios of capacity to mean annual runoff and capacity and annual sediment load (with the axes reversed). The figure shows that RESCON results imply that, in general, flushing is potentially technically feasible in cases where the reservoir capacity to mean annual runoff ratio is less than 0.3 years and where the capacity to sediment load ratio is less than 100 years. This implies that flushing could be the preferred sediment management technique when reservoirs are hydrologically small and the sediment loads are relatively high. The ratio of reservoir capacity to sediment load approximates the number of years it will take for a reservoir to completely fill with sediment if it is assumed that all the inflowing sediment deposits in the reservoir. Whether the cut-off should be at 100, 200 or more years should be determined by economic analysis such as that offered by RESCON. However, the general trend of the recommendation appears to make sense. For example, in the extreme case, when a reservoir will take, say, 1,000 years to fill with sediment, it is unlikely that pro-active sediment management techniques will be required to ensure sustainable use of the resource. At the other extreme, if a reservoir would fill with sediment within, say, one year, pro-active sediment management would definitely be required to ensure sustainable use.

The lines indicating the areas below which flushing is considered to be technically feasible by Basson and Rooseboom (1997) are also shown on Figure 6.2. It is concluded that the RESCON results compare favorably with their findings.

Gould's Gamma Function for Yield

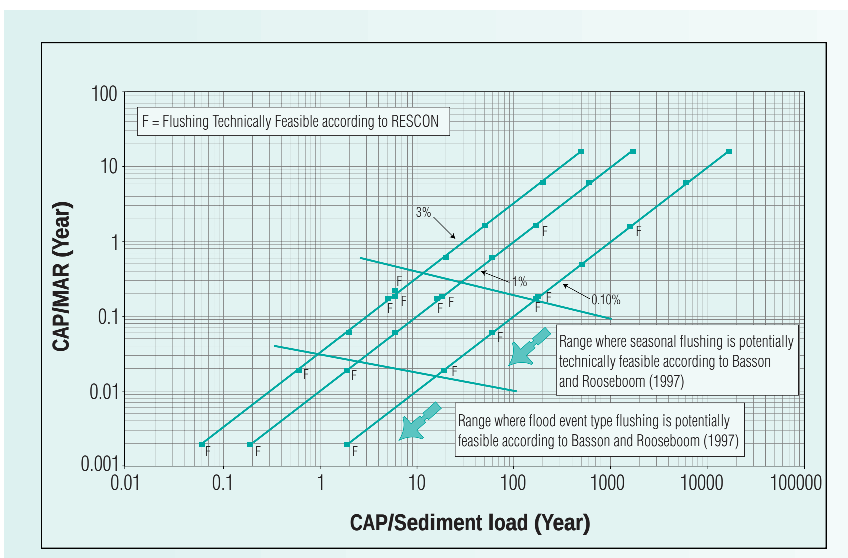
Reservoir yields are estimated using Gould's Gamma function. The model was run and the yields for seventeen dams were determined using RESCON. The results show that there are definite cases where the equation is applicable and where it is not. In general: all reservoirs with yield/MAR greater than 0.4 exhibit the trend that increasing probability of failure (decreased reliability of supply) allows more yield to be taken from the reservoir. This agrees with reality. However, when yield/MAR is less than 0.2, the model predicts a reduction in yield for an increase in the reliability of supply. Clearly this is not realistic. In summary:

RESCON performs well for reservoirs where the reservoir yield is at least 40 percent of the mean annual runoff. For situations where the yield is less than 20 percent of the mean annual runoff, RESCON results are unreliable.

Sensitivity to Economic Parameters

Changes in economic parameters may alter not only the ranking of desirable sediment management strategies, but could also affect the amount of sediment removed with each strategy and magnitude of variables such as the timing of decommissioning and any retirement fund contributions. Sensitivity analysis was performed on key economic parameters of the Tarbela Dam case study to investigate these effects and test the model for consistency with economic intuition. The following parameters were

FIGURE 6.2
RESCON FLUSHING RESULTS



varied: price of net reservoir yield (P1), rate of discount (r), market rate of interest (m), cost of operations and maintenance coefficient (omc) and costs of sediment removal for different techniques. The results of this sensitivity analysis are reported below.

Sensitivity to P1: Unit Value of Reservoir Yield

When P1 is doubled from US$0.1/$m^3$ to US$0.2/$m^3$, the NPV for all strategies increases by nearly US$140 billion. However, the increase in NPV for sustainable solutions is somewhat higher than that for non-sustainable solutions. Also, the Long Term Capacity Ratio (LTCR) increase by 31 percent and 6 percent respectively for dredging and trucking. It follows that the higher water prices generate incentives to keep more storage capacity. In the case of flushing, changes in economic parameters do not affect LTCR because the latter is determined by engineering features rather than economic optimization.

Sensitivity to r: Discount Rate

The discount rate determines the weight of future benefit and cost relative to the present. When the discount rate is lowered from 5 percent to 3 percent, NPV for each strategy increases by nearly 50 percent but there is no change in rankings. Furthermore, the long-term capacity for dredging and trucking increases, respectively, by 33 percent and 4 percent. Thus, as with the increase in unit benefit of reservoir yield, lowering of the discount rate also encourages retaining higher storage volumes.

Sensitivity to m: Market Rate of Interest

The annual retirement fund is calculated using the market interest rate (i.e., the rate of return on investing the fund). The value of this annual contribution is reported only when decommissioning cost exceeds any benefit of dam removal. For the Tarbela case study simulation, it is assumed that US$2.5 billion is the net cost of decommissioning the dam. The corresponding annual retirement fund is US$2 million with 5 percent market rate of interest. If the interest rate increases from 5 percent to 8 percent, the annual retirement fund contribution decreases to US$290K. Thus, the annual retirement fund contribution is highly sensitive to the market interest rate. One should also expect that the annual retirement fund will decrease with changes in economic parameters that increase the longevity of dams.

Sensitivity to omc: Operations and Maintenance Costs

Operations and maintenance costs are represented in the model by the parameter omc, which is a coefficient defined as the ratio of annual operations and maintenance cost to initial construction cost. Thus, an omc value of 0.01 means that the annual operations and maintenance cost is 1 percent of initial construction cost. The results of change in this coefficient from 0.01 to 0.05 have been tested. Since annual operations and maintenance cost is independent of sediment management strategies, the change in omc reduces the NPVs for all strategies by the same amount except for non-sustainable ones with decommissioning. As no annual operations and maintenance cost is incurred after dam removal, the change in NPV for non-sustainable (decommissioning) strategies is slightly lower. Long-term capacity, frequency of sediment removal and the amount of sediment removal are all independent of the change in annual operations and maintenance cost.

Parameters Describing the Cost of Sediment Removal

Costs of sediment removal depend on the technique used. The parameters associated with each technique have been varied as shown below.

- *Flushing:* S2 (fraction of storage benefits which can be used in a year in which flushing occurs) increased from 0.5 to 0.75.
- *HSRS:* PH (unit value of water released downstream during hydrosuction operations) decreased from US$0.005 to US$0.003/m^3.
- *Dredging:* CD (unit cost of dredging) decreased from US$2.62 to US$2.00/m^3.
- *Trucking:* CT (unit cost of trucking) decreased from US$50 to US$40/m^3.

When the cost of sediment removal is reduced, NPV increases regardless of the strategy used. Long-term capacities for dredging and trucking are increased. These results imply that the reduction of sediment removal costs increases the difference between NPV with sediment removal and that with no removal. More importantly, the magnitudes involved suggest the need for technological innovation in sediment removal because a marginal reduction in unit cost of removal has the potential to save million of dollars over the long term.

Conclusions

The case studies and sensitivity analysis results are encouraging for the RESCON software, indicating that it is meeting the objective for which it was developed, i.e., to identify a management approach and optimal techniques for management of sediment in reservoirs at *pre-feasibility level*. The possible approaches evaluated are:

- Sustainable management with sediment removal
- Non-sustainable management with no sediment removal
- Non-sustainable management with partial removal of sediment.

With non-sustainable management, the reservoir is either decommissioned at an optimally determined time, or it is allowed to operate as a run-of-river facility after complete siltation. Sediment management techniques considered include flushing, dredging, trucking and HSRS. Of the seven reservoirs tested, sustainable dredging and flushing were the overwhelming choices by RESCON in terms of net economic benefits.

The case studies indicate that the RESCON results are, within limits, confirmed by practical experience. The long-term capacities predicted by RESCON for the reservoirs are generally lower than what is anticipated in practice, which reflects the simplifying assumptions made in the calculation of LTCR, as well as the RESCON model's inability to consider multiple techniques in parallel.

The case studies also brought to light (Unazuki and Sakuma reservoirs) the need to consider flood control functions to better model water yield values at certain reservoirs. Furthermore, it would be desirable to assess multiple management techniques in order to allow judgment regarding the desirability of such management at a given site.

In the sensitivity analysis, examination of the RESCON version of Basson and Rooseboom's plot (Figure 6.2) confirmed, on economic grounds, that flushing could be the preferred sediment management technique when reservoirs are hydrologically small and the sediment loads are relatively high. Also as a part of sensitivity analysis, RESCON's use for hydrologically small reservoirs (Se/MAR less than 0.1) was tested, where yield is calculated with Gould's Gamma function using a 1 percent probability of failure. It was decided that the 1 percent probability of failure would be used for all values of Se/MAR to eliminate discontinuities in cases where Se/MAR does fall below 1 percent during the lifetime of a reservoir. Although this is a simplification and may be acceptable, it is an example of why RESCON is a pre-feasibility tool and why judgment should be exercised in interpreting results.

Finally, sensitivity analysis on key economic parameters was performed for a particular case study, namely, Tarbela Dam. The results show consistency with economic intuition and are also suggestive of interesting policy implications in terms of higher water prices and returns on research to lower sediment removal costs.

7. COUNTRY DIALOGUE

Introduction

In many regions of the world there is an urgent need to make the best use of existing reservoirs, improving the performance of their operation and incorporating the lessons learnt into the planning and construction of new assets. In consideration of this, the RESCON project undertook country dialogues and training activities with the aim of launching concrete actions or projects on the ground. The objective of such projects is the sustainable management of reservoirs within the framework of life cycle management.

Three countries were visited: Kenya, Morocco and Sri Lanka. Each has specific sedimentation problems and varying degrees of management established. The RESCON field team met with local engineers and managers to determine what the perceived needs are, conducted reconnaissance of the problem reservoirs and surveyed sedimentation volumes at some sites. The RESCON team applied the RESCON model[11] to a selection of reservoirs in an effort to aid the countries in their planning strategies.

Kenya

The RESCON team visited Kenya in December 2001 to confirm findings pertaining to sediment yield and reservoir sedimentation that were made during the first Integrated Water Resource Management Strategy Mission that took place in September 2001 and to investigate sedimentation of a number of river intakes. Surveys were conducted and storage loss calculated on three dams; studies of catchment sediment yield for two catchments were completed. Kenyan engineers were trained to use survey equipment and to direct surveys. Such activities and the resulting system knowledge will help Kenya develop a plan of action for future reservoir management. The Kenya project is discussed in detail in Annex G.

Although the RESCON model was not used in Kenya, the country report is included as part of this book because it covers two important topics: a) watershed management; b) sedimentation surveys.

Morocco

Country dialogue began with Morocco in May 2001. A RESCON team worked with staff of the Direction Générale d'Hydraulique (DGH) to appraise ten existing reservoirs. Discussions with Moroccan engineers indicated that the results of the RESCON analysis were in line with their experience and understanding of the reservoirs that were investigated. The RESCON approach produced optimal reservoir sedimentation management strategies for all ten reservoirs.

An interesting observation of the work in Morocco is the sensitivity of the model results to the unit cost of dredging assumed.

As a follow-up step, the study recommended a pre-feasibility study that will extend the pilot application to all ninety-seven reservoirs in the country with the objective of identifying optimal sediment management strategies.

Details on the Morocco application are given in Annex H.

[11] The RESCON program used in the missions was an early version which has since been updated.

Sri Lanka

In Sri Lanka, a pre-feasibility level sediment management study began in May 2002 by prioritizing the existing reservoirs and dams in terms of relative importance. The Mahaweli Authority of Sri Lanka (MASL) and the RESCON team surveyed three reservoirs in the Mahaweli River cascade to determine sedimentation rates in August 2002. Sri Lankan engineers were trained to use survey equipment. Thereafter the five reservoirs were analyzed using a specialized cascade system-version of the RESCON model to preliminarily identify management strategies for the reservoirs.

A workshop was given in Sri Lanka to discuss the preliminary results of the RESCON model analysis. Engineers were also given a tutorial with hands-on experience in using the RESCON model. The study allowed the preparation of draft terms of reference for a Reservoir Conservation Management Plan. The reservoir conservation management plan will include recommendations pertaining to the execution of more detailed feasibility studies and implementation actions. Details of the Sri Lanka study are in Annex I.

8. CONCLUSION OF THE STUDY AND RECOMMENDATIONS

Summary of the Problem

Dams and associated water reservoirs are aging around the world. Dam aging can be counteracted when necessary with appropriate operation, maintenance and management policies and rehabilitation interventions. Reservoir aging is determined by sediment accumulation rates. The “creeping” problem of lost storage and reduced production capacity in the water sector has several facets:

- The lost storage capacity has an opportunity cost in the form of replacement costs for construction of new storage if the present level of supply is to be maintained.
- There are direct economic losses in the form of less hydropower production capacity available for sale, less irrigated land to produce food and reduced flood routing capacity.
- The filled reservoirs, with no benefits to pay for their maintenance, will continue to be a liability to their owners and may become a hazard.
- The filled reservoirs may create a problem of decommissioning that has both direct and indirect costs.

Storage retirement or decommissioning is emerging gradually, in developed countries, as a new challenge for the engineering community. To date only small dams have been decommissioned. Decommissioning of large dams is very costly, full of technical uncertainties and highly contentious on environmental and social grounds. Sediment management becomes a key issue when decommissioning is perceived as a viable alternative.

Sustainability and Intergenerational Equity

Dams are part of our strategic infrastructure with a potentially very long life span. Prolonging the useful life of storage reservoirs constitutes a huge opportunity for sustainable development that should not be missed by the engineering community and by society at large.

Inter-generational equity is a concept that needs to be applied to water storage projects. The concept discourages the utilization of an asset by one generation if a subsequent generation is encumbered with its consequences.

Where the annual inflow of sediments into a reservoir can be balanced by an economically, socially and environmentally acceptable sediment management technique an opportunity exists for attaining sustainable use of the reservoir and hence intergenerational equity.

Where it is forecasted that this balance cannot be achieved and that the reservoir will eventually be filled with sediments, appropriate planning is required for dealing with the resulting problem. Actions can comprise substantial plant modification (e.g., protecting the intakes and converting to a run-of-river scheme), change of purpose (e.g., to recreation, cultivation, environment creation) and in extreme cases dam retirement using partial or complete removal of the dam. Financial coverage for such actions can be achieved by establishing a retirement fund into which sufficient sums of money are deposited annually to pay for any actions required at the terminal time. Such a fund will need to be established from the start of the project and will require periodic reviews and adjustments to ensure that it is growing sufficiently. This points out the importance of adequate sedimentation monitoring during the operation of the reservoir.

Sediment Management Alternatives

There are numerous ways of managing and mitigating reservoir sedimentation problems. These include measures to:

- Reduce sediment inflows into the reservoir
- Manage sediments within the reservoir
- Evacuate sediments from the reservoir
- Replace lost storage.

Each measure can be further sub-divided and each has technical, environmental and economic benefits and consequences. Each has been used for managing sedimentation problems around the globe and sufficient expertise and tools are available for their technical appraisal at the feasibility level and beyond.

Environmental and Social Safeguards

In too many cases in the past, insufficient attention has been paid to the environmental and social impacts of water storage projects. As a result there have been some notable environmental and social impacts. Environmental and social issues must be accorded a status equal to economic expediency. Potential environmental and social impacts and where possible potential opportunities for enhancement need to be identified early on in the project life cycle (i.e., at pre-feasibility stage) so that they can be investigated thoroughly and dealt with appropriately during project development. Where environmental and social impacts that are unlikely to be mitigated sufficiently are identified, a mechanism for abandoning an option or the offending element of that option must be in place. This book promotes the use of the "safeguards" approach to identify in broad terms the environmental and social impacts of a project so that they can be studied further in the next phase when the project evaluation procedure and mitigation actions are designed.

An Economic Approach

Research and literature to date on sediment management in reservoirs has focused mostly on engineering aspects (e.g., Morris and Fan, 1997). A review undertaken for this book showed that there is apparently very little, if any, published information on the economics of reservoir sedimentation and its implication for sustainable development. A framework is needed to assess the economic feasibility of sediment management strategies that would allow the life of reservoirs to be prolonged indefinitely. Such a framework should be able to answer two related but distinct questions:

- Is the extra cost incurred in undertaking sediment management activities worthwhile in terms of extending the productive life of a dam?
- Is it economical to extend the life of a dam indefinitely?

National level policy makers have a long list of priorities. Management of existing reservoirs, including sediment management, very rarely rises close to the top of the list. Two actions are required to change this attitude: (i) awareness raising; and (ii) development of a decision making tool that can be used at the policy level.

Planners and policy makers need a tool to be able to quickly and with little data appraise the technical, economic, environmental and social feasibility of various methods available for managing sedimentation problems in order to prioritize capital expenditures. The RESCON approach provides a way of assessing whether a project is sustainable or not and, when not, allows for the costs of establishing a retirement fund.

The RESCON computer model was developed as a demonstration tool of the RESCON approach. The model does not evaluate all possible sediment management methods. However, the options available should enable the user to ascertain, at a pre-feasibility level, what type of method is likely to be most effective. The model also has built into it an environmental and social safeguarding mechanism which, as well as acting as a checklist for identifying major impacts, also guides the user in the identification of a particular option that is unlikely to be acceptable.

The model is intended for use by experienced practitioners of water resources management. It is released as a "beta version" for further testing and improving in the field and as such it is acknowledged that it may contain errors. Users are advised to use caution and sound engineering judgment when interpreting the results.

The model has been tested against data from numerous dams around the world and has been shown to yield results in agreement with prototypes and proven detailed mathematical models. The RESCON approach to reservoir sedimentation management was also field-tried in Morocco and Sri Lanka, where managers and engineers were trained and the approach used to appraise methods of sediment management on a representative sample of reservoirs.

Policy Implications

The RESCON concept, as its application develops, has important policy implications, including:

- Influencing the way policy makers and engineers approach dam design
- Promoting sustainable dam projects through the application of the life cycle management approach
- Introducing the concept of intergenerational equity
- Encouraging the establishment of a retirement fund.

Recommendations for Further Work

The RESCON project has stepped up to the challenge of finding a way to achieve reservoir conservation and sustainable management of dams. It is hoped that this small, initial step will encourage other key players to follow in this path, which will require considerable effort to reach its goal.

There is a lot of work still to be done. Some of the more important aspects are outlined below.

Watershed management

Too little is understood about catchment erosion and its relationship to river sediment yields. This impacts the ability to develop mathematical relationships to estimate the benefits of various watershed management techniques on reservoir sedimentation. Further research into this field is definitely necessary.

Multi-criteria analysis

The method developed in RESCON is based primarily on an economic analysis of options. Environmental and social impacts are dealt with using the "safeguard" approach. This is a type of safety net to prevent options which have unacceptable impacts that cannot be mitigated from being selected as the preferred solution.

An alternative means of considering environmental and social issues (and for that matter other issues that may be of concern) is to use the concept of multi-criteria analysis (MCA). In its simplest form MCA appraises each option against each criterion independently and reports the results independently.

One of the benefits of using the MCA approach to option appraisal is that it allows for the assessment of options where environmental and social enhancements have been included.

Improvements to the RESCON Model

There are more than forty 45,000 large dams and reservoirs worldwide, and about 300 hundred new facilities are added each year, mainly in developing countries. Each dam and reservoir has its unique characteristics. Users should regard the RESCON model as a preliminary tool to be improved and adapted as necessary. Based on preliminary applications, we recommend the following:

- Further runs of the model using real field data to identify errors or limitations
- Explicit inclusion of flood management functions
- Explicit inclusion of other sediment management options, such as: density current venting, sluicing and reservoir bypass
- Ability to model a cascade of reservoirs may be "Better at
- Ability to model seasonal flow patterns to be able to better distinguish hydrological conditions that are more favorable to flushing than others
- Ability to set a limit to sediment concentrations to be released downstream as part of the environmental constraints
- Ability to include variable costs of environmental mitigation for each option analyzed.

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Annex A: LAUNCH WORKSHOP

Workshop Objectives

The first step of the RESCON team was to seek advice from a group of highly qualified experts in a workshop session held in Washington, DC, USA on December 9-10, 1999. The workshop was attended by twenty-five representatives from a broad range of stakeholders, including end-users (owners), academic and other research institutions, development organizations and consultants. Several Bank staff attended as well. The objectives of the workshop were as follows:

- ❖ Describe the processes that define relationships within and between the various parameters that determine the economic feasibility of sustainable management of water storage reservoirs
- ❖ Identify the principal parameters that impact sustainable management of storage reservoirs
- ❖ Determine whether, in principle, it is possible to develop functional relationships, which can be presented mathematically or graphically, to describe the behavior of the identified parameters
- ❖ Formulate mathematical relationships for the selected parameters, where possible
- ❖ Propose alternative means to analyze and incorporate the impacts of identified parameters that cannot be expressed in terms of mathematical relationships in the economic optimization
- ❖ Identify criteria that can be used to evaluate the technical feasibility of managing sediment in reservoirs and to evaluate environmental impact, social impact, retirement of dams and ancillary facilities and to decide on the economic feasibility of sustainable management of resources
- ❖ Identify feasible scenarios that can be used to facilitate the economic optimization of the problem.

Workshop outcomes

The expert input in the early stages of the research proved to be invaluable. Consensus was reached on several key aspects that substantially influenced the RESCON project. The conclusions of the workshop are summarized below.

Reliability of Current Predictive Tools on Sediment Related Problems

- ❖ Catchment soil erosion is less well understood than the process of reservoir sedimentation.
- ❖ The Universal Soil Erosion equation should not be used in other environments than those in which it was developed and calibrated (California), not even for sensitivity analyses.
- ❖ The most reliable approaches for quantifying erosion rates are considered to be (in order of increasing complexity): (i) sediment yield maps (where available); (ii) flow-sediment relationships (when sufficient data are available); and (iii) unit stream power equations (process oriented).

Stochastic Nature of Erosion/Sedimentation Processes

Long-term average values of sediment yield and sensitivity analysis should be used at option assessment or at pre-feasibility level. A more rigorous approach such as Monte Carlo simulations or fuzzy sets techniques would be more appropriate at project feasibility level.

Catchment Management

Catchment management should be considered as a factor influencing the sediment deposited annually in the reservoir by means of a coefficient that takes into account management practices. Until a literature review has produced better data, a sensitivity analysis based on current evidence should be used at option assessment and at pre-feasibility level. At the project feasibility level, more specific analysis by experts in the subject may be required. However, except in very small catchments, catchment management alone should not be relied on to significantly reduce sediment inflows to reservoirs.

Environmental and Social Aspects

Environmental and social aspects are complex issues that are difficult to quantify in monetary terms. Nonetheless they should be given the same "weight" as technical and economic aspects and be considered at an early stage of the option assessment process using a classification/ranking approach. This will help to inform the subsequent feasibility analysis.

Economic Analysis in the Presence of Long Life Span Periods

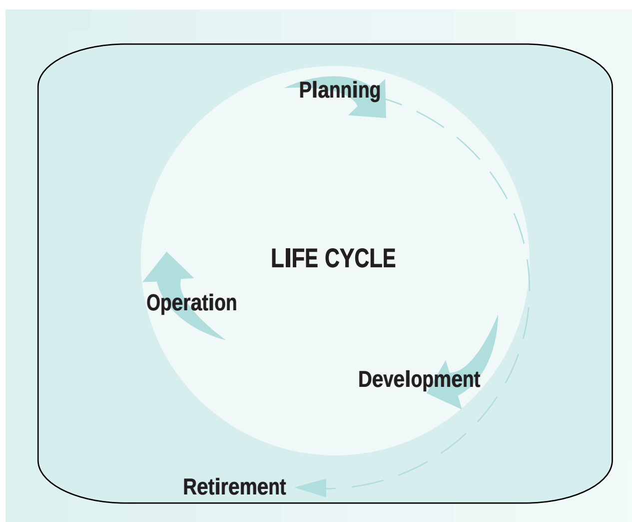
The choice of discount rates to assess the economic viability of reservoir projects is a controversial and extensively studied subject in academia. However, there is no reason why reservoir projects, although having a much longer life span than most other infrastructure projects, should be granted discount rates different than other project types. The workshop concluded that a constant discount rate rather than one that varies over time should be used and, as with all projects, the sensitivity of the economic viability of the project should be tested using a range of discount rates.

The longer project life of reservoirs results in costs and benefits occurring far into the future. The inability of traditional discounting techniques to assess these can be ameliorated by the use of a suitable financial plan for funding asset retirement or replacement.

Financial Approach for Funding Asset Retirement/Replacement

Retirement is only one of the available options, not necessarily the preferred option, or even an inevitable one. At the feasibility stage, the retirement plan should be addressed on a conceptual level. The plan should ensure resources for project retirement and site restoration. Monitoring of a reservoir's aging (notably sedimentation, structural condition, materials, change in use) should assist in determining how the residual life of the asset compares with the one anticipated at project conception. Annual deposits to the fund should be increased if the current estimate of residual life falls short of that anticipated. Deposits could be reduced in the opposite case (longer residual life). This mechanism should provide an incentive for allocating suitable funds for recurrent operation and management of the assets.

FIGURE A.1
LIFECYCLE OF A DAM



Available Technologies for Recovering Heavily Silted Reservoirs

Several sediment management techniques have been developed and validated on reservoirs around the world. There is consensus on the readiness of such techniques for reliable application, provided well identified pre-conditions are fulfilled.

Life Cycle and Evaluation Process

The life cycle of a dam should be used as the general framework for sediment management studies. Sustainability should be defined in terms of the reservoir's purpose. Planning, development and operation are the key phases of a continuous process. The benefits the dam provides should be periodically reviewed through an evaluation process.

ANNEX B: LITERATURE REVIEW

Introduction

Sediment accumulation leads to reductions in storage capacity, flood control benefits, power generation capability, regulation of irrigation and water supply releases, navigational and recreational use; and in extreme cases it can lead to dam failure. The purpose of this review is to provide a brief introduction to various aspects of reservoir sedimentation as they relate to the needs of the RESCON project. The focus is on economics and policy issues pertaining to sediment management, with some coverage of the engineering and physical sciences literature. The major topics included in the review are:

- ❖ General benefit-cost analysis and its application to sediment management
- ❖ Sustainability and intergenerational equity
- ❖ Reservoir sedimentation management
- ❖ Watershed management
- ❖ Multipurpose dams and multi-objective optimization
- ❖ Retirement of dams.

Benefit-cost Analysis

The literature on benefit-cost analysis in relation to dams has traditionally focused on individual dams (e.g., Paranjpye. 1988; Goldsmith and Hildyard, 1984-94) though there are a few prominent papers that are more conceptual. For example Cochrane (1989), Baecher, Pate and Neufville (1980), Pate-Cornell and Tagaras (1986) deal with the economics of dam failure. Another example is Miltz and White (1987), which explains a method of selecting an optimum reservoir size, taking sedimentation rate into account. In this method the optimum size is arrived at when the marginal cost for extra storage is equal to dredging cost, provided that the additional cost is utilized to store sediment.

Economic analyses of water projects involve an uncertain flow of costs and benefits, arising from the stochastic nature of stream flows. Hence a basic problem for the benefit-cost analyst is that of incorporating this uncertainty into measures of costs and benefits (see, for example, Quirk,1985).

Some studies of wider economic impact of dams also exist. For example, Aleseyed, Rephann and Isserman (1998) examine the effects of dams on country income, earnings and employment growth in local regions in the United States for dams built between 1975 and 1984. They find that the dams built for flood control and those built away from cities and with fewer people within 100 km had less impact on the economy. They also observe that a project may be recommended on the basis of positive impact on the nation but could have the opposite effect on the local economy.

In the past, dam projects did not appropriately consider sediment accumulation and its downstream environmental effects. An indication of the growing importance the environment has with regard to dams becomes apparent when a hydropower dam comes up for re-licensing; authorities in the United States, for example, consider the effects on endangered species, fisheries and other downstream activities. The costs of minimizing downstream impact can be substantial.

In general, environmental consequences are difficult to evaluate in monetary terms. Economists have developed various non-market valuation techniques—such as the contingent valuation method, the property value method and the travel cost method—to help in this regard (Freeman, 1993).

Selection of discount rate is another controversial topic, particularly in reference to long-lived assets such as dams. Concerns about intergenerational equity often lead to recommendations of low discount rates. This is discussed further in the following section.

Sustainability and Intergenerational Equity

Sustainability may be broadly viewed as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" WCED (1987). However, there is much ongoing debate over the precise definition of sustainability, sustainable development and related terms. Some of the key papers for the reader interested in following the debate are Asheim, Buchholz and Tungodden (2000), Chichilnisky (1997), Costanza and Patten (1995), Dasgupta and Maler (1995), Farmer and Randall (1997), Howarth, (1997), Howe (1997), Lele (1991), Norton and Toman (1997), Pezzey (1997), Solow (1992). The conclusion is that sustainability and intergenerational equity are closely linked. For example, Solow (1974) proposes that sustainability should allow intergenerational trade-offs, but no generation should be favored over any other. Indeed, independent sustainable preferences can define shadow prices for sustainable solutions, which can be used for project evaluation and for the characterizations of optimal solutions (Chichilnisky, 1997). Howe (1997) links sustainability to the supply side and to the capacity of a society to maintain or increase the level of some measure of aggregate utility while Howarth (1997) argues that intergenerational justice can be assured by endowing future generations with a structured bequest package. According to Norton (1995) this package includes specific endowments of reproduced capital, technological capacity, natural resources and environmental quality.

There have been a few case studies conducted on sustainable management of water resources, e.g., by Arntzen (1995), Bobba (1997), Carroll (1997), Charlton (1997), Nguyen (2000). These studies strongly call for incorporating the sustainability criteria in early stages of planning. A balance must be struck between current and future water requirements on the one hand and maintenance of a minimum water level for flood control and ecosystems, on the other. An economic analysis of sustainable sediment management in the context of dams is presented in Palmieri, Shah and Dinar (2001). In their model, reservoir storage space is reduced due to accumulation of sediment, leading to a decrease in benefits obtained. Sediment management can be practiced on sustainable basis, if the amount of sediment removed is equal to the incoming quantities. Even under non-sustainable alternatives, intergenerational equity can be achieved with a suitably defined retirement fund.

Estimate the NPV of a project requires choice of a discount rate. Higher discount rates lead to rapid utilization of the endowment, leaving little for future generations. Controversy still exists regarding the proper choice of a discount rate and this is highlighted in a special issue of the *Journal of Environmental Economics and Management* (1990). According to Moore and Viscusi (1990), 2 percent is a desirable rate to be used for many cases, with higher rates for positively correlated net benefits and lower for negative benefits. Lyon (1990) addresses the problem of determining discount rate policies that take into account economic principles and real world constraints. He suggests the use of a shadow price of capital approach to improve discounting policy. Scheraga (1990) argues that discount rates should vary according to resources under consideration and the time period involved. There is consensus that no particular discount rate is suitable for all possible applications (see, for example, Lind, 1990). There is also the opinion that "a defensible philosophical basis for long-term intergenerational discounting has yet to be found" Howe (1990).

Reservoir Sedimentation Management

Dam construction disrupts transport of sediments in rivers causing an imbalance between in flow and outflow. The problems this causes are diverse, i.e., they can occur upstream and downstream and vary widely from one site to another. A major effect of sedimentation on reservoirs is the loss of storage capacity. The extent of storage loss depends on the sediment yield as well as other physical site characteristics. Average annual storage loss worldwide is 0.5-1 percent (White, 2000). Sedimentation may also clog dam outlets and greatly accelerate abrasion of hydraulic machinery and structures (e.g., spillways), thereby decreasing efficiency, increasing maintenance costs and reducing safety. Increased loads on a dam by sediment build up may also lead to reductions in safety factors against sliding and overturning of some dams.

Sedimentation reduction measures include upstream soil conservation practices, control of distribution of deposits, construction of debris basins and control of turbidity (Yang, 1999). Sediments may also be removed from the reservoir by various means. Common techniques for such removal include flushing, hydraulic dredging, trucking and hydrosuction. These techniques are described briefly below. See also Morris and Fan (1998).

Watershed Management

Watershed management is a broad concept incorporating the plans, policies and activities used to control water and related resources and processes in a given watershed. Watershed management activities can range from hands on guidance to farmers about how to control runoff to multi-state initiatives like those under way to improve the health of the Chesapeake Bay in the USA. Successful watershed management strives for a better balance between ecosystem and watershed integrity and provision of social and economic goals. Stanford (1997) discusses several general objectives that can be managed within a watershed context.

Government attempts at watershed management have been ongoing in the United States for more than half a century, but the science of watershed management is still evolving and many of our current activities are, in essence, experimental. Organizations for watershed management are most likely to be effective if their structure matches the scale of the problem.

Watersheds release soil and water to downstream areas with consequences that may have beneficial and/or harmful dimensions (see White and Runge, 1994). Watershed management can be important for environmental issues like water quality, flood control, sedimentation control, as well as economic benefits like hydropower generation. Dixon and Hufschmidt (1986) report that watershed management could be economically attractive for the Nam Pong water resources project only with a low discount rate. Two possibilities were considered, one with watershed management and one without. The results are shown in Table B.1.

Wang, Hu and Kao (1998) describe application of watershed management on the Ming-Hu and Ming-Tan reservoirs in Taiwan, the primary objective being reduction of sediment deposition and a consequent increase in hydropower production. The benefit-cost analysis of such management for both dams (using a discount rate of 5 percent over the period from 1981 to 2010, with 1995 as the base) yielded a benefit-cost ratio of 1.182 and NPV of 1,589 million new Taiwan dollars.

TABLE B.1

50 YEAR GROSS BENEFITS OF NAM PONG WATER RESOURCES PROJECT (million Baht)

	With watershed management	Without watershed management
0% discount rate	12,542	11,398
6% discount rate	4,029	4,095
10% discount rate	2,550	2,701

Based on statistics found on page 161 of Dixon & Hufschmidt (1986).

Flushing

Flushing is the term given to the lowering of the reservoir level by means of low-level outlets in the dam to induce riverine conditions throughout the reservoir and thus mobilize and evacuate sediments previously deposited. The technique has been practiced on many dams throughout the world, some with great success.

Factors influencing flushing are (see White, 2000):

- Reservoir shape (best results from long and narrow reservoirs)
- Reservoir volume (the smaller the reservoir volume in comparison to the annual flood volume the better the results)
- Hydraulic conditions (best results from induction of riverine conditions in the reservoir)
- Predictability and magnitude of the annual flood
- Mobility of reservoir sediments.

Major factors limiting the application of flushing are: downstream effects and the temporary loss of storage and water head in the reservoir (a particular problem for hydroelectric stations).

Hydraulic Dredging

The hydraulic dredging technique involves physical removal of sediment and deposition at a suitable disposal site. The reservoir is not emptied. Rather, barges are used for collection and transportation of sediment. Dredging may focus on removing silts, organic sediments and cleaning specific areas such as hydropower intakes, navigational channels and recreational areas. An important issue with dredging is availability of suitable disposal sites. When calculating dredging costs, the cost of disposal land should be included. A compilation of dredging cost has been carried out by Basson and Rooseboom (1999).

Trucking

This technique, like hydraulic dredging, involves physical removal of sediment but requires drawdown of the reservoir. After the water is removed, sediment is transferred into trucks and transported to a suitable site. A limitation hindering its frequent use is the availability of a suitable site to dump the excavated sediment. The cost of drawdown, transportation cost and, if applicable, land cost of the dumping site should be included in the benefit-cost calculations.

Hydrosuction

This is one of the lesser used techniques for sediment removal (Hotchkiss and Huang, 1995). The technique is similar to that of traditional dredging but uses the hydraulic head created by the dam as the source of energy for sediment removal. Sediments are deposited downstream of the dam. Hydrosuction may be of two types, hydrosuction dredging and hydrosuction bypassing. Dredging involves the removal of previously deposited sediments, while bypassing intercepts incoming sediments before settling in the reservoir. According to Hotchkiss and Huang (1995) this technique has certain criteria of applicability, such as particle size, reservoir elevation and turbidity, which need to be verified in advance.

Economics of Multipurpose Dams and Multiple Objective Programming

Dams may be multipurpose, i.e., used for irrigation, hydroelectricity generation, water supply, recreation and flood control. Multipurpose dams can be managed using multiple objective decision techniques or multi-criteria analysis (MCA). The typical procedure is to create a mathematical model emphasizing the primary objective and incorporating the secondary objectives as constraints. Multi-objective programming is a valuable tool for assisting in optimally managing water resource systems in particular and socio-ecological systems in general. The range of applications includes transportation, project selection for research activities, economic production, quality of life, managing an academic department, game theory and many others. The method is designed to find the preferred solutions to a problem in which discrete alternatives are evaluated against criteria or factors ranging from cost (quantity criterion) to aesthetics (quality criterion). This often provides a viable way for structuring and presenting a problem that is otherwise not well defined.

There is considerable literature on the theory and applications of multi-objective (multi-criteria) decision techniques—see, for example, Cohon (1978) and Harboe (1992). A special edition of the *Water Resources Bulletin* (28, 1992) is devoted to this topic and explains the various techniques involved. Hipel, (1992) provides an overview of all the articles published in this special issue. Ko et al (1992) apply several multi-objective tasking methods such as goal programming, compromise programming and trade-off development programming to the Han River Reservoir system in Korea in order to choose the best method. Also, a manual published by the Department of the Environment, Transport and the Regions (DETR), UK, explains in detail various aspects of MCA. It describes MCA as a technique that "can be used to identify a single most preferred option, to rank options, to short-list a limited number of options for subsequent detailed appraisal, or simply to distinguish acceptable from unacceptable possibilities" (Dodgson, et. al, 2000). Another type of approach is presented in Krawcyzk (1995), who develops an optimization model using a decision support tool to arrive at environmentally acceptable decisions. This model makes use of control-through-levies which provides a range of feasible options, each with a different trade-off between economic and environmental indicators.

Economics of Dam Decommissioning

Dams may be decommissioned for several reasons, including structural safety, reservoir siltation and modification of societal values (ASCE, 1997). To date, concerns over safety have been the primary reason for decommissioning. Siltation reduces storage capacity, affects the turbines and consequently increases the cost for electricity production and reduces benefits. As these benefits decrease, the pressure to retire or decommission increases.

There are three basic options for managing an aging dam. The dam can be rehabilitated, modified, or completely removed. Decommissioning should consider sediment management in detail as removal of a dam might cause an uncontrolled release of sediment downstream affecting the ecosystem, geomorphology and human activities. See Zhou and Donnelly (2002).

Partial or complete removal may be accomplished as a staged process extending over a period of years to reduce the rate of sediment release. An in-depth explanation of the evaluation method for this, along with case studies, is available in the *Guidelines for Retirement of Dams and Hydroelectric Facilities* (ASCE, 1997). An example of retirement is the case of the four dams built on Lower Snake River in the United States. See Lansing (1995) and also World Commission on Dams (2000).

Economics requires analysis of different retirement alternatives, calculation of the values of each alternative and finally comparison of benefits and costs. The benefits and costs should be analyzed in a manner that is equitable from an intergenerational perspective. According to Solow (1974) "…earlier generations are entitled to draw down the pool so long as they add to the stock of reproducible capital."

ANNEX C: WATERSHED MANAGEMENT

State of Knowledge

Some of the principal reasons for the current lack of understanding of sediment transport processes and how they relate to catchment processes are a lack of accurate and appropriate data, inability to correctly formulate the physics of sediment transport processes in mathematical terms or to successfully simulate sediment transport or catchment processes in a way that allows solution of practical problems. Erosion and sediment transport processes are extremely complex and are driven by interaction of large numbers of variables.

Measurement of sediment load in rivers requires determination of the magnitude of the sediment load that is in suspension in the water as well as the proportion of the load that is transported along the riverbed. The suspended load varies as a function of space and time in the water column and accurate measurement is almost impossible. Similarly, bed load transport varies over the width of the river in both space and time, making its measurement very difficult. Adams (1980) indicated that the measurement error in the data that he used to estimate sediment yield could vary between +100 percent and -50 percent, which is not unusual.

The current formulation of sediment transport and catchment processes is empirical in nature. All sediment transport equations that are now used to simulate sediment transport phenomena are empirical correlations of experimental or field observations, not representative formulations of physical processes. Similarly, erosion processes are formulated in terms of loosely defined coefficients and products of the same (e.g., the Universal Soil Loss Equation) or, in the most advanced form, are represented partly by empirical sediment transport and partly by other empirical mathematical expressions. When comparing sediment transport calculations with observed data it is found that the error is between 50 percent and 150 percent (Yang 1996).

Sediment transport in rivers is only one component of the whole process, from the original erosion of sediment particles in a catchment, erosion from riverbanks and streambeds, to the re-deposition and re-suspension of sediment as it is transported from source to sink. This increases the complexity of the problem—compounded by variations of the processes in both time and space, which are integrally related—making it difficult to solve with any accuracy. For example, the amount of sediment transported in a river is dependent on the availability of the sediment and the sediment transport capacity of the river. It may happen that the sediment transport capacity of a river is very high, but that its bed consists of rock. While transport capacity may be high, this is not a guarantee that large loads of sediment are actually carried by the river. The sediment supply may vary in time; further, a river's particular sediment transport can result in a wide range of sediment discharges.

Sediment Delivery Ratio

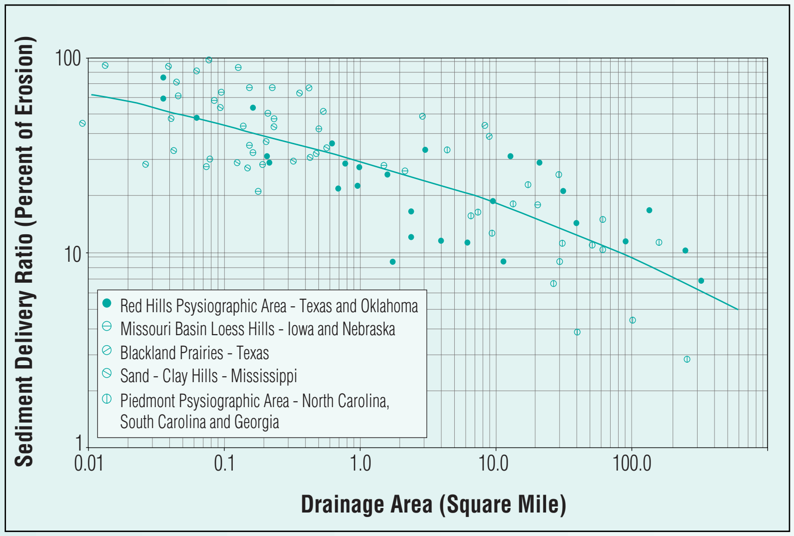
The relationship between catchment processes and the amount of sediment discharged in rivers also is complex and is affected by processes that vary in space and time. Sediment that is discharged in rivers originates from riverbanks, riverbeds and from tributaries and gullies throughout catchments. Part of the sediment flowing in tributaries and gullies originates from surface flow that causes erosion of soil.

The process of erosion can dislodge large volumes of material. However, not all eroded material ends up in rivers. The proportion that finds its way to the rivers is often referred to as the sediment yield of a catchment. The sediment yield carried by a river is related to catchment erosion by making use of a coefficient known as the Delivery Ratio, which is calculated as the ratio between the volume or mass of sediment discharged in a river and the volume or mass of soil eroded in its catchment.

An example of the relationship between Delivery Ratio and catchment area for selected areas in the United States is shown in Figure C.1.[11] This figure indicates that the Delivery Ratio can vary between 5 percent and 70 percent, depending on the size of the catchment. For catchments greater than 100 km^2 the figure indicates that delivery ratios can be significantly lower than 10 percent. This demonstrates the large amount of sediment storage that can be found in the river systems of a catchment. Furthermore, for a given catchment size there is significant spread of sediment delivery ratios. Catchment size is obviously not the only factor defining Delivery Ratio. Topography, stream pattern, climate and a number of other factors determine this relationship.

FIGURE C.1

DRAINAGE AREA VS SEDIMENT DELIVERY RATIO



Details related to certain procedural and technical as Figure C.1 Drainage Area vs Sediment Delivery Ratio

Source: Boyce, R.C.,1975. "Sediment Routing with Sediment-Delivery Rations," pp.61-65. In *Present and Prospective Technology for Predicting Sediment Yields and Sources*. ARS-S-40. USDA Sedimentation Lab., Oxford, Miss.

Full understanding of these relationships is lacking. For example, by using exactly the same data set, Griffiths (1979) and Adams (1980) estimated sediment yield from rivers in the Southern Alps of South Island, New Zealand that differed by 70 percent. On one of the rivers there was a 48-fold difference in sediment yield estimates (Morris and Fan 1997). In spite of these differences these two authors view their results as being in "general agreement." This degree of uncertainty is typical of sediment transport work.

Spatial variability

Sediment yield in rivers varies as a function of space. Data from around the globe show specific sediment yield ratios from as little at 10t/km^2/yr to as much as 20 000t/km^2/yr (Vanoni 1975). For a given climatic and geological zone specific sediment yields often show an inverse relationship to catchment area, i.e., the bigger the catchment the lower the sediment yield per unit of area. This is demonstrated by Strand and Pemberton (1982) for the semi-arid regions of the Western United States (Figure C.2).

Satisfactory determination of the impact of spatial parameters on sediment yield is complex because of the large number of factors involved. Factors that should be considered include the stream pattern and order, climate and climate change, vegetation, geology, soil types, catchment activities like agriculture and urbanization, rainfall characteristics, likelihood of stream bank and streambed erosion, the presence and frequency of landslides, topographic features, etc.

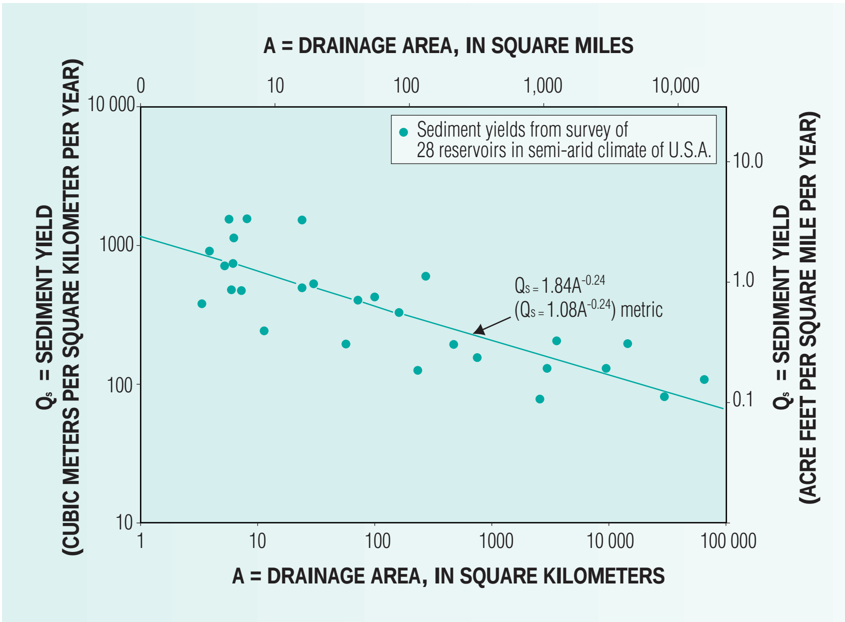
Temporal variability

Erosion from catchments and sediment discharge in rivers vary as a function of time, within storm or flood events, seasonally, inter-annually and over the long term.

An example of how sediment discharge varies during the course of a flood event is shown in Figure C.3. This figure shows variation in sediment

FIGURE C.2

CATCHMENT AREA VS SPECIFIC SEDIMENT YIELD



Source: Strand, R.I., and Pemberton, E.L., 1987. "Reservoir Sedimentation," In *Design of Small Dams*. U.S. Bureau of Reclamation, Denver.

concentration during the course of a flood in the Mississippi River at Chester, Illinois, USA. The figure is a good example of a typical phenomenon—where sediment concentrations are often higher during the rising limb of a hydrograph and lower at the peak.

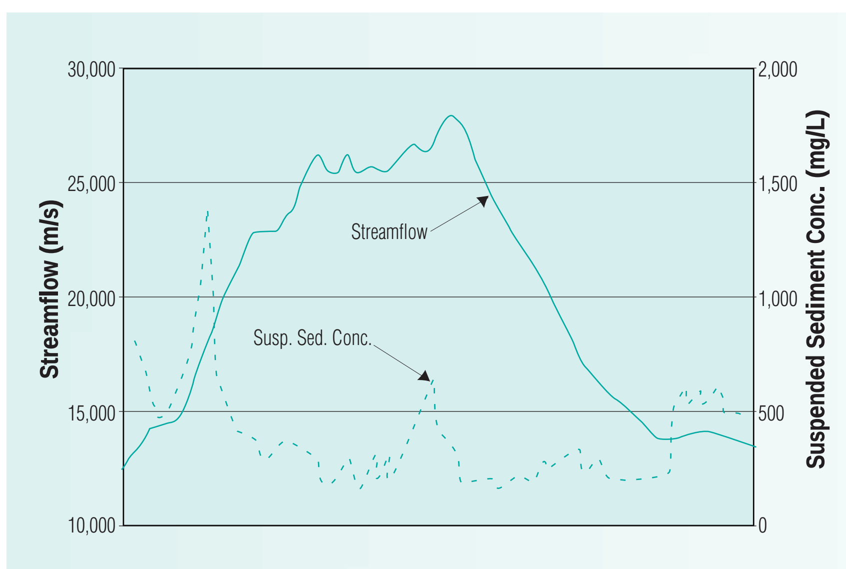
This phenomenon causes particular problems for the hydrologist trying to predict sediment inflows to a reservoir. Sediment data are often scarce compared to hydrological data. Therefore the hydrologist will be tempted to derive a relationship from sediment concentrations and flow records in an effort to predict sediment inflows, even though there is no unique relationship between flow rate and sediment concentration. See Figure C.4, which shows sediment load in the Caledon River in South Africa (Rooseboom, 1992). This river mainly carries fine grained sediment and the amount of sediment discharged by the river is dependent on the availability of sediment at any one point in time.

Seasonal changes in sediment transport result from differences in rainfall and streamflow, changes in vegetation characteristics of the catchment and a host of other factors. Inter-annual variability can occur for the same reasons.

Long tem changes can result from changes in catchment conditions. Rooseboom (1992) presents a mass curve of sediment load in the Orange River as a function of time from 1930 to 1970 (Figure C.5). A change in trend is observed around 1950. The exact reason for this change in slope is not known. One explanation could be that soil conservation structures became effective, but the exact relationship between when they were built and when the effect materialized is unknown. During this same

FIGURE C.3

VARIATION OF SEDIMENT CONCENTRATION DURING A FLOOD EVENT

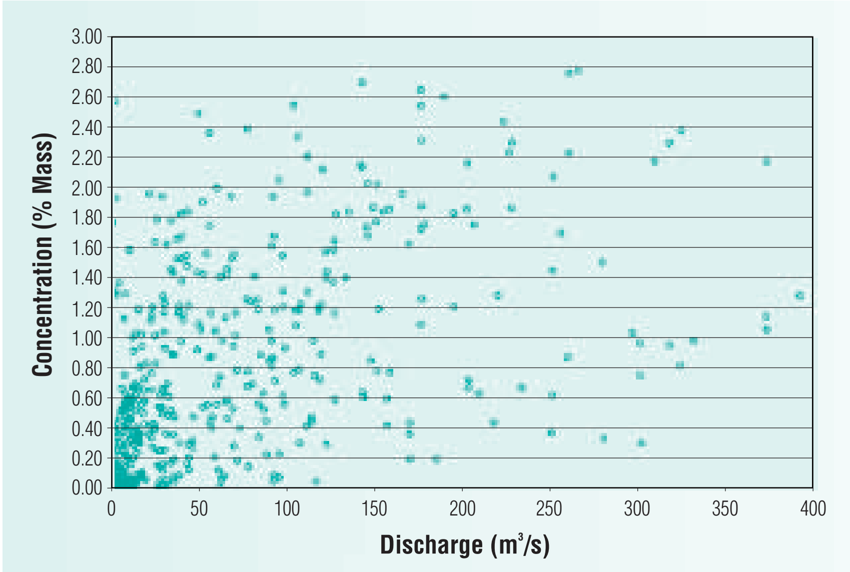


Source: Holmes, R.R., and Oberg, K.A., 1996. "Sediment and Hydraulic Data Collected During the Upper Mississippi River System Flood of 1993," pp.8.38–8.44, *6th Federal Interagency Sedimentation Conf., Las Vegas*.

period, the number of sheep in the catchment of the Orange River increased quite significantly. Following conventional argument, one would reasonably expect that erosion and therefore sediment yield should increase if the sheep population increases. Sheep graze grass down to the roots and expose more soil to the erosive forces of water. Although a change in sediment load has been observed, the relationship between catchment processes and yield is not clearly known. Prediction of the impact of alternative catchment management techniques is therefore not reliable at this point in time.

FIGURE C.4

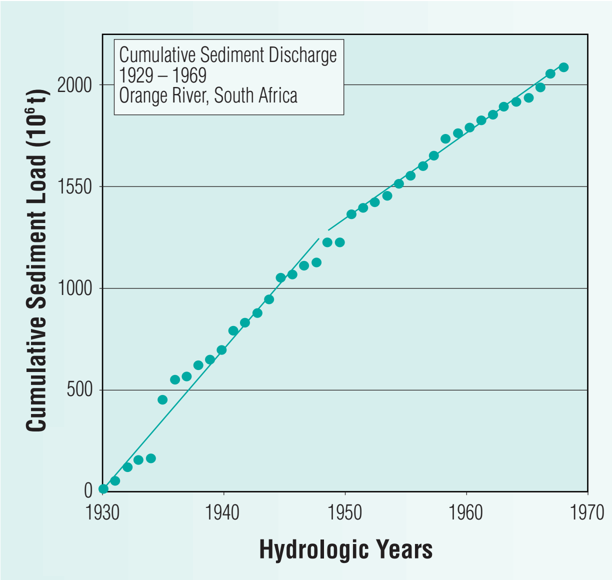
DISCHARGE VS SEDIMENT CONCENTRATION



Source: Rooseboom, A., 1992. “Sediment Transport in Rivers and Reservoirs: A South African Perspective,” Report to Water Research Commission of South Africa, by Sigma Beta Consulting Engineers, Stellenbosch.

FIGURE C.5

LONG-TERM VARIATION OF CATCHMENT SEDIMENT YIELD



Source: Rooseboom, K. 1992. “Sediment Transport in Rivers and Reservoirs: A South African Perspective,” Report to Water Research Commission of South Africa, by Sigma Beta Consulting Engineers, Stellenbosch.

ANNEX D: ASSESSING FEASIBILITY OF FLUSHING

Introduction

In many areas of the world the life span of reservoirs is determined by the rate of sedimentation, which gradually reduces storage capacity and eventually prevents facilities from reliably supplying water and power. Many major reservoirs are approaching this stage in their life.

One way of preserving reservoir storage is to flush sediments through purpose built outlet works. This technique can be applied to existing dams (with modification of the engineering works) and to new dams. However the technique is only effective under certain favorable conditions and is not universally applicable. This section outlines the criteria required to make flushing successful.

A recent study carried out by HR Wallingford (White, 2001) has evaluated where and when the flushing of sediment may be an appropriate method of sustaining reservoir storage. The study included the following aspects:

- An assessment of the scale of the problem of reservoir sedimentation
- An estimation of the volume of storage that is likely to be required to meet continuing demand internationally
- A review of the current state of knowledge of the mechanism of sediment flushing from reservoirs
- A review of the worldwide experience of sediment flushing from reservoirs
- Identification, in general terms, of the areas of the world where flushing is likely to be most useful.

Definition of Flushing

Flushing is the term given to the removal of incoming and deposited sediments in a reservoir by making use of the natural energy of the flowing water.

There is a distinction between sediment flushing and sediment sluicing. Sediment flushing is concerned with the removal of sediments which have settled in the reservoir at a previous time as well as passing through incoming sediments during the flushing event, whereas sediment sluicing is concerned with only passing sediments through the reservoir during times of flood. The distinction is sometimes difficult to make but, generally, sediment flushing is used to remove sediments up to and including sands and gravels whereas sediment sluicing generally removes only the finer fractions.

Factors that Influence Viability and Efficiency of Sediment Flushing

The following sections outline the factors that influence the viability and efficiency of flushing. The reader is referred to Atkinson (1996), who details the methodology for estimating efficiency of flushing at a given reservoir based on reservoir geometry, sediment types, discharge regimes and flushing capacity, etc. The relationships presented there have been used to determine the technical feasibility of flushing of a given reservoir in the RESCON model. Where more detailed studies are required, the relationships in Atkinson together with daily flows can be used. Volume II of this book outlines the methodology detailed by Atkinson.

Hydraulic conditions required for efficient flushing

Riverine conditions must be created in the reservoir for a significant length of time. The reservoir level must be held low throughout the flushing period, possibly with minor fluctuations in level to activate sediment movement. To achieve this:

- The hydraulic capacity of the outlet must be sufficient to maintain the reservoir at a constant level during the flushing period.
- Flushing discharges of at least twice the mean annual flow are required.
- Flushing volumes of at least 10 percent of the mean annual runoff should be anticipated.
- For best results the flushing outlet should be situated close to the dam and as near as possible to the original river bed elevation.

Quantity of water available for flushing

There must be enough water available to transport the required volume of sediment. This has the following implications:

- Reservoirs where the annual runoff is large compared with the volume of the reservoir are best suited for sediment flushing.
- A regular annual cycle of flows and a defined flood season provide optimum conditions for sediment flushing. This favors sites in monsoon areas and sites where flood flows are generated by annual snowmelt in the spring and summer months.
- A balance must be achievable between the significant quantities of water required for sediment flushing and water required to satisfy demands at other times of the year—for irrigation and hydropower, for example.

Mobility of reservoir sediments

The nature and quantity of river sediments are important factors in determining whether the quantity of water available for flushing is adequate to remove the desired quantity of sediment from the reservoir.

Graded bed sediments produce conditions which are the most conducive to efficient flushing. Such conditions are typical of gravel rivers with a varying bed material composition. In large rivers this situation is found where the longitudinal bed gradient is between, say, 0.001 and 0.002. In smaller rivers the equivalent range may be 0.002 to 0.005.

From the point of view of sediment size alone, delta deposits of fine sand and coarse silt are the most easily flushed. Coarser material is difficult to move and tends to deposit at the upstream end of the reservoir. Finer material which deposits in the body of the reservoir outside any incised channel will not be available for remobilization during flushing.

Site-specific factors

The most suitable conditions for flushing are to be found in reservoirs which approximate in shape the incised channel that develops during flushing. Long, relatively narrow reservoirs are better suited to flushing than short, wide, shallow reservoirs.

Where reservoirs are very wide, flushing will only produce a narrow incised channel through the deposited materials and only a portion of the original capacity can be regained.

Summary

Reservoirs in the "upper and middle reaches" of rivers are likely to be best suited to sediment flushing for the following reasons:

- In the lower reaches reservoirs are likely to have inundated areas that had previously been flood plains and these areas would not be reached by the incised flushing channel which is inevitably of limited width.
- The longitudinal slope available for the flushing channel is relatively small thus limiting the amount of sediment transported.
- Reservoir volumes in the lower reaches are likely to be larger compared with the mean annual runoff and hence water availability becomes a restraint on sediment flushing.

Worldwide Experience of Sediment Flushing

White, 2001, looked at fifty reservoirs which are being or have been flushed. In some cases the flushing was successful, in others there was little or no success. The main findings from this worldwide review, some of which confirm directly the semi-independent analysis of those hydraulic factors that favor sediment flushing, are:

- ***The hydrology and sedimentology of the catchment:*** The hydrology and sedimentology of the catchment need to be fully understood in the planning of flushing facilities for new or existing reservoirs and to provide the background for analyses of past sedimentation and flushing performance.
- ***The storage capacity of the reservoir:*** Successful hydraulic flushing is more likely to be practicable in reservoirs which are hydrologically small, with

a storage capacity less than 30 percent of the mean annual inflow. The smaller the reservoir, the greater the chance of it being successfully flushed and the larger the likely residual storage capacity.

- *The sediment deposition potential:* Flushing is vital for the preservation of long-term storage in reservoirs where the sediment deposition potential is greater than 1 percent to 2 percent of the original capacity.
- *The shape of the reservoir basin:* Worldwide experience confirms that the shape of the reservoir basin can have a large impact on the practicability of effective flushing and the residual storage capacity. Narrow steep-sided reservoirs in valleys with a steep longitudinal slope are the easiest to flush. Wide valleys where the impoundment covers former floodplains can be less effectively flushed, because the deposits tend to consolidate and are remote from the flushing channel.
- *The deployment of full or partial drawdown:* Full drawdown and empty flushing have been found to be much more effective than partial drawdown.
- *The low-level outlet facilities provided:* Worldwide experience confirms that, for effective flushing, the low-level outlets must be both low enough and of sufficient capacity to allow significant drawdown of water levels to be controlled during the time of year when flushing is undertaken. Proportionately larger outlets are required for flood-season sediment sluicing during the flood season than for sediment flushing at the outset of the flood season.
- *The scope for enhancements to flushing:* Fluctuations in water level and discharge during flushing are beneficial to the promotion of bank slumping, increasing the rate of sediment movement. Also, the deployment of lateral and longitudinal diversion channels has been successful in promoting flushing in reservoirs which are hydrologically large or contain significant proportions of deposition in areas remote from the main flushing channel.
- *Operational limitations:* Operational considerations, such as water and power demands, can inhibit the ability to flush successfully.
- *Downstream impacts:* Downstream impacts can act as a constraint in the planning and operation of sediment flushing. In some cases flushing may be ruled out, whereas sediment sluicing, which approximately preserves the seasonal distribution of sediment load, may be a practicable alternative during the early life of a reservoir.

Geographical Areas Suited to Flushing

Climatic zones

An understanding of the precipitation regimes throughout the world may allow the definition of climatic zones based on temperature and precipitation regimes. This may in turn permit the definition of areas of high and low erosion rates. It is difficult to classify distinct climatic zones as they tend to merge into one another rather than have sharp boundaries, but a number of general models have been produced.

There have been many climatic classifications produced but one of the most common is based on the original Koppen classification (Pidwirny, 1999) with eight climatic regions based on four temperature zones and one moisture zone and the seasonal domination of air masses. These regions are as follows:

- Tropical Wet
- Tropical Wet and Dry
- Tropical Desert
- Mid-Latitude Wet
- Mid-Latitude Winter Dry
- Mid-Latitude Summer Dry (Mediterranean Climate)
- Polar Wet and Dry
- Polar Desert.

Hydrological characteristics

Experience has shown that low reservoir water levels provide the most effective conditions for sediment flushing. To allow water levels to be lowered requires confidence that rainfall can be relied upon to refill the reservoir. It follows that well defined wet and dry seasons will be favorable for a sediment flushing regime. Such a climate is defined by Koppen as tropical wet and dry. Also, there are areas in the mid-latitudes where spring snowmelt provides a regular and predictable annual pattern of high flows.

River discharges must also be sufficient to transport sediment loads through the reservoir. Regions of low precipitation like the Sahara and other desert environments will therefore not be suitable for flushing even if they exhibit a defined seasonal effect.

The availability of water will also affect the duration and discharge rate of the flow required for flushing. Where there is a limited amount of water it is better to use a high discharge for a short period of time than a low discharge for a long period of time. This increases the amount of sediment that is removed.

Areas of the world best suited to reservoir flushing

It is not possible to define precisely which specific areas of the world will provide conditions for successful flushing. In reality there is a spectrum of conditions ranging from those sites where conditions are ideal to those sites which are quite unsuited to sediment flushing.

Given the foregoing, the requirements for successful flushing are most likely to be met in the following locations:

- Parts of Central America extending into South America
- Areas in North and South America where the rivers are fed by the Rockies and the Andes
- Parts of Central Africa from the Ivory Coast in the west to Sudan in the east
- Areas in Central Asia where the rivers are fed by the Himalayas including Pakistan, India and Nepal
- Parts of Asia including Cambodia, Vietnam and Thailand.

Design Implications for Flushing Facilities for New and Existing Reservoirs

The requirement to establish riverine conditions in a reservoir for successful flushing results in construction of low-level outlets that are often very large. Where flushing is being investigated as an option for managing sediments in an existing dam this poses particular problems and will require specialist investigations. There are numerous stages for such investigations. The following is an indicative list, which should be reviewed and amended according to specific project circumstances.

Layout

Flushing facilities have to be able to withstand high velocity flows with high concentrations of sediment. Such flows are highly abrasive and expensive steel lining will normally be required to avoid undue damage to the structures. Hence it is important that the site allow for construction of relatively compact flushing facilities, either orifices within the dam itself or relatively short tunnels or channels. Energy dissipation works will normally be required at the downstream side and it is an advantage if these facilities can be shared with other outlets such as high head spillways or irrigation outlets. It is better to have the flushing facilities discharge to the downstream channel well away from power station outlets as any local deposition of sediments will increase tailwater levels and reduce power output.

The reservoir itself requires a detailed survey to establish its topography. This is needed to check whether the reservoir basin is a suitable shape for sediment flushing and also to provide input data for detailed modeling of the sedimentation process within the reservoir.

Hydrological investigations

As noted above, there are certain requirements for successful sediment flushing related to the amount of water available and its annual and seasonal reliability. Hence inflows to the reservoir need to be established with confidence. This involves the acquisition of historical records of river flows going back at least 30 years and preferably longer. Records of river flows can often be extended further back in time by considering local rainfall records, which often go back 100 years or more and undertaking catchment modeling to convert rainfall into runoff.

The rate of sediment transport is related to river discharge through a power function. Sediment transport rates are therefore highly sensitive to changes in river flows. Mean values of inflows are not adequate to estimate sedimentation rates. The smaller the time step the better the predictions will be. However, for most situations a daily time step should be adequate.

The ideal situation for sediment flushing is an annual inflow of water of at least 3 times the volume of the reservoir (original volume in the case of existing reservoirs) and an annual hydrograph which shows distinct wet and dry seasons.

Sediment investigations

The amount and nature of the sediment entering or likely to enter the reservoir needs to be established.

This requires measurements over many years to establish the results with confidence. There are various approaches to this task. Most commonly sediment transport is measured at a gauging station not too far upstream of the reservoir and a relationship between flow rate and sediment transport rate is established. The long hydrological record is then used to compute the total amount of sediment passing the gauging station by integrating over the period of the record. There are some dangers in doing this because there is no unique relationship between flow rate and sediment transport rate for fine cohesive sediments, the quantities of sediment being determined by the amount being washed off the catchment, not the capability of the river to transport them. Bed load is difficult to measure and is often estimated as 10 percent of the total sediment load. An alternative approach is to calculate the bed load using established predictive techniques.

In the case of existing reservoirs, information about the amount of sediments entering the reservoir can be augmented by surveys of the amount and nature of the material settling within the reservoir. This can be undertaken using bathymetric surveys and borehole samples taken from the sediments. Care is required, however, to allow for the amount of mainly fine material that passes through the reservoir without deposition.

Bed material sampling should be undertaken in the reservoir and in the rivers that feed the reservoir. A sound knowledge of the nature of these sediments, including their size and specific gravity, is an essential requirement to provide inputs for numerical models that simulate sediment movement.

Hydraulic modeling

Sophisticated numerical (computer) modeling of the way sediment is likely to behave within the reservoir and the amount and nature of the sediment that will be passed to the downstream reach is the cornerstone of any detailed evaluation of flushing facilities. One dimensional models with quasi two-dimensional simulation of the incised channel which develops during sediment flushing are the most appropriate tools. These models are computationally efficient and are capable of making long-term simulations, decades rather than hours or days. They have reached reliability levels which permit them to be used "cold" on new reservoirs that are only at the investigative stage. When used on existing reservoirs they have the added benefit of measured sedimentation data for verification purposes.

Computer simulations of reservoirs ideally use representative, long-term sequences of water and sediment inflows to the reservoir. The models are capable of looking at the effectiveness of various aspects that affect reservoir sustainability over periods of up to 50 or 60 years, including:

- Measures to reduce the amount of sediments entering reservoirs such as catchment conservation or upstream storage.
- Measures to manage sediments within reservoirs such as variations in the operating rule curves for the reservoir. Rules that permit emptying of the reservoir annually promote movement of sediment towards the dam. Rules that maintain high water levels ensure storage of sediments at the upstream end of the reservoir and help to extend reservoir life albeit with the penalty of reduced water yield.
- Measures to evacuate sediment from the reservoir including dredging and sediment flushing.

Engineering and costs

The design of the civil works involved in all the options for helping to sustain reservoir capacity needs to be estimated so that the best solution can be found.

System simulation modeling

System simulation modeling is required to evaluate the conflicting demands of hydropower production, irrigation and other requirements and must be able to assess the impacts of the various reservoir operating strategies. The simulation model must be able to replicate the outputs of water and power under a range of operating strategies so that an optimal economic and technical solution may be identified. In addition, it must be possible to take account of the effects of other reservoirs upstream and downstream of the one under consideration.

ANNEX E: ENVIRONMENTAL CONSIDERATIONS

Introduction

This annex provides an expanded discussion of the environmental considerations outlined in the main text. While the safeguards approach presented there is an important step, a more careful consideration of environmental costs is necessary to determine the true costs of alternative sediment management strategies.

The world's ecosystems are an asset that, if properly managed, yields a flow of vital services. Unfortunately, relative to other forms of capital, ecosystems are poorly understood, rarely monitored and many are undergoing rapid degradation and depletion. More often than not, the importance of ecosystem services is widely recognized and appreciated only upon their loss.

Worldwide, ecosystems are being protected or restored to control floods, filter water, enhance soil fertility, mitigate climatic extremes and provide for human enjoyment. These developments all involve putting a "price tag" on nature. Individuals and societies already assess the value of nature implicitly in their collective decision making, often considering ecosystem services as "free." Until recently, such an approach was generally acceptable, because generally speaking ecosystem capital was abundant and the impacts of economic activity were minimal. However, as ecosystem capital becomes increasingly scarce, it is critical to understand both how to value ecosystems and the limits of such valuations.

To establish sound policy, the "production functions" that describe how ecosystems generate services need to be characterized and the interactions among the functions quantified. To begin, the sources and consumers of ecosystem services must be catalogued. For any given location this would document service flows occurring locally, regionally and globally. The production functions would also reveal critical points and interdependencies in the supply of services and in the time frame over which services are amenable to repair. Yet these are currently poorly known and are likely to remain elusive. Ecosystems typically respond to perturbation in a nonlinear fashion. Putting theory into practice will require locally based information.

There are three fundamental steps in decision making. The first step, identification of alternatives, is probably the most important and frequently the most underrated. In this decision making tree the RESCON Model provides the first step. The analysis of the model will provide a set of feasible alternatives for sediment management. The second step requires that all impacts be identified and measured for each alternative; everything from immediate needs for labor, capital and other inputs to long-term biophysical and social impacts. Rarely does sufficient knowledge exist to make precise estimates, but it is important to try to quantify uncertainties and the risks of proceeding. This annex provides an overview of the impact parameters, the values of which should be considered in determining the environmental cost of each of the feasible alternatives generated by the RESCON Model. The third and final step, valuation, translates the consequences of maintaining the status quo and opting for each alternative into comparable units of impact on human wellbeing, now and in the future. The common measuring unit is typically monetary. There are drawbacks associated with most ways of inferring value and coupled with the functional lack of information on ecosystem services, valuation is especially difficult. Another key problem is the relative weight given to current issues versus future costs and benefits. In theory, any valuation process should allow for social and intergenerational equity.

This annex does not purport to solve the issues associated with the valuation of ecosystem services, nor does it try. Rather, valuation should be seen as a way of organizing information to help guide decision making, not a solution. As a result the annex provides a discussion of the factors that should be considered in the decision making process without proposing any weighting of factors or specific valuation process. These considerations in valuation can then be placed in a context within the conceptual decision making flow model described below. This suggested decision making process implicitly suggests that environmental costs be added to the costs of feasible sediment management strategies, in order to determine a true cost for sediment management.

It must be remembered that each application of this analysis will be unique, because the flow of ecosystem services is site-specific.

Description of the Decision making Process

Step 1.

Run the RESCON Model. Output of the RESCON Model will provide feasible engineering alternatives for sediment management.

Go to Step 2

Step 2.

Determine the environmental impacts (temporary and/or permanent loss of ecosystem services). This will require a site-specific analysis. This annex provides an overview of possible considerations.

Go to Step 3

Step 3.

Determine if there is an applicable regulatory framework in which a decision will be made. In many developed countries there is a complex regulatory framework in which the project will be evaluated. In some countries there are no appropriate regulations. If a regulatory framework exists:

Go to Step 4.

If no regulatory frame exists:

Go to Step 5

Decisions within Regulatory Framework:

Step 4.

The impact analyses will be evaluated within the framework and a decision will be made allowing the project to proceed with mitigation. Where impacts cannot be adequately mitigated the project will be prohibited from proceeding. This analysis should be conducted for each alternative, recognizing that the environmental impacts rather than the engineering feasibility or cost may be the primary determining factor.

4-A.

If various alternatives are acceptable then the cost of the mitigations should be determined and added to the cost of the sediment management alternatives to determine the economically preferred alternative.

4-B.

If no alternatives are permitted, the existing or proposed dam is not sustainable.

No Regulatory Framework Exists:

Step 5.

There is no regulatory framework that will determine the decision making.

The value of ecosystem services that will be permanently lost should be calculated and added to the value of interim loss of ecosystem services. The sum of these two factors will equal the environmental cost for each alternative and can be added to the sediment management cost to obtain total cost. Any ecosystem benefits that may exist should also be evaluated and added to the project benefits.

Step 6

If the total environmental cost is less than the economic benefit derived from the new project then the project should go ahead. If the total environmental cost is more than the economic benefit derived from the proposed project, then the project should not go ahead.

Step 5 Note. These are the most sensitive calculations. Weighting of factors, social and intergenerational equity and the difficulty in providing precise valuation of ecosystem services will be the most pronounced in Step 5, making this the most difficult calculation.

It must however be pointed out that, beyond scientific challenges, defensibility of any "calculation," and reaching stakeholder agreement on results, represents the real challenge.

Environmental Impacts to be Considered in a Valuation Procedure

The following is a brief discussion of the environmental impacts that should be considered when attempting to evaluate the environmental cost of any sediment management alternative. The list cannot be regarded as exhaustive, because the number of potential variables is enormous. It is also important to remember that all listed parameters may not apply to each dam, or even each sediment management alternative at a specific dam.

The environmental variables discussed here are in relation to sediment management only. They are not intended to provide a comprehensive evaluation of whether a new dam should be built, except to the extent that if sediment management cannot be cost effective because of the environmental cost, then implementation should be reconsidered.

In order to evaluate the benefits/costs of sediment management it is necessary to examine the overall impacts of dams and then evaluate how sediment management would yield positive or negative value to the system.

Geomorphology and Turbidity

Reservoirs act as a sediment trap, holding back sediments, especially gravel and cobbles. The river downstream of the dam, deprived of its sediment load, tends to erode the downstream channel and banks. This can result in the undermining of bridges and other riverbank structures. Within nine years of the impoundment of Hoover Dam Reservoir in the United States, the riverbed below the dam had been lowered by more than four meters. River deepening will also lower the groundwater table along the river, threatening native vegetation and requiring the irrigation of agricultural products where it had been previously unnecessary. The depletion of river gravel reduces habitat for many gravel spawning fish species and for invertebrates such as mollusks, insects and crustaceans.

The depletion of the sediment source caused by the impoundment of a reservoir can have effects many kilometers downstream. These effects include reduction of sediment sources to the river delta or estuary as it enters the sea, resulting in the gradual erosion of the delta. Deltas and estuaries are complex ecosystems that support many habitats (including salt marshes) and species and therefore they need to be protected.

However, the decommissioning of a dam or the implementation of a sediment management program which passes sediments downstream will not necessarily improve the geomorphology and ecosystems downstream; detailed studies by specialists will be required.

Hydrological Effects

Reservoirs change the flow pattern of rivers, by affecting their seasonal variations. The nature of the impacts depends on the size of the reservoir in comparison with the annual inflows, purpose and operation of the dam, among other things. River estuaries are particularly rich ecosystems, which depend on the volume and timing of nutrients and freshwater. It has been estimated that 80 percent of the world's fish catch comes from these environments. The alteration of flows reaching estuaries because of upstream consumptive water uses has been linked to the decline of sea fisheries in the Gulf of Mexico, the Black and Caspian Seas, California's San Francisco Bay, the eastern Mediterranean and others. Overall hydrological changes can alter all downstream riverine habitats. Detailed fisheries impact data are lacking for most dams, but where available the habitat alterations caused by dam building appear to have been severe. The reduction in freshwater flows to the mouth of the river can also result in saltwater intrusion, a problem in the Sacramento River Delta of California, United States.

Flood Patterns

The impounding of water by reservoirs attenuates[12] flood peaks. Riverine and floodplain ecosystems are closely adapted to a river's flooding cycle. The native plants and animals depend on its variation for reproduction, hatching, migration and other important lifecycle changes. Annual floods deposit nutrients on the land, flush out backwater channels and replenish wetlands. Floods are important in the maintenance of fish communities even in relatively simple

[12] Reduces peak flood discharge rate and delays the timing of the flood peak.

systems. In the West Fork of the San Gabriel River system in southern California, United States, flooding removes riparian trees and opens the canopy in patches. This improves the habitat for an endemic sucker, which feeds on the epilithic diatoms that flourish under the open patches in the canopy. The canopy, however, keeps summer water temperatures down for a sympatric trout. The alterations in river hydrograph and the temperature of releases have significant effects on the fauna. Since the Waitaki River in New Zealand was dammed, the river has become excellent habitat for the exotic Chinook salmon, while the black stilt (bird) has become so endangered that fewer than 100 individuals remain, largely as a result of patterns of sandbar formation and stabilization. A similar pattern has been seen in the Colorado River of the southwestern United States where dam releases of cold clear water have produced an excellent non-native trophy trout fishery at the expense of the native big river fish of the Colorado River, all of which are now listed as endangered.

The floodplain itself is also affected. Studies on the floodplain of the Pongolo River in South Africa have shown a reduction in forest species after it was dammed. Forests along Kenya's Tana River appear to be slowly dying out because of the reduction in high floods due to a series of dams. The eucalyptus forests of the Murray floodplain in Australia depend on periodic flooding for germination, which has been curtailed by the water impoundment.

The Kainji Dam on the Niger River is reported to have adversely affected hundreds of thousands of people by reducing yam production and fisheries. Also, former wetlands that had been seasonally inundated no longer provided essential grazing for livestock at the end of the dry season or water for flood recession cultivation of rice and other crops.

Environmental considerations of flushing

Introduction

Sediment control in reservoirs is often associated with downstream sedimentation. In cases where downstream aquatic organisms depend on clean gravels for spawning, such deposition of fine sediments may significantly degrade downstream habitats for gravel spawners. The deleterious impacts of fine sediment deposition on spawning gravels and the resultant effects on hatching success, fry survival etc. have been most completely studied for salmonids. However, most of these studies provide only single factor analyses. Even when multiple factors such as dissolved oxygen, flow velocity through gravel, fine sediment size/quantity, etc. are studied, they are treated independently and predictive relationships are developed only for single factors. It is clear from the results of these studies however, that in-gravel incubation environments are complex systems, which are simultaneously affected by many factors. Fu-Chun Wu, 2000, attempted to integrate three quantitative relationships in order to predict embryo survival as a function of sediment deposition. His model integrates variations of substrate permeability with sediment deposition, apparent velocity with substrate permeability and embryo survival rate with apparent velocity. His analyses indicate that embryo survival is most sensitive to fine sediment-gravel size ratio. Wu then applies his model to analyze the timing of flushing flows. Wu's results were not tested experimentally nor field verified and they do not address factors known to be critical, such as dissolved oxygen, pH, temperature, interspecies variation and other temporal and spatial variables.

Flushing Flow Prescriptions

It is recommended that Wu's relationships between timing of the flushing flows and survival rates be used as a guideline for determining periodicity of flushing flows. Among Wu's assumptions is that seasonally high periods of runoff are frequently correlated with spawning times, so that spawning may be affected by sediment deposition as a result of the seasonally high runoff (releases of sediment from reservoirs may follow a similar pattern). Additionally, it is suggested that one management option in a controlled stream is to allow sediment accumulation and then flush the sediments periodically. This concept can be extended to sediment management in reservoirs. Because almost any sediment management option that involves movement of reservoir sediments downstream will result in some deposition of fine sediments in downstream gravel, Wu's model can be used to determine the amount of flushing that will be necessary to achieve acceptable sediment releases. If this model is used, the stream impacts should be studied and the methodology adjusted to meet the specific conditions on the river in question. The next value to consider is the magnitude of the flushing flow; again data from individual rivers are best but general guidelines are available. Parker and Klingman (1982) suggest that fine sediments can be removed from the gravels when the flushing flows are sufficient to break up the armor layer. Such a method would be an alternative when there are sufficient gravels, but if sufficient gravels are not available, such a flushing flow could result in armoring of the stream with material too large for spawning and could scour any eggs/larvae currently in the substrate.

The above only provides initial guidelines that may require adjustment depending on the actual stream parameters and target species. In order to accurately determine the needs of a specific river, natural flows should be studied, but in the absence of actual stream data, the above guidelines can be applied, then modified as necessary based on collection of data documenting the results of the generalized flushing flow prescription.

General Applicability

The above recommendations are based on studies of salmonids. Salmonids are a widely distributed Boreal species. Their range has been significantly expanded due to introductions in both the northern and southern hemispheres. They frequently provide important commercial and/or recreational fisheries throughout their distribution. The recommended flow prescriptions should be generally applicable. Flushing flows are by definition, predetermined discharges for a specific duration designed to remove fine sediments from river gravels (Reiser et al., 1989). Therefore, the above generalizations should be of use as general guidelines whenever the purpose is to remove fines from potential spawning gravels (some tropical species are also gravel spawners, i.e., some cichlids), as long as the limitations of the guidelines are recognized and local measurements are collected to refine the initial generalizations.

One final consideration: periodic high discharges can also be used to enhance other riverine ecosystem functions, such as sand/gravel bar formation or overbank flooding. These should not be termed flushing flows and flow releases for these purposes may not follow the parameters of flushing flows described above.

Environmental Valuation

Some of the potential ecosystem costs are quantifiable, while others are not. Measurements of loss of productivity of floodplain agriculture, costs of fertilizer, reduction or increase in fisheries catch, etc. are readily quantifiable. Biodiversity losses or losses of ecosystem integrity, on the other hand, are virtually impossible to quantify. The quantification of losses of subsistence activities such as artisanal fisheries is also difficult to quantify. Many economists simply account for the economic loss of the product while neglecting to account for the social impact that the loss of a particular way of life has on the affected community as a whole.

In order to go beyond the safeguards approach presented in Chapter 4, it is necessary to initially split valuations into two categories. First are cases that involve the permanent loss or reduction of an ecosystem service and second are situations where there is only an interim loss of ecosystem services. Valuation of cases that involve a permanent loss or reduction may be based on the cost of replacement of the lost services. Permanently lost services can sometimes be “replaced” by similar services. For example, at Morris Dam (San Gabriel River, California, USA), sluicing has been used to manage reservoir sedimentation but has caused the permanent destruction of downstream ecosystem services. As a result, the project was mitigated through the acquisition of similar habitat on another river. Because this was done in the United States, where there is a regulatory framework, the efficacy of the mitigation was evaluated within that framework and the project proponent had to demonstrate that the replacement habitat supplied the same ecosystem services as the one destroyed. Replacement which involves the purchase or donation of land is directly quantifiable. Restoration costs are also quantifiable, but they involve the cost of restoration along with the cost of the interim loss of services.

Valuations of interim service loss can use a direct valuation in cases such as a temporary reduction of fisheries catch by determining the percent of the service lost in year 1, translating that to quantity of fish lost (in weight) times a discount factor (3 percent commonly used in environmental calculations). This would then equal the discounted effective fisheries loss. The form of the recovery curve and the time to recovery must be determined. Then, for each year during the recovery period, the discounted effective fisheries loss could be calculated. The total interim loss is therefore the sum of the annual discounted effective fisheries losses. A very simple example is shown in the table below. In this example there is a 50 percent loss of fisheries catch due to sediment management, but the system recovers in a linear fashion in a period of four years. The baseline catch is assumed to be 100 tons.

The monetary value of 97.9 tons of fish represents an environmental cost of sediment management in this scenario. This scenario assumes natural recovery without restoration. This valuation procedure has been borrowed from habitat equivalency analysis, which is commonly used to value the cost of natural resource damages.

In the case of biodiversity loss or other non-quantifiable impacts, the valuation procedure would at the very least involve an enumeration of the impacts to be considered in the decision making process.

TABLE E.1

EXAMPLE OF USING DISCOUNTING TECHNIQUES TO QUANTIFY ENVIRONMENTAL LOSSES

Year	% Service Loss	Effective Fisheries Loss (in tons)	Discount Factor (3% discount rate)	Discounted Effective Fisheries Loss (tons)
2001	50.0	50.0	1.00	50.0
2002	33.3	33.3	0.97	32.3
2003	16.6	16.6	0.94	15.6
2004	0.0	0.0	0.91	0.0
Total Discounted Effective Fisheries Loss				97.9

ANNEX F: WATER PRICING

One of the inputs necessary for the RESCON analysis is the value of the water that is stored in the reservoir. While this parameter has great implications for optimal management of the reservoir, it is usually unavailable to the decision maker.

There exist several sources for calculation of the value of water in various uses, including Gibbons (1986), Young (1996 and 2003). However, quite extensive preparatory work is needed in order to estimate the value of water using the procedures suggested in these sources.

A range of water prices in various sectors and uses could also be used as a reference. Available sources include: Dinar and Subramanian (1997), Ahmad (2000), OECD (1998a), OECD (1998b), OECD (1999), Jones (2000) and Savedoff and Spiller (1999), Dinar (2000).

A compilation of observed prices from various countries and sectors is provided in the Table F.1 below. The prices are expressed in 1997 US$ values, so they should be easy to use and compare. It should be emphasized that the values in the Table do not necessarily represent the true worth of water but are based on water prices that have been observed in various countries. Therefore, appropriate care and caution should be exercised when making use of these numbers.

TABLE F.1

RANGES OF WATER PRICES FOR VARIOUS SECTORS AND COUNTRIES

(1997 US$)

	Agriculture		Domestic		Industry	
	Fixed	Variable	Fixed	Variable	Fixed	Variable
Country	(per hectare per year or season)	(per cubic meter)	(per household per year or month)	(per cubic meter)	(per plant per year or month)	(per cubic meter)
Algeria	3.79–7.59	0.019–0.022		0.057–0.27		4.64
Australia	0.75–2.27	0.0195	9-162	0.23–0.54		7.82
Austria		0.36–0.98		0.85		
Belgium				2.06–2.47		
Botswana				0.28–1.48		
Brazil	3.50	0.0042–0.032		0.40		
Canada	6.62–36.65	0.0017–0.0019		0.34–1.36		0.17–1.52
Czech Republic				0.68		
Denmark		0.71		3.18		
Egypt				0.07–0.09		0.12–0.59
Finland				2.76		
France		0.11–0.39		0.36–2.58		0.36–2.16
Germany				1.69		1.022–3.704

(continued on next page)

TABLE F.1

RANGES OF WATER PRICES FOR VARIOUS SECTORS AND COUNTRIES (continued)

(1997 US$)

Country	Agriculture Fixed (per hectare per year or season)	Agriculture Variable (per cubic meter)	Domestic Fixed (per household per year or month)	Domestic Variable (per cubic meter)	Industry Fixed (per plant per year or month)	Industry Variable (per cubic meter)
Greece	92–210	0.021–0.082		1.14		
Hungary				0.82		
India	0.164–27.47		0.824	0.0095–0.082	5.49	0.136–0.290
Israel		0.16–0.26		0.36		0.26
Italy	20.98–78.16			0.14–0.82		
Japan	246			1.56		
Jordan		0.01–0.04		0.27–1.03		0.12–0.35
Lebanon			8.71			
Luxembourg				1.01		
Madagascar	6.25–11.25		0.075–0.25	0.392		
				0.325–1.25		
				0.9–1.75		
Mexico	33-60					0.08–0.35
Namibia	53.14	0.0038–0.028	1.54–4.28	0.22–0.45		
				0.33–1.38		
Netherlands				3.16		0.57–1.71
New Zealand	6.77–16.63		16–164	0.31–0.69		
Pakistan	1.49–5.80		0.25–1.63	0.06–0.10		0.38–0.97
Palestinian Authority (Gaza)				0.33		
Palestinian Authority (WB)				0.79–1.12		
Poland						0.20–0.94
Portugal		0.0095–0.0193	4.46–1937	0.1526–0.5293	8.86–2,705	1.19
Saudi Arabia				0.04–1.07		
South Korea				0.27		
Spain	0.96–164.48	0.0001–0.028		0.0004–0.0046		0.0004–0.0046
Sudan	4.72–11.22		1.67–3.33	0.08–0.10	1.67–3.33	0.08–0.10
Switzerland		0.33–1.96		1.29		
Syria	50.00		3.21	0.11–0.53		0.71
Taiwan	23.30–213.64			0.25–0.42		
Tanzania		0.260–0.398		0.062–0.241		0.261–0.398
Tunisia		0.020–0.078		0.096–0.529		0.583
Turkey		12–80				
Uganda				0.38–0.59		0.72–1.35
United Kingdom			152–171	0.0095–0.0248		
United States		0.0124–0.0438				

Source: Dinar, (2000)

ANNEX G: COUNTRY REPORT – KENYA

Introduction

General

The Masinga Dam created the largest storage and regulatory structure on the Tana River for regulating flows for four downstream hydropower dams. It was designed on the basis of annual sediment input of 3 million tons/yr and commissioned in 1981. By 1988, the Masinga Reservoir was actually receiving 10 million tons of sediment per year according to a reservoir survey conducted during that year.

The City of Nairobi is concerned about loss of storage due to sedimentation in its reservoirs and negative impact on efficiency of their Mwagu Intake, also as a result of sedimentation.

The Athi-Galana-Sabaki River sediment discharges into the Indian Ocean have increased from an estimate of about 50,000 tons/yr (0.7 $t/km^2/yr$) in the late 1950s to an estimate of 8,400,000 t/yr (120 $t/km^2/yr$) in 1992 (JICA, 1992), a 170 fold increase.

On the same river, the World Bank financed the Mombassa Water supply intake at Baricho. This water supply project was commissioned in 1982, but because of siltation problems and high turbidities (about 6,000 NTUs[13]) and the associated extremely high operations and maintenance costs (tripled coagulant doses at the treatment plants, daily manual de-silting of the intakes and replacement of pump bearings every two weeks because of the abrasive action of the sediments), the entire scheme was abandoned by 1988, barely six years after commissioning.

This annex briefly reviews the impact of catchment management activities on water and sediment yield and provides a summary of ecological management approaches in forested areas as they relate to water supply. The methods and results of the reservoir surveys are also reported.

Deforestation: Impacts on Water and Sediment Yield

Kenyan forests play an important role in providing a sustainable and reliable water supply, since all major rivers in the country originate in them. The forests have always been considered to be important components of water supply in Kenya and the main ones, including the forests on the Mau Complex, Mount Kenya, Aberdares Mountains, Mount Elgon and Cherengani, have been fondly nicknamed the "Water Towers."

There is an extensive literature on the effects of deforestation and, to a lesser extent, reafforestation on runoff and river flows (Bruijnzeel, 1992). Deforestation has a number of hydrological effects, including decreased canopy interception of rainfall, (usually) decreased transpiration from the replacement vegetation, (usually) increased evaporation from the exposed soil surface, decreased soil infiltration because of changes in soil structure and increased velocity of runoff after removal of surface litter and roughness. In addition, in cloud forests the trees intercept mist and this source of moisture is lost after logging. The "mist harvesting" effect amounts to between 5-20 percent of total precipitation (Bruijnzeel and Proctor 1995). There is also evidence that extensive areas of forest cover cause convective currents that increase local precipitation but the size of this effect is difficult to establish.

Some of these effects increase runoff and others reduce it. There is strong evidence from well conducted, paired catchment studies[14] that the net effect is for mean annual runoff to increase after deforestation, although the amount depends on fac-

[13] Nephelometric Turbidity Units.

[14] A paired catchment study is where two catchments with similar hydrological properties and experiencing the same climatic conditions are compared; one still has its original forest cover and the other is cleared.

tors such as annual rainfall, soil characteristics, type of replacement vegetation (Zhang, et al, 2001). Flows following moderate to large storms also increase in size and flashiness because of the quicker runoff when the forest is replaced with crops and grasses. However, the vegetation cover (forest, crop or grass) has very little effect on runoff from very large storms, either because the ground rapidly becomes saturated or the precipitation is so intense that it cannot infiltrate into the ground quickly enough.

The effect of deforestation on flows during non-rain periods, or baseflows, is less clear cut. It depends on factors such as the vegetation cover that replaces the trees, the quality of the land management and the aquifer structure. For most replacement vegetation, the decrease in evapotranspiration is the dominant effect particularly when annual crops (such as maize) and grasses replace the forest. Thus, more water accumulates in the soil and baseflows increase after deforestation. There are exceptions to this generalization, such as when the "mist harvesting" effect is lost in cloud forests, when the infiltration is severely reduced and when deep-rooted perennial plants (e.g., mature tea plantations) replace the trees. In these cases, there is experimental evidence that baseflows will remain the same or even decrease after deforestation.

The clearance of forest in the "Kenyan Water Towers," below the level of cloud forest, is most likely to result in increases in both storm flows and baseflows, as seen at Mbeya, as long as the soils retain good infiltration and there is no widespread use of surface and groundwater. Flows are likely to decrease if cloud forest is cleared.

However, the reality is that, when forest is cleared for gardens there are many other hydrological effects apart from just those from the vegetation removal. The density of settlement is such that significant groundwater is abstracted, surface runoff is intercepted in pans, and areas such as paths and around houses become heavily compacted, although cropped areas retain good infiltration characteristics. Consequently, the widespread observation of river flows decreasing after forest clearance is more likely to be the result of the dense settlement patterns or other causes of abstraction than a direct result of the clearance. Thus, the lowered water table in the Njoro catchment and decreases in the flow of the Njoro river feeding Lake Nakuru are most likely to have arisen from the increased use of surface and groundwater in the region rather than from the clearance of forests *per se*.

In addition to the impact on the availability of water and the magnitude of floods, deforestation can also result in increased erosion and higher sediment loads in rivers. As the sediment that is transported by rivers deposits in reservoirs behind dams, the storage capacity of these facilities reduces. This requires building additional and larger storage facilities to ensure the reliability of water supply.

Reservoir Survey Methods

A Starlink Invicta 210S DGPS receiver supported by the Omnistar Satellites was used to establish the locations of the depth measurements (longitude and latitude) throughout the surveys. The satellites conduct differential calculations that improve the accuracy of the longitude and latitude readings. The accuracy that can be obtained with the Omnistar satellites is within one meter, whereas the accuracy without the use of the same provides an accuracy of plus or minus three meters. Using the Omnistar satellites in Kenya was the most cost effective way to benefit from Differential GPS (DGPS). Determination of the locations of depth measurements (longitude and latitude) with the DGPS is considered to be significantly more accurate than any other previous surveys.

A Garmin GPSmap 168 Sounder with a 200 kHz, 20° Transducer was used to determine the distance to the reservoir bottom throughout the surveys. The depth soundings were correlated with tape measurements at the beginning and end of survey sessions. The manual depth measurement and the echo-sounder depth sounding correlated very well, within a few centimeters.

The survey was analyzed and bathymetric maps produced to calculate reservoir volumes and elevation/storage curves.

Limitations and Assumptions

Surveys of existing reservoirs are currently conducted by making use of echo-sounding equipment to determine water depth and GPS to determine location. Such surveys are usually conducted when reservoirs are full of water. This allows determination of their total capacity without the need for additional data.

Given the field conditions under which the survey was conducted and the urgency to collect data for this project a limitation was introduced. Three of the four reservoirs that were surveyed were not full. The survey data that were collected had, therefore, to be enhanced.

Ruiru Dam was the only facility with a full reservoir, allowing the survey data to be directly analyzed for determination of the total reservoir capacity. Topographic maps for the other dams were obtained from the owners and the full supply level was digitized from these maps for incorporation into the survey database.

The map for Ndakaini Dam (also known as Thika Dam) was shifted and rotated from the actual coordinate system making application of this information difficult. The topographic maps for Masinga Dam had a slight, inconsistent distortion at some locations. Coordinates were converted where possible.

The fact that the Masinga Reservoir was not full furthermore resulted in some of the deposited sediment in the upstream reaches of the reservoir not being incorporated into the survey. These sediments were located above the water surface elevation that existed when the reservoir was surveyed.

The map for Sasumua Dam is based on a local coordinate system that was not readily convertible to UTM[15] coordinates. Furthermore, the reservoir of this dam contains extensive borrow pits with unusual (non-natural) shapes. The vertical cliffs of the borrow pits make extrapolation of the results less reliable. Sasumua Reservoir appears to have experienced significant siltation, which caused the boat to get stuck a number of times, jeopardizing the accuracy of the data collection. These difficult conditions were exacerbated by problems with navigation and adverse, cold and windy atmospheric conditions. The survey data for Sasumua Dam and Reservoir were of poor quality and could not be analyzed.

Results

Ruiru Dam

Ruiru Dam, located on the Ruiru River and commissioned in 1950 has a catchment area of 66.80 km^2 and supplies water to the City of Nairobi. The reservoir's original capacity was 2.98 Mcm. The survey indicated that the current reservoir storage capacity is 2,496,762 m^3, which is a loss of 483,238m^3 that has occurred over the last 52 years. This indicates that the average sediment yield from the catchment upstream of Ruiru Dam is on the order of 180 t/km^2/yr.

Ndakaini Dam (Thika Dam)

Ndakaini Dam (also known as Thika Dam) was recently constructed. It is located on the Thika River and has a catchment area of 71 km^2. The dam supplies water to the City of Nairobi. The reservoir's original capacity was 70 Mcm. The survey was executed when the water surface elevation in the reservoir ranged between 2,036.01m and 2,036.09m. The original capacity of the reservoir at this elevation was 56 Mcm. The survey indicated that the current reservoir storage capacity at this elevation is still 56 Mcm, which indicates that the storage loss up to this elevation is negligible. The dam is relatively new and if any storage loss due to sedimentation occurred, it is likely to be very low, with sediment deposits most probably occurring at a higher elevation than what the dam was surveyed at.

Thika was the first reservoir that was surveyed during this mission and the resolution of survey that was used is very high. Approximately 19,000 survey elevations of the reservoir basin were collected to determine the reservoir capacity. The density of these readings is likely to be significantly greater than that of any other survey that was conducted before.

The original storage/elevation curve for Ndakaini Reservoir is still valid and a new curve was not developed.

Masinga Dam

Masinga Dam, located on the Tana River and commissioned in 1981, has a catchment area of 7,335 km^2 and regulates water for hydropower production in the Seven Cascades System. The reservoir's original capacity was estimated as 1,560 Mcm. A survey that was conducted in 1988 found that the reservoir has lost 5.57 percent of its storage capacity, which was equivalent to 87.2 Mcm. This indicates that the average sediment yield from the catchment upstream of Masinga Dam by 1988 was on the order of 1,750 t/km^2/yr.

[15] Universal Transverse Mercator.

The 2001 survey indicates a total volume of 1,100 Mcm giving an average annual loss of 23 Mcm/year corresponding to a catchment yield of 4,000 t/km^2/yr. This is unrealistically high.

Further investigations of the 1988 survey and the original pre-impoundment height capacity curves indicated that these are likely to be erroneous. Therefore the original and 1988 storage volumes are unknown and it is not possible to determine the annual average sedimentation in the reservoir.

Sasumua Dam

Sasumua Dam, located on the Chania River and originally commissioned in 1956 has a catchment area of 12,800 ha and supplies water to the City of Nairobi. The reservoir's original capacity was 7.57 Mcm. The dam was raised over the period 1965 to 1968, increasing the total capacity to 13.25 Mcm.

The survey data that were collected at Sasumua Dam and Reservoir proved to be unusable. The principal reason for this is that the weather conditions on the day of the survey were bad, with high winds and cold impacting the survey. Navigation was difficult and the boat was stuck in deposited sediment a number of times.

It was not possible to determine the current capacity of Sasumua Dam and Reservoir because of the poor quality of the data.

The team however observed that the sediment deposition in this reservoir is potentially large. The importance of this dam to the water supply to Nairobi makes it advisable that another survey be conducted.

TABLE G.1

ESTIMATED STORAGE LOSS IN SELECTED RESERVOIRS

Reservoir	Original Capacity (10^6 m3)	Current Capacity (10^6 m3)	Percentage Storage Loss (%)	Date Commissioned
Ruiru	2.98	2.496	16%	1950
Thika	56	56	0%	1994
Sasumua	7.57 to 13.25	Not determined	Not determined	Commissioned in 1956, dam raised by 1968
Masinga	1,560[a]	1,100	29%[a]	1981

(a) The original height-capacity curve on which these figures are based has been called into question by this study.

ANNEX H: COUNTRY REPORT – MOROCCO

Introduction

Morocco is an arid country that relies heavily on water supplied by surface water reservoirs. Dams are built to form reservoirs that store floodwater for later use. Floods generally occur on an irregular basis and long periods of drought, spreading over several years, are not uncommon. To ensure the reliability of water supply, it is therefore important to conserve reservoir storage space. Loss of storage space due to sediment deposition in surface water reservoirs is inevitable and poses a significant problem to Morocco. The reservoirs behind the 97 dams currently owned by the Kingdom of Morocco on average lose 65 million cubic meters of storage space per year, which is equivalent to losing the average storage space of one reservoir every two years. Implementation of technically and economically feasible reservoir sedimentation management techniques can lead to the sustainable use of water resources and associated infrastructure.

The RESCON approach was implemented in Morocco in order to identify optimal reservoir management strategies on a selection of dams.

Objective

The study was undertaken in May 2001. The Government of Morocco selected 10 dams and reservoirs for analysis using the RESCON model. The objective was to identify the optimal reservoir management techniques that are both technically and economically feasible and to demonstrate the use of RESCON to the Government of Morocco and assess its potential value in developing programs that will support sustainable management of water resources and water resource infrastructure in Morocco.

Reservoirs Analyzed

The ten reservoirs that were selected for the study are shown in Table H.1. The pertinent information

TABLE H.1.
LIST OF RESERVOIRS ANALYSED

Reservoir	Original Capacity (million m^3)	Current Capacity (million m^3)
Abdel Karim El Khattabi	11.3	8.9
Bin El Quidane	1,507.5	1,253.4
Ennakhla	9.0	4.9
Hassan I	272.0	245.0
Ibn Battouta	43.6	33.9
Mohammed V	725.8	362.6
Moulay Youssef	197.2	159.4
Qued El Makhazin	788.0	773.0
Sidi Driss	7.2	2.8
Timi N'Outine	5.6	2.4

that was used in the RESCON analysis, for each of the dams, is presented in Table H.4

The selected dams range from relatively small, with a reservoir capacity of 5.6 million m^3, to large, with a reservoir capacity of 1.5 billion m^3. The table also shows that the storage loss in some of these reservoirs is significant.

The Timi N'Outine Dam and Reservoir is used as a diversion structure downstream of Moulay Youssef. Because of its use and location, the process of sedimentation and determination of its economic value is complex. It has therefore been omitted from the analysis at this point in time.

Results

A summary of the results of the RESCON analysis is provided in Table H.2. It contains a summary of the optimal reservoir conservation management strategies, showing the first, second and third choices for each facility.

A sensitivity analysis was conducted for the dredging cost, using the dredging cost provided by Moroccan engineers and that calculated[16] by the RESCON program. This analysis was made merely to determine how sensitive the results would be to dredging cost. The results in the table show that the recommended optimal management strategy changes, depending on the dredging cost. When using the default dredging costs calculated by the RESCON program (which are higher than US$2.50/m^3; see Table H.3 for values), the optimal reservoir conservation management approach shifts to flushing for three of the reservoirs.

Interesting results are shown for Hassan I and Oued El Makhazin, which indicate that the optimal

[16] Where the user does not input a cost, the RESCON model calculates a unit cost of dredging based on an internal algorithm.

TABLE H.2.
RESULTS OF STUDY

		Sustainable				Run-of-River		Non-Sustainable	
Option	Name	Flushing	Dredging	HSRS	Trucking	HSRS	No Action	HSRS	No Action
Dredging Cost = US$ 2.50/m^3	Abdel Karim El Khatabi	Second	First						Third
	Hassen I		Third			Second	First		
	Ibn Battouta		First		Third				Second
	Mohammed V	Second	First		Third				
	Mouley Youssef		First		Third		Second		
	Sidi Driss	First	Second						Third
	Bin El Ouidane								
	Timi N'Outine								
	Ennakhla	Second	First						Third
	Qued El Makhazin						First		
RESCON dredging cost	Abdel Karim El Khatabi	First	Second						
	Hassen I		Third			Second	First		Third
	Ibn Battouta		Second		First				
	Mohammed V	First	Second		Third				Third
	Mouley Youssef				First		First		
	Sidi Driss	First			Third				Second
	Bin El Ouidane								
	Timi N'Outine								
	Ennakhla	First	Second						Third
	Qued El Makhazin						First		

First Second Third

TABLE H.3

LONG TERM CAPACITY AND METHOD FOR RESERVOIR CONSERVATION

		Optimal Approaches							
			Long Term Capacity		Years	Frequency of		No. of	
Option	Name	Method	10^6 m^3	%	to LTC	1st Phase	2nd Phase	Equipment	Comment
Dredging cost = $2.50/m³	Abdel Karim El Khatabi	Dredging	3.4	30%	33	3 years	1 year	1	Considering "flushing reach" only. If complete reservoir is considered, dredging is most probably appropriate technique.
	Hassen I	No Action	0	0%	140	N/A	N/A	N/A	
	Ibn Battouta	Dredging	4.4	10%	32	32 years	3 years	1	Flushing not technically feasible. The net benefit of dredging, no action and trucking are very close.
	Mohammed V	Dredging	72.6	10%	35	10 years	1 year	3	
	Mouley Youssef	Dredging	197.2	100%	18	18 years	5 years	1	Benefits slightly different.
	Sidi Driss	Flushing	3.4	47%	2	2 years	N/A		
	Bin El Ouidane								
	Timi N'Outine								
	Ennakhla	Dredging	1.8	20%	19	2 years	1 year	1	
	Qued El Makhazin	No Action	0	0%	324	N/A	N/A	N/A	
RESCON Dredging cost	Abdel Karim	Flushing	4	35%	30	30 years	2 years	N/A	Considering "flushing reach" only. Flushing every two years in second phase may not be possible due to lack of enough water.
	Hassen I ($6.36/m³)	No Action	0	0%	140	N/A	N/A	N/A	
	Ibn Battouta ($9.70/m³)	No Action	0	0%	600	N/A	N/A	N/A	Is 82,000 metric tons per year of sediment inflow into the reservoir correct?
	Mohammed V ($4.96/m³)	Flushing	29.8	4%	37	37 years	2 years	N/A	Flushing need to be investigated in more detail because gates could be blocked after 37 years, making it impossible. Require feasibility study.
	Mouley Youssef ($4.02/m³)	No Action							Benefits for dredging, trucking and no action, run-of-river are almost identical.
	Sidi Driss ($10.68/m³)	Flushing	3.4	47%	2	2 years	2 years	N/A	
	Bin El Ouidane								
	Timi N'Outine								
	Ennakhla	Flushing	1.8	20%	19	19 years	2 years	N/A	
	Qued El Makhazin	No Action	0	0%	324	N/A	N/A	N/A	

management solution is to allow the reservoirs to fill with sediment over the long term and use the head provided by the dam to generate run-of-river hydroelectric power, having foregone the benefit of storage. This result is independent of the cost of dredging used.

The recommended solution for Moulay Youssef using a cost of dredging of US$2.50/$m^3$ is to dredge the annual inflow of sediments to achieve a sustainable solution. However, if RESCON is allowed to calculate its own cost of dredging (US$4.02/$m^3$) the results are balanced such that the economic value of reservoir use is maximized to approximately the same value, whether it is done by conserving reservoir storage by means of dredging or trucking, or allowing the reservoir to silt up completely and using the head at the dam to generate run-of-river power.

Table H.3 shows further detailed results, including the estimated long-term capacity and more detail pertaining to the frequency of executing sediment management operations. Results are shown for the two optional dredging cost estimates. The dollar value per cubic meter in the first column of the second part of the table is the cost of dredging calculated by RESCON.

The table shows more detailed information pertaining to what is estimated to be achievable in terms of reservoir conservation. For example, in the case of Sidi Driss it is estimated that the stable long-term capacity would be on the order of 3.4 million m^3, which is 47 percent of the original storage capacity and that the optimal sediment management technique is flushing. In order to maintain this capacity, it is required to flush the reservoir every two years to maximize the economic benefit.

The table also shows the frequency of implementing sediment operations for two phases. The first phase is the period prior to reaching the long-term capacity and the second phase is the period after the long-term capacity has been reached. The frequency of implementing sediment management techniques during the first phase sometimes differs from the frequency of implementation in the second phase. For example, Mohammed V reservoir is flushed only once in the first phase (after 37 years) if the RESCON calculated cost for dredging is used, it should be flushed every 2 years in Phase 2 to maintain the long-term capacity. This frequency of operation maximizes the long-term value of Mohamed V reservoir.

Recommendations

Preliminary discussions with Moroccan engineers on the outcome of the study indicated that the results of the RESCON analysis are in line with their experience and understanding of the reservoirs that were investigated. In order to maximize the value of this survey, a pre-feasibility study should be carried out to identify optimal sediment management strategies for all 97 reservoirs in the country.

The pre-feasibility study should commence by prioritizing the existing reservoirs and dams in terms of relative importance. Thereafter the reservoirs could be analyzed using the RESCON program to identify optimal management strategies for each of the reservoirs. This study will indicate which of the existing reservoirs can potentially be managed in a sustainable manner and which ones should be left to be used in a non-sustainable fashion.

TABLE H.4
DATA USED IN RESCON ANALYSIS

Reservoir	Original storage volume (Mcm)	Current storage volume (Mcm)	Reservoir bottom width (m)	Reservoir side slope	Normal water level (m)	Bed level (m)	Flushing water level (m)	Reservoir length (m)	MAR (MCm)	MAR Cv	Acceptable probability of failure	Water T(ºC)	Sediment density (ton s/m^3)	Avg. annual sediment in flow (tonnes)
Abdel Karim El Khattabi	11.3	8.87	600	0.05	140	115	130.0	1,600	48.2	0.8	0.01	18	1.20	217,000
Bin El Quidane	1,507.5	1,253.4	1,000	0.28	810	710		20,000	1,050	0.58	0.01	12	1.20	7
Ennakhla	9	4.9	250	0.21	190.65	150	152.52	1,800	55	0.56	0.01	12	1.20	235,200
Hassan I	272	245	500	0.41	966	862	890.0	6,000	288.5	0.5	0.01	10	1.35	2.65
Ibn Battouta	43.6	33.94	600	0.06	48	24	27.5	11,275	52.3	0.81	0.01	10	1.20	82,000
Mohammed V	725.75	362.55	2,300	0.15	218	170	179	10,500	750	0.51	0.01	20	1.20	12.8
Moulay Youssef	197.2	159.35	1,200	0.14	877.5	795	797	3,000	287	0.5	0.01	12	1.20	651,000
Qued El Makhazin	788	773	1,550	0.10	61.5	13	23.17	35,000	809	0.67	0.01	12	1.20	3
Sidi Driss	7.189	2.755	50	0.23	643.5	615	630.8	4,000	125	0.75	0.01	20	1.35	243,000
Timi N'Outline	5.6	2.4	100	0.05	793.5	780	781.4	70	5.6	0.5	0.01	10	1.10	0.15

ANNEX I: COUNTRY REPORT – SRI LANKA

Introduction

Background

Sri Lanka is dependent on its water storage reservoirs to supply the country with water for irrigation, urban and industrial use and hydropower. The reliability of water and power supply during the dry season, when rainfall and resulting runoff in the rivers are low, is dependent on the storage capacity of the reservoirs.

Reduced reservoir storage capacities caused by sedimentation result in less reliable water and power supply. This is particularly true of the reservoirs in the upper Mahaweli basin, which make significant contributions to the economy of the country. These reservoirs also play an important role in managing floods. Management of sediment in existing reservoirs can potentially lead to more economical solutions that may also result in sustainable use of both the water resources and the water resource infrastructure of the country.

The Mahaweli River Cascade (Figure I.1) consists of several major dams that were constructed between 1976 and 1991. These include: Kothmale, Polgolla, Victoria, Randenigala, Rantambe and a weir on the main Mahaweli River. These facilities provide approximately 45 percent of the country's power requirements. A post-evaluation study of the Victoria Project that was carried out in 1987 showed that 110 to 940 tons of sediment per square kilometer of river basin flows in Mahaweli River annually. Results of a hydrographic survey carried out in 1993 indicated that more than 4 Mcm of storage had been lost since the project was commissioned in 1985.

Recently several hydrographic surveys were undertaken in two regulating reservoirs; Polgolla and Rantambe to assess the amount of silt accumulation. Results indicated that 45 percent and 32 percent of reservoir storage have been lost respectively due to sediment deposition in these reservoirs. The studies also revealed that Polgolla Reservoir has reached a regime condition. At present silt inflows into this reservoir spill to Victoria Reservoir, located downstream and it was also found that a certain amount of suspended silt passed through the power tunnel and turbines. Removal of deposited silt in the reservoir has not been done due to estimated high cost.

A hydraulic flushing exercise was carried out on the Rantambe Reservoir, with the intent of flushing out the deposited sediment during high floods. It was observed that 10-15 percent of deposited silt was removed.

The objective of the RESCON mission was to investigate the technical and economic feasibility of managing sediments in the reservoirs in the Mahaweli basin and to identify the optimal management strategies for ensuring sustainable use of the reservoirs.

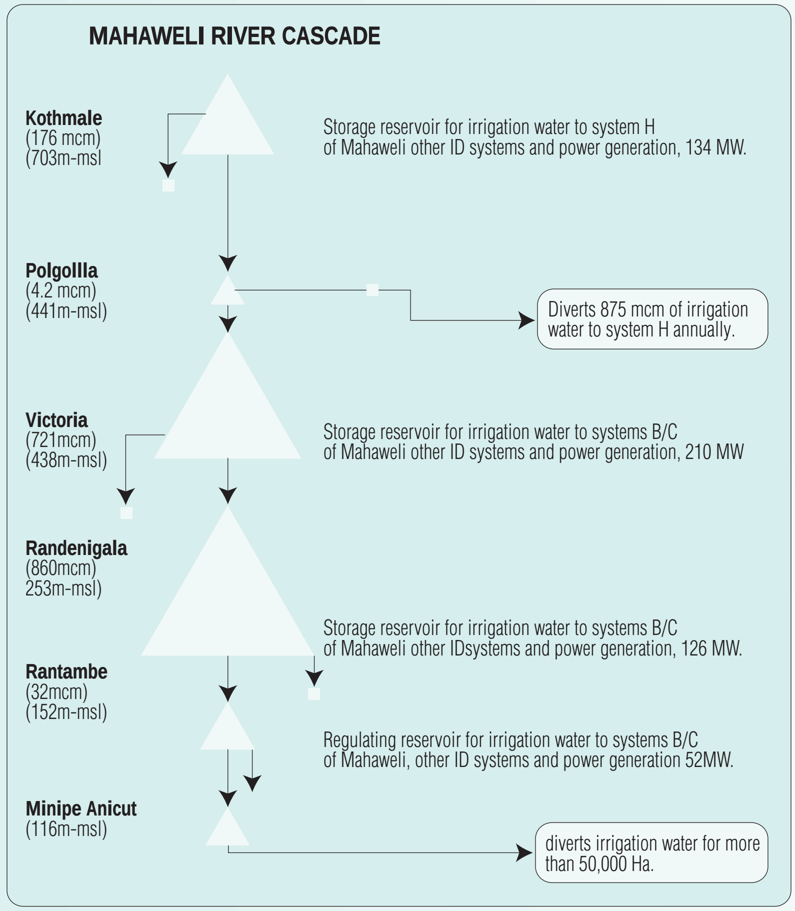
Study Phasing

The study has been undertaken in two phases. The first mission was in March 2002. The study team assisted the Mahaweli Authority of Sri Lanka (MASL) in identifying a portfolio of dams in the Mahaweli cascade (Figure I.1) for further sediment management studies. Preliminary data were collected from MASL and a survey plan was set out for reservoir sedimentation estimation

Phase II consisted of technical and economic analysis using the RESCON model and execution of reservoir surveys. Reservoir surveys were conducted August 14 to 25, 2002. RESCON modeling was conducted during 26 to 28 August, with a workshop presented in Colombo on 29 August to a large gathering of MASL engineers and officials. A smaller group of engineers at MASL received an in-depth RESCON tutorial on 30 August.

Overall Objectives

FIGURE I.1
THE MAHAWELI CASCADE



The overall objectives of the project were to:

- Quantify the storage depletion trends at system level by integrating current knowledge with measurements in the surveyed reservoirs
- Determine the economic and engineering feasibility of managing sediment in the reservoirs in the Mahaweli river basin
- Conduct an early identification of the environmental and social issues relevant to managing sediment in the reservoirs, to be used for the preparation of terms of reference for the feasibility studies
- Identify and prioritize the optimal management strategies for ensuring sustainable use of the reservoirs, should sustainable use be feasible; if marginally feasible, propose alternatives
- Prioritize the reservoirs, considering their vulnerability to sedimentation, for subsequent execution of feasibility studies including catchment management measures
- Train Sri Lankan engineers in the use of the RESCON approach and software and in modern hydrographic survey techniques.

Estimated Reservoir Storage Loss

The Mahaweli Authority of Sri Lanka (MASL) selected reservoirs to be surveyed based on the relative importance of the facilities and the perceived level of storage loss due to sedimentation and availability of other data. Reservoirs selected and surveyed were Victoria, Rantambe and Polgolla in the Mahaweli cascade.

The surveys were undertaken over a period of two weeks. The equipment used in the surveys comprised a Starlink Invicta 210S DGPS receiver supported by the Omnistar Satellites to establish the locations of the depth measurements (longitude and latitude) throughout the surveys. A Garmin GPSmap 168 Sounder with a 200 kHz, 8º Transducer was used to determine the distance to the reservoir bottom throughout the surveys. The depth soundings were correlated with tape measurements at the beginning of survey sessions. The manual depth measurement and the echo-sounder depth sounding correlated very well, within a few centimeters.

Bathymetric surveys should be undertaken when the reservoirs are full. This allows determination of their total capacity without the need for additional survey data. Polgolla was the only facility with a full reservoir, allowing the survey data to be directly analyzed for determination of the total reservoir capacity. Topographic maps for the other dams were obtained from the MASL and the full supply level was digitized from these maps for incorporation into the survey database. This is a difficult and inaccurate means of supplementing bathymetric data and results in an underestimation of reservoir sedimentation due to the inability to estimate the volume of sediments deposited above the reservoir level at the time.

Reservoir survey data collected in Sri Lanka required reduction to create contour maps of the new reservoir topography for each surveyed reservoir. The depth soundings were used to calculate bed elevations by subtracting them from the water surface elevations on the day the reservoir was surveyed. The survey data were analyzed to develop existing conditions, bathymetric maps and calculate existing reservoir capacity. Original reservoir capacity was also calculated by digitizing reservoir topography data from the time of dam completion provided by MASL. The difference between the two values gives the total loss to sedimentation to date.

At the time of publishing, Rantambe is the only reservoir for which the sedimentation analysis has been completed. The analysis for other reservoirs is awaiting further information.

Rantambe's estimated sedimentation rate is 339,342 m^3/year. The existing capacity of Rantambe is estimated to be 6,687,450 m^3 at the retention level of 152 m, which is a 38 percent reduction in capacity since reservoir impoundment in 1990.

Estimates of storage loss for Kotmale, Polgolla, Victoria and Randenigala Reservoirs in the Mahaweli Cascade used as input to the RESCON model were obtained from MASL or historically published documents (HR Wallingford, 1995). Due to the lower level of accuracy of older bathymetric survey methods, these numbers should be viewed as preliminary.

RESCON Modeling

General

The RESCON model was developed to identify optimal sustainable management strategies for single isolated reservoirs and is not suited for application to systems of reservoirs like the Mahaweli Cascade. Sediment management decisions at upstream reservoirs in such systems affect downstream reservoirs. For example, if sediment were released from an upstream reservoir by flushing or other means, the sediment inflow into downstream reservoirs would increase, thereby affecting their operation and useful life. When considering reservoirs in system context, it is therefore necessary to devise management strategies that will optimize the economic value and sustainability of the system as a whole.

In order to apply the RESCON model to this project, the software was modified to optimize operating rules for the system as a whole, instead of for a single reservoir. In particular, the modification incorporated the effects of discharging sediment into the river downstream of a dam by flushing, dredging or hydrosuction. In the case of trucking, it was assumed that the sediment would be completely removed from the river system and not discharged downstream to lower lying reservoirs. The modified model automatically runs all possible combinations of reservoir management schemes, considers the impact that management schemes at particular reservoirs have on each other and determines which set of sediment management techniques for the system as a whole will produce the optimal economic benefit.

The drawback of the cascade model is that the run time is approximately 18 hours on a Pentium 3 computer. For five reservoirs, the RESCON cascade model runs the original RESCON model 4,096 times and tabulates results.

Input Data

Data were collected by MASL for the RESCON model input for all five reservoirs in the Mahaweli Cascade. See Table I.1. The mean annual sediment inflow to Rantambe has been estimated from the surveys undertaken by this study. The values for the other reservoirs are based on data provided by MASL and other studies.

RESCON Model Results

The original RESCON model for a single isolated reservoir and the cascade system-model were used with the estimated data for each of the five reservoirs to develop strategies for sustainable reservoir management by MASL.

Development of a prioritized scheme for implementing sediment management strategies can be based on the anticipated project life of the reservoirs in the Mahaweli Cascade. Table I.2 provides a sum-

TABLE I.1
RESCON PARAMETERS

Parameter	Units	Kotmale	Polgolla	Victoria	Randenigala	Rantambe
Initial Storage Capacity	(10^6 m^3)	176.8	4.681	722.0	835.0	10.759
Existing Storage Capacity	(10^6 m^3)	170.1	2.558	713.1	768.8	6.687
Representative reservoir bottom width	(m)	340	118	108	50	50
Representative reservoir side slope		2	2	2	3	5
Normal Pool Elevation	(m)	703.0	440.7	438.0	232.0	152.0
River bed elevation	(m)	638.0	434.3	340.0	148.5	118.5
Flushing water elevation	(m)	645.0	434.3	352.0	170.0	139.0
Reservoir length	(m)	10450	7644	24800	12500	3100
MAR	(10^6 m^3)	871	1,838	1,571	2,085	2,387
Cv for MAR		0.14	0.15	0.28	0.25	0.22
Average annual inflow of sediments	(tonnes)	522,105	878,483	728,163	5,404,898	1,382,502

Sediment type: 650, fine grained sediments, density = 1.2 t/m^3

mary of the project life of the five reservoirs that were analyzed, for current conditions and when feasible reservoir sedimentation management strategies are implemented. Without implementing any sediment management techniques Rantambe is identified as the reservoir with the shortest project life (24 years) and Victoria as the reservoir with the longest project life (1 197 years).

The project lives of each of these reservoirs can be extended to a greater or lesser extent if feasible sediment management techniques are implemented. The most significant result is for Rantambe, which can be extended from 24 years to perpetuity. See Table I.2.

From the perspective of project life and its potential extension, it is recommended to prioritize future feasibility studies as follows:

- Rantambe
- Polgolla
- Randenigala

Implementation of pro-active sediment strategies is not required at Victoria and Kotmale reservoirs because their project lives are several hundred years each.

Using the preliminary results of the RESCON modeling and using engineering judgment and knowledge of the reservoirs and sediment management techniques, the sediment management strategies for each reservoir were prioritized. The results are given in Table I.3.

Rantambe Reservoir

Rantambe Reservoir is expected to silt up fastest (24 years) if no action is taken. This makes Rantambe the highest priority reservoir for sediment management in the Mahaweli Cascade. Sustainable dredging is shown as the first choice for Rantambe. It is estimated that a long-term capacity of approximately 95 percent of the original can be maintained if a single dredger is used constantly. The RESCON analysis furthermore indicates sustainable HSRS provides a long-term capacity of approximately 60 percent of

TABLE I.2
APPROXIMATE RESERVOIR LIFE

Reservoir	Approximate Number of Years until Reservoir is Completely Silted	
	No Removal Option	Partial Removal Option[a]
Kotmale	427	598
Polgolla	36	37
Randenigala	177	185
Rantambe	24	Infinite
Victoria	1 197	1 283

[a] Partial removal occurs via HSRS that is potentially capable of sustainable removal for Rantambe Reservoir according to RESCON analyses, extending its life in perpetuity.

the original and that flushing every three years provides a long-term capacity of 45 percent of original.

It is recommended that dredging, HSRS and flushing be studied in further detail.

Polgolla Reservoir

Currently, the expected life of Polgolla Reservoir is 36 years if no sediment management is undertaken. Flushing is known to be successful at Polgolla, because it is currently flushed when the barrage gates are lifted to allow flood flows to pass. With this site experience confirming the RESCON results, flushing is considered the first choice for sediment management at Polgolla.

Sand mining is also presently executed in the main body of Polgolla Reservoir with apparent success in keeping this area free of sediment. This site knowledge along with RESCON results suggests that dredging should be considered as a second management priority, particularly at intake towers.

Although RESCON shows HSRS as the third most economical solution, it is unlikely to be technically feasible due to the long reservoir.

It is recommended that flushing and sand mining continue as currently practiced and that supplemental dredging at intake towers be considered, either using conventional dredging or HSRS.

Randenigala Reservoir

Randenigala Reservoir had the largest initial capacity of all the reservoirs in the cascade. However, according to the data assumed in this study, it has had the highest sediment inflow rate over its lifetime compared to the other five reservoirs. Randenigala is predicted to have a moderately long

TABLE I.3
PRIORITISED SEDIMENT MANAGEMENT OPTIONS

Reservoir	Initial Volume (Mcm)	Existing Volume (Mcm)	Sustainable reservoir volume				Run-of-river	
			Flushing	Dredging	HSRS	Trucking	HSRS (Partial)	No action
Kotmale	176.8	170.1	3rd	2nd				1st
Polgolla	4.7	2.6	1st	2nd				
Randenigala	835.0	768.8	1st	Tactical				
Rantambe	10.8	6.7	3rd	1st	2nd			
Victoria	722.0	713.1	3rd	2nd				1st

life of about 177 years without any pro-active sediment management.

Examining the RESCON model prioritization, sustainable dredging was chosen to produce the highest economic benefit, but six dredges would be required to meet the inflowing sediment demand. Thus, dredging is not a feasible option (from a practical and technical point of view). The second choice of the RESCON model is HSRS partial removal. However, Table I.2 shows that the increased life provided by partial removal HSRS is negligible. HSRS, too, is disregarded as a possible solution.

Flushing is the third highest economic alternative chosen by the RESCON model. The model predicts that flushing every 16 years provides the optimum economic return and will keep Randenigala operational at a long-term capacity of 477.5 Mm^3 (57 percent of original capacity). This option will require construction of new low-level service gates because existing service gates have inadequate capacity. An initial estimate for total gate length required is at least 55 m. This is very wide considering the width of the entire dam.

It is recommended that Randenigala Reservoir be studied further for flushing potential in a feasibility level study. It must be verified that flushing is technically feasible for sustaining a reasonable capacity and a reasonable economic return. Localized dredging can be used at critical structures but dredging is not capable of producing a sustainable system alone.

Sensitivity to Discount Rate

The main runs of the model were undertaken using a discount rate of 10 percent and the sensitivity of the results to altering the discount rate to 5 percent and 15 percent tested. The results show that:

- The predicted life of each reservoir did not change for the different values of discount rate.
- Economic benefit generally decreases with increasing discount rate.
- The discount rate did not generally affect the highest economic benefit choice of the model.
- The second and third highest benefit choices varied slightly for different discount rates. In general, as the discount rate increases, the benefit of the no action and partial removal alternatives increase slightly relative to the sustainable removal alternatives. The NPV decreased by approximately 50 percent by changing discount rate from 5 percent to 10 percent. The value decreased by approximately another 33 percent by changing the discount rate from 10 percent to 15 percent.

Sensitivity to Cost of Dredging

The unit cost for dredging used in the study is US$5/$m^3$. This is considered to be a reasonable pre-feasibility level assumption which includes the cost of dredging and some costs of storage/disposal at an offsite location. The raw results of RESCON show that at this unit cost, dredging is the preferred economic option for every reservoir. Increasing the unit cost to US$15/$m^3$, dredging becomes much less favorable, only being chosen at one reservoir as most economic and at one reservoir as second most economic. In other words if the cost of disposal of the dredged sediments is likely to be substantial then dredging is unlikely to be economically feasible.

Environmental and Social Impacts

Table I.4 lists anticipated environmental and social impacts of sediment management on the Mahaweli Cascade using the RESCON methodology. Issues that were considered in this application include whether management will:

- Require the reservoir to be emptied and for how long?
- Affect water quality downstream of the dam?
- Require off-site disposal of sediment?

"No Removal" of sediment, with either non-sustainable or run-of-river assumptions, will not cause environmental or social impacts prior to complete siltation of the reservoir. For the "no-removal" options, Table I.4 assumes that complete loss of storage by siltation is infinitely far into the future as predicted by the RESCON results, so no impacts will be seen for "No Removal," granting it a rating of 6 for no impact.

Non-sustainable partial removal of sediment, partial removal of sediment with a run-of-river option and sustainable strategies that use HSRS will produce environmental results similar to one another. The reason for this is that HSRS is used in each of these optional sediment management strategies. It is expected that the concentration of sediment discharged downstream of the dam via HSRS can be controlled to produce positive conditions for fish downstream of the dam. This will create minor permanent changes to the existing ecosystem. Because of these minor ecosystem changes, fisheries species ratios may be altered, affecting human uses. Other social aspects should not be affected, so HSRS options receive a rating of 8 or minor overall impact in Table I.4.

When dredging sediments are removed to the river downstream of the dam, the concentration of the sediment discharge will determine whether this is a positive or negative environmental affect. Table I.4 assumes that this concentration can be controlled to produce positive conditions for fish downstream of the dam. This will create minor permanent changes to the existing ecosystem. Because of these minor ecosystem changes, fisheries species ratios may be altered, affecting human uses. Other social aspects should not be affected, so dredging also receives a rating of 8 or minor overall impact in Table I.4.

Flushing received the highest impact rating in Table I.4 at a value of 10 with one 3, so it is considered a moderate impact. During initial stages of flushing, sediment concentrations can be quite high downstream of the dam, which will cause temporary impacts to natural habitats. Fisheries will see impacts during the immediate aftermath of flushing, thus impacting human uses. Indigenous peoples will have altered and limited access to drinking water, fishing and washing in the reservoirs during flushing. Social categories not mentioned should not see impacts. Table I.4 assumes the reservoir emptying occurs for a short period only and that flushing facilities are already in place at said reservoir.

TABLE I.4
ENVIRONMENTAL & SOCIAL SAFEGUARD RATINGS

Possible Strategies	Technique	Environmental Safeguards Rating (Value 1 to 4)						Cumulative Safeguard Rating	Category
		Natural Habitats	Human Uses	Resettlement	Cultural Assets	Indigenous Peoples	Transboundary Impacts		
Non-sustainable No Removal	N/A	1	1	1	1	1	1	6	No impact
Non-sustainable No Removal Run-of-River	N/A	1	1	1	1	1	1	6	No impact
Non-sustainable Partial Removal	HSRS	2	2	1	1	1	1	8	Minor impact
Non-sustainable Run-of-River Partial Removal	HSRS	2	2	1	1	1	1	8	Minor impact
Sustainable	Flushing	2	2	1	1	3	1	10	Moderate impact
Sustainable	HSRS	2	2	1	1	1	1	8	Minor impact
Sustainable	Dredging	2	2	1	1	1	1	8	Minor impact
Sustainable	Trucking	2	3	1	1	2	1	10	Moderate impact

Trucking is not a first management choice for any of the reservoirs in the Mahaweli Cascade. Nevertheless, its safeguard rating would be a moderate impact (value of 10) due to temporary impacts to natural habitats (including permanent off-site disposal) and indigenous peoples and significant impacts to human uses of power generation while the reservoir is empty for trucking. Trucking requires that a reservoir be empty far longer than flushing.

Because the reservoirs on the Mahaweli River are existing, the impact of sediment management is minimized in terms of social and environmental considerations. The RESCON results are used to provide environmental impact expectations.

In summary, Victoria and Kotmale will not have an adverse environmental impact in the foreseeable future. If local dredging is later used to clear intake towers minor impacts are expected. Rantambe and Randenigala are expected to have minor social and environmental impacts due to the use of either dredging or HSRS. Polgolla and the river downstream of it are expected to experience moderate environmental and social impacts due to flushing and minor additional impact due to localized dredging. The above considerations should be addressed in detail in the environmental impact assessment that will be carried out at the feasibility level.

ANNEX J: SENSITIVITY ANALYSES

Introduction

This annex provides the details of the sensitivity tests undertaken on the model and which are summarized in Chapter 6.

General Sensitivity Testing

By selecting pre-existing geometries, the number of variables that is arbitrarily varied within the expected range of possibilities is reduced because relationships for the various geometric parameters to the capacity are fixed. The geometric parameters were scaled according to the relationships taken from the geometry data available for each site. Parameters representing the geometric relationship are given in Table J.1.

Once the geometric parameters based on a given capacity were set for each reservoir site, other parameters were varied to test model sensitivity. Each parameter was varied within values representing physical reality. The parameters that were varied are shown in Table J.2.

TABLE J.1
GEOMETRIC PARAMETERS

Parameter Description	Parameter Symbol
Original (initial) storage capacity of the servoir.	S_o
Existing storage capacity of the reservoir.	S_e
Reservoir length at the normal pool elevation.	L
Representative bottom width for the reservoir.	W_{bot}
Minimum bed elevation just upstream of dam.	EL_{min}
Water surface elevation at flushing gates during flushing.	EL_f
Elevation of top water level in reservoir (normal pool).	EL_{max}
Available head = normal pool elevation minus tailwater elevation	h
Representative side slope for the reservoir.	SS_{res}

TABLE J.2
PHYSICAL PARAMETERS VARIED IN ADDITION TO GEOMETRY CHANGES

Parameter Description	P arameter Symbol	Range of Values
Mean annual sediment inflow mass	M_{in}	0.1–3.0 % of inflow
Multiplier for reservoir and its sediment (Tsinghua University method)	Y	180, 300, –650, 1600 (depending on site)
Representative discharge passing through reservoir during flushing	Q	10–3,000 m^3/s (depending on site)
Frequency of flushing events	N	1–15 year intervals
Duration of flushing after complete drawdown	Tf	1 day– 2 months
Coefficient of Variation of Annual Run-off volume	Cv	0.1–2.0
Number of pipes used for hydro-suction sediment removal.	NP	1 – 3 pipes
Pipe diameter for hydrosuction	D	1 – 3.5 feet

TABLE J.3
CONSTANT PARAMETERS IN SENSITIVITY ANALYSIS

Parameter Description	Parameter Symbol
Density of in-situ reservoir sediment.	r_d
Estimated reservoir water temperature.	T
Sediment type category to be removed by hydrosuction dredging (medium sand/smaller or gravel).	Type
Reservoir similar to Chinese reservoirs? "3": if reservoir sediments are significantly larger than median grain size (d50) = 0.1mm or if the reservoir has been impounded for more than 10 years with out sediment removal. Use "1": if otherwise. A value of "3" was used throughout the analysis.	ANS
Is reservoir yield ever used for hydroelectric power?	HP
Sediment type for Brune Curve calculations.	Brune curve

TABLE J.4
ASSUMED CONSTANT REMOVAL PARAMETERS

Parameter Description	Parameter Symbol	Assumed Value
Acceptable probability of failure to provide reservoir yield in a given year (as decimal).	pr	0.01
Maximum fraction of total yield that is allowed to be used in HSRS operations.	YA	1
Maximum percent of capacity loss allowable at any time in reservoir. Allowable loss must be greater than the existing loss.	cl	75%
Percent of accumulated sediment dredged per event.	ASD	80 %
Percent of accumulated sediment trucked per event.	AST	80 %
Concentration by weight of sediment removed to water removed by traditional dredging.	Cw	30 %

Parameters that were assumed constant and determined with available data and judgment for each reservoir are listed in Table J.3.

A few parameters can be adjusted to produce variations in NPV; however, for simplicity, these parameters were assumed constant as indicated in Table J.4.

The model outcomes from changes in the physical input parameters generally followed anticipated trends. For example, increasing widths of reservoirs for a constant value of flushing flow result in lower long-term capacity ratios and increasing the sediment load results in more sediment being deposited in the reservoir prior to removal. Inspection of the results leads to the conclusion that the RESCON model is consistent.

Gould's Gamma Function Sensitivity Testing

Yield calculated using Gould's Gamma function was tested for the following reservoirs: Baira and Ichari (India); Sefid Rud (Iran); Abdel Karim El Khattabi, Bin El Ouidane, Ennakhla, Hassan I, Ibn Battouta, Mohammed V, Moulay Youssef, Oued El Makhazin, Sidi Driss and Timi N'Outine (Morocco); Tarbela (Pakistan); Polgolla and Victoria (Sri Lanka); and Gebidem (Switzerland). Data used in this analysis are in Table J.6.

The analysis of Gould's Gamma yield function resulted in definite cases where the equation is applicable and where it is not. The reservoir yield divided by mean annual runoff is the key parameter. All reservoirs with Wt/MAR greater than 0.4 exhibit the trend that increasing probability of failure (decreased reliability of resource) allows more yield to be taken from the reservoir. However, when Wt/MAR is less than 0.2, the trend is less predictable with increasing probability of failure and yield is even negative for 5 percent probability of failure, which is a physical impossibility. Wt/MAR performs marginally but acceptably in the range of 0.2 to 0.4. This limitation can be easily removed by: (a) using more complex yield-storage relationships than the Gould Gamma, or (b) by using actual relationships derived from hydrological records for the specific reservoir. We thought that a) would have made the RESCON model unnecessarily complicated and that b) would necessarily have to be carried out at the feasibility level.

TABLE J.5
ECONOMIC PARAMETER ASSUMPTIONS.

Parameter Description	Parameter Symbol	Assumed Value
If dam being considered is an existing dam enter 0. If the dam is a new construction project, enter 1.	E	0
Unit Cost of Construction. This cost is estimated using So specified in Reservoir Geometry.	c	Default Calculation
Cost of Dam Construction. The default cost is estimated as unit cost of construction times initial reservoir storage volume ($C2 = S_o * c * E$).	C2	Default Calculation
Reservoir (Dam) Operation and Maintenance Coefficient	omc	0.01
Dam Salvage Value Coefficient	a	0
Discount Rate (decimal)	r	0.05
Price of Net Reservoir Yield.	P1	0.01/m^3
Unit Value of Water Used released downstream during actual flushing operations (water lost during drawdown is internally assigned a value of zero).	PF	\$0.005/m^3
Unit value of water released downstream of dam in river by hydrosuction operations.	PH	\$0.005/m^3
Unit value of water used in dredging operations.	PD	\$0.005/m^3
Unit cost for hydrosuction operations expressed as \$/m^3 of sediment removed.	CH	\$5/m^3
Unit cost of traditional dredging	CD	Default Calculation

TABLE J.6
INPUT FOR GOULD'S GAMMA FUNCTION TESTING.

Reservoir	Existing Capacity (10^6 m^3)	Average Annual Inflow (10^6 m^3)	Standard Deviation of Average Annual Inflow (m^3)
Polgolla, Sri Lanka	2.6	1,838.0	275.7
Victoria, Sri Lanka	713.1	1,571.0	439.9
Abdel Karim El Khattabi, Morocco	8.9	48.2	38.6
Bin El Quidine, Morocco	1253.0	1,050.0	609.0
Ennakhla, Morocco	4.9	55.0	30.8
Hassan I, Morocco	245.0	288.5	144.3
Ibn Battouta, Morocco	33.9	52.3	42.4
Mohammed V, Morocco	362.6	750.0	382.5
Moulay Youssef, Morocco	159.4	287.0	143.5
Qued El Makhazin, Morocco	773.0	809.0	542.0
Sidi Driss, Morocco	6.0	500.0	335.0
Timi N'Outine, Morocco	2.4	5.6	2.8
Baira, India	2.0	1,000.0	500.0
Gebidem, Switzerland	8.9	429.0	214.5
Ichari, India	3.9	5,300.0	2,650.0
Sefid Rud, Iran	1320.0	5,000.0	2,650.0
Tarbela, Pakistan	11,360.0	8,000.0	2,650.0

TABLE J.7
SENSITIVITY TO VALUE OF UNIT RESERVOIR YIELD
(P1=$0.1/M^3 TO P1=$0.2/ M^3)

Possible Strategies	Technique	Change in NPV ($ 1000 million)	Change in NPV (%)
Non-sustainable (Decommissioning)-with No Removal	N/A	138.4	100
Non-sustainable (Decommissioning)-with Partial Removal	HSRS	138.4	100
Non-sustainable (Run-of-River)-with No Removal	N/A	138.7	100
Non-sustainable (Run-of-River)-with Partial Removal	HSRS	138.7	100
Sustainable	Flushing	139.2	100
Sustainable	HSRS	N/A	N/A
Sustainable	Dredging	142.3	101
Sustainable	Trucking	138.8	115
	Change in LTC (million m^3)	Change in LTC (%)	
Long term reservoir capacity for Flushing	0	0	
Long term reservoir capacity for HSRS	N/A	N/A	
Long term reservoir capacity for Dredging	+1,890	31%	
Long term reservoir capacity for Trucking	+405	6%	

Sensitivity to Economic Parameters

Changes in economic parameters may alter not only the ranking of desirable sediment management strategies, but could also affect the amount of sediment removed with each strategy and magnitude of variables such as the timing of decommissioning and any retirement fund contributions. Sensitivity analysis was performed on key economic parameters of the Tarbela Dam case study to investigate these effects and test the model for consistency with economic intuition. The following parameters were varied: price of net reservoir yield (P1), rate of discount (r), market rate of interest (m), cost of operations and maintenance coefficient (omc) and costs of sediment removal for different techniques. The results of this sensitivity analysis are reported below.

P1: Price of Net Reservoir Yield

When P1 is doubled from US$0.1 ($/m^3) to US$0.2 ($/m^3), NPV for all strategies increases by nearly US$140 billion. However, the increase in NPV for sustainable solutions is somewhat higher than that for non-sustainable solutions. Also, the long-term capacity ratio (LTCR) increases by 31 percent and 6 percent respectively for dredging and trucking. It follows that the higher water prices generate incentives to keep more storage capacity. In the case of flushing, changes in economic parameters do not affect LTCR because the latter is determined by engineering features rather than economic optimization.

r: Discount Rate

The discount rate determines the weight of future benefit and cost relative to the present. When the discount rate is lowered from 5 percent to 3 percent, NPV for each strategy increases by nearly 50 percent but there is no change in rankings. Furthermore, the long-term capacity for dredging and trucking increases, respectively, by 33 percent and 4 percent. Thus, as with the increase in price of net reservoir yield, lowering of the discount rate also encourages retaining higher storage volumes.

TABLE J.8

SENSITIVITY TO DISCOUNT RATE

(r reduced from 5% to 3%)

Possible Strategies	Technique	Change in NPV ($ 1000 million)	Change in NPV (%)
Non sustainable (Decommissioning)-with No Removal	N/A	70.2	51
Non sustainable (Decommissioning)-with Partial Removal	HSRS	70.2	51
Non sustainable (Run-of-River)-with No Removal	N/A	72.2	52
Non sustainable (Run-of-River)-with Partial Removal	HSRS	72.2	52
Sustainable	Flushing	81.7	59
Sustainable	HSRS	N/A	N/A
Sustainable	Dredging	89.1	63
Sustainable	Trucking	37.9	31

	Change in LTC (million m^3)	Change in LTC (%)
Long term reservoir capacity for Flushing	0	0
Long term reservoir capacity for HSRS	N/A	N/A
Long term reservoir capacity for Dredging	2,025	33
Long term reservoir capacity for Trucking	270,056	4

m: Market Rate of Interest

The annual retirement fund is calculated using the market interest rate (i.e., the rate of return on investing the fund). The value of this annual contribution is reported only when decommissioning cost exceeds any benefit of dam removal. For the Tarbela case study simulation, it is assumed that US$2.5 billion is the net cost of decommissioning the dam. The corresponding annual retirement fund is US$2 million with 5 percent market interest rate. If the interest rate increases from 5 percent to 8 percent, the annual retirement fund contribution decreases to US$0.29 million. Thus, the annual retirement fund contribution is highly sensitive to the market interest rate. One should also expect that the annual retirement fund will decrease with changes in economic parameters that increase the longevity of dams.

Operations and Maintenance Coefficient (omc)

The operations and maintenance coefficient is defined as the ratio of annual operations and maintenance cost to initial construction cost. Thus, an omc value of 0.01 means that annual operations and maintenance cost is 1 percent of initial construction cost. The results of change in this coefficient from 0.01 to 0.05 are summarized in Table J.9. Since annual operations and maintenance cost is independent of sediment management strategies, the change in omc reduces the NPVs for all strategies by the same amount except for non-sustainable ones with decommissioning. As no annual operations and maintenance cost is incurred after dam removal, the change in NPV for non-sustainable (decommissioning) strategies is slightly lower. Long-term capacity, frequency of sediment removal and the amount of sediment removal are all independent of the change in annual operations and maintenance cost.

Sensitivity to Cost of Sediment Removal Parameters (S2, PH, CD, CT)

Costs of sediment removal depend on the technique used. The parameters associated with each technique are varied as below and impacts reported. All pa-

TABLE J.9

SENSITIVITY TO OPERATION & MAINTENANCE COEFFICIENT

(omc = 0.01 to omc = 0.05)

Possible Strategies	Technique	Change in NPV ($ 1000 million)	Change in NPV(%)
Non sustainable (Decommissioning)-with No Removal	N/A	–1.801	–1.3
Non sustainable (Decommissioning)-with Partial Removal	HSRS	–1.801	–1.3
Non sustainable (Run-of-River)-with No Removal	N/A	–1.830	–1.3
Non sustainable (Run-of-River)-with Partial Removal	HSRS	–1.830	–1.3
Sustainable	Flushing	–1.830	–1.3
Sustainable	HSRS	N/A	N/A
Sustainable	Dredging	–1.830	–1.3
Sustainable	Trucking	–1.830	–1.5

TABLE J.10

SENSITIVITY TO COST OF SEDIMENT REMOVAL PARAMETERS

(S2, PH, CD, CT)

Possible Strategies	Technique	Change in NPV ($ 1000 million)	Change in NPV(%)
Non sustainable (Decommissioning)-with No Removal	N/A	0	0
Non sustainable (Decommissioning)-with Partial Removal	HSRS	0.2	0
Non sustainable (Run-of-River)-with No Removal	N/A	0	0
Non sustainable (Run-of-River)-with Partial Removal	HSRS	0.2	0
Sustainable	Flushing	1,367.2	1.0
Sustainable	HSRS	N/A	N/A
Sustainable	Dredging	264.6	0.2
Sustainable	Trucking	3,310.16	2.7
	Change in LTC (million m³)	**Change in LTC (%)**	
Long term reservoir capacity for Flushing	0	0	
Long term reservoir capacity for HSRS	N/A	N/A	
Long term reservoir capacity for Dredging	810	13	
Long term reservoir capacity for Trucking	135	2	

rameter changes decrease the cost of sediment removal, but by different amounts.

- *Flushing:* S2 (fraction of storage benefits that can be used in a year in which flushing occurs) increased from 0.5 to 0.75.
- *HSRS:* PH (unit value of water released downstream during hydrosuction operations) decreased from US$0.005 to US$0.003.
- *Dredging:* CD (unit cost of dredging) decreased from US$2.62 to US$2.00/m^3.
- *Trucking:* CT (unit cost of trucking) decreased from US$50 to US$40/m^3.

When the cost of sediment removal is reduced, NPV increases regardless of the strategy used. Long-term capacities for dredging and trucking are increased. These results imply that the reduction of sediment removal costs increases the difference between NPV with sediment removal and that with no removal. More importantly, the magnitudes involved suggest the need for technological innovation in sediment removal because a marginal reduction in unit cost of removal has the potential to save million of dollars over the long term.

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Among the many sessions of the Third World Water Forum, held in Japan, March 2003, there was one titled "Sedimentation Management Challenges for Reservoir Sustainability". Two main messages emerged from that session:

- Whereas the 20th century focused on reservoir development, the 21st century will necessarily focus on sediment management; the objective will be to covert today's inventory of non-sustainable reservoirs into sustainable infrastructures for future generations.
- The scientific community at large should endeavor to devise solutions for conserving existing water storage facilities in order to enable their functions to be delivered for as long as possible, possibly in perpetuity.

These important messages are very much in line with the World Bank's Water Resources Sector Strategy that calls the Institution to address management of existing infrastructure, as well as to develop much needed priority water infrastructure.

In fact, many poor countries facing similar climate variability as rich countries, have as little as 1/100th as much water infrastructure capacity. The result is great vulnerability to the vicissitudes of climate variability, a vulnerability which is exacerbated by climate change. There is much that can and must be done by managing watersheds better, and managing demand.

The present book can assist in making existing reservoirs sustainable, as well as in the sustainable design of new surface storage facilities. The book addresses the issue of reservoir sustainability from an economic angle, a perspective hardly explored so far.

We hope that this initial step will encourage others to follow, both in additional research, and in actions aimed at conserving water storage assets for future generations.

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