AFRICA CENTER OF EXCELLENCE FOR WATER MANAGEMENT

ADDIS ABABA UNIVERSITY

RESERVOIR SEDIMENTATION AND ITS MITIGATION MEASURES IN ETHIOPIA

A Seminar submitted to the Africa Center of Excellence for Water Management, Addis Ababa University in partial fulfillment of the requirements for the Degree of Master of Science in Water Management (Hydrology and Water Resource Management).

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LIST OF ACRONYMS

DEM……………………………Digital Elevation Model
DSL……………………………Dead storage level
FAO…………………………... Food and Agricultural Organization
FRL……………………………Full reservoir level
FSL……………………………Full supply level
GIS……………………………Geographical Information System
Ha………………………………Hectare
GPS……………………………Global Positioning System
ICOLD…………………………International Commission on Large Dams
IWM…………………………… Integrated Watershed Management
IWMP………………………… Integrated Watershed Management Plan
Km_2……………………………Kilometer square
LE………………………………Life of Expectancy
M ………………………………Meter
MAE……………………………Mean Absolute Error
M.a.s.l ………………………….…Meter Above Sea Level
MCM or Mm_3 ……………………......…Million meter cube
MW……………………………..…Mega Watt
RBE……………………………..Reservoir Bed Elevation
RMSE…………………………...Root Mean Square Error
SD………………………………Sounding Depth
SR……………………...……. Sediment Deposition Rate
SV………………………………Sediment Volume
T/ha/yr………………………....Tone per Hectare per Year
T/km2/yr………………………..Tone per Kilometer Square per Year

ABSTRACT

Sedimentation in reservoirs is becoming more problematic as water storage and supply become increasingly endangered with the aging Ethiopian infrastructure. Three general strategies for addressing reservoir sedimentation are currently utilized: reduction of incoming sediment yield, minimization of sediment deposition, and removal of sediment from reservoirs. This paper addresses the latter two strategies and their associated management methods. The main management methods associated with minimizing sediment deposition are construction of sediment bypass structures, sediment pass-through (or sluicing), and venting of a sediment-laden density current. The main overall advantage of sediment bypass structures is that they do not interfere with regular reservoir operation; however, the method is difficult to apply, requires careful planning, and cannot be utilized in arid climates where the need for water is high. Sluicing is one of the more often used sediment-management techniques, but depends upon the existing structure of the dam and can cause adverse impacts to the downstream environment if not carefully monitored. Density current venting is seldom-used due to its reliance on the existence and surveying of a density current; however, it has been shown to be effective under certain circumstances. The main management methods associated with removing sediment from reservoirs nearing critical storage loss are flushing and dredging. Drawdown flushing has been studied extensively and has been found to work optimally on narrow, gorge-shaped reservoirs where the water can be fully drawn down. Pressurized flushing is not implemented as often as drawdown flushing as its main purpose is in clearing the area immediately surrounding the bottom outlets of the dam. Flushing generally has more noticeable effects on the downstream ecosystem than sluicing. Dredging, the most often used sedimentation management technique is also a highly expensive and time-consuming practice, although efficacious when complimented by other methods, particularly for settling basins at the inlet of the reservoirs.

Keywords: - Reservoir sedimentation, Storage Capacity, Sediment Yield, Mitigation measures.

1. INTRODUCTION

1.1. Background

The reservoir sedimentation process is a universal phenomenon, which has been considered the most critical environmental hazard of modern times (Jain and Kothyari, 2000).Sediment deposition in reservoirs is a serious offsite consequence of soil erosion that threatens the sustainability of dams built for various purposes throughout Ethiopia (Haregeweyn et al., 2006) as well as in other parts of the world. In the present situation, the world wide loss of storage capacity in surface water reservoirs due to sedimentation is higher than the increase in storage volume achieved through construction of new reservoirs (White, 2010).

Reservoir sedimentation is a severe problem around the world, as it reduces the original capacity of the reservoir significantly which affects the irrigation, hydropower and drinking water supply, flood control and recreational activities.

Due to lack of reservoir management practices such as periodical sediment flushing, reservoir sediment routing and catchment management to reduce the soil erosion, the sedimentation of reservoirs is inevitable and it has gradually becoming a greater threat for many countries around the world (Haregeweyn et al., 2012).

Analysis of sedimentation has usually been done through direct and indirect approaches. Direct methods contain the real measurement of the volume of sediments accumulations in the reservoir through mostly hydrographic surveys (Vente et al., 2003).

The deposition of sediment in reservoirs creates a variety of problems, such as depletion of storage capacity, increased flood risks, interruption in hydropower generation and downstream river bed degradation; other problems such as degradation of water quality, increased complexity in reservoir operation and maintenance leads a consequent increase in their associated costs (Kothyari et al., 2002).

The purpose of this study is to assess the reservoir sedimentation and its mitigation measures of the country's reservoir by reviewing different literatures. It addresses the determination of sediment deposition, integrated watershed management practice, and different soil, and water conservation practices done on the country reservoirs, and watersheds

1.2. Objective

The general objective of this study is viewing of literatures about reservoir sedimentation and its mitigation measures on different reservoirs located in Ethiopia.

The specific objectives of study are summarized below.

- Knowing the rate of Sedimentation of Some Reservoirs of the country.
- Assessment of existing watershed resources and management practices
- Evaluating the effect of soil and water conservation practices and micro dams on land and water degradation

2. METHODOLOGY

The main methods used to do this seminar study is referring different literatures ,published articles, and journals that are mainly done on reservoir sedimentation, sediment management techniques, Integrated watershed managements, and lake management studies in different basins of the country Ethiopia.

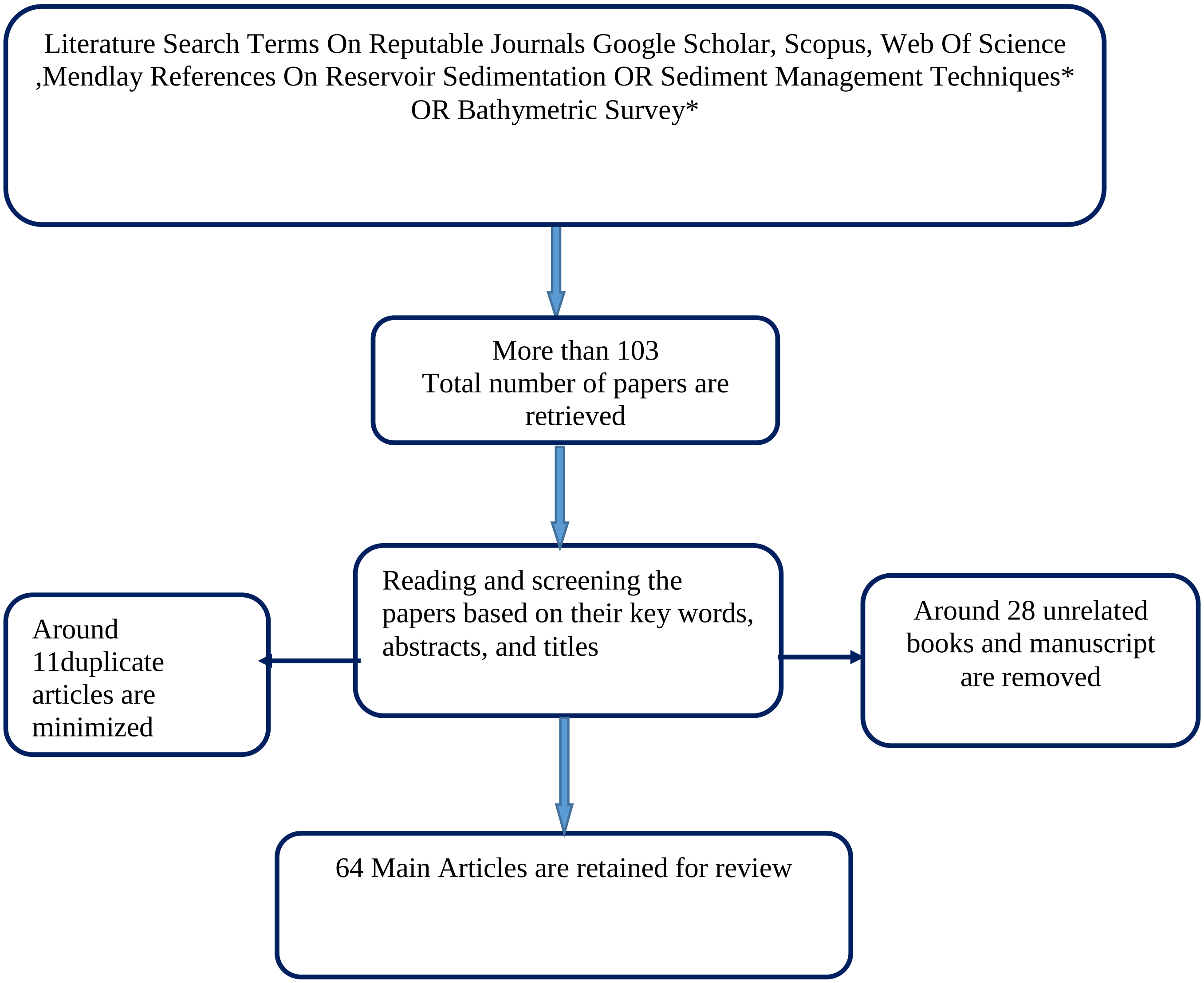

Figure 1:- Methodology of the study.

3. LITERATURE REVIEW

3.1. General Concepts on Sediment Transport and Deposition of Reservoir

The construction of a dam causes a reduction of in inflow momentum and turbulence resulting in settling of sediments carried by the incoming rivers or generally changes the hydraulic characteristics of flow and resultant sediment transport capacity (Yonas, 2005).The Major part of the sediment (bigger suspended particles and most of the bed load) transported into the reach is deposited in the backwater influence area and in the reservoir whereas finer particles may travel some more distance and may finally get deposited farther down in the reservoir (Morris and Fan, 1998) .The retention of sediment in a reservoir depends mostly on the capacity- inflow ratio of the reservoir, inflow sediment type and content.

The reservoir with high capacity-inflow ratio and low sediment content will have low rate of silting and vice versa. The other factors which influence the rate of sedimentation are reservoir operation , discharging facilities, length, size, shape and age of the reservoir, watershed characteristics, land use pattern, geological formation, construction and mining activities, rainfall amount and rainfall intensity, peak discharge, climatic factors, proportion of sediment trapped by upstream reservoir (Strand and Pemberton, 1982).

3.1.1. World Experience on Reservoir Sedimentation

There are a number of studies on sediment measurements which have been conducted to estimate the deposit of sedimentation in reservoirs. There are no accurate data on the rates of reservoir sedimentation worldwide. From the available data about 1% of the worldwide capacity is lost annually, which is equivalent to about 50 km3 of annual capacity loss (Mahmood, 1987). China has 82,000 reservoirs which are losing storage capacity at an average annual rate of 2.3%, the highest rate of loss of any country in the world, and China also has half of the world's large dams and not surprisingly, China has considerable experience in the management of reservoir sedimentation (Morris and Fan, 1998) The U.S. geological survey has completed a number of reservoirs sedimentation studies in Kansas using a combination of bathymetric surveying and sediment coring. The results indicated that decreases in total water storage capacity ranged from less than 5% to about 55%. The worldwide loss in reservoir storage capacity is estimated to be between 0.5% and 1% per annum (Mahmood, 1987, White, 2010).

3.1.2. Reservoir Sedimentation in Ethiopia

The country possesses 12 major river basins, which form four major drainage systems: -The Nile basin (including Abbay or Blue Nile, Baro-Akobo, Setit-Tekeze/Atbara and Mereb) covers 33 per cent of the country and drains the northern and central parts westwards; -The Rift Valley (including Awash, Denakil, Omo-Gibe and Central Lakes) covers 28 per cent of the country; -The Shebelli-Juba basin (including Wabi-Shebelle and Genale-Dawa) covers 33 per cent of the country and drains the southeastern mountains towards Somalia and the Indian Ocean; -The North-East Coast (including the Ogaden and Gulf of Aden basins) covers 6 per cent of the country. Integrated development master plan studies and related river basin surveys undertaken at the end of the 1990s indicate that the aggregate annual runoff from nine Ethiopian river basins is about 122km3. The Abbay, Baro-Akobo and Omo-Gibe basins account for about 76 per cent of the total runoff from an area that is only 32 per cent of the total area of the country. Most of the rivers in Ethiopia are seasonal and about 70 per cent of the total runoff is obtained during the period June-August.

Sediment deposition in reservoir is a consequence of soil erosion that threatens the sustainability of dams built for various purposes in Ethiopia. Previous studies on sediment yield and impacts, conducted mainly in northern Ethiopia have shown that the spatial variability of sediment yield in that region is generally high (Haregeweyn et al., 2006, Tamene et al., 2006).

Many dams constructed to store water for irrigation or drinking purposes were silted up while under construction (Amare, 2005). There were extreme sedimentation cases in Ethiopia such as the Borkena Dam in Wollo, which costed 35 million USD in 1991 and Adrako Dam (Ebinat, South Gondar) where the dead storage volume of the reservoir silted up before completion of its construction (Haregeweyn et al., 2006).

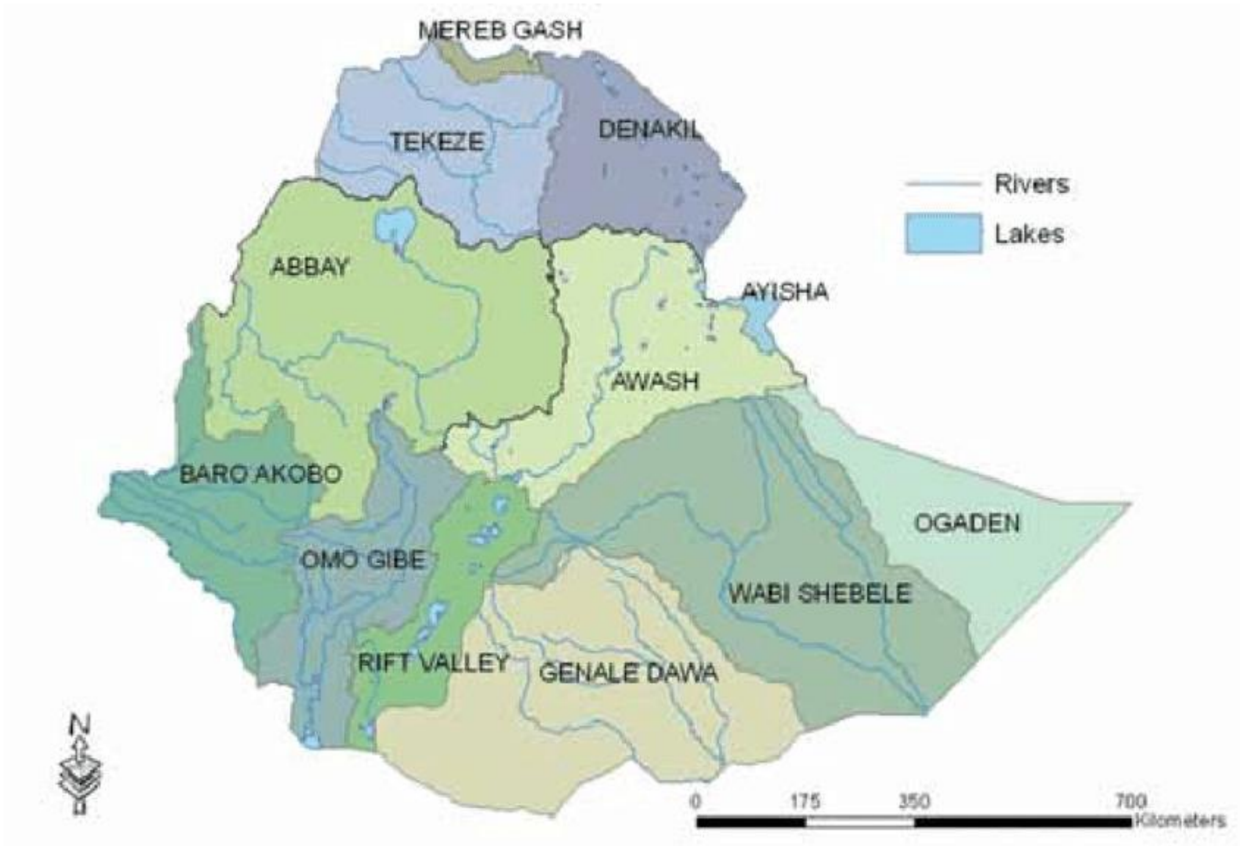

Figure 2:- location of basins of the country.

The following are the main sedimentation studies done on our country Ethiopia:-

- In 1980, the BCEOM investigated Legedadi and Gefersa reservoirs in different ways and generated maps for both reservoirs. A study was carried out with, bathymetric surveys, hydrologic analysis and reservoir operation. Bathymetric maps were produced for the Legedadi and Gefersa Reservoirs. Moreover, frequency analysis of annual peak rainfall depth and inflows into the reservoirs were computed for the period 1958 to 1979. The average annual inflow into Legedadi Reservoir was estimated at 64MCM (million cubic meters).

- Legedadi reservoir supplies 60% of water demand to Addis Ababa city, delivering 165, 000 cubic meters of water per day. A 20 years bathymetric survey (1978-1998) of this reservoir shows an average silt accumulation of 26, 000 m^3 year, which results in a water shortage for the rapidly increasing Addis Ababa city residents (over 4 million people) (Gessese, 2008).

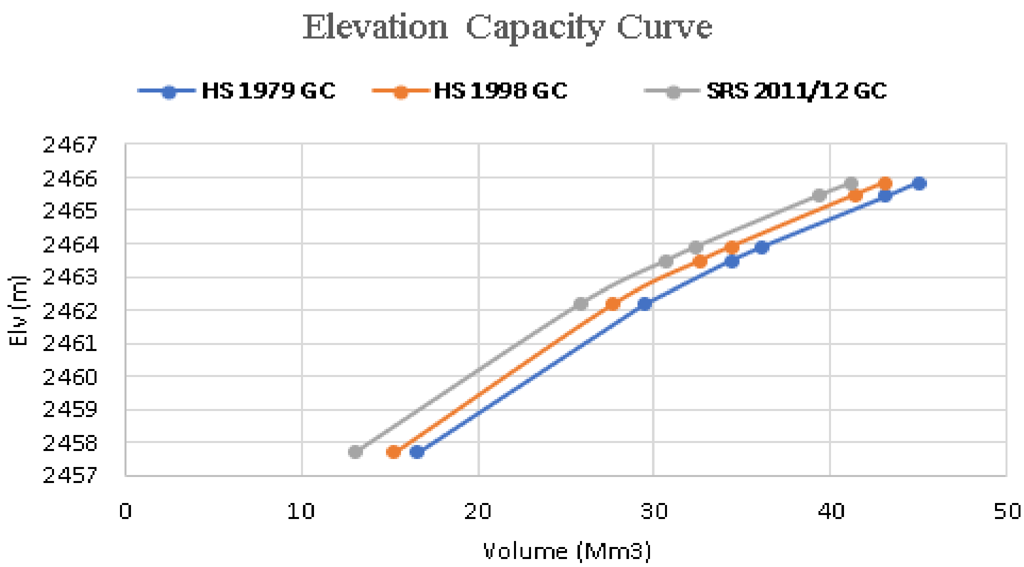

Figure 3:- Reservoir Elevation Capacity curve of Legedadi Reservoir Live Storage Zone.

- Tenaw, 2020, study on upper blue basin with title investigation of reservoir sedimentation using geographic information system and remote sensing approaches and his methodology was tested in Koga, Shina and Selamko reservoirs all in the Upper Blue Nile basin. His result indicated that Koga reservoir has reduced from 83.10 to 81.179 Mm3, showing annual storage loss of 0.33%. For Shina and Selamko reservoirs annual storage loss due to sediment deposition was found to be 1.67% and 2.29% exceeding the annual average worldwide rate for reservoir sedimentation of 1%. Consequently, the annual rate of sedimentation was found to be 27×104 m3/year for Koga, 2.1136×104 m3/year for Shina and 2.3755×104 m3/year for Selamko reservoir.

- Sediment inflow to Lake Tana has been estimated, by JICA (1977) to be 10 million m3 per year and predicted that the lake will lose 6% its storage within 100 years with trap efficiency of 50%. Based on bathymetric surveying study, WRDA (1990) stated that the trap efficiency of the lake is 97% (as sited in Ligdi, et al., 2010).

- According to (Borji, 2013) with the topic sedimentation and sustainability of hydropower reservoirs case in Grand Ethiopian renaissance dam in Ethiopia and concluded that downstream inside Sudan, in rosaries reservoir, the average annual sedimentation rate at rosaries was 1.8% between 1966 and 1985. 335m3 of initial capacity lost over 19 years of operation. The risk of losing storage capacity in the long term due to reservoir sedimentation is series for hydropower projects in the area and the main issue concerning sustainability of reservoir.

- Angereb Dam, which was constructed in early 1980 on Angereb River, a tributary of the Blue Nile, was primarily built to adequately supply drinking water to Gondar town (Musa *et al*., 2005). The dam was feasible in terms of cost consideration and a judicious use of abundantly available local materials. Nevertheless, the Angereb Reservoir has not lived up to the design expectations because of siltation, in which about 1.4 Mm^3 sediment has been accumulated (Amare, 2005; Hathaway, 2008). Other estimates by Musa *et al*. (2005) shows that the mean annual sedimentation rate in Angereb reservoir is 1200 t/km^2/year. They predicted that the reservoir will lose 30% of its volume by the year 2015

- Zeberie (2020), conducted study on the Upper Awash basin, with the title of assessment of sediment yield and conservation practices in Akaki watershed. His study focused on estimating the sediment yield, determining the spatial variability of sediment yield and evaluating different scenarios to reduce sediments. From the result of the study, it could be concluded that the average annual yield of sediment for all watersheds was 2.12ton/ha/year.

- The total sediment deposited in Koka reservoir in period 1961-1981 has been estimated at 0.34km3, yielding an average of 17Mm3/yr (Shahin, 1993).

- The Aba-Samuel dam in Addis Ababa provided one of the first electric power generating stations in the country. Sedimentation is so prolific that the reservoir's initial water carrying capacity has been reduced by half due to silt accumulation (4.45 tones of silt km^{-2}) and eutrophication (Devi *et al*., 2007). Another, estimate indicates that it is losing storage capacity at a rate of 664, 980 t $year^{-1}$ for the 43 years following construction (Amare, 2005).

- The Gilgel Gibe I hydroelectric dam has a capacity of 917 Mm^3 water (Devi *et al*.2007). Hathaway (2008) indicated that according to the 1997 Environmental Assessment on this reservoir, a high sedimentation load was anticipated. The expectation has proven to be true because investigation by Devi *et al.* (2007) showed that the reservoir capacity has been reduced by annual sediment loads of 4.50×10^7 t $year^{-1}$ (from which Gilgel Gibe River contributes 277, 437 t $year^{-1}$) which could occupy 3.75×10^7 m^3 $year^{-1}$.

- Haile and Govers (2006), conducted research in Tigray, southern Ethiopia and resulted in specific sediment yield values between 237 to 1817 ton/ km2/year.

- Estimating of reservoir sedimentation using Bathymetry survey conducted on maiambelay reservoir in October, 2017 indicates that maiambelay reservoir has lost 10.27% of its capacity due to sedimentation in 7 years operation period. The average rate of sedimentation is estimated to be 108560.2 m3/y with1.46% annual rate of loss. The study indicated that the sedimentation rates in dead storage and live storage zones are 39714.28 m3/y and 68857.15 m3/y respectively this shows that the dead storage and live storage zones have been losing 31.23 % and 7.40% of their storage capacity respectively after 7years of operation.

- To mitigate agricultural crisis from recurrent drought and erratic rainfall, the government of Ethiopia, in collaboration with other organizations, constructed more than 50 micro-dams (for irrigation scheme) in the Tigray region between 1994 and 2002 (Haregeweyn *et al.*, 2008). Investigation of these micro-dams by Tamene *et al.* (2005), showed that the area specific sediment yield of the reservoirs ranged between 345 and 4935 t km^{-2} $year^{-1}$ with a mean of 1900 t km^{-2} $year^{-1}$. This is somewhat higher than the Global and African averages, about 1500 and 1000 t km^{-2} $year^{-1}$, respectively.

- Belete, (2013), studied on the impact of sedimentation on the hydrological status of Lake Hawassa, in southern Ethiopia with hydrographic survey methods, used an echo sounder for depth measurement by 500m*500m grid spaces. He concluded that the annual reduction in storage capacity of Lake due to sedimentation was about 0.08%.

Table 1:- Estimated sediment load for some reservoirs (Devi *et al.*, 2007)

Station	Area (km^2)	Specific Sediment Load (million T/year)	Total load (million T/year)	Specific Sediment Yield (T/km^2)	Method	Year
Kessie	64,060	188	217	3384	Rating curve	1973-2009
		143	165	2576	Rating curve	1973-1994
		154	177	2774	Rating curve	2009
		154	177	2774	Average Concentration	2008-2010
		147	169	2640	Average Concentration	2009
		-	134	2100	SDR (45%)	
Burie	94,490	218	250	2645	Average Concentration	2008-2010
Guder	524	0.044	0.05	97	Rating Curve	1960-2001
Tato	43	0.009	0.01	247	Rating Curve	1996-2004
GERD	177,700	-	187	1052	SRD (45%)	
El-deim	178,200	161	187	1050	Average Concentration	1970-1994
		130	150	839	Average Concentration	1993
Roseires	195,000	-	155	795	Bathymetric Survey (deposit density=1 t/m3)	1966-2007
		-	186	954	Bathymetric Survey (deposit density=1.2 t/m3)	1966-2007

Table 2:- Estimated sediment yield at different locations (Borji, 2013)

Reservoir	Capacity reduced /expected to reduced	Sources
Koka	2302 t/km2/year	Amare (2005)
Aba-Samuel	50% lost, 664,980 t/year accumulate	Amare (2005)
Gilgel-Gibe-I	Designed for 70 years but will function for 24 years.	Devil et al. (2007)
Melka Wakena	Greatly reduced	Hathaway (2008)
Angereb	Annual siltation 1200 t/km2, 50% will lost by end of 2010	Musa et al. (2005)
Borkena and Adrako	Silted up before their construction ended	Haregeweyn et al. (2006)
Legedadi	26,000 m3/ year	Gessese (2008)
Gilgel Gibe-III	1/3 reserved for sediment	Hathaway (2008)
Tekeze	30 Mm3/year is expected, not threatening	http://www.eepco.gov.et/file
More than 50 micro-dams in Tigray	50% of studied reservoirs will lose their economic life before half of design period	Tamene et al. (2005), and Haregeweny et al. (2006)
Filiglig	Economic life time reduced 5 times	Aynekulu et al. (2006)
Grashito	Economic life time reduced 5 times	Aynekulu et al. (2006)

3.2. Impact of Reservoir Sedimentation

The major impact of sedimentation was to decrease storage capacity of reservoir, which leads to a serious problem on water resources development by reducing water supply, hydropower production, the supply of irrigation water, and the effectiveness of flood manipulate schemes. Growth of the delta deposits at the upstream end of the reservoir due to deposition might cause improved flooding or possibly a rising groundwater level in the backwater upstream. Sediment trapping and flow control aggregates also have a drastic impact on the ecosystem, transparency of water, balance of sediments, nutrient budgets, and downstream river morphology of the reservoir. As such, reservoir sediment accumulation was most likely the major issue that impeded the sustainable use of surface water supplies that have already been built and will be developed in the future (Wang, Wu, and Wang, 2005). Among the impacts: reduction in volume, increase in turbidity, and loss of life expectancy of reservoir were the most essential ones (Issa et al., 2015).

1. Reduction in Volume

Sedimentation is the major factor that affects the storage capacity of reservoir by increasing the level of sediment deposit within the reservoir. The loss of storage, associated with water supply for domestic use.Sediment aggregation in supplies diminishes their capacity and limits their valuable life in case it isn't controlled in a few ways. When a barrier was constructed over a stream, the stream cross-area dynamically increments and the stream velocity decrease toward the dam. The velocity flow and energy of watery has condensed as the stream entered to reservoirs, most of this sediment settles to the bottom of reservoir where it becomes trapped.

Over many years without sustainable management, the sediment will gradually displace the volume that was previously used for water storage until the reservoir becomes filled with sediment (Alias and Mansor, 2017).

2. Increase Turbidity of Water

Turbidity is a measurement of how cloudy the water is in a lake or river. Particulate include sediment - particularly clay and silt, first-class organic and inorganic matter, solvent-colored organic compounds, green growth, and other microscopic organisms. Turbidity can also increase water temperature because suspended fragments absorb greater heat.

High turbidity can reduce the aesthetic great of lakes and streams, having a harmful impact on recreation and tourism (Quality, 2008). White, (2010), concluded that most of the sediment that was scoured from the land surface was transported in watercourses as a suspended load. These fine sediments account for the turbidity typically determined in rivers and their fall velocity in water is therefore low that the turbulence maintains them in suspension. A tiny proportion of the sediment, maybe around 10 percent, is coarser material that is transported as bed load. Coarser sediments tend to be deposited towards the upstream finish of reservoirs whereas the finer sediments accumulate additional downstream. Throughout the early stages in the life of a reservoir, abundant the incoming sediment is cornered and forms areas of alleviation that progress downstream from the upstream finish of the reservoir.

3. Life of Expectancy of Reservoir

The life Expectancy of the reservoir is usually calculated from the ratio of storage capacity to the mean annual sediment yield trapped in the reservoir. The analysis of reservoir sedimentation requires an understanding of the physical process to predict possible changes in sediment during the lifetime of the reservoir. The life of the reservoir is reduced when the rate of sedimentation is higher than the design rate (Garg and Jothiprakash, 2008).

Reservoir shape is a vital thing in calculating the deposition profile. For example, the flow coming into a huge reservoir spreads out, accordingly lowering transport capacity, but the direction of expanding float does no longer necessarily follow the reservoir boundaries (Ezugwu, 2013)

3.3. An Overview on Integrated watershed management

IWM is the process of organizing and guiding land, water, and other natural resources used in a watershed to provide the appropriate goods and services while mitigating the impact on the soil and watershed resources. It involves socio-economic, human-institutional, and biophysical inter-relationships among soil, water, and land use and the connection between upland and downstream areas (Ffolliott et al., 2002). Watershed is the main source of floods and sediment yield which heavily impact on up/downstream communities, water and energy (Swallow et al., 2001). Integrated Watershed Management Plan (IWMP) is process of managing human activities and natural resources on a watershed basis. This approach allows us to protect important water resources, while at the same time addressing critical issues such as the current and future impacts of rapid growth and climate change (Heathcoat, 2009).

IWM builds upon the foundational principles of watershed management to integrate various social, technical, and institutional dimensions, as well as conservation, social, and economic objectives (German et al. 2007). This integration generates ‘‘an adaptive, comprehensive, integrated multi-resource management planning process that seeks to balance healthy ecological, economic, and cultural/social conditions within a watershed.

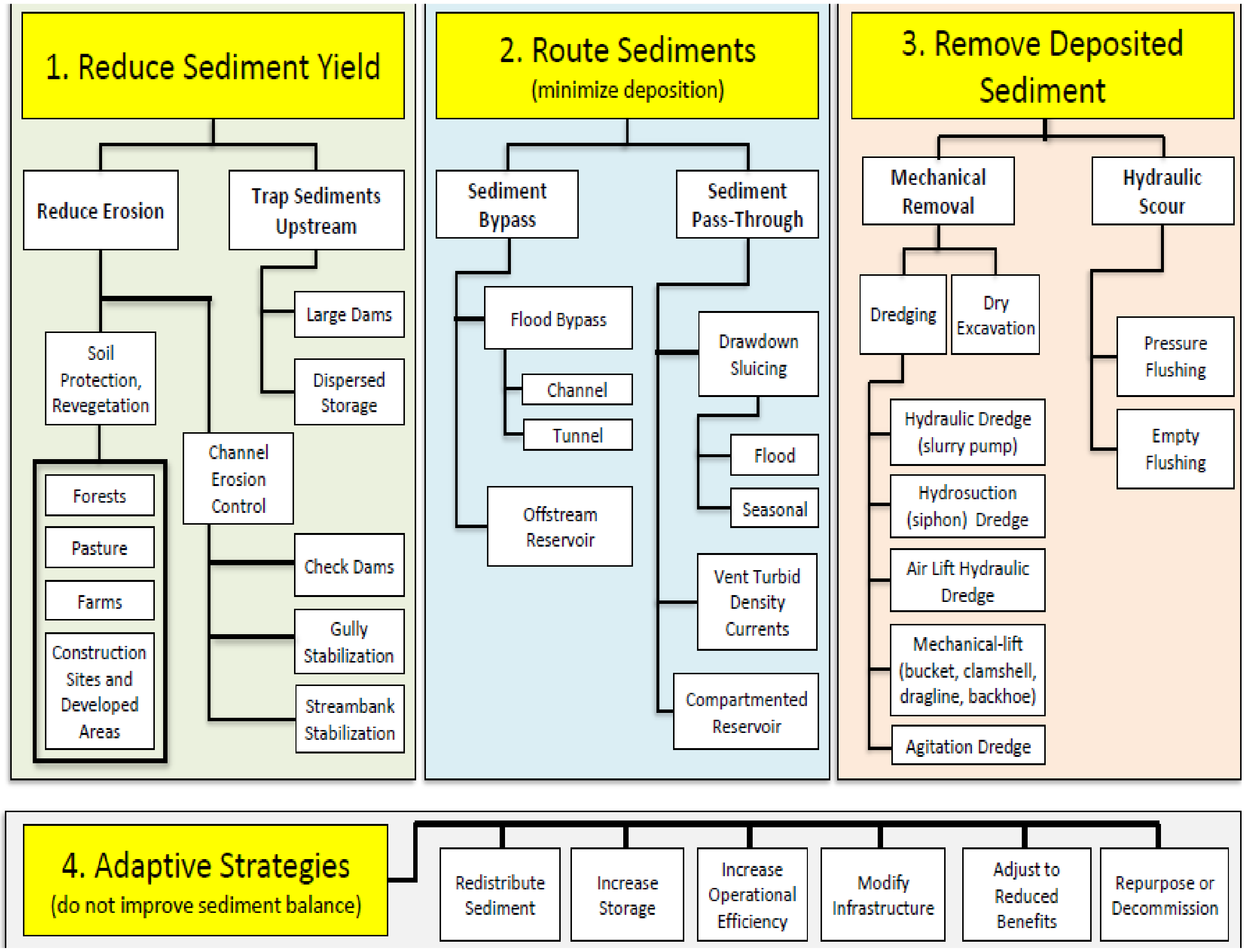

Figure 4:- Classification of Sediment Management Strategies in Reservoirs.

3.4. Methods of Removing Sediments/Deposits

Removing sediment is quickly becoming an issue of great concern as reservoirs which were constructed decades ago without any consideration of sediment management have slowly built up enormous deposits of silt and sand and now are reaching levels which impede recreation and impact water supply. The main management methods associated with removing sediment from submerged reservoirs are flushing and dredging. Flushing can be further characterized as either drawdown or pressurized.

A. Drawdown Flushing Drawdown flushing is highly similar to sluicing; however, it is not executed during flood season. Rather, it is done when the river is at low-flow conditions so that drawing down the water level takes less effort and does not affect the water supply (Annandale, 2013). The operationally-favorable conditions for drawdown flushing generally occur before the flood season or at the end of the dry season (Batuca and Jordaan, 2000).

B. Pressurized Flushing Pressurized flushing removes only a fraction of the amount of sediment when compared to drawdown flushing. This method is rarely used and its main purpose is to clear the area immediately surrounding the bottom outlets (Annandale, 2013). As the sediment is flushed out, the area around the outlet forms a funnel-shaped crater, known as a "flushing cone" (Emamgholizadeh et al., 2006).

C. Dredging An expensive but effective solution to extreme storage loss in reservoirs, dredging is perhaps the most often used sediment-management technique. Dredging removes deposited sediment from the bottom of reservoirs using pumps, hydraulic suction, or clamshell buckets (Utah Division of Water Resources, 2010).

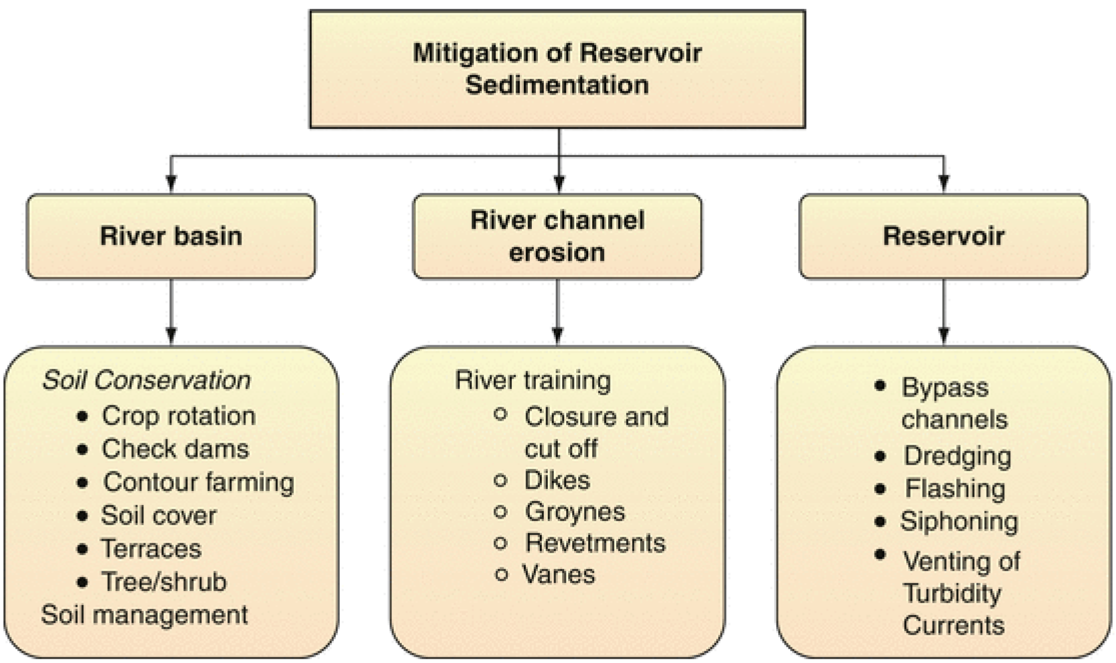

Figure 5:- Classification of Sediment Management Strategies in Reservoirs.

4. CONCLUSION, AND RECOMMENDATION

Sedimentation in Ethiopia is a serious problem in reservoirs, and river system due to its undulating topography, and poor sediment management practices.

Sedimentation Study in reservoirs are not well done on our country Ethiopia, and most of the bathymetric survey study was done on some small, and micro reservoirs.

It is important that doing a bathymetric study on large, and medium reservoirs, and taking appropriate sediment management practices prior to the loss of reservoirs life.

Generally, it is recommended that there is urgent need to commence sedimentation and general reservoir management studies in all reservoirs of our country to save them from rapid siltation and loss of benefits.

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