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Evaluating Sediment handling strategies for Banja Reservoir using the RESCON2 model

A comprehensive study of the rapid assessment tool for sustainable sediment management

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Submission date: June 2017
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ABSTRACT

Banja Reservoir along Devoll River basin, Albania is in threat of loss in storage due to sedimentation. Catchment of Devoll river draining into Banja reservoir has prominent sheet erosion and mass wasting due to intense rainfall and weak geology. This has resulted in higher sediment yield measured along the river. To ensure sustainable operation of Banja reservoir, timely measures for sediment management is necessary.

The purpose of this study is to evaluate sediment handling strategies for Banja Reservoir using RESCON2 model, which is a rapid assessment tool for sustainable sediment management strategies in terms of their technical feasibility and economic viability to the project either new or existing. Contrary to contemporary practice of adopting design life philosophy in planning reservoir, RESCON2 incorporates life-cycle management approach that would facilitate the sustainable development of dams and reservoirs. RESCON2 at prefeasibility level can be useful tool to the planners. However, results from the model depends upon the quality of data available at the conception phase of the project. Sediment load to the reservoir is one of the important input which is generally not available and thus require some estimate. For Banja reservoir, it is planned to run the model in two different stages viz. now (2017) and future (2050) where climate change is expected to change the sediment yield. Thus, RUSLE model has been prepared with climate change data to estimate sediment yield for Banja reservoir.

The main finding from RUSLE model is that, there will be decreased sediment yield due to decreased annual precipitation in Devoll catchment. RUSLE made quite optimistic estimate of sediment yield of 2.42 million tonnes /year. With this estimate, RESCON2 applied to Banja in different scenario found dredging in combination with catchment management, flushing, sluicing and by-pass to be the most successful and sustainable management option in terms of physical and economic performance. However, to take care of associated uncertainties with climate in future and sediment yield estimate, sensitivity analysis has been performed to test robustness of the anticipated sustainable sediment management options.

PREFACE

This thesis is submitted in partial fulfilment of the requirements for Master's Degree in Hydropower Development at the Department of Civil and Environmental Engineering, Norwegian University of Science and Technology(NTNU). This contains the work done from mid-January to mid-June 2017 under supervision of Associate Professor Nils Rüther (NTNU) and co-supervisor Siri Stokseth (Statkraft).

This study has made an attempt to evaluate the sediment management strategies for a reservoir to assess its sustainability. RESCON2(beta version) model released by the World Bank on September 2016, proved to be a useful tool for rapid assessment of a reservoir in this study. RUSLE model developed in this study is author's first experience to estimate sediment yield from a catchment, using open source data readily available at planning phase of a reservoir. It has been a significant learning experience and immensely rewarding in terms of knowledge gained about model useful in planning sediment management to a reservoir.

This thesis work has been possible due to kind co-operation lent by many individuals and organizations. I am highly indebted to my supervisor Nils Rüther (NTNU) and co-supervisor Siri Stokseth (Statkraft) for their continuous guidance as well as for providing necessary information regarding the project. I am thankful to Mr. Pravin Karki from the World Bank. Sebastian Palt and Nikolaos Efthymiou from Fichtner consulting, Germany, for providing RESCON2 model and all supporting data. I would like to appreciate Tor Haakon Bakken from SINTEF Energy for sharing his studies and experience on climate change in Devoll river basin.

Last but not the least, I would like to thank all my friends and families who supported me indirectly. Special thanks to Sanat Kumar Karmacharya for his comments and suggestions.

Trondheim, June 2017

Santosh Adhikari

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ABBREVIATIONS

CCKP	: Climate Change Knowledge Portal
CIR	: Capacity Inflow Ratio
DDR	: Draw Down Ratio
DEM	: Digital Elevation Model
FWR	: Flushing Width Ratio
GCM	: Ground Circulation Model
H.P.P.	: Hydro-Power Project
HRWL	: Highest Regulated water level
HSRS	: Hydro suction Sediment Removal System
ICOLD	: International Commission on Large Dams
IRTCES	: International Research and Training Centre on Erosion and Sedimentation
LRWL	: Lowest Regulated water level
LTCR	: Long Term Capacity Ratio
MAF	: Mean annual Inflow
MAS	: Mean annual sediment Inflow
Masl	: Meter above sea level
NPV	: Net Present Value
PROR	: Peaking Run-of-River
RESCON	: Reservoir Conservation
ROR	: Run-of-River
RUSLE	: Revised Universal Soil Loss Equation
SBR	: Sediment Balance Ratio
SDR	: Sediment Delivery Ratio
TWR	: Top Width Ratio
USLE:	: Universal Soil Loss Equation
USPED	: Unit Stream Power based Erosion Deposition model
WEAP	: Water Evaluation and Planning

Chapter 1 : INTRODUCTION

1.1 General

Water is essential resources for survival of human being, consumed for sustaining life and for other human activities. However, the spatial and temporal distribution of water is so varying that, it is not always available when needed and where needed. So, to tackle such problem, dams are constructed along or off the river course and the water is impounded in reservoirs. In the database of ICLOD, 45000 large scale dams have been registered, which in total impounds around 7000 km^3 of water (ICOLD, 2011).Reservoirs are used for different purposes such as irrigation, water supply, Hydropower generation, flood control and navigation etc.

However, with growing needs and challenges due to climate change and other factors, reliability of the water yield from reservoir is at greater risk. One of the major challenge to the reservoirs is sedimentation, which poses a significant threat to the longevity, utility, and sustainable operations of reservoirs. Concern about loss of reservoir capacity due to sedimentation was raised by Mahmood (1987) and has recently been expressed in many forms and publications. It is estimated that more than 0.5 percent of the total reservoir storage volume in the world is lost annually because of sedimentation (White, 2001).). This translates into the need to add some 45 km3 of storage per year worldwide. Costs would be on the order of US$13 billion per year and the associated environmental and social impacts significant. The creeping problem of sedimentation has several implications such as loss of storage, loss of hydropower production, less irrigated land to produce food and reduced flood routing capacity(Alessandro Palmieri, June 2003).In this regard, sedimentation of reservoir, its problems and mitigations has been a topic for research among scientist and engineers.

1.2 Background

The World Bank dealing with the water scarcity, is closely involved in the development of sustainable infrastructure worldwide. Brundtland report on 1987 defined Sustainable development as, *"Development that meets the needs of the present without compromising the ability of future generations to meet their own needs*. All reservoirs subjected to sedimentation which, without adequate prevention and mitigation counter-measures, threatens their sustainability (Anton J. Schleiss, 2011). This might lead the future generation to face scarcity of water and to pay without getting any benefits. Recognizing the importance of creating and maintaining reservoir storage , the World Bank developed a model called the reservoir conservation (RESCON) approach (George W.Annandale, 2016) to facilitate rapid assessment of technically feasible and economically viable sediment management strategies. With the advancement of research, greater understanding of reservoir sedimentation and management has lead The World Bank to upgrade RESCON model to RESCON2 version. Understanding this latest model and applying to the project became one of the interest to the author to write this thesis work on evaluating the sediment handling strategy for Banja Reservoir, which is upcoming project in the semi-arid river basins having a threat of sedimentation. In semi-arid region, reservoirs are commonly the most important water sources with acceptable reliability which strongly depends on their sustainability (De AraÚJo, GÜNtner, & Bronstert, 2006).Thus sustainability is a challenge to Banja reservoir.

1.3 Objective of Study

The overall objective of this study is to evaluate the sustainable sediment handling strategies, technically feasible and economically viable to Banja Reservoir Project, Albania, making use of RESCON2 Model. Specific objectives for the study have been defined to focus the study and to elaborate the findings for future reference. List of the specific objectives are below:

1. To understand the RESCON2 model, regarding its process and applicability.
2. To Prepare the required data set for Modelling Banja Reservoir in RESCON2.
3. To elaborate the application of model for climate change scenario.

1.4 Scope of the study

This study is based on the data sets available for 10 different projects as provided by the RESCON2 model developer from The World Bank and consultants. While for the application, Banja Reservoir in Devoll river basin, owned by Statkraft, Norway has been considered. Scope of the study listed as below:

1. To understand the RESCON2 model and its Principle.
2. To prepare and run the model for 10 different projects.
3. To gather all required data for Banja Reservoir from different sources.
4. To estimate the Sediment Yield for Banja reservoir.
5. To incorporate the climate change scenario in sediment yield estimation.
6. To evaluate the sustainable sediment management strategies in both normal scenario and in climate change context.

1.5 Methodology

To evaluate the sustainable sediment management for Banja Reservoir, this study attempts to model the reservoir in RESCON2 by gathering all relevant data sets. Sediment yield estimation is one of the major input to the model, estimated by RUSLE model. It is felt necessary to estimate sediment yield in future, since climate change is expected to change rainfall pattern.

Information regarding the hydrology and geometry of the reservoir were collected from the available documents published by Norconsult on behalf of Devoll Hydropower Project. Hydrological data were collected from Tor Hakkon Bakken from SINTEF Energy Research, for climate change scenario generated by WEAP model as a part of Master thesis by Christian Almestad (2015, NTNU) and the data set generated from Climate Change Knowledge Portal by World Bank were considered to calculate the new annual rainfall and hence to calculate new R factor for RUSLE model. Discussion about the calculation is done in chapter 3.

The overall steps followed to come up with results for this study is presented in the Figure 1.1.

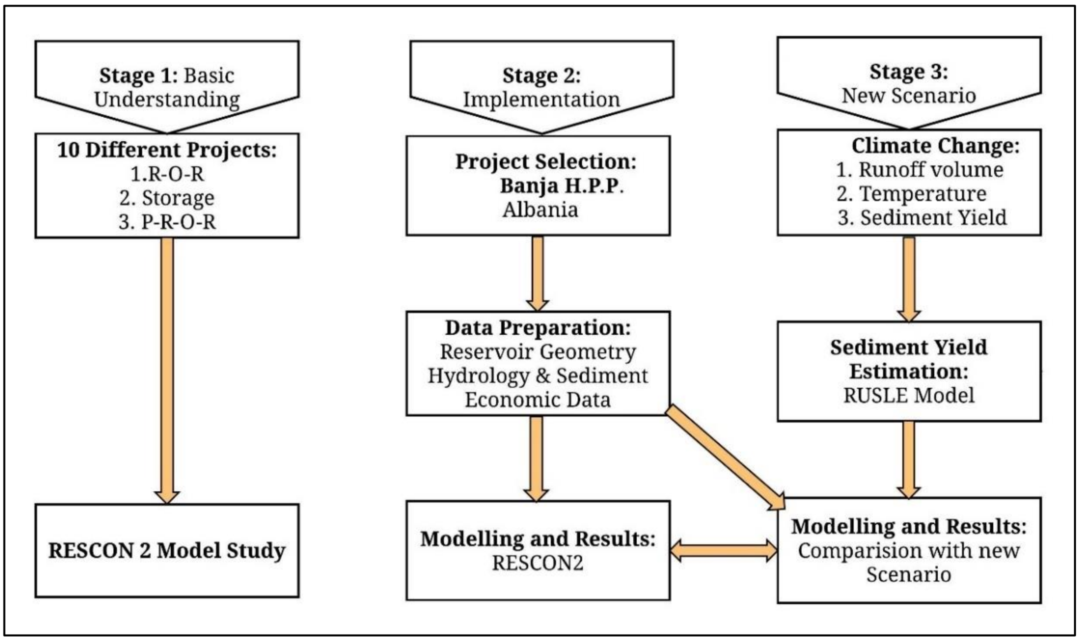


Figure 1.1: Methodology for Evaluating Sediment Handling Strategy for Banja Reservoir.

1.6 Structure of the thesis

This thesis is presented in five chapters and annexes. Each of the chapters comprises the contents listed as follows:

*Chapter 1***:** Covers the general information about the reservoir sedimentation problem seeming worldwide and presents the motivation behind this thesis work. Study objectives and scope of the work and the methodology followed to achieve those are defined in this chapter.

*Chapter 2***:** Structure of Reservoir Conservation (RESCON2-beta version) model, along with the state of art regarding the sediment management methods are presented in this chapter. To get used with the model, 10 different example projects analysed are presented in brief.

Chapter 3: Sediment yield estimation methods in use are discussed in short. Revised Universal soil loss equation (RUSLE) model prepared for study area is presented in this section.

Chapter 4: Modelling of study area in RESCON2 to come up with sustainable sediment management options is presented in this chapter. It comprises data preparation and model run in different user defined scenario.

Chapter 5: Conclusion of the work and associated limitations and recommendations for future work is presented in this chapter.

List of data used for 10 different projects and other relevant graphs and figures are presented in Annexes.

1.7 Description of the Study Area

Geographic location and Climate

Banja Hydropower is first stage power plant in Devoll river basin, Albania. Concretely, Albanian climate is a part of Mediterranean climate characterized by hot dry summer and cool wet winters(Porja, 2014). Project lies in semi-arid region in south east Europe. Devoll river is the main tributary of Seman river located 70 km southeast of capital of Albania, Tirana as shown in Figure 1.2. Devoll has catchment area of approximately 3119 km^2 with elevation ranging from 22m to 2386 m as shown in Digital Elevation model (DEM)of 50 m ×50 m cell size in Figure 1.3.

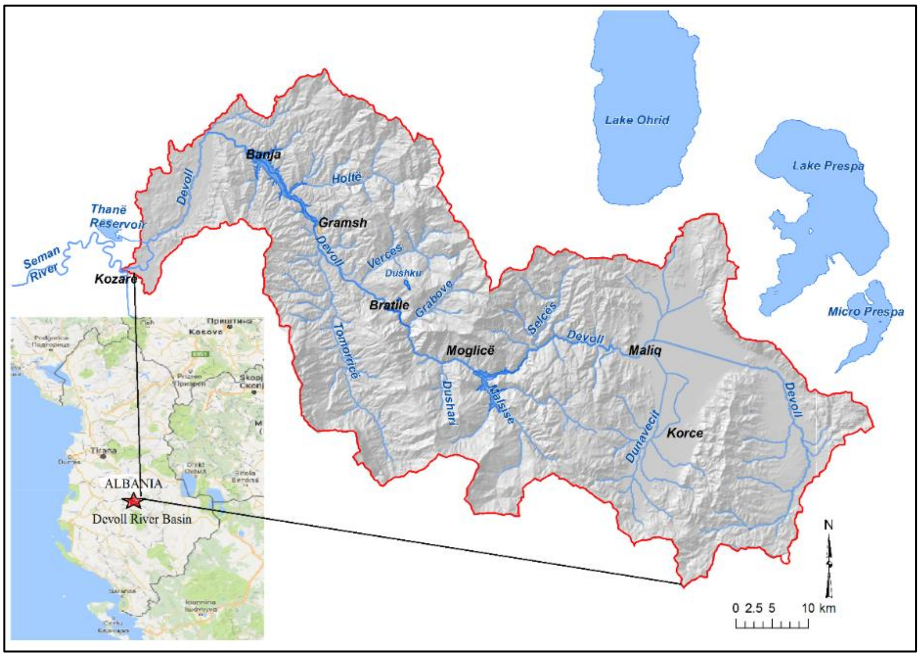


Figure 1.2: Geographical location of Devoll River Basin (Source: Norconsult,2011)

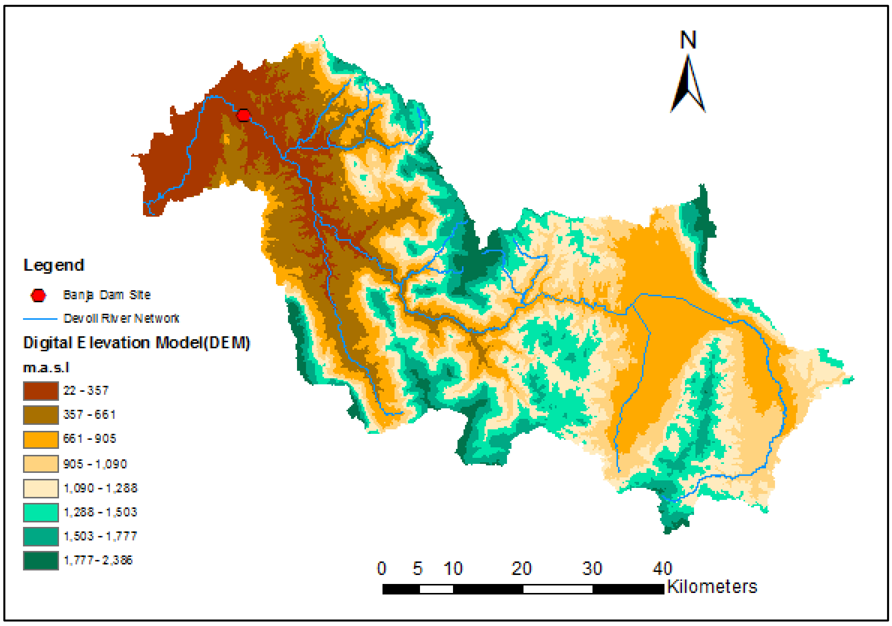


Figure 1.3: Digital Elevation Model for Devoll River Basin

Flow in the basin comprises the precipitation in western part and snow melting in eastern part. Average annual precipitation distribution in Albania is highly influenced by the geographical position, distance from coastline and the elevation above the sea level. Annual precipitation varies from minimum of 600 mm in southeast part to 3000 mm in northern part of the country with average value of 1485 mm from the study by Proja,2014 as shown in Figure 1.4 (a).Devoll basin lies in the region where average annual precipitation is in the range of 600 mm to 1900 mm. While, the mean annual temperature varies from $7.5^o C$ in upper part to $14.7^o C$ in lower part.

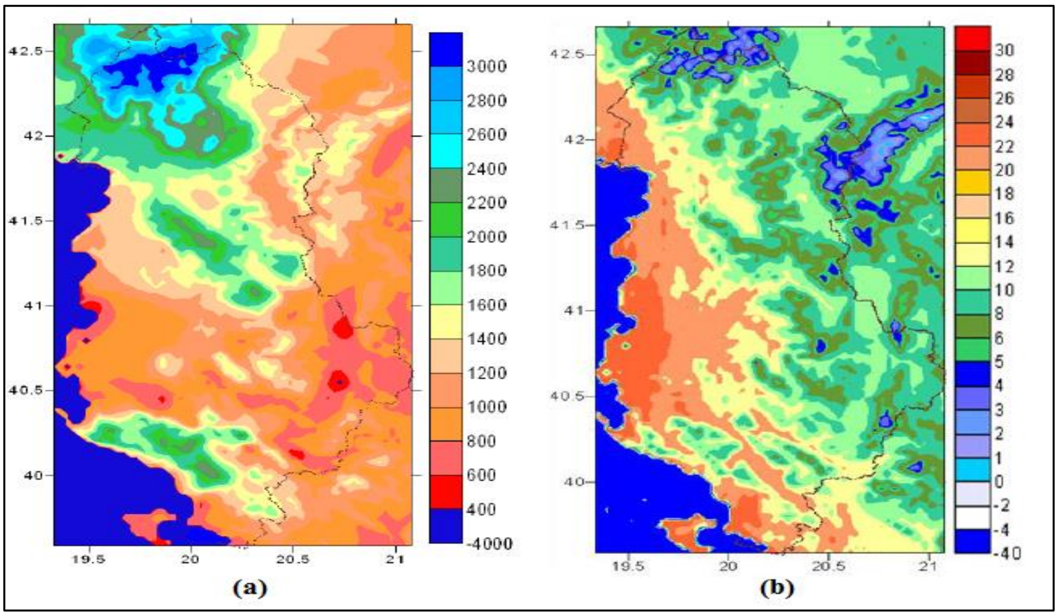


Figure 1.4: Mean annual Distribution of (a) Precipitation (b) Temperature in Albania (Source: Proja,2014)

Sub Basins

Devoll River basin comprises 9 sub basins. In total, 20 metrological stations and 10 gauging stations are available in the basin. For this study, 9 sub catchments and their characteristics at gauging stations are listed in Table 1-1. Overall geographical features and nearby water bodies to the catchment can be seen in the image retrieved from google earth as in Figure 1.5. Size of each sub basin and their location in Devoll catchment is as shown in Figure 1.6.

Table 1-1: Characteristics of gauging stations at Sub-basins in Devoll catchment(Source:(Almestad, 2015))

Gauging Stations	Record period	Drainage Area(km^2)	Mean Daily runoff(m^3/s)	Annual Runoff (Million m^3)
Miras	1958-1999	89.4	1.59	50.3
Sheqeras	1956-1985	430.2	5.22	168.1
Turhan	1951-1989	272.8	3.24	101.9
Lozhan	1951-1954	100	1.54	48.5
Gjinikas	1970-1995	1375	12.38	395.9
Poshtme	1976-1985	63	2.3	72.4
Kokel	1953-1989	1897.3	28.28	857
Bardhaj	1980-1989	375.5	5.74	181
Darzeze	1983-1984	2900	35.25	111.6
Kozare	1950-1985	3120.6	46.6	1492

Figure 1.5: Banja Dam Site in Devoll River Basin (Retrieved from: Google Earth)

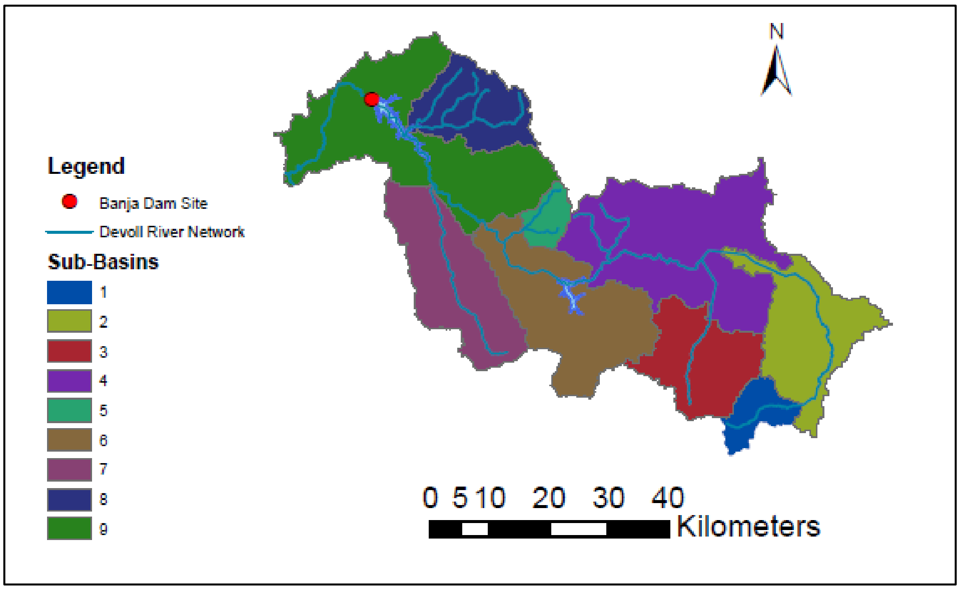


Figure 1.6: Banja Dam site and Sub Basins in Devoll River Basin

Chapter 2 : RESCON2 MODEL

2.1 Structure of the RESCON2 Model and Process

As reservoir sedimentation issues triggered several factors that challenge sustainability of reservoir projects in long run. The World Bank in 1999 initiated a research project to develop an approach to assessment and promotion of sustainable management of reservoir(Nikolaos Efthymiou, November 2016).As a result, excel based RESCON model was developed and applied for the projects. To improve the user interface, add more sediment management methods and calculation capacity, the RESCON model has been upgraded to RESCON2-Beta Version, though theoretical background is same for both versions.

RESCON2 model is designed for use in pre-feasibility studies to rank the economic performance of a selection of sediment management techniques for Greenfield projects. While, it is equally applicable to the existing project having single or multiple use. The data input as well as reading of results are performed through a Graphical User Interface(GUI) and the calculations are done in Excel(Nikolaos Efthymiou, November 2016).The flow chart of RESCON2 is as shown in Figure 2.1.

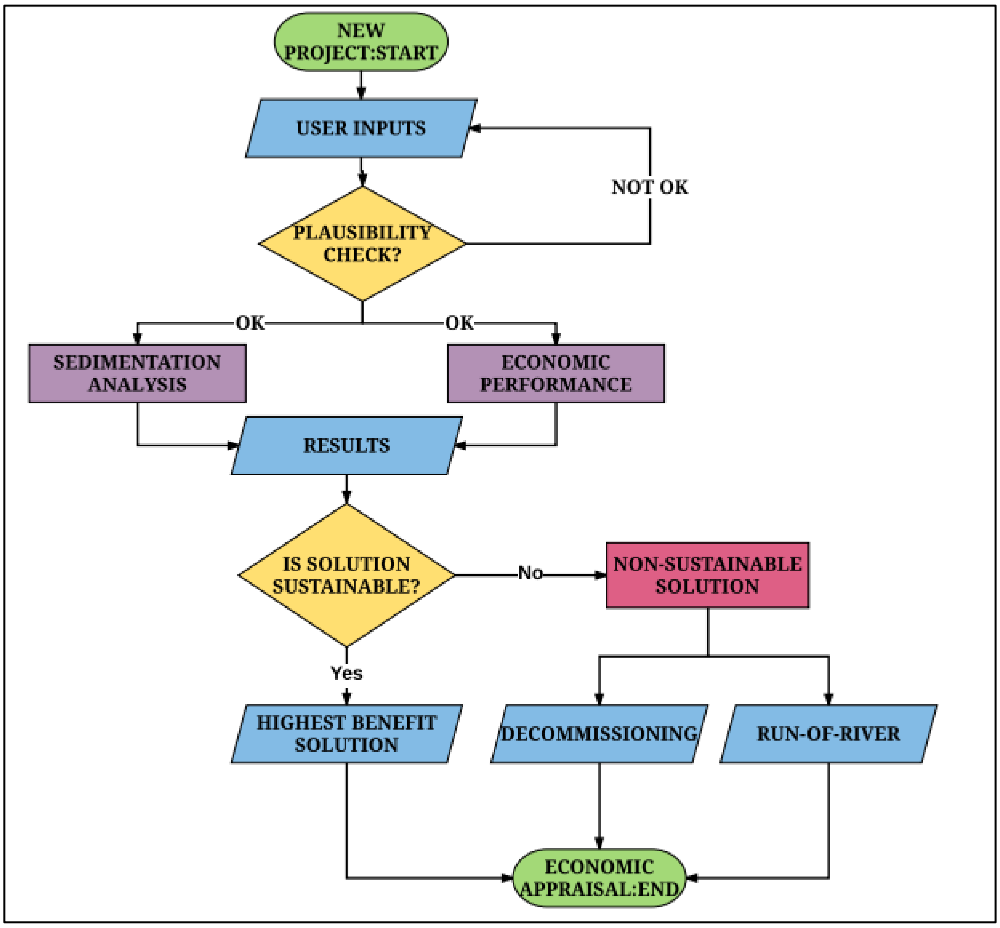


Figure 2.1: Flow chart for RESCON2 Model.

The user input comprises:

- Reservoir Geometry
- Hydrological Data
- Sediment characteristics
- Sediment Management Parameters
- Economic Parameters
- Climate Change
- Environmental and social Safeguard ratings

The data set can be prepared from the actual site specific values such as reservoir geometry, some values from experience and judgement such as selection of methods for multiple management strategy, data from web based database such as for climate change etc. Over all analysis and the results from the model depends upon the reliability and accuracy of the data.

The key algorithm of the model is an economic optimization function, supported by engineering relationships(Alessandro Palmieri, June 2003).The relation used for economic optimization is as:

$$Maximize\sum_{t=0}^{T} NB_t d^t - C_2 + Vd^T$$
$$Subject: S_{t+1} = S_t - M + X_t$$

Equation 2-1

Where, NB_t: Annual Net Benefits in year t
D: Discount Factor defined as (1/(1+r)), where r is rate of discount.
C_2: Initial cost of construction for the proposed dam (= 0 for existing)
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.

Here, NB_t, Depends upon physical as well as economic consideration for each sediment handling strategy.

One of the important consideration made in RESCON2 is the life of reservoir determined based on life cycle management approach rather than the design life approach, which assumes a finite project life. Palmieri *et al.* proposed a new "life cycle management" approach for sustainable management and use of hydraulic infrastructure. The ultimate goal of this approach is sustainable use, where major functions of dam are preserved by good management and maintenance (Shavkat Rakhmatullaev, 2010). In design life approach, the decommissioning cost of dam is not foreseen, this might lead the future generation to bear all the costs, while in life cycle management approach, the decommissioning costs are taken into consideration through a retirement fund and hence it can establish intergenerational equity.

Compared to previous version RESCON model, beta version RESCON2 incorporates the possibility to evaluate extended sediment management methods. So, in RESCON 2, Sediment management alternatives are categorised as:

- **Catchment Management Method** (Available in RESCON2 only)
- **Removal of Deposition** (Available in both versions): Trucking, Dredging, Hydro suction Sediment Removal System (HSRS) and Flushing
- **Sediment Routing** (Available in RESCON2 only): Sluicing, Sediment By-Pass and Density Current Venting
- **Multiple Management Methods:** Combination of above methods.

Selection criteria and theoretical background for each of the methods will be presented in next section.

Preliminary assessment to identify whether, the sediment management alternative is sustainable solution, is done with the help of chart developed by George Annandale (2013) from the study of existing reservoirs in different parts of World. The chart is presented as Figure 2.2.

From Figure 2.2, it can be said that a reservoir's hydrological capacity heavily influences the sediment management techniques. Thus, before analysing any technique in RESCON2, a preliminary assessment can be done quickly and then decide whether to include the method. This assessment is equally important in determining the multiple methods in RESCON2.

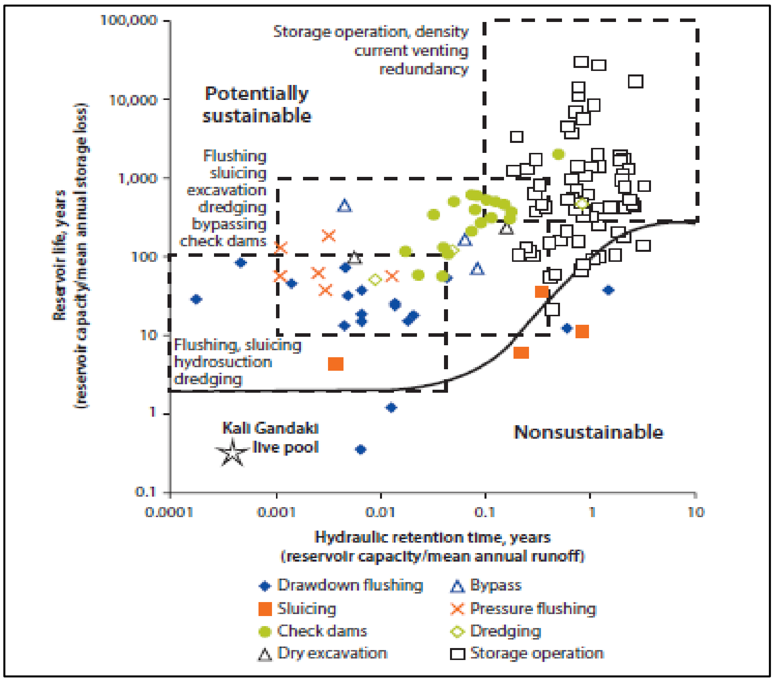


Figure 2.2: Applicability of Sediment Management Techniques Based on Hydrologic Capacity and Sediment Loading(Source:(George W.Annandale, 2016))

2.2 Reservoir Sedimentation and Sediment Handling Strategies

Reservoir sedimentation issues has been studied since ages and yet it remains as a challenge to all existing and upcoming projects in such regions, where geology is weak and the soil erosion process is significant. Sediments enter the reservoir because of erosion due to rainfall and transportation by the streams and channels formed in the catchment. Lots of studies have been done to predict how the sediment is transported and deposited along the reservoir. Knowledge of both the rate and pattern of sediment deposition in a reservoir is required to predict the type of services impairments which will occur, time frame and frequency of occurrence and remedial solutions applicable(Gregory L. Morris, 1998). Before going into detail about the handling strategies, an overview of depositional and erosional patterns occurring in a reservoir is presented as below.

2.2.1 Erosion and Deposition pattern in reservoir

When a flowing river carrying sediment enters a reservoir, flow velocity decreases and the carrying capacity of the water drops to the level that the deposition of the sediment begins. The bed load and the coarse fraction of the load are deposited immediately to form delta deposits, while fine sediments having low settling velocity are further carried into the reservoir by either stratified of non-stratified flow(Gregory L. Morris, 1998).Longitudinal deposition in reservoir can be divided into three major zones viz. *Topset beds* comprises the delta deposit of coarse sediments, *Foreset deposits* covers the face of the delta advancing into the reservoir and are differentiated from topset beds by increase in slope and decrease in grain size as stated by Morris(1998). Third zone is *Bottemset beds*, consist of fine deposits along with organic matters carried by turbidity currents or non-stratified flow. This bed reach the body of dam in long run as shown in Figure 2.3.

Longitudinal deposition pattern is not always same in all reservoirs, as this is influenced by the reservoir geometry and other various factors such as discharge, grain size and operational strategy of reservoir.

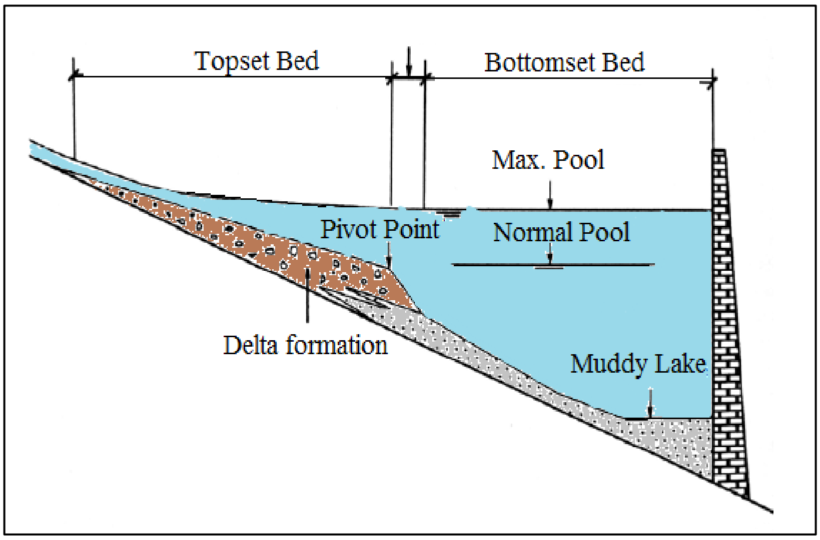


Figure 2.3: Generalised Longitudinal deposition in reservoir (Retrieved and edited from (Gregory L. Morris, 1998))

Morris and Fans (1998), have generalised four different depositional geometry presented in Figure 2.4.

- **Delta Deposit:** Consist of large fraction of coarse sediment load (d > 0.062 mm).
- **Wedge-shaped Deposit**: Turbidity current carrying fine sediments towards dam body leads to thicker deposition near dam and thinner upstream and ultimately forms wedge-shaped deposits. Such pattern is usually found in small reservoir with large fine sediment load or large reservoir operated at low level during flood.
- **Tapering Deposit:** Deposition is progressively thinner towards dam body. Usually occur in longer reservoir with high pool level.
- **Uniform Deposit:** Generally, not found such pattern. However, in narrow reservoir with frequent water level fluctuation and small sediment load can produce almost uniform deposit.

All the sediment entering a reservoir is not deposited into it. Deposition in a reservoir is determined by the Trap efficiency of the reservoir. Defining the trap efficiency for the reservoir is one of the important parameter in RESCON2 Model.

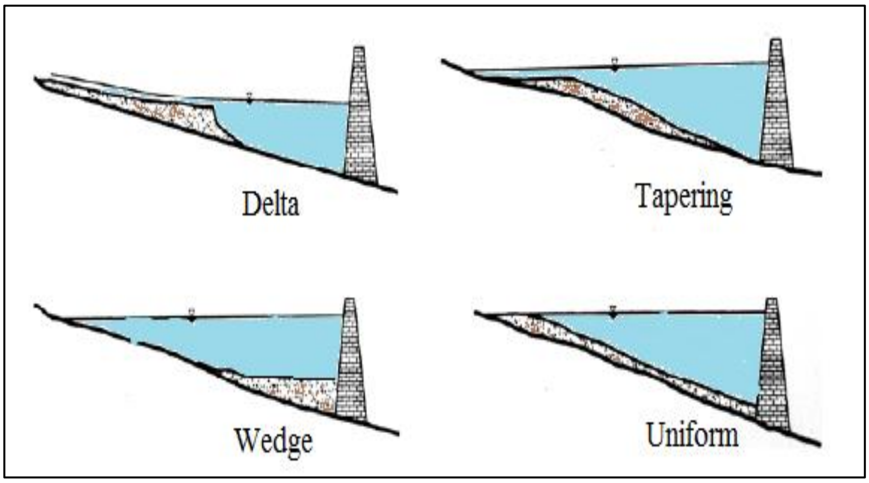


Figure 2.4: Longitudinal deposition geometries in reservoir (Retrieved and edited from (Gregory L. Morris, 1998))

RESCON2 has input tools to select the type of trap efficiency as following methods.

- Brune (1952)
- Churchill (1948)
- Borland(1971)

Brune Curve:

According to Brune (1953), trap efficiency of reservoir depends upon number of factors. Among these, important are the ratio between storage capacity and inflow, age of the reservoir, shape of basin, outlet types, grain size distribution of sediment and the behaviour of the finer sediment fractions under various conditions(Brune, 1953).From the records of forty four reservoirs, Brune (1953) generalised the trap efficiency as presented in Figure 2.5.

This is most widely adopted method for estimating the sediment trap efficiency of a reservoir. However, this method gives reasonable value for reservoir in long term. So, for reservoir with short term alteration in flow conditions, this is not appropriate. For such condition, Churchill curve can be used.

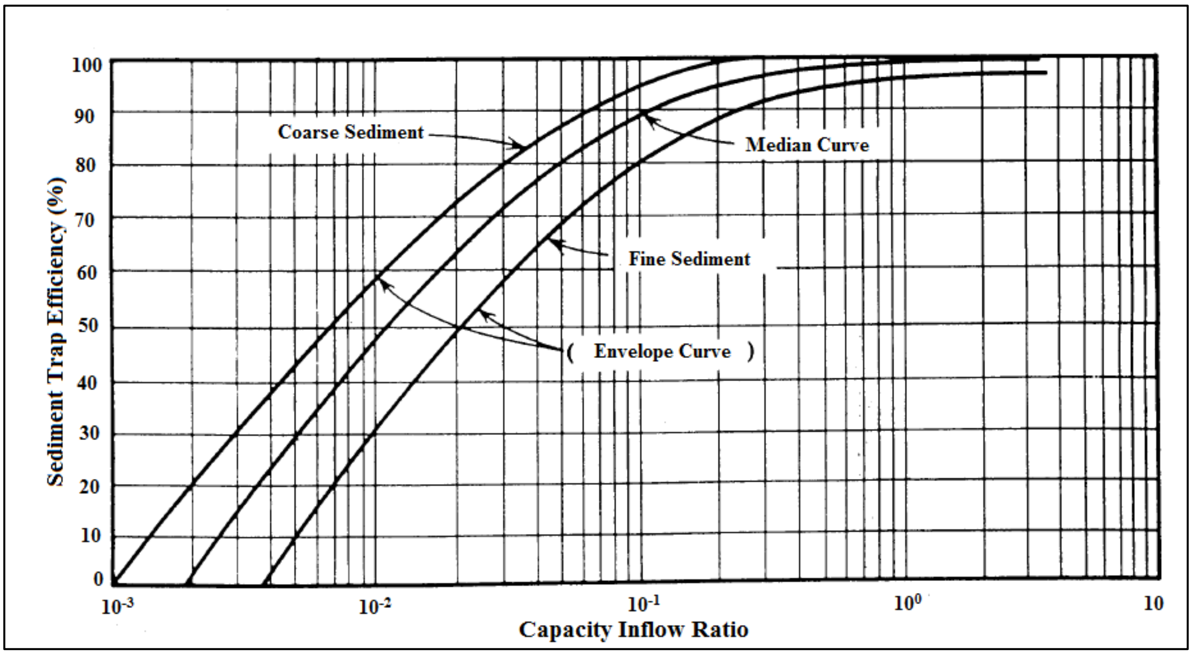


Figure 2.5: Brune Curves for Trap Efficiency (Adopted from (Brune, 1953))

Churchill Curve:

Churchill (1948) developed the relationship between sediment release efficiency to sedimentation index, which is the ratio of retention period to the mean flow velocity through reservoir(Gregory L. Morris, 1998) as shown in Figure 2.6. This method is applicable to wide range of reservoir types and even to the reservoir where sediment management is applied(Nikolaos Efthymiou, November 2016).

RESCON2 Model suggest to adopt either Churchill or Borland method for the short-term predictions of trap efficiency.

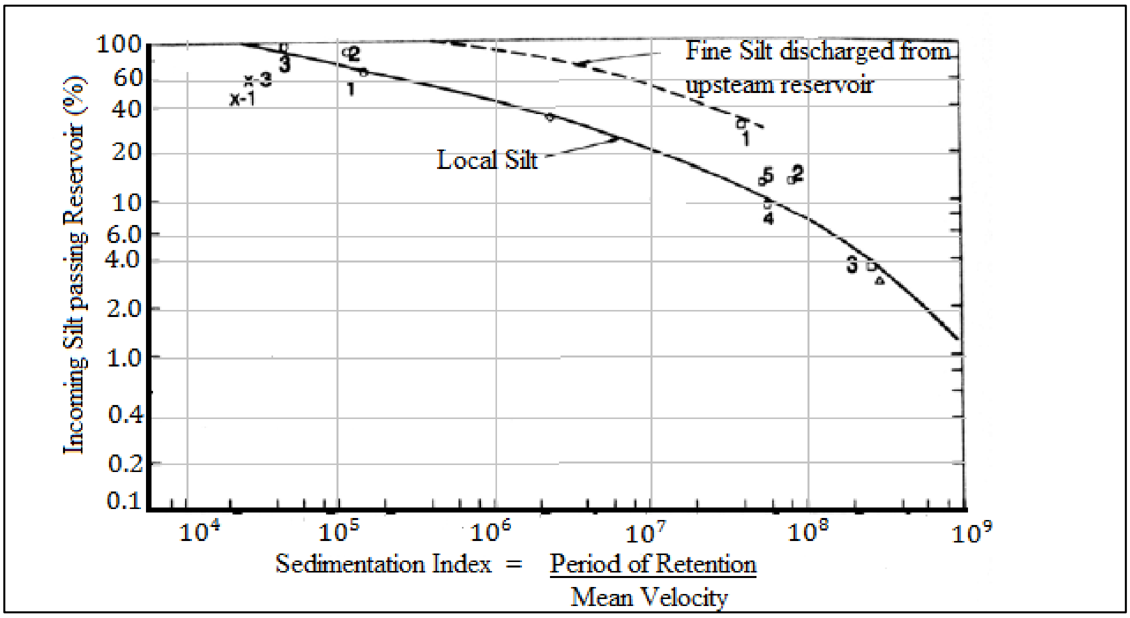


Figure 2.6: Churchill Curve for estimating sediment release efficiency (adapted from Churchill (1948))

Borland Equation:

This method is also applicable for short term predictions as Churchill method. It is based on the equation of Borland (1971) as reported by Van Rijn (2013):

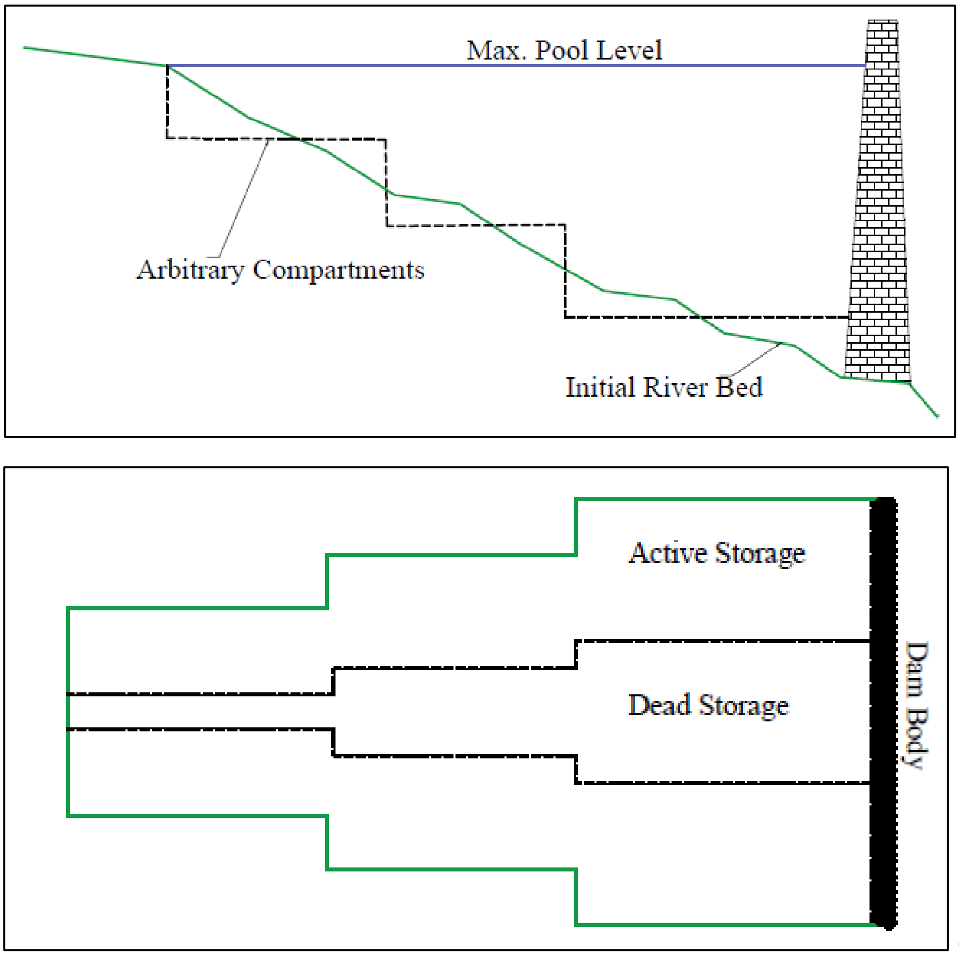
$$TE_{Borland} = 100(1 - e^{-1.055\left(\frac{L}{h}\right)\left(\frac{w_S}{u}\right)})$$

Equation 2-2

Where,

$TE_{Borland}$ = Trap Efficiency (%)
L = Length of Reservoir(m)
h = Mean Flow depth of Reservoir(m)
W_s = Settling Velocity (m/s)
u = Mean flow velocity in reservoir(m/s)

In RESCON2, once the trap efficiency is defined for the reservoir, it calculates the deposition in active and inactive storage based on reservoir geometry defined by the user. For simplicity, the whole reservoir is divided into number of compartments, at max. 10 as shown in Figure 2.7 (a)&(b).



(a)

(b)

Figure 2.7: Reservoir after Schematization in compartments (a) Longitudinal View (b) Plan View (Concept:(Nikolaos Efthymiou, November 2016))

In each compartment, distribution of deposits in done in compartment loop and inter-annual loop as shown in Figure 2.8.

Once the reservoir storage and geometry determined at the end of hydrological year following the steps mentioned in Figure 2.8, RESCON2 calculates the water Yield from the reservoir using Gould-Dincer approach.

According to Gould-Dincer , the dimensionless water yield can be expressed as a function of reservoir storage, coefficient of variance and annual inflow (Nikolaos Efthymiou, November 2016) by the Equation 2-3.

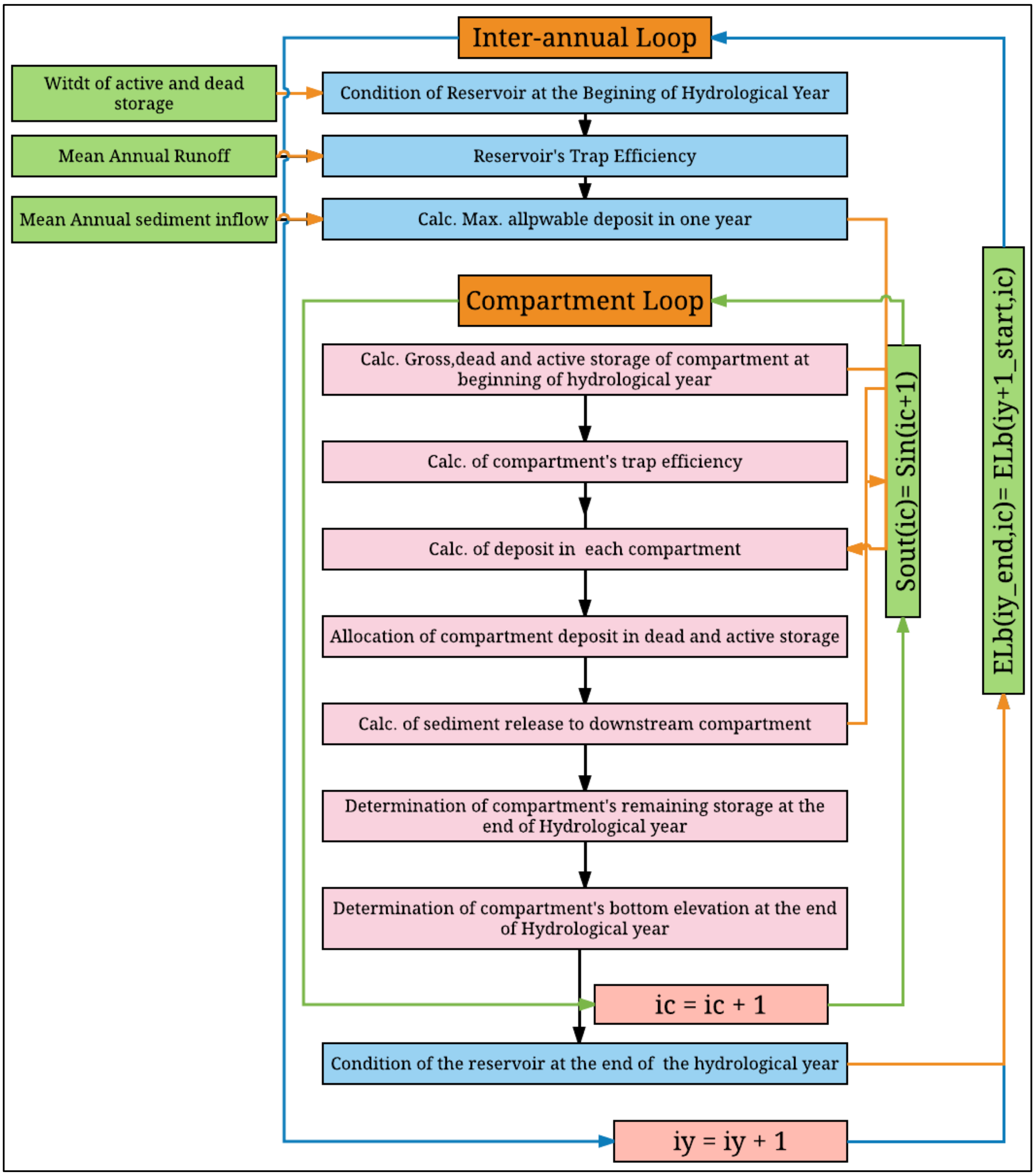


Figure 2.8: Flow chart for calculation of deposition in reservoir by RESCON2 (Source:(Nikolaos Efthymiou, November 2016))

$$\alpha_{Storage} = 1 - \frac{C_v^2 Z_p^2}{4\tau}$$

Equation 2-3

Where,

$\alpha_{Storage}$ = Dimensionless water yield for storage scheme
Z_p = Standardized normal variate (-) at 100p% non-exceedance
C_v = Coefficient of Variation of Annual Water Inflow to reservoir.
τ = Dimension less Reservoir active storage

While, for the Run-of-river facility, the dimension less water yield is calculated by the equation as below:

$$\alpha_{Storage} = 1 + C_v Z_p$$

Equation 2-4

Flexibility exist in the model, as the user can select between gamma, log-normal and normal distribution for the annual flow. For Normal distribution, Equation 2-3 and Equation 2-4 holds true, while for gamma distribution, Z_p is replaced by Z_g calculated based on the Wilson Hilferty transformation as mention in Equation 2-5.

$$Z_g = \frac{2}{\gamma}\left\{\left[1+\frac{\gamma}{6}\left(Z_P - \frac{1}{6}\right)\right]^3 - 1\right\}$$

Equation 2-5

Where, γ = Skewness, RESCON2 incorporates empirical approach such that skewness is 2.5 times the coefficient of hydrological variability.

While, log-normal variate $Z_{\ln}$ replaces Z_p in Equation 2-3, which is calculated based on equation by Chow (1964):

$$Z_{\ln} = \frac{1}{C_v}\left[e^{Z_p}\sqrt{\ln\left(1+C_v^2\right)} - 0.5\ln\left(1+C_v^2\right) - 1\right]$$

Equation 2-6

Annual revenue based on economic data defined by user is calculated once the yield is estimated. Besides, the annual costs in terms of Operation and Maintenance is calculated specific to each sediment management alternative selected. Finally, from the costs and revenue, Net Present Value for each sediment management strategy is obtained and compared so that the alternative having highest NPV technically accepted by the model is the best suited management strategy for the project. While, the strategy sustaining reservoir life more than 300 years is called a sustainable solution.

2.2.2 Sediment Handling Strategies adopted by RESCON2

RESCON2, compared to RESCON, incorporates additional sediment management alternatives. Those methods are generalised in major classes as:

- No action
- Catchment Management
- Removal of Deposition
- Sediment Routing

No action:

Under this approach, the model calculates for no any sediment management plan implemented, such that the result can be considered as a baseline for comparing other sediment management plans which requires some cost to implement.

Catchment Management:

Catchment management done to reduce the sediment inflow to the reservoir. This method comprises two group of techniques. One of them is watershed management, which is achieved through improved agriculture practice, re-forestation and de-intensification of land use practice. Other is implementation of check structures, for instance check dams upstream of reservoir.

Preliminary assessment for suitability of method can be done using Figure 2.2 Proposed by Annandale (2013). RESCON2 evaluates the method based on technical constraints as defined by user in terms of maximum allowable storage loss before its implementation following the process described in section 2.2.1.

Removal of Deposition:

This category of sediment management method comprises Flushing, Dredging, Hydro-suction Sediment Removal System (HSRS) and Trucking. Preliminary assessment for each of the methods can be done before opting the method using Figure 2.2 by Annandale (2013).

Flushing:

Flushing is the scouring out of deposited sediment from the reservoirs through low level outlets to lower water levels , and so increase the flow velocity in the reservoir(Atkinson, 1996).In RESCON2, the basis for assessment of flushing feasibility in a reservoir is Atkinson(1996) model. Effective flushing has generally been observed where the drawdown level is below the half height of dam and the flushing capacity exceeds the mean annual flow by at least a factor of 2 (J.D. Pitt, July 1984).In Atkinson model , major criteria for assessment of flushing feasibility are the Sediment Balance Ratio(SBR) and Long term Capacity Ratio (LTCR). For RESCON2, fulfilling SBR criteria is enough though, LTCR should be met, but failure doesn't eliminate the method.

Atkinson (1996), expressed SBR as ratio of sediment mass flushed annually to the sediment mass deposited annually, should be greater than unity, to achieve sediment balance in reservoir. While, the LTCR is the ratio of reservoir's sustainable capacity to original capacity, which is calculated in RESCON2 as the ratio of scoured valley area to simplified reservoir area at dam location. Scour area depends on side slopes calculated using Mignoit Equation as below:

$$SS_S = \frac{Cal\_SS_{FL}}{\frac{31.5}{5}\rho_d^{4.7}}$$

Equation 2-7

Where,

SS_S = Side Slope of Scoured Valley
Cal_SS_{FL} = Calibration Parameter (10 is Default)
ρ_d = Specific weight of in-situ reservoir sediment (t / m^3)
In addition to above criteria, Atkinson has developed four more criteria. RESCON2, adopts these criteria for additional conformation. Four additional criteria and their recommended values are presented in Table 2-1.

Table 2-1: Additional criteria for flushing feasibility (Proposed: Atkinson (1996))

Criteria	Guidelines	Recommended Values
FWR	Checks predicted flushing width is greater than representative bottom width of reservoir	>1
DDR	Ratio of extent or reservoir drawdown to normal impounding level	>0.7
TWR	Checks that the scoured valley width at top water level greater than reservoir top width	>1
SBR	Sediment balance ration independent of drawdown	>1

Once, the criteria are met, the economic performance of reservoir is done to calculate its Net present value. All mathematical relations for the model, are found in Atkinson (1996).

Results for Flushing criteria will be discussed for Banja Reservoir in later Chapter.

Hydro suction Sediment Removal System(HSRS):

Hydro suction removes the sediment from the reservoir using the hydraulic head represented by the difference between the water levels upstream and downstream from the dam. The potential energy thus stored drives the sediment and water into sediment removal pipelines without any external energy requirement (Hugan, June 1995).From Figure 2.2 by Annandale (2013), HSRS is generally appropriate for small reservoirs having hydrological reservoir size in in between 0.0001 and 0.04 along with the reservoir life between 2 and 100 years. In RESCON2, the technical feasibility of the HSRS method is limited by the length of pipe, which is in worst case is equal to the length of reservoir. If length of reservoir is more than 5000 m, hydraulic losses in the pipes are so high , reducing the performance of hydro suction (Nikolaos Efthymiou, November 2016).

Apart from this, user can provide the technical constraints in terms of maximum percentage of capacity loss (CHL) and maximum fraction of total yield that is allowed in HSRS operation, which limits the possible implementation of HSRS.

RESCON2 considers that the HSRS will be performed annually, so implementation schedule comprises only the year of installation of equipment. Year of Installation can be defined explicitly by the user or can be determined from the economic optimization module in the model itself. For, the method to be sustainable solution, removal capacity of HSRS should be in between minimum and maximum annual deposits(Nikolaos Efthymiou, November 2016).Details of the mathematical relations for calculation of feasibility of HSRS can be found in Hugan (1995).

Dredging:

Dredging refers to removal of sediment by means of pumping the sediment laden water from reservoir bed (Turner 1996). Based on study by Annandale (2013), Figure 2.2, Dredging is relatively more feasible for small and medium size reservoirs having hydrological size in between 0.0001 and 0.4 along with the reservoir life between 2 and 500 years.

RESCON2 evaluates the dredging system in a reservoir with an assumption that the method is always technically feasible. However, user defined technical constraints such as maximum percentage of capacity loss and maximum allowable percentage of accumulated sediment removed per dredging can limit the applicability of the method. For a typical system, highest sediment volume removal by dredging is approximately 11 million m^3(Nikolaos Efthymiou, November 2016), which should be kept in mind while evaluating this method.

Trucking:

Trucking refers to removal of deposited sediment from a reservoir after complete draining. Thus, during the year in which trucking is performed, the water yield from reservoir is zero and therefore benefit is null. Based on Annandale (2013) study, trucking is more appropriate for middle sized reservoir having hydrological reservoir size between 0.001 and 0.4. And, life span between 20 and 500 years.

Technical feasibility of trucking depends upon volume of sediment that must be physically removed within the limited time frame and accessibility of the reservoir for heavy equipment(Nikolaos Efthymiou, November 2016).Similar to the Dredging, RESCON2 assumes trucking is technically feasible regardless of the rate or removal required. This requires practical judgement by the user.

Sediment Routing:

Sediment routing includes any method to manipulate reservoir hydraulics, geometry or both to pass sediment through or around the reservoir to minimize the deposit(Gregory L. Morris, 1998). Aim of this approach is to predict the sediment laden inflow and manage it differently than clear water. Family of Sediment routing strategies comprises:

- Pass-Through: Sluicing, Density Current Venting
- By-pass: Diversion of sediment laden water, off-stream reservoir

As presented in Figure 2.9.

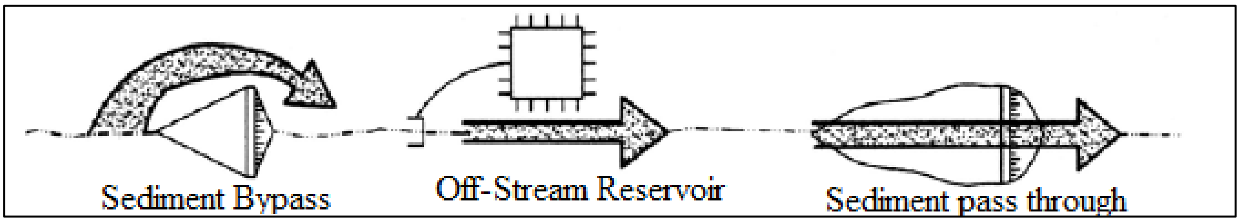


Figure 2.9: Classification of Sediment Routing strategies(Source:(Gregory L. Morris, 1998))

Sluicing:

Sluicing in a reservoir is performed by lowering the pool elevation during the flood season to increase flow velocity and decrease detention time and sediment trapping(Gregory L. Morris, 1998).Figure 2.10 presents the schematic illustration of sluicing operation in a reservoir during As mentioned earlier, Preliminary assessment of this method can be done with the help of study by Annandale (2013). According to which, sluicing method is effective for those reservoirs having hydrological size between 0.001 and 0.4. And reservoir life between 20 and 500 years. Appropriate low level outlets in reservoir is necessary for any reservoir to be technically feasible for sluicing. However, in RESCON2, user defined constraints in terms of maximum percentage of allowable capacity loss and maximum allowable duration for sluicing are determining for feasibility of the process. Once the method is found to be technically feasible to the reservoir, economic analysis is performed to conclude whether the method is sustainable.

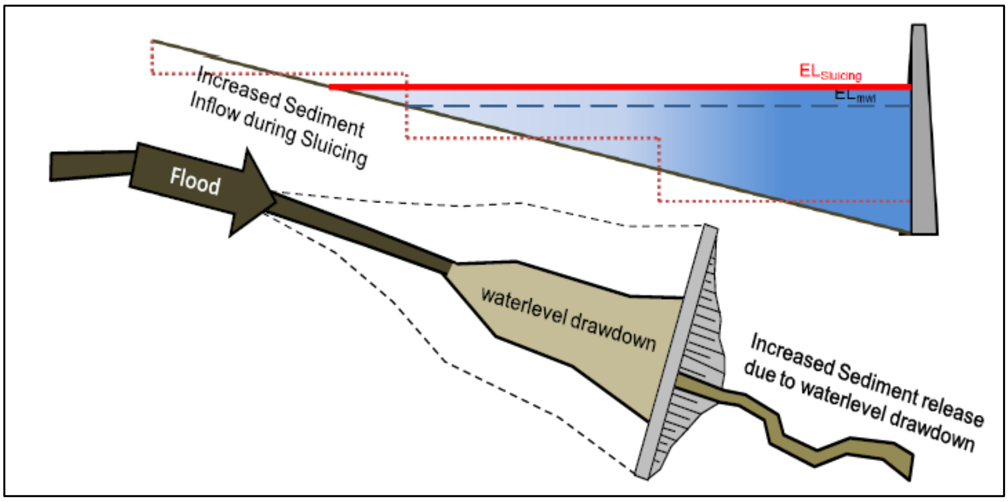


Figure 2.10: Schematic representation of Sluicing process in reservoir(Source:(Nikolaos Efthymiou, November 2016).

Bypass:

Sediment bypass in a reservoir is performed to divert sediment laden water around the reservoir. This results in minimizing the possibility of deposit in the reservoir. Typically, the sediment-laden water is diverted at a weir upstream of the reservoir into a high capacity tunnel or diversion channel, which conveys the water downstream of the dam to re-join the river(G. Mathias Kondolf, 2014).Diversion can be done for both on stream and off-stream reservoir. The conceptual representation of diversion process is shown in Figure 2.11 (a), (b) & (c). By-pass has some notable advantages such as, it delivers the coarse sediment to downstream and helps to minimize the river bed degradation. Another advantage is that, this method doesn't interfere normal operation of reservoir, which leads to uninterrupted water yield from the reservoir for its intended use. However, this method is not always feasible for all reservoir. Preliminary assessment done by Annandale (2013) indicates that, this method is appropriate for reservoir having hydrological capacity between 0.001 and 0.4, while the life of reservoir in between 20 and 500.

Topography around the reservoir is also equally important for implementing this method since, it is required to have feasible topography and geology for construction of diversion tunnel and channels. Also, reservoir length limits the applicability of this method since, by-pass tunnel more than 5000 m is not economically justified. This should be kept in mind while selecting this method for analysis in RESCON2.Results and analysis for by-pass scheme will be done for Banja Reservoir, in coming chapter.

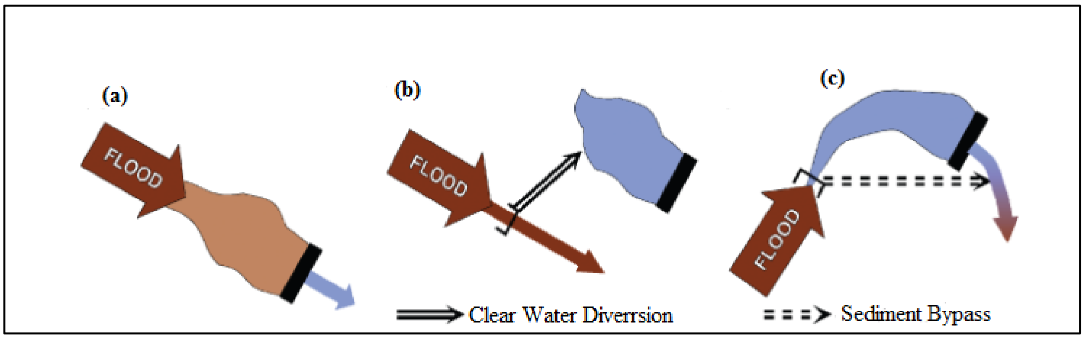


Figure 2.11: Schematic representation of By-pass (a) Approaching flood (b) Off-stream reservoir bypass (c) In stream reservoir bypass.(Source:(G. Mathias Kondolf, 2014)).

Density Current Venting:

Density Current is the gravity induced movement of one fluid under, through, or over another fluid, caused by density difference between two layers(Gregory L. Morris, 1998).Layers are created due to difference in density induced by temperature stratification in reservoir. Turbidity due to fine sediment in reservoir water is transported by temperature induced density current, plunge beneath the clear water. The Plunging current can move as an underflow over a long distance towards the dam to form a submerged muddy lake(Lee, Lai, Tan, & Sung, 2014).In long run , fine sediment deposit as muddy lake gets consolidated such that it cannot be released easily from the bottom outlet. However, the density current can be vented through low level outlets as it reaches the dam (Gregory L. Morris, 1998) as shown in Figure 2.12. As stated by Annandale (2013), density current venting can be appropriate for the reservoir having hydrological size between 0.1 and 10, while its life span between 300 and 100,000 years. In RESCON2, technical feasibility of this method is done by applying methodology proposed by Morris and Fan (1998).

One of the important criteria for this method to be feasible under given reservoir conditions is formation of density current. If the required flow depth at plunge point as shown in Figure 2.12 is smaller than the available flow depth in the reservoir, this means density current might occur, if not, its formation is not possible(Nikolaos Efthymiou, November 2016).

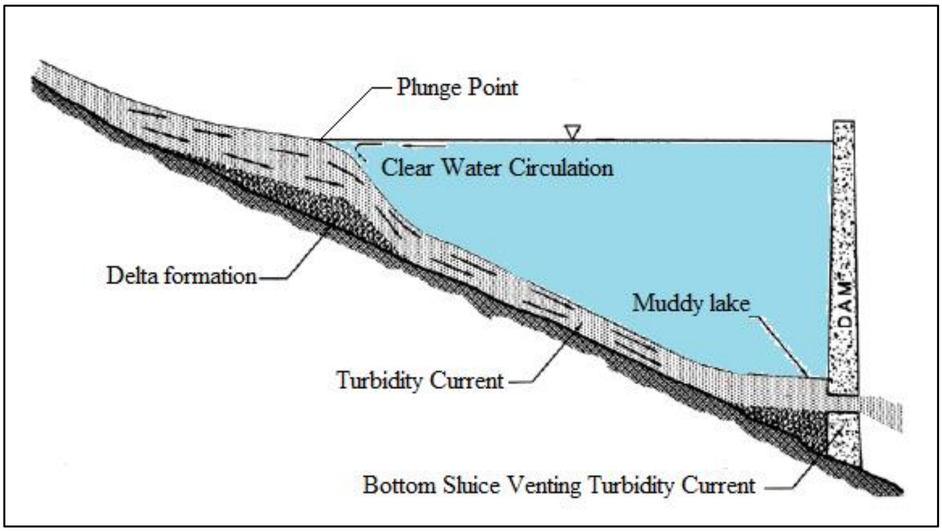


Figure 2.12: Density Current Venting in reservoir(Retrieved and edited:(Gregory L. Morris, 1998))

RESCON2 utilizes the iterative procedure presented by Morris& Fan (1998) for calculating the feasibility of this method. In the very first step, calculation of the water depth at the plunge point is done using the equation mentioned below:

$$h = \left(\frac{Q}{F_p B} \right)^{\frac{2}{3}} \left(\frac{\Delta\rho}{\rho} g \right)^{-\frac{1}{3}}$$

Equation 2-8

Where,

Q : Average Inflow Flow rate(m^3 / s)
B : Reservoir Bottom Width (m)
$\Delta\rho$: Density difference between clear and turbid water.
$\rho^{'}$: Density of turbid Water
ρ : Density of clear water dependent on Temperature.
F_p : Densiometric Froude number at the plunge point (obtained from different studies)

From the above calculation, it is determined whether density current is feasible for the given scenario. In next step, RESCON2 calculates the longitudinal slope of the reservoir bottom and the sediment load at the reservoir carried by density current venting. For determining the flow velocity of density current, following equation is used. Followed by calculating the maximum grain size that can be transported by the density current based on second order polynomial fitting proposed by Morris & Fan (1998) as mentioned in equation 2-10. Finally, deposition in reservoir and remaining storage is calculated to perform economic analysis of the reservoir to determine whether the density current venting is sustainable solution or not.

$$V = \sqrt[3]{\left(\frac{8}{f}\frac{\Delta\rho}{\rho}g\frac{Q}{B}S\right)}$$

Equation 2-9

Where,

S : Average reservoir longitudinal gradient at bottom.
f : Interfacial frictional effect including channel bed plus boundary layer. Default for RESCON2 is 0.025

$$d_{90} = -0.0085V^2 + 0.0395V - 0.0004$$

Equation 2-10

Where,

d_{90} : Maximum size of grain transported (mm)
V : Turbidity current velocity as calculated from Equation 2-9. (m/s)

Multiple Management Methods:

RESCON2 has ability to incorporate up to five above mentioned methods under multiple management strategy to the reservoir. The methods involved in the sediment management strategy are subjected to the same technical constraints as standalone application(Nikolaos Efthymiou, November 2016).

Selecting the multiple management methods and sequence of their implementation requires user's judgement and experience. Main aim of the combination of the methods is to obtain the sequence which yield highest net present value.

2.3 Application of RESCON2 to some example projects

As mentioned earlier, one of the objectives of this study is to be familiar with RESCON2 model and to be prepared for future implementation. As a part of Doctoral thesis at NTNU by Hari Shankhar Shrestha, in 2012, sustainability assessment of Kulekhani reservoir (Nepal) was done using RESCON model. From his study, he found the results from RESCON in compliance to the field test value (Shrestha, 2012).His work further arose curiosity to implement newer version of RESCON model .To achieve this, 10 different projects were analysed in RESCON2, provided by the World Bank and developers of model. List of the projects and their basic information are presented in Table 2-2, where coding is in accordance to the guidelines used by ICOLD, where H is hydropower, I is irrigation, S is drinking water supply and C is flood Control(ICOLD, 2011).Some of the important user inputs for each of the projects are presented in table in Annexe A.

Table 2-2: Example projects to understand RESCON2 model.

Project	Country/Region	Status	Scheme	Purpose	Code
Tarbela	Pakistan	Existing	Storage	HI	PRO.1
Mohammed V	Morocco	Existing	Storage	S	PRO.2
Upper Karnali	Nepal	Greenfield	R-O-R	H	PRO.3
Abdel Karim El Khattabi	Morocco	Existing	Reservoir	S	PRO.4
Bin El Quidine	Morocco	Existing	Reservoir	S	PRO.5
N/A	South East Asia	Existing	R-O-R with large existing reservoir	SH	PRO.6
N/A	Europe	Existing	Storage (reservoir in cascade system)	SH	PRO.7
Kaligandaki	Nepal	Existing	Peaking R-O-R	H	PRO.8
N/A	Asia Himalaya	Greenfield	Daily Peaking R-O-R	SH	PRO.9
N/A	Iran	Greenfield	Storage (no inactive storage)	HI	PRO.10

First task for each of the projects was to determine the possible sediment management options based on preliminary assessment criteria by Annandale (2013). In this study, assessment is done only based on hydrological capacity of reservoir, since life of reservoir is not available in each case. Results from this assessment are presented in Table 2-3

Table 2-3: Results from preliminary screening using Annandale (2013) Criteria

Code	Reservoir Capacity (Mill.m^3)	Res. length (m)	MAF (Mill. m^3)	C:I	MAS (MT/yr)	Potentially sustainable solutions
PRO.1	14350	88000	73800	0.194	194.3	CM,DG,TK,SB,DS,DCV
PRO.2	725.75	10500	750	0.968	12.8	DCV
PRO.3	17.86	9100	15667	0.001	31.5	CM,DG,TK,SB,DS
PRO.4	11.333333	1600	48	0.236	0.22	CM,DG,TK,SB,DS,DCV
PRO.5	1507.5	20000	1050	1.436	7	DCV
PRO.6	148	3500	2400	0.062	6.2	CM,DG,TK,SB,DS
PRO.7	2700	70000	6400	0.422	18	CM,DG,TK,SB,DS,DCV
PRO.8	7.7	5000	8211	0.001	41.05	FL,DG,HS,TK,SB,DS,DCV
PRO.9	6	6000	3300	0.002	4.4	FL,DG,HS,TK,SB,DS
PRO.10	1760	40000	5008	0.351	58	CM,DG,TK,SB,DS,DCV

Where, in the Table 2-3, CM stands for Catchment Management method, similarly, FL: flushing, DG: Dredging, HS: Hydro suction sediment removal, TK: Trucking, SB: Sediment By-pass, DS: Drawdown sluicing, DCV: Density current venting. Same notation will be used in coming tables and figures in this report.

Table 2-3 is based on only one parameter i.e. Capacity inflow (C: I). From preliminary assessment, 80% of the projects have capacity inflow ratio in the range of 0.001 to 0.4, thus the methods feasible for those projects are trucking, dredging, sediment by-pass, drawdown sluicing and density current venting, which means that these methods are applicable in wide range of projects and are the most common. Followed by Catchment management method, which can be feasible for 6 projects. Only 2 of the projects have very small C: I in the range of 0.0001 to 0.04, thus flushing and hydro suction sediment removal method seem to be feasible. However, there are additional technical constraints for each method as discussed in section 2.2.2. In RESCON2 model all other possible constraints are defined and analysed for each project and summarised as most attractive project based on highest net present value(NPV). For non-sustainable solution, yet technically feasible, this model evaluates whether to adopt decommissioning of the project or to continue as Run-of- river (R-O-R).

Results from RESCON2 for each project along with strength and weakness of the model is discussed in following section.

Table 2-4: RESCON2 results for example projects.

Project Code	Technically Feasible options	Most Attractive (Highest NPV)		
		Sustainable solution	Non-sustainable: Decommissioning	Non-sustainable: R-O-R
PRO.1	CM,FL,BP,DCV,DG,TK	DG	CM	DS
PRO.2	CM,DS,BP,DCV,FL,DG,TK	FL	DS	-
PRO.3	DG,CM,DS,FL,TK,BP	DG	NA	NA
PRO.4	CM,DS,BP,FL,HS,DG,TK,DCV	FL	NA	-
PRO.5	DG,CM,DS,BP,DCV,TK	DG	CM	-
PRO.6	DG,HS,CM,DS,BP,FL,TK	DG	HS	NA
PRO.7	FL,CM,DS,BP,DCV,DG,TK	FL	CM	CM
PRO.8	DG,HS,CM,DS,BP,TK	DG	HS	NA
PRO.9	CM,DS,BP,FL,DG,TK	DG	CM	NA
PRO.10	FL,DS,CM,BP,DG,TK,DCV	FL	DS	DS

Where, NA stands for no action, means none of the sediment management strategy is applied. This is the baseline for comparing and evaluating the other methods applied to the project.

For each of the above examples, some of the strength and weakness for evaluating in RESCON2 are presented as below.

PRO.1:

According to Annandale (2013) flushing is not feasible option for this project. Result from RESCON2 has shown that flushing is technically feasible. The reservoir can maintain sediment balance ratio of 7.58 which is a good indicator. Apart from SBR, the reservoir also satisfies the other conditions related to DDR,FWR SBR_d as mentioned in Table 2-1.Dredging option is the most attractive, but , the weakness of RESCON2 is that it considers dredging can remove any quantity of deposits. Calculations from RESCONS has shown that, dredging should remove 1296 million m^3 of sediment per dredging event planned in 10 years.

PRO.2:

For this project, except HSRS, all other sediment management options are feasible. HSRS is not feasible since the reservoir length is 10,500 m which is higher compared to maximum feasible length of 5,000 m. Based on this criterion, RESCON2 eliminates this method for further analysis. As per Table 2-3, density current venting is only sustainable solution, but RESCON2 evaluates other methods and evaluates on the ground of different criteria as mention in section 2.2.2 and finally concludes that flushing is the only sustainable solution to this project.

PRO.3:

Sluicing, by-pass, dredging, flushing and trucking are the sustainable solutions for this project. Among them, dredging is the most attractive option. This result almost match to the preliminary assessment done by Annandale (2013) criteria. Here, maximum amount of sediment removed per dredging event is 6.3 million m^3, which is acceptable compared to maximum limit of 11 million m^3.

PRO.4:

Flushing is the most promising and sustainable solution for the project as evaluated by RESCON2. Based on hydrological reservoir size, flushing may not be the sustainable solution as in Table 2-3. RESCON2 has powerful calculating ability to consider all relevant criteria to assess flushing feasibility and hence concludes it to be sustainable solution to the reservoir. Apart from this, dredging and trucking are also sustainable solution.

PRO.5:

This project comprises reservoir having Capacity inflow ratio (C:I) 1.43, due to which, according to Annandale (2013), density current venting is only sustainable solution. However, RESCON2 evaluates the density current venting on the ground of Equation 2-8,Equation 2-9& Equation 2-10, and finally concludes that density current venting is not technically feasible for this project. Thus, it can be said that RESCON2 model has scientific basis for evaluating any method.

PRO.6:

Referring results in Table 2-3, Catchment management, dredging, trucking, sediment by pass and sluicing are the sustainable solutions to the given reservoir. However, RESCON2 takes other physical and economical inputs to the project under and evaluates the project. From RESCON2 evaluation, dredging, trucking and flushing are the sustainable solution options.

Catchment management and by-pass options are no more sustainable solution based on their economic performance.

PRO.7:

Almost all methods are applicable to this project, however, considering the results of RESCON2, only Flushing, dredging and trucking are sustainable solution. Contrary to the preliminary assessment results in Table 2-3,RESCON2 has powerful ability to evaluate flushing option and finally it is most sustainable solution to this project.

PRO.8:

According to Annandale (2013), flushing is the sustainable solution for this project having Capacity inflow ratio of 0.001. But from the evaluation by RESCON2, flushing is not technically feasible due to higher annual sediment inflow and lower capacity of flushing limited by flushing discharge. While Density current venting is not feasible on the ground of inability to formation of density current.

PRO.9:

On evaluating this project in RESCON2, Sluicing, by pass, flushing, dredging and trucking are the sustainable solutions. While, catchment management, despite begin technically feasible, can no longer be sustainable solution based on economic performance calculated by RESCON2.Though, Table 2-3 reflects that density current venting can be sustainable, RESCON2 calculated the technical feasibility of density current venting as per the equations mentioned in section 2.2.2. Finally, it's not possible to form density current in this project set up and hence eliminates this method for further evaluation.

PRO.10:

Considering only the reservoir size for this project, Flushing is not feasible option as mention in Table 2-3. However, analysis based on available reservoir information, hydrological and sedimentological data, RESCON2 can evaluate this option in detail and finally found flushing option to be most attractive sustainable solution of all. Thus, this depicts the strength of RESCON2 to evaluate sediment management options under specified scenario.

2.4 Discussion and Conclusion

From the discussion for individual projects in section 2.3, some of the findings can be generalised and can be taken as useful learnings for future application of the model. Flushing and dredging in general are the most sustainable methods to the projects under consideration. RESCON2 has strong theoretical basis for evaluating flushing, which might be the reason that the model justified the usefulness of flushing to most of the projects. Sediment routing methods are introduced in RESCON2 model, their technical feasibility and economic viability are also well justified as we have seen that in most of the case, bypass, sluicing and density current venting are sustainable solution. However, due to capital cost associated with them, as well as operation maintenance cost being higher and amount of sediment excluded comparatively lower, these methods are less attractive to the projects under consideration compared to sediment removal techniques. Catchment management option has been simplified for analysis based on very little information, is also not effective solution for immediate results. But can be very useful in long run. Since this method in most of the above cases requires higher cost for implementation and subsequent benefit is not achieved immediately, Net present value is generally low and cannot compete to the methods which have immediate effects for instance flushing, trucking, HSRS and dredging.

Data set required for the project is comparatively simple and easy to prepare since most of the inputs can be easily obtained from the technical reports and simple calculations on hydrological data series. Whether the project is existing or upcoming i.e. greenfield, model is equally applicable. For upcoming projects, its results can be guidelines for incorporating the relevant sediment management methods in overall planning and design of the project. While, for existing projects, its results can be useful for selecting and implementing the sediment management strategies to achieve the sustainability of the reservoir.

Finally, evaluating 10 projects having differences in purpose, size, geographical location, hydrological and sedimentological characteristics in RESCON2, one of the objective of this study was achieved. This process helped author to getting used to the model and gain confidence for further implementation to Banja Reservoir.

Chapter 3 : SEDIMENT YIELD ESTIMATION

3.1 Sediment yield estimation in practice

Sediment yield refers to the amount of sediment exported by a basin over a period, which is also the amount which will enter a reservoir located at the downstream(Gregory L. Morris, 1998).Estimate of the amount of sediment transported by rivers are important for evaluating the impacts of reservoir sedimentation (George W.Annandale, 2016).Sediment yield estimation is one of the challenging task for any catchment, since, there is no any absolute model that can estimate the yield exactly. However, from ages long research and field experiments, lots of models have been developed by different scientists and engineers around the world.

Zingg(1940) is often credited with the development of the first erosion prediction equation to evaluate erosion problem (Agassi, 1996). By 1950s, different regional equations to predict soil erosion were developed in United states(U.S.). Later on, W.H.Wischmeier, D.D. Smith and associates began to assemble and analyse data from more than 10,000 plots in U.S.and came up with Universal Soil Loss Equation(USLE).This method was originally introduced for computing factor values for range, woodland and similar land uses as experimental plot(Agassi, 1996),so its application was limited. In the meantime, different approaches were developed to improvise the model. The Pacific Southwest Interagency Committee(1968) developed PSIAC method for use in western United States, which considers the yield contribution from all types of erosion sources, and not just surface erosion as in the USLE.(Gregory L. Morris, 1998).Modified Universal soil loss equation(MUSLE) by Williams,1975, Areal Nonpoint Source Watershed Environmental Resources Simulation (ANSWERS) by Beasley *et al.*,1980,Unit Stream Power based Erosion Deposition (USPED) by Mitasova *et al.*,1996 are other examples. Meanwhile, in U.S. Department of Agriculture (USDA), revised Universal soil loss equation(RUSLE), was developed by Renard *et al.*, 1997.

RUSLE method became landmark in estimating the soil loss from a catchment, and sediment yield is simply estimated by multiplying the soil loss value with the sediment delivery ratio(SDR) of the catchment. SDR is expressed as the percentage of gross soil erosion by water that is delivered to a point of interest in the drainage system. Thus, combining the soil loss estimation using RUSLE with SDR became a powerful tool in estimating the sediment yield.

So far, lots of computer based application and regional models have been developed based on RUSLE for sediment yield estimation.

Considering the simplicity of use and availability of data, RUSLE model in GIS application has been developed for Banja catchment during this study, which will be presented in detail in section 3.3.

3.2 Estimation using BQART Model

RESCON2 has built in tool to calculate the sediment yield using BQART model, from the catchment where data is limited and quick assessment is required. BQART model developed by Syvitski & Milliman (2007), incorporates many of the basin scaling relationship between basin properties, including area, relief, temperature, runoff, lithology and ice cover(J. P. M. Syvitski 2008) .The equation for estimation of sediment load by BQART model is as following:

$$Y_s = \begin{Bmatrix} w \times B \times Q^{0.31} \times A^{0.5} \times R \times T \ \ for \ T \ \geq 2^o C \\ 2w \times B \times Q^{0.31} \times A^{0.5} \times R \times T \ \ for \ T \geq \ 2^o C \end{Bmatrix}$$

Equation 3-1

Where, Y_S: Long term mean annual total sediment load , w: constant for sediment load unit transformation(0.02 for load in unit kg/s, 0.0006 for Million ton/year), Q : Mean annual water flow (km^3/year), A: Basin area (km^2), R: Maximum relief of drainage basin (km) , T : Basin average temperature (degree Celsius), B :Term accounting influence of geological condition.

To compare the results from RUSLE model as in section 3.3, BQART model was applied to Banja reservoir.

Inputs and results from the model are summarised in Table 3-1.

BQART model estimates, the annual total sediment mass inflow to Banja reservoir is 2.08 Million tons/year. This value will be compared to RUSLE estimate in next section. Considering the extend of data available for preliminary assessment, this estimate can be considered reasonable.

Table 3-1: Inputs to BQART model and result in RESCON2

Description	Value	Source
Drainage Area[km²]	**2895**	(Norconsult,2010a)
Maximum Basin Relief[km]	**2.38**	DEM, Figure 1.3
Average Basin Temperature[°C]	**14.7**	(Norconsult,2011)
Basin averaged lithology class	**2****	Global map, Average basin lithology
Ice cover as percentage of total drainage area (%)*	**7**	Calculated(Norconsult,2010a)
Basin Trap Efficiency (%)	**50**	Global Map, basin trap efficiency
Basin human-influenced soil erosion class	**Mixed**	Assumed
Mean annual Total) sediment inflow mass. (mill. Tons/year)	**2.08**	Calculation in RESCON2

Note: * Estimation of ice cover percentage done by considering 1750 m as snowline in Albania (Emil Gachev, 2012) and hence calculated from the topographic map.

** Class 2 refers to sedimentary rock, unconsolidated sedimentary cover and alluvial deposit.

3.3 Estimation using RUSLE Model:

Erosion and sedimentation caused by water involve the process of detachment , transport and deposit of soil particle (Foster 1982).Erosion may be unnoticed in exposed soil surface despite the fact that raindrops are eroding the soil materials, but it can be dramatic in such regions where concentrated flow creates rill and gully system(K.G. Renard, 1997).Renard and Foster 1983 summarised the factors affecting the erosions in the form of Equation 3-1.

$$E = f\,(C,S,T,SS,M)$$

Equation 3-2

Where, Erosion (E) is the function of C: Climate, S: soil Properties, T: Topography, SS: Soil Surface conditions and M: Human activities. This equation is the foundation for developing the Universal Soil loss equation by quantifying the factors and finally the equation was revised to RUSLE.

The Revised Universal Soil Loss Equation (RUSLE) is an erosion model predicting long term average annual soil loss (A) resulting from rainfall and runoff over a land having specific slope and cropping and management systems(K.G. Renard, 1997).The equation for predicting the annual soil loss by RUSLE model is as shown in Equation 3-3.

$$A = R \times K \times LS \times C \times P$$

Equation 3-3

Where,

A : Average Annual Soil Loss ($tons / ha \times Year$)
R : Rainfall-Runoff Erosivity Factor ($(MJ \times mm) / (ha \times h \times year)$
K : Soil Erodibility factor ($(\text{tons} \times \text{h})/(\text{MJ} \times mm)$
LS : Slope Length and Steepness factor (Unit less)
C : Cover Management Factor (Unit less)
P : Support Practice factor (Unit less)

These factors can be easily quantified from the various data types. Generalised approach in determining the factors for RUSLE model and calculating the Average annual soil loss for the basin in Arc GIS platform is shown in Figure 3.1.

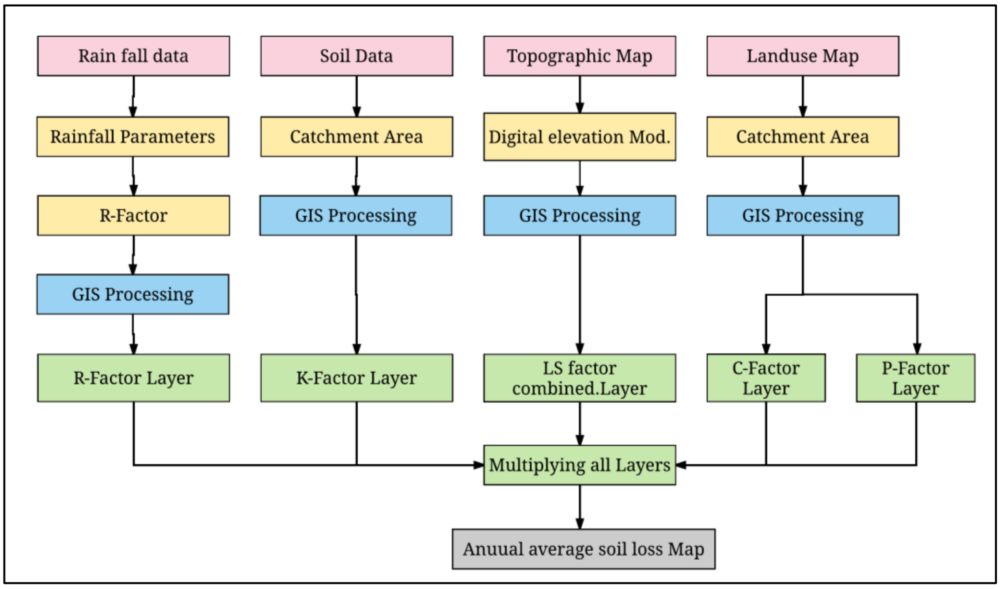


Figure 3.1: Methodology for RUSLE factors preparation and computation in Arc GIS.

To estimate the average annual soil loss in Devoll river basin and hence to estimate the Sediment yield to Banja reservoir, RUSLE model has been prepared. Previously, Marc Omelan (2015) as a part of his Master thesis estimated annual sediment yield in Devoll river basin by RUSLE model having resolution of 81 m × 81 m and found annual sediment yield value of 8.8

million tones/year. As one of the aim of this study is to evaluate the sediment yield under climate change scenario as mentioned in Figure 1.1, section 1.3, all other factors are taken constant while the change in R factor due to immediate change in rainfall is recalculated and hence annual soil loss map is recalculated for new Scenario. Compared to model by Omelan (2015), it is expected to get new LS factor for revised cell size of 50 m × 50 m and change in total soil loss in future is anticipated.

Individual factors for RUSLE model in Devoll River basin are discussed below:

R-Factor:

In order to evaluate the Rain fall erosivity factor (R-factor) for Devoll catchment, rainfall data for the catchment measured at 20 meteorological stations from the period of 1950-1995 was used as the baseline scenario and applied the delta change in annual precipitation according to the results from climate change scenario generated from climate change Knowledge portal (CCKP)(http://sdwebx.worldbank.org/climateportal) by World Bank.

From the historical data set, the average annual rainfall for each station was calculated and considered as present situation. To evaluate rainfall, change due to climate change by 2050, results from 3 different emission scenarios Viz. A1b, A2 and B1 using 22 different Ground Circulation Models(GCM) for the time of 2050-2059 was considered and it was found that there will be decrease in annual precipitation by 7.3%. Results obtained from CCKP can be found in Annexe B.

In addition to this, results from the climate change study on Devoll River Basin by Christian Almestad (2015) as a part of his Master thesis, are also compared to the results from CCKP. Christian considered Representative Concentration Pathway (RCP) scenario, RCP4.5 and found the annual precipitation change in the order of – 10% to -15% in year 2046-2065. Summary of the results from two different sources are presented in Table 3-2.

Table 3-2: Summary of Climate change in Devoll River Basin (Source: CCKP)

Average Change in Annual Precipitation (%)	-7.3
Average Change in Annual Runoff (%)	-9.6
Average Change in Temperature(Absolute)	2.1

Table 3-3: Precipitation and Temperature change in Devoll according to RCP4.5(Source:(Almestad, 2015))

Months	2016-2035	2046-2065	2081-2100
Oct-Mar (%)	-10	-10	-10
Apr-Sep (%)	-10	-15	-20
Avg. Annual temp.change(^{0}c)	1.1	1.9	2.4

Results from both sources as mention in Table 3-2, 3-3 have shown that there will be decrease in annual rainfall in Devoll River basin by 2050 due to climate change. For calculation of R factor, change in annual rain fall by 7.3 % resulted from CCKP is considered keeping in mind that the results from RUSLE model is the input for RESCON2 developed by World Bank. Annual rainfall after climate change by 2050 calculated simply by reducing by 7.3% for all basins is summarised in Table 3-4 along with the present annual rainfall.

Once annual rainfall for each meteorological stations were calculated, R factor was estimated using simple models proposed by Torri et al.(2006) Equation 3-4 , and model for Tuscany used by Grimm et al (2003) Equation 3-5 as discussed in (Nazzareno Diodato, 2010).

$$R_{Torri} = b_O \times P + b_1$$

Equation 3-4

Where ,P is annual average rainfall (mm), b_O is 1.99 $MJh^{-1}ha^{-1}$ and b_1 is -278 $MJmmha^{-1}h^{-1}y^{-1}$ (Nazzareno Diodato, 2010).

$$R_{Tuscany} = a \times P$$

Equation 3-5

Where a is in the range of 1.1 to 1.5. However, for this study considering the Mediterranean climate, 1.2 value was used.Using Kriging Interpolation tool in ArcGIS, R- factor map of 50m× 50 m cell size was created as in Figure 3.2. Summary of R factors for each meteorological station is as shown in Table 3-5.

Table 3-4: Present and Future Annual Precipitation in Devoll basin meteorological stations

ID	Weather Station	Record Period	Present Annual Preci.(mm)	Future Annual Preci.(mm)
1	Bilisht	1950-1994	660	612
2	Dardhe	1950-1998	1001	928
3	Dushar	1950-1992	1332	1235
4	Gjinar	1950-1992	1870	1733
5	Grabove	1950-1998	1273	1180
6	Gramsh	1950-1991	1095	1015
7	Jaronisht	1950-1995	1292	1198
8	Kokel	1961-1992	1007	933
9	Korca	1950-1994	660	612
10	Kucove	1950-1994	863	800
11	Kukur	1950-1994	1235	1145
12	Lemnush	1950-1993	969	898
13	Maliq	1950-1981	732	679
14	Miras	1961-1992	821	761
15	Pojan	1950-1961	919	852
16	Prenjas	1950-1992	1175	1089
17	Sheqeras	1953-1999	603	559
18	Ujanik	1957-1994	1320	1224
19	Voskopoje	1950-1999	945	876
20	Zvirine	1950-1991	681	631

Table 3-5: R-factor calculated for each Meteorological station

ID	Weather Station	Annual Prec.(mm)	Torri	Tuscan	Average, R
1	Bilisht	612	939.5	734.2	836.9
2	Dardhe	928	1568.6	1113.5	1341.0
3	Dushar	1235	2179.2	1481.7	1830.4
4	Gjinar	1733	3171.6	2080.2	2625.9
5	Grabove	1180	2070.3	1416.1	1743.2
6	Gramsh	1015	1742.0	1218.1	1480.0
7	Jaronisht	1198	2105.4	1437.2	1771.3
8	Kokel	933	1579.6	1120.2	1349.9
9	Korca	612	939.5	734.2	836.9
10	Kucove	800	1314.0	960.0	1137.0
11	Kukur	1145	2000.2	1373.8	1687.0
12	Lemnush	898	1509.5	1077.9	1293.7
13	Maliq	679	1072.3	814.3	943.3
14	Miras	761	1236.5	913.3	1074.9
15	Pojan	852	1417.3	1022.3	1219.8
16	Prenjas	1089	1889.6	1307.1	1598.3
17	Sheqeras	559	834.4	670.8	752.6
18	Ujanik	1224	2157.0	1468.4	1812.7
19	Voskopoje	876	1465.3	1051.2	1258.2
20	Zvirine	631	978.3	757.5	867.9

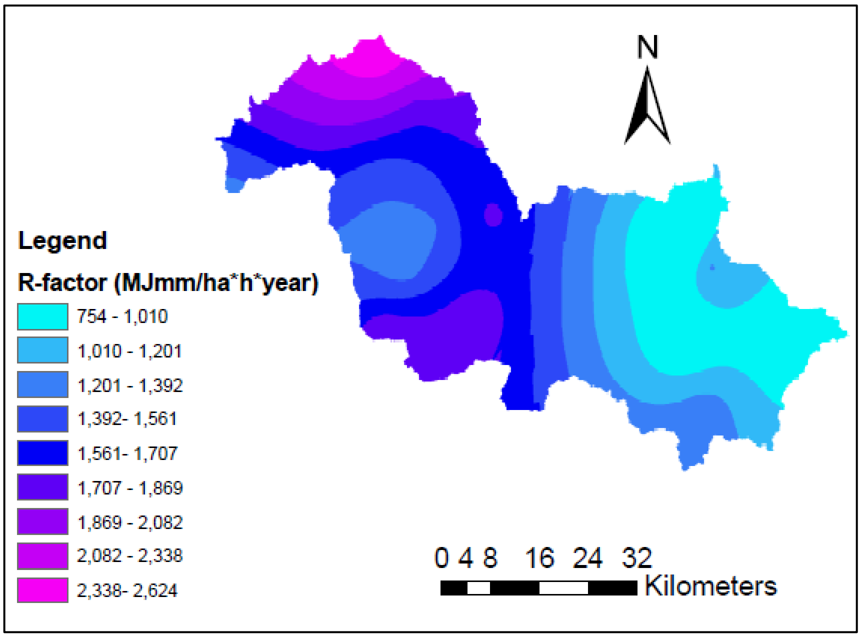


Figure 3.2: R- factor map for Devoll River Basin

K-Factor:

As mentioned in Equation 3-1, erosion is dependent on the soil characteristics in the region under consideration. K factor express the susceptibility of soil to erode, related to various soil properties such as organic matter content, texture, permeability etc. In practical sense, K is a lumped parameter representing an integrated annual average of soil and profile reaction to erosion and hydrological process(K.G.Renard, 2010).Estimating K value is a challenge due to availability of data set and specific methodology. However, Wischmeier & Smith in 1978 proposed Nomograph, which can estimate value of K based on five soil parameters for the region where USEL was developed in United states. For reference, Nomograph is included in Annexe B.

For Devoll River basin in Albania, one of the source to estimate the K factor is to make use of high resolution soil erodibility map of Europe which was developed from Land use/Cover Area frame Suvey in 2009, consisting of about 20,000 Points across member states(Panos Pangos, 2014).From the study, average soil erodibility factor for Europe is found to be 0.032 tons *h/MJ*mm.500 m cell size data set for Devoll river basis has been obtained and processed by Marc Omelan in his master thesis ,so for this study, his data layer was used and resampled to 50 m × 50 m cell size so as to match the resolution of DEM.

Soil Erodibility factor (K-factor) used for this model is as shown below:

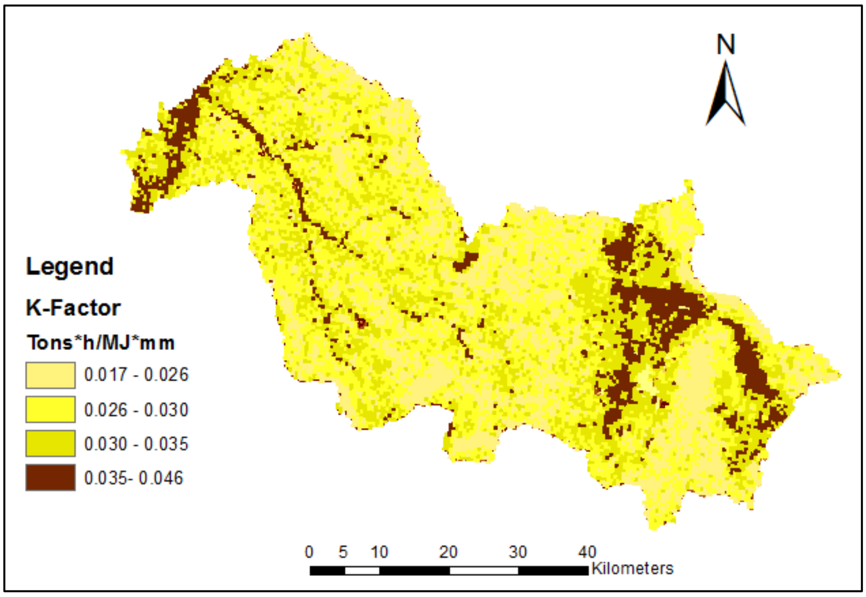


Figure 3.3: K-factor map for Devoll River Basin

From Figure 3-3, it can be said that the soil erodibility in the Devoll river Basin ranges from 0.017 to 0,046 ton*h/MJ*mm with average value of 0.029 ton*h/MJ*mm. Higher values are towards the eastern and north western region. From the Study and field visit by Marc Omelan (2015), it was found that the region consists of about 62% of heavy clay, sandy loam, loamy fine sand, while 36 % comprises clay loam, silty clay, loam, and rest 2% loamy very fine sand, silt loam, very fine sandy loam, and silty clay loam.

LS-Factor:

Slope steepness factor (S) and Slope Length factor (L) are the factors that depend upon the topography of the region under consideration. L-factor is the ratio of soil loss from slope length relative to standard erosion plot length of 22.1 m. Actual slope length which is the horizontal distance of the plot is calculated by the equation proposed by ((K.G. Renard, 1997)) as below.

$$L = \left(\frac{\lambda}{22.1} \right)^m$$

Equation 3-6

Where, L is the slope length factor, λ is the actual slope length and m is the slope length exponent which is expressed as ratio of rill to inter rill erosion. Similarly, the Slope steepness factor(S) is the ratio of soil loss relative to 9% slope used as a standard slope in plots used for developing Universal Soil Loss Equation .S- factor can be calculated as function of slope using the equation by McCool *et.al* (1987) (K.G. Renard, 1997).

$$S = \begin{cases} 10.8 \times \sin(\theta) + 0.03 \; for S < 9\% \\ 16.8 \times \sin(\theta) - 0.5 \; for S \geq 9\% \end{cases}$$

Equation 3-7

On the basis of these equations, Unit Stream Power based Erosion Deposition model(USPED) has been developed which can predict the erosion and deposition rate for steady state overland flow with uniform rainfall excess conditions for transport capacity(Helena Mitasova, 1996).This model estimates the LS factor using the equation proposed by Moore and Bruch(1986a) as follows:

$$T = \left(\frac{A}{22.13}\right)^m \times \left(\frac{\sin\beta}{0.0896}\right)^n$$

Equation 3-8

For simplicity, USPED has developed algorithm based on Moore and Bruch (1986a) equation to calculate the LS factor using the DEM for the area. Same algorithm has been followed to prepare the LS Factor map for Devoll River Basin. Algorithm for LS factor calculation in Arc GIS is as mentioned in Equation 3-9.

LS= Power ("Flow_accumulation_layer" × cell Size /22.1,0.4) × power(sin("slope_degree_Layer"*0.01745)/0.089,1.4) × 1.4

Equation 3-9

Using DEM of 50 m cell size, Flow direction map followed by flow accumulation map were created using the hydrology tool under spatial analyst tool in ArcGIS. Both maps are in Annexe B, for reference. Again, slope map in degree was created using spatial analyst tool. Finally, using Equation 3-9, LS factor was calculated and a layer generated presented as below:

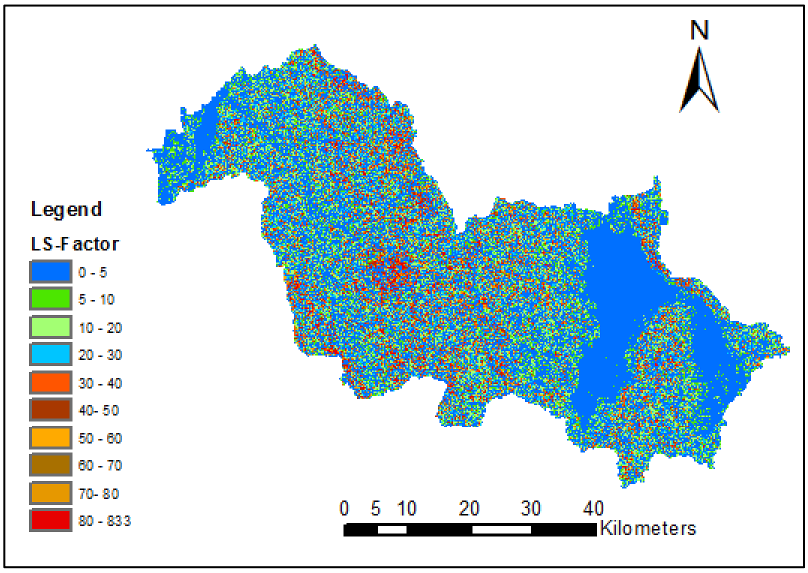


Figure 3.4: LS factor map for Devoll River Basin

From Figure 3.4, it was found that the LS factor in about 30% of area ranges from 5 to 10. While 95% of the area has LS value less than 20. In an average, LS factor for the basin is 15.

C-Factor

Cover management Factor (C-factor) ranges from 0 to 1 and is the ratio of soil loss from land cropped under specified continuous fallow condition and is perhaps the most important terms in RUSLE because it represents conditions that can be managed most easily to reduce soil erosion(Agassi, 1996).C factor of 0.2 means there will be 20% of erosion compared to continuous fallow conditions. C factor is related to vegetation percentage and it depends on vegetation type , cover management and stage of growth(WH Wischmeier, 1978).

Determining C factor is one of the challenging task since the accuracy of the value depends on field measurement and good land use data. For this study, field visit was not possible and hence the cover management map produced by Marc Omelan (2015) has been used for RUSLE model. The values of C factor in Devoll River Basin were determined based on CORINE Land Cover 2006 (CLC) database on a scale of 1:1000000(Omelan, 2015).From the land cover data set, Devoll is divided into 24 CLC classes presented in table in Annexe B. And appropriate C factor values determined to each class. Finally using the land use shape file in ArcGIS, C factor map was generated and presented as below:

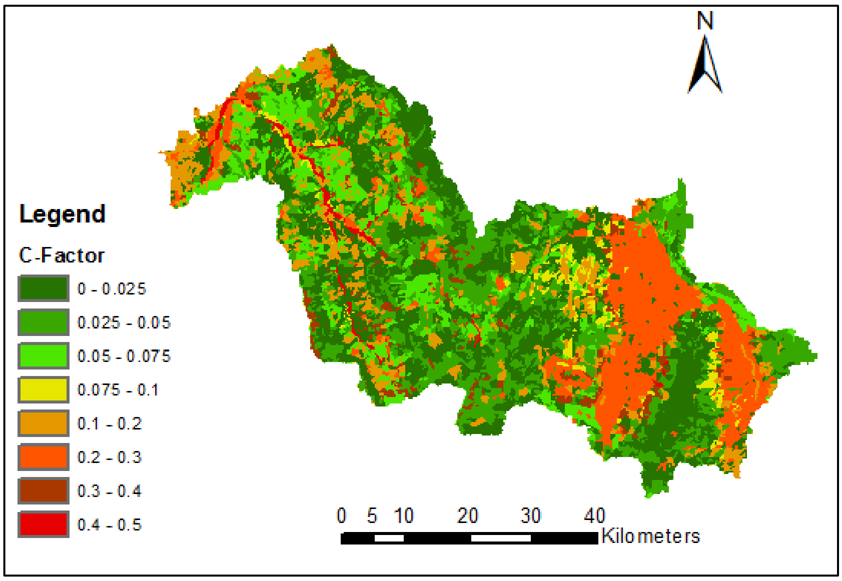


Figure 3.5: C-factor map for Devoll River Basin(Modified from ,Omelan,2015)

From Figure 3-5, it is found that the C factor in Devoll River basin ranges from 0 to 0.5., with mean value being 0.089. About 80% of the value lies in the range of 0 to 0.075. This means the soil erosion compared to condition fallow condition is not high.

P-Factor

Support practice factor (P factor) is the ratio of soil loss with specific support practice to the corresponding loss with up and down slope conditions, P factor mainly represents the effect of surface conditions on flow path due to the practice cultures such as contouring, tillage marks etc. Support practices such as improved tillage practices, sod-based crop plant rotations, fertility treatments and larger extents of crop residues left on the cultivation field contribute to control of soil erosion(WH Wischmeier, 1978).There are two different methods to identify the P factor, one of them is based on agricultural practice with regards to land use map and other is based on the relation between practices and slope(Omelan, 2015).

Range of P factor is between 0 to 1 depending upon the soil management activities. Value 1 corresponds to area having no support practice while minimum value is assigned to built-up-land and plantation area with strip and contouring practice. Thus, lower value is most efficient practice for the area. Marc Omelan(2015) prepared the P factor map based on relation between contouring and slope for Devoll river basin in his study. Due to limitation of data, his map is further considered for RUSLE model. Support practice factor classified for Devoll river basin is as in Table 3-6.

Table 3-6: Support practice factor according to types of Cultivation and slope (Shin ,1999)(Omelan,2015)

Slope (%)	Contouring	Strip Cropping	Terracing
0.0-7.0	0.55	0.27	0.1
7.0-11.3	0.6	0.3	0.12
11.3-17.6	0.8	0.4	0.16
17.6-26.8	0.9	0.45	0.18
>26.8	1	0.5	0.2

Using the slope map estimated in percentage using DEM for Devoll river basin, values for P were added as per Table 3-5 and hence P factor map was generated and resampled to 50 m × 50 m cell size.

As shown in Figure 3.6, support practice factor for Devoll river Basin ranges from 0.55 to 1 with an average of 0.85. The results show that the biggest portion of catchment has P value in the range of 0.8 to 1. This means the support practice is not so prominent thus this can accelerate the erosion.

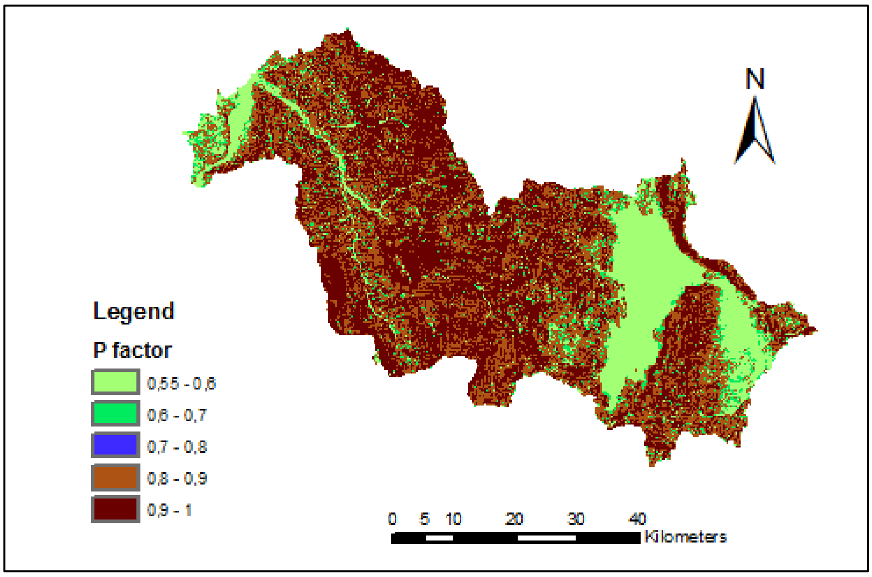


Figure 3.6: P-factor map for Devoll River Basin (Modified from, Omelan,2015)

Annual Soil Loss Map (A)

After all the factors for Devoll catchment were prepared in ArcGIS, annual soil loss (tons/(ha*year)) for the whole catchment was calculated by using the raster calculator to multiply the layer under same projection system and same cell size of 50 m ×50 m. The result from ArcGIS is presented in the following figure 3.7.

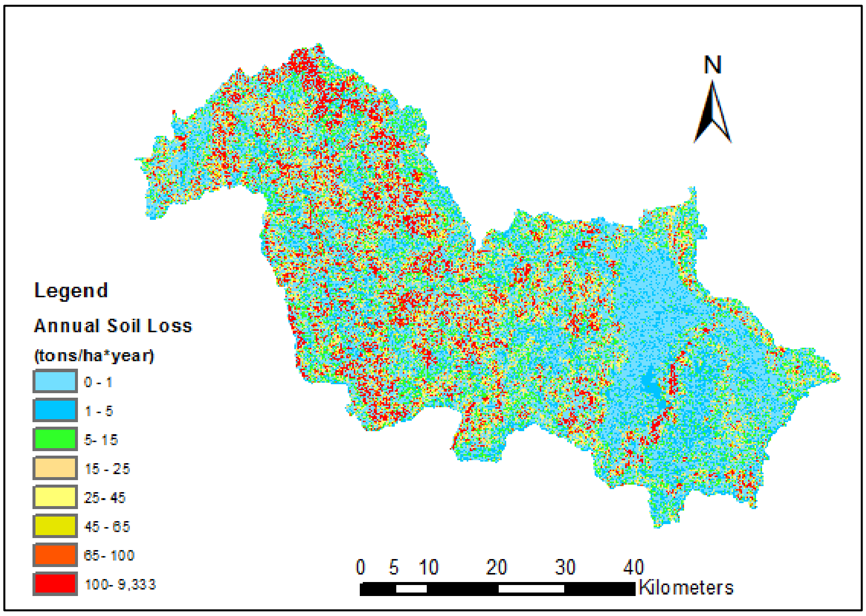


Figure 3.7: Annual Soil Loss (tons/ha*year) map for Devoll River Basin

From Figure 3.7, it can be said that the annual soil loss in Devoll River Basin is higher towards the North-West region which is up to 9333 tons/ha*year. In average, annual soil loss is 38.9 tons/ha*year. In most of the region the soil loss is low and lies in the range of 1 to 15 tons/ha*year.

Sediment Delivery Ratio(SDR)

Sediment delivery ratio represents the fraction of the material eroded from a site which reached the downstream where it is measured. For an entire basin, it represents the ratio of gross erosion within a watershed to sediment yield during the same period(Gregory L. Morris, 1998).Generally ,SDR is expressed in percentage and is higher for small catchment having steep slopes and composed of fine grained materials. From the literature, it can be found that lots of studies have been done to estimate the sediment delivery ratio for different catchment around the world. From those studies, some of the models have been proposed, which estimate the sediment delivery ratio based on the catchment area. For instance, Renfro (1972) developed an equation relating SDR values mainly with the drainage area observed in 14 watersheds in Black land Prairie area in Texas (Demetris Zarris, 2011).The model can be written as follows:

$$\log SDR = 1.7935 - 0.14191 \times \log A$$

Equation 3-10

Where A is catchment area in km^2.

From the study by Zarris et al. (2011) in Nestos River Basin in Bulgaria and Greece, it was found that the estimated SDR in the basin is in good correspondence to the value estimated by equation 3-10, Thus, for this study, this equation is adopted to calculate SDR, since Greece and Bulgaria have almost similar climate to Albania.

Further, more models were considered for estimating SDR for Devoll river basin. Among them, model by power function developed by Vanoni (1975), which was developed from the data from 300 watersheds throughout the world. The model is as follows:

$$SDR = 0.4724 \times A^{-0.125}$$

Equation 3-11

Furthermore, relations developed by USDA (1972) and Boyce (1975) can be used to estimate the SDR for Devoll river Basin. The models are as below:

$$SDR = 0.5656 \times A^{-0.11} \text{ (USDA)}$$

Equation 3-12

$$SDR = 0.375 \times \grave{A}^{-0.2382} \text{ (Boyce)}$$

Equation 3-13

Where, A is in km^2.

Using Equation 3-10,3-11 & 3-12, the Sediment delivery ratio for each sub catchment was calculated and summarised in Table 3-7.

Table 3-7: Summary of SDR calculated for Devoll river basin and its sub-basins.

Name		Catchment area(km^2)	Renfro Model	Vanoni Model	USDA model	Boyce model	Average
Devoll R. Basin		3119	0.20	0.17	0.23	0.06	0.16
Banja Reservoir.		2895	0.20	0.17	0.24	0.06	0.17
No	**SubBasin**						
1	Miras	89	0.33	0.27	0.35	0.13	0.27
2	Shequeras	341	0.27	0.23	0.30	0.09	0.22
3	Turhan	272	0.28	0.23	0.31	0.10	0.23
4	Gjinikas	654	0.25	0.21	0.28	0.08	0.20
5	Posthme	63	0.35	0.28	0.36	0.14	0.28
6	Kokel	459	0.26	0.22	0.29	0.09	0.21
7	Tomorrice	376	0.27	0.23	0.29	0.09	0.22
8	Bardhaj	226	0.29	0.24	0.31	0.10	0.24
9	Kozare	639	0.25	0.21	0.28	0.08	0.20

Table 3-7 indicates that the estimate of SDR by Renfro and USDA model are comparatively higher than the estimate of Vanoni and Boyce model. Since, there is no absolute model to give perfect estimate, the average from these models is taken as the SDR for each basin. On calculating the SDR for whole basin, Devoll has SDR in the range of 0.06 to 0.23 with an average of 0.16. Since, Banja reservoir is not at the outlet of catchment 9, its catchment is only 2895 $km^{2.}$ Thus, for the Banja Reservoir, over all SDR is in the range of 0.06 to 0.24, whereas the average is 0.17. This is a quite good estimate as compared to the catchments in Mediterranean region found in different studies.

3.4 Results and Discussion

To estimate the sediment yield for Banja reservoir, sediment yield estimation for each sub-catchment was done separately using the average SDR for each of them as mentioned in Table 3-7. As seen from the Figure 1.6, not all the area of sub catchment 9 drains into Banja Reservoir. Out of 639 km^2, only 415 km^2 drains into Banja Reservoir. This has been considered while calculating the sediment yield to Banja Reservoir in Devoll River Basin

Average annual soil loss for each sub catchments were calculated after clipping the sub catchment boundary to the annual soil loss map and then using the Get Raster Properties tool in ArcGIS to evaluate the mean value. The results from ArcGIS processing is presented as below.

Table 3-8: Annual Soil loss for sub basins calculated by RUSLE model.

SubBasin	Catchment Area(Km^2)	Average Annual Soil Loss(Tons/ha*year)	SDR (Avg)	Annual Soil loss(MT/yr)	Sediment Yield mill.ton/year
Miras	89	11.36	0.27	0.1	0.03
Shequeras	341	10.55	0.22	0.3	0.08
Turhan	272	30.13	0.23	0.82	0.19
Gjinikas	654	19.66	0.20	1.29	0.26
Posthme	63	62.84	0.28	0.4	0.11
Kokel	459	49.96	0.21	2.29	0.49
Tomorrice	376	61.86	0.22	2.33	0.51
Bardhaj	226	61.76	0.24	1.40	0.33
Kozare*****	639	49.15	0.20	2.04	0.42
		Total		**11.02**	**2.42**

Note: ***** only 65% of the total area is draining into Banja Reservoir.

Results from the RUSLE model as presented in Table 3-8, the annual soil loss in the catchment is 11.02 million tons/year. Considering the sediment delivery ratio from Table 3-7, the total sediment load at Banja Reservoir site is 2.42 Million tons/year. With this, the specific sediment yield for the catchment is 834.7 tons/km^2*year. This value is comparable to the estimate by BQART though the estimate by BQART in section 3.2 is 14% less than that of RUSLE.

Chapter 4 : EVALUATING SUSTAINABILITY OF BANJA RESERVOIR IN RESCON2

4.1 About the project

Devoll Hydro-power Project (DHP):

Planned in Albania, owned by Statkraft, Project consist of three hydropower projects in Devoll valley with an installed capacity of 256 MW and estimated annual production of 729GWh. Banja ,Moglice and Kokel are the three power plants planned along the Devoll river. Among them Banja lies in the most downstream, while Moglice in most upstream. All three power plants are located on Devoll river , about 65 kilometres south east of the capital Tirana, planned to utilise a head of 555 meters in the river between 650 and 95 meters(Statkaft, 2017).The project company was initially owned by 50/50 joint venture of Statkraft and Austrian energy company EVN,since 2013, Statkraft acquired 50 percent share from ENV and hence the project company is now under 100 percent ownership of Statkraft AS.

Banja Hydro Power Project:

Banja Hydropower with installed capacity of 73 MW is a reservoir scheme planned along Devoll River. Banja reservoir is impounded by 80 m high and 930 m long with HRWL of 175 m.a.s.l by clay core rock-fill dam. The power plant utilize the head of 77 m between 175 masl and 95 masl.The live storage for the reservoir is 178 Mm^3 with a dead storage of 225 Mm^3 and total capacity of 403 Mm^3(Norconsult, 2011).Mean annual inflow to the reservoir is 1484 Mm^3, hence the capacity inflow ratio for the reservoir is 27%. This reflects that the reservoir is in the medium size range. Image of the reservoir at present, retrieved from google earth is as presented in Figure 4.1. Banja catchment is characterised by very active erosion process. In some place, whole mountain sides are eroded away and the remaining slope are steep and unstable(Norconsult, 2010b) , creating the site more vulnerable to soil loss.

Figure 4.1: Banja Reservoir at present (Retrieved: Google Earth, 08, May 2017)

An example of such erosion, Figure 4.2, can be seen in the photograph from site on March,2017 taken by Sigurd Sørås. This is one of the important reason for having measured sediment load more than estimated by RUSLE model.

Figure 4.2: Mass wasting seen in the Banja Catchment near Kokel Measurement site (Photo Credit: Sigurd Sørås,NTNU)

Geology in the catchment comprises mixed sedimentary stones which can be easily eroded and hence producing more sediment loads to the river. Throughout the reservoir area and its catchment, heavily deposited colluvium is prominent , while the under lying dominant bed rocks are sandstone, mudstone, flysch (Mark Gill, 2017).Geological distribution in the reservoir site and its catchment can be seen in Figure B.0.4 in Annexe B.

For validation of the result from RUSLE, the measurement of suspended sediment along the Devoll river basin done for the period of 1951- 2005 has been considered. Along the Devoll river, there are four suspended sediment measurement stations by water sampling method. Among them, Kokel station lies upstream of Banja and Kozare station lies downstream. Figure 4.3 presents the location of those stations and the record is presented in Table 4-1.

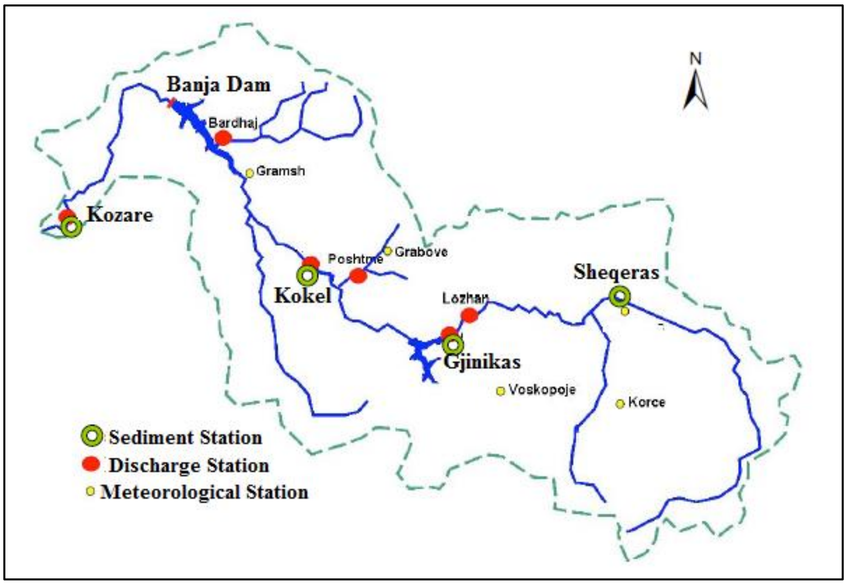


Figure 4.3: Sediment Measurement station along Devoll River (Norconsult,2010b)

Table 4-1: Suspended sediment measurement (1973-1984) (retrived from Norconsult ,2010b)

Station	Average Annual load(Mill.tons/year)	Specific Sediment Yield(tons/km^2*year)
Shequeras	0.09	210
Gjinikas	0.42	307
Kokel	1.45	770
Kozare	2.85	913

From the Table 4-1, the sediment yield per unit area for Kokel is 770 (tons/km^2*year) and Kozare is 913 (tons/km^2*year). Banja lies in between these two stations and from section 3.4, the sediment yield in Banja calculated by RUSLE is 834.7 (tons/km^2*year). This can be taken as a good estimate since the values are comparable.

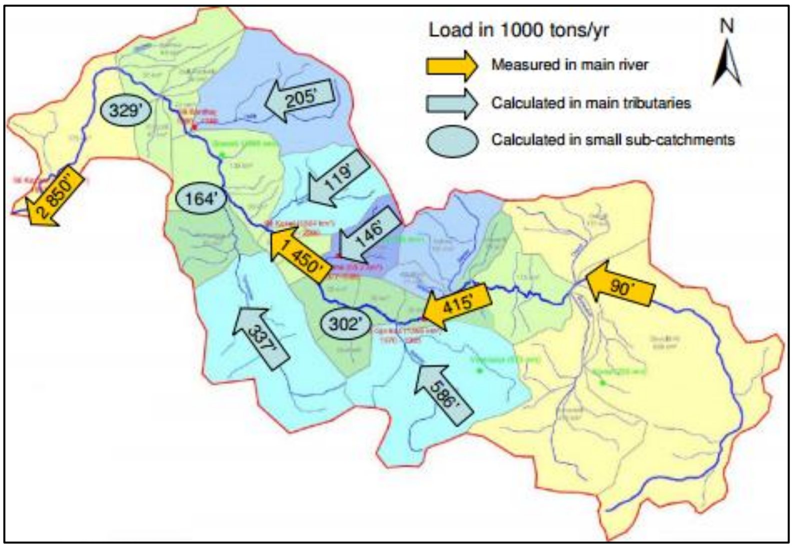


Figure 4.4: Calculated and estimated annual load based on data from 1974-1983(Norconsult,2010b)

From Figure 4.4., it can be said that the annual sediment yield to the Banja Reservoir is 2.521 Mt/year. However, from RUSLE Model, the estimated sediment load is 2.42 Mt/year. Thus, result from RUSLE indicates that there will be reduced sediment yield in Devoll catchment by 2050 due to climate change.

4.2 Data preparation

Good quality data and most representative parameters are desired for modelling in RESCON2. For Banja Reservoir., most of the required data were obtained from the technical reports published by Devoll Hydropower. Some of them were calculated using the raw data and some from the ArcGIS, while for those data which are not readily available at this stage, default value as suggested by the RESCON2 are used. Description about the data source and category are done in following sub sections.

Reservoir Geometry:

Defining the reservoir geometry is important for assessment of technical feasibility of various sediment management methods and to evaluate the sediment deposition and yield from the reservoir. For determining the representative bottom width and the length of reservoir, measurement using the 5-m. interval contour shape file was done in ArcGIS. The input values for reservoir geometry is summarised in Table 4-2.

Table 4-2: Banja reservoir Geometry input for RESCON2

Description	Value	Source
Original gross storage capacity of the reservoir[m³]	**403,000,000**	Norconsult,2011
Original active storage capacity of the reservoir[m³]	**178,000,000**	Norconsult,2011
Original dead storage capacity of the reservoir[m³]	**225,000,000**	Norconsult,2011
Existing storage capacity of the reservoir[m³]	**403,000,000**	Norconsult,2011
Existing active storage of the reservoir[m³]	**178,000,000**	Norconsult,2011
Existing dead storage of the reservoir[m³]	**225,000,000**	Norconsult,2011
Representative river bed width at the envisaged dam location[m]	**270**	Measured from Contours, ArcGIS
Maximum pool elevation of reservoir[masl]	**175**	www.statkraft.no
Minimum operation water level[masl]	**160**	www.statkraft.no
Minimum reservoir bed elevation at dam site[masl]	**95**	www.statkraft.no
Reservoir length[m]	**16,000**	www.statkraft.no
Number of reservoir compartments	**5**	Assumed

Hydrological Data:

Hydrological inputs to the model are usually obtained from the historical data set. For Devoll river basin, measurements from 10 gauging stations along the main river are available. Using those measurements for further statistical analysis, helped to gather all required data. For determining the coefficient of Variance, the data set from the gauging station upstream of Banja Reservoir, i.e. Bardhaj station are used and further statistical analysis performed. Results from the calculation is summarised in table below, while the flow record at Bhardaj station can be found in Annexe C, Figure C.0.4. For determining the inter-annual distribution of flow, the gauging station near by Banja Dam outlet, i.e. Darzeze is used and statistical analysis performed. Results can be found in Table 4-3, and flow duration curve prepared from historic data for Darzeze gauging station is in Annexe C, Figure C.0.3.

Table 4-3: Banja Reservoir Hydrological data input for RESCON2

Description	Value	Source
Mean annual reservoir water inflow [million m³/a]	**1,484**	(Norconsult, 2011)
Coefficient of variation of annual run-off volume	**0.28**	Calculated. Ref. Annexe C
Representative water temperature in the reservoir[°C]	**14.7**	(Norconsult, 2011)
Inter-Annual Flow Variation		
Probability of Exceedance (%)	%Flow	
20	**55**	Statistical analysis of Flow record at Darzeze. Result FDC in Annexe C, Figure C.O.3
40	**38**	
80	**9**	

Sediment Characteristics:

Sediment characteristics comprises the total sediment load, suspended sediment concentration and bed load percentage. For Banja reservoir, the total sediment load to the reservoir is estimated using RUSLE model in chapter 3. However, it is not possible to partition the total sediment load from RUSLE into suspended load and bed load. In order to make some reliable estimate, bed load is estimated as a percentage of total sediment inflow using the criteria suggested by Maddock & Borland(1950) and Lane & Borland (1951) retrieved from (Jens M.Turowski, 2010).From the measurement at Banja dam site in 2012 by the team from Norwegian Water Resources and Energy Directorate , the average suspended sediment concentration is 36 g/l. Referring to the Figure C.0.5, Annexe C, the bed load can be in the range of 10 to 20%. Inputs to RESCON2 are summarised in Table 4-4

Table 4-4: Banja Reservoir Sediment characteristics data input for RESCON2

Description	Value	Source
Specific weight of in-situ reservoir sediment [tonnes/m³]	**1.4**	(Norconsult, 2012)
Mean annual total sediment inflow mass [million tonnes/a]	**2.42**	RUSLE
Average annual concentration of suspended load[g/l]	**36**	From report (Truls E Bønsnes, 2012)
% Bed load Transport	**10**	Assumed from Maddock &Borland (1950) Annexe C
Duration of Bed Load Transport (%)	**5**	Assumed

Sediment Management Parameters:

Under this section, various parameters for different sediment management techniques as discussed in section 2.2, are defined. The inputs for each of the sediment management method is mentioned in the following sections.

Catchment Management Method:

Catchment management method is given special attention for Banja reservoir, since mass wasting and loss of soil due to catchment exploitation is prominent as seen in Figure 4.2. This method comprises both technical and non-technical solutions to lower the sediment yield in the catchment. For, Banja Reservoir, to evaluate whether this method is economically viable solution, preliminary assessment done using the criteria mentioned by Annandale (2013). Banja reservoir has Capacity inflow ratio of 0.27 and the life of reservoir calculated considering the sediment mass inflow estimated by RUSLE is about 166 years. Thus, for this range of CIR and life or reservoir referring the preliminary assessment criteria, the most attractive measure can be constructing the Check dams. However, other methods will be considered in other scenario to compare the overall performance of catchment management strategy. Inputs to the model for catchment management are summarised in Table 4-5

Table 4-5: Catchment Management Parameters for Banja Reservoir.

Description	Value	Source
Catchment management method	**Check Dams**	Annandale (2013)
Expected reduction of bedload inflow in reservoir due to CM [%]	**100**	User Manual RESCON2
Expected reduction of suspended load inflow in reservoir due to CM [%]	**0**	User Manual RESCON2
Effect of CM felt after how many years? [Years]	**1**	Assumed
Costs for implementation [US$]	**20,000,000**	Generalised
Annual O & M cost [US$/Year]	**200,000**	Generalised
Implementation year of catchment management [years]	**5**	Assumed for Trial
Maximum allowable storage loss before implementation [%]	**1**	Assumed for Trial

For other methods , the expected reduction of bed and suspended load are obtained from the generalised value from various relevant case studies published in different literatures ((Nikolaos Efthymiou, November 2016).Table is mentioned in Annexe C.

Removal of Deposits

Under this category, flushing, dredging, Hydro Suction removal of Sediment (HSRS) and trucking are considered. Inputs to the model are summarised in Table 4-6. Values were adopted relevant to Banja from different sources. Regarding the Tsinghua University Method, this is suggested by RESCON2 manual and the list of the values can be found in Annexe C. For the costs of some methods such as HSRS, it is generalised value from the example projects considered in this study. As far as possible, implementation schedule for each option is optimized by internal routine of the model.

Table 4-6: Sediment removal method parameters for Banja Reservoir.

Description	Value	Source
Flushing		
Description	**Value**	**Source**
Indicator of deposits type	**650**	Tsinghua University Method
Sediment removal difficulty	**3**	Removal of old deposit
Representative flushing discharge [m3/s]	**300**	Capacity for Bottom outlet
Flushing after complete drawdown [days]	**5**	Assumed
Calibration parameter for Mignot equation	**10**	Default
Max. capacity loss allowable [%]	**80**	Optimized Value
Fraction of run-of-river benefits [%]	**50**	Assumed
Fraction of storage benefits [%]	**50**	Assumed
Water elevation during flushing[masl]	**130**	Dam Water Elevation Curve
Elevation of Bottom Outlet [masl]	**110**	Dam cross-section, Annexe C
Dredging		
Description	**Value**	**Source**
Concentration by weight of sediment removed [%]	**30**	Default
Max. capacity loss allowable for dredging [%]	**50**	Assumed
Max. storage that can be restored by dredging [%]	**20**	Trial Value
Amount of sediment removed per dredging [m3]	**1,000,000**	Optimized by model
Unit value of water used in dredging [$/m3]	**0**	No re-use of water
Duration of phase 1 (No dredging) [years]	**117**	Optimized by model
Cycle length in phase 2 (Dredging)[years]	**27**	Optimized by model
HSRS		
Description	**Value**	**Source**
Sediment type category to be removed by (HSRS)	**1**	For medium sand
Assume a trial pipe diameter for HSRS[m]	**1**	Trial Value
Fraction of total yield to be used in HSRS [%]	**10**	Assumed
Max. capacity loss that is allowable for HSRS [%]	**100**	Assumed
Cost of capital investment to install HSRS [US$]	**20,000,000**	Generalised
The expected life of HSRS [Years]	**20**	Generalised
Trucking		
Description	**Value**	**Source**
Max. capacity loss allowable for trucking [%]	**80**	Trial
Max. reservoir storage restored by trucking [%]	**30**	Trial
Amount of sediment removed per trucking [m3]	**10,000,000**	Optimized by model
Unit Cost of trucking [US$/m3]	**13**	Default
Implementation year [years]	**10**	First Trial
Frequency of trucking operation [years]	**5**	First Trial
Fraction of water yield the year trucking occurs [%]	**0**	Assumed

Sediment Routing:

This comprises by-pass, draw down sluicing and density current venting methods. From preliminary assessment, all three methods are feasible for Banja reservoir, thus data set required for each method has been prepared for further evaluation. The data used in initial trial are mentioned in the table below:

Table 4-7: Sediment Routing Parameters for Banja Reservoir.

By-Pass		
Description	**Value**	**Source**
Cost for implementation of by-pass structure [US$]	**30,000,000**	Generalized
Annual O&M Costs of by-pass structures [US$/Year]	**300,000**	Generalized
Implementation year of by-pass [years]	**5**	Trial
Duration of sediment by-pass [months]	**4**	From Hydrological Study
Max. storage loss before by-pass [%]	**100**	Default
Max. duration of by-pass operation [months]	**6**	Default
Water by-pass efficiency [%]	**80**	Generalized
Bedload by-pass efficiency [%]	**100**	Generalized
Suspended load by-pass efficiency [%]	**60**	Generalized
Draw Down Sluicing		
Description	**Value**	**Source**
Reservoir pool elevation during sluicing [masl]	**168**	Norconsult,2010b
Cost for implementation of sluicing structure [US$]	**0**	Included in total cost
Annual O&M cost of sluicing structures [US$/Year]	**200,000**	Assumed
Implementation year of sluicing [years]	**1**	Trial
Duration of sluicing operation [months]	**4**	From Hydrological Study
Max. storage loss before sluicing [%]	**100**	Default
Max. duration of sluicing [months]	**6**	Trial
Density Current Venting		
Description	**Value**	**Source**
Duration of density current venting [months]	**1**	Trial
Implementation year of density current venting [years]	**50**	Trial
Max. storage loss before density current venting [%]	**100**	Trial
Reservoir benefits the year density current venting [%]	**50**	Generalized
Cost of capital investment for sluicing structures [US$]	**0**	Included in total cost

Economic Parameters:

Economic analysis to identify the most viable option i.e. the one with highest Net Present Value (NPV) depends on how representative is the data set defined for the project. Under economic parameter, users need to define the unit benefit from reservoir, cost associated with the reservoir and the discount rates to be applied. The interest rate for short term and long term investment in Albania can be in the range of 9% to 6% respectively ("Albania-Project Financing," 2016).Thus 6 % is adopted as discount rate for Banja. Considering the annual inflation of 2%, the annual retirement fund is calculated at the market rate of 8%. Economic data set is presented in following table.

Table 4-8: Economic Analysis parameters for Banja Reservoir.

Description	Value	Source
Unit cost of construction per m3 of reservoir capacity [$/m3]	**0.36**	calculated from total cost
Total cost of reservoir impoundment [$]	**143,871,000**	Omelan,2015
Discount rate [%]	**6**	Albania Project Financing,2016
Market interest rate of annual retirement fund [%]	**8**	2% inflation added
Unit benefit of reservoir yield [$/m3]	**0.4**	Adopted equivalent to morocco
Decommissioning cost [$]	**50,000,000**	Generalized 35% of total cost
Capacity loss for characterization of a reservoir as non-sustainable [%]	**95**	Generalized
Total annual operation & maintenance costs [$/year]	**1,440,000**	1% of total cost

However, the projects with a time horizon that stretches over more than one generation, a declining discount rate might be applied as an alternative to a constant rate (Nikolaos Efthymiou, November 2016).Declining discount rates based on the assumption that the uncertain future rate can be calculated as certainty equivalent discount rate. RESCON2 holds capability to evaluate the economic performance under declining interest rate. In case of Banja Reservoir, the declining rate as used by UK Treasury was defined to compare the results with constant discount rate. This includes the following rates:

Table 4-9: Declining interest rate for Banja Reservoir

Years	Rate [%]
0-30	6
31-75	5.14
76-125	4.28
126-200	3.42
201-300	2.58
300+	1.72

4.3 Results from RESCON2 Model

Once the first set of data was prepared, the model was run to get the initial results. All the results obtained from RESCON2 in excel were used to make a plot in MATLAB. To compare the results from different simulation scenario, three scenarios were defined as in Figure 4.5. Conditions for each of the scenario and the results are presented as below:

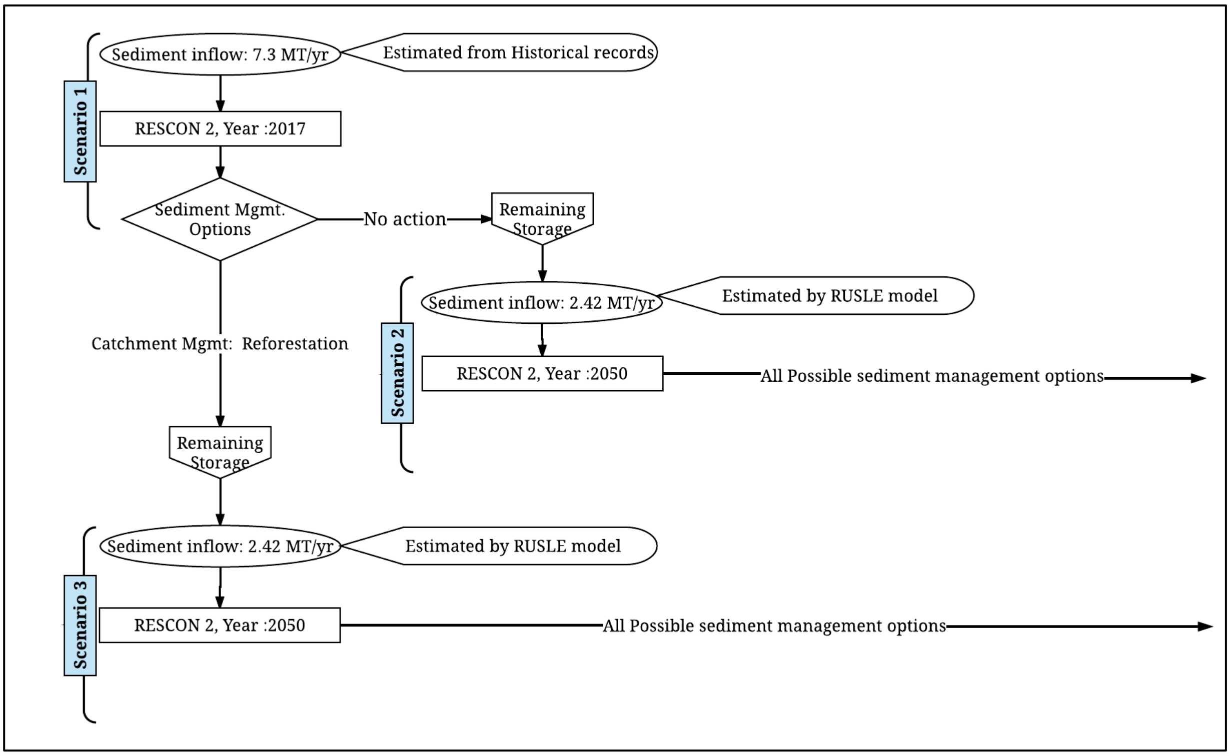


Figure 4.5: Scenario for evaluating Banja Reservoir sediment management strategy in RESCON2

Scenario 1:

Scenario 1 is for the initial data set as presented in section 4.2. Under this condition, temperature, annual runoff volume is as obtained from the historical records. While the sediment inflow is 7.3 million tonnes per year estimated based on sediment data from Kozare gauging station ,while, the bed load is assumed to be 30% (Hydropower, 2012).

Under this scenario, none of the sediment management options are into effect till 30 years. From the study report by DHP on sedimentation issue to Banja reservoir, it is expected that the project will not suffer severely within first 20 years of operation , nevertheless, loss of benefit is expected to start within 25 to 50 years of operation (Norconsult, 2012). Results from this run are presented as below:

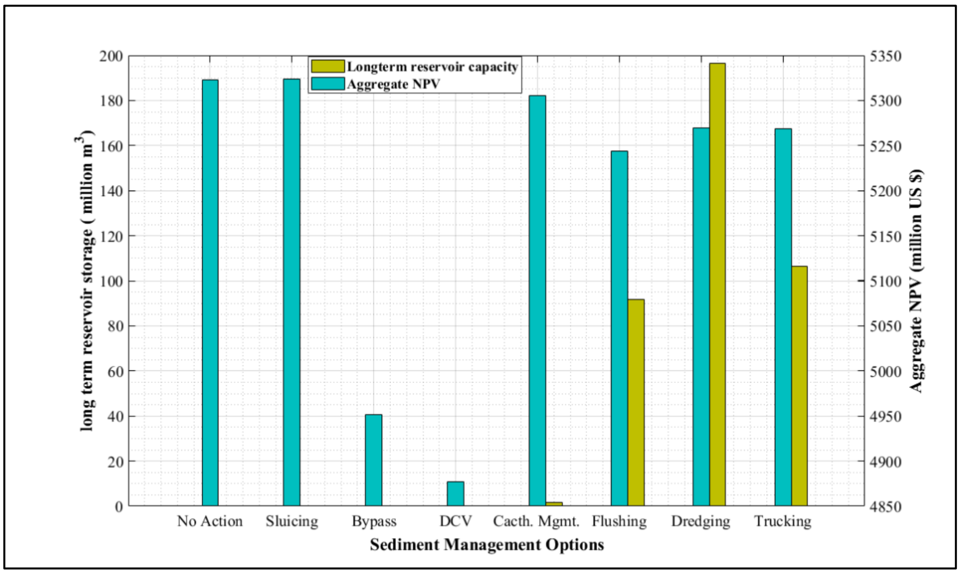


Figure 4.6: Long term capacity and economic performance for Scenario 1

From Figure 4.6, it is found that no action, sluicing, by-pass, Density current venting (DCV) and catchment management methods can hardly sustain reservoir capacity in long run. However, flushing, dredging and trucking options are found to be effecting in sustaining the reservoir capacity to acceptable limit with reservoir life more than 300 years.

As mentioned earlier, there is no sediment management options in effect before 30 years. Storage development for no action is presented in Figure 4.7.

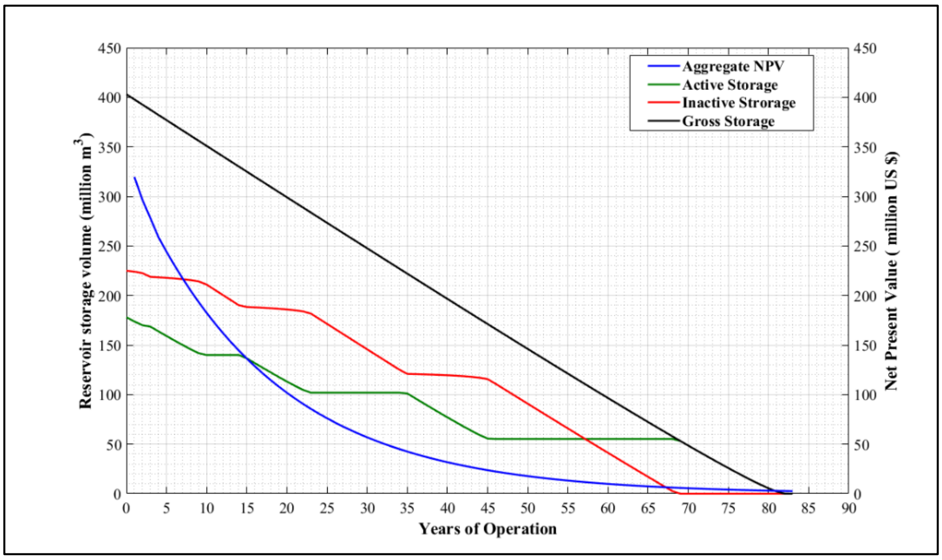


Figure 4.7: Physical and economic performance of Banja reservoir under no sediment management options.

From Figure 4.7, it is evident that the reservoir will be filled with sediment in 83 years if none of the sediment management options are applied. However, aim of this study is to find such solution which can sustain reservoir life more than 300 years. Technical feasibility and practicality of the methods will be discussed for each of them based on results from scenario 2.

Scenario 2:

Under this scenario, the annual runoff volume and the temperature is changed to what is expected by 2050 (after 33 years of operation from now-2017), in line with the climate change model results. While, the new sediment yield to the reservoir is 2.42 million tonnes/year estimated by RUSLE model in section 3.3. Thus, the annual runoff volume is decreased by 10 % so the new value is 1335.6 million m^3, and the annual average temperature is increased by 2.2 ^{o}C such that the new value is 17 ^{o}C. At this stage, after 33 years of operation, new storage volume to reservoir thus from scenario 1 under no action is used for further analysis. New volumes are listed in table below.

Storage	Volume (m^3)
Active	101,928,127
Inactive	130,311,286
Gross	232,239,414

Once again, model was run with new sets of reservoir volume and sediment characteristic. While, the technical parameters for each of the sediment management options remain same as mentioned in Table 4.2 – 4.8.

Result from RESCON2 reveals that flushing, dredging, trucking, bypass are the solutions sustaining reservoir life more than 300 years, while sluicing, density current venting (DCV) and catchment management methods are non-sustainable. Economic performance and the resultant reservoir storage at the end of reservoir life obtained from scenario 2 is presented in Figure 4.8.

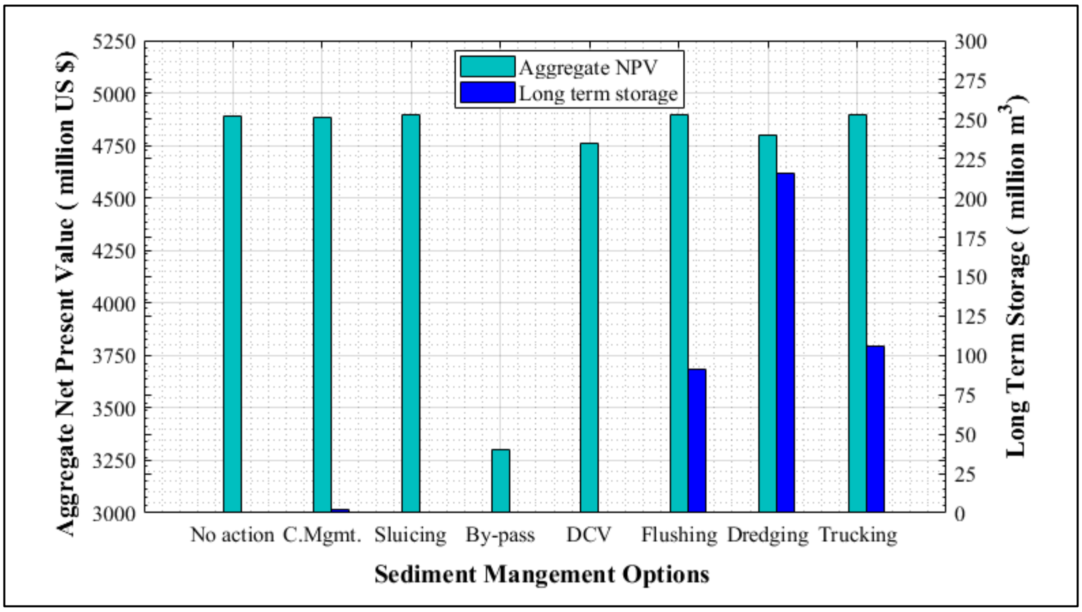


Figure 4.8: Economic and physical performance of sediment management methods under scenario 2

Hydro suction sediment removal (HSRS) is not technically feasible since reservoir length is exceeding the maximum feasible length i.e. 5000 m. Physical and economic performance along with practicality of each of the methods is assessed in following section.

Dredging Results:

For RESCON2, the duration of phase 1 i.e. installation year is 13 years and the frequency of dredging is every 6 years assumed for trial. Annually it should remove 10.2 Million m^3 of sediment which is possible since sediment volume removed by typical system for one year is 11 Million m^3(Nikolaos Efthymiou, November 2016). Also, an attempt was made to determine the implementation year for dredging by economic optimization routine of the model, accordingly it was found that it would have higher economic performance if dredging starts from 1 years of operation and continued in every 33 years. But, it requires to remove 56 million m^3 of sediment per event. This is practically impossible. Finally, after some trials, implementation year and frequency of operation mentioned earlier was found to be most suitable.

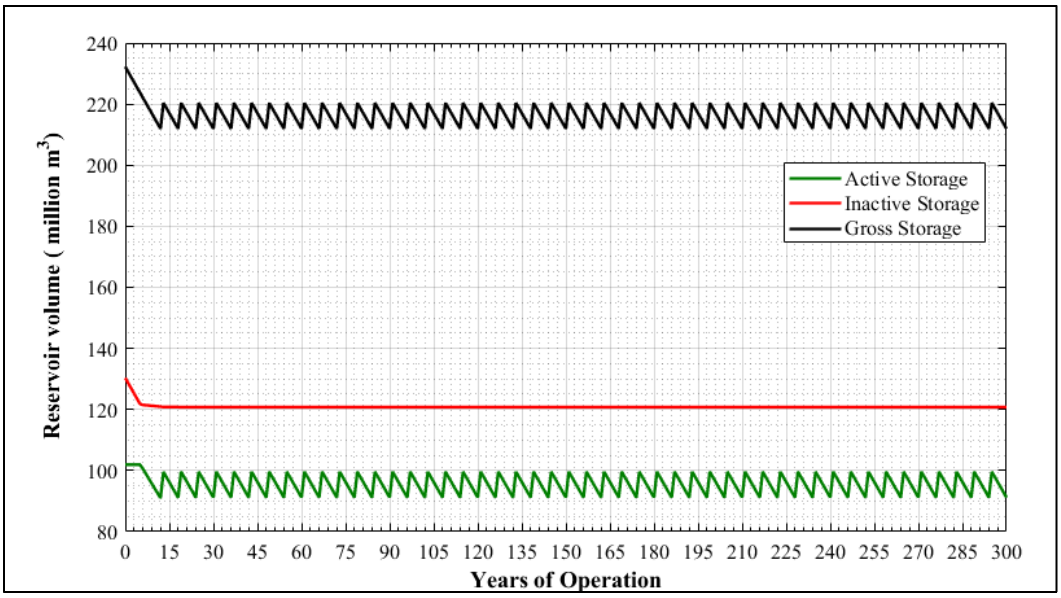


Figure 4.9: Reservoir Storage development due to Dredging in Banja Reservoir.

As result from RESCON2 presented in Figure 4.9, after implementation of dredging option, the active storage can be restored to 96 million m^3 after each event, thus the reservoir use can be prolonged to more than 300 years, while dredging is not able to able remove the sediment from inactive storage. The annual sediment removal and the reservoir water yield follows the trend as shown in Figure 4.10.

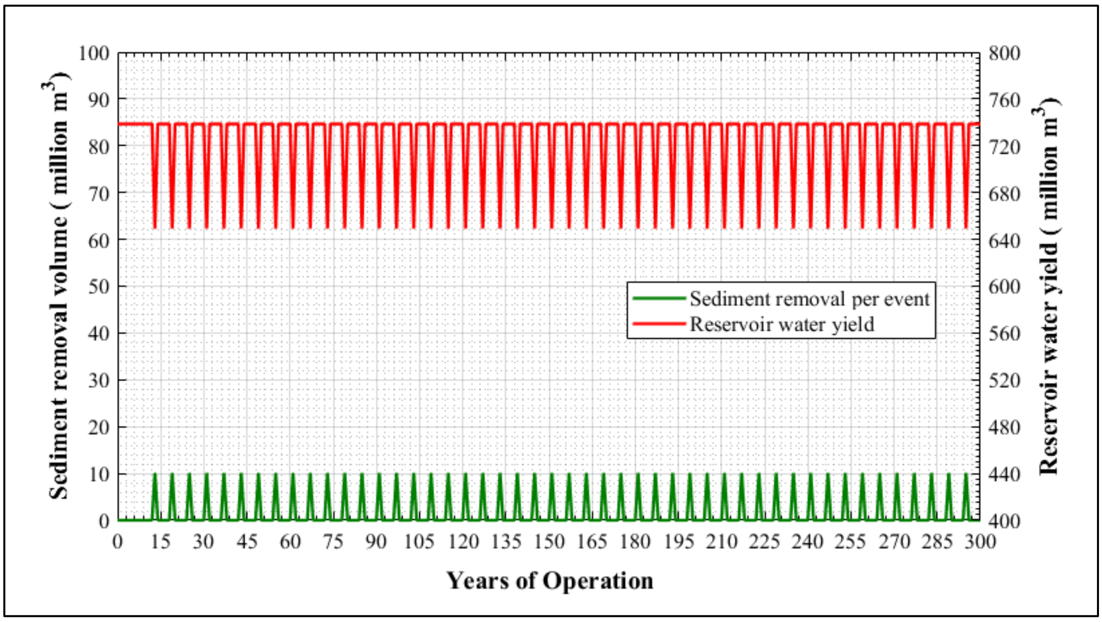


Figure 4.10: Annual sediment removal and reservoir water yield after Dredging in Banja Reservoir.

Flushing results:

Regarding the flushing feasibility criteria for Banja reservoir under the conditions defined in Table 4-6, only sediment balance ratio was satisfied, while other criteria were below the required range. Results from the model are presented as below:

Table 4-10: Results for Flushing feasibility criteria obtained from RESCON2

Criterion	Value Range	Calculated
SBR	Required > 1	**6.23**
LTCR	Preferably > 0.35	**0.23**
DDR	Suggested > 0.7	**0.69**
FWR	Suggested > 1	**0.82**
TWR	Suggested > 1	**0.23**
SBR_d	Suggested > 1	**9.68**

From Table 4-10, it is found that the sediment balance ratio is well satisfied. Long term capacity ratio is not satisfied which might result in less storage availability in future. Apart from this, careful consideration to the width of the reservoir and the flushing width is required. Flushing width formed while flushing should exceed the representative bottom width of the reservoir.

The representative flushing width formed under given condition is calculated by the relation as follows:

$$W_f = 12.8 \times Q_f^{0.5} \quad \text{(IRTCES,1985)}$$

Equation 4-1

Where, Q_f is flushing discharge and for our case it is 300 m^3/s, hence flushing width (W_f) calculated using equation 4-1 is 221 m. This value is lower than the representative bottom width of 270 m measure at the dam site. This can limit the effective channel formation during the flushing. Thus, single bottom outlet available in the Banja Dam may not be sufficient to flush the sediment effectively.

Despite these constraints, the sediment removal and water yield from the reservoir are found to be satisfactory enough to call this method, a sustainable solution. For Banja, the storage development with time on applying the flushing measure is presented in Figure below:

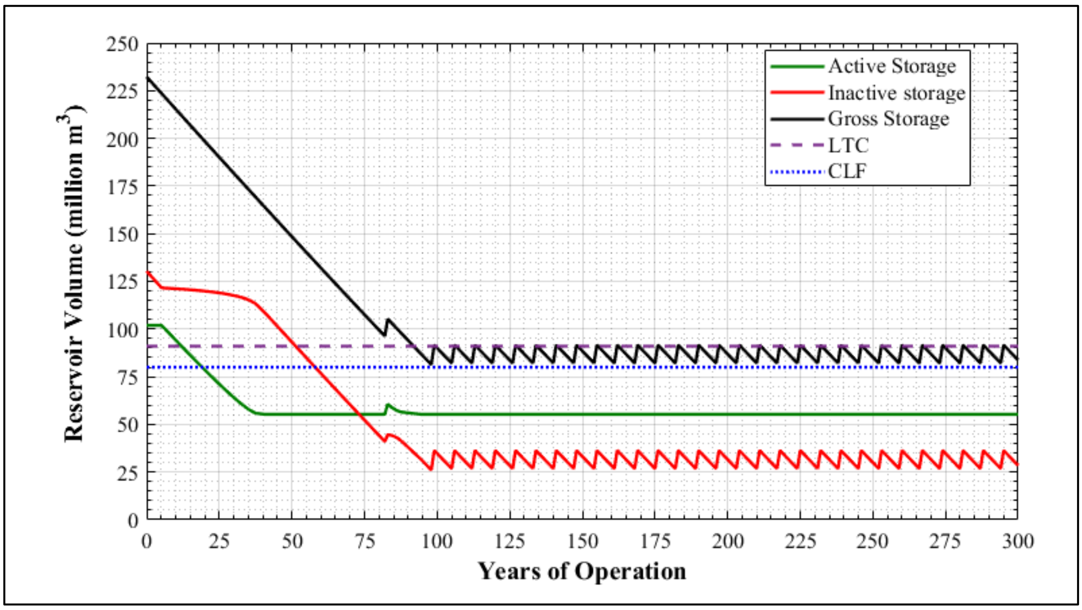


Figure 4.11: Storage development in Banja reservoir due to flushing

RESCON2 optimizes the implementation time for flushing per equation 2.1 and hence the optimum time for implementation of flushing is 83 years during non-sustainable phase, while frequency of operation during sustainable phase is 7 years. From Figure 4.11, after 83 years of operation, long term capacity (LTC) of the reservoir i.e. 91 million m^3 is achieved, thence the reservoir life is sustained more than 300 years. Amount of sediment removed and reservoir yield during the flushing operations is presented in the Figure 4.12.

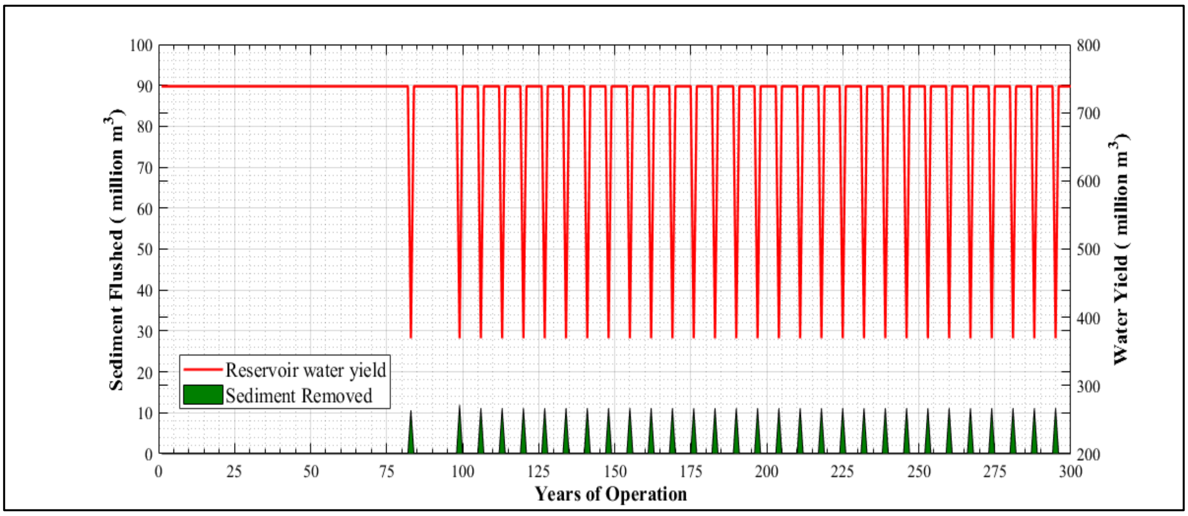


Figure 4.12: Sediment flushed and water yield in Banja Reservoir

From Figure 4.12, there is considerable drop in reservoir water yield during the flushing operation and soon it is maintained constant. This results in varying Net benefit of the reservoir. Present value of net benefit from the reservoir is presented in Figure 4.13.

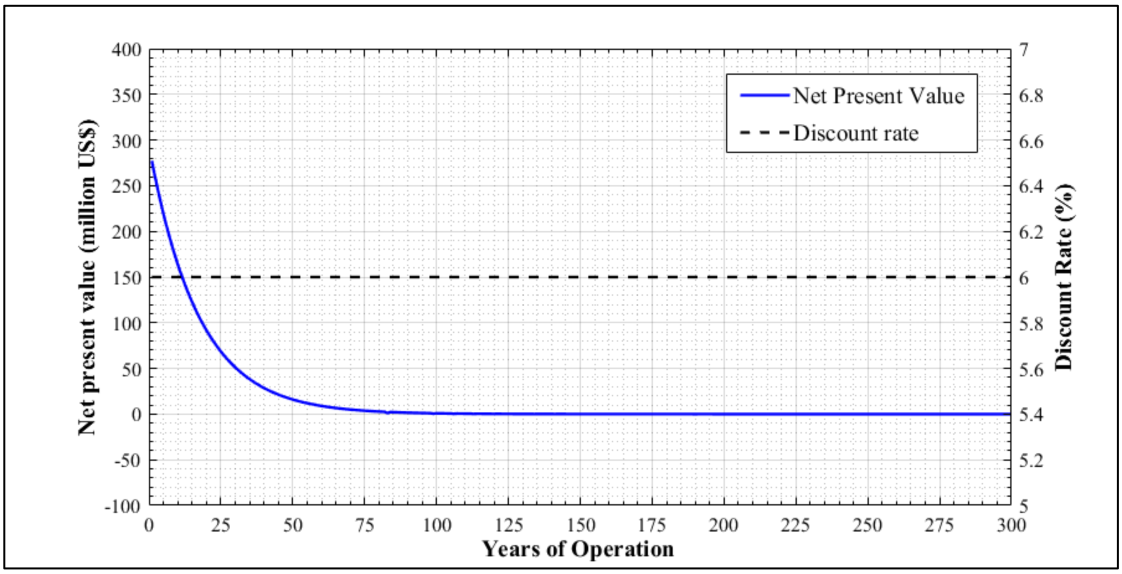


Figure 4.13: Economic Performance of Banja reservoir due to periodic flushing

As seen in Figure 4.13, there is sharp drop in annual benefit till 83 years, after that due to flushing and recovering of storage, the water yield and hence the net benefit is improved.

Trucking results:

Trucking is technically feasible and even sustainable option from RESCON2 results. But, it requires practical assessment whether the desired volume as calculated by RESCON2 can be removed in a year. The storage development and the amount of sediment to be removed by trucking after economically optimizing the implementation schedule is presented in Figure 4.14. RESCON2 determines the optimum years for implementation of trucking is 91 years after operation with frequency of 16 years in second phase to achieve sustainable solution. From Figure 4.14, trucking event requires to remove 25 million m^3 of sediment volume, which is not practically possible in one year even with the truck of highest capacity 96 m^3 per truck load employed in the field. Thus, trucking is not practically possible to Banja Reservoir under this scenario.

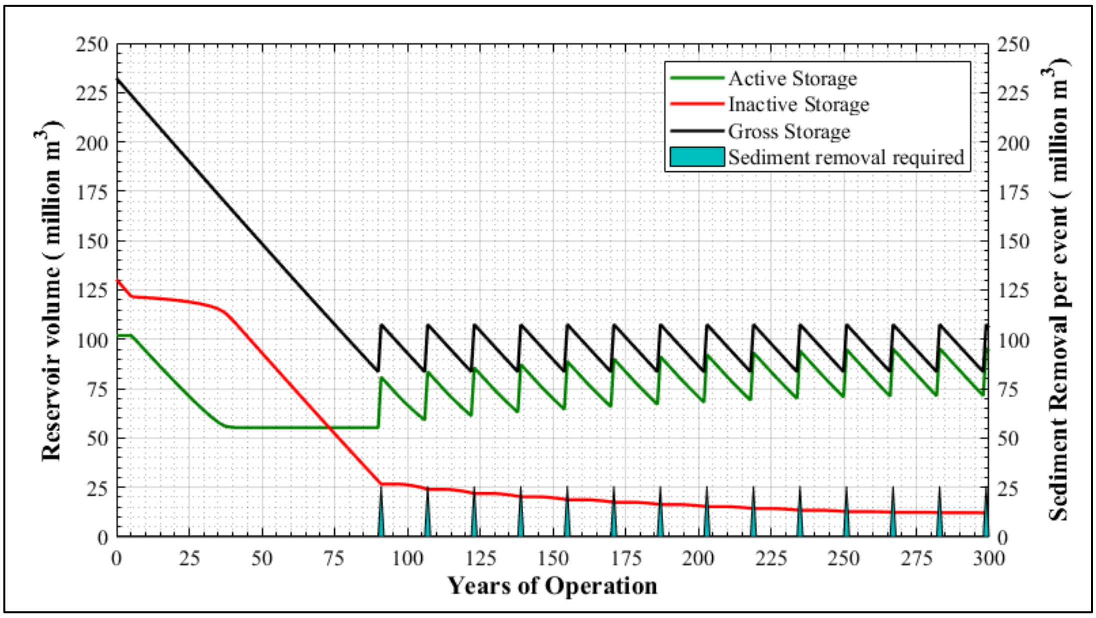


Figure 4.14: Storage development and sediment removal after trucking in Banja Reservoir

By-pass results

Sediment bypass is technically feasible for Banja Reservoir. However, its physical performance and economic viability is determined by the availability of appropriate structures, i.e. diversion weir and diversion tunnel or open channel. Nevertheless the sediment bypass via tunnel in the world is limited primarily due to high investment and maintenance costs (Anton J. Schleiss, 2011).For Banja Reservoir, it would be necessary to design the appropriate structures. In RESCON2 analysis, generalized cost of 30 million US $ is taken as capital investment for bypass structure. It is suggested from practical viewpoint, bypass tunnel longer than 5 km is usually uneconomic, thus for Banja which is 16 km long, its application needs careful assessment.

Implementation schedule of Bypass determines whether the solution can achieve sustainable reservoir life. For the first trial, it is considered that by-pass is implemented after 5 years of operation and done annually for 4 months of higher flows as suggested by hydrological study reports. In such environment, the solution can be sustainable but not economically attractive.

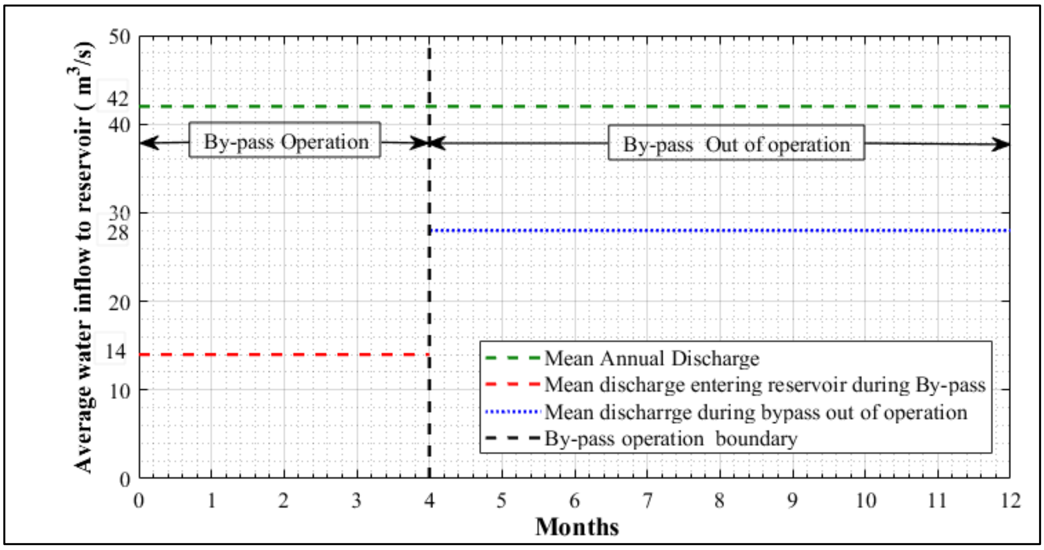


Figure 4.15: Bypass operation rule to Banja reservoir determined by RESCON2

Figure 4.15 shows the average water inflow to the reservoir during and out of by-pass operation. During bypass operation for four months, reservoir will receive only 14 m^3/s water inflow while 28 m^3/s of water is diverted to downstream via by pass structures. This considerably affects the economic performance of the reservoir during bypass period. The Net present value for the scheme due to by-pass is presented in Figure 4.16.

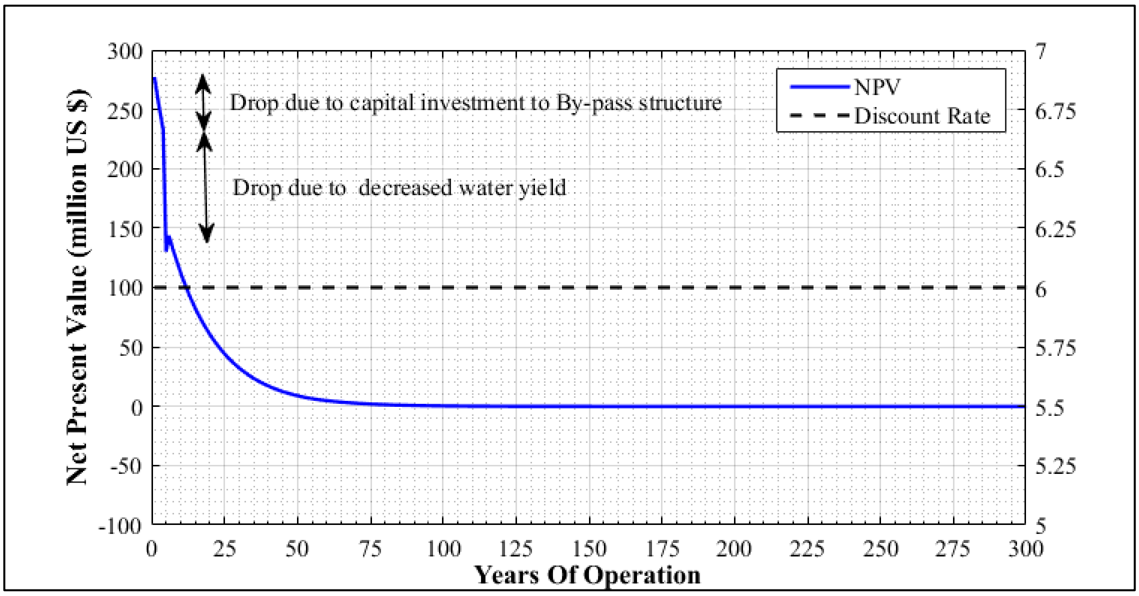


Figure 4.16: Economic Performance of Banja Reservoir due to by-pass of sediment

As seen in the economic performance of Banja reservoir Figure 4.16, there are two prominent drops in the net present value of the reservoir soon after 5 years of operation. First drop is due to incurred capital cost associated with by-pass structures and second drop is due to decreased water yield during bypass operation which lasts for 4 months. After that, there is improvement in the net benefit and hence the reservoir is found to sustain more than 300 years.

However, the RESCON2 model has inbuilt optimization framework to determine the implementation schedule. In the above case, implementation schedule was explicitly defined by user. Once again, the model was run to see how the economic and overall performance of would be, if the implementation schedule determined by economic optimization. On doing so, the economic performance was improved considerably. NPV improved from 3535 million US $ 4900 million US $ but the solution becomes non-sustainable. The economic performance is presented in Figure 4.17.

From Figure 4.17, we can see there is improvement in economic performance due to implementation of by-pass as per the schedule optimized by the model. In accordance with the result from RESCON2, implementation of by-pass after 153 years of operation, annually for 1 month would be the best in terms of economic performance.

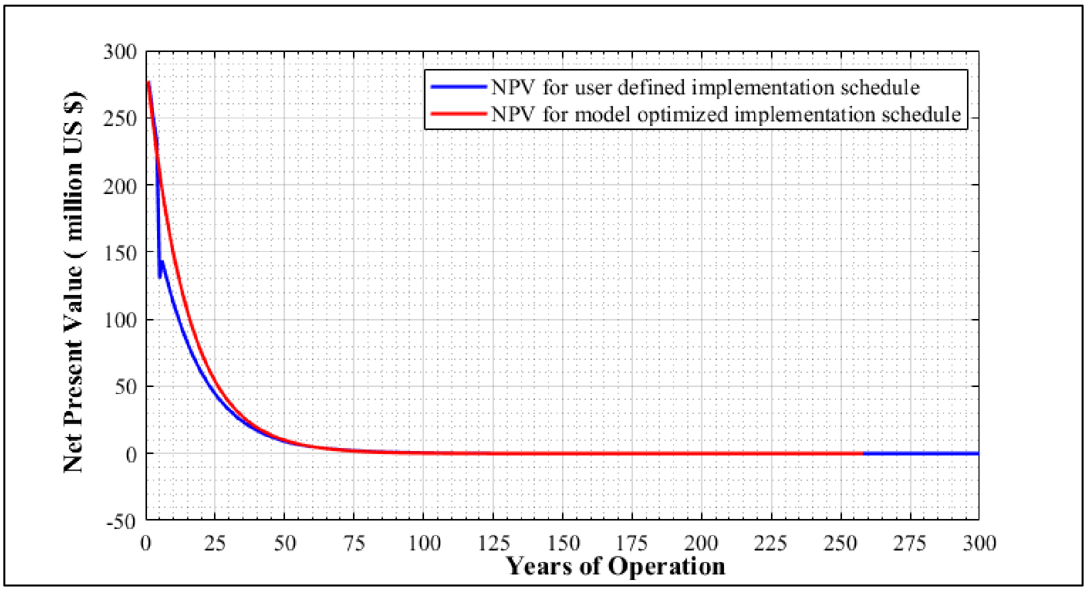


Figure 4.17: Comparison of Economic Performance of Banja Reservoir due to by-pass

Non-Sustainable Solutions:

In compliance with the results from RESCON2 for scenario 2, only four of the above-mentioned methods can sustain reservoir life above 300 years. While, other methods though technically feasible and economically viable to the scheme, their physical performance cannot sustain the reservoir life more than 300 years. Economic and physical performance in terms of NPV and life of reservoir respectively, are presented in the figure as follows. As seen in Figure 4.18, Sluicing can sustain the reservoir life up to 261 years with good economic performance. This is followed by Catchment Management method. Assessment of each of the methods and their results from RESCON2 is done in following sections.

From Figure 4.18, it can be said that the economic performance of all management options is satisfactory enough, while, the physical performance in terms of reservoir life sustained is below 300 years. Among them, no action has only 130 years and at the end the reservoir volume is completely lost. Thus, only economic performance is not enough for accepting any sediment management options. Long term reservoir capacity and life of reservoir should also be in acceptable range and hence a balance between economic and physical performance can be established.

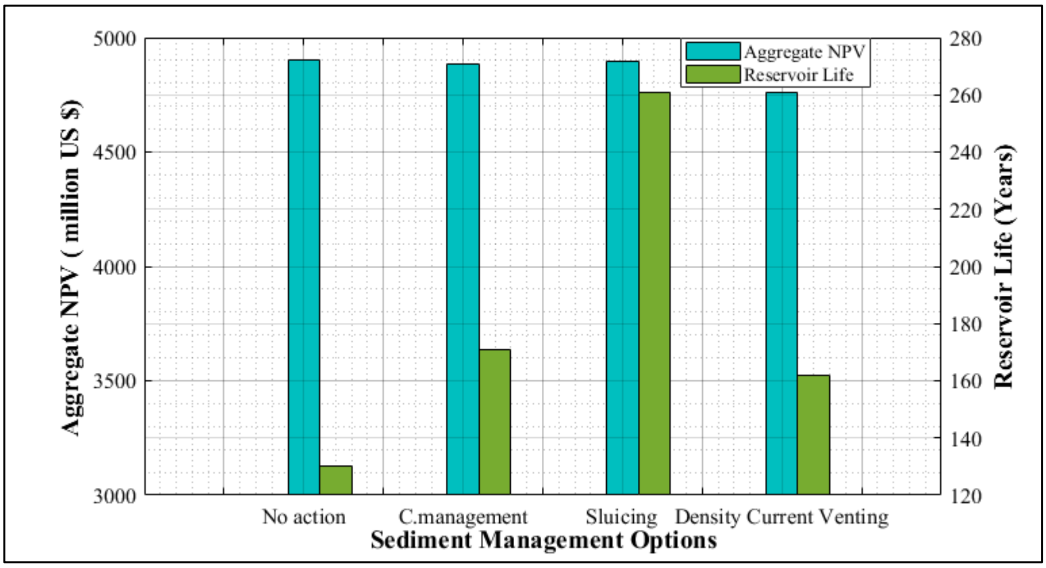


Figure 4.18: Physical and Economic performance of non- sustainable sediment management options to Banja Reservoir

Sluicing results:

Sluicing is technically feasible at Banja reservoir, since 3 flood gates of dimension (L×H) 20 m × 3 m are included in the dam body. However, their physical performance to release the sediment laden inflow needs to be evaluated by calculating the sediment removed and the reservoir volume sustained. RESCON2 calculates all such features and in accordance to the results, sluicing is not able to achieve sustainable reservoir life for Banja. The sluicing Operation rule in line with the technical features of low level outlet and mean annual distribution of discharge is as shown in the Figure 4.19. The sediment removal and the storage development due to sluicing operation in Banja is shown in Figure 4.20, which clearly states that after 117 years of operation, the inactive storage of the reservoir is filled with sediment, eventually by 261 years, the storage capacity collapse to almost zero. However, from the economic performance, it would be beneficial to run the project further as run-of river scheme rather than decommissioning the dam structure.

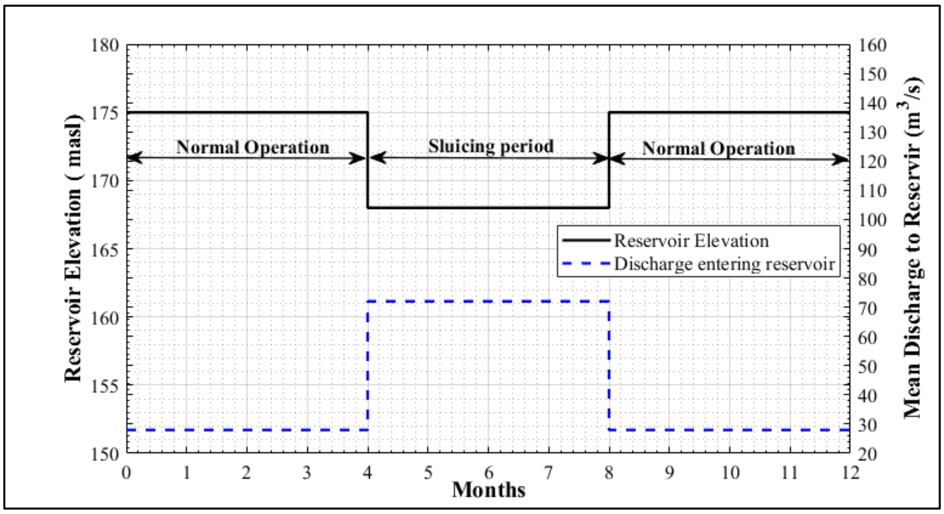


Figure 4.19: Sluicing Operation Rule for Banja Reservoir

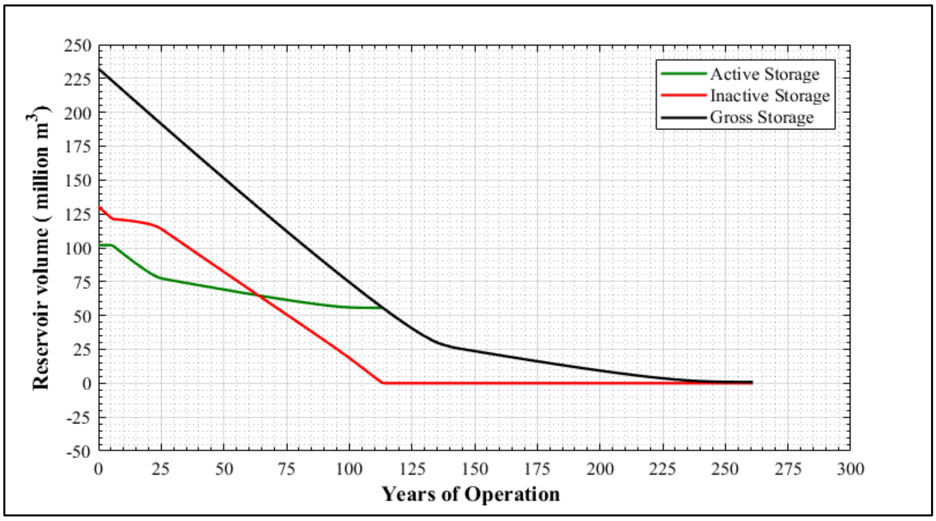


Figure 4.20: Storage Development due to sluicing operation in Banja Reservoir

Catchment management method results:

Economic performance of reservoir due to catchment management is satisfactory enough. In line with the results from RESCON2, this method can sustain the reservoir life up to 172 years as shown in Figure 4.21. After this, it would be better to continue the project as Run-of – river scheme.Net present value drops to negative value after 172 years since this method is capital intensive and requires huge investment at once.

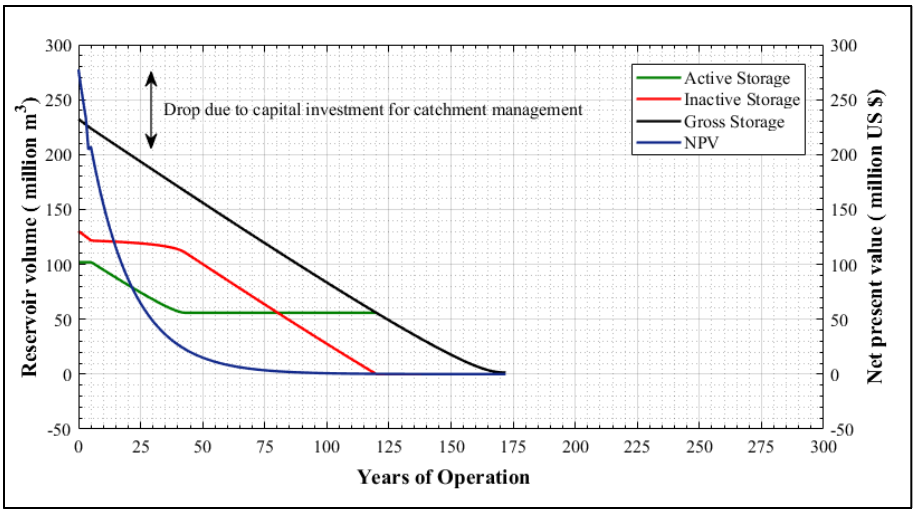


Figure 4.21: Physical and economic performance of Banja reservoir after implementation of catchment management method

Sediment control by applying check dam measures, limits only to the trap of bed load which is comparatively less than suspended load. Thus, other catchment management measures can be more attractive compared to check dams. This will be done in next scenario in detail.

Density current venting results:

The average concentration of sediment inflow, reservoir water temperature and geometry favour the formation of density current in Banja reservoir. Is it equally important to have a bottom outlet of sufficient capacity, which is available for Banja. Thus, technical feasibility of density current venting is well justified. However, the physical and economic performance of the reservoir is of great interest to assess whether the solution is sustainable option. Implementation of density current venting takes time since plunging current moves towards the dam very slowly and under favourable conditions only. Thus, for this analysis, it is supposed to have DCV in effect after 50 years of operation. In conformity with the results from RESCON2, density current venting can sustain the reservoir life for 162 years. Figure 4.22

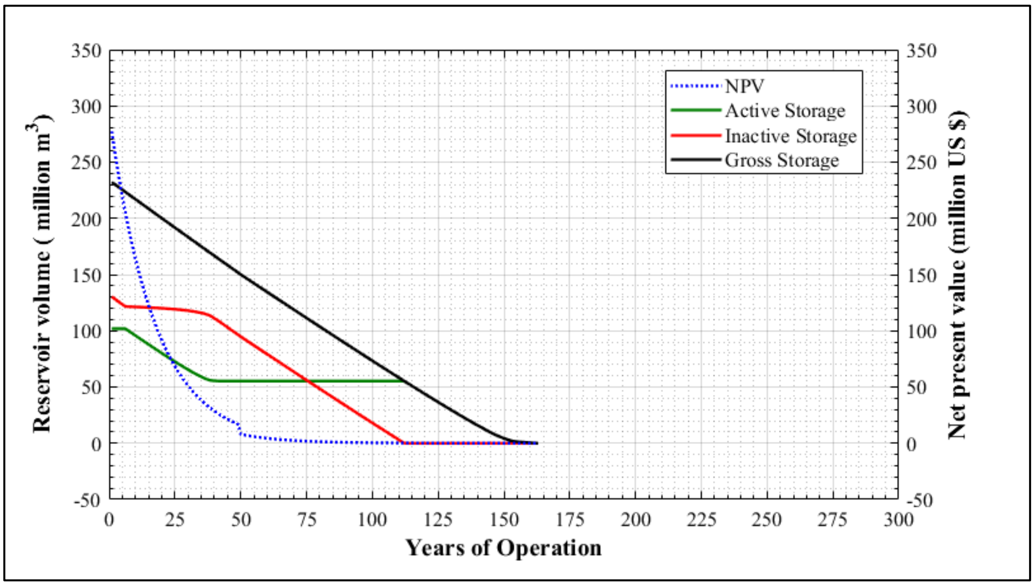


Figure 4.22:Physical and economic performance of Banja reservoir after implementation of density current venting

As seen in Figure 4.22, there is drop in the reservoir active storage till 50 years and as soon as density current venting comes into effect it remains constant, while the inactive is still declining. This means the density current venting is not so effective to minimize the loss of inactive storage and hence by 110 years, it is completely lost and further by 162 years, whole system volume is lost, thence, it would be beneficial to run as run-of- river scheme.

Declining Discount rate results:

Since all the calculations above were done for a constant discount rate of 6%, once again, the model was run after defining the declining discount rate as mentioned in Table 4-9. Results from the model is presented in Figure 4.23. Though there is considerable improvement in the economic performance, the physical performance remains same. Hence for qualitative judgement, it doesn't affect whether constant or declining interest rate is considered. Therefore, for consistency, constant discount rate is used for all scenario.

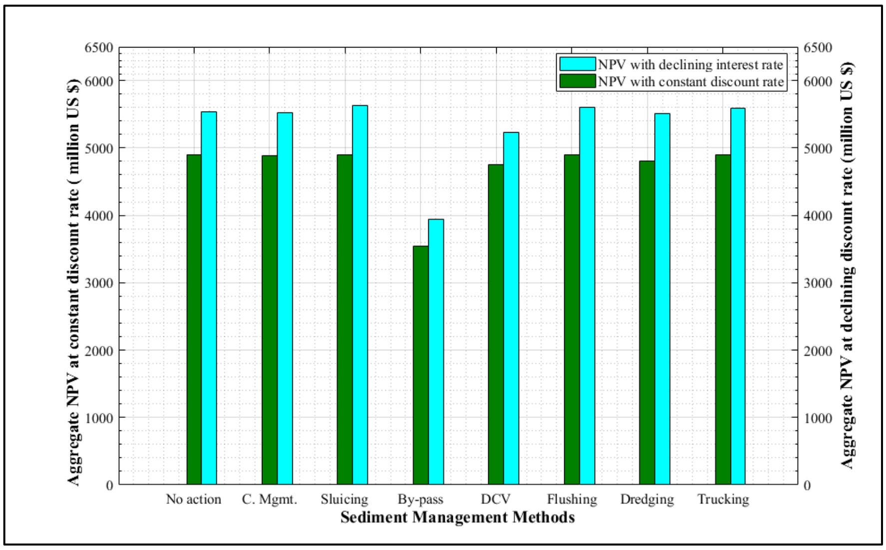


Figure 4.23:Economic performance comparison for constant to declining discount rate

Scenario 3

Once again, to make the analysis further realistic, it is supposed that catchment management methods would come into effect within first 5 years of operation. The storage development would be different from what has been obtained for no action condition. Finally, the storage development after catchment management method is taken as the storage remaining by 2050 and hence further analysis was done. New remaining storage are listed in Table 4-11. From the Table 4-11, it is evident that compared to scenario 1, there is about 30 million m^3 more storage available in inactive region. The reason behind it is trapping of sediment by the improved forest and pasture land.

Table 4-11: Storage by 2050 due to reforestation in Banja catchment within first 5 years

Storage	Volume (million m^3)
Gross	261,724,912
Active	101,928,128
Inactive	159,796,784

Here, catchment management method was given special focus. Reason behind it is, loss of 1421 hectares of forest and pasture land due to Devoll Hydropower project (DHP) is reported in DHP Environment and social management plan (2013). Out of this, Banja reservoir alone deforests 600 hectares of forest and pasture land. In line with Albanian Forestry Law No.4/2013, DHP needs to reforest 1347.8 ha of forest and improve 73.6 ha of pasture (Hydropower, 2013). Results from scenario 1 and 2 depict the usefulness of catchment management method in Banja reservoir. Thus, catchment management method with reforestation and combined approach is further evaluated in RESCON2.

Changes are made to the percentage of bed load and suspended load reduction due to reforestation and deintensification of land, based on general recommendations derived from relevant case studies as summarised in Table C.0-1 in Annexe C. The time lag between its implementation and realization of effect is taken as 5 years, since suggested value is more than 3 years. However, parameters for other sediment management options remain same as in scenario 2. While, cost estimate for the implementation of reforestation is done at the rate determined by the World Bank form its latest experience of reforestation program in Albania. According to (Polat, 2016), in general it costs 1625 US $/ ha to reforest and improve pasture land in Albania. Considering this unit rate and area of land to be reforested by DHP, it would cost 2.31 million US $ to implement reforestation program. Results from the model with the changes as mentioned earlier are presented as follows.

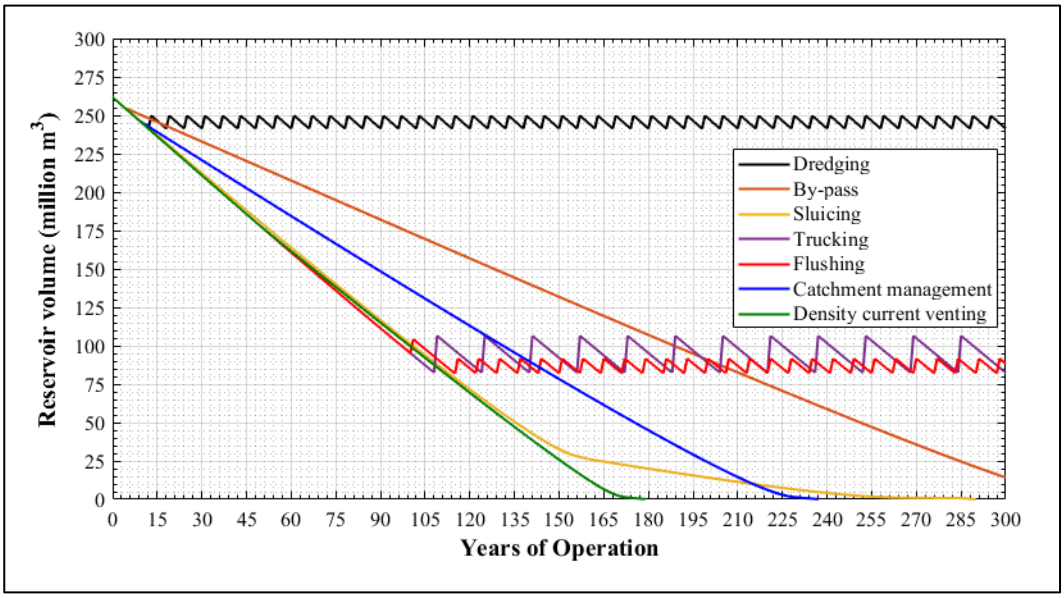


Figure 4.24: Reservoir storage development due to reforestation in Banja catchment

Figure 4.24 presents the storage development with reforestation in the Banja catchment. Reforestation is supposed to reduce the suspended sediment yield by 30 % while bed load by 10%. Immediate effect due to reduced sediment yield is increased long term storage for all options. Effect in dredging options is more than other options since there will be decrease in amount of sediment removed and hence the interval of dredging can be increased from 6 to 7 years which can save amount up to 30 million US $ per dredging event

Performance of By-pass is also improved due to increased gross storage and decreased sediment inflow and hence it can sustain reservoir life more than 300 years and maintain 14 million m^3 of gross storage. Performance of trucking and flushing option remains same since the technical constraints remain same and increase in reservoir volume has no considerable effect as emptying of reservoir is required for both options.

Mass wasting is more prominent in the catchment as discussed earlier. This requires immediate control. To model such situation, once again the model was run for new sediment reduction scenario by applying both check dams and reforestation program. It is supposed to reduce the suspended sediment inflow by 30 % while bed load by 50 % (Table C.0-1, Annexe C). Results and comparisons with previous scenario is done in this way.

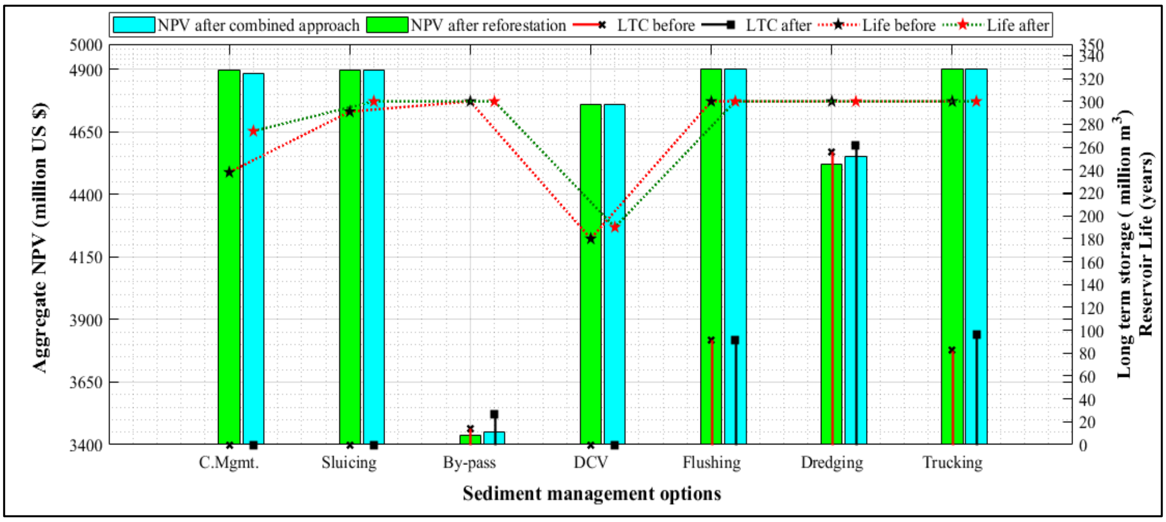


Figure 4.25: Comparison of economic and physical performance for different catchment management scenario in Banja Reservoir

From Figure 4.25, it is seen that due to combined method of catchment management applied in initial years, the physical performance of the by-pass system improves. Reason behind it can be availability of more water for by-pass and hence improved efficiency of the system. For catchment management, there will be drop in economic performance since initial investment is increased from 2.31 to 20 million US $ for implementation of the combined methods. However, reservoir life sustained is increased from 238 to 274 years. Similarly, for flushing and sluicing, there is no substantial increase in NPV and long term capacity of the reservoir, since these factors are limited by the capacity bottom outlet and flood gate and their level.

Performance of dredging is rationally improved as its long-term storage capacity goes to 261 from 256 million m^3, and NPV rises by 20 million US $. This marks the management option to be still attractive compared to other.

Multiple Management method:

RESCON2 holds capacity to evaluate implementation of different methods in succession. This might be beneficial if only one method cannot sustain the reservoir life more than 300 years. Selecting the time period is a major challenge. For simplicity, all time periods are selected after economically optimizing the performance and deteriming the implemenatation time by the model.Thus , it is belived that this can be the best time to implement the methods in succession while they have good economic value.

Table 4-12: Implementation schedule for Multiple management options for Banja Reservoir

Method	Implementation Year		NPV (Million US $)	Remaining Storage (% of gross storage)
	From	To		
Catchment Management	1	12	2463.323	94
Dredging	13	108	2253.99	87
Flushing	109	168	8.768	50
Sluicing	169	176	0.103	46
By-pass	177	300	0.94	10

Here in Figure 4.26, flushing and sluicing methods are less effective in recovering the loss of storage. Dredging can recover the loss in storage and sustain active and inactive storage capacity at 124 million m^3 till 103 years. After that implementation of flushing cannot sustain same volume, however, by 150 years, the active storage capacity drops to 55 million m^3 and remain constant on periodic flushing, while, the inactive storage keep on declining.

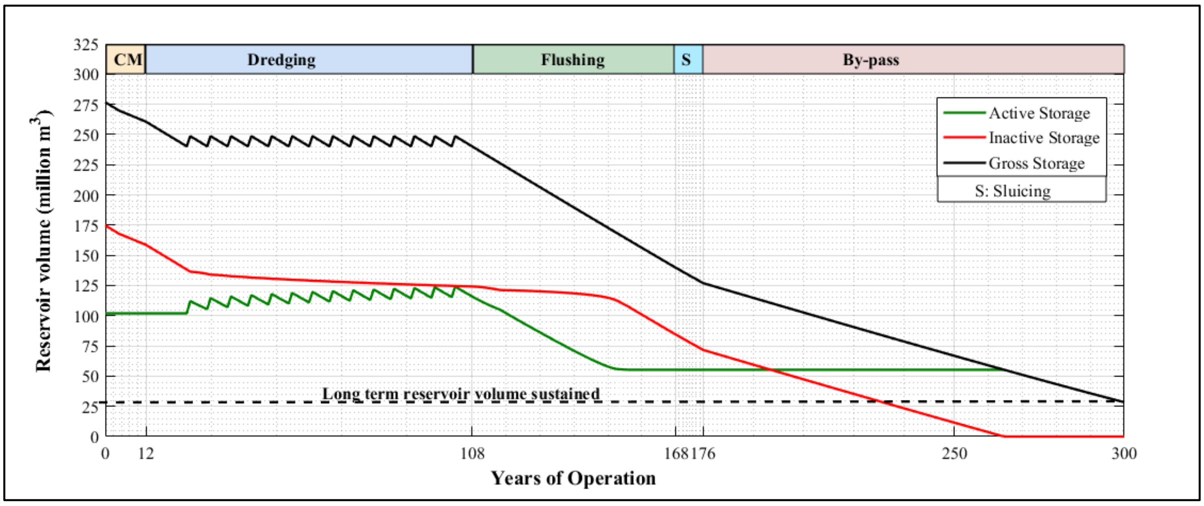


Figure 4.26: Physical performance of Banja reservoir under multiple management methods

169 years onward, sluicing and by-pass operation in succession maintains active storage constant till 260 years. After that, By-pass operation alone cannot sustain the inactive storage and hence it is completely lost. Meanwhile, the active storage keeps on declining and finally by 300 years of operation, 28 million m^3 volume will be maintained in the reservoir. This is 10 % of the initial gross volume and hence the reservoir can be called a sustainable.

Multiple management scheme can be economic in implementation since, it can save the capital investment required and operation and maintenance cost incurred. For instance, dredging is the only option that requires higher operation cost. In our case, at the rate of 3 US $/$m^3$ for dredging, it would cost 30 million US $ in each event. Thus, curtailing the time of dredging by applying other less costly options after and before as in Figure 4.26, can save substantial amount of money. Therefore, multiple management method is well justified.

4.4 Climate change results from RESCON2

RESCON2 has inbuilt capacity to analyse the effect of climate change in a basin and hence calculate the changes in net present value for each of the possible sediment management options. This process relies upon the availability of basin climate change data. World bank climate change knowledge portal (CCKP) can provide the basin data projected to future using 22 GCM for three scenarios of emission. Once again the model was run for the initial set up in scenario 1 along with basin data for Albania accessed via CCKP.

As discussed in scenario 2, attempt has been made earlier to incorporate the climate change by estimating new sediment yield, changing runoff volume and average annual temperature. From that scenario, we got the results in terms of physical and economic performance of each alternative. Here, in this case, RESCON2 using its internal routine can give only the results in term of economic performance. Thus, it is possible to compare the consistency of results from different scenarios to reach a conclusion regarding the robust sediment management option for anticipated future change.

Under this method, to assess the risk of adapting the climate change in wrong way, regrets for any given climate change is calculated by the model. The regret is defined as the difference of the infrastructure performance under the evaluated project configuration i.e. sediment management strategy and tested future climate with optimum performance sediment management strategy (Nikolaos Efthymiou, November 2016). Finally, the robust sediment management adaptation strategy is the one which minimizes the maximum calculated regrets.

Table 4-13: Regret results from RESCON2 for climate change uncertainty in Banja Reservoir.

Sediment Management Strategy	**Reservoir Sustainability**		**Aggregate Net Present Value Regrets [million US$]**					
			No Change	**Climate Change Scenario**				**Max. Regret (million US $)**
				Low Variability Future		**High Variability future**		
				Wettest	**Wetter**	**Drier**	**Driest**	
Flushing	Sustainable		79.7	106.3	106.3	94.5	94.5	106.3
Dredging	Sustainable		53.8	60.5	60.5	60.5	60.5	60.5
Trucking	Sustainable		54.9	56.4	56.4	54.8	54.8	56.4
Sluicing	Non-Sustainable	Decomm.	4.5	11.1	11.1	9.9	9.9	11.1
		R-O-R	0.0	0.4	0.4	0.4	0.4	0.4
By-Pass	Non-Sustainable	Decomm.	372.0	345.1	345.1	307.3	307.3	372.0
		R-O-R	371.3	342.3	342.3	304.8	304.8	371.3
DCV	Non-Sustainable	Decomm.	446.8	413.0	413.0	367.1	367.1	446.8
		R-O-R	424.9	376.0	376.0	334.2	334.2	424.9
C. Mgmt.	Non-Sustainable	Decomm.	23.8	29.7	29.7	28.3	28.3	29.7
		R-O-R	18.7	17.6	17.6	17.6	17.6	18.7

From Table 4-13, it is evident that Trucking, Dredging and Flushing are the options that seem to be robust to climate change. Of all, trucking has minimum maximum regret value, but its practicality to the site has been a challenge for all scenario. Followed by dredging, which still have low maximum regret and is sustainable option. This result is in line to the result that we obtained from the analysis in pervious scenario. Apart from this other non- sustainable solution viz. sluicing, catchment management are still found to be capable to cope with climate change uncertainty since their maximum regret value is lower than that of dredging. This is a good indicator that these options can be combined in a way to achieve a robust sustainable management solution as we did in multiple management methods.

4.5 Sensitivity Analysis

From the analysis performed in different scenario, dredging option after successful catchment management methods followed by other sediment management options are feasible for Banja reservoir. However, changes in sediment yield can impact the economic and physical performance. Sensitivity analysis by changing one parameter at a time as listed in Table 4-14 was performed. Here sensitivity analysis for scenario 2 is performed as sediment yield may vary when there is no sediment management plan till 2050.

Table 4-14: Changes in parameter for sensitivity analysis

Parameter	Initial	Change		
Sediment yield % change	0%	50%	100%	150%
Sediment yield (MT/year)	2.42	3.63	4.84	6.05

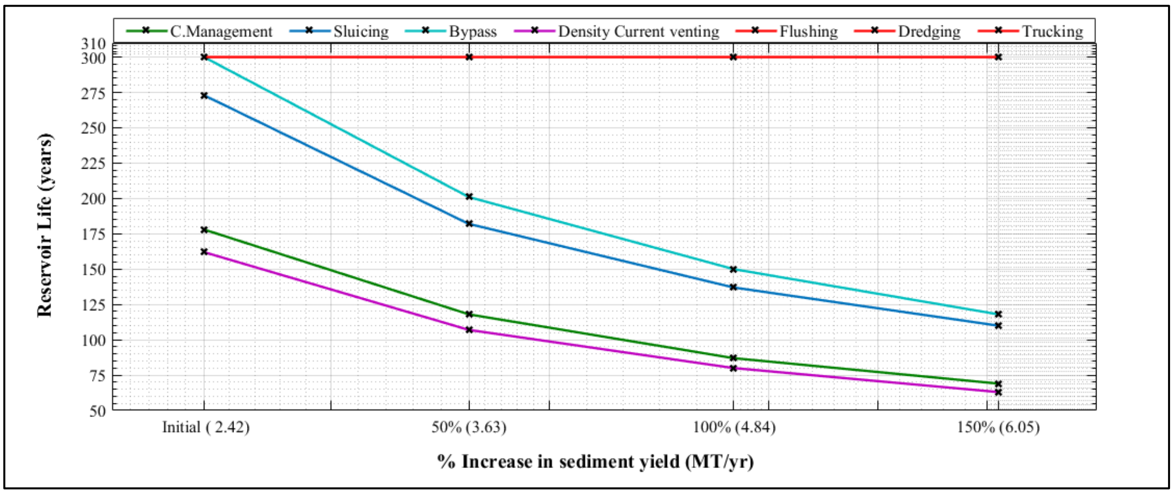


Figure 4.27: Changes in reservoir life due to change in sediment yield

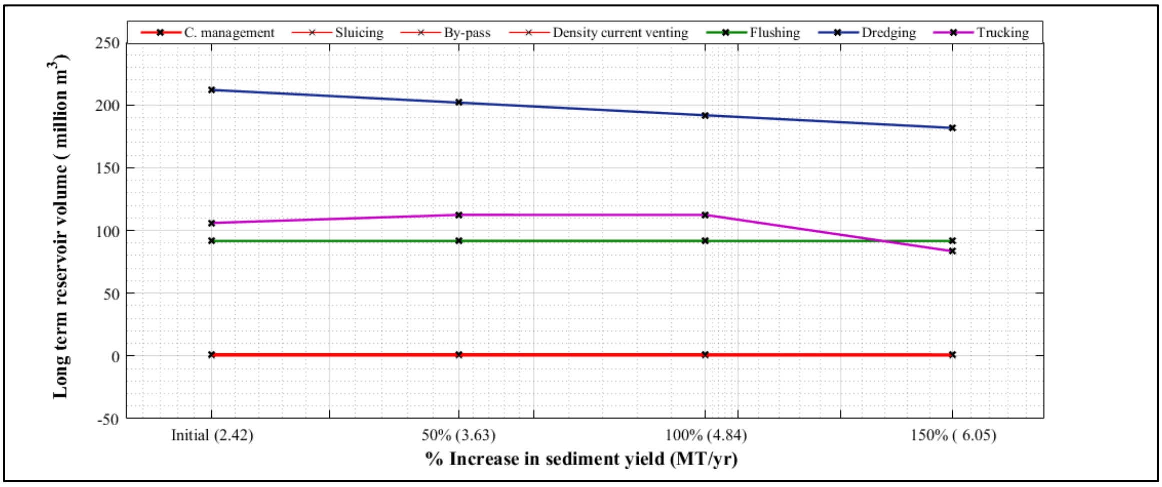


Figure 4.28 : Changes in long term reservoir capacity due to change in sediment yield

From Figure 4.27, it is seen that the reservoir life sustained more than 300 years by the sediment management options viz. flushing, dredging and trucking. In case of flushing, sediment balance ratio is high as 6.36 in the initial condition and hence, it is capable to sustain the changes in sediment yield up to 150 % without changes in reservoir life and the long-term capacity (Figure 4.28,4.29). This proves that flushing system if technically possible to the site, it is good enough to maintain the reservoir volume in long run. Trucking is found to be sustainable even on changing the sediment yield, but the volume of sediment required to be removed limits its applicability. Dredging is susceptible to change in sediment yield in terms of long term capacity as seen in Figure 4.28, however, it can maintain the reservoir life more than 300 years for any such changes. Volume of sediment removal per event cannot exceed 11 million m^3, so frequency of operation needs to be decreased. Sediment balance ratio and frequency of dredging operation changed due to change in sediment yield is presented in Figure 4.29. This can lead to increased cost for sediment management, which needs to be justified based on cost-benefit analysis.

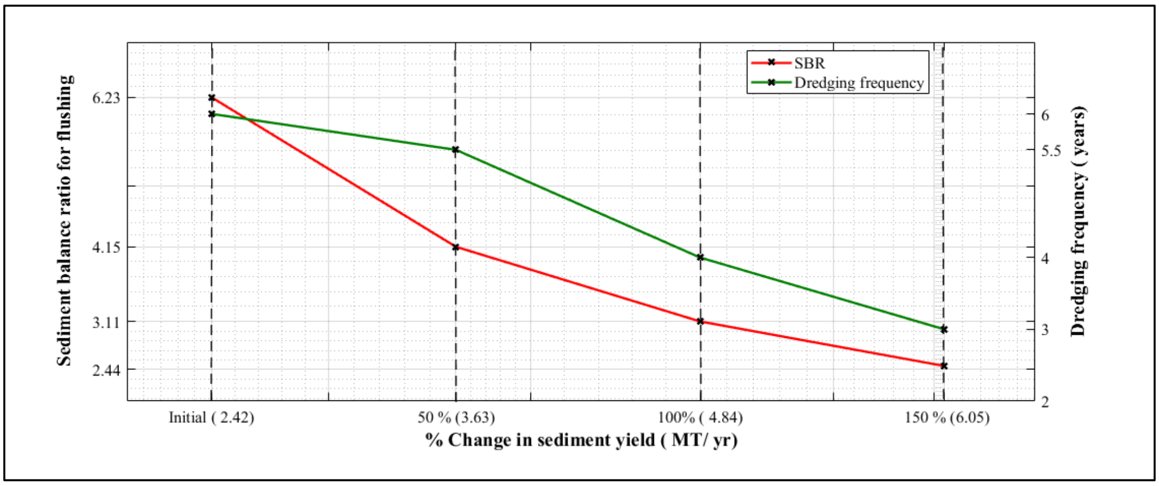


Figure 4.29: Changes in sediment balance ratio and frequency of dredging

Chapter 5 : CONCLUSION AND RECOMMENDATION

5.1 Conclusion

It is so far clear that reservoir volume loss due to sedimentation is severe in those parts of the world where soil loss due to younger and weak geology is eminent. Albania, located in South-east Europe with Mediterranean climate is exposed to severe soil loss due to intense rainfall and hence planning hydropower reservoir in such region requires special attention from the very beginning. To evaluate possible impacts of sedimentation and to be prepared from the very beginning for future is the urge of the sustainable development. RESCON2, used in this study is found to be a useful tool in planning for sustainable reservoir from the very beginning. One of the important thing that we need to keep in mind before evaluating any reservoir for sediment management in RESCON2 is that it is not dealing with design life approach; thus, any solution can sustain life for instance,100 years, still this value is low, since a reservoir needs to treated as renewable resources and should serve for many generations. 300 years and more is taken as minimum to be called a sustainable solution. This is the reason why we have higher reservoir life and still calling it as non-sustainable and less attractive solution.

RESCON2 has got a lot of strength and weakness. One of the strength realised from this study is that it can give overall picture of reservoir sedimentation most likely in future and justifies technical feasibility and economic viability of sediment management options supported by strong theoretical basis which have been followed and validated by their use since ages. Inputs to the model require variety of data which are generally available when a project is conceived.

However, some of the values need trial before reaching an optimal value. This requires experience of user. So, for the beginner, it creates a challenge to reach to optimal solution. One of the major drawback of the model is that the results from the model needs careful assessment to reach to a conclusion whether it is practical or not. Dredging and trucking volume per event are two such values which requires practical judgement. Another weakness of the model is that it cannot evaluate two or more sediment management methods which can be applied simultaneously. Evaluating one method at a time might underestimate its performance specially when multiple management methods are adopted for a project. Sediment yield estimation at the conception phase of a project is another challenge for this model. BQART model inbuilt in RESCON2, is underestimating the sediment yield compared to what has been measured in some of the existing projects considered in chapter 2. This requires a separate modelling to come up with sediment yield as input to RESCON2.

RUSLE model developed for Devoll catchment for this study is simple and convenient process. However, validating it result is always a challenge. Estimate of 2.42 MT / year is low but likely figure only if rainfall erosivity factor is changing in future. There might be more sediment than what has been estimated since flash flood and mass wasting events are quite common in Devoll catchment. This is not considered by RUSLE model which is its major weakness. But, in this study, to accommodate such uncertainty, analysis for different scenario with increased value of sediment yield has been done. And still the results are acceptable for qualitative decision.

Finally, results from RESCON2 are found to be good enough for evaluating the possible sediment management options for Banja Reservoir. In line with the results from scenario 1 in chapter 4, without sediment management option, the reservoir at present condition of sediment yield of 7.3 MT/yr. and annual flow of 1484 million m^3 can hardly survive 83 years. This is not what we want to be the fate of Banja reservoir. This result further justified why we need to plan for sediment management options to Banja reservoir. Since aim of this study is to find such solution, that can sustain reservoir life more than 300 years. Defining future scenario 2 and scenario 3 and estimating the future sediment inflow to apply RESCON2 in two different stages i.e. at the very beginning of its operation (2017) and by 2050 is believed to be more realistic than evaluating once at the beginning with all parameters being constant.

Results from scenario 2 and 3, favours dredging and flushing operation compared to other. While, trucking is practically not possible since it is required to remove 25 million m^3 sediment annually. Flushing is possible only if the bottom outlet can be re-opened, which further need technical assessment before adopting it. Availability of single bottom outlet at 110 masl with cross section of approximately 20 m^2 and maximum capacity of 300 m^3/s is one of the limiting factor to flushing width formation. Apart from this, reservoir representative width i.e. approximately 270 m may localise the flushing channel in certain part only. Hence flushing may not be efficient enough. This might be the reason that the long-term capacity sustained by flushing is only 91 million m^3. Dredging is most flexible and promising sediment management option from all scenario. The cost associated with dredging is higher compared to other options. Benefit from reservoir due to higher sustainable volume and longer reservoir life that can be maintained by periodic dredging after 43 years from now at frequency of 6 years might out weight the cost incurred.

Catchment management method, sluicing, density current venting and By-pass are found to be non-sustainable options from all scenario. But, their economic performance and robustness as tested by sensitivity analysis and regret results in Table 4-13, is satisfactory enough and hence they can be effective if applied under multiple management scheme. As mass wasting is severe in Devoll catchment, implementing catchment management method by constructing check dams and reforestation in bare lands can reduce the sediment yield. Actual reduction estimation requires detail study and some numerical modelling, but in RESCON2, it is generalised to reduce the suspended sediment load by 30 % and bed load by 50 %. This is found to be more beneficial to dredging operation since it increases the cycle length of dredging from 6 to 7 years which can save up to 30 million US $ when dredging cost is calculated at 3 US $/$m^3$.Further, to save the sediment management cost, moving from catchment to reservoir and ultimately to dam, results from multiple management methods in scenario 3 suggests to implement catchment management from the very beginning till 13 years and then continue dredging every 7 years till 108 years, after which flushing would have high economic performance till 168 years and finally, sluicing operation followed by by-pass can sustain volume to 28 million m^3 by the end of 300 years of operation. This can be the sustainable solution to Banja reservoir.

5.2 Recommendation

Results from two different models used in this study i.e. RUSLE and RESCON2 are satisfactory for rapid assessment in Pre-feasibility level. However, there are always some space for improvement for better results.

In RUSLE model, estimating sediment yield in future can be improvised if the future land use and perceived changes are available by some studies. This affects the K, C and P factor. If possible during pre-feasibility lever, field measurement of the soil quality and erodibility can be incorporated while estimating K-factor.

In RESCON2, it would be more realistic if it is possible to define the expected trend of change in future sediment yield, rather than using value and taking it as constant for ever. In case of sediment management options, it would be better to consider their efficiency of operations, for instance flushing in wide reservoir may not be efficient, though possible, due to availability of bottom outlet and other structures. During economic analysis, it would be better to define the value of water in reservoir according to the purpose, for instance value of water supplied to irrigation may be different to the value of water for electricity generation. Thus, for reservoir with primary function of electricity generation, energy equivalent calculation and price of energy per unit would be more realistic in cost benefit analysis. Calibration and validation of the result is always a challenge in RESCON2, thus it would be better to incorporate more calibration parameters than what is in use at present. Finally, in multiple management options, it would be better if there is one more routine to evaluate the alternatives which can be applied simultaneously to the reservoir under consideration.

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ANNEXES

Annexe A. Basic inputs of 10 example projects.

Country	Pakistan**(PRO1)**	
Project	Tarbela Reservoir	
Status	Existing	
Function	HI	
Reservoir Geometry		
Description	Value	
Original gross storage capacity of the reservoir[m³]	14,350,000,000	
Original active storage capacity of the reservoir[m³]	10,967,000,000	
Original dead storage capacity of the reservoir[m³]	3,383,000,000	
Existing storage capacity of the reservoir[m³]	9,383,000,000	
Existing active storage of the reservoir[m³]	6,000,000,000	
Existing dead storage of the reservoir[m³]	3,383,000,000	
Representative river bed width at the envisaged dam location[m]	1,650	
Maximum pool elevation of reservoir[masl]	472.4	
Minimum operation water level[masl]	420	
Minimum reservoir bed elevation at dam site[masl]	380	
Reservoir length[m]	88,000	
Hydrological Data		
Description	**Value**	
Mean annual reservoir water inflow [million m³/a] (MAR)	73,800	
Coefficient of variation of annual run-off volume	0.12	
Representative water temperature in the reservoir[°C]	15	
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.34	
Mean annual total sediment inflow mass [million tonnes/a](MAS)	194.3	
Average annual concentration of suspended load[g/l]	2.6	
Bed load Transport (%)	1	
Duration of Bed load Transport (%)	5	
Inter-Annual Variation		
Probability of Exceedance (%)	**%MAR**	**%MAS**
16	58	40
32	30	10
44	8	2
Economic Inputs		
Description	**Value**	
Unit cost of construction per m3 of reservoir capacity[$/m3]	0.15	
Total cost of reservoir impoundment [$]	2,152,500,000	
Discount rate [%]	5	
Market interest rate of annual retirement fund [%]	6	
Unit benefit of reservoir yield[$/m3]	0.1	
Capacity loss for characterization non-sustainable [%]	95	

Country	Morocco**(PRO2)**
Project	Mohammed V
Status	Existing
Function	S

Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	725,750,000
Original active storage capacity of the reservoir[m³]	400,000,000
Original dead storage capacity of the reservoir[m³]	325,750,000
Existing storage capacity of the reservoir[m³]	330,000,000
Existing active storage of the reservoir[m³]	2,000,000,000
Existing dead storage of the reservoir[m³]	130,000,000
Representative river bed width at the envisaged dam location[m]	2,300
Maximum pool elevation of reservoir[masl]	218
Minimum operation water level[masl]	179
Minimum reservoir bed elevation at dam site[masl]	170
Reservoir length[m]	10,500

Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	750
Coefficient of variation of annual run-off volume	0.51
Representative water temperature in the reservoir[°C]	20
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.2
Mean annual total sediment inflow mass [million tonnes/a](MAS)	12.8
Average annual concentration of suspended load[g/l]	15.36
Bed load Transport (%)	10
Duaration of Bed load Transport (%)	5

Inter-Annual Variation		
Probability of Exceedance(%)	**%MAR**	**%MAS**
25	40	40
50	20	20
75	10	10

Economic Inputs	
Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	2.21
Total cost of reservoir impoundment [$]	1,603,907,500
Discount rate [%]	6
Market interest rate of annual retirement fund [%]	7
Unit benefit of reservoir yield[$/m3]	0.4
Decommissioning cost [$]	37,000,000
Capacity loss for characterization as non-sustainable [%]	95

Country	Nepal**(PRO3)**
Project	Upper Karnali
Status	Greenfield
Function	H

Reservoir Geometry

Description	Value
Original gross storage capacity of the reservoir[m³]	17,860,000
Original active storage capacity of the reservoir[m³]	16,860,000
Original dead storage capacity of the reservoir[m³]	1,000,000
Existing storage capacity of the reservoir[m³]	17,860,000
Existing active storage of the reservoir[m³]	16,860,000
Existing dead storage of the reservoir[m³]	1,000,000
Representative river bed width at the envisaged dam location[m]	100
Maximum pool elevation of reservoir[masl]	637
Minimum operation water level[masl]	633
Minimum reservoir bed elevation at dam site[masl]	614
Reservoir length[m]	9,100

Hydrological Data

Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	15,667
Coefficient of variation of annual run-off volume	0.17
Representative water temperature in the reservoir[°C]	15
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.5
Mean annual total sediment inflow mass [million tonnes/a](MAS)	31.5
Average annual concentration of suspended load[g/l]	1.71
Bed load Transport (%)	15
Duration of Bed Load Transport (%)	30

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
3	86	40
10	64	25
30	32	14

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	2.65
Total cost of reservoir impoundment [$]	47,350,355
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	5
Unit benefit of reservoir yield[$/m3]	0.1
Decommissioning cost [$]	0
Capacity loss for characterization as non-sustainable [%]	95

Country	Morocco**(PRO4)**
Project	Abdel Karim EI Khattabi
Status	Existing
Function	S

Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	11,333,333
Original active storage capacity of the reservoir[m³]	11,333,333
Original dead storage capacity of the reservoir[m³]	0
Existing storage capacity of the reservoir[m³]	8,866,666
Existing active storage of the reservoir[m³]	8,866,666
Existing dead storage of the reservoir[m³]	0
Representative river bed width at the envisaged dam location[m]	600
Maximum pool elevation of reservoir[masl]	140
Minimum operation water level[masl]	130
Minimum reservoir bed elevation at dam site[masl]	130
Reservoir length[m]	1,600

Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	48
Coefficient of variation of annual run-off volume	0.8
Representative water temperature in the reservoir[°C]	18
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.2
Mean annual total sediment inflow mass [million tonnes/a](MAS)	0.22
Average annual concentration of suspended load[g/l]	4.12
Bed load Transport (%)	10
Duration of Bed Load Transport (%)	5

Inter-Annual Variation		
Probability of Exceedance (%)	**%MAR**	**%MAS**
25	35	35
50	18	18
75	10	10

Economic Inputs	
Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	2.21
Total cost of reservoir impoundment [$]	25,046,666
Discount rate [%]	10
Market interest rate of annual retirement fund [%]	12
Unit benefit of reservoir yield[$/m3]	0.4
Capacity loss for characterization as non-sustainable [%]	95

Country	Morocco**(PRO5)**
Project	Bin EI Quidine
Status	Existing
Function	S
Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	1,507,500,000
Original active storage capacity of the reservoir[m³]	1,507,000,000
Original dead storage capacity of the reservoir[m³]	500,000
Existing storage capacity of the reservoir[m³]	1,253,400,000
Existing active storage of the reservoir[m³]	1,253,300,000
Existing dead storage of the reservoir[m³]	100,000
Representative river bed width at the envisaged dam location[m]	1,000
Maximum pool elevation of reservoir[masl]	810
Minimum operation water level[masl]	740
Minimum reservoir bed elevation at dam site[masl]	710
Reservoir length[m]	20,000
Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	1,050
Coefficient of variation of annual run-off volume	0.58
Representative water temperature in the reservoir[°C]	12
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.2
Mean annual total sediment inflow mass [million tonnes/a](MAS)	7
Average annual concentration of suspended load[g/l]	6
Bed load Transport (%)	10
Duration of Bed Load Transport (%)	10

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
25	75	60
50	50	30
75	25	25

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	0.27
Total cost of reservoir impoundment [$]	407,025,000
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	6
Unit benefit of reservoir yield[$/m3]	0.4
Decommissioning cost [$]	37,000,000
Capacity loss for characterization as non-sustainable [%]	95

Region	South-East Asia**(PRO6)**
Project	R-O-R
Status	Greenfield
Function	SH
Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	148,000,000
Original active storage capacity of the reservoir[m³]	46,000,000
Original dead storage capacity of the reservoir[m³]	102,000,000
Existing storage capacity of the reservoir[m³]	42,000,000
Existing active storage of the reservoir[m³]	22,000,000
Existing dead storage of the reservoir[m³]	20,000,000
Representative river bed width at the envisaged dam location[m]	50
Maximum pool elevation of reservoir[masl]	231
Minimum operation water level[masl]	225
Minimum reservoir bed elevation at dam site[masl]	130
Reservoir length[m]	3,500
Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	2,400
Coefficient of variation of annual run-off volume	0.2
Representative water temperature in the reservoir[°C]	20
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.35
Mean annual total sediment inflow mass [million tonnes/a](MAS)	6.2
Average annual concentration of suspended load[g/l]	2.33
Bed load Transport (%)	10
Duration of Bed Load Transport (%)	5

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
30	40	25
60	20	5
90	3	3

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	0.88
Total cost of reservoir impoundment [$]	130,240,000
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	6
Unit benefit of reservoir yield[$/m3]	0.1
Capacity loss for characterization as non-sustainable [%]	95

Region	Europe **(PRO7)**	
Project	Srorage in cascade	
Status	Existing	
Function	H	
Reservoir Geometry		
Description	Value	
Original gross storage capacity of the reservoir[m³]	2,700,000,000	
Original active storage capacity of the reservoir[m³]	2,300,000,000	
Original dead storage capacity of the reservoir[m³]	400,000,000	
Existing storage capacity of the reservoir[m³]	2,200,000,000	
Existing active storage of the reservoir[m³]	1,900,000,000	
Existing dead storage of the reservoir[m³]	300,000,000	
Representative river bed width at the envisaged dam location[m]	50	
Maximum pool elevation of reservoir[masl]	296	
Minimum operation water level[masl]	240	
Minimum reservoir bed elevation at dam site[masl]	170	
Reservoir length[m]	70,000	
Hydrological Data		
Description	**Value**	
Mean annual reservoir water inflow [million m³/a] (MAR)	6,400	
Coefficient of variation of annual run-off volume	0.4	
Representative water temperature in the reservoir[°C]	20	
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.35	
Mean annual total sediment inflow mass [million tonnes/a](MAS)	18	
Average annual concentration of suspended load[g/l]	2.53	
Bed load Transport (%)	10	
Duration of Bed Load Transport (%)	5	
Inter-Annual Variation		
Probability of Exceedance (%)	**%MAR**	**%MAS**
20	40	20
60	20	10
90	5	3
Economic Inputs		
Description	**Value**	
Unit cost of construction per m3 of reservoir capacity[$/m3]	0.15	
Total cost of reservoir impoundment [$]	405,000,000	
Discount rate [%]	5	
Market interest rate of annual retirement fund [%]	6	
Unit benefit of reservoir yield [$/m3]	0.1	
Decommissioning cost [$]	200,000,000	
Capacity loss for characterization as non-sustainable [%]	95	

Country	Nepal **(PRO8)**
Project	Kaligandaki
Status	Existing
Function	H

Reservoir Geometry

Description	Value
Original gross storage capacity of the reservoir[m³]	7,700,000
Original active storage capacity of the reservoir[m³]	3,100,000
Original dead storage capacity of the reservoir[m³]	4,600,000
Existing storage capacity of the reservoir[m³]	3,100,000
Existing active storage of the reservoir[m³]	3,100,000
Existing dead storage of the reservoir[m³]	0
Representative river bed width at the envisaged dam location[m]	100
Maximum pool elevation of reservoir[masl]	524
Minimum operation water level[masl]	518
Minimum reservoir bed elevation at dam site[masl]	490
Reservoir length[m]	5,000

Hydrological Data

Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	8,211
Coefficient of variation of annual run-off volume	0.4
Representative water temperature in the reservoir[°C]	15
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.5
Mean annual total sediment inflow mass [million tonnes/a](MAS)	41.04
Average annual concentration of suspended load[g/l]	4.9
Bed load Transport (%)	1
Duration of Bed Load Transport (%)	5

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
15	50	20
30	24	2
50	12	1

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	4.1
Total cost of reservoir impoundment [$]	31,570,000
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	6
Unit benefit of reservoir yield [$/m3]	0.1
Decommissioning cost [$]	0
Capacity loss for characterization as non-sustainable [%]	95

Region	Asia,Himalayas**(PRO9)**
Project	Daily Peaking R-O-R
Status	Greenfield
Function	SH
Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	6,000,000
Original active storage capacity of the reservoir[m³]	4,000,000
Original dead storage capacity of the reservoir[m³]	2,000,000
Existing storage capacity of the reservoir[m³]	6,000,000
Existing active storage of the reservoir[m³]	4,000,000
Existing dead storage of the reservoir[m³]	2,000,000
Representative river bed width at the envisaged dam location[m]	30
Maximum pool elevation of reservoir[masl]	765
Minimum operation water level[masl]	755
Minimum reservoir bed elevation at dam site[masl]	735
Reservoir length[m]	6,000
Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	3,300
Coefficient of variation of annual run-off volume	0.4
Representative water temperature in the reservoir[°C]	20
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.35
Mean annual total sediment inflow mass [million tonnes/a](MAS)	4.4
Average annual concentration of suspended load[g/l]	1.33
Bed load Transport (%)	15
Duration of Bed Load Transport (%)	8

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
30	45	20
60	25	10
90	5	3

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	4.67
Total cost of reservoir impoundment [$]	28,020,000
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	6
Unit benefit of reservoir yield [$/m3]	0.1
Decommissioning cost [$]	10,000,000
Capacity loss for characterization as non-sustainable [%]	95

Country	Iran **(PRO10)**
Project	No inactive storage
Status	Greenfield
Function	HI
Reservoir Geometry	
Description	Value
Original gross storage capacity of the reservoir[m³]	1,760,000,000
Original active storage capacity of the reservoir[m³]	1,760,000,000
Original dead storage capacity of the reservoir[m³]	0
Existing storage capacity of the reservoir[m³]	0
Existing active storage of the reservoir[m³]	0
Existing dead storage of the reservoir[m³]	0
Representative river bed width at the envisaged dam location[m]	150
Maximum pool elevation of reservoir[masl]	271.6
Minimum operation water level[masl]	189.6
Minimum reservoir bed elevation at dam site[masl]	189.6
Reservoir length[m]	40,000
Hydrological Data	
Description	**Value**
Mean annual reservoir water inflow [million m³/a] (MAR)	5,008
Coefficient of variation of annual run-off volume	0.12
Representative water temperature in the reservoir[°C]	20
Specific weight of in-situ reservoir sediment [tonnes/m³]	1.2
Mean annual total sediment inflow mass [million tonnes/a](MAS)	58
Average annual concentration of suspended load[g/l]	9.8
Bed load Transport (%)	15
Duration of Bed Load Transport (%)	10

Inter-Annual Variation

Probability of Exceedance (%)	**%MAR**	**%MAS**
10	67	55
30	28	15
60	10	2.5

Economic Inputs

Description	**Value**
Unit cost of construction per m3 of reservoir capacity[$/m3]	0.15
Total cost of reservoir impoundment [$]	264,000,000
Discount rate [%]	5
Market interest rate of annual retirement fund [%]	6
Unit benefit of reservoir yield [$/m3]	0.1
Decommissioning cost [$]	0
Capacity loss for characterization as non-sustainable [%]	95

Annexe B: Table and Figures for RUSLE Model

Table B.0-1: Climate change and its effect summary from CCKP.

Report on Emissions Scenarios (SRES)									
Scenario	**A1B**			**A2**				**B1**	
Global Circulation Model	**Mean Temp in Absolute Change**	**Annual Precipit. in % Change**	**MAR in % Change**	**Mean Temp in Absolute Change**	**Annual Precipit. in % Change**	**MAR in % Change**	**Mean Temp in Absolute Change**	**Annual Precipit. in % Change**	**MAR in % Change**
bccr_bcm2_0	1.99	-11	-13.76	2.24	-13.24	-15.27	1.36	-8.51	-11.07
cccma_cgcm3_1	1.98	-2.57	-5.64	2.4	-7.1	-10.04	1.8	-3.23	-4.74
cnrm_cm3	3.13	-20.12	-23.14	2.51	-17	-19.68	1.84	-7.19	-9.18
csiro_mk3_0	0.97	-5.51	-7.82	1.63	-15.46	-18.24	0.78	3.64	1.91
csiro_mk3_5	2.16	-7.65	-10.87	2.14	-2.55	-4.38	1.73	-1.42	-6.04
gfdl_cm2_1	2.32	-12.37	-13.06	2.31	-20.84	-21.08	1.31	-5.93	-7.97
giss_model_e_r	1.74	-4.25	-3.87	2	-8.16	-8.02	1.28	-6.58	-8.48
inmcm3_0	2.68	-10.26	-11.82	2.15	-3.56	-5.74	1.72	-6.02	-8.51
ipsl_cm4	2.5	-5.4	-7.38	2.87	-10.58	-12.57	2.2	-11.27	-13.48
miroc3_2_medres	3.31	-0.23	-3.13	2.85	-2.25	-4.06	2.72	2.13	-0.3
mpi_echam5	2.44	-11.03	-14.04	2.37	-6.33	-9.09	1.62	-3.58	-5.72
mri_cgcm2_3_2a	1.86	-5.87	-8.29	1.2	-2.42	-3.07	1.6	-4.77	-7.39
ncar_ccsm3_0	3.21	-9.88	-12.88	3.04	-12.8	-17.15	1.76	-5.04	-8.07
Average	**2.33**	**-8.16**	**-10.44**	**2.29**	**-9.41**	**-11.41**	**1.67**	**-4.44**	**-6.85**

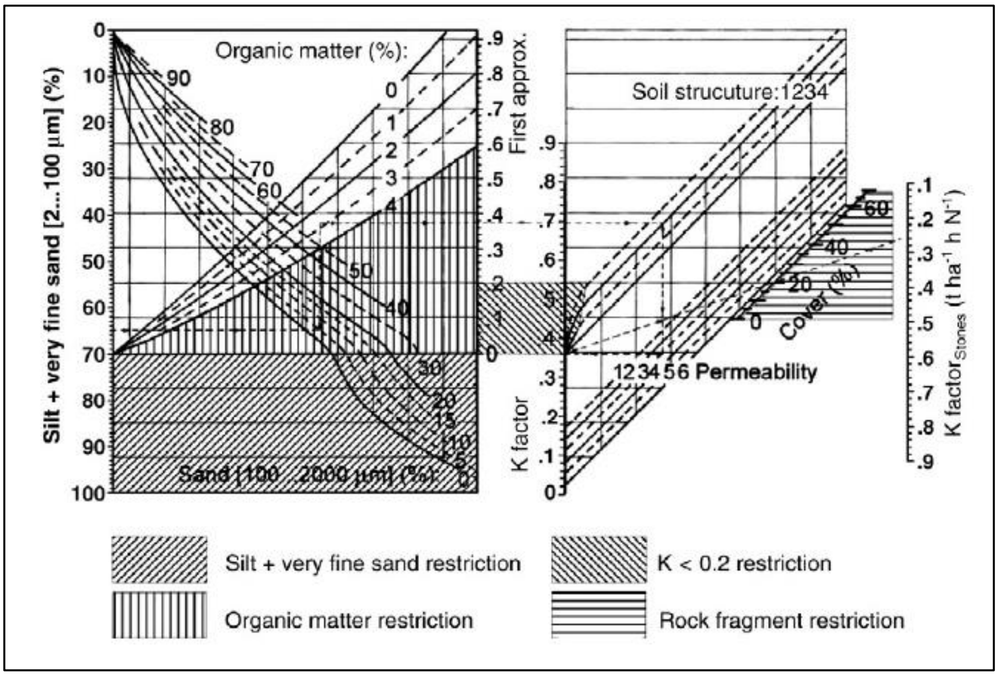

Figure B.0.1: Nomograph retrieved from : https://www.researchgate.net/figure

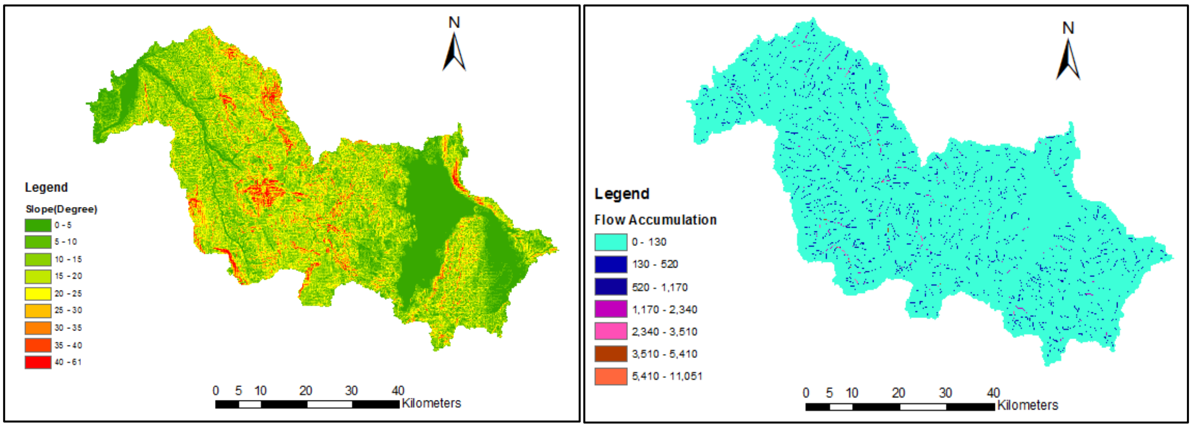

Figure B.0.2 :Slope and Flow Accumulation Map Layers

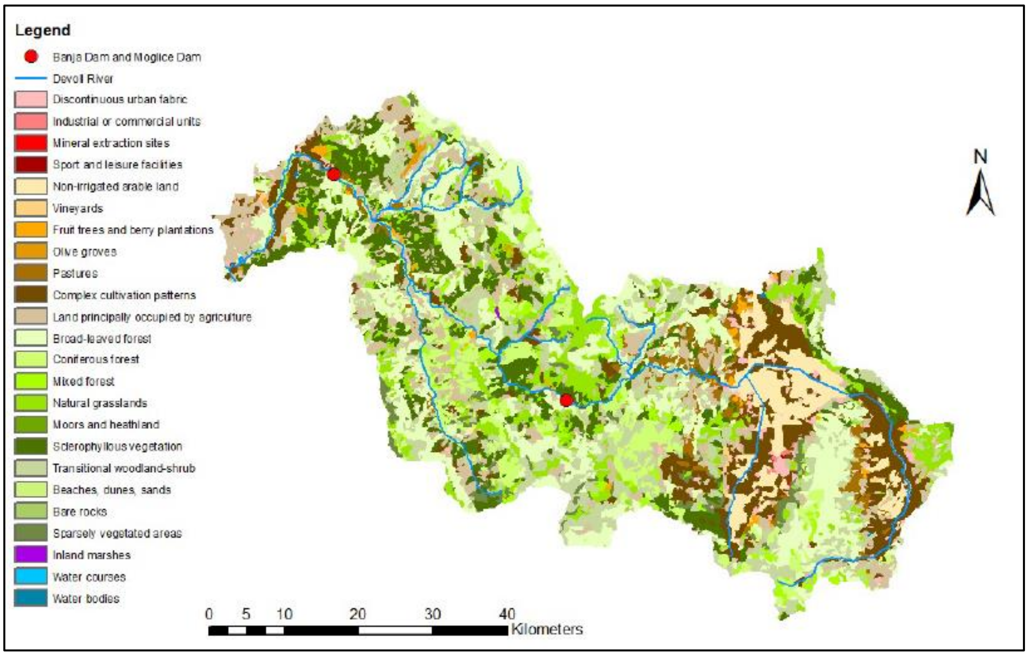

Figure B.0.3:Landuse Map for Devoll River Basin (Omelan,2015)

Table B.0-2 :CLC class table for Devoll(Prepared by Marc Omelan)

CLC class	Label 3	C factor		
		Minimum	Average	Maximum
112	Discontinuous urban fabric	0	0	0
121	Industrial or commercial units	0	0	0
131	Mineral extraction sites	0	0.5	1
142	Sport and leisure facilities	0.001	0.0255	0.05
211	Non-irrigated arable land	0.1	0.27	0.44
221	Vineyards	0.15	0.35	0.55
222	Fruit trees and berry plantations	0.1	0.325	0.55
223	Olive groves	0.1	0.325	0.55
231	Pastures	0.001	0.0755	0.15
242	Complex cultivation patterns	0.07	0.2025	0.335
243	Land principally occupied by agriculture, with significant areas of natural vegetation	0.05	0.175	0.3
311	Broad-leaved forest	0.0001	0.00505	0.01
312	Coniferous forest	0.0001	0.00505	0.01
313	Mixed forest	0.0001	0.00505	0.01
321	Natural grasslands	0.001	0.0405	0.08
322	Moors and heathland	0.001	0.0505	0.1
323	Sclerophyllous vegetation	0.001	0.0505	0.1
324	Transitional woodland-shrub	0.001	0.0255	0.05
331	Beaches, dunes, sands	0	0.5	1
332	Bare rocks	0	0.45	0.9
333	Sparsely vegetated areas	0.1	0.325	0.55
411	Inland marshes	0.001	0.0055	0.01
511	Water courses	0	0	0
512	Water bodies	0	0	0

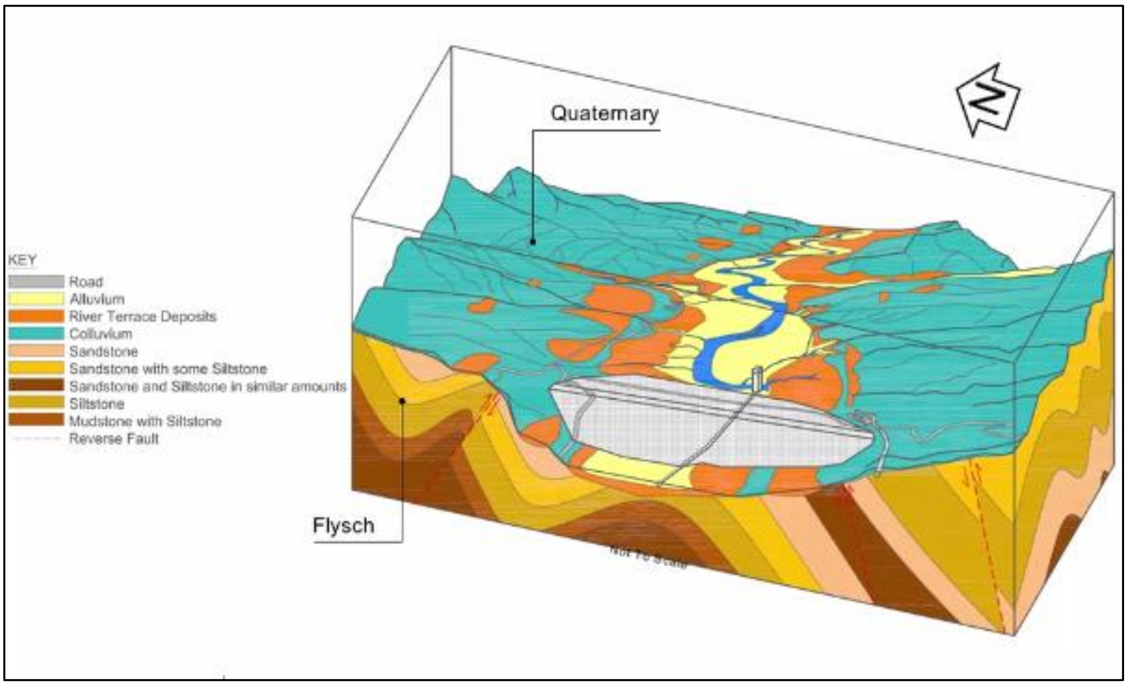

Figure B.0.4: Geology of the reservoir area (Retrieved from video lecture by : Mark Gill)

Annexe C: Data For Banja Reservoir

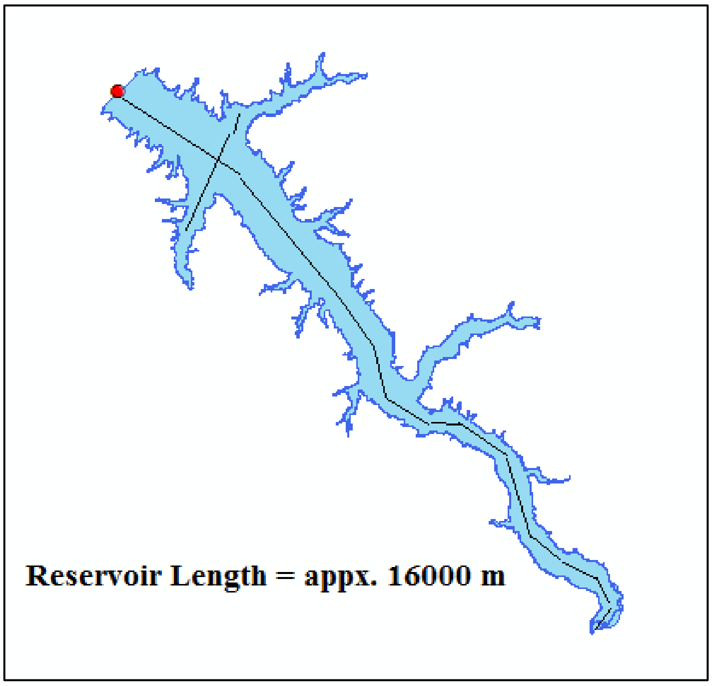

Figure C.0.1: Approximate Reservoir length measurement in ArcGis

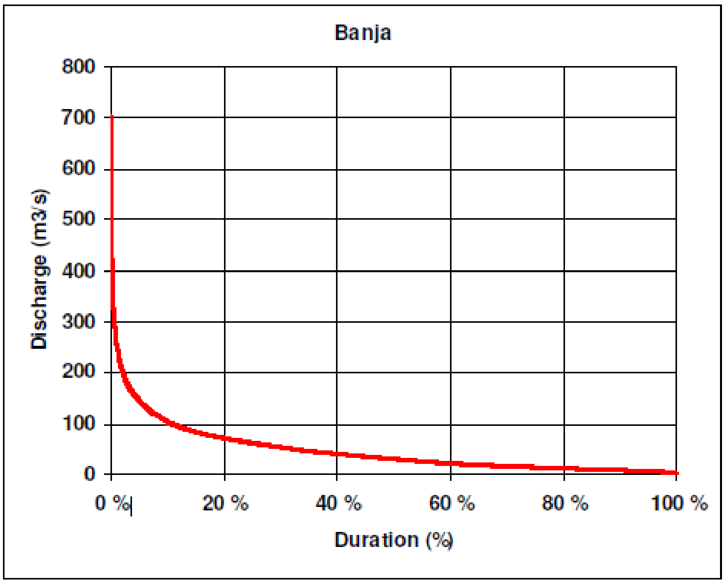

Figure C.0.2 Flow Duration Curve for Banja Reservoir(Norconsult,2010a)

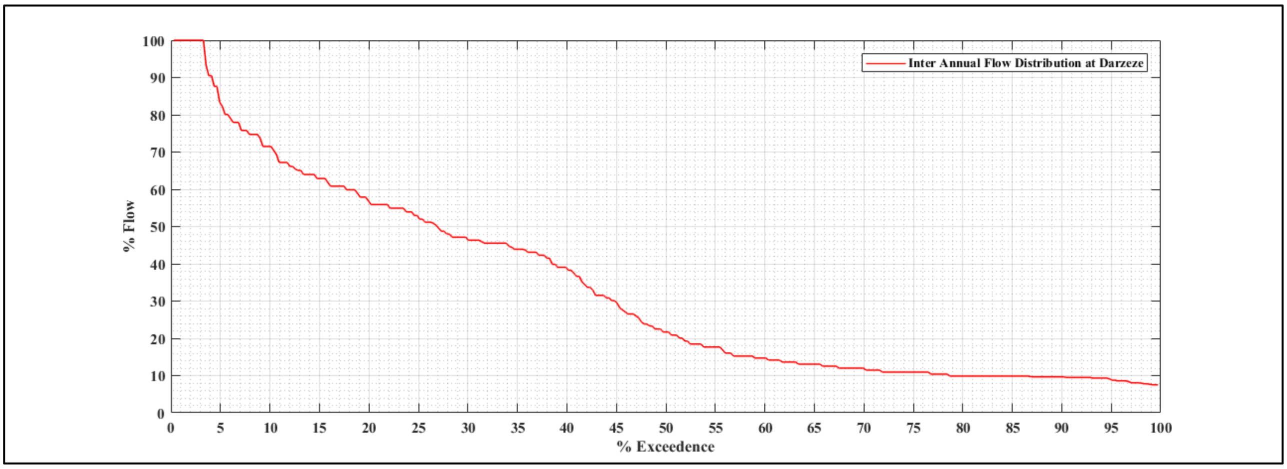

Figure C.0.3: Inter annual Flow distribution at Darzeze Gauging station

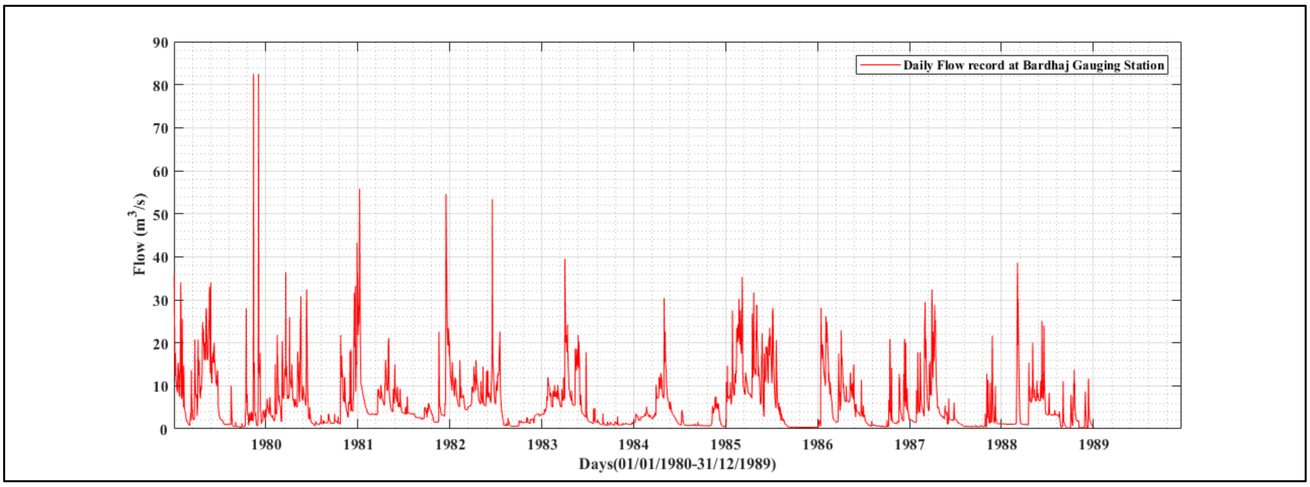

Figure C.0.4: Daily Flow record at Bhardaj gauging station

Fraction of total load transported as bedload as a function of suspended sediment concentration.

Suspended sediment concentration (p.p.m.)	Bedload fraction in gravel-bed streams				Bedload fraction in sand-bed streams			
	Maddock & Borland (1950)	Lane & Borland (1951)	Data mean	Data standard deviation	Maddock & Borland (1950)	Lane & Borland (1951)	Data mean	Data standard deviation
<1000	0·05	0·05 to 0·11	0·26	0·27	Up to 0·5	0·2 to 0·6	0·51	0·33
1000 to 7500	0·05 to 0·1	0·05 to 0·11	0·055	0·085	0·1 to 0·2	0·09 to 0·26	0·10	0·089
>7500	0·02 to 0·08	0·02 to 0·07	0·088	0·054	0·1 to 0·2	0·05 to 0·13	0·035	0·032

Figure C.0.5: Partitioning due to Maddock & Borland(1950)(Retrieved from (Jens M.Turowski, 2010)

Table C.0-1: Suspended and bed load reduction due to Catchment Management (Retrieved from Nikolas, 2016)

Catchment Management Method	Reduction of bedload	Reduction of suspended load	Timing of appearance of impact
Check Dams	up to 100%	0%	Immediate
Reforestation	10%	30%	> 3 years after implementation
improved agricultural management practices	10%	30%	>3 years after implementation
De-intensification of land use practices	10%	30%	>3 years after implementation
Combination of methods	50%	30%	Immediate

Table C.0-2 : Indicator of deposit type for flushing in RESCON2

Tsinghua University Method	
Description	**Value**
Fine and Loose Sediments	1600
Sediment median size less than 0.1 mm	650
Sediment median size larger than 0.1 mm	300
Flushing discharge < 50 m^3/s for any grain size	180

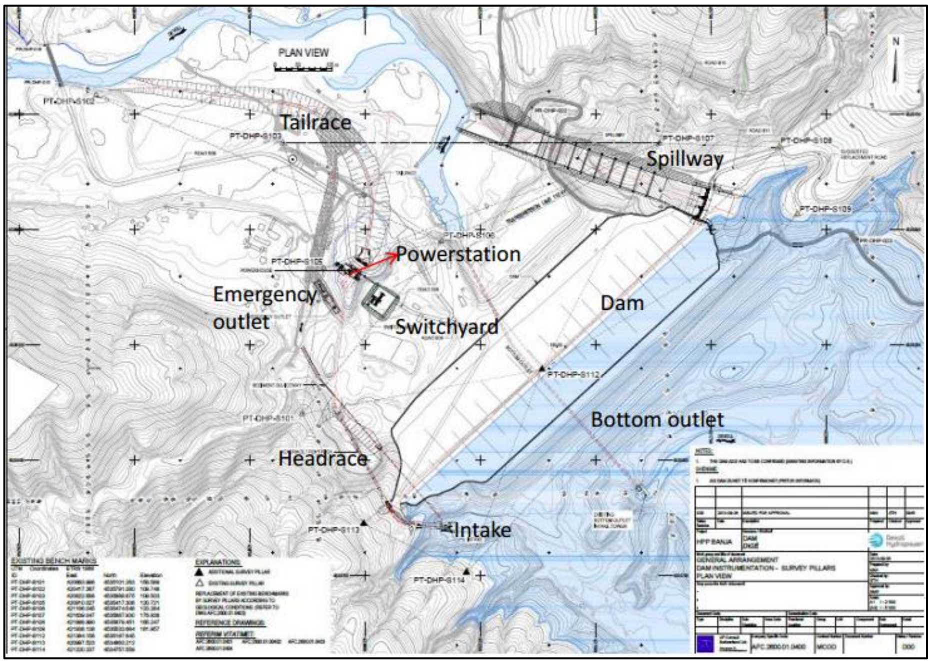

Figure C.0.6: Dam site plan view (Source: Siri Stokseth, Statkraft)

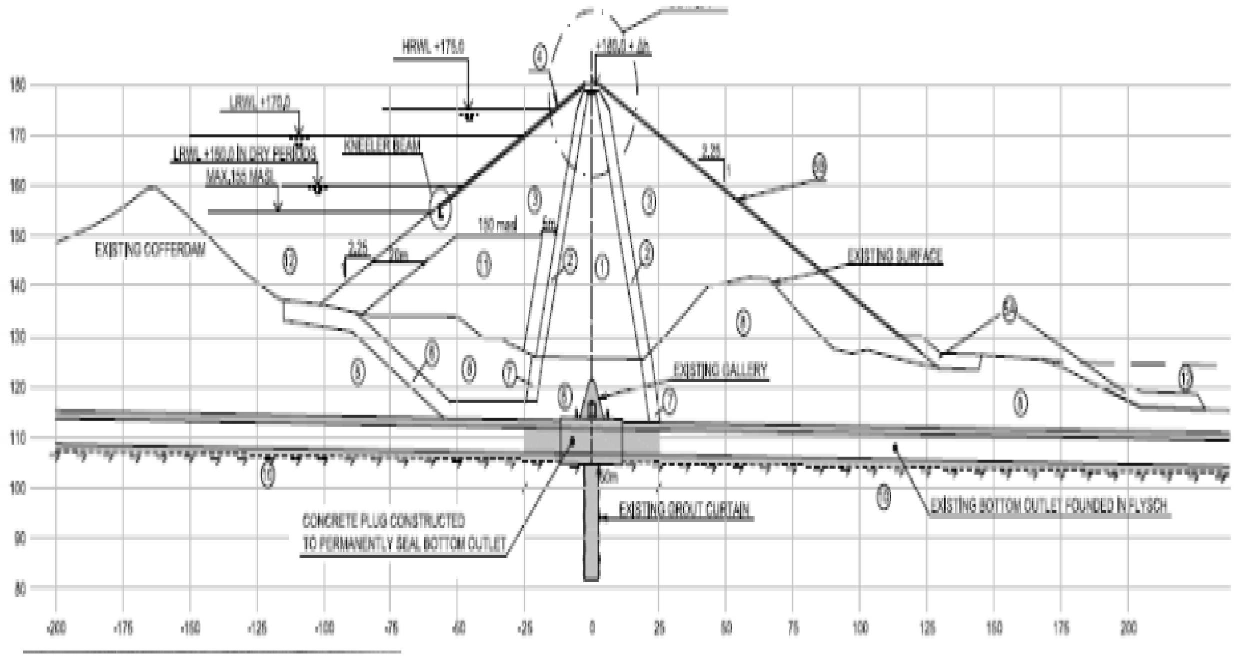

Figure C.0.7 : Cross-section of Banja Dam (Source: Siri Stokseth,Statkraft)

Figure C.0.7 : Graphical user interface of RESCON2

Annexe D: Master thesis Description

Main title:

Evaluating sediment handling strategies for Banja Reservoir using the RESCON2 model

Sub title:

A comprehensive study of the rapid assessment tool for sustainable sediment management

Background:

Reservoirs are used worldwide to provide reliable water supply, hydropower, and flood management services. They are particularly useful in areas of the world with high hydrologic variability, where the amount of water flowing in rivers varies significantly both seasonally and from year to year. In these areas, storing enough water for use during long, multiple-year droughts, and thereby ensuring the reliability of water and power supply, requires very large reservoir storage spaces. In countries where hydropower is the primary source of energy, there are often both reservoir and run-of-river (ROR) projects.

It is widely recognized that sedimentation poses a significant threat to the longevity, usefulness, and sustainable operations of both storage reservoirs and ROR projects. Over time, as sediment builds up in reservoirs, it results in the loss of storage space, which, in turn, negatively affects hydropower generation, reduces the reliability of water supply and flood management services, and degrades aquatic habitat. The current estimate of total reservoir storage worldwide is around 7,000 km3 (ICOLD, 2011). This storage is used for water supply, irrigation, power generation and flood control. Concern about loss of reservoir capacity due to sedimentation was raised by Mahmood (1987) and has recently been expressed in many forms and publications. It is estimated that more than 0.5 percent of the total reservoir storage volume in the world is lost annually because of sedimentation (White, 2001). This translates into the need to add some 45 km3 of storage per year worldwide. Costs would be on the order of US$13 billion per year and the associated environmental and social impacts significant. The introduction of sediment management measures in some older dams, where appropriate, and in the design of new ones could help to reduce this need for additional storage.

The World Bank developed a model to estimate the best possible sediment management strategy for hydro power plants in general. This model is supposed to help the planner in the prefeasibility study. It gives an insight in the deposition characteristic and how this is to be mitigate depending on the individual plant.

Goal:

The overall goal of the thesis is to evaluate an existing reservoir in terms of its sediment management plan. Through a literature study, the candidate will come up with a total load per year washed into the Devoll River. Based on these values and on the available data, the student will use the RESCON2 model to evaluate sediment strategies and the one implemented in the project. In addition, the candidate will run the RESCON2 model on 10 different cases to get familiar with the software and to have an overview of what are the different options in the model.

Data available:

- Input data for 10 different hydropower cases in excel form.
- Input data for Banja Reservoir

Working tasks:

1. Up-to-date literature study on the sediments and hydro power.
2. Introduction to the RESCON model
3. A detailed review on the RESCON2 model concerning the 10 different examples given
4. Application of the RESCON2 model to the Banja reservoir with special attention to the catchment management alternatives.

Cooperation:

The work is conducted in cooperation with Statkraft (Siri Stokseth), the World Bank (Pravin Karki) and Fichtner consulting, Germany (Sebastian Palt and Nikolaos Efthymiou).

Co-supervisor:

Siri Stokseth (Statkraft)

Reference:

ICOLD (2011), World Register of Dams, International Commission on Large Dams, Paris, France.

Mahmood, K.. 1987. Reservoir sedimentation: impact, extent, and mitigation. World Bank technical paper ; no. WTP 71. Washington, D.C. : The World Bank.

White, R., 2001. Evacuation of sediments from reservoirs. Thomas Telford, London

Trondheim, 12.01.2017 – Associate Prof. Nils Rüther(Suprevisor)