# COST ANALYSIS OF SEDIMENT REMOVAL TECHNIQUES FROM RESERVOIR

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

TUÇE ARAS

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

MAY 2009

Approval of the Thesis;

COST PRODUCTION OF SEDIMENT REMOVAL FROM RESERVOIR

Submitted by **TUÇE ARAS** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering, Middle East Technical University** by,

Prof. Dr. Canan Özgen
Dean, Graduate School of **Natural and Applied Sciences** _______________

Prof. Dr. Güney Özcebe
Head of Department, **Dept. of Civil Engineering** _______________

Asst. Prof. Dr. Şahnaz Tiğrek
Supervisor, **Dept. of Civil Engineering, METU** _______________

Assoc. Prof. Dr. Murat Gündüz
Co-Supervisor, **Dept. of Civil Engineering, METU** _______________

**Examining Committee Members:**

Prof. Dr. Metin Ger
Civil Engineering Dept., METU _______________

Asst. Prof. Dr. Şahnaz Tiğrek
Civil Engineering Dept., METU _______________

Prof. Dr. Melih Yanmaz
Civil Engineering Dept., METU _______________

Assoc. Prof. Dr. Murat Gündüz
Civil Engineering Dept., METU _______________

Dr. Hande Akçakoca
GAP Administration _______________

**Date:** _______________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Tuçe Aras

Signature:

**ABSTRACT**

COST ANAYSIS OF SEDIMENT REMOVAL TECHNIQUES FROM RESERVOIR

ARAS, Tuçe
M.S., Department of Civil Engineering
Supervisor: Asst. Prof. Dr. Şahnaz TİĞREK
Co-supervisor: Assoc. Prof. Dr. Murat GÜNDÜZ

May 2009, 166 pages

Siltation in reservoirs is becoming an important problem as the dams are getting older in the world. The general dam practice has been implemented in a sequence that; planning, design, construction, operation of dam until the accumulated sediment prevents its purpose function or functions. Unfortunately, effects of sedimentation and fate of the left over dams in the future are not figured. Indeed, these negative effects could be avoided, life of the reservoir can be prolonged and even the reservoir will last forever by minimizing the sedimentation.

Therefore in this study, the methods that provide extension of reservoir life are discussed hydraulically, economically and applicability point of view. In addition, there is open source package program RESCON which examines and compares some sediment removal techniques economically and also hydraulically. RESCON is used in conjunction with several cases; namely

Çubuk Dam-I, Borçka Dam and Muratlı Dam. Moreover, some sensitivity analyses are carried out in order to scrutiny of the program for Turkish economic conditions.

Keywords: Reservoir siltation, reservoir sedimentation, feasibility of desiltation techniques, sustainability of dams, RESCON

**ÖZ**

REZERVUARDAN RÜSUBAT KALDIRMA TEKNİKLERİNİN
MALİYET ANALİZİ

ARAS, Tuçe
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Yrd. Doç. Dr. Şahnaz TİĞREK
Yardımcı Tez Yöneticisi: Doç. Dr. Murat GÜNDÜZ

Mayıs 2009, 166 sayfa

Baraj göllerindeki rusubat birikimi dünyadaki barajlar yaşlandıkça önemli bir problem olmaktadır. Genel anlamda baraj uygulamaları; planlama, tasarım, inşa ve biriken rusubat amaçlanan işlev veya işlevlerini engelleyene kadar işletim olarak gerçekleşmektedir. Maalesef rusubat birikimi etkileri ve barajdan geriye kalanların geleceği dikkate alınmaz. Biriken rüsubatı en aza indirerek bu kötü etkilerden kaçınılabilir, barajın ömrü uzatılabilir ve hatta sonsuza kadar yaşatılabilir.

Dolayısıyla bu çalışmada barajın ömrünü uzatacak yöntemler ekonomik ve uygulanabilirlik esaslarına göre tartışılmaktadır. Ayrıca, rusubat giderme tekniklerini ekonomik ve hidrolik olarak tetkik eden ve karşılaştıran bir açık kaynak paket program olan RESCON mevcuttur. Çubuk Barajı-I, Borçka Barajı ve Muratlı Barajı için yapılan vaka analizlerinde RESCON kullanılmıştır.

Ayrıca programın Türkiye ekonomik koşullarına uygunluğunu anlamak için duyarlılık analizleri yapılmış ve tartışılmıştır.

Anahtar Kelimeler: rezervuar siltasyonu, rezervuar sedimentasyonu, desiltasyon teknikleri fizibilitesi, barajların sürdürülebilirliği, RESCON

# ACKNOWLEDGEMENTS

This study was suggested and has been completed under the supervision of Assist. Prof. Dr. Şahnaz Tiğrek in Civil Engineering Department of the Middle East Technical University in Ankara, Turkey.

I would especially thank Assist. Prof. Dr. Şahnaz Tiğrek. She was always with me throughout every step of this study, providing me with insight, support and guidance. It would be very difficult for me to move forward when I felt stuck, without her support. It is an honour for me to know her.

I would like to express my sincere thanks to; my family, my fiancée Murat Şaşmaz and my housemate Zeynep Zelal Kankotan for their love, encouraging and calming words whenever I need to accomplish such a demanding work.

Special thanks go to Nihat Birkan Dedekli (MNG Holding) and Özcan Çevik for their kind assists in providing data.

Sincere thanks to all my friends and my colleagues for their support and encouraging me with endless patience and sincerity throughout this period.

**TABLE OF CONTENTS**

## LIST OF FIGURES

## LIST OF TABLES

## LIST OF SYMBOLS

| | |
|---|---|
| $A_f$ | cross sectional area of valley scoured out by flushing ($m^2$) |
| $A_r$ | cross sectional area of reservoir in reach immediately upstream from the dam ($m^2$) |
| $C_o$ | reservoir capacity ($m^3$) |
| DDR | drawdown ratio |
| $El_f$ | water surface elevation at the dam during flushing (m) |
| $El_{min}$ | minimum bed elevation (m) |
| $El_{max}$ | top water level elevation (m) |
| FWR | flushing width ratio |
| $h_f$ | a height defined in Figure 2.8 (m) |
| $h_l$ | a height defined in Figure 2.8 (m) |
| $h_m$ | a height defined in Figure 2.8 (m) |
| L | reservoir length (m) |
| LTCR | long term capacity ratio |
| MAR | mean annual river runoff |
| $M_f$ | sediment mass flushed annually from the reservoir (t) |
| $M_{dep}$ | sediment mass deposited annually in the reservoir (t) |
| $M_{in}$ | mean annual sediment inflow ($m^3$) |
| MSY | mean annual sediment yield |
| $Q_f$ | representative discharge passing through reservoir during flushing ($m^3$/s) |
| $Q_s$ | sediment load during flushing (t/s) |
| S | longitudinal slope during flushing |
| SBR | sediment balance ratio |
| $SBR_d$ | sediment balance ratio calculated for full drawdown |
| SEPS | sediment evacuation pipeline system |

| | |
|---|---|
| $SS_s$ | representative side slope for the deposits exposed during flushing |
| $SS_{res}$ | representative side slope of reservoir |
| $S_t$ | remaining reservoir capacity after year t |
| TE | trapping efficiency |
| $T_f$ | duration of flushing (days) |
| TWR | top width ratio |
| $V_{in}$ | mean annual inflow volume ($m^3$) |
| W | the representative width of flow for flushing conditions (m) |
| $W_{bf}$ | scoured valley bottom width for complete drawdown (m) |
| $W_{bot}$ | representative bottom width for the reservoir (m) |
| $W_f$ | width of flow at the bed of flushing channel (m) |
| $W_{res}$ | representative reservoir width in the reach upstream from the dam at the flushing water surface elevation (m) |
| $W_t$ | reservoir width at the top water level (m) |
| $W_{td}$ | width at top water level of the scoured valley, when drawdown is complete (m) |
| $W_{tf}$ | scoured valley width at top water level for complete drawdown (m) |

## ABBREVIATIONS

| | |
|---|---|
| ASKİ | General Directorate of Ankara Water and Canalization Administration |
| BO | Build - Operate |
| BOT | Build – Operate – Transfer |
| CAT | Caterpillar |
| DSI | State Hydraulic Works |
| EPDK | Energy Market Regularity Authority |
| EÜAŞ | Electricity Generation Co. Inc |
| GIS | Geographical Information System |
| HSRS | Hydrosuction Sediment Removal System |
| ICOLD | International Commission of Large Dams |
| IRTCES | International Research and Training Center on Erosion and Sedimentation |
| N/A | Not Applicable |
| NPV | Net Present Value |
| O&M | Operation and Maintenance |
| ppm | Parts Per Million |
| RESCON | Reservoir Conservation |
| RMB | Renminbi (Chinese Yuan) |
| SEPS | Sediment Evacuation Pipeline System |
| TEDAŞ | Turkey Electricity Distribution Co. Inc. |
| TEİAŞ | Turkey Electricity Transmission Company |
| TETAŞ | Turkey Electricity Trade Co. Inc. |

# CHAPTER 1

# INTRODUCTION

## 1.1. Introduction of the Problem and Scope of the Study

Water is a vital component for the continuity of the life of human being. In the history, the civilizations had settled down generally riversides in order to get basic needs in daily life. However, the scarcity of water due to population increase, climate changes, drought etc., causes need to store the fresh water. As a result, dams had been constructed to store the water. Dams have been used for flood prevention too. Moreover, they have been used for power generation purposes for the last 100 years. Nevertheless as the dams getting older some environmental damages have been observed. One of the reasons is trapping of sedimentation on the upstream of the dam body.

Reservoir sedimentation is a very serious problem for many countries, especially in semi-arid regions. There are approximately 45,000 dams in the World and they loose their reservoir capacity 0.5 – 1.0 % every year (Mahmood, 1987). Moreover, in arid climate conditions the capacity lost is as high as 6,000 – 8,000 $m^3/km^2$/year (White, 2000).

The deposited sediment in reservoirs causes not only reservoir capacity loss but also downstream and upstream negative influences. In addition, operation performance of dam decreases significantly such that the benefits gained from hydroelectric power generation, irrigation, water supply and flood control decreases in a considerable amount because of the reservoir sedimentation. Nevertheless, the downstream and upstream faces of the dam are indirectly affected. In the downstream sediment loss causes degradation in channel and changes in aquatic life. That is why a normal river conditions change the sediment-free water conditions due to sedimentation deposition in the upstream. On the other hand, increase of local ground water table, channel flood capacity reduction, decrease of bridge navigational clearance, and water diversions and withdrawals influence are negative effects of sedimentation in upstream of a reservoir (Fan, 1985).

Generally, the design life approach is adopted by design engineers that the sedimentation accumulation is only used for economic life calculation. At the design stage, the benefit – cost calculation is performed by using a specified time. For instance, Dams in Turkey have been designed for 50 years economic life period, whereas it can change depending on the local circumstances. This design life is defined as the feasible operation time period of the project. The environmental and social issues of the project are included only at the initial stage. In addition any changes during this design life are not included in the design stage (Palmieri et al., 2003). On the other hand, World Bank is promoting life cycle management approach, which includes the issues that design life approach does not consider. Through life cycle management approach; sedimentation, social and environmental safeguards, reservoir sediment management alternatives, economical optimization and also decommissioning and retirement of dam items are included in the pre-feasibility level.

In the life cycle management approach sediment management alternatives are put into effect after loss of certain percentage of storage capacity which provides life extension of reservoir (Palmieri et al., 2003).

This study is based on the life cycle management approach. Basin water storage capacity management techniques are discussed in order to achieve in sustainable management of reservoir and water quality preserving. The techniques are categorized in three parts such that; prevent sediment inflow, sustainable management of the reservoir and search for new storage alternatives. In addition, an already existing, excel based open source package program RESCON, which examine and compare some sediment evacuation methods and decommissioning, is used. RESCON is a spreadsheet-based program written in Visual Basic programming language and works with macros. Some specific data should be put in the two input pages of RESCON. The difficulty of usage of program is come into the stage at this point. All input data are researched in order to conform to the conditions of Turkey. Then three case studies are performed namely; Çubuk Dam-I, Borçka Dam and Muratlı Dam. These dams are endangered with sedimentation problem; the reason for selection.

Moreover, in order to see how change in input parameters affects the results of case studies, some sensitivity analyses are presented. The results of this sensitivity analyses may enhance the estimation of effect of changes in input parameters on the prediction.

There will be easy to predict the changes of result values, in case of changing in input parameters, through.

As a result; in Chapter-1 brief description of the importance of the problem and scope of the study are explained. In Chapter-2 Reservoir Sediment Management Techniques are defined and also discussed. Chapter-3 is reserved for introduction to RESCON and explanation of working principle of RESCON. Working principle is discussed in technical and economical frameworks. Case Studies and Sensitivity Analyses are explained in Chapter-4. In addition, discussions of the economic results and input parameters are included in this chapter. Finally in Chapter-5, conclusion of this study is presented.

### 1.2. Literature Survey

International Commission on Large Dams (ICOLD) classified the dams such that a dam is a large dam if the height is higher than 15 m from the foundation or the volume of the reservoir is equal to or more than 3,000,000 $m^3$. As it is mentioned that there are 45,000 large dams around the world and China has the most; 22,000 of in total. As far as the Mediterranean Area is concerned, Spain takes the first place with 1,196 dams. Turkey follows Spain with 625 dams and France with 566 dams is the third in ranking. Table 1 shows the storage, power and sedimentation of dams according to region in world wide.

Ludwig (2008) shows water storage capacity distribution in Mediterranean Region during the second half of the $20^{th}$ century in Figure 1.1. In addition, Poulus and Collins (2002) examined 69 rivers out of 169 rivers of the Mediterranean drainage basin, which incorporates more than 160 rivers with catchments greater than 200 $km^2$. They concluded that sediment supply is reduced approximately 50% because of construction of hundreds of dams around the Mediterranean Sea. As a matter of fact, this reduction is mainly responsible for the loss of deltaic land. Further, in Figure 1.2 dramatic increase in the number of dams during the second half of the $20^{th}$ century could be seen.

**Table 1.1 Worldwide Storage, Power and Sedimentation (RESCON Manual Volume I, 2003, After White, 2001)**

| 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) |
|---|---|---|---|---|---|
| Worldwide | 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 |

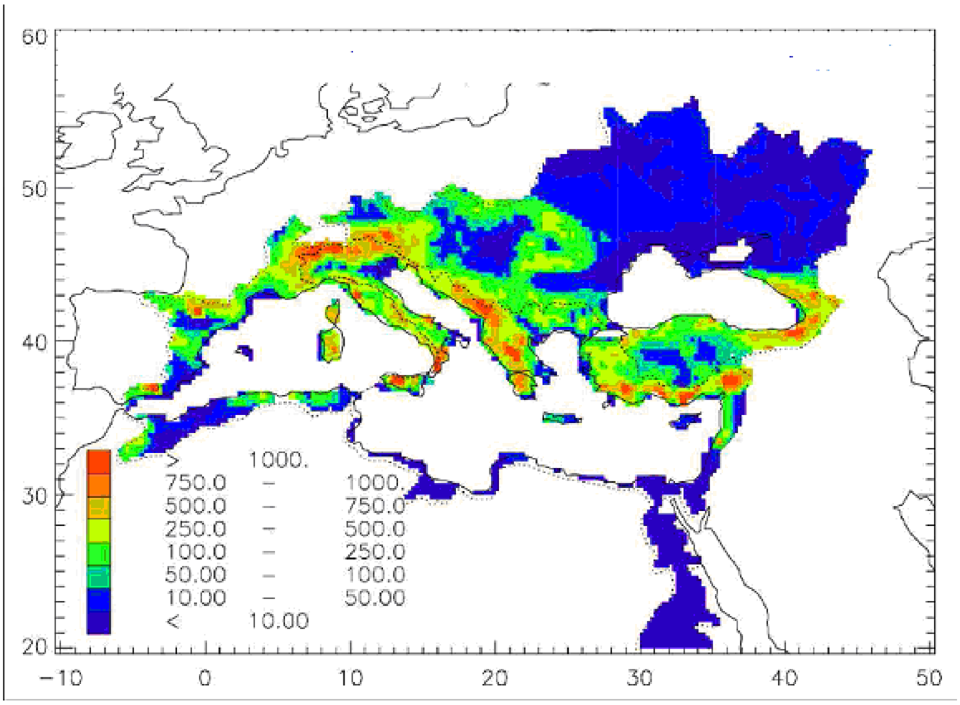



Figure 1.1 Increase of water storage capacity of the riparian countries of the Mediterranean Sea. (Ludwig 2008).

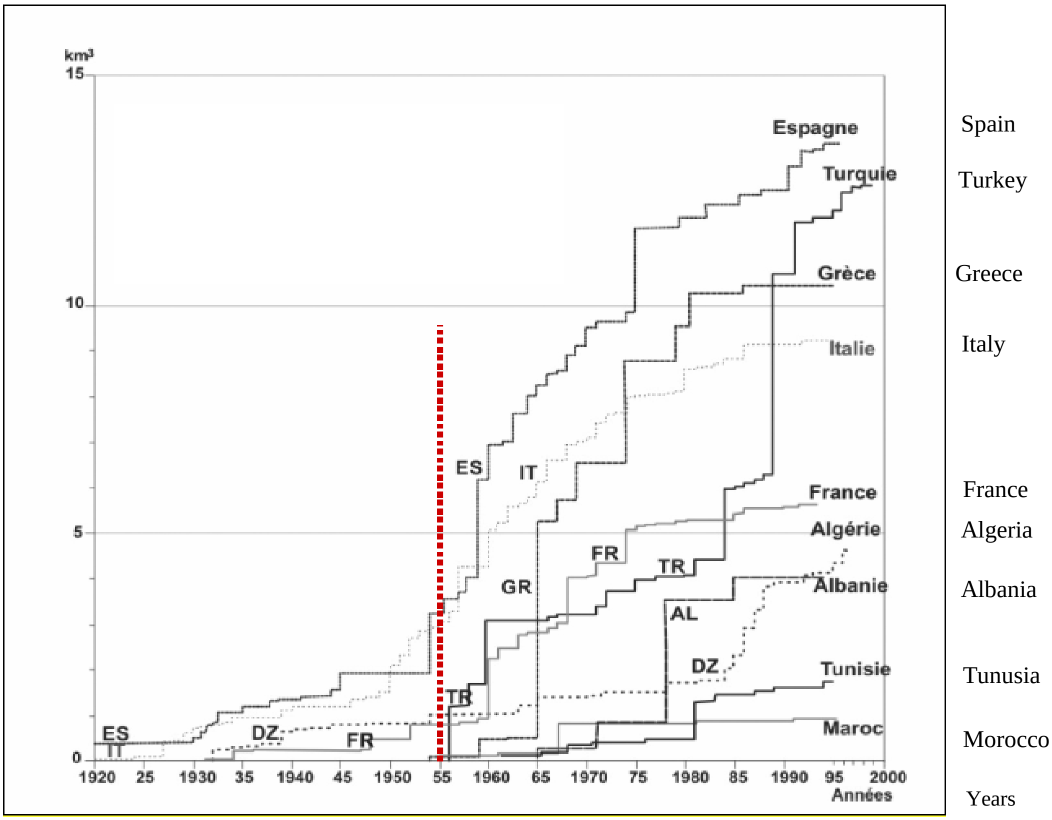



Figure 1.2 Sediment Yield of the Mediterranian Drainage Basin (Ludwig, 2008)

In Turkey, precipitation quantities show large variations because of climate diversity of Turkey like other Mediterranean countries. Basically, the climate diversity occurs because of diversity in the topography. The average annual precipitation depth in Turkey is around 643 mm, which is lower than 800 mm, the average precipitation depth of the world (Usul, 2005). Inner Anatolia and Eastern Anatolia receive heavy snow in winter. Therefore, the annual flows of many of the large basins are inconsistent. Nearly every 30 years, a drought period takes place. However, the periods between these drought seasons have shortened after 1960. The last drought was in 1994 and lasted five years (Komuscu, 2005).

Average annual surface water in Turkey is 193 billion $m^3$ and groundwater is 41 billion $m^3$. The total amount of exploitable surface water is 110 billion $m^3$ and groundwater safe yield is 12 billion $m^3$. The quantity of water per capita is around 1700 $m^3$/year for a population of 67.8 million.

Today, Turkey utilizes only 39.3 billion $m^3$ of its capacity. However, it is expected that in 2030, the amount of available water per capita will be less than 1000 $m^3$ per year. As a result, dam construction in Turkey will continue although there 625 large dams already built up.

The first dam built in Turkey during the Republic Era is Çubuk I Dam, completed in 1936, built for the domestic water requirement of the capital city of Ankara. After the Second World War, an increase in construction of dams and hydroelectric power plants can be observed in Turkey. The state constructed more than 1,000 dams and most of the rivers were taken under control. Most of these dams have reservoir volume smaller than 100,000,000 $m^3$, and their technical accessories are simpler than in case of large dams. Consequently, they are even more endangered by siltation. The specific sediment-yield of the watersheds in mountainous areas of Turkey where the most dams are and will be constructed is considerably high.

Fakioglu (2005), studied on Seyhan Dam which is located on the Seyhan River which discharges to Mediterranean Sea. Fakioglu has evaluated the sediment yield by comparing the hydrographical maps produced in different periods and considered causes of sedimentation and counter measures accordingly. It is found out that the active volume of the reservoir was 1,238,000,000 $m^3$ in 1966 and has decreased to 831,000,000 $m^3$ by 2005. Also, the accumulated sediment volume is 407,000,000 $m^3$ in 2005.

Another case study on the effect of change of flow and sediment transport on the river bed scour in downstream is made by Işık et al. (2006). Sediment rating curves in Lower Sakarya River are determined and compared by using measured suspended load before and after the construction of Gökçekaya Dam in the Middle Sakarya Basin. It was observed that the sediment transport was decreased at a rate of 40-65% after the construction of Gökçekaya Dam Consequently, the comparison of cross section measurements in 1965 and 2003 points out an enlargement in the width and a scour up to 7 m in the depth of the river.

A case study on Kızılırmak Basin, which is shown in Figure 1.3, (outlet to the Black Sea, also the third largest basin of Turkey) shows that 12 important dams built on Kizilirmak River (İmranlı, Yamula, Bayramhacılı, Hirfanlı, Kesikkopru, Kapulukaya, Bura, Obruk, Dutludere, Boyabat, Altınkaya and Derbent Dams), for the purpose of energy, flood control and irrigation, have been trapping the alluvium and therefore the solid material reaching the coastline has decreased by 98%. This has been resulted with a decrease or even a stop in the increase rate of the delta and the coastal stream and waves cause erosion of delta. A numeric illustration for the second consequence which is studied by Guler et al. (2002) points out that yearly setback is around 30 m and Kokpinar et al. (2000) gives the total setback between 1990 and 2000 as 1 km.

Although there are significant environmental effects of siltation start to appear under coast line of Black Sea after 50 years of dam construction, design life approach is being used in the design stage of new dams. There are limited studies about reservoir siltation, focusing on the design life of the dam (Yilmaz et.al.2005). Sonmez and Dincsoy (2002) prepared a report for the determination of annual sediment yield and possible precautions for Ivriz Dam, which is located in the Central Anatolia, by using Geographical Information System (GIS).


Figure 1.3 Kızılırmak Basin

Çetinkaya (2006) examine the sediment removal strategies (flushing, hydrosuction sediment removal, dredging and trucking) by using RESCON. Especially technical parameters for RESCON were analyzed deeply and high efforts were made by him to obtain them. Sediment measurements which are made by governmental agencies in Turkey are presented. This study is a kind of follow up investigation in order to extend the Çetinkaya's (2006) work.

# CHAPTER 2

## SUSTAINABLE DEVELOPMENT OF BASIN WATER STORAGE CAPACITY

The main reason for losing the water storage capacities is siltation in basin area. In the world there are some techniques in order to overcome this siltation problem. Some of these techniques deal with inflowing sediment. On the other hand, some of them try to remove siltation. However, in the world the problematic regions do not use the same techniques. Because every basin has different characteristics such that; geological, geographical and climatic, etc. For example, the dredging technique is mostly used in semi-arid regions like China. On the other hand, in the north European countries, in rainy regions, use flushing techniques.

Nevertheless, in this study the basin water storage capacity management techniques used in World is categorized as follows:

1. Preventing Sediment Inflow into the reservoir,
    - Watershed Management
    - Upstream Check Structures (Debris Dams)
    - Reservoir Bypass

2. Sustainable Management of the Reservoir,
    - Evacuation of Sediments from Reservoir
        - Flushing
        - Sluicing

- Density Current Venting
- Mechanical Removal
    - Dredging
    - Hydrosuction Removal System (HSRS)
    - Trucking

- Management of Reservoir
    - Operation Rules
    - Tactical Dredging

3. Lost Storage Replacement Techniques or Decommissioning of Dam (Retirement of dam).
    - Raising Dam Height
    - Build New Dam
    - Decommissioning

## 2.1. PREVENTING SEDIMENT INFLOW

The sediment silted in reservoir causes several major problems. If the sediments coming from the upper reaches of the river could be stopped or diverted before reaching the dam body, then the majority of problem will decrease to a large extent. There are some methods for preventing sediment inflow explained in the following sections.

### 2.1.1. Watershed Management

Watershed management is a method which is used to reduce the reservoir siltation coming from the upstream basin of the reservoir by using some techniques such that; forestation, prevention of erosion by vegetation and tillage management, sediment trap and change in land usage. As a matter of fact, watershed management aims to conserve soil and consequently conserve water. In order to achieve this aim, techniques should be combined efficiently.

According to White, the storage losses in China and India are because of low forest covers which are 16.5% and 23%, respectively. As it is seen from Table 2.1, China and India are losing their storage capacity approximately 2.3 % and 0.46 %. On the other hand, storage losses of Japan and Southeast Asia are lower than China and India as a result of having high forest cover (White, 2000). Hence, in order to control the amount of sediment entering a reservoir, it is recommended that the soil surrounding the reservoir should be controlled, in other words Watershed Management should be done.

**Table 2.1 Storage loss rates in different countries (Liu, Liu, Ashida, 2002)**

| Location | Annual Sedimentation Rate (%) | Total Sedimentation Rate (%) | Source |
|---|---:|---:|---|
| China | 2.30 | 14.2 | Hu, 1995 |
| India | 0.46 | 9.6 | White, 2001 |
| Japan | 0.15 | 8.8 | NISA, 2001;<br>ANRE, 1984-2000 |
| Southeast Asia | 0.30 | 8.0 | White, 2001 |
| South Africa | 0.34 | 11.4 | White, 2001 |
| **Turkey** | **1.50** | **59.7** | **White, 2001** |
| UK | 0.10 | - | White, 2001 |
| USA | 0.22 | 3.9 | Morris & Fan, 1987 |
| World | 1.00 | 11.8 | White, 2001 |

Although, watershed management is one of recommended reservoir sedimentation prevent technique in literature, there are some opposite research results about its efficiency. For example, an extensive watershed management project was executed in Mangla watershed in Pakistan before the dam construction.

Mangla Dam is a multipurpose, 112 m high earth-rockfill dam on Jhelum River in Pakistan with a crest level of 376.1 m (Mahmood, 1987). Its catchments area is 33,333 $km^2$ and total storage capacity is 9.47 $km^3$. The schematic catchments area of Mangla Dam is shown in Figure 2.1. From the data shown in Figure 2.1, the highest sediment concentration is coming from Kanshi River.

The main object of the Mangla watershed management project was reducing the sediment load at Mangla. Project was started at 1959 and it contains a large number of structural and non-structural measures. The whole project duration was 30 years such that the observation phase took 7 years (1959 - 1966) and the operation phase took 23 years. For the purpose of evaluation of sediment loads, gauging stations were used. From data coming from gauging station shows that no discernible difference in sediment loads is noted over a period of 4 – 14 years (Mahmood, 1987). As a consequence, the Mangla watershed management project effected the local environment and productivity positively. However, for the purposes of decreasing of sediment load in Mangla watershed, its contribution is insignificant.

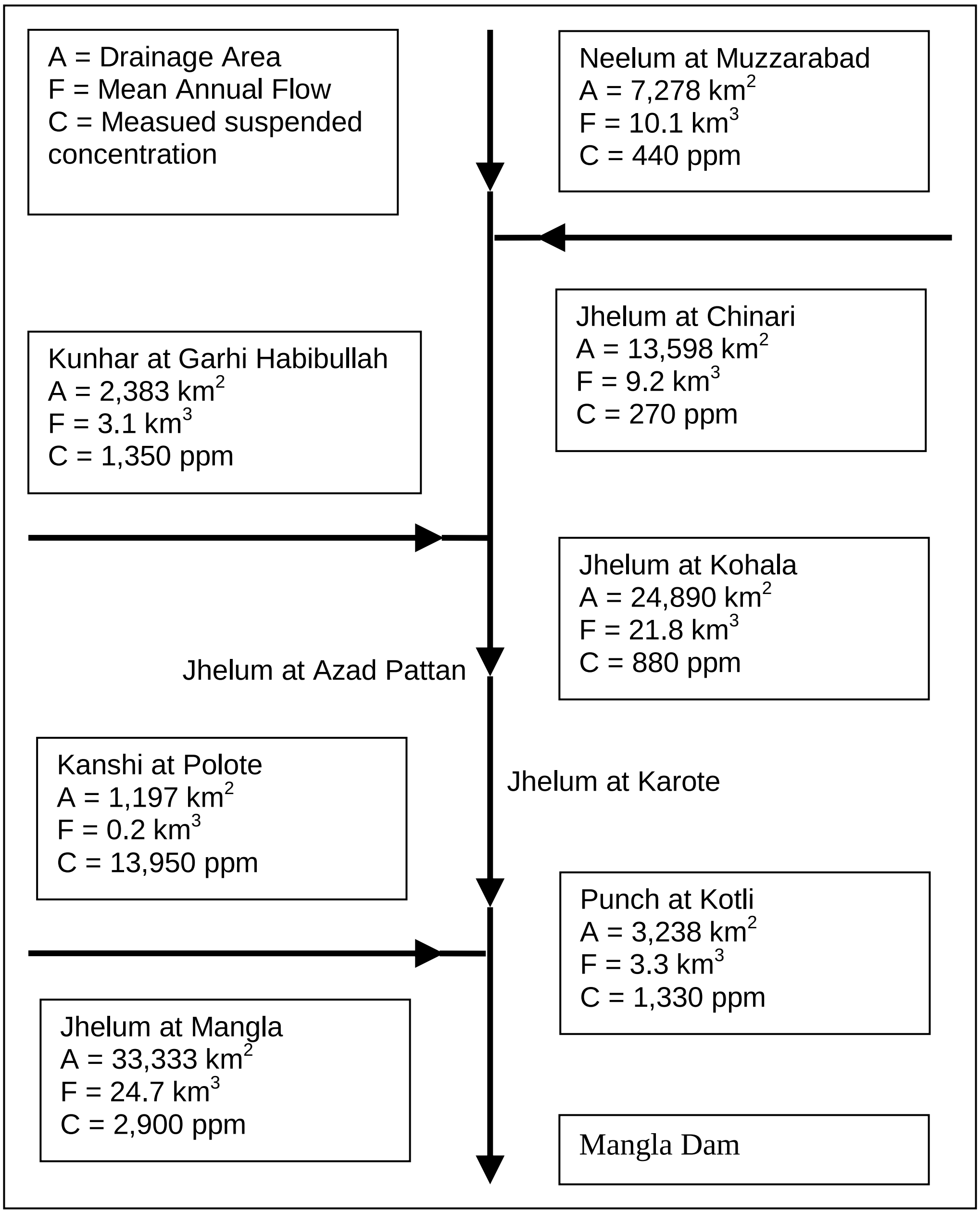



Figure 2.1 Schematic Catchment of River Jhelum at Mangla Dam

Actually, especially for semi-arid regions, the reservoir shoreline management should be considered beside river basin management. In the shoreline there would be high erosion rates. However, mostly it is not feasible to protect the whole shoreline against erosion because of long length except in localized specific areas where high value property or structures are threatened (Morris and Fan, 1997). The use of riprap, sheet piling and reduction of boat speeds to minimize wake, which is the path left by boat in water, are some shoreline erosion prevention practices.

### 2.1.2. Upstream Check Structures (Debris Dams)

Debris dams are relatively smaller in size than the main dam provided by spillway structures. Their function is to stop the major part of the incoming sediment coming from tributaries to the reservoir of a dam which will be used to supply either power or water supply. It can definitely extend the life of the dam but in return the debris dam itself will require reservoir sediment management program.

From economical viability point of view, short lifetime and relatively high cost of debris dams are the problems. Sediment concentration of tributary conversely effects the lifetime of debris dam. This means, if sediment concentration in the tributary is large, lifetime of the debris dam is short. In addition, debris dams are not active to reduce the design flood. Cost of debris dam is another problem, since debris dam construction is again a dam construction and foundation treatment, auxiliary structures etc. are must also be constructed. More than often, increasing the main dam capacity weighed against debris dam capacity is more economical and useful than to build an additional debris dam.

On the other hand, these upstream check structures are useful to retain the coarse material, which causes backwater deposits in the main reservoir. So usages of these structures prevent serious problems (Mahmood, 1987).

The cost effectiveness problem of the upstream check structures should be overcome by finding a way to get benefit from it. For example, if accumulated sediment in the debris dam is used for construction purposes, like roadway construction material, etc., these check structures would be cost-effective. However, the authorizations should arrange institutional and legal procedures according to this purpose, that there will be no unnecessary obstructions for investors. In other words, the institutional and legal procedures should encourage the investors.

### 2.1.3. Reservoir Bypass System

Reservoir bypassing is to let the sediment-laden flow pass from a channel, meanwhile keeping the sediment-free water. This method is composed of a channel within reservoir on the river (Howard, 2000). If this small reservoir is fed from river by main gravity or by pumping, it is called Off-Channel Storage. Because of environmental restrictions, off-channel reservoirs are more commonly used than on-channel reservoirs.

Actually, reservoir bypass system is very hard to apply. First of all, it should be designed correctly and operation should be planned carefully since it is a very expensive system. As a matter of fact, in order get a feasible Bypass System some special conditions should be provided at the same time. For example, topography conditions and size distribution of sediment load are very important factors that should be considered. Sediment excluders (sand traps) can be used in arid areas. Because bypassing sediment-laden water from channel is not acceptable for arid areas where need water seriously. However, it should not be expected that sediment excluders will remove significant quantities of silts and clay; actually of the sand load, the excluders can optimally remove only about half of the load with one-tenth of the flow (Mahmood, 1987).

It should be noted that water during the flood is diverted by the bypass system, there is no need for large-capacity spillway at the main dam.

Some reservoirs that uses bypass system effectively are (Howard, 2000); Gmünd Reservoir in Austria, Tedzen Reservoir in Turkmenistan, Amsteg Reservoir & Palagnedra Reservoirs in Switzerland where several reservoirs have bypass system, Syiya, Yanshuigon and Lushuihe Reservoirs in China.

## 2.2. SUSTAINABLE MANAGEMENT OF THE DAMS

### 2.2.1. Evacuation of Sediments from Reservoir

#### 2.2.1.1. Flushing

**Definition of Flushing**

Flushing is a sediment removal technique that deposited sediment is scoured from reservoir by increasing flow velocity and then transported through low level outlets. Flushing can be operated in two ways such that; by lowering water level or without lowering water level, which are called "pressure flushing" and "empty (free-flow) flushing", respectively. Pressure Flushing is to release water through the bottom outlets by keeping reservoir water level high. Nevertheless, it is not commonly used technique and it is less effective than empty (free-flow) flushing. On the other hand, empty (free-flow) flushing is to release water by emptying reservoir and also to route inflowing water from upstream by providing riverine conditions. There are two types of empty flushing; flood season and non-flood season. Both of them are successful in practice, flood season flushing is more effective since it provides larger discharges to route the sediment (Morris and Fan, 1997).

Flushing is not used widely because of some restrictions about its effectiveness. For example; flushing is generally effective in narrow dams. In addition, a considerable amount of water should be passed through the reservoir for drastic flushing operation. Also, the most important restriction is that, the reservoir is required to be empty for drawdown flushing (the most effective technique). This is the most limiting condition; because for hydropower dams being empty is not acceptable for energy point of view. Moreover, the water released in flushing have very high sediment concentration that much higher than natural riverine conditions. This extreme concentration caused unacceptable conditions for downstream.

**Criteria for Flushing Operation**

Basson and Rooseboom (1997) has prepared a diagram, shown below, where 177 dam cases had been reviewed, for the selection of reservoir operation. This diagram enables to make a preliminary judgement about whether flushing is an effective technique or not. The mentioned judgement is done by calculating $K_w$ and $K_t$ which are the ratios of storage to mean annual river runoff and storage to mean annual sediment yield respectively, and then see which zone of the diagram the controlled reservoir takes place.

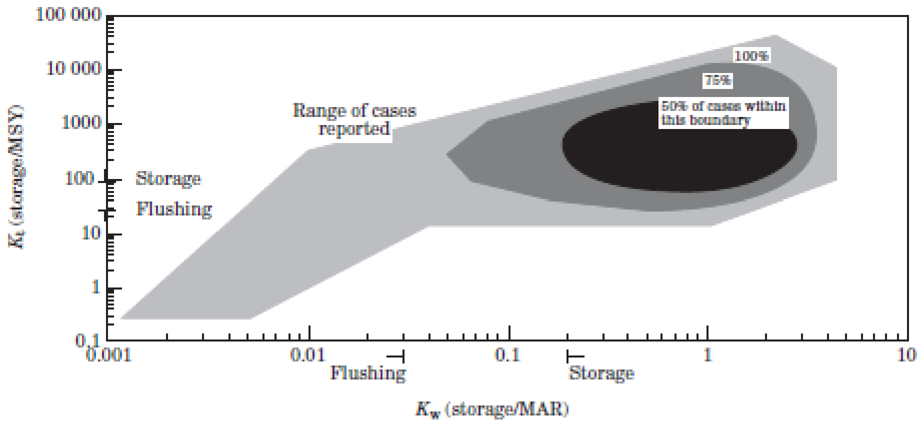



Figure 2.2 Basson's diagram on reservoir operation modes. Modified from Basson (1997)

The empirical indices in the Basson's diagram are:

$K_w$: $C_0$ / MAR (2.1)

$K_t$: $C_0$ / MSY (2.2)

in which $C_0$ is reservoir capacity, MAR is mean annual river runoff and MSY is mean annual sediment yield.

The right upper part of the diagram, where $K_w$ is larger than 0.2, is denser than other parts since most of the reservoirs in the world have been designed for 100 or more year's sediment accumulation and these reservoirs have not enough water for flushing operation or reservoir drawdown. Because of not having excess water for flushing, density current venting can be practiced at these reservoirs and dredging can be used to recover lost storage capacity (Basson, 2004). In regions where $K_w$ value is variable from 0.03 to 0.2, seasonal flushing is suggested. Furthermore, in case $K_w$ is smaller than 0.03 sediment sluicing and flushing should be carried out during floods and through large bottom outlets, preferably with free conditions especially in semi-arid regions (Basson, 2004). On the other hand, according to the ratio $K_{t,}$ lower part of the diagram where $30<K_t<100$ excess water is available and flushing is efficient.

**Flushing Operation Selection Case Study: Çubuk Dam-I**

As a case study, Çubuk Dam I is analyzed where the ratios are stand in Basson's Diagram.

$C_o$ = 7.1 $Mm^3$

MAR = 65.5 $Mm^3$

MSY = 60,000 m

$K_w$ = 7.1 / 65 = 0.1092

$K_t$ = 7,100,000 / 60,000 = 118

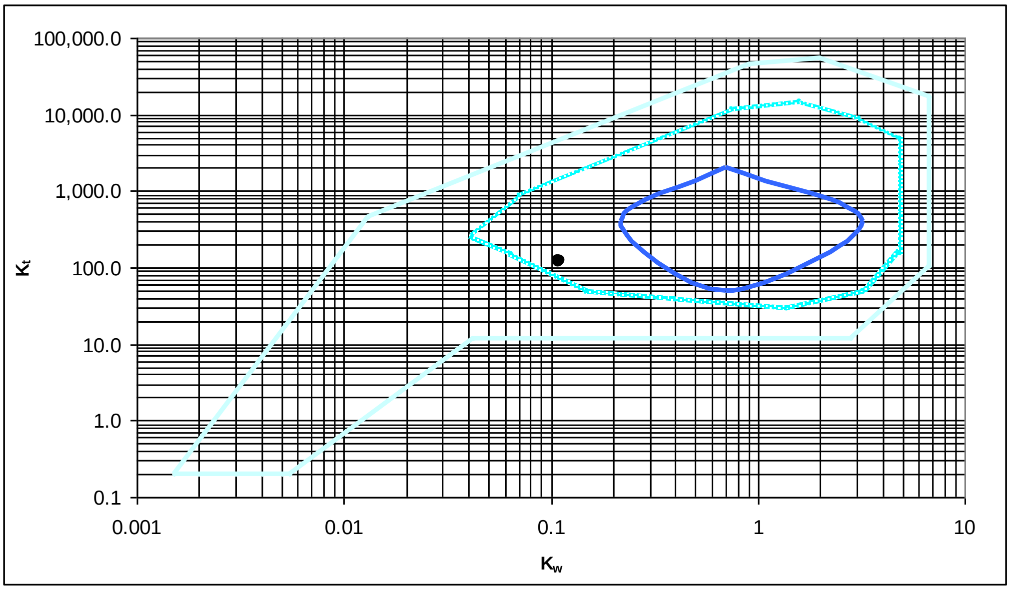



Figure 2.3 Çubuk Dam-I in Basson's Diagram

Çubuk Dam-I is in the zone of %75, $K_t$ value is not appropriate for flushing but $K_w$ is between 0.03 and 0.2. Therefore, seasonal flushing can be suggested according to Basson's empirical table.

If appropriate sediment management study were carried out during the planning stage, it would have been possible to apply seasonal flushing. That is, Çubuk Dam-I wouldn't have been out of function as it is today.

**Factors effecting Flushing Viability and Efficiency**

Hydraulic requirements, available water quantity, sediment mobility in reservoir and special conditions of site are factors that affect the flushing efficiency (Howard, 2000). These factors are discussed below:

- Hydraulic requirements: for flushing operation hydraulic conditions in reservoir should be as same as river conditions. This river condition maintained by sufficient bypass capacity, at least twice of mean annual runoff as flushing discharge and at least %10 of mean annual runoff as flushing volume (Howard, 2000).
- For transporting enough sediment from reservoir; the reservoirs, having smaller capacity compared with annual runoff, are preferred. Nevertheless, demand water should be balanced (Howard, 2000).
- In order to determine the required water for flushing, sediment sizes and also sediment mobility should be defined well. In common, it is known that fine sand and coarse silt are the most successful sizes for flushing (Howard, 2000).
- The width and shape of the reservoir are the important site specific features for flushing. Because long and narrow reservoirs are suitable for flushing operation (Howard, 2000).

In practice, geographical factors also give sign to decide if the area is suitable for flushing or not. These factors are:

- Erosion rate
- Sediment Yield
- Climatic Zones: According to Koppen classification of climatic zones, the best flushing efficiency is gained in “Tropical Wet and Dry Region” and also it can be said that “Tropical Wet Region” is also suitable. These regions are;
    - Parts of Central America extending into Brazil in South America
    - A region of central Africa from the Ivory Coast in the west to Sudan in the east would be suitable
    - Parts of central Asia including Pakistan, India, Nepal, China, Vietnam and Thailand (Howard, 2000).

As mentioned in the above paragraph, Turkey does not take place in the list of best flushing region according to climatic zone. Indeed, in the map of climatic zones the middle Anatolia is seen as the defined region and it is suitable for flushing in terms of climatic conditions.

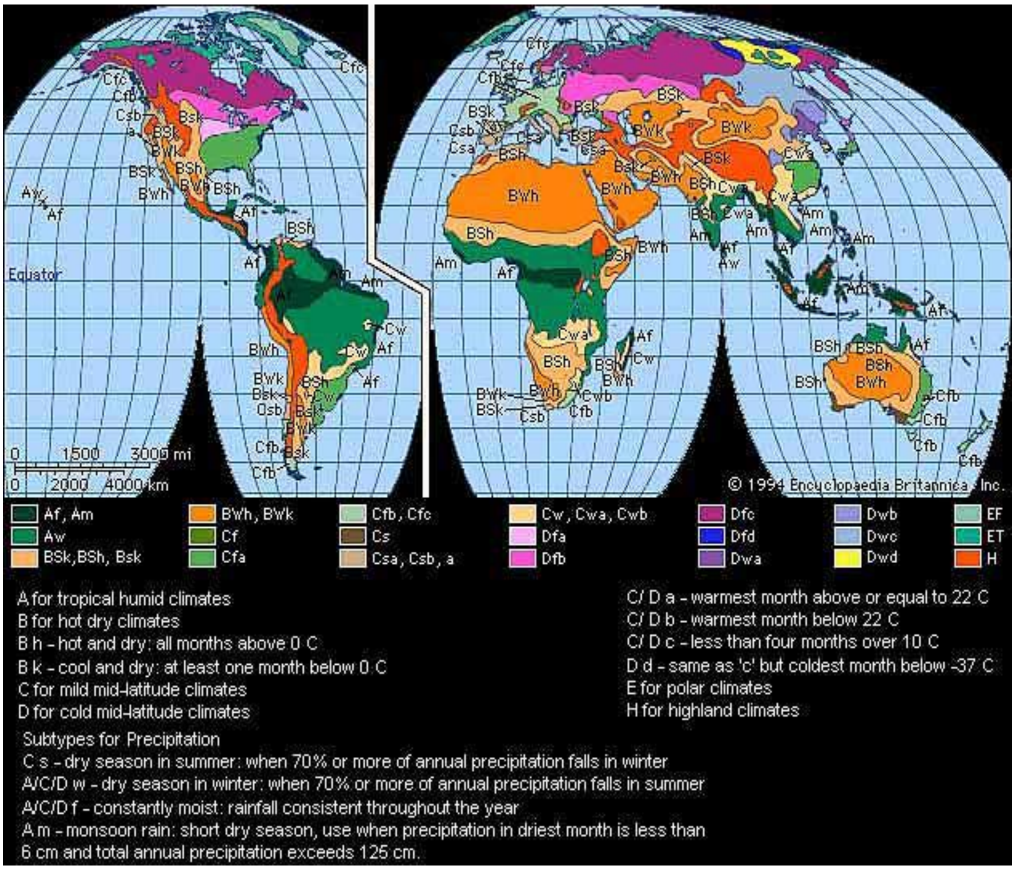



Figure 2.4 Koppen Climatic Zones

#### 2.2.1.2. Sluicing

Sediment sluicing is defined as an operational design in the worldwide that in most cases the reservoir is drawn down in flood season and then sediment carrying inflow is directly passed through the reservoir. So that sediment has no chance to settle down. After the flood season, clear water will be stored and reservoir will be raised for the next season usage.

The reason of why this method is applied during flood season is to get sufficient sediment to be transported. During rising water level of a flood the out-flowing sediment discharge is always smaller than that of the inflow, due to the backwater effect causing a substantial decrease in the velocity. Oppositely, during lowering of the water level, the out-flowing sediment discharge is greater than the inflow because there is no backwater effect and there is erosion in the reservoir (Fan, 1985). Therefore, sluicing in flood season is efficient from hydraulics point of view.

One of the advantages of sluicing over flushing is that, the sediment problems of downstream reaches regarding to high concentration flow will be minimized by using this method. Because the transport capacity of downstream flood discharge is greater than transport capacity of reservoir flood discharge (Fan and Morris, 1992b).

There are also other advantages of sluicing over other evacuation methods. For example, sediment concentration of released water to downstream is lower in sluicing operation than in flushing operation (Morris and Fan, 1997). Furthermore, consolidated cohesive sediment movement in significant amount is impossible by flushing operation (Basson and Rooseboom, 1997). Also, the velocity needed to move the eroded sediments is much higher than the velocity to keep the sediments suspended (Hu, 1990; Basson & Rooseboom, 1997). In other words, sluicing is preferable since it maintain incoming sediment in suspension.

Excess runoff availability, grain size of sediments and reservoir morphology are the main factors that affect sluicing efficiency. In the worldwide usage, sluicing and flushing are used together.

**Sluicing Usage in World**

The Aswan Dam was built during 1898 – 1902 on the Nile River, to provide summer irrigation supplies to the Middle Egypt. It was raised twice in 1912 and

1933 (Mahmood, 1987). The reservoir storage capacity is 5.6 km$^3$ and the annual run-off was estimated at 84 km$^3$. The dam had 180 sluice gates in four groups. The sluices had 2,240 m$^2$ cross sectional area with 6,000 m$^3$ flood discharge capacity during normal flood level or more than twice flow rate during high flood. The gates are kept open during flood months of July, August and September. Hence, from October, reservoir is filled with clear water up to 121 m and kept constant to provide sufficient irrigation requirements. According to this operation, surveys show that the sedimentation is not significantly affecting the reservoir.

Another example is Roseires Dam on Blue Nile in Sudan. The reservoir storage capacity is 7.4 km$^3$ and the annual run-off was estimated at 50 km$^3$. The proposed operation program is shown in Fig. 2.5 (Mahmood, 1987).

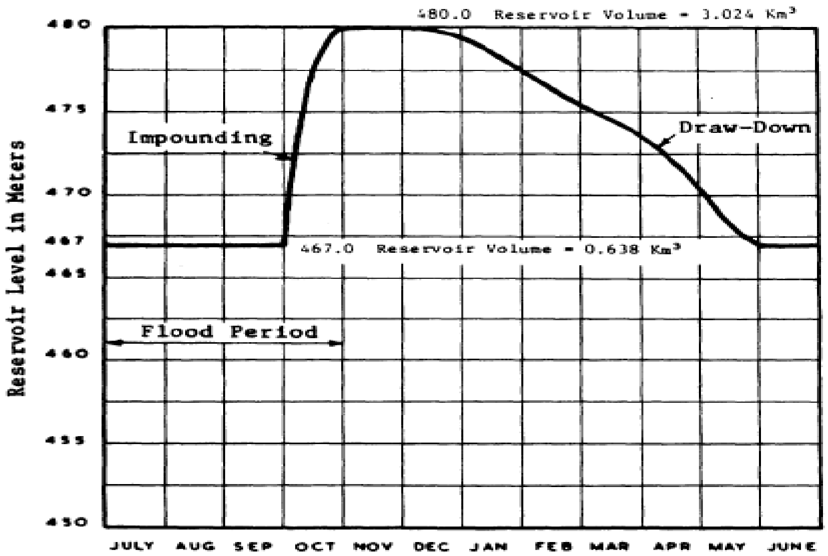



Figure 2.5 Design Operating Program for Roseires Dam: Median Inflow and full use of storage (After Schmidt, 1983; Mahmood, 1987)

According to the operation program, it was planned that in the flood period – July, August, and September – the reservoir level will be maintained at 467 m. After flood period, during October, the reservoir will be filled up to 480 m. Then up to end May drawdown is done to the elevation 467m. However, the efficiency of this sluicing operation is not effective as expected. Reasons for that difference can be seen from the comparison as depicted in table 2.2 (Mahmood, 1987).

**Table 2.2 Comparison For Aswan and Roseires Dams (Mahmood, 1987)**

| COMPARISON FOR ASWAN AND ROSEIRES DAMS | | |
|---|---|---|
| | Old Aswan | Roseires |
| River Bed Level, m | 87.5 | 435.5 |
| Conservation Pool Level, m | 121 | 480 |
| Height of Conservation Pool above River Bed, H, m | 33.5 | 44.5 |
| Mean Annual Flow, $km^3$ | 84.0 | 50.0 |
| Capacity at Conservation Pool, $km^3$ | 5.6 | 3.0 |
| Capacity: Inflow | 0.067 | 0.060 |
| Annual Sediment Load, $Mm^3$ | 80.0 | 86.6 |
| Dam Length, L, km | 2.14 | 13.5 |
| L/H | 63.9 | 303.4 |
| Measured Trap Efficiency, percent | 0.0 | 46.0 |

Reservoir width at the maximum height is nearly five times greater in Roseires Dam. Because of this reason, the sediments are deposited on the overbank area and the sluicing cannot affect this area. Subsequently, if sluicing operation will be designed reservoir morphology should be taken into consideration earnestly.

#### 2.2.1.3 Density Current Venting

The literal meaning of density current is that moving of two fluids, with similar state, towards each other because of different densities. Venting density currents means to route the sediment-laden flow through the stored water in the reservoir. Then sediment-laden flow will get to the downstream. From the figure, the movement of density current through reservoir and vented through low-level outlet could be observed.

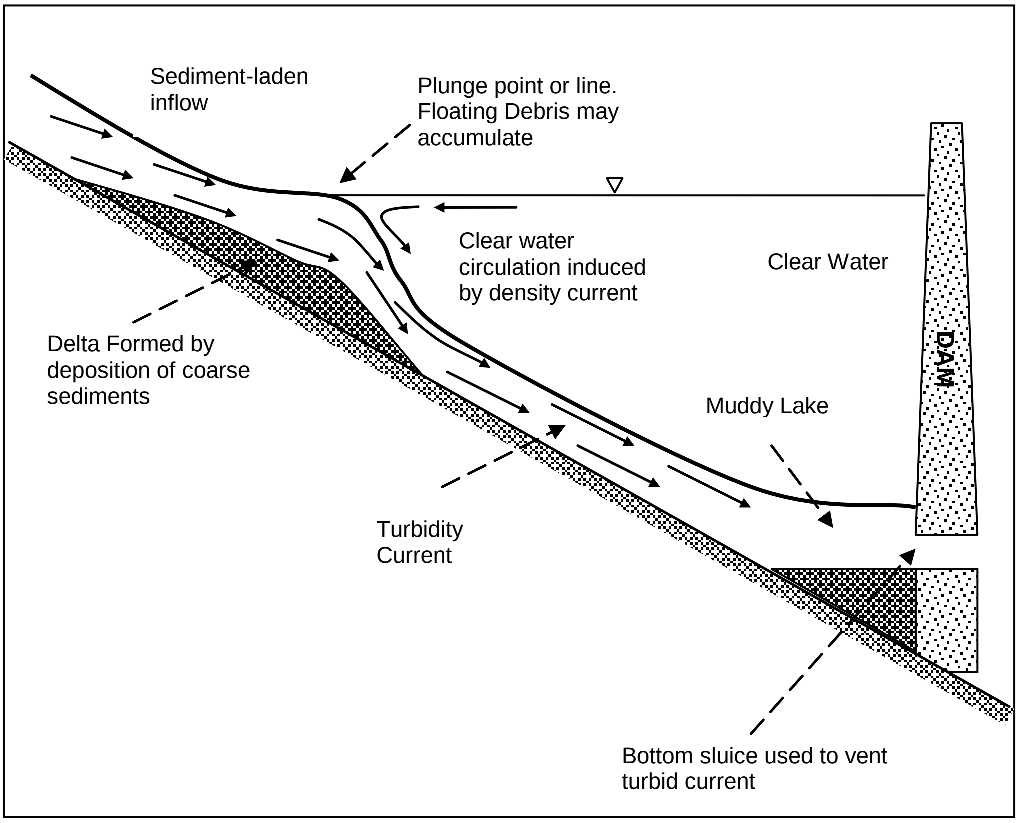



Figure 2.6 Schematic Diagram of the passage of a turbid density current through a reservoir and being vented through a low level outlet

In order to have successful density current venting, the incoming sediment-laden flow would have enough velocity and fine particles to form turbid flow. If these favourable conditions exist, current should be able to reach dam. Then the bottom outlet will be opened causing the current be vented through. Timing of density current venting is very important. Chen and Zhao (1992) have pointed that timing of gate opening and closing is very crucial. If sluice operation is too late or sluice gates openings are too small, these cause small amounts of sediment discharge. On the contrary, if the gate is opened too early or the opening is too large, not only the loss of valuable water occurs, but also a strong velocity field of clear water will be formed in front of the outlet and prevent the turbid flow from entering outlet (Chen and Zhao, 1992).

Density Current Venting efficiency depends on some factors such as reservoir topography, thermal and salinity related stratifications, conditions of incoming flow, sediment characteristics and outlet facilities. It is obviously seen that, because of all these variables, there is an uncertainty in the flow path of density current. Providing multi-level multiple outlets is a way to overcome this problem (Mahmood, 1987).

Another advantage of density current venting is that, it is no need to decrease the reservoir water level unlike flushing or sluicing.

***Density Current Venting Method Usage in the World***

The usage of this method is not common in global scale, but there are some cases of usages. For example, Bajiazui Dam in China is a very successful enlargement of this operation method. The density current venting provides an average release ratio of 46% (Howard, 2000). On the other hand, in Sefid Rud Reservoir in Iran venting of density current is not very effective as Bajiazui Dam. 6 million tons of sediment was released by density current venting but the coming sediment is approximately between 40 million to 50 million tons (Parhami 1986; Amini & Fouland, 1985; Howard, 2000). Therefore, the original storage of dam, $1.8 \times 10^9$ $m^3$ in 1962 has decreased to $1 \times 10^9$ $m^3$ in 1981 (Howard, 2000).

**Mechanical Removal**

Evacuating sediments from the reservoir is not only done hydraulically but also done mechanically. The mechanical removal techniques are classified as dredging, hydrosuction removal system (siphoning), and trucking (dry excavation). The techniques are explained below in more detail.

***Dredging***

Dredging is picking up the accumulated sediment from the reservoir or lake bed and then transporting them to another area. There are several types of dredging equipment in the conventional usage.

Dredging systems can be classified as hydraulic and mechanical. In the hydraulic systems, the deposited sediment is lifted with water and then this sediment-water slurry formation transported from the output point to the point of placement. See below figure 2.7 as hydraulic dredging equipment. Hydraulic dredging is more widely used than mechanical dredging. Hydraulic dredging advantages are:

- Low unit cost of sediment removal
- Production rates are high
- Working ability in a reservoir that no interfere with impoundment process
- Effective both fine and large materials removal, but larger materials removal have higher cost

The disadvantage of hydraulic dredging is the difficulty to bulk the fine sediments to the point of placement and the need for dewatering operation for lifted sediment-water slurry.

Figure 2.7 Hydraulic dredging equipment

Figure 2.8 Hydraulic dredging disposal example

Mechanical systems, on the other hand, use buckets in order to dig the reservoir bed and then pick up the sediment. Figure 2.8 and 2.9 are examples of mechanical dredging equipments.

Figure 2.9  Mechanical Dredging Equipment

The sediments, dredged by using mechanical dredging equipments, have low water entrainment. Therefore, for arid areas mechanical dredging is more advantageous than hydraulic dredging. However, mechanical dredging production rate is lower than hydraulic dredging.

Dredging method is suitable for medium and small size reservoirs, which do not have enough water for flushing. Dredging is used for the removal of coarse sediment. The most important difficulty of the dredging is to find a suitable area for damping the removed sediments. Therefore the cost of disposal land is an important item in the calculation of dredging cost. A compilation of dredging cost has been carried out by Basson and Rooseboom (1997).

Dredging is the most commonly used technique in China and Japan. Especially in Northwest China, because the dredging cost is relatively cheap; dredging has been used for more than 10 reservoirs since 1975 (Liu, Ashida, Hindley, 1994 and Wang, 1996).

As listed in Table 2.1, the unit cost of dredging and cost of siphoning system are 103.7 x $10^3$ RMB (Chinese Yuan) and 0.21 RMB/$m^3$, respectively, for Xiaohuasha reservoir. This means that, since dredged sediment quantity is 406 x $10^3$ $m^3$, the total cost of dredging is 85.26 x $10^3$ RMB. Obviously cost of dredging is relatively cheaper than cost of siphoning.

**Table 2.3 Sediment removal practices in China by siphon dredging system**

| Reservoir | Tianjiavan | Xiahuasha | Youhe | Xihe | Taoshupo | Beichaji | Xihe |
|---|---|---|---|---|---|---|---|
| Damsite (city, ovince) | Yuci,Shanxi | Huaxian, | Weinan, | Lintong, | Fengxiang, | Nijing, | Lintong, |
| Dam Height (m) | 29.5 | 33 | 32 | 35 | 32.5 | 15 | 39.8 |
| Original Storage Capacity | 9.43 | 1.77 | 24.5 | 3.94 | 1.54 | 2.75 | 6.74 |
| Annual runoff (106 m3) | 3.95 | 2.5 | 33.6 | 4.6 | 1.31 | 1.09 | 3.69 |
| Annual sediment load ($10^3$ ton) | 320 | 50 | 650 | 450 | 73 | 163 | 440 |
| Annual sediment | 82 | 20 | 19.3 | 87.5 | 55.6 | 150 | - |
| Completion year | 1960 | 1959 | 1959 | 1969 | 1959 | 1972 | 1971 |
| Survey year | 1978 | 1978 | 1978 | 1978 | 1982 | 1978 | 1978 |
| Operation period (year) | 18 | 19 | 19 | 9 | 23 | 6 | 7 |
| Total deposition ($10^3$ ton) | 4,000 | 525 | 8,985 | 3,100 | 782 | 528 | 5,780 |
| Annual deposition ($10^3$ ton) | 220 | 276 | 473 | 344 | 34 | 88 | 340 |
| Discharging structure | Outlet | Pivot Gate | Draw-off | Flexible | Outlet | Bottom | Outlet |
| Discharging capacity ($m^3/s$) | 2.5 | 5 | 5.5 | 2 | - | 10 | 2 |
| Staring year of dredging | 1975 | 1976 | 1976 | 1977 | 1978 | 1977 | 1978 |
| Gross work head (m) | 17.4 | - | - | - | - | - | - |
| Effective work head (m) | 5.5 – 8.8 | 0 -20.8 | 9 – 14.0 | 5 – 10.0 | 6 – 8.0 | 6 -14.0 | - |
| Diameter of pipe (m) | 0.55 | 0.3 | 0.72 | 0.3 | 0.25 | 0.23 – 0.5 | 0.18 |

**Table 2.3 (continued) Sediment removal practices in China by siphon dredging system**

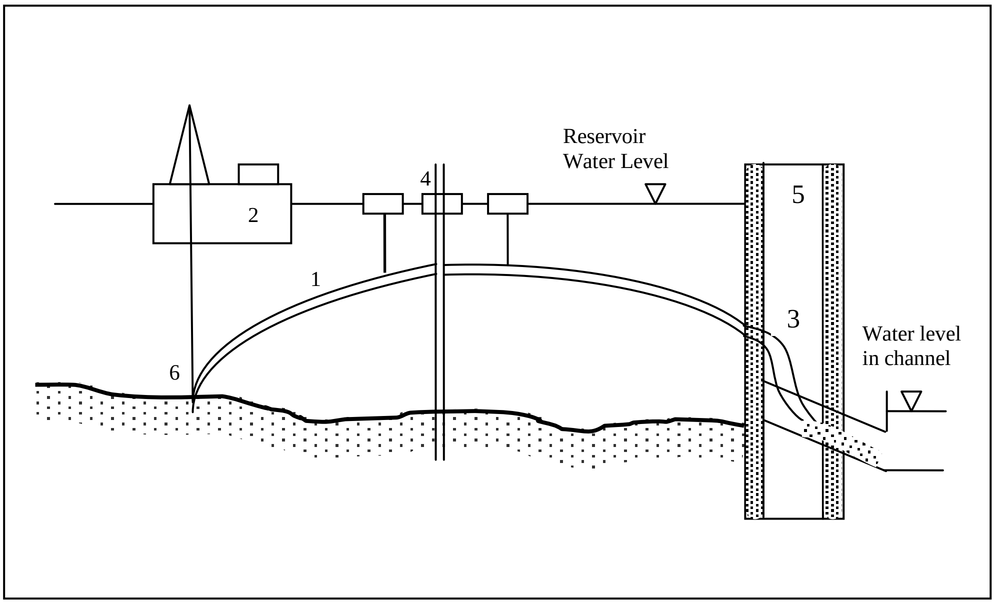
| **Reservoir** | Tianjiavan | Xiahuasha | Youhe | Xihe | Taoshupo | Beichaji | Xihe |
|---|---|---|---|---|---|---|---|
| Length of pipe (m) | 229 | 83 - 350 | | | | | |
| Pipeline discharge ($m^3/s$) | 1.2 | 0.3 | 0.72 | 0.3 | 0.25 | 0.23-0.5 | 0.18 |
| Suction head type | Aspirator | Aspirator | Cutter | Cutter | Aspirator | Aspirator | Cutter |
| Water depth of reservoir | 3 | 12.8-2.7 | 6-8.0 | 2-8.0 | 2-6.0 | 15-5.0 | - |
| Mean sediment concentration ($kg/m^3$) | 190 | 136-168 | - | - | 87.7 | 484 | 3 |
| Max sediment concentration ($kg/m^3$) | 480 | 720 | 581.5 | 1,080 | 50.5 | 1,143 | - |
| Use of release sediment | Irrigation | Irrigation | Irrigation | Irrigation | Irrigation | Irrigation | Irrigation |
| Grain size at outlet, $d_{50}$ (mm) | 0.007 | 0.024-0.044 | 0.015-0.029 | - | - | 0.005-0.096 | - |
| Dredging Period | 1975-77 | 1976-86 | 1978-86 | - | - | - | 1078-86 |
| Dredging hours | 695 | 4619 | 4203 | - | - | - | 4353 |
| Dredged Sediment ($10^3$ $m^3$) | 320 | 406 | 325 | - | - | - | 213 |
| Hourly dredged sediment ($m^3/hr$) | 460 | 88 | 77 | - | - | - | 49 |
| Cost of siphon dredging system ($10^3$ RMB) | - | 103.7 | 99.8 | - | - | - | 32.2 |
| Dredging unit cost ($RMB/m^3$) | 0.045 | 0.21 | 0.16 | - | - | - | 0.22 |

In addition, they overcome the disposal area problem by transporting dredged sediment through irrigation canals to recharge the topsoil of cropland (Liu, Ashida, Hindley, 1994; Wang, 1996).

***Hydrosuction Removal System (HSRS)***

Hydrosuction Removal System (HSRS) is simply a siphon and airlift system, which uses the potential energy stored by hydraulic head at the dam, removes the sediments through a floating or submerged pipeline to an outlet. This system is known as Hydrosuction Removal System (HSRS) and Sediment Evacuation Pipeline System (SEPS) in USA, and as Geolidro System in Italy. (Liu, Ashida, Hindley, 1994; Hotchkiss & Huang, 1995)

The system is composed of a barge, a pipeline and appurtenant valves to control flow. Barge is used to control the flow in upstream and downstream of the pipeline, and also move the upstream end of the pipe in order to provide movement of suction head of the pipe. A sketch of HSRS system is given in figure below. As depicted in the sketch the silted sediments removed through pipeline to downstream end of the reservoir (Fig. 2.10).




1=Submerged Pipeline, 2= Operation ship (Barge), 3= Connector, 4= Pontoons, 5= Outlet Equipment, 6= Suction Head, 7= Deposit Surface

Figure 2.10 Siphon Dredging System at Tianjiawan reservoir (After Zhang and Xie, 1993)

Figure 2.11 Silted sediments removed from pipeline

HSRS has some advantages over dredging. For example, since potential energy stored by hydraulic head is used as a driver there is no need for any equipment to produce energy. Therefore, the operating costs are substantially lower than those of traditional dredging. In addition, there is no need to find suitable disposal site with HSRS, since sediment is moved to the downstream end of the reservoir; an environment friendly operation.

On the other hand, the major disadvantage of HSRS is that the system can be used in relatively short reservoirs, not longer than approximately 3 km, and also dependent on the elevation of the dam and reservoir (ResCON Manual Vol.1, 2003).

HSRS is one of the less frequently used techniques for sediment removal (Hotchkiss and Huang, 1995).However, in China this technique is used effectively. The first usage of a siphon system for sediment removal is applied in the Tianjiawan Reservoir. The system consists of a barge and a floating pipeline of 229m in length and 550mm in diameter connected to the dam outlet (Liu, Liu, Ashida, 2002).

This technique is used in case of lack of sufficient amount of water for flushing. The released water and sediment was used for irrigation.

***Trucking (Dry Excavation)***

Trucking (also known as dry excavation) is excavation of the accumulated sediment from reservoir like dredging but it requires drawdown of reservoir. The excavated sediment is transported to a suitable disposal area by using traditional earth moving equipment. Cost of drawdown, transportation cost and suitable area cost makes the method very expensive. That is why trucking method is not widely used. Indeed, dry excavation methods are generally more expensive than dredging. They are more than often used in reservoirs along their upper reaches (Howard, 2000).

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 suitable for sediment management by trucking, such as 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.

### 2.2.2. Management Techniques of Sediment within Reservoir

- *Operating Rules*:
  The reservoir operating rule can effect where the sediment deposition occurs. For example, during flood season if reservoir water level is high then the sediment is mostly deposited in the upper reaches of the reservoir. On the contrary, during flood season if reservoir is drawdown then the sediments tend to deposit in dead storage zone of the reservoir.

- *Tactical Dredging*
  There is one more dredging type Tactical Dredging, which is used for local sediment removal. For example, for dams built for hydropower generation it is important to keep the vicinity of the outlets clear in order to prevent blockage of the outlets. Blocked outlets will cause energy production to stop. Furthermore, the mechanical equipments, like turbines will be damaged because of sediments. Thus, the useful life of the reservoir will be shortened and operation and maintenance costs will unexpectedly be increased. Therefore it can be understood that localized dredging utility is an effective tool to prolong the dam reservoir life and its determined utility and that is why it is currently being used in a worldwide.

## 2.3. LOST STORAGE REPLACEMENT TECHNIQUES AND DECOMMISSIONING

### *2.3.1. Raising Dam Height*

Raising of a dam height is to increase the reservoir capacity in order to compensate the storage loss due to sedimentation. Especially in arid regions raising should be seen a cost-effective method. However, in the long term period it is not a solution for sediment problem but a remedy to store more water. In addition, this method requires very careful engineering and also it causes relatively some problems such that (Howard, 2000):

- Socio-economic and political issues related to resettling of people
- Increased water losses due to evaporation and seepage
- Dam safety aspects which could lead to high raising costs
- Impacts of dam use.

### *2.3.2. Building a New Dam*

In order to replace the storage lost of an existing dam, a new dam can be built downstream or upstream of existing reservoir or on another river. Generally, dam practice in Turkey has been followed this way to replace the lost storage capacity but it is a temporary solution and it is not an environmentally friendly method.

### *2.3.3. Decommissioning*

Decommissioning is removing all the structures of a dam project and so ending the operation life of the dam. Decommissioning of a dam is not a reservoir sediment technique; on the contrary it is an economical option if the dam useful life is finished. In other words, if an operation cost of the reservoir is more than benefits gained from reservoir, decommissioning is economically an option for further actions.

In addition to economical reasons other reasons to make consider dam removal are such that (Howard, 2000):

- Water quality improvement
- Flora and fauna improvement
- Public Safety Hazard Elimination
- Aesthetically improvement

- Existence of an alternative which provide same advantages as dam after decommissioning
- Recreational development

# CHAPTER 3

## RESCON (Reservoir Conservation Method)

In the previous chapter, methods to achieve “Sustainable Development of Basin Water Storage Capacity” are discussed separately. However, there is an open source package program RESCON in order to examine and compare some sediment evacuation methods and decommissioning, economically and hydraulically. These sediment evacuation methods are; flushing, hydrosuction sediment removal (HSRS), dredging and trucking.

RESCON, which is a World Bank sponsored project, was developed in order to make preliminary decisions for policy makers. RESCON key algorithm is based on economic optimization and supported by technical evaluation of basic parameters. The economic optimization results determine which sediment management technique is the most viable. In addition, sustainability of the evacuation methods is identified by the program and technical evaluation results can be found. If the sustainable usage is failed then program compute the annuities for the retirement fund.

### 3.1. The General Working Principle of RESCON

RESCON philosophy is actually “Life Cycle Management Approach”, which is an alternative of “Design Life Approach”. Life Cycle Approach basis is the sustainable usage of projects infinitely opposite to the Design Life Approach which assume finite project life. If sustainable usage is not achievable the decommissioning of dam within a finite time is proposed and the necessary annuity for the retirement fund is calculated. The program structure is sketched in Figure 3.1 (RESCON Manual, Vol-I).

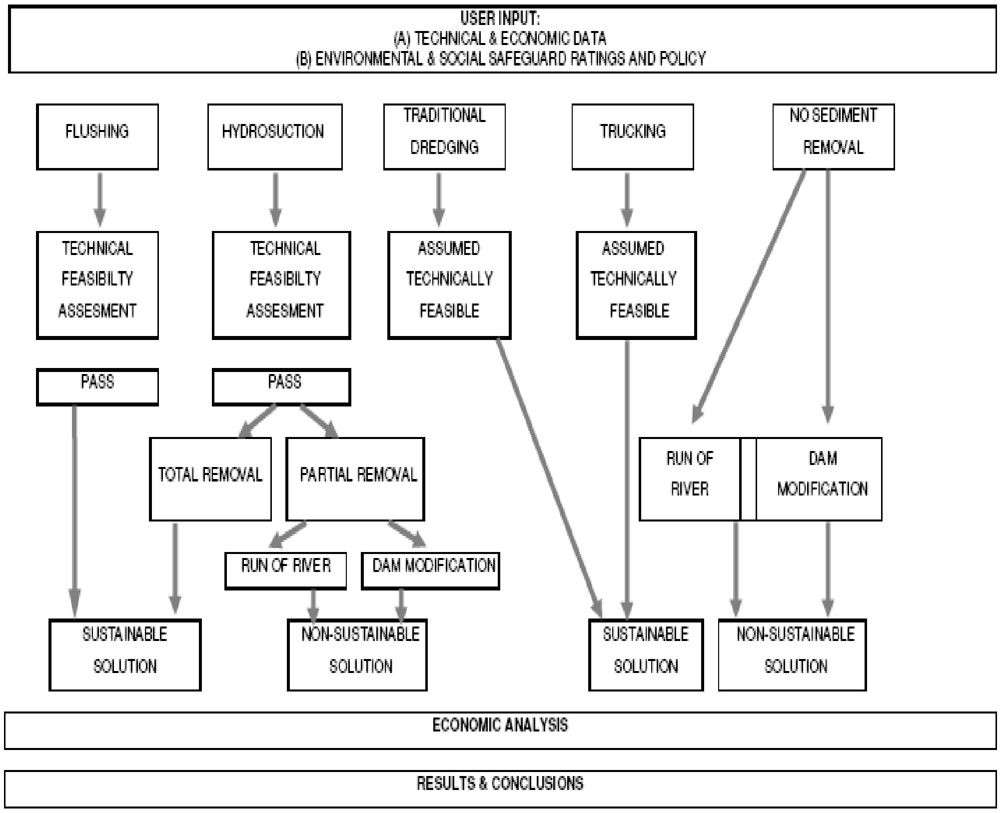



Figure 3.1 RESCON Program Structure

RESCON is a spreadsheet-based program written in Visual Basic programming language and works with macros. There are two sheets to input the required data. Seven class of data should be input into the first sheet such that; Reservoir Geometry, Water Characteristics, Sediment Characteristics, Removal Parameters, Economic Parameters, Flushing Benefits Parameters and Capital Investment. In the second sheet, for the selection of a desirable sediment management strategy information about Environmental and Social Safeguard Policies are asked. These input parameters are given in Table 3.1

**Table 3.1 First sheet : User Input (Checklist)**

| **Reservoir Geometry** | | |
|---|---|---|
| **Parameter** | **Units** | **Description** |
| $S_o$ | ($m^3$) | Original (pre-impoundment) capacity of the reservoir |
| $S_e$ | ($m^3$) | Existing storage capacity of the reservoir |
| $W_{bot}$ | (m) | Representative bottom width for the reservoir--use the widest section of the reservoir bottom near the dam to produce worst case for criteria |
| $SS_{res}$ | | Representative side slope for the reservoir. 1 Vertical to $SS_{res}$ Horizontal. |
| $EL_{max}$ | (m) | Elevation of top water level in reservoir--use normal pool elevation. |
| $EL_{min}$ | (m) | Minimum bed elevation--this should be the riverbed elevation at the dam. |
| $EL_f$ | (m) | Water elevation at dam during flushing - this is a function of gate capacity and reservoir inflow sequence. Lower elevation will result in a more successful flushing operation |
| L | (m) | Reservoir length at the normal pool elevation. |
| h | (m) | Available head--reservoir normal elevation minus river bed downstream of dam |
| **Water Characteristics** | | |
| $V_{in}$ | ($m^3$) | Mean annual reservoir inflow (mean annual runoff) |
| Cv | ($m^3$) | Coefficient of Variation of Annual Run-off volume. Determine this from statistical analysis of the annual runoff volumes |
| T | ($^oC$) | Representative reservoir water temperature |

**Table 3.1 First sheet : User Input (continued)**

| **Sediment Characteristics** | | |
|---|---|---|
| $\rho_d$ | (tonnes/$m^3$) | Density of in-situ reservoir sediment. Typical values range between 0.9 - 1.35 |
| $M_{in}$ | (metric tonnes) | Mean annual sediment inflow mass. |
| Ψ | 1600,<br>650,<br><br>300,<br><br>180 | Select from:<br>1600 for fine loess sediments;<br>650 for other sediments with median size finer than 0.1mm;<br>300 for sediments with median size larger than 0.1mm;<br>180 for flushing with Qf < 50 $m^3$/s with any grain size. |
| Brune Curve No | 1<br>2<br>3 | Is the sediment in the reservoir:<br>(1) Highly flocculated and coarse sediment<br>(2) Average size and consistency<br>(3) colloidal, dispersed, fine-grained sediment |
| Ans | 3 or 1 | This parameter gives the model a guideline of how difficult it will be to remove sediments. Enter "3" if reservoir sediments are significantly larger than median grain size ($d_{50}$) = 0.1mm or if the reservoir has been impounded for more than 10 years without sediment removal. Enter "1" if otherwise. |
| Type | 1 or 2 | Enter the number corresponding to the sediment type category to be removed by hydrosuction dredging: 1 for medium sand and smaller; 2 for gravel. |

**Table 3.1 First sheet : User Input (continued)**

| **Removal Parameters** | | |
|---|---|---|
| HP | 1 or 2 | Is this a hydroelectric power reservoir? Enter 1 for yes; 2 for no. |
| $Q_f$ | ($m^3$/s) | Representative flushing discharge. This should be calculated with reference to the actual inflows and the flushing gate capacities. |
| $T_f$ | (days) | Duration of flushing after complete drawdown. |
| N | (years) | Frequency of flushing events (whole number of years between flushing events) |
| D | (feet) | Assume a trial pipe diameter for hydrosuction. Should be between 1 - 4 feet. |
| NP | 1, 2, or 3 | Enter the number of pipes you want to try for hydrosuction sediment removal. Try 1 first; if hydrosuction cannot remove enough sediment, try 2 or 3. |
| YA | Between 0 and 1 | Maximum fraction of total yield that is allowed to be used in HSRS operations. This fraction of yield will be released downstream of the dam in the river channel. It is often possible to replace required maintenance flows with this water release. Enter a decimal fraction from 0 - 1. |
| CLF | (%) | Maximum percent of capacity loss that is allowable at any time in reservoir for Flushing. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely. |

**Table 3.1 First sheet : User Input (continued)**

| | | |
|---|---|---|
| CLH | (%) | Maximum percent of capacity loss that is allowable at any time in reservoir for Hydrosuction. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely. |
| CLD | (%) | Maximum percent of capacity loss that is allowable at any time in reservoir for Dredging. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely. |
| CLT | (%) | Maximum percent of capacity loss that is allowable at any time in reservoir for Trucking. For an existing reservoir, this number must be greater than the percentage of capacity lost already. Sustainable solutions will attempt to remove sediment before this percent of the reservoir is filled completely. |
| ASD | (%) | Maximum percent of accumulated sediment removed per dredging event. Sustainable removal dredging will be subject to this technical constraint. |
| AST | (%) | Maximum percent of accumulated sediment removed per trucking event. Sustainable removal trucking will be subject to this technical constraint. |

**Table 3.1 First sheet : User Input (continued)**

| | | |
|---|---|---|
| MD | ($m^3$) | Maximum amount of sediment removed per dredging event. The user is warned if this constraint is not met, but the program still calculates the NPV. Use default value unless better information is available. |
| MT | ($m^3$) | Maximum amount of sediment removed per trucking event. The user is warned if this constraint is not met, but the program still calculates the NPV. Use default value unless better information is available |
| Cw | (%) | Concentration by weight of sediment removed to water removed by traditional dredging. Maximum of 30%. Do not exceed this default unless there is information about the considered reservoir. |
| **Economic Parameters** | | |
| E | 0 or 1 | If dam being considered is an existing dam enter 0.<br>If the dam is a new construction project enter 1. |
| c | ($\$/m^3$) | Unit Cost of Construction. The default value given here is a crude estimate based on original reservoir storage capacity. The user is encouraged to replace this value with a project specific estimate. |

**Table 3.1 First sheet : User Input (continued)**

| | | |
|---|---|---|
| C2 | (\$) | Total Cost of Dam Construction. This cost is calculated as unit cost of construction times initial reservoir storage volume ($C2 = S_o*c*E$). If you entered E = 0 above, your total construction cost will be taken as 0; if you entered E = 1, this cost will be calculated in the above manner. |
| r | decimal | Discount rate |
| Mr | decimal | Market interest rate that is used to calculate annual retirement fund. This could be different from discount rate "r". |
| P1 | (\$/$m^3$) | Unit Benefit of Reservoir Yield. Where possible use specific data for the project. If no data is available refer to Volume 1 report for guidance. |
| V | (\$) | Salvage Value. This value is the cost of decommissioning minus any benefits due to dam removal. If the benefits of dam removal exceed the cost of decommissioning, enter a negative number. |
| omc | | Operation and Maintenance Coefficient. This coefficient is defined as the ratio of annual O&M cost to initial construction cost. Total annual O&M cost is calculated by the program as C1= omc*c* So. |
| PH | (\$/$m^3$) | Unit value of water released downstream of dam in river by hydrosuction operations. This could be zero, but may have value if downstream released water is used for providing some of required yield. |

**Table 3.1 First sheet : User Input (continued)**

| | | |
|---|---|---|
| PD | (\$/m$^3$) | Unit value of water used in dredging operations. This could be zero, but may have a value if settled dredging slurry water is used for providing some of required yield. |
| CD | (\$/m$^3$) | Unit Cost of Dredging--The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, enter "N/A" to instruct the program to calculate a default value of the unit cost of dredging. The calculated value is reported in Econ. Results. & Conclusion Page. |
| CT | (\$/m$^3$) | Unit Cost of Trucking--The user is encouraged to input her/his own estimate. Should this be difficult at the pre-feasibility level, the default value is recommended. |
| **Flushing Benefits Parameters** | | |
| s1 | decimal | The fraction of Run-of-River benefits available in the year flushing occurs (s1 ranges from 0 to 1). |
| s2 | decimal | The fraction of storage benefits available in the year flushing occurs (s2 ranges from 0 to1). |
| **Capital Investment** | | |
| FI | \$ | Cost of capital investment required for implementing flushing measures. The cost entered will be incurred when flushing is first practiced. |
| HI | \$ | Cost of capital investment to install Hydrosuction Sediment-Removal Systems (HSRS). |
| DU | Years | The expected life of HSRS. |

Second Sheet: User Input (Environmental and Social Safeguards Page) If the user interested in the Environmental and Social Safeguards Policies, this second sheet should be filled according to the related project data. Otherwise, there are already existing default values and user should not change these. Default values and what does these means explained below from Table 3.2 to Table 3.5 which is taken from original RESCON program User Input sheet.

As a default value, RESCON takes safeguard rating as “1” and Safety Policy Criteria as “D” in.

**Table 3.2 Safeguard Ratings for Sediment Management Strategies**

| Safeguard Ratings for Each Sediment Management Strategy | Safeguard Ratings |
|---|---|
| No impact and potential benefits | 1 |
| Minor impact | 2 |
| Moderate impact | 3 |
| Significant impact | 4 |

**Table 3.3 Safeguard Ratings**

| Safeguard Policy Criteria | Interpretation | Policy Level |
|---|---|---|
| 6 | No impact and potential benefits | A |
| 7 to 11, with no 3's | Minor impact | B |
| 12 to 15 or at least one 3 | Moderate impact | C |
| 16 or higher, or at least 4. | Significant impact | D |

**Table 3.4 Estimated Environmental and Social Impact Levels**

**Estimated Environmental & Social Impact Levels (Enter 1 to 4)**

| **Possible Strategies** | **Technique** | **Natural Habitats** | **Human Uses** | **Resettlement** | **Cultural Assets** | **Indigenous Peoples** | **Transboundary Impacts** | **Total** |
|---|---|---|---|---|---|---|---|---|
| Nonsustainable (Decommission) with No Removal | N/A | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Nonsustainable (Decommission) with Partial Removal | HSRS | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Nonsustainable (Run-of-River) with No Removal | N/A | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Sustainable | Flushing | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Sustainable | HSRS | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Sustainable | Dredging | 1 | 1 | 1 | 1 | 1 | 1 | 6 |
| Sustainable | Trucking | 1 | 1 | 1 | 1 | 1 | 1 | 6 |

**Table 3.5 Safeguard Policy Level**

| Safety Policy Criteria | Policy Level |
|---|---|
| Maximum allowable environmental and social damage | (A to D) |

After these above mentioned data provided and the results are calculated and the output of the program gives information in different sheets successively such that;

- Flushing Technical Results
- HSRS Technical Results
- Flushing Technical Calculations
- HSRS Technical Calculations
- Economic Results & Calculations
- Safeguard Results

The above mentioned output values provided as a consequence of a technical and economical optimization. These optimizations working principle is discussed below.

## 3.2. Working Principle of RESCON for Technical Optimization

There are varying sediment management methods as defined previous sections. However, RESCON considered and analyze some of them not the all techniques.

These are:

- Flushing
- HSRS

- Traditional Dredging
- Trucking

In addition to these, for the sake of comparison, the “No sediment removal” case is also technically studied by RESCON. The program takes two possibilities for “No Sediment Removal” case after the end of the useful life of dam:

- ➢ Run-off river
- ➢ Decommissioning

In order to bring the run-off river operations, the reservoir is assumed to be fully depleted with sediment and the dam is functioning to generate power. After these conditions are gained then the existing and fully depleted dam should be maintained for the run-off river operations.

If decommissioning of dam is considered then program calculates the most appropriate time, called optimal time, to remove the dam. The optimal time of decommissioning depends on annual net benefits and salvage value of the dam, which is defined by user. The cost of dam removal will be calculated by the program with the parameters of the optimal time and the salvage value. Then, in order to accumulate the necessary amount of money the annual retirement fund is calculated by the program.

The formulas related to these will be explained in the Economical Optimization part.

### 3.2.1. Technical Principle of Flushing in RESCON

The optimization framework of RESCON in flushing is based on the Atkinson Model, (Atkinson, 1996).

**Flushing Parameters and Calculation Procedure of the Atkinson Model**

According to Atkinson defined the criteria of feasible reservoir flushing as follows,

- If the long term balance between sediment flushed and sediment deposited in the reservoir is provided, then the transported sediment through low level outlets by flushing will be sufficient enough for sustainability of the reservoir.
- In order to get a specified volume of the storage, after sediment balance the remaining volume of sediment will be as small as possible.
- The economical side of the problem should be considered that the cost of flushing does not exceed the benefits.

In order to understand above feasibility criteria, definitions and calculation procedure of Atkinson is reviewed below.

**1. Sediment Balance Ratio (SBR):**

Sediment balance ratio is the ratio of sediment mass flushed annually $M_f$ to the annual sediment mass deposited $M_{dep}$.

$$SBR = \frac{M_f}{M_{dep}} \quad (3.1)$$

SBR calculation can be done by using the following steps:

i. Derivation of a representative reservoir width from the dam at the flushing water surface elevation according to the reservoir bathymetry:

$$W_{res} = W_{bot} + 2\, SS_{res}\,(El_f - El_{min}) \quad (3.2)$$

Where, $W_{bot}$ is the width of the reservoir at the bottom and $El_f$ is calculated from outlet sill elevation plus the water depth above that sill at the flushing discharge.

ii. Actual flushing width calculation using a best fit equation resulting from empirical data:

$$W_f = 12.8 \times Q_f^{0.5} \quad (3.3)$$

where $Q_f$ is the flushing discharge ($m^3/s$).

Flushing Width is computed by using the following formula which is derived by IRTCES (1985), Jaggi and Kashyap (1984) and Jarecki and Murphy (1963) (Atkinson, 1996).

iii. Take the minimum of $W_{res}$ and $W_f$ as representative width of flow for flushing, W, because the bottom width of before impoundment is a limitation for the channel width achieved by flushing.

iv. Estimation of Longitudinal Slope during flushing is:

$$S = \frac{El_{max} - El_f}{L} \quad (3.4)$$

where L is reservoir length and $El_{max}$ is the top water level elevation.

v. Estimation of the parameter Ψ, determined by sediment type, for $Q_s$ prediction in order to use empirical equation developed by the Tsinghua University. This method is obtained on the basis of observations at China reservoirs which uses flushing.

Ψ = 1600 for fine loess sediments

Ψ = 650 for $D_{50} < 0.1$mm (median size of sediments are finer than 0.1)

Ψ = 300 for $D_{50} \geq 0.1$mm (median size of sediments are larger than 0.1)

Ψ = 180 for low discharge (say less than 50 $m^3/s$) with any grain size

vi. Calculation of the sediment load during flushing.

$$Q_s = \psi \times \frac{Q_f^{1.6} \times S^{1.2}}{W^{0.6}} \text{ (Tones / sec)} \tag{3.5}$$

In order to use this equation S is limited by $0.000006 < S < 0.016$.

In addition, if the reservoir in question is not similar to Chinese reservoirs studied, $Q_s$ should be reduced by a factor of 3.

vii. Determination of the sediment flushed annually.

$$M_f = 86.400 \times T_f \times Q_s \text{ (tones)} \tag{3.6}$$

where $T_f$ is duration of flushing in days and 86.400 is the number of seconds in a day.

viii. Choose the value of Trap Efficiency (TE) according to Brune's Curve.

Trapping efficiency is the percentage of the trapped sediment related to inflowing sediment. Brune (1953) developed a curve which shows the correlation between reservoir capacity and water inflow with trap efficiency. Actually Brune Curve consist of three curves which are classified such that;

- Highly flocculated and coarse sediment curve
- Median curve for normal pounded reservoirs and average sediment size
- Fine sediment

If sluicing is applied to the reservoir TE is 100 %, otherwise by using the Capacity (C) and inflow (I) from the Brune's Curve TE is founded.

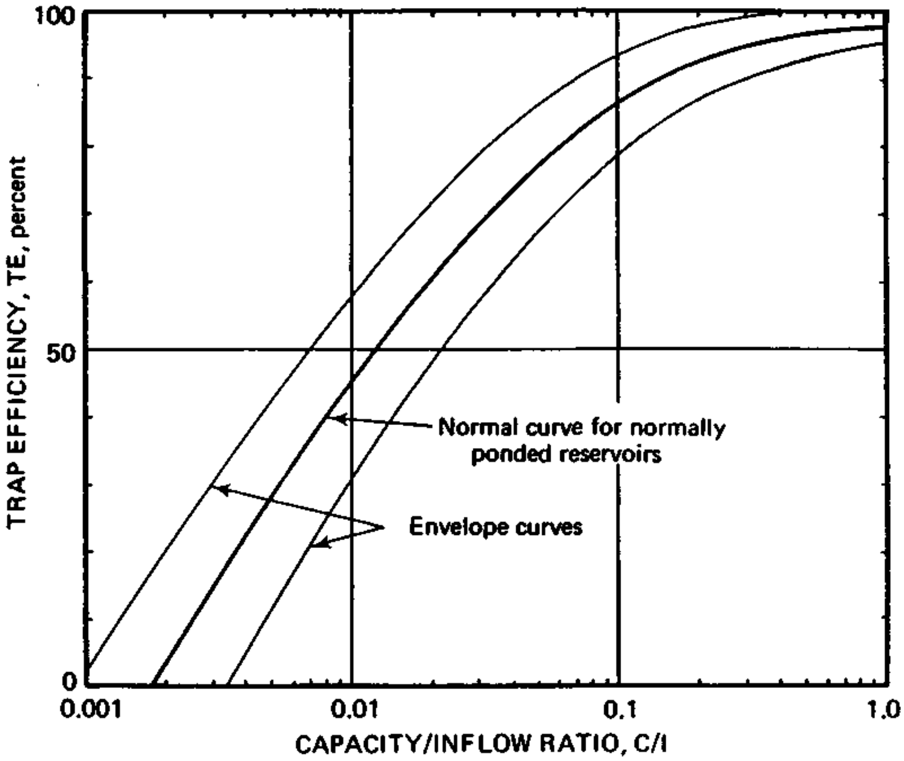



Figure 3.2 Brune's Curve (Brune, 1953)

ix. Calculation of the annual sediment mass deposited, $M_{dep}$

$$M_{dep} = M_{in} \times TE / 100 \tag{3.7}$$

x. Calculation of Sediment Balance Ratio, SBR

$$SBR = \frac{M_f}{M_{dep}} \tag{3.8}$$

If SBR>1.0, sediment mass flushed annually is bigger than sediment mass deposited annually, then it is expected that sediment balance is achieved.

On the other hand; if SBR is too low, then flushing may only be feasible at higher discharges, which may be possible by changing the period when the reservoir is to be flushed, or providing larger flushing outlets in the dam (Atkinson, 1996).

**2. Long Term Capacity Ratio (LTCR):**

Long term capacity ratio, LTCR is defined as the ratio of sustainable capacity to the original capacity. LTCR is expressed as:

$$LTCR = \frac{\text{Sustainable Capacity}}{\text{Original Capacity}} \tag{3.9}$$

Sustainable Capacity is the storage capacity of the reservoir gained due to flushing operations. In other words, before the flushing operation there is a flat deposition in the reservoir, and then when flushing occurs a scoured channel will be formed approximately like a trapezoidal shape (Figure 2.5). This trapezoidal shape channel volume is the sustainable capacity of the reservoir in long term. In the below figure, the simplified geometry of scoured channel could be seen.

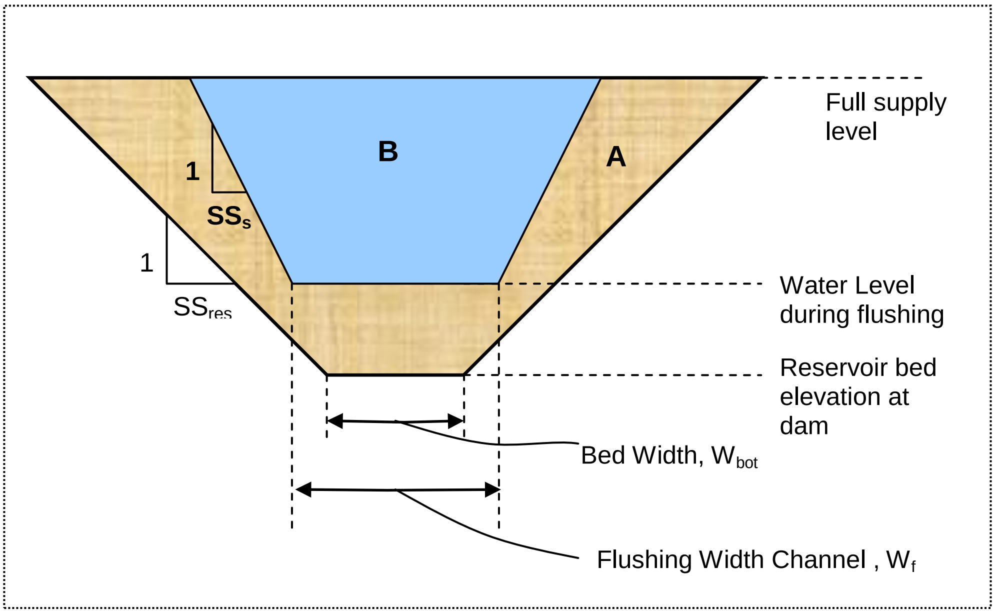



Figure 3.3 Enlarged Section immediately upstream of a dam

According to the Figure 3.3 the Long Term Capacity Ratio, LTCR, is approximated to:

LTCR = Area B / (Area A + Area B)

LTCR should be calculated by following the steps explained below:

i. Determination of the scoured valley width at the top water level. Scoured Valley width is actually depending on the W.

$$W_{tf} = W + 2 \times SS_s \times (El_{max} - El_f) \qquad (3.10)$$

where $SS_s$ is the representative side slope for the deposits exposed during flushing.

The prediction of side slopes studies essentially based on the force balance shown below Figure 2.6, that simply assuming friction forces parallel to the slope is equal to the down slope gravity forces.

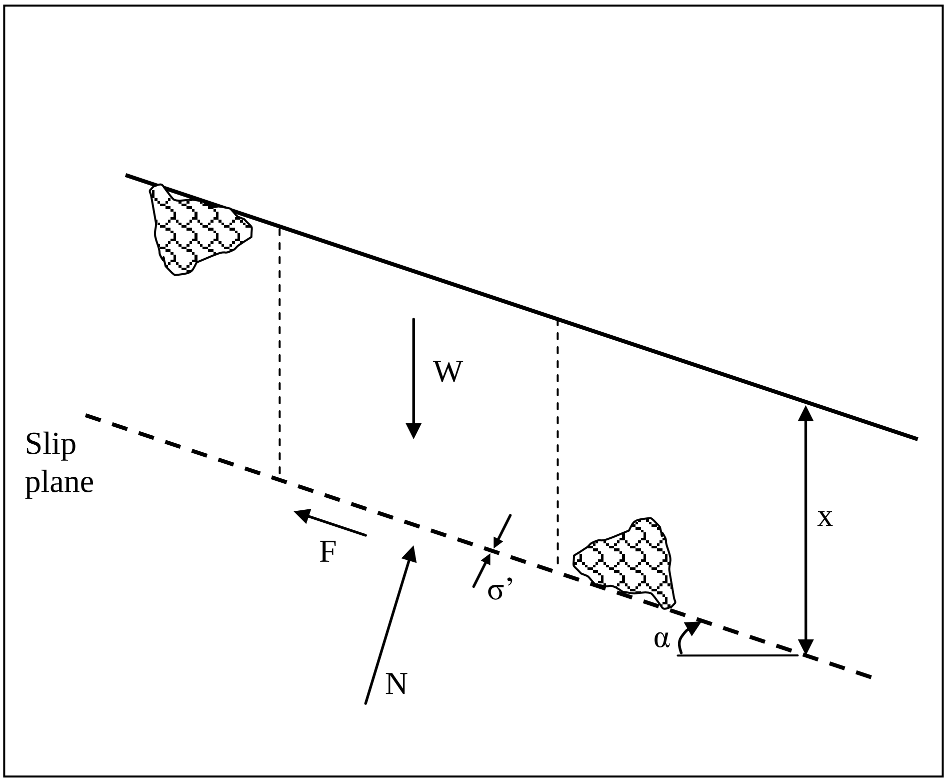



Figure 3.4 Force Balance on a side slope (Atkinson, 1996)

From the Figure 3.4, the side slope can be calculated from force equilibrium such that:

In figure W is the weight and expressed as:

$W = \rho_{bulk}$ x g ($N/m^2$) (3.11)

in which $\rho_{bulk}$ is bulk density and g is gravitational acceleration.

And N is the normal force which is defined as:

N = W cosα (3.12)

in which α is the angle of slope

And friction force in case no water pressures:

F = N tanϕ (3.13)

where ϕ is angle of friction

F = σ' tanϕ (3.14)

where σ' is effective stress

Then, there is two methods for prediction of side slope such that; the prediction chart and Migniot's equation which is adopted with multiplier 5 (five) in order to account the difference between submerged and exposed deposits (Atkinson, 1996). The chart and Migniot's equation are below:

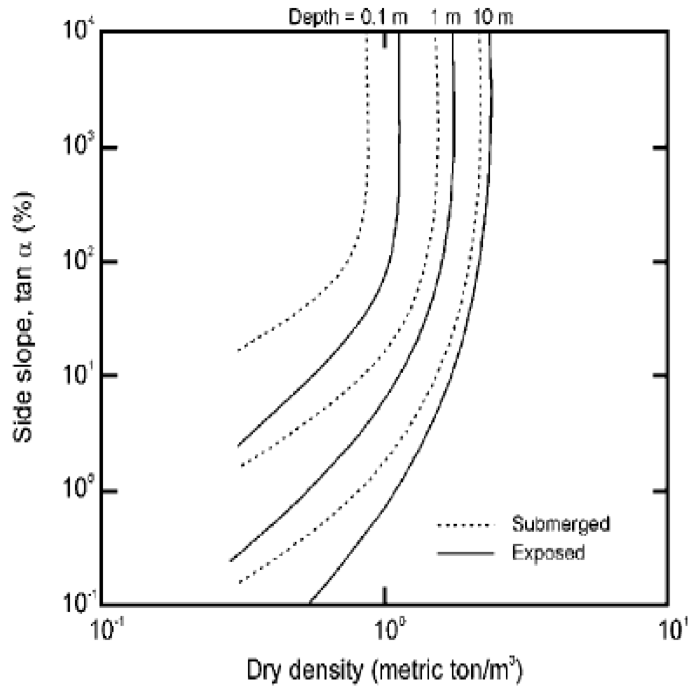



Figure 3.5 Side Slope predictions at the limit of stability (Atkinson, 1996; Simones and Yang)

Migniot's equation:

$$\tan\alpha = \frac{31.5}{5} \times \rho_d^{4.7} \tag{3.15}$$

where $\rho_d$ is dry density in t/m$^3$.

ii. Determination of the reservoir width at elevation ($El_f$) for the assumed simplified geometry.

$$W_t = W_{bot} + 2 \times SS_{res} \times (El_{max} - El_{min}) \tag{3.16}$$

iii. If $W_{tf} \leq W_t$ this means that reservoir geometry does not constrict the scoured valley width. Then cross sectional area of scoured valley can be calculated by following.

$$A_f = \frac{W_{tf} + W}{2} \times (El_{max} - El_f) \tag{3.17}$$

iv. If $W_{tf} > W_t$ this means that reservoir geometry constrict the scoured valley width. Then cross sectional area of scoured valley will be as shown below.

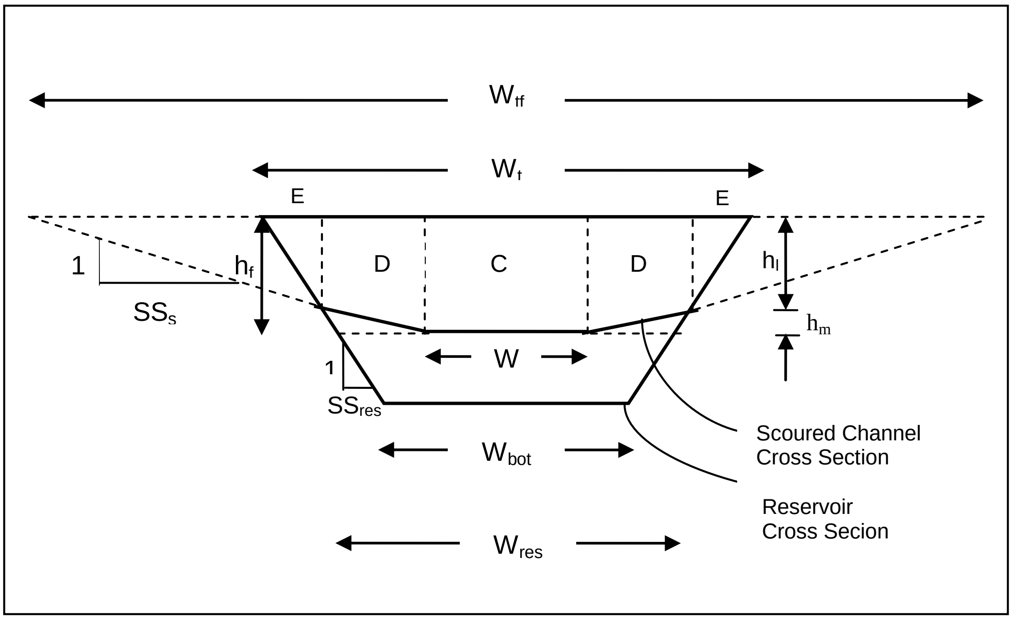



Figure 3.6 Cross section immediately upstream of dam for simplified reservoir geometry and the scoured channel constricted by reservoir sides (Atkinson, 1996)

According to the Figure 2.6;

$$h_m = \frac{W_{res} - W}{2 \times (SS_s - SS_{res})} \tag{3.18}$$

$$h_l = El_{max} - El_f - h_m \tag{3.19}$$

$$h_f = El_{max} - El_f \tag{3.20}$$

Then $A_f$ if the sum of the areas C, D and E.

$$A_f = W \times h_f + (h_f + h_l) \times h_m \times SS_s + h_l^2 \times SS_{res} \tag{3.21}$$

v. Calculation of reservoir cross sectional area is done by using the following formula.

$$A_r = \frac{W_t + W_{bot}}{2} \times (El_{max} - El_{min}) \tag{3.22}$$

vi. Finally LTCR should be defined.

$$LTCR = \frac{A_f}{A_r} \tag{3.23}$$

If LTCR > 0.5 the sustainable capacity criteria will be achieved, an effective flushing operation is done (Atkinson, 1996).

**3. Extent of Drawdown (DDR)**

The extent of reservoir drawdown is unity minus a flow depth ratio which is flushing water level to flow depth for the impounding level. This ratio gives an idea if the drawdown executed effectively.

$$DDR = 1 - \frac{El_f - El_{min}}{El_{max} - El_{min}} \tag{3.24}$$

The drawdown is insufficient for effective flushing if DDR < 0.7, (Atkinson, 1996).

**4. Drawdown Sediment Balance Ratio ($SBR_d$)**

$SBR_d$ is calculated in a similar way of Sediment Balance Ratio (SBR), but this new ratio is calculated for full drawdown conditions. In other words, in steps (i) and (iv) of SBR calculation use $El_f$ instead of $El_{min}$. $SBR_d$ >1.0 is preferred. (RESCON Manual, 2003)

**5. Flushing Channel Width Ratio (FWR)**

The flushing width ratio is check whether the predicted flushing width is greater than the representative bottom width or not.

$$FWR = \frac{W_f}{W_{bot}} \tag{3.25}$$

It will be an important constraint if the FWR is less than one (Atkinson, 1996).

**6. Top Width Ratio (TWR)**

The ratio of the scoured valley width at top water level to the reservoir actual top width gives the Top Width Ratio, which is used to quantify side slope. Due to the fact that, side slope can be a constraint for flushing when FWR value is less than unity or when scoured valley width is smaller than actual top width relatively.

$$TWR = \frac{W_{td}}{W_t} \tag{3.27}$$

where $W_{td}$ calculated as follows:

$$W_{td} = W_{bf} + 2 \times SS_s \times (El_{max} - El_{min}) \tag{3.28}$$

If FWR value is important than TWR value should exceed 2 in order to overcome the FWR constraint. Otherwise TWR≈1 is enough (Atkinson, 1996).

On the other hand, the RESCON model determines the technical feasibility of flushing based on SBR alone (RESCON Manual, Volume-II, pg.5). The program does take into consideration neither FWR nor TWR.

The program assumes two phases for flushing operations, namely; Phase I and Phase II. In Phase I, flushing is done periodically until the reservoir reach its long term capacity (LTC). Then, in order to provide long term capacity in its original level, flushing is done periodically for all subsequently accumulated sediment. In the figure below, this process is depicted.

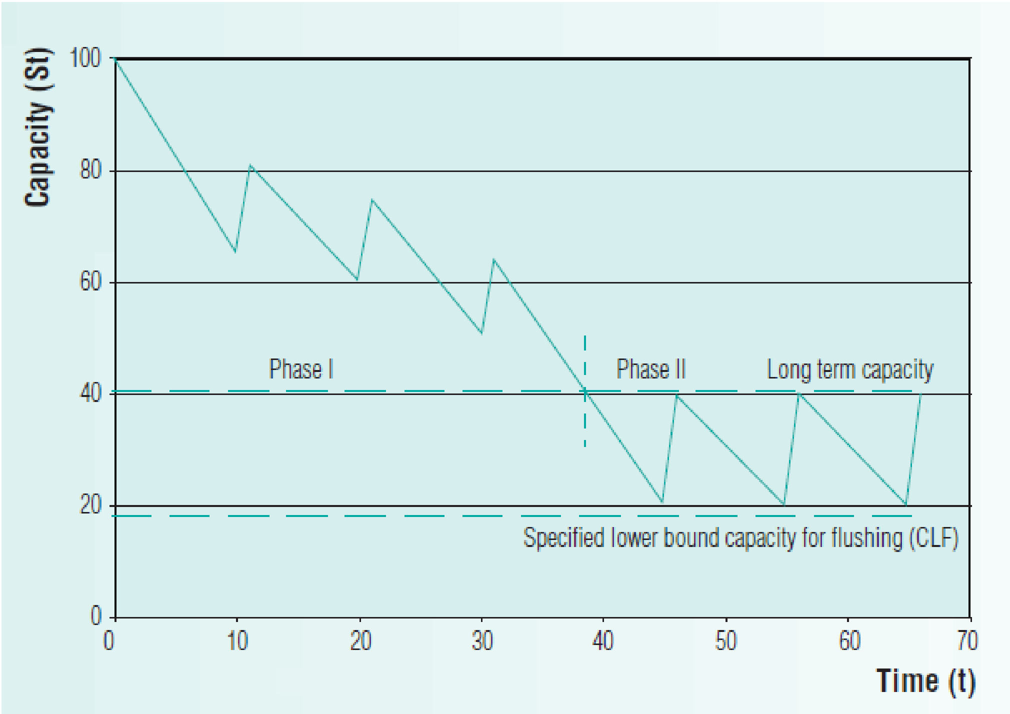



Figure 3.7 Possible Time Path of Remaining Capacity for Flushing

The amount of sediment removed by flushing in Phase-II is:

LTCR * (So – St) (3.29)

Where “So-St” is the difference of original storage capacity and remaining storage capacity, in other words accumulated sediment. It is obviously noted that if remaining storage capacity decrease, the quantity of removed sediment will increase for each cycle.

In addition, if the frequency level of flushing is shorter, then the remaining capacity will be higher than long term capacity. It could also be discerned from the figure. However, RESCON does not consider this effect and the optimal cycle length is rather calculated by taking into consideration the determined long term capacity defined at the initial steps of the program.

Then the Net Present Values for all possible cycles are calculated by the program, and optimal cycle length and also removed sediment are determined for Phase-II. This optimal cycle is calculated independently from Phase-I.

After that, net benefits of Phase-I and Phase-II are summed up and the Phase-I cycle length is chosen such that the total NPV is maximized.

It should be noted that user specifies lower bound for flushing (CLF) in the User Input page of the program.

### 3.2.2. Technical Principle of HSRS in RESCON

The optimization framework of RESCON in HSRS is based on the Hotchkiss and Huang (1995) model which was explained in the previous chapter. For the calculation, the user specifies the reservoir length, available energy head at the dam, deposited sediment information and a hydrosuction pipe diameter in the User Input page of the program. In addition, user also specifies lower bound capacity (CLH) for HSRS.

The program works on two cases for HSRS. These are:

- Sustainable case: all the incoming sediment will be removed each year.

- Non-sustainable case: although HSRS is installed, its capacity may be inadequate to remove all the incoming sediment and to prevent the accumulation of sediment. Then the program works on two possible scenarios.
    - Decommissioning
    - Run-off river

In the sustainable case, according to the specified CLH the program determine the long-term capacity. For the non-sustainable case, decommissioning and run-off river operations scenarios are discussed. As a result, program reports the optimal timing of HSRS installation time, the amount of sediment removed every year, terminal time for the case of partial removal and also retirement fund for decommissioning case. (RESCON Manual, Volume-II, Pg.7) The figure below shows the possible time path.

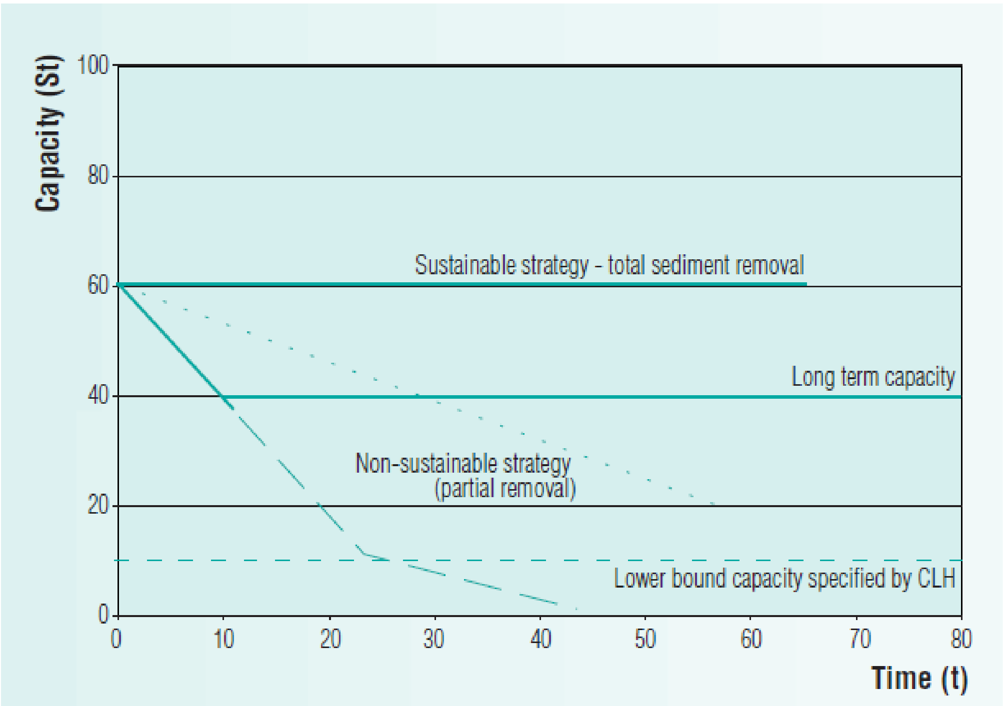



Figure 3.8 Possible Time Path of Remaining Capacity for Hydrosuction

### 3.2.3. Traditional Dredging and Trucking Technical Principle in RESCON

There are many types of dredging methods and different types of dredging equipments used in the world. However, the program uses the aforementioned traditional dredging, removing the silted sediment from reservoir bed by pumping water (Turner, 1996).

The technical feasibility of dredging and trucking does not depend on the sediment removal rate, unlike the previously mentioned methods. They are assumed always to be feasible. Therefore, the user should pay attention to the results and be cautions. Furthermore, in some cases, even though the program claims that the method is feasible; the use of method may not be practical.

The user specifies the followings:

- CLD: Maximum percent of the capacity loss that is allowable at any time in reservoir for Dredging
- CLT: Maximum percent of the capacity loss that is allowable at any time in reservoir for Trucking
- ASD: Maximum percent of the accumulated sediment removed per dredging event
- AST: Maximum percent of accumulated sediment removed per trucking event
- MD: Maximum amount of the sediment removed per dredging event
- MT: Maximum amount of the sediment removed per trucking event
- CD: Unit cost of dredging (there is an option in the program that default value can be used by entering “N/A”)
- CT: Unit cost of trucking

During the subsequent execution phase of the program as if the reservoir is new, in Phase-I sediment removal is not considered, as for Phase-II the sediment removal is considered to be constant for each cycle, so that sustainability is provided. Then after economic optimization, Smin (lower bound of reservoir capacity) and LTC (long term capacity) are determined according to the optimal duration of Phase-I and optimal cycle length of Phase-II respectively, by the program. It should be noted that Phase-I duration is independent from the Phase-II cycle duration. (Figure 3.9)

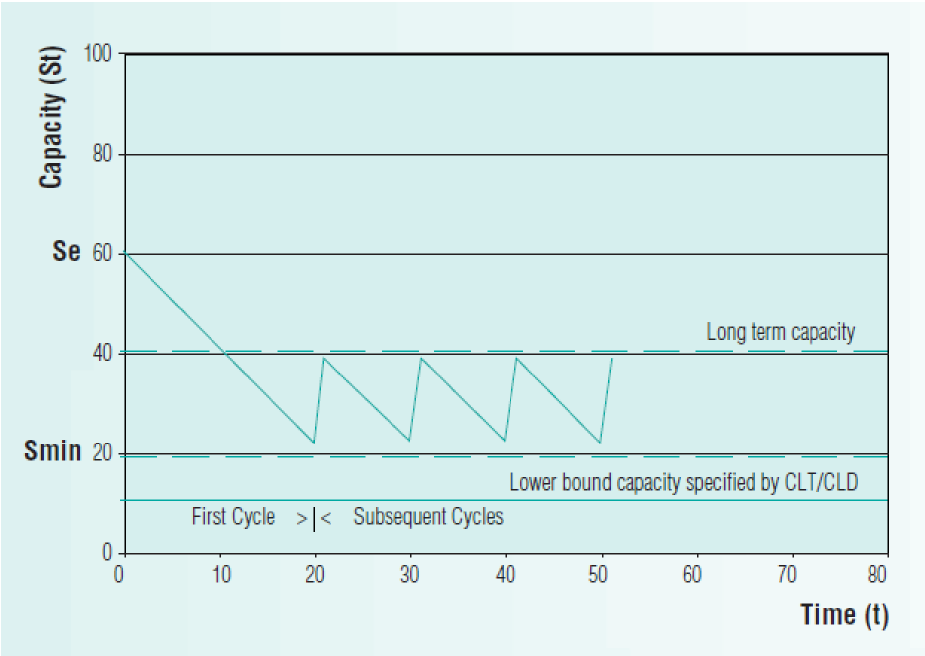



Figure 3.9 Possible Time Path of Remaining Capacity for Dredging and Trucking (Se > Smin)

The optimization can be done for an existing reservoir also. If the existing reservoir capacity, Se, is lower than optimally determined minimum reservoir capacity, Smin, then optimal time path will be recalculated (RESCON Manual, Volume-II, pg.9). An immediately sediment removal occurs and the amount of this initial removal will be determine LTC as shown in Figure 3.10.

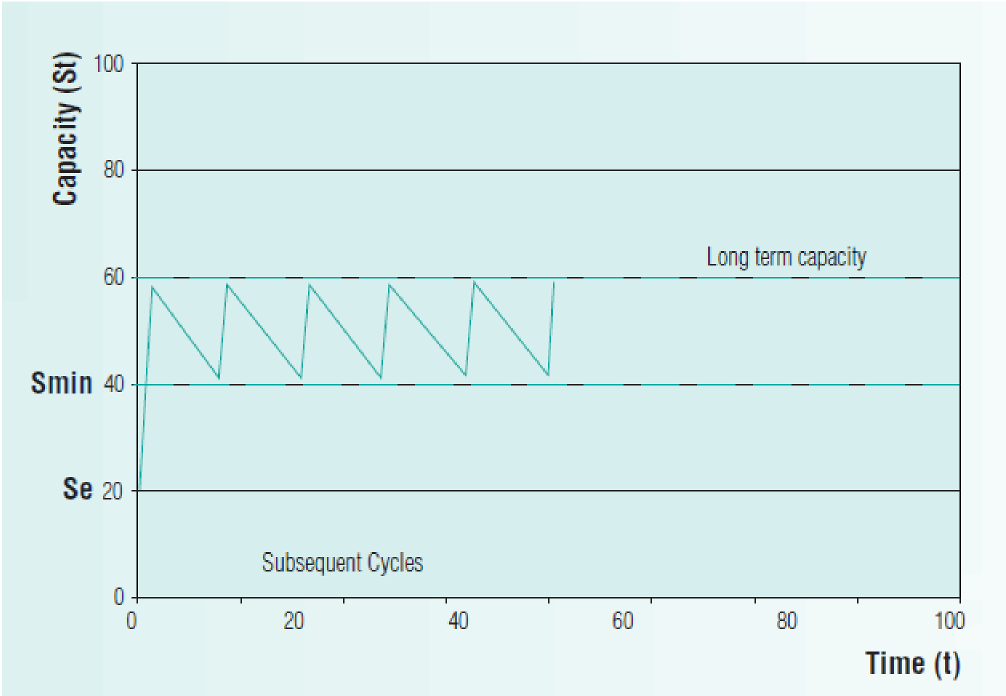



Figure 3.10 Possible Time Path of Remaining Capacity for Dredging and Trucking (Se < Smin)

## 3.3. Economic Optimization Working Principle of RESCON

RESCON is a preliminary tool for decision makers to decide whether the investment is feasible or not. RESCON enable them to see the whole picture in advance. From economical point of view, the RESCON principle is based on to maximize the life-time aggregate Net Present Value. The following optimization is used for all four sediment evacuation techniques mentioned above and also for the "do nothing alternative".

$$\text{Maximize } \sum_{t=0}^{T} NB_t.d^t - C2 + V.d^T \qquad (3.30)$$

Subject to: $S_{t+1} = S_t - M + X_t$ (3.31)

where;

$NB_t$=annual net benefits in year t

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

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

V=salvage value

T=terminal year

$S_t$=remaining reservoir capacity in year t

M=trapped annual incoming sediment

$X_t$=sediment removed in year t

(RESCON Manual Vol.II, 2003)

According to the above optimization, the most beneficial sediment evacuation method will be chosen. The highest value of the objective function gives the best solution. The Net Benefit calculation is different for different sediment evacuation methods. These are explained below.

The parameters used in calculation of Annual Net Benefit equations are defined below:

P1= Unit Value of Reservoir Yield

$W_t$ = Annual Reservoir Yield, which is a function of $S_t$

$S_t$ = Remaining Reservoir Capacity

$X_t$ = The Amount of Sediment Removed

$Y_t$ = the needed water for sediment removal

C1 = annual operations and maintenance cost

PH = Downstream value of water used during hydrosuction

PD = Downstream value of water used during dredging

CH = Unit Cost of sediment evacuating with HSRS

CD = Unit Cost of sediment evacuating with dredging

CT = Unit Cost of sediment removal with trucking

FI = Capital Cost of installing a Flushing system

There are three different Net Benefit calculations for Flushing method. If the amount of evacuated sediment is zero, then Net Benefit is equal to the net income minus net outcome. In other words, the unit value of reservoir yield multiplied by annual reservoir yield, minus annual operations and maintenance cost. Moreover, if the amount of evacuated sediment is bigger than zero, then in first flushing the capital cost of installing a flushing system will be an outcome for Net Benefit.

For Flushing:

$$NB_t = \begin{cases} P1\cdot W(S_t) - C1 \text{ if } X_t = 0 \\ P1\cdot \left[s1\cdot W(0) + s2\cdot (W(S_{t+1}) - W(0))\right] - C1 - F1 \text{ if } Xt > 0, First\cdot Flushing \\ P1\cdot \left[s1\cdot W(0) + s2\cdot (W(S_{t+1}) - W(0))\right] - C1 \text{ if } Xt < 0, Subsequent\cdot Flushing \end{cases} \quad (3.32)$$

For HSRS:

$$NB_t = P1\cdot W(S_t) - (P1 - PH)\cdot Y_t - C1 - CH\cdot X_t \quad (3.33)$$

Cost of sediment evacuating with HSRS and water used for HSRS will be taken as outcome. On the other hand, if water used during HSRS has a downstream value, it will be income.

For Traditional Dredging:

$$NB_t = P1\cdot W(S_t) - (P1 - PD)\cdot Y_t - C1 - CD(X)\cdot X_t \quad (3.34)$$

Its logic is exactly the same as HSRS. Cost of sediment evacuating with dredging and water used for dredging will be taken as outcome. On the other hand, if water used during dredging has a downstream value, it will be income.

For Trucking:

$$NB_t = P1 \cdot W(S_t) - C1 - CT \cdot X_t \tag{3.35}$$

(with $W_t = 0$ if $X_t > 0$ )

Basically since the reservoir should be empty for trucking method there is no income. As an outcome cost of sediment removal with trucking will be taken.

For no removal:

$$NB_t = P1 \cdot W_t - C1 \tag{3.36}$$

The Net Benefit is obviously seen from the equation that; net income minus net outcome.

In addition to these, Annual Reservoir Yield ($W_t$) which is a function of Remaining Reservoir Capacity ($S_t$) is calculated via Gould's Gamma Function (RESCON Manual Vol-I, 2003).

$$W_t = \frac{4 \cdot S_t \cdot V_{in} - Zpr^2 \cdot sd^2 + 4 \cdot Gd \cdot sd^2}{4 \cdot \left( S_t + \frac{Gd}{V_{in}} \cdot sd^2 \right)} \tag{3.37}$$

where;

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

sd = standard deviation of incoming flows (annual runoff)

$Z_{pr}$ = standard normal variate of p %

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

Since this economical function is another academic area and its understanding is not important for the usage of RESCON, its details are not discussed in this study. It is included only for information. However, it should be noted that $W_t$ (annual reservoir yield) is calculated for every step, t, in the economic model (RESCON Manual Vol-I, 2003).

In case of sediment removal, the required water to do successful sediment evacuation for each and every sediment evacuation method used in the economical model of RESCON is discussed below.

### 3.3.1. Flushing

During Flushing, since the reservoir will be emptied the water yield, $W_t$ is determined as follows:

$$W_t = s1 \cdot W(0) + s2 \cdot (W(S_{t+1}) - W(0)) \tag{3.38}$$

in which;

s1 = the fraction of Run-of river benefits available in the year flushing occurs
W(0) = water yield from Run-of river project
s2 = the fraction of the storage benefits available in the year flushing occurs
$W(S_{t+1})$ =water yield from storage capacity after flushing

### 3.3.2. HSRS

The required water for evacuation of deposited sediment from reservoir by HSRS, $Y_t$ is expressed as;

$$Y_t = \left( \frac{Q_m}{Q_s} \right) \cdot X_t \tag{3.39}$$

where:

$Q_m$ = mixture flow rate
$Q_s$ = sediment flow rate
$X_t$ = sediment removed in year t.

**3.3.3. Dredging (Traditional)**

The required volume of water for removing specified volume of sediment, $Y_t$ is expressed as;

$$Y_t = \left( \frac{100 * 2.65}{C_w} \right) \cdot X_t \tag{3.40}$$

where $C_w$ is specified by user, which is the concentration of sediment weight to water removed.

**3.3.4. Trucking**

The $W_t$ assumed to be zero for simplicity. Because for trucking process the reservoir should be empty and there is no need for water.

Thereto, RESCON calculate a retirement fund and a terminal time, if the reservoir will be decommissioned. The accumulation of this Retirement Fund in the duration of Terminal Time provides the necessary cost amount for the decommissioning of dam at the end of the reservoir life. The program calculates the retirement fund by using the below equation:

$$k = -mV / ((1+r)^T - 1) \quad (3.41)$$

where:

k = annual retirement fund

m = rate of interest (different from the discount rate r)

V = Salvage Value

T = terminal year

As a result of this Net Benefit and Retirement Fund calculations; program gives the solution in two forms.

1) If the reservoir performs its task forever, this case is called ***"Sustainable".***
2) If the reservoir performs its task within a finite period, this case is called ***"Non-sustainable".***

   There are two possibilities for non-sustainable case.

   a) Decommissioning of dam at its Terminal Time
   b) After the siltation of dam the reservoir can be used as a run-off river project.

RESCON economic calculation based on the below presented formulas and relationship.

### 3.3.5. Unit Cost of the Evacuation Methods used in RESCON

- Hydrosuction (HSRS) Unit Cost is determined as:

$$CH = \frac{HI}{DU \cdot Q_s} \quad (3.42)$$

where:

CH = unit cost of hydrosuction

HI = cost of capital investment to install HSRS

DU = the expected life of HSRS

$Q_s$ = the annual maximum transport rate

The HI and DU is specified by user in the User Input Page of RESCON excel sheet. The annual maximum transport rate, $Q_s$, is automatically calculated by the program and this value can be found in the HSRS Technical Calculations excel page of the program.

- Dredging Unit Cost is determined as follows:

If X < 150,000 $m^3$ CD (X) = 15.0

If X > 16,000,000 $m^3$ CD (X) = 2.0

Else CD(X)=(6.61588727859064)*(X/(10^6))^-0.431483663524377 (3.43)

where:

X = amount of sediment dredged per cycle ($m^3$)

CD = unit cost of dredging (US$/$m^3$)

Although the program calculates the unit cost of dredging by using above formula, the program encourages the users to enter their own values. In the User Input page of RESCON program, the CD value area is ready for user to input the specific cost data of dredging. From the above formula it is obviously seen that the dredging cost decreases if the volume of removed sediment increase.

- Construction Unit Cost is determined as follows:

If So > 500,000,000 $m^3$ c = US$ 0.16 / $m^3$

Else c = 3.5 – 0.53 * LN (So/1000000) (3.44)

where:

So = original storage capacity

c = unit construction cost

The default unit cost of construction is calculated by program if the users should not be able to enter their own value.

From the equation it is understand that the unit cost of construction decreases if the original storage volume increases.

- Annual operations and maintenance cost is determined below:

C1 = omc * c * So (3.45)

Where:

C1 = annual operations and maintenance cost, US$,

c = unit cost of dam construction, US$/ $m^3$

omc = operations and maintenance coefficient

The operations and maintenance coefficient, omc, is provided by user in the User Input page of the program.

## 3.4. Evaluation and Comments about Economic Results of RESCON

One of the output pages of RESCON is “Economic Results & Calculations” page. Although the alternatives have different NPV calculation method, they are compared to each other on the same basis. In order to understand how this comparison work out, the difference between “Design Life” and “Life Cycle” terms should be known very well. RESCON tries to determine how to manage the facility in the most optimal way by using infinite time in other words in perpetuity.

In order to compare the alternatives on the same basis, the RESCON use 300 years to define perpetual time for all the sustainable projects. Therefore, the sustainable optimal management procedures for removing sediment are defined. The NPV calculation is done for 300 years; since the life cycles of each method are different, the time of remove are different. For example, in 300 years the dredging method may be used 10 times but the trucking method may be used for 5 times.

On the other hand, in the calculation of non-sustainable cases, which means the reservoirs eventually silt up completely and has to be decommissioned or used as a run-off river, a finite design life is used. In addition, for decommissioning case, an investment fund is determined to save enough money for decommissioning to the future generations.

# CHAPTER 4

# RESCON CASE STUDIES FOR DAMS IN TURKEY

## 4.1. Reservoir Sedimentation in Turkey

The siltation in dams is a growing dangerous problem for World dams as much as for Turkey. The life of a dam directly depends on the sedimentation. Besides, the magnitude of sedimentation depends on several natural factors such as; climate, geographic – geological conditions. As a result, life of a dam is indirectly affected by natural conditions.

Turkey have semi-arid climate and this is the most unpredictable condition for sediment production. According to the world records the measurements of sediment production for semi-arid conditions in the world are high as 6000 – 8000 $m^3/km^2$/year. Therefore, the deposited sedimentation in Turkey reservoirs should be highly considered.

## 4.2. Economical Parameters in Turkey for Case Studies

The Economic Parameters are obtained from a construction firm, in order to achieve realistic results from RESCON case studies. As a result of personal communication values are given in Table 3.1 (Dedekli, 2008).

**Table 4.1 Economic Parameters of Turkey**

| Parameter | Unit | Type | Value* |
|---|---|---|---|
| Discount Rate (r) | % | Hydroelectric Power Dam | 10 |
| Discount Rate (r) | % | Domestic Water Supply | 10 |
| Discount Rate (r) | % | Irrigation | 10 |
| Market Interest Rate (Mr) | % | - | 10 |
| Unit Benefit of Reservoir Yield (P1) | ($/kWh) | Hydroelectric Power Dam | 0.069 |
| Unit Benefit of Reservoir Yield (P1) | ($/m$^3$) | Domestic Water Supply | 0.93 |
| Unit Benefit of Reservoir Yield (P1) | ($/m$^3$) | Irrigation | 0.39 |
| Salvage Value (V) | ($) | | Variable according to dam |
| Operation and Maintenance Coefficient (omc) | % | - | 1.0 |
| Unit Value of Water used in HSRS (PH) | ($/m$^3$) | | 0.001 |
| Unit Value of Water used in Dredging (PD) | ($/m$^3$) | | 0.001 |
| Unit Cost of Dredging (CD) | ($/m$^3$) | | 15.00 |
| Unit Cost of Trucking (CT) | ($/m$^3$) | | 4.00 |

(*) Note: The exchange rate is taken as 1$ = 1.4 YTL

## 4.3. Çubuk Dam-I

Çubuk Dam-I is the first dam of Turkey after the establishment of the Turkish Republic. It is construction was started in 1929 and it was commissioned in 3 November 1936 (Figure 4.1). Çubuk Dam-I is located on the Çubuk stream and 12km north of the Ankara city. It is a concrete gravity dam and its reservoir area is approximately 0.94 $m^2$. The project cost was 3,500,000 TL in 1936.

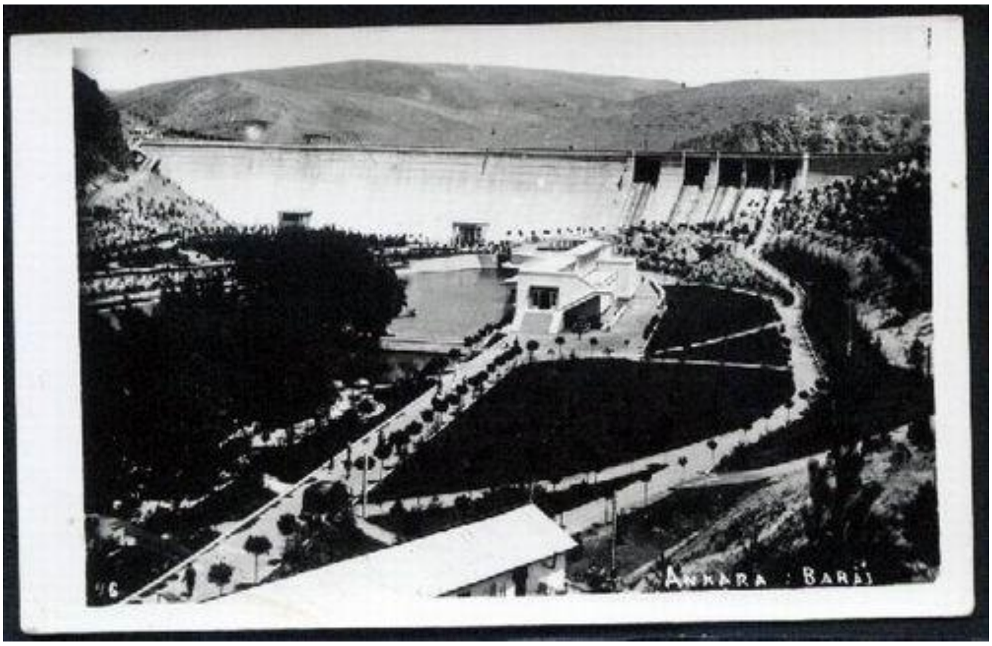



Figure 4.1 A view from Çubuk Dam-I

The design of reservoir and the appurtenant structures was done by Prof. Dr. Walter Kunze with the collaboration of DSİ engineers. In addition, he worked as a consultant during the construction stage.

Main characteristics of Çubuk Dam-I are listed below.

Hydrological Data:

- Drainage Area: 720 $km^2$
- Mean Annual Precipitation: 450mm
- Estimated annual average run-off: 140 x $10^6$ $m^3$

Reservoir Data:

- Active volume: 10 x $10^6$ $m^3$
- Gross reservoir capacity : 12.5 x $10^6$ $m^3$
- Maximum reservoir volume: 13.5 x $10^6$ $m^3$
- Normal water surface elevation: 906.61 m
- Maximum water surface elevation: 907.61 m
- Maximum reservoir surface area: 16.5 $km^2$

Dam:

- Type: Concrete gravity, circular axis
- Height above lowest foundation: 58.00 m
- Height above ground level: 25.00 m
- Crest elevation: 908.61m
- Crest length: 250m
- Crest width: 4m

Spillway Data:

- Type: Gated, 5 span
- Crest length : 2 – span part, 16.40 m
  : 3 – span part, 19.88m
- Crest elevation: 905.61m
- Type of gates: Electrical and manually operated taintor (radial) gates
- Combined maximum discharge capacity: 227 $m^3$/sec

The purpose of the Çubuk Dam-I was not only to supply domestic and industrial water to the city but also to control flood. However, because of siltation the reservoir can not maintain its function (Figure 4.2). It has been used only for recreational purposes since the reservoir loose its functionality.

Figure 4.2 Siltation in Çubuk Dam-I

In the literature there are some discrepancies about the amount of deposited sediment in Çubuk Dam-I. In this study for the capacity loss, Yılmaz (2003)'s study is taken into account corresponding to %50 storage loss in Çubuk Dam-I due to deposited sediment.

### 4.3.1. Çubuk Dam-I Parameters & RESCON Analyze

The case studies that were examined are previously performed by Çetinkaya, 2006. The necessary technical parameters for RESCON were analyzed in detail by him with an extreme in gathering them. This study is an effort to improve and enhance his work. Therefore, the technical parameters on Çetinkaya's study are checked from related references and then revised if necessary. Then, they are used to examine the aforementioned cases. The parameters used in RESCON in user input page are made available in Appendix-A RESCON Inputs and Results of Çubuk Dam-I.

Kılıç determined the characteristics of sediment (permeability, grain size, percentage, etc.) in laboratory experiments by taking different samples from reservoir basin of Çubuk Dam-I. As a result of analyses; Kılıç reported that since grain size is smaller than 0.147 mm (100 no. sieve diameter) and reservoir size is small, reservoir can be cleared by mechanical mixing method.

The $CaCO_3$ rate, which is % 10-16, in sediment increases the probability of solidification of deposited material under particular depth. However, it is impossible to use this sediment as a normal construction material because of the handling difficulty of the deposited sediment which is high plasticity inorganic clay (Kılıç, 1986). In addition, cleaning of sediment is very difficult because of the mentioned reason. On the other hand, low specific weight of sediment indicates that cleaning process with mechanical mixing can be done easily. Furthermore, because the type of clay is montmorillonit and illit, it can not be used for manufacturing of tile or brick (Kılıç, 1986). The sediment characteristics coming from basin is an important parameter for the purposes of cautions to decrease the rate of siltation. By taking into consideration these circumstances, the inflow coming from basin and especially from Çubuk Dam-II should be rested before coming into reservoir (Kılıç, 1986).

Çubuk Dam-I was built in year 1936 and Çubuk Dam-II was built in year 1963. Between 1936 and 1963, the sediment yield value of basin was 372 ton/year/km$^2$. On the other hand, after the construction of Çubuk Dam-II and between years 1964-1983 the sediment yield value of basin was 350 ton/year/km$^2$. As a result of Kılıç analyses, Çubuk Dam-II does not affect the sediment yield value significantly. Therefore in this study the effect of Çubuk Dam-II in sediment yield value is neglected.

The Sediment Characteristics in the Input Sheet of RESCON is deeply studied in this study. According to RESCON, the density value of in-situ reservoir sediment should be between 0.9 – 1.35. However in this study for Çubuk Dam-I the density of sediment is taken as 1.8 tonnes/m$^3$ (Kılıç) because the deposited sediment has not been cleared for years. Therefore the density of sediment in Çubuk Dam-I is higher than default RESCON values.

One of the Sediment Characteristics, $\Psi$ value is taken 180 because $Q_f$ value is smaller than 50m$^3$/s. The Brune Curve Number in input sheet is 3 means the sediment in the reservoir is colloidal, dispersed and fine-grained, In addition, “Ans” value is taken as 3, because the reservoir has been impounded for 60 years without sediment removal. For Hydrosuction Dredging, the sediment type is 1 which is for medium and smaller sand.

Although the default values of CLF (%), CLH (%), CLD (%) and CLT (%) in RESCON is 100 %, in this study they are taken as 60 %. Because Çubuk Dam-I is not operated and 50 % is already filled with sediment.

The unit benefit of reservoir yield is taken from ASKİ tariff dated 06.03.2008.

**Case Study of Çubuk Dam-I for Flushing Feasibility**

According to Atkinson's calculation procedure, analyses of Çubuk Dam-I is presented in the following sections. All criteria are discussed in order to decide if flushing is appropriate for Çubuk Dam-I. The necessary data for analysis is listed below.

$C_o$ = 7.1 $Mm^3$
L = 6,500 m
$El_{max}$ = 907.6 m
$El_{min}$ = 882.6 m
$W_{bot}$ = 57 m
$SS_{res}$ = 1: 1
$V_{in}$ = 65.5 $Mm^3$
$M_{in}$ = 81,000 t
$Q_f$ = 27 $m^3/s$
$T_f$ = 5 days (120 hours)
$El_f$ = 895 m (assumed due to not knowing sill elevation)
$\rho_d$ = 1.35 t / $m^3$
tan α = (31.5 / 5) x $1.35^{4.7}$ = 25.82 (corrected divided by 10) =2.582
$SS_s$ = 1 / tan α =0.387

**1. SBR Calculation**

i. The representative reservoir width at the flushing water surface elevation:

$W_{res}$ = 57 + 2 x 1 x (895 – 882.6) = 81.8 m

ii. Actual Flushing With
$W_f$ = 12.8 x $27^{0.5}$ = 66.5 m

iii. Take the minimum of $W_{res}$ and $W_f$ as the representative width

W = 66.5 m

iv. The longitudinal slope during flushing

$$S = \frac{907.6 - 895}{6500} = 0.0019$$

v. The value of Ψ is 180.

vi. The sediment load during flushing is:

$$Q_s = 180 \times \frac{27^{1.6} \times 0.0019^{1.2}}{66.5^{0.6}} = 1.556 \text{ t/s}$$

Then this value is reduced by a factor of three according to Atkinson's criteria, since the reservoir in question is not similar to Chinese reservoirs.

$Q_f$ =0.519 t/s

vii. Sediment Mass flushed annually is:

$M_f$ = 86,400 x 5 x 0.519 = 224,168 t

viii. From Brune's median curve is used and capacity inflow ratio is:

$C_o$ / $V_{in}$ = 7.1 / 65.5 = 0.108 then TE= 88 %

ix. Sediment mass deposited annually is:

$M_{dep}$ = 81,000 x 0.88 = 71,280 t

x. SBR = 224,168 / 71,280 = 3.14

The SBR value is bigger than unity, means sediment mass flushed annually is bigger than sediment mass deposited annually. It is expected to have successful flushing operation.

**2. LTCR Calculation:**

i. The Scoured valley width is:

$W_{tf}$ = 66.5 + 2 x 0.387 x (907.6 - 895) = 76.25 m

ii. The reservoir width at this elevation is:

$W_t$ = 57 + 2 x 1 x (907.6 – 882.6) = 107 m

iii. Since $W_{tf} \leq W_t$ then scoured valley cross sectional area is:

$A_f$ = ((76.25 + 66.5) /2) x (907.6 – 895) = 899 $m^2$

iv. Reservoir cross section area is:

$A_r$ = ((107 + 57) /2) x (907.6 – 882.6) = 2,050 $m^2$

v. Finally Long Term Capacity Ratio is:

LTCR = 899 /2,050 =0.44

The LTCR value 0.44 is not bigger than 0.5 thus the operation wouldn't be effective regarding to this criteria.

**3. Extent of Drawdown (DDR)**

The DDR is:

$$DDR = 1 - \frac{895 - 882.6}{907.6 - 882.6} = 0.504$$

This value is not bigger than 0.7 criteria, suggesting that the flushing is inefficient according to this criterion.

**4. Drawdown Sediment Balance Ratio ($SBR_d$)**

i. The representative reservoir width at the flushing water surface elevation is:

$W_{res} = 57 + 2 \times 1 \times (895 - 895) = 57$ m

ii. Actual Flushing Width is:

$W_f = 12.8 \times 27^{0.5} = 66.5$ m

iii. Take the minimum of $W_{res}$ and $W_f$ as the representative width

W = 57 m

iv. The longitudinal slope during flushing

$$S = \frac{907.6 - 882.6}{6500} = 0.0038$$

v. The value of Ψ is 180.

vi. The sediment load during flushing is

$$Q_s = 180 \times \frac{27^{1.6} \times 0.0038^{1.2}}{57^{0.6}} = 3.869 \text{ t/s}$$

Then this value is divided into three since the conditions are not same as those in China.

$Q_f = 1.290$ t/s

vii. Sediment Mass flushed annually is:

$M_f = 86{,}400 \times 5 \times 1.290 = 557{,}280$ t

viii. From Brune's median curve is used and capacity inflow ratio is $C_o$ / $V_{in}$ = 7.1 / 65.5 = 0.108 then TE= 88 %

ix. Sediment mass deposited annually is:
$M_{dep}$ = 81,000 x 0.88 = 71,280 t

x. SBR = 557,280 / 71,280 = 7.82

The SBR value is extremely bigger than unity. For full drawdown conditions, it is expected to get a successful flushing.

**5. Flushing Channel Width Ratio (FWR)**

The flushing width ratio is;

$$FWR = \frac{66.5}{57} = 1.17$$

This ratio is not a constraint because of being higher than one. Since the predicted flushing width is higher than representative bottom width of the reservoir.

**6. Top Width Ratio (TWR)**

In order to calculate top width ratio, first $W_{td}$ should be calculated. $W_{bf}$ , bottom width of scoured valley at full drawdown, should be taken as the minimum of $W_f$ (66.5 m) and $W_{bot}$ (57m).

$W_{td}$ = 57 + 2 x 0.387 x (907.6 – 882.6) = 76.35

$$TWR = \frac{76.35}{107} = 0.714$$

where $W_{td}$ calculated as follows:

Since FWR is not a constraint, TWR=0.714 ≈1 is enough.

As a result of Atkinson's calculation procedure flushing of Çubuk Dam-1 will not be effective. Although SBR value is sufficiently large, LTCR value does not meet the criterion for effective flushing operation. If both SBR value and LTCR values meet the Atkinson criteria, the other criteria will be examined.

### 4.3.2. Çubuk Dam-I RESCON Results & Comments

RESCON optimization results by using Technical and Economical Parameters of Çubuk Dam-I are given in Appendix-A RESCON Inputs and Results of Çubuk Dam-I.

The economic results should be evaluated such that; the aggregate net benefit of non sustainable solutions is calculated according to their finite design life. However, the aggregate net benefit of sustainable solutions is calculated according to their life cycle principle which has infinite lifetime but assumed 300 years by the program.

As a result of optimization, for Çubuk Dam-I, the highest net aggregate benefit, 229.440.860,27 $, is achieved by using HSRS technique, which should be seen from Table A.2 and A.3. In this analyze the real water yield value, 0.93 $/m3, is used for optimization. On the other hand, value of water is a controversial issue, such that in some areas water is free of charge. Therefore, in this optimization procedure of RESCON the net aggregate benefit differentiate but it is highly depends on water yield value and it should not be taken as net benefit.

In order to sustain the dam HSRS long term capacity, which is 3,550,000 m3 (Table A.7), the approximate number of years result is 1 year (Table A.8). The long term capacity ratio is depends on the CLD (%) value in the input sheet of RESCON. CLD default value is 100 %, however since the Çubuk Dam-I have not been in operation because of sedimentation and it is already filled with 50

%, CLD value is taken as 60 %. As a result of this assumption LTCR value decreases for HSRS method.

Nowadays, Ankara Municipality is cleaning the Çubuk Dam-I by trucking method. However, according to RESCON total trucking cost is 9,453,152 $ which is nearly half of the total cost of dam calculated by the program, 17,474,163 $.

Further once again it should be underline that RESCON is using perpetually 300 year thus it is assumed that the structure of the dam will last for 300 years.

## 4.4. Borçka Dam

Borçka Dam is located on the Çoruh River, in Lower Çoruh Basin, which is in the North-eastern Anatolian Region of Republic of Turkey. It is one of the Çoruh Basin Project Bunch which includes 27 projects on Çoruh Basin.

The Borçka Dam site is nearly 25 km northwest of Artvin City and 2.5 km upstream of Borçka District. In addition, the dam site is nearly 300 m downstream of the intersection of the Çoruh River and the Murgul Creek, one of the major tributary of the main stream. Borçka Dam is a clay core, earthfill dam with a reservoir capacity of 418.98 x $10^6$ $m^3$.


Figure 4.3 A view from Borçka Dam

The purpose of Borçka Dam is hydroelectric power generation. The installed capacity and total annual energy production are 300 MW and 1,039 GWh respectively. The construction of Borçka Dam was started in 1998 and now it is completed and the energy production has been started. Main characteristics of Borçka Dam are given in Table 4.2.

**Table 4.2 Main Characteristics of Borçka Dam**

| | |
|---|---|
| **Reservoir Data** | |
| Maximum flood water level | 187.00 m |
| Maximum operation water level | 185.00 m |
| Minimum operation water level | 170.00 m |
| Thalweg elevation | 103.00 m |
| Total storage capacity | 418.95 $hm^3$ |
| Active storage capacity | 150.78 $hm^3$ |
| Dead storage capacity | 268.17 $hm^3$ |
| Reservoir maximum surface area (at elev.185) | 10.84 $km^2$ |
| Reservoir length | 30.50 km |
| **Dam characteristics** | |
| Type | Zoned fill with central core |
| Crest elevation | 189.00 m |
| Height above thalweg | 86.00 m |
| Embankment crest length | 557.00 m |
| Crest Length including concrete structures | 728.00 m |
| Crest width | 10.00 m |
| Total embankment volume | 7,785,000 $m^3$ |
| **Diversion Facilities** | |
| Number of diversion tunnels | 2 |
| Cross section type | Horseshoe |
| Inside diameter | 7.50 m |
| Length (No.1) | 355.00 m |
| Length (No.2) | 351.00 m |
| Diversion capacity | 1,690 $m^3$/sec |
| Inlet bottom elevation | 104.00 m |
| Outlet bottom elevation | |
| Crest elevation of upstream cofferdam | 139.00 m |

**Table 4.2 Main Characteristics of Borçka Dam (continued)**

| | |
|---|---|
| Crest elevation of downstream cofferdam | 112.50 m |
| **Spillway** | |
| Type | Overflow-controlled |
| Type of energy dissipation | Chute ending with stilling basin |
| Sill elevation | 168.00 m |
| Design discharge | 10.639 m³/sec |
| Reservoir elev. at design discharge | 187.00 m |
| Number of gate | 4 |
| Type of gates | Tainter gates |
| Dimension of gates (V/H) | 17.00 m/ 16.00 m |
| **Bottom Outlet** | |
| Location | 2. Diversion tunnel |
| Number of bottom outlet | 1 |
| Maximum capacity | 287.0 m³/sec |
| Type of bottom outlet gates | Slide gates |
| Dimension of gates (V/H) | 3.50 m/ 2.50 m |
| Axis elevation | 103.58 m |
| Inlet sill elevation | 140.00 m |
| **Energy Generation Structures** | |
| **Water Intake Structure** | |
| Type | Concrete Gravity |
| Number | 2 |
| Approach channel elevation | 149.00 m |
| Water intake axis elevation | 154.70 m |
| Intake invert elevation | 151.20 m |
| Service gate type | Slide gate |
| Dimensions of service gate (V/H) | 5.05 m/7.00 m |

**Table 4.2 Main Characteristics of Borçka Dam (continued)**

| | |
|---|---|
| Crest Elevation | 189.00 m |
| Reservoir maximum operating level | 185.00 m |
| Reservoir minimum operating level | 170.00 m |
| **Penstock** | |
| Type | Partly exposed |
| Number | 2 |
| Inner diameter | 7.00 m |
| Length from service gate up to butterfly valve | 207.10 m |
| **Switchyard** | |
| Type | Outdoor |
| Inlet line voltage and number | 380 kV,2 |
| Outlet line voltage and number | 380/154 kV,2/3 |
| Type of auto-transformer | Single phase |
| Voltage ratio of auto-transformer | 380/154 kV/kV |
| Number of transformer | 6 |
| Transformer capacity | 252 (3x84) MVA |
| **Powerhouse** | |
| Type | Indoor |
| Number of units | 2 |
| Continuous power | 68.40 MW |
| Installed capacity | 300 MW |
| Continuous energy | 600 GWh |
| Secondary energy | 439 GWh |
| Total Energy | 1,039 GWh |
| Load factor | 0.40 |
| Type of inlet valve | Butterfly valve |
| Inner diameter of inlet valve | 5.20 m |
| Turbine type | Vertical shaft Francis |

**Table 4.2 Main Characteristics of Borçka Dam (continued)**

| | |
|---|---|
| Turbine axis elevation | 92.00 m |
| Total head | 89.00 m |
| Net head (at operation of one unit) | 87.46 m |
| Maximum discharge | 2x234.5 $m^3$/sec |
| Velocity | 136.36 rev/min |
| Crane capacity of transfer building | 100/10 ton |
| Generator type | Vertical shaft synchronous |
| Voltage between phases | 14.40 kV |
| Frequency | 50 Hz |

### 4.4.1. Borçka Dam RESCON Results & Comments

RESCON optimization results by using Technical and Economical Parameters of Borçka are shown in Appendix-B RESCON Inputs and Results of Borçka Dam.

As a consequence of optimization of Borçka Dam, the highest net aggregate benefit is gained by using Flushing Method. The highest net aggregate benefit is 4,825,000,000 $, which is calculated for 300 years perpetuity assumption.

If the characteristics of Borçka Dam are considered, the flushing method solution is the most appropriate method. Borçka Dam has very high water inflow capacity and also it has very high sediment inflow capacity. In addition, the elevation of Borçka Dam is significantly high. Because of these characteristics it will be very difficult to remove deposited sediment by dredging method or HSRS method. Moreover, the program already warns about dredging, trucking and HSRS. These results actually show that RESCON can be used for Dams in Turkey. Therefore the most feasible sediment removal system can be decided at the planning stage.

The most feasible method Flushing characteristics, also all methods analysis, can be followed from Tables in Appendix-B. For example, the long term capacity for flushing is 209,895,362 $m^3$, can be seen from Table B.7 and Phase-I length of flushing and number of flushing events in Phase-I are 55 years and 9 times, respectively.

The sediment removed in Phase-I is 21,330,291 $m^3$, on the other hand the sediment removed in Phase-II is 14,788,981 $m^3$. The removed sediment values are different since the long term capacity is smaller than reservoir capacity.

Although the Borçka Dam has not been designed considering the Flushing method, according to the RESCON results Flushing can be used by using existing sluiceway. Therefore the Flushing sediment removal operation can be integrated to the existing system of Borçka Dam.

As is mentioned, Borçka Dam is one of the completed projects within the scope of Çoruh Basin Project. The completed and planned projects can be seen in below, Figure 4.4. In the future, when the planned projects of Çoruh Basin Project will be completed, the total incoming sediment to the Borçka Dam will be decreased. As a result the computed flushing results will change so that the removal of sediment every fifth years by Flushing may be sufficient. Therefore, when the Çoruh Basin Project completed, an integrated sediment management should be performed for the entire basin.

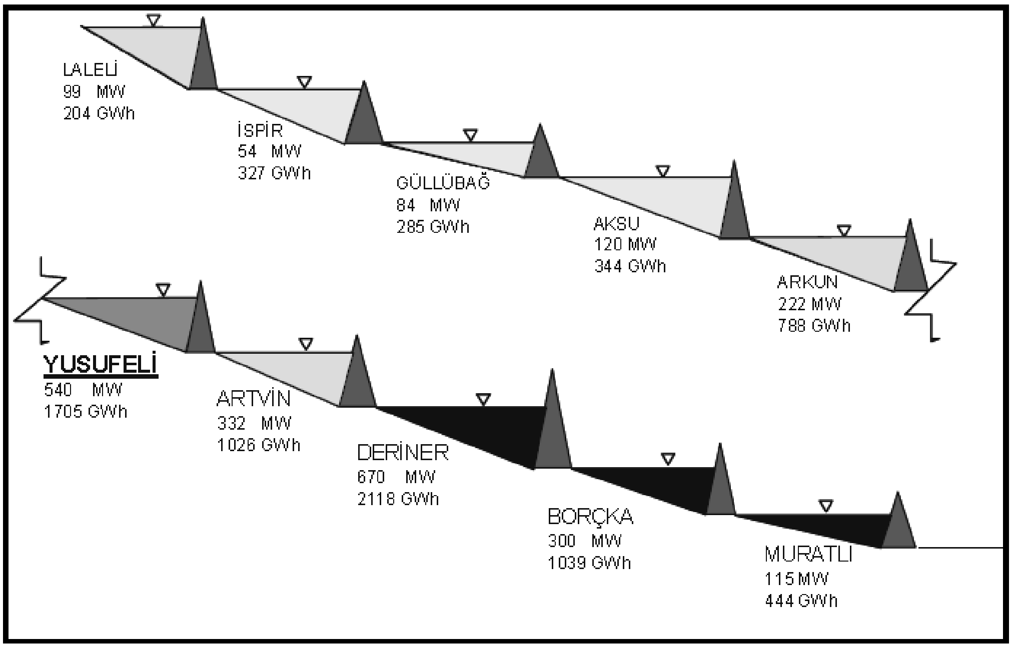



Figure 4.4 Completed and Planned Projects in Çoruh Basin

## 4.5. Muratlı Dam

Muratlı Dam is also one of the Çoruh Basin Projects like Borçka Dam. Muratlı Dam is located on Çoruh River in Lower Çoruh Basin. The dam site is nearly 17 km downstream of Borçka Town, 2 km upstream of Muratlı Town and 44 km northwest of Artvin City.

The purpose of Muratlı Dam is hydroelectric power generation. The installed capacity is 115 MW and the annual energy generation is 444.12 GWh.

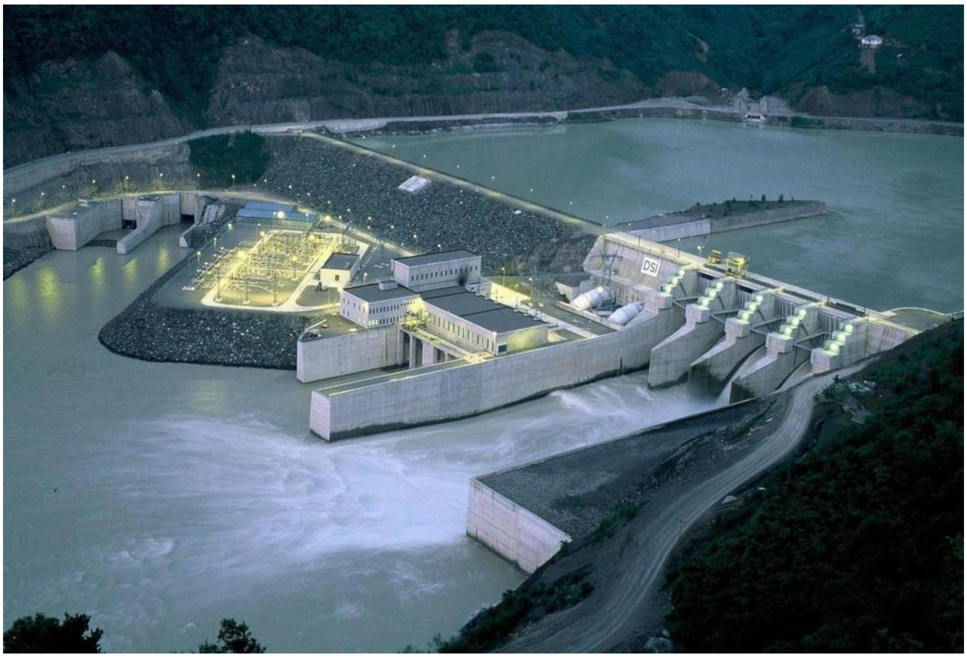


Figure 4.5 A view from Muratlı Dam

Main characteristics of Muratlı Dam are given in Table 4.3 below.

**Table 4.3 Main Characteristics of Muratlı Dam**

| | |
|---|---|
| Reservoir Data | |
| Maximum flood water level | 98.00 m |
| Maximum operation water level | 96.00 m |
| Minimum operation water level | 91.00 m |
| Thalweg elevation | 56.00 m |
| Total storage capacity | 74.80 $hm^3$ |
| Active storage capacity | 19.94 $hm^3$ |
| Dead storage capacity | 54.86 $hm^3$ |
| Reservoir maximum surface area (at elev.185) | 4.115 $km^2$ |
| Reservoir length | 18.00 km |
| Dam characteristics | |
| Type | Rock fill with asphalt lining on the upstream face |
| Crest elevation | 100.00 m |
| Height above thalweg | 44.00 m |
| Embankment crest length | 240.00 m |
| Crest Length including concrete structures | 438.00 m |
| Crest width | 10.00 m |
| Total embankment volume | 1,981,000 $m^3$ |
| Diversion Facilities | |
| Number of diversion tunnels | 2 |
| Cross section type | Horseshoe |
| Inside diameter | 10.00 m |
| Length (No.1) | 300.65 m |
| Length (No.2) | 364.00 m |
| Diversion capacity | 1,725.00 $m^3$/sec |
| Inlet bottom elevation | 59.50 m |
| Outlet bottom elevation | 58.20 m |

**Table 4.3 Main Characteristics of Muratlı Dam (continued)**

| | |
|---|---|
| Crest elevation of upstream cofferdam | 72.50 m |
| Crest elevation of downstream cofferdam | 66.00 m |
| Spillway | |
| Type | Overflow-controlled |
| Type of energy dissipation | Stilling basin |
| Sill elevation | 79.00 m |
| Design discharge | 10.961 m³/sec |
| Reservoir elev. at design discharge | 98.00 m |
| Number of gate | 4 |
| Type of gates | Tainter gates |
| Dimension of gates (V/H) | 18.00 m/ 16.00 m |
| Bottom Outlet | |
| Location | 1. Diversion tunnel |
| Number of bottom outlet | 1 |
| Maximum capacity | 250.0 m³/sec |
| Type of bottom outlet gates | Slide gates |
| Dimension of gates (V/H) | 3.00 m/ 2.05 m |
| Energy Generation Structures | |
| Water Intake Structure | |
| Type | Concrete Gravity |
| Number | 2 |
| Approach channel elevation | 75.00 m |
| Water intake axis elevation | 79.75 m |
| Service gate type | Slide gate |
| Dimensions of service gate (V/H) | 5.90 m/7.50 m |
| Crest Elevation | 100.00 m |
| Reservoir maximum operating level | 96.00 m |
| Reservoir minimum operating level | 91.00 m |

**Table 4.3 Main Characteristics of Muratlı Dam (continued)**

| | |
|---|---|
| Penstock | |
| Type | Partly exposed |
| Number | 2 |
| Inner diameter | 7.50 m |
| Length | 90.60 m |
| Switchyard | |
| Type | Outdoor |
| Inlet line voltage and number | 154 kV,2 |
| Outlet line voltage and number | 154 kV,2 |
| Powerhouse | |
| Type | Indoor |
| Number of units | 2 |
| Continuous power | 28.90 MW |
| Installed capacity | 115 MW |
| Continuous energy | 253.34 GWh |
| Secondary energy | 190.78 GWh |
| Total Energy | 444.12 GWh |
| Load factor | 0.44 |
| Type of inlet valve | Butterfly valve |
| Inner diameter of inlet valve | 5.60 m |
| Turbine type | Vertical shaft Francis |
| Turbine axis elevation | 56.00 m |
| Total head | 37.00 m |
| Net head (at operation of one unit) | 36.04 m |
| Maximum discharge | 180.78 $m^3$/sec |
| Velocity | 111 rev/min |
| Generator type | Vertical shaft synchronous |
| Voltage between phases | 13.8 kV |
| Frequency | 50 Hz |

### 4.5.1. Muratlı Dam RESCON Results & Comments

RESCON optimization results by using Technical and Economical Parameters of Muratlı Dam are shown in Appendix-C RESCON Inputs and Results of Muratlı Dam.

Similar to the Borçka Dam results, Muratlı Dam RESCON results show that the highest net aggregate benefit is gained by using Flushing Method. This is an expected result because Borçka Dam and Muratlı Dam are both located on the Çoruh River. In addition, although Muratlı Dam is the last downstream project in Çoruh Basin Project, it is the first constructed one, it is endangered to be filled by sediment.

Similar to the Borçka Dam, Flushing management technique should be integrated to existing system of Muratlı Dam. The sedimentation problem in Muratlı Dam could be overcome by Flushing.

## 4.6. Sensitivity Analyses

In order to distinguish the most critical input values of RESCON, some parameters are changed and then the program run in many instances. Borçka Dam Case study is used for sensitivity analyses. The basic parameters used in these sensitivity analyses are:

- Unit Benefit of Reservoir : P1
- Discount Rate : r
- Market Interest Rate : Mr
- Salvage Value: V

#### 4.6.1. Unit Value of the Reservoir Yield

In order to see how the results are affected by the changing of user input parameters, some of the important parameters are analyzed. One of them is Unit value of the reservoir yield, which directly affects the Aggregate Net Benefit.

The Unit Reservoir Yield of Borçka Dam is 0.16 $/m$^3$ ± 5 %. The change of Aggregate Net Benefit is shown in Table 4.4.

The results show that the estimation of the water yield is an important parameter in the calculated aggregate benefit. As the unit value of reservoir yield increases, the total net benefit increases, too.

**Table 4.4 Results of Unit Value of Reservoir Yield Change from 0.11 $/m3 to 0.22 $/m3**

| | | Aggregate Net Present Value ($) | | | | | |
|---|---|---|---|---|---|---|---|
| | Water Yield ($/m3) | 0.11 | 0.13 | 0.15 | 0.18 | 0.20 | 0.22 |
| **Possible Strategies** | **Technique** | | | | | | |
| Do nothing | N/A | 4.76352E+09 | 5.67639E+09 | 6.58926E+09 | 7.95856E+09 | 8.87142E+09 | 9.78429E+09 |
| Nonsustainable (Decommissioning) with Partial Removal | HSRS | 4.76342E+09 | 5.67635E+09 | 6.58927E+09 | 7.95865E+09 | 8.87158E+09 | 9.78450E+09 |
| Nonsustainable (Run-of-River) with No Removal | N/A | 4.76633E+09 | 5.67971E+09 | 6.59310E+09 | 7.96318E+09 | 8.87656E+09 | 9.78995E+09 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | 4.76623E+09 | 5.67967E+09 | 6.59311E+09 | 7.96328E+09 | 8.87672E+09 | 9.79016E+09 |
| Sustainable | Flushing | 4.82466E+09 | 5.74888E+09 | 6.67310E+09 | 8.05943E+09 | 8.98364E+09 | 9.90786E+09 |
| Sustainable | HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS |
| Sustainable | Dredging | 4.77203E+09 | 5.68996E+09 | 6.60849E+09 | 7.98734E+09 | 8.90722E+09 | 9.82764E+09 |
| Sustainable | Trucking | 4.78819E+09 | 5.70916E+09 | 6.63089E+09 | 8.01437E+09 | 8.93704E+09 | 9.85992E+09 |

According to the Turkish law, water is the property of the public; it is not a tradable good. However the price of the service can be changed. Therefore estimation of the water value is a quite speculative topic. Here we estimate the price of water according to the EPDK. On the other for Çubuk Dam-I the price of water estimated according to the available application of the city of the Ankara. Even the water can be served with free of charge. Thus the NPV values should not be taken as a profit but the burden to the state.

However, if one compares different management techniques the program results can be safely used.

Moreover, the changes of unit value of reservoir yield may affect the parameters below,

- Long term reservoir capacity for dredging
- Long term reservoir capacity for trucking
- Approximate # of years until dam is sustained at long term capacity for Dredging
- Approximate # of years until dam is sustained at long term capacity for Trucking
- Removal frequencies of dredging
- Removal frequencies of trucking
- Sediment Removed per event of trucking
- Optimal values of ASD/AST and CLF/CLD/CLT of dredging
- Optimal values of ASD/AST and CLF/CLD/CLT of trucking
- Number of Truck Loads Required to Complete Sustainable Sediment Trucking Removal Option

These parameters are computed by RESCON; changes in these parameters are negligible and do not change the suggested best method.

#### 4.6.2. Discount Rate

The original value of discount rate used in Borçka Dam Case Study is 0.10. However, different values are studied which are from 0.0000001 to 0.12 in order to see how the results change. The range of the discount rate is very high since aggregate net benefit is very sensitive to the discount rate.

**Table 4.5 Results of Discount Rate Change from 0.0000001 to 0.12**

| | | Aggregate Net Present Value ($) | | | | | |
|---|---|---|---|---|---|---|---|
| | **Discount rate** | **0.0000001** | **0.00001** | **0.001** | **0.10** | **0.11** | **0.12** |
| **Possible Strategies** | **Technique** | | | | | | |
| Do nothing | N/A | 3.16470E+10 | 3.16392E+10 | 3.08736E+10 | 6.58926E+09 | 6.01267E+09 | 5.52258E+09 |
| Nonsustainable (Decommissioning) with Partial Removal | HSRS | 3.16755E+10 | 3.16677E+10 | 3.09007E+10 | 6.58927E+09 | 6.01258E+09 | 5.52243E+09 |
| Nonsustainable (Run-of-River) with No Removal | N/A | 7.84671E+14 | 7.87370E+12 | 1.05081E+11 | 6.59310E+09 | 6.01478E+09 | 5.52376E+09 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | 7.84671E+14 | 7.87373E+12 | 1.05108E+11 | 6.59311E+09 | 6.01469E+09 | 5.52360E+09 |
| Sustainable | Flushing | 5.88623E+15 | 5.88744E+13 | 5.99953E+11 | 6.67310E+09 | 6.05994E+09 | 5.54904E+09 |
| Sustainable | HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS |
| Sustainable | Dredging | 5.95557E+15 | 5.95555E+13 | 5.95442E+11 | 6.60849E+09 | 6.02272E+09 | 5.52790E+09 |
| Sustainable | Trucking | 6.26783E+15 | 6.26789E+13 | 6.27349E+11 | 6.63089E+09 | 6.03504E+09 | 5.53473E+09 |

Discount rate affects the aggregate net benefit results but it does not change the best solution. If the discount rate decreases the aggregate net benefit will increases drastically and therefore the differences between the methods can be noticed but the best solution does not change. On the other hand, the discount rate is a different specialty and should be evaluated by experts on economics. It should be noted that the net aggregate benefits should not be interpreted as the profit of the investor.

### 4.6.3. Market Interest Rate

In the economic optimization framework of RESCON, market interest rate is used only for the calculation of retirement fund of non sustainable options. Therefore, change in market interest rate does not affect the aggregate net benefits and the best solution. The change of retirement funds is shown in Table 4.6.

According to the sensitivity analyses if market interest rate increases, the retirement fund for non sustainable options decreases. For example, in order to save the salvage value, the retirement fund is 4794 $ and 7248 $ for 0.11 and 0.10 market interest rate respectively. It is an anticipated result from the economical point of view. Since the present value of money is more valuable if the market interest rate is high.

**Table 4.6 Results of Market Interest Rate Change from 0.08 to 0.13**

| | Annual Retirement Fund | | | | | |
|---|---|---|---|---|---|---|
| **Market Interest Rate (decimal)** | **0.08** | **0.09** | **0.10** | **0.11** | **0.12** | **0.13** |
| **Possible Strategies** | | | | | | |
| Do Nothing | 16,343 | 10,913 | 7,248 | 4,794 | 3,161 | 2,080 |
| Nonsustainable (Decommissioning) with Partial Removal | 16,343 | 10,913 | 7,248 | 4,794 | 3,161 | 2,080 |

### 4.6.4. Salvage Value

Salvage Value is an important parameter for non-sustainable alternatives, because the annual retirement fund is directly affected by salvage value. From the sensitivity analyses of salvage value, it is obviously observed that if the salvage value increases the annual retirement fund will increase. In addition there will be some changes in Aggregate Net Benefit of non-sustainable alternatives but these are negligible. Related sensitivity analyzes results shown in Table 4.7.

**Table 4.7 Results of Salvage Value Change from 5.000.000 $ to 30.000.000 $**

| | Annual Retirement Fund | | | | | |
|---|---|---|---|---|---|---|
| **Salvage Value ($)** | **5,000,000** | **10,000,000** | **15,000,000** | **20,000,000** | **25,000,000** | **30,000,000** |
| **Possible Strategies** | | | | | | |
| Do Nothing | 2,416 | 4,832 | 7,248 | 9,663 | 12,079 | 14,495 |
| Nonsustainable (Decommissioning) with Partial Removal | 2,416 | 4,832 | 7,248 | 9,663 | 12,079 | 14,495 |

## 4.7. Discussions about RESCON Input Values

### 4.7.1. Unit Benefit of Reservoir Yield (P1)

Unit Benefit of Reservoir Yield depends on purpose of the dam. The dam may be used for the purposes of municipal, irrigation or energy production. Therefore the unit value of the water has shown differences. In addition, the country and even the region is also affect the water value. Because of these reasons, P1 should be calculated separately for each dam and then put in RESCON.

Since Çubuk Dam-1 is used only for domestic purposes, P1 is obtained from ASKİ 06.03.2008 dated Water and Wastewater Tariff.

On the other hand, for hydropower dams it is very difficult to define P1. The P1 value should be put in RESCON as a unit of $/m$^3$. However, in practice the P1 value of hydropower dams has a different unit; the market prefers a unit of $/kWh. Therefore, this unit should be converted to unit $/m$^3$ for RESCON usage. In this study, according to reservoir inflow and total head the P1 value is calculated for Borçka Dam and Muratlı Dam separately. P1 is taken as 9.67 Ykr/kWh according to the EPDK (Energy Market Regularity Authority). The converting formula for Borçka Dam is given below:

Power = 9.81 x Q x h x n

where;

Q: reservoir inflow (m$^3$/s)

n: efficiency

h: total head (operation level – turbine axis elevation)

Turbine axis elevation: 92m

Maximum operation water level: 185 m

Minimum operation water level:  170 m

The installed capacity of 300 MW is taken as power value. The reservoir inflow is calculated from the mean annual reservoir inflow 5.66 x 10$^9$ m$^3$, that Q is 180m$^3$/s. Efficiency for both turbine and generator, is approximately 0.9. The total head is not a constant value. Although, the turbine axis elevation does not change, the operation level changes between 185 m and 170 m. Therefore the total head changes between 93m to 78m. As a consequence, the operation level is taken as 185 m and so that the total head is calculated as 93m. By the way, it is assumed that the dam works under the full performance condition such that all coming flow is used for energy production.

The benefit gained from the generated power = 300 x 1000 x 9.67 = 2 901 000 Ykr

This power is generated with a 180m$^3$/s water flow through 93m head.

Thus the flow of 180m$^3$/s for this reservoir makes 2,901,000 Ykr money. Then the unit benefit gained from per m$^3$ of water is 19.5 Ykr / m$^3$.

The parity rate is taken as 1.4 according to the DSI unit prices, therefore P1 ≈ 14 Cent/m$^3$ = 0.14 \$/m$^3$

Although, the market energy value is taken as 9.67 Ykr according to the EPDK, it is subject to change and volatile. The electric market operation system is shown schematically below; it is a complex system. That is why it is very difficult to come up with an exact energy value; it is an exchange commodity. For example, the energy value of TEDAŞ is 23 Ykr / kWh. However, the independent producer might be agreed with customer on 21 YKr /kWh. In another case is that the firms might produce their own energy and sell the remaining to the TETAŞ, that there may be a special contract between them about selling price. Because of this complexity the value of EPDK, the most confident value is used.

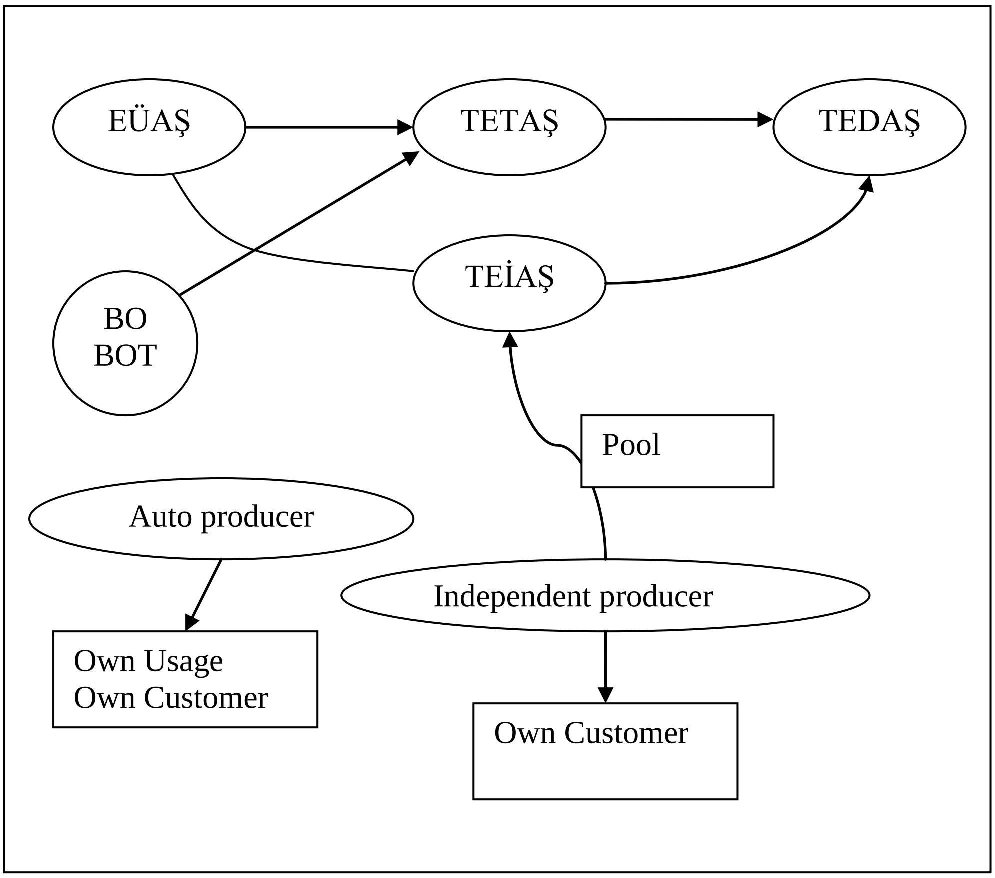



Figure 4.6 Energy Productions and Sale Relation

4.7.2. Total Cost of Dam Construction

According to the economic optimization framework of RESCON, the program automatically calculates the total cost of dam construction, C2. For example, since Borçka Dam reservoir capacity is smaller than 500,000,000 $m^3$, program automatically calculates C2 by using below formula:

c = 3.5 – 0.53 * LN (So/1000000) = 125,674,606 $

However, the total cost of dam construction is known as 233,829,318 $.

This study aims to examine the plausibility of the practical usage of RESCON for Turkey's conditions. Coming from this approach, sometimes the necessary modifications has been done in the program. In order to obtain the approximate C2 value for Borçka Dam, the formula has been changed as following:

$$c = 3.5 – 0.487 * LN (So/1000000) = 234.452.874 \$$$

The formula above is definitely valid only for Borçka Dam. However, if there were a database for the cost of dam construction in Turkey, a general modification could have been done to make a major contribution to RESCON. Therefore, the cost of dam construction in Turkey should be immediately analyzed in further academic works.

#### 4.7.3. Salvage Value

Since decommissioning of a dam is not a common execution in the world the estimation of the salvage value is not defined exactly in the literature. There are some researches and papers, but not definite calculation procedure. Therefore, as salvage value the expropriation value is used in this study.

# CHAPTER 5

# CONCLUSION

Reservoir sedimentation is a very serious problem for Dams in Turkey. However, sometimes this problem is not taken into consideration by designers and also investors. Therefore, reservoir sedimentation should be emphasized and sedimentation management techniques should be studied in depth for Turkey conditions.

In this study, the importance of the sediment problem in the World and especially in Turkey is mentioned. In addition the techniques to get sustainable development of basin water storage capacity are discussed in detail. They are defined under three category; the techniques preventing sediment inflow into the reservoir, the techniques for sustainable management of reservoir and lost storage replacement techniques, and decommissioning of dams. The sediment evacuation methods from a reservoir are discussed under the heading of sustainable management of reservoir. The methods include flushing, sluicing, density current venting and mechanical removal techniques comprising of; dredging, hydrosuction removal system and trucking.

The program RESCON has been run for three reservoirs; which are Çubuk Dam-I, Borçka Dam and Muratlı Dam, in order to examine the applicability of the program for Turkey. The program analyzes flushing, dredging, trucking and hydrosuction removal system techniques economically and hydraulically.

The following conclusions are obtained based in the output of the RESCON analyzes.

1. The Çubuk Dam: The sediment in the dam already filled and non-operating can be evacuated by HSRS method.
2. The Borçka and Muratlı Dam: These are new dams and they are the components of the Çoruh Basin Project. Nevertheless, they are endangered with sedimentation problem because of significant amount of incoming sediment load of Çoruh Basin which are located at the most downstream of the river. The expectation of the executive agency is that their sediment load will be decreased after the completion of upstream dams of Çoruh Basin Project, especially the Deriner Dam. However the realization of this expectation is within the frame of the design life approach. The conservation of the delta is not considered. However, the results of the RESCON for Borçka Dam and Muratlı Dam show that the flushing is a feasible method. Although the dams were not designed taking the sediment management techniques into account, their existing facilities are appropriate to flush the sediment.
3. Nevertheless, after the completion of Çoruh Basin Project, analysis should be revised in order to facilitate an integrated sediment management technique for all branches.

The following conclusions can be derived for the utility of RESCON program.

1. The results of technical calculation of the RESCON can be safely used. The technical results of the RESCON are well understood within the scope of the study.
2. RESCON is a practical tool especially at pre-feasibility level to decide which sediment removal technique is economically feasible. However, in order to get the net profit values, the discount rate and the unit value of the water should be evaluated by experts on economics.

Furthermore, the lack of information in the area of the salvage value estimation seems to be a draws.

3. Although this program is launched at 2003, the literature available so far is not enough to have a database for the input parameters.

# REFERENCES

***Annandale, G.W.,*** Engineering and Hydrosystems Inc., Personal Communication, 2008.

***Atkinson, E.,*** The Feasibility of Flushing Sediment from Reservoirs. TDR Project R5839, Report OD 137, HR Wallingford, November 1996.

***Basson, G.,*** Hydropower Dams and Fluvial Morphological Impacts – An African Perspective, United Nations Symposium on Hydropower and Sustainable Development, Beijing International Convention Centre, Beijing, China, United Nations Dept. of Economics and Social Affairs 2004: 1-16.

***Basson, G., Rooseboom, A.,*** Dealing with Reservoir Sedimentation, Water Research Commission, South Africa, December 1997.

***Çetinkaya, O.K.,*** Management of Reservoir Sedimentation Case Studies from Turkey, M. Sc. Thesis, Middle East Technical University, 2006.

***Dedekli, N.B.,*** MNG Holding, Personal Communication, 2008.

***Fan, J., Morris, G.L.,*** Reservoir Sedimentation I: Delta and Density Current Deposits, Journal of Hydraulic Engineering, Vol. 118, No: 3, 1992.

***Fan, J., Morris, G.L.,*** Reservoir Sedimentation II: Reservoir Desiltation and Long-term Storage Capacity, Journal of Hydraulic Engineering, Vol. 118, And No:3, 1992.

***Fakıoğlu, M.,*** Seyhan Barajı Hidrografik Harita Alımı Değerlendirmesi ve Sonuçları, Harita ve Kadastro Mühendisleri Odası, Mühendislik Ölçmeleri STB Komisyonu, 2. Mühendislik Ölçmeleri Sempozyumu, ITU, Istanbul, 23 – 25 Kasım 2005.

***Güler, I., Drama, Y. and Kökpınar, M.A.,*** Kızılırmak Ağzı Kıyı Çizgisi Değişimi, 4. Kıyı Mühendisliği Ulusal Sempozyumu Bildiriler Kitabı, Cilt:2, s. 713-730, Antalya, 2002.

***Hotchkiss, R.H., Huang, X.,*** Hydrosuction Sediment-Removal Systems (HSRS): Principles and Field Test, Journal of Hydraulic Research, pp. 479-489, June 1995.

***Howard, C.D.D.,*** Operations, Monitoring and Decommissioning of Dams, Thematic Review IV.5 prepared for the World Commission of Dams, Cape Town, March 2000.

***Huffaker, R., Hotchkiss, R.,*** Economic Dynamics of Reservoir Sedimentation management: Optimal Control with Singularly Perturbed Equation of Motion, Journal of Economic Dynamics & Control 30 (2006) 2553 - 2575.

***Isik, S., Sasal, M., and Dogan, E.,*** Investigation on Downstream Effects of Dams in the Sakarya River, J. of Fac. Eng. Arc. Gazi University, Vol. 21, No:3, pp. 401 – 408, 2006.

***Kawashima, S., Johndrow, T.B., Annandale, G.W., Shah, F.,*** Reservoir Conservation, Volume-II: RESCON Model and User Manual, The World Bank, June 2003.

***Kılıç, R,*** Çubuk I (Ankara) Baraj Gölünde Depolanan Sedimentlerin Sedimentolojisi ve Mineralojisi, Gazi Üniversitesi, Cilt 1, No 1, 97-112, 1986.

***Kokpinar, M.A., Guler, I., Darama, Y.,*** Bafra Ovası Kizilirmak-Karadeniz Birleşimindeki Kıyı Erozyonunun İncelenmesi. III. Ulusal Kıyı Mühendisliği Sempozyumu, s. 507-524, Çanakkale, 2000.

***Komuscu, A.U, Erkan, A., Turgu E.,*** Normalleştirilmiş Yağış Indeksi Metodu (SPI) ile Türkiye'de Kuraklık Oluşumunun Coğrafik Analizi, 2005.

***Liu, J., Liu, B., Ashida, K.,*** Reservoir Sedimentation Management in Asia, Fifth International Conference on. Hydro-Science and Engineering, ICHE, September 18-21, Warsaw, Poland, pp:1-10, 2002

***Ludwig, W.,*** River Inputs to the Mediterranean Sea, http://www.cnrm.meteo.fr/hymex/global/documents/Presentations_janvier_2007/Session_E/Rivers_input_Ludwig_Wolfgang.pdf , last accessed date May 2009

***Mahmood, K.,*** Reservoir Sedimentation: Impact, Extent and Mitigation, World Bank Technical Paper Number 71, Washington, D.C., September 1987.

***Morris, G.L. and Fan, J.,*** Reservoir Sedimentation Handbook, McGraw-Hill, New York, 1997.

***Palmieri, A., Shah, F., Annandale, G.W., Dinar, A.,*** Reservoir Conservation, Volume-I: The RESCON Approach, The World Bank, June 2003.

***Poulos, S.E., Collins M.B.,*** Fluviatile Sediment Fluxes to the Mediterranean Sea: a quantitative approach and the influence of dams, Geology Society Special Publications, London, UK, Geological Society of London, V.191, p.227-245, 2002.

***Sönmez, B., Dinçsoy, Y.,*** Konya-Ereğli İvriz Barajı Erozyon ve Rüsubat Kontrolu Planlama Raporu, State Hydraulic Works, Ankara, 2002.

***Turner, T.M.,*** Fundamentals of Hydraulic Egineering, American Society of Civil Engineers, 2nd Ed., New York, 1996.

***Ural, O.M., Ungan, Ü.,*** Large Dams in Turkey, The General Directorate of State Hydraulic Works Ministry of Power and Natural Sources, August 1967.

***White, W.R.,*** Contributing Paper: Flushing of Sediments from Reservoirs, prepared for Thematic Review IV.5: Operations, Monitoring and Decommissioning of Dams, HR Wallingford, UK, 2000.

***Yalçınkaya, F.,*** Reservoir Sedimentation in Turkey, M.Sc. Thesis, Middle East Technical University, 1991.

***Yılmaz, C.,*** Kızılırmak Deltasında Meydana Gelen Erozyonun Coğrafi Analizi, Türkiye Kuvaterner Sempozyumu, s. 227-234, 2005.

***Yılmaz, Ş.,*** Prediction of Reservoir Siltation: Theory and Practice, 34th International Post-Graduate Course on Hydrology, Hungary, 2003.

**APPENDIX A**

**RESCON USER INPUTS AND RESULTS OF CUBUK DAM-I**

**Table A.1 User Input Pages of Cubuk Dam-I**

| **Reservoir Geometry** | | |
|---|---|---|
| **Parameter** | **Units** | **Value** |
| $S_0$ | ($m^3$) | 7,100,000 |
| $S_e$ | ($m^3$) | 3,550,000 |
| $W_{bot}$ | (m) | 57.0 |
| $SS_{res}$ | - | 1.0 |
| $EL_{max}$ | (m) | 907.6 |
| $EL_{min}$ | (m) | 882.6 |
| $EL_f$ | (m) | 895 |
| L | (m) | 6500 |
| h | (m) | 25.0 |
| **Water Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $V_{in}$ | ($m^3$) | 28,000,000 |
| $C_v$ | ($m^3$) | 0.1 |
| T | ($^oC$) | 10.0 |
| **Sediment Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $\rho_d$ | ($tones/m^3$) | 1.80 |
| $M_{in}$ | (metric tones) | 81,000 |
| $\Psi$ | | 180 |
| Brune Curve No | | 3 |

**Table A.1 User Input Pages of Çubuk Dam-I (continued)**

| | | |
|---|---|---|
| Ans | - | 3 |
| Type | - | 1 |
| **Removal Parameters** | | |
| **Parameter** | **Units** | **Value** |
| HP | - | 2 |
| $Q_f$ | ($m^3/s$) | 27 |
| $T_f$ | (days) | 5 |
| N | (years) | 1 |
| D | (feet) | 4.0 |
| NP | - | 3 |
| YA | - | 0.1 |
| CLF | (%) | 60 |
| CLH | (%) | 60 |
| CLD | (%) | 60 |
| CLT | (%) | 60 |
| ASD | (%) | 90 |
| AST | (%) | 90 |
| MD | ($m^3$) | 1,000,000 |
| MT | ($m^3$) | 3,600,000 |
| $C_w$ | (%) | 30 |
| **Economic Parameters** | | |
| **Parameter** | **Units** | **Value** |
| E | - | 0 |
| C | ($\$/m^3$) | 2.46 |
| C2 | ($) | 0 |
| R | (decimal) | 0.1 |
| Mr | (decimal) | 0.1 |
| P1 | ($\$/m^3$) | 0.93 |

**Table A.1 User Input Pages of Çubuk Dam-I (continued)**

| | | |
|---|---|---|
| V | ($) | 4,500,000 |
| omc | - | 0.01 |
| PH | | 0.001 |
| PD | | 0.001 |
| CD | ($/m$^3$) | 15.00 |
| CT | ($/m$^3$) | 4.00 |
| **Flushing Benefits Parameters** | | |
| s1 | (decimal) | 0.9 |
| s2 | (decimal) | 0.9 |
| **Capital Investment** | | |
| FI | ($) | 2,000,000 |
| HI | ($) | 1,000,000 |
| DU | (years) | 10 |

## Economic Results and Conclusions for Çubuk Dam-I

**Table A.2 Economic Results Summary of Çubuk Dam I**

| Possible Strategies | Technique | Aggregate Net Present Value |
|---|---|---|
| Do nothing | N/A | 230,041,523.91 |
| Nonsustainable (Decommissioning) with Partial Removal | HSRS | Partial Removal with HSRS is technically infeasible, See Total Removal with HSRS |
| Nonsustainable (Run-of-River) with No Removal | N/A | 230,042,358.29 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | Partial Removal with HSRS is technically infeasible, See Total Removal with HSRS |
| Sustainable | Flushing | 228,657,260.45 |
| Sustainable | HSRS | 231,507,568.02 |
| Sustainable | Dredging | 229,440,860.27 |
| Sustainable | Trucking | 227,412,020.74 |

**Table A.3 Economic Conclusion of Çubuk Dam I**

| | |
|---|---|
| Strategy yielding the highest aggregate net benefit: | Sustainable |
| Technique yielding the highest aggregate net benefit: | HSRS |
| The highest aggregate net benefit is: $ | 2.315E+08 |

Nonsustainable Alternatives

**Table A.4 Nonsustainable (Decommissioning) Alternatives Details of Çubuk Dam-I**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | Not applicable | years |
| # of years until retirement for Decommission-with No Removal Option: | 85 | years |
| # of years until retirement for Decommission: Partial Removal Option with HSRS: | Not applicable | years |
| Remaining reservoir capacity at retirement for Decommission-with No Removal Option: | 5,068 | $m^3$ |
| Remaining reservoir capacity at retirement for Decommission: Partial Removal Option with HSRS: | Not applicable | $m^3$ |

**Table A.5 Annual Retirement Funds for Decommissioning for Nonsustainable (Decommissioning) Alternatives of Çubuk Dam-I**

| | | |
|---|---|---|
| Annual Retirement Fund Payment for nonsustainable options: Decommission | 136 | $ |
| Annual Retirement Fund Payment for nonsustainable options: Partial Removal with HSRS | Not applicable | $ |

**Table A.6 Nonsustainable (Run-off River) Alternatives Details of Çubuk Dam-I**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | Not applicable | years |
| Approximate # of years until dam is silted for Run-of-River-with No Removal Option: | 86 | years |
| Approximate # of years until dam is silted for Run-of-River-with Partial Removal Option: | Not applicable | years |

Sustainable Alternatives

**Table A.7 Long Term Capacities of Sustainable Alternatives of Çubuk Dam-I**

| | | |
|---|---|---|
| Long term reservoir capacity for Flushing | 2,957,561 | $m^3$ |
| Long term reservoir capacity for HSRS | 3,550,000 | $m^3$ |
| Long term reservoir capacity for Dredging | 2,879,843 | $m^3$ |
| Long term reservoir capacity for Trucking | 5,200,929 | $m^3$ |

**Table A.8 Phase-I Lengths of Sustainable Alternatives of Çubuk Dam-I**

| | | |
|---|---|---|
| Approximate # of years until dam is sustained at long term capacity for Flushing | 19 | years |
| Approximate # of years until dam is sustained at long term capacity for HSRS | 1 | years |
| Approximate # of years until dam is sustained at long term capacity for Dredging | 17 | years |
| Approximate # of years until dam is sustained at long term capacity for Trucking | 17 | years |

**Table A.9 Times of Flushing Event in Phase-I**

| | | |
|---|---|---|
| Approximate # of Flushing events until dam is sustained at long term capacity | 0 | times |

**Table A.10 Removal Frequencies for Çubuk Dam-I**

| **Strategy** | **Technique** | **Cycle/Phase** | **Frequency of Removal (years)** |
|---|---|---|---|
| Nonsustainable-with Partial Removal | HSRS | Annual cycle | Not applicable |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | Not applicable |
| Sustainable | Flushing | Phase I | No Flushing occurs |
| Sustainable | Flushing | Phase II | 2 |
| Sustainable | HSRS | Annual cycle | 1 |
| Sustainable | Dredging | Phase I | 17 |
| Sustainable | Dredging | Phase II | 1 |
| Sustainable | Trucking | Phase I | 17 |
| Sustainable | Trucking | Phase II | 56 |

**Table A.11 Sediment Removed per event for Çubuk Dam-I**

| Strategy | Technique | Cycle/Phase | Sediment Removed ($m^3$) |
|---|---|---|---|
| Nonsustainable-with Partial Removal* | HSRS | Annual cycle | Not applicable |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | Not applicable |
| Sustainable | Flushing | Phase I | 0 |
| Sustainable | Flushing | Phase II | 84,403 |
| Sustainable | HSRS | Annual cycle | 42,202 |
| Sustainable | Dredging | Phase I | N/A |
| Sustainable | Dredging | Phase II | 42,202 |
| Sustainable | Trucking | Phase I | N/A |
| Sustainable | Trucking | Phase II | 2,363,288 |

**Table A.12 Optimal values of ASD/AST and CLF/CLD/CLT for Çubuk Dam-I**

| Technique | ASD/AST(%) | CLF/CLD/CLT |
|---|---|---|
| Flushing(Phase I) | N/A | 60 |
| Flushing(Phase II) | 2 | |
| HSRS | 1 | 50 |
| Dredging(Phase I) | N/A | 59 |
| Dredging(Phase II) | 1 | |
| Trucking(Phase I) | N/A | 59 |
| Trucking(Phase II) | 56 | |

**Table A.13 Technical Comments for Çubuk Dam-I**

| | | |
|---|---|---|
| Average expected concentration of sediment to water flushed per flushing event: | 19,417 | ppm |
| Average expected concentration of sediment to water released downstream of dam per hydrosuction event: | 478 | ppm |
| Average expected concentration of sediment to water removed from reservoir per dredging event: | 300,000 | ppm |
| Note: Because reservoir is dewatered prior to a trucking event and river is diverted during a trucking event, material removed is moist sediment (negligible water). | | |

**Table A.14 Number of Truck Loads* Required to Complete Sustainable Sediment Trucking Removal Option for Çubuk Dam-I**

| Truck Model Number | $m^3$/Truck Load | Number of Loads(Phase I) | Number of Loads(Phase II) |
|---|---|---|---|
| 769D | 16.2 | N/A | 145,882 |
| 771D | 18 | N/A | 131,294 |
| 773D | 26 | N/A | 90,896 |
| 775D | 31 | N/A | 76,235 |
| 777D | 42.1 | N/A | 56,135 |
| 785B | 57 | N/A | 41,461 |
| 789B | 73 | N/A | 32,374 |
| 793C | 96 | N/A | 24,618 |

*1997. Caterpillar Performance Handbook, Ed. 28. CAT Publication by Caterpillar Inc., Peoria, Illinois, USA. October 1997.

**Table A.15 Number of Dredges Required to Complete Sustainable Sediment Dredging Removal Option for Çubuk Dam-I**

| Volume Removed per Dredge ($m^3$/Dredge) | No. of Dredges (Phase I) | No. of Dredges (Phase II) |
|---|---|---|
| 11,000,000 | N/A | 1 |

**Table A.16 Unit Cost of Sediment Removal for Çubuk Dam-I**

| | Phase I | Phase II |
|---|---|---|
| **Unit Cost of Dredging($/m$^3$)** | N/A | 15.00 |
| **Unit Cost of HSRS($/m$^3$)** | 1.77 | |

## APPENDIX B

## RESCON USER INPUTS AND RESULTS OF BORÇKA DAM

### Table B.1 User Input Pages of Borcka Dam

| **Reservoir Geometry** | | |
|---|---|---|
| **Parameter** | **Units** | **Value** |
| $S_0$ | ($m^3$) | 418,980,000 |
| $S_e$ | ($m^3$) | 418,980,000 |
| $W_{bot}$ | (m) | 385.0 |
| $SS_{res}$ | - | 1.0 |
| $EL_{max}$ | (m) | 187 |
| $EL_{min}$ | (m) | 103 |
| $EL_f$ | (m) | 113 |
| L | (m) | 30,500 |
| h | (m) | 84.0 |
| **Water Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $V_{in}$ | ($m^3$) | 5,660,000,000 |
| $C_v$ | ($m^3$) | 0.1 |
| T | ($^oC$) | 10 |
| **Sediment Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $\rho_d$ | (tones/$m^3$) | 1.20 |
| $M_{in}$ | (metric tones) | 10,501,677 |
| $\Psi$ | - | 650 |
| Brune Curve No | - | 2 |

**Table B.1 User Input Pages of Borcka Dam (continued)**

| | | |
|---|---|---|
| Ans | - | 3 |
| Type | - | 1 |
| **Removal Parameters** | | |
| **Parameter** | **Units** | **Value** |
| HP | - | 1 |
| $Q_f$ | ($m^3$/s) | 287 |
| $T_f$ | (days) | 5 |
| N | (years) | 1 |
| D | (feet) | 4 |
| NP | - | 1 |
| YA | - | 0,3 |
| CLF | (%) | 100 |
| CLH | (%) | 100 |
| CLD | (%) | 100 |
| CLT | (%) | 100 |
| ASD | (%) | 100 |
| AST | (%) | 100 |
| MD | ($m^3$) | 1,000,000 |
| MT | ($m^3$) | 500,000 |
| $C_w$ | (%) | 30 |
| **Economic Parameters** | | |
| **Parameter** | **Units** | **Value** |
| E | - | 1 |
| C | ($/$m^3$) | 0.56 |
| C2 | ($) | 233,829,318.28 |
| R | (decimal) | 0.1 |
| Mr | (decimal) | 0.1 |
| P1 | ($/$m^3$) | 0.11 |

**Table B.1 User Input Pages of Borcka Dam (continued)**

| | | |
|---|---|---|
| V | ($) | 15,000,000 |
| omc | - | 0.01 |
| PH | ($/m$^3$) | 0.011 |
| PD | ($/m$^3$) | 0.011 |
| CD | ($/m$^3$) | 15.0 |
| CT | ($/m$^3$) | 4.0 |
| **Flushing Benefits Parameters** | | |
| s1 | (decimal) | 0.9 |
| s2 | (decimal) | 0.9 |
| **Capital Investment** | | |
| FI | ($) | 2,000,000 |
| HI | ($) | 1,000,000 |
| DU | (years) | 25 |

## Economic Results and Conclusions for Borcka Dam

**Table B.2 Economic Results Summary of Borcka Dam**

| Possible Strategies | Technique | Aggregate Net Present Value |
|---|---|---|
| Do nothing | N/A | 6,589,255,222 |
| Nonsustainable (Decommissioning) with Partial Removal | HSRS | 6,589,269,107 |
| Nonsustainable (Run-of-River) with No Removal | N/A | 6,593,100,308 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | 6,593,114,194 |
| Sustainable | Flushing | 6,673,099,060 |
| Sustainable | HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS |
| Sustainable | Dredging | 6,608,489,562 |
| Sustainable | Trucking | 6,630,887,998 |

**Table B.3 Economic Conclusion of Borcka Dam**

| | |
|---|---|
| Strategy yielding the highest aggregate net benefit: | Sustainable |
| Technique yielding the highest aggregate net benefit: | Flushing |
| The highest aggregate net benefit is: $ | 6.673E+09 |

Nonsustainable Alternatives

**Table B.4 Nonsustainable (Decommissioning) Alternatives Details of Borcka Dam**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | 1 | years |
| # of years until retirement for Decommission-with No Removal Option: | 56 | years |
| # of years until retirement for Decommission: Partial Removal Option with HSRS: | 56 | years |
| Remaining reservoir capacity at retirement for Decommission-with No Removal Option: | 4,888,529 | $m^3$ |
| Remaining reservoir capacity at retirement for Decommission: Partial Removal Option with HSRS: | 5,382,680 | $m^3$ |

**Table B.5 Annual Retirement Funds for Decommissioning for Nonsustainable (Decommissioning) Alternatives of Borcka Dam**

| | | |
|---|---|---|
| Annual Retirement Fund Payment for nonsustainable options: Decommission | 7,248 | $ |
| Annual Retirement Fund Payment for nonsustainable options:Partial Removal with HSRS | 7,248 | $ |

**Table B.6 Nonsustainable (Run-off River) Alternatives Details of Borcka Dam**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | 1 | years |
| Approximate # of years until dam is silted for Run-of-River-with No Removal Option: | 57 | years |
| Approximate # of years until dam is silted for Run-of-River-with Partial Removal Option: | 57 | years |

Sustainable Alternatives

**Table B.7 Long Term Capacities of Sustainable Alternatives of Borcka Dam**

| | | |
|---|---|---|
| Long term reservoir capacity for Flushing | 209,895,362 | $m^3$ |
| Long term reservoir capacity for HSRS | Not applicable | $m^3$ |
| Long term reservoir capacity for Dredging | 123,200,378 | $m^3$ |
| Long term reservoir capacity for Trucking | 411,585,509 | $m^3$ |

**Table B.8 Phase-I Lengths of Sustainable Alternatives of Borcka Dam**

| | | |
|---|---|---|
| Approximate # of years until dam is sustained at long term capacity for Flushing | 55 | years |
| Approximate # of years until dam is sustained at long term capacity for HSRS | Not applicable | years |
| Approximate # of years until dam is sustained at long term capacity for Dredging | 40 | years |
| Approximate # of years until dam is sustained at long term capacity for Trucking | 38 | years |

**Table B.9 Times of Flushing Event in Phase-I**

| | | |
|---|---|---|
| Approximate # of Flushing events until dam is sustained at long term capacity | 9 | times |

**Table B.10 Removal Frequencies Borcka Dam**

| **Strategy** | **Technique** | **Cycle/Phase** | **Frequency of Removal (years)** |
|---|---|---|---|
| Nonsustainable-with Partial Removal | HSRS | Annual cycle | 1 |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | 1 |
| Sustainable | Flushing | Phase I | 5 |
| Sustainable | Flushing | Phase II | 2 |
| Sustainable | HSRS | Annual cycle | Not applicable |
| Sustainable | Dredging | Phase I | 40 |
| Sustainable | Dredging | Phase II | 1 |
| Sustainable | Trucking | Phase I | 38 |
| Sustainable | Trucking | Phase II | 38 |

**Table B.11 Sediment Removed per event for Borcka Dam**

| Strategy | Technique | Cycle/Phase | Sediment Removed ($m^3$) |
|---|---|---|---|
| Nonsustainable-with Partial Removal* | HSRS | Annual cycle | 8,985 |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | 8,985 |
| Sustainable | Flushing | Phase I | 21,330,291 |
| Sustainable | Flushing | Phase II | 14,788,981 |
| Sustainable | HSRS | Annual cycle | Not applicable |
| Sustainable | Dredging | Phase I | N/A |
| Sustainable | Dredging | Phase II | 7,394,491 |
| Sustainable | Trucking | Phase I | N/A |
| Sustainable | Trucking | Phase II | 280,990,641 |

**Table B.12 Optimal values of ASD/AST and CLF/CLD/CLT for Borcka Dam**

| Technique | ASD/AST(%) | CLF/CLD/CLT |
|---|---|---|
| Flushing(Phase I) | Varies | 53 |
| Flushing(Phase II) | 7 | |
| HSRS | N/A | N/A |
| Dredging(Phase I) | N/A | 71 |
| Dredging(Phase II) | 2 | |
| Trucking(Phase I) | N/A | 67 |
| Trucking(Phase II) | 78 | |

**Table B.13 Technical Comments for Borcka Dam**

| | | |
|---|---|---|
| Average expected concentration of sediment to water flushed per flushing event: | 186,530 | ppm |
| Average expected concentration of sediment to water released downstream of dam per hydrosuction event: | 177 | ppm |
| Average expected concentration of sediment to water removed from reservoir per dredging event: | 300,000 | ppm |
| Note: Because reservoir is dewatered prior to a trucking event and river is diverted during a trucking event, material removed is moist sediment (negligible water). | | |

**Table B.14 Number of Truck Loads* Required to Complete Sustainable Sediment Trucking Removal Option for Borcka Dam**

| Truck Model Number | m3/Truck Load | Number of Loads(Phase I) | Number of Loads(Phase II) |
|---|---|---|---|
| 769D | 16.2 | N/A | 17,345,101 |
| 771D | 18 | N/A | 15,610,591 |
| 773D | 26 | N/A | 10,807,332 |
| 775D | 31 | N/A | 9,064,214 |
| 777D | 42.1 | N/A | 6,674,362 |
| 785B | 57 | N/A | 4,929,660 |
| 789B | 73 | N/A | 3,849,187 |
| 793C | 96 | N/A | 2,926,986 |

*1997. Caterpillar Performance Handbook, Ed. 28. CAT Publication by Caterpillar Inc., Peoria, Illinois, USA. October 1997.

**Table B.15 Number of Dredges Required to Complete Sustainable Sediment Dredging Removal Option for Borcka Dam**

| **Volume Removed per Dredge (m3/Dredge)** | **No. of Dredges (Phase I)** | **No. of Dredges (Phase II)** |
|---|---|---|
| 11,000,000 | N/A | 1 |

**Table B.16 Unit Cost of Sediment Removal for Borcka Dam**

| | Phase I | Phase II |
|---|---|---|
| **Unit Cost of Dredging($/m3)** | N/A | 15.00 |
| **Unit Cost of HSRS($/m3)** | 4.45 | |

## APPENDIX C –

## RESCON USER INPUTS AND RESULTS OF MURATLI DAM

### Table C.1 User Input Pages of Muratli Dam

| **Reservoir Geometry** | | |
|---|---|---|
| **Parameter** | **Units** | **Value** |
| $S_0$ | ($m^3$) | 74,800,000 |
| $S_e$ | ($m^3$) | 74,800,000 |
| $W_{bot}$ | (m) | 385.0 |
| $SS_{res}$ | - | 1.0 |
| $EL_{max}$ | (m) | 98.0 |
| $EL_{min}$ | (m) | 56.0 |
| $EL_f$ | (m) | 66 |
| L | (m) | 18,000 |
| h | (m) | 42.0 |
| **Water Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $V_{in}$ | ($m^3$) | 6,060,000,000 |
| $C_v$ | ($m^3$) | 0.1 |
| T | ($^oC$) | 10.0 |
| **Sediment Characteristics** | | |
| **Parameter** | **Units** | **Value** |
| $\rho_d$ | (tones/$m^3$) | 1.20 |
| $M_{in}$ | (metric tones) | 10,501,677 |
| Ψ | - | 650 |
| Brune Curve No | - | 2 |

**Table C.1 User Input Pages of Muratli Dam (continued)**

| | | |
|---|---|---|
| Ans | - | 3 |
| Type | - | 1 |
| **Removal Parameters** | | |
| **Parameter** | **Units** | **Value** |
| HP | - | 1 |
| $Q_f$ | ($m^3$/s) | 250 |
| $T_f$ | (days) | 5 |
| N | (years) | 1 |
| D | (feet) | 4 |
| NP | - | 1 |
| YA | - | 0.3 |
| CLF | (%) | 100 |
| CLH | (%) | 100 |
| CLD | (%) | 100 |
| CLT | (%) | 100 |
| ASD | (%) | 100 |
| AST | (%) | 100 |
| MD | ($m^3$) | 1,000,000 |
| MT | ($m^3$) | 500,000 |
| $C_w$ | (%) | 30 |
| **Economic Parameters** | | |
| **Parameter** | **Units** | **Value** |
| E | - | 1 |
| C | ($/$m^3$) | 0.54 |
| C2 | ($) | 225,974,930.06 |
| R | (decimal) | 0.1 |
| Mr | (decimal) | 0.1 |
| P1 | ($/$m^3$) | 0.15 |

**Table C.1 User Input Pages of Muratli Dam (continued)**

| | | |
|---|---|---|
| V | ($) | 10,644,365.54 |
| omc | - | 0.01 |
| PH | ($/m$^3$) | 0.015 |
| PD | ($/m$^3$) | 0.015 |
| CD | ($/m$^3$) | 15.00 |
| CT | ($/m$^3$) | 4.00 |
| **Flushing Benefits Parameters** | | |
| s1 | (decimal) | 0.9 |
| s2 | (decimal) | 0.9 |
| **Capital Investment** | | |
| FI | ($) | 2,000,000 |
| HI | ($) | 1,000,000 |
| DU | (years) | 25.0 |

## Economic Results and Conclusions for Muratlı Dam

**Table C.2 Economic Results Summary of Muratli Dam**

| Possible Strategies | Technique | Aggregate Net Present Value |
|---|---|---|
| Do nothing | N/A | 2,624,004,134 |
| Nonsustainable (Decommissioning) with Partial Removal | HSRS | 2,625,065,040 |
| Nonsustainable (Run-of-River) with No Removal | N/A | 2,780,808,924 |
| Nonsustainable (Run-of-River) with Partial Removal | HSRS | 2,781,869,830 |
| Sustainable | Flushing | 3,673,119,588 |
| Sustainable | HSRS | Total Removal with HSRS is technically infeasible, See Partial Removal with HSRS |
| Sustainable | Dredging | 3,624,713,276 |
| Sustainable | Trucking | 3,371,593,293 |

**Table C.3 Economic Conclusion of Muratli Dam**

| | |
|---|---|
| Strategy yielding the highest aggregate net benefit: | Sustainable |
| Technique yielding the highest aggregate net benefit: | Flushing |
| The highest aggregate net benefit is: $ | 3.673E+09 |

Nonsustainable Alternatives

**Table C.4 Nonsustainable (Decommissioning) Alternatives Details of Muratli Dam**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | 1 | years |
| # of years until retirement for Decommission-with No Removal Option: | 18 | years |
| # of years until retirement for Decommission: Partial Removal Option with HSRS: | 18 | years |
| Remaining reservoir capacity at retirement for Decommission-with No Removal Option: | 458,150 | $m^3$ |
| Remaining reservoir capacity at retirement for Decommission: Partial Removal Option with HSRS: | 556,041 | $m^3$ |

**Table C.5 Annual Retirement Funds for Decommissioning for Nonsustainable (Decommissioning) Alternatives of Muratli Dam**

| | | |
|---|---|---|
| Annual Retirement Fund Payment for nonsustainable options: Decommission | 233,433 | $ |
| Annual Retirement Fund Payment for nonsustainable options:Partial Removal with HSRS | 233,433 | $ |

**Table C.6 Nonsustainable (Run-off River) Alternatives Details of Muratli Dam**

| | | |
|---|---|---|
| # of years until Partial Removal Option with HSRS is practiced: | 1 | years |
| Approximate # of years until dam is silted for Run-of-River-with No Removal Option: | 19 | years |
| Approximate # of years until dam is silted for Run-of-River-with Partial Removal Option: | 19 | years |

Sustainable Alternatives

**Table C.7 Long Term Capacities of Sustainable Alternatives of Muratli Dam**

| | | |
|---|---|---|
| Long term reservoir capacity for Flushing | 29,889,464 | $m^3$ |
| Long term reservoir capacity for HSRS | Not applicable | $m^3$ |
| Long term reservoir capacity for Dredging | 70,669,897 | $m^3$ |
| Long term reservoir capacity for Trucking | 70,669,897 | $m^3$ |

**Table C.8 Phase-I Lengths of Sustainable Alternatives of Muratli Dam**

| | | |
|---|---|---|
| Approximate # of years until dam is sustained at long term capacity for Flushing | 54 | years |
| Approximate # of years until dam is sustained at long term capacity for HSRS | Not applicable | years |
| Approximate # of years until dam is sustained at long term capacity for Dredging | 1 | years |
| Approximate # of years until dam is sustained at long term capacity for Trucking | 9 | years |

**Table C.9 Times of Flushing Event in Phase-I**

| | | |
|---|---|---|
| Approximate # of Flushing events until dam is sustained at long term capacity | 13 | times |

**Table C.10 Removal Frequencies Muratli Dam**

| Strategy | Technique | Cycle/Phase | Frequency of Removal (years) |
|---|---|---|---|
| Nonsustainable-with Partial Removal | HSRS | Annual cycle | 1 |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | 1 |
| Sustainable | Flushing | Phase I | 3 |
| Sustainable | Flushing | Phase II | 2 |
| Sustainable | HSRS | Annual cycle | Not applicable |
| Sustainable | Dredging | Phase I | 1 |
| Sustainable | Dredging | Phase II | 1 |
| Sustainable | Trucking | Phase I | 9 |
| Sustainable | Trucking | Phase II | 9 |

**Table C.11 Sediment Removed per event for Muratli Dam**

| Strategy | Technique | Cycle/Phase | Sediment Removed ($m^3$) |
|---|---|---|---|
| Nonsustainable-with Partial Removal* | HSRS | Annual cycle | 5,758 |
| Run-of-River (Nonsustainable)-with Partial Removal | HSRS | Annual cycle | 5,758 |
| Sustainable | Flushing | Phase I | 13,656,729 |
| Sustainable | Flushing | Phase II | 8,260,206 |
| Sustainable | HSRS | Annual cycle | Not applicable |
| Sustainable | Dredging | Phase I | N/A |
| Sustainable | Dredging | Phase II | 4,130,103 |
| Sustainable | Trucking | Phase I | N/A |
| Sustainable | Trucking | Phase II | 37,170,925 |

**Table C.12 Optimal values of ASD/AST and CLF/CLD/CLT for Muratli Dam**

| Technique | ASD/AST(%) | CLF/CLD/CLT |
|---|---|---|
| Flushing(Phase I) | Varies | 71 |
| Flushing(Phase II) | 16 | |
| HSRS | N/A | N/A |
| Dredging(Phase I) | N/A | 6 |
| Dredging(Phase II) | 100 | |
| Trucking(Phase I) | N/A | 50 |
| Trucking(Phase II) | 100 | |

**Table C.13 Technical Comments for Muratli Dam**

| | | |
|---|---|---|
| Average expected concentration of sediment to water flushed per flushing event: | 123,226 | ppm |
| Average expected concentration of sediment to water released downstream of dam per hydrosuction event: | 124 | ppm |
| Average expected concentration of sediment to water removed from reservoir per dredging event: | 300,000 | ppm |
| Note: Because reservoir is dewatered prior to a trucking event and river is diverted during a trucking event, material removed is moist sediment (negligible water). | | |

**Table C.14 Number of Truck Loads* Required to Complete Sustainable Sediment Trucking Removal Option for Muratli Dam**

| Truck Model Number | m3/Truck Load | Number of Loads(Phase I) | Number of Loads(Phase II) |
|---|---|---|---|
| 769D | 16.2 | N/A | 2,294,502 |
| 771D | 18 | N/A | 2,065,051 |
| 773D | 26 | N/A | 1,429,651 |
| 775D | 31 | N/A | 1,199,062 |
| 777D | 42.1 | N/A | 882,920 |
| 785B | 57 | N/A | 652,121 |
| 789B | 73 | N/A | 509,191 |
| 793C | 96 | N/A | 387,197 |

*1997. Caterpillar Performance Handbook, Ed. 28. CAT Publication by Caterpillar Inc., Peoria, Illinois, USA. October 1997.

**Table C.15 Number of Dredges Required to Complete Sustainable Sediment Dredging Removal Option for Muratli Dam**

| Volume Removed per Dredge (m3/Dredge) | No. of Dredges (Phase I) | No. of Dredges (Phase II) |
|---|---|---|
| 11,000,000 | N/A | 1 |

**Table C.16 Unit Cost of Sediment Removal for Muratli Dam**

| | Phase I | Phase II |
|---|---|---|
| **Unit Cost of Dredging($/m3)** | N/A | 15.00 |
| **Unit Cost of HSRS($/m3)** | 6.95 | |