Investigating reservoir sedimentation for two micro earth dams in the Ethiopian Highlands.

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ABSTRACT: Reservoirs serve multiple purposes, such as providing water for irrigation and domestic use, flood control, and hydropower generation. However, they are prone to sediment accumulation due to watershed erosion. Understanding erosion and sedimentation processes is essential to determine sedimentation rates and identify factors contributing to these issues. Various methods exist for estimating sediment delivery, and this study employed a bathymetric survey to assess sediment deposition and erosion in the Anjeb and Abrajit reservoirs. Additionally, RUSLE was used to simulate watershed sedimentation. The findings revealed significant differences in sediment impoundment between the reservoirs, with noticeable bathymetric changes due to sedimentation. Both reservoirs were found to be heavily silted before reaching their intended lifespans. The RUSLE analysis estimated annual soil loss at 1374.71 t/km²/y for Abrajit and 1518.23 t/km²/y for Anjeb, much lower than the bathymetric results of 9362.29 t/km²/y and 12889.61 t/km²/y, respectively. The soil loss rates and spatial patterns align reasonably well with records and prior studies. In 2013 and 2021, Anjeb's capacities and sediment volumes were 1.0720 and 0.9534 Mm³, respectively, with an estimated live storage capacity loss of 0.119 Mm³. The long-term average annual sedimentation rate was 12,889.61 t/km²/y for Anjeb (8 years) and 9,362.29 t/km²/y for Abrajit (13 years). Bathymetric surveying revealed average annual storage losses of 11.12% for Anjeb and 4.5% for Abrajit.

Keywords: Reservoir, sedimentation, Bathymetric, RUSEL, watershed

1. INTRODUCTION

Reservoirs serve various purposes, including water supply, flood control, and hydropower, but are prone to sedimentation from watershed erosion. Sedimentation, caused by natural and human-induced processes, fills reservoirs with sediment carried by streams. This universal issue, considered a critical environmental hazard (Jain & Das, 2010), has reduced many reservoirs' active storage volumes, impairing their functionality and reflecting catchment erosion processes.

Erosion processes are influenced by terrain, soil, surface cover, drainage networks, and rainfall-related attributes (Tamene, 2006)), all of which impact reservoir functionality. Estimating sedimentation rates and the time before sediment accumulation hinders reservoir operation is essential. Traditionally, dams are designed with a "design life" approach, which involves estimating sedimentation rates, trap efficiency, and allocating sediment storage volume for a specified lifespan (typically 50 or 100 years) (Olsson et al., 2016). Reservoir designs must ensure sufficient sediment storage capacity to prevent sediment buildup from obstructing inlets during the project's operational life.

The lack of sufficient local data on sediment yield has led reservoir designers to rely on adaptable sediment yield and erosion hotspot assessment models. Additionally, further research is essential to understand erosion and sedimentation, determine sedimentation rates, and identify factors or practices that exacerbate these processes after constructing small and large-scale dams in the country. Various methods exist for estimating catchment erosion and sediment delivery, including distributed physically-based models, which are increasingly (Verstraeten & Poesen, 2000) popular (Verstraeten & Poesen, 2000). Sediment yield can also be estimated through intensive bathymetric surveys by comparing pre-impoundment sediment levels with current levels. Measuring sediment thickness using sediment pits is another option, though it requires careful supervision and can be costly. Despite the intensive fieldwork required at certain stages, bathymetric surveying is a faster and more efficient method for estimating sediment deposition in small reservoirs like Anjeb and Abrajit. The goal of this study is to assess and evaluate sedimentation in these two micro earth dams in the Ethiopian highlands.

2. MATERIALS AND METHODS

2.1 Description of the study area

The study area is located in Goncha Siso Enese Woreda, East Gojam Zone, Amhara Region (Figure 3-1). The Anjeb micro earth dam is situated approximately 125 km from Debre Markos and 17 km southwest of Gunde Weyn. The dam site is accessed via a 3 km diversion from the Gundeweyn–Addis Ababa asphalt road (Figure 3-1). In contrast, the Abrajit micro earth dam is located 12 km from Debre-Work and 120 km from Debre Markos (Figure 3-1). The dam site is accessed by a 7 km diversion from the Debre-Work–Addis Ababa asphalt road (Figure 1a). The geographic coordinates of Anjeb dam are approximately 10.37°N, 37.0°E, with a catchment area of 1062.34 ha while Abrajit dam's coordinates are 10.38°N, 38.12°E, with a catchment area of 750.51 ha.

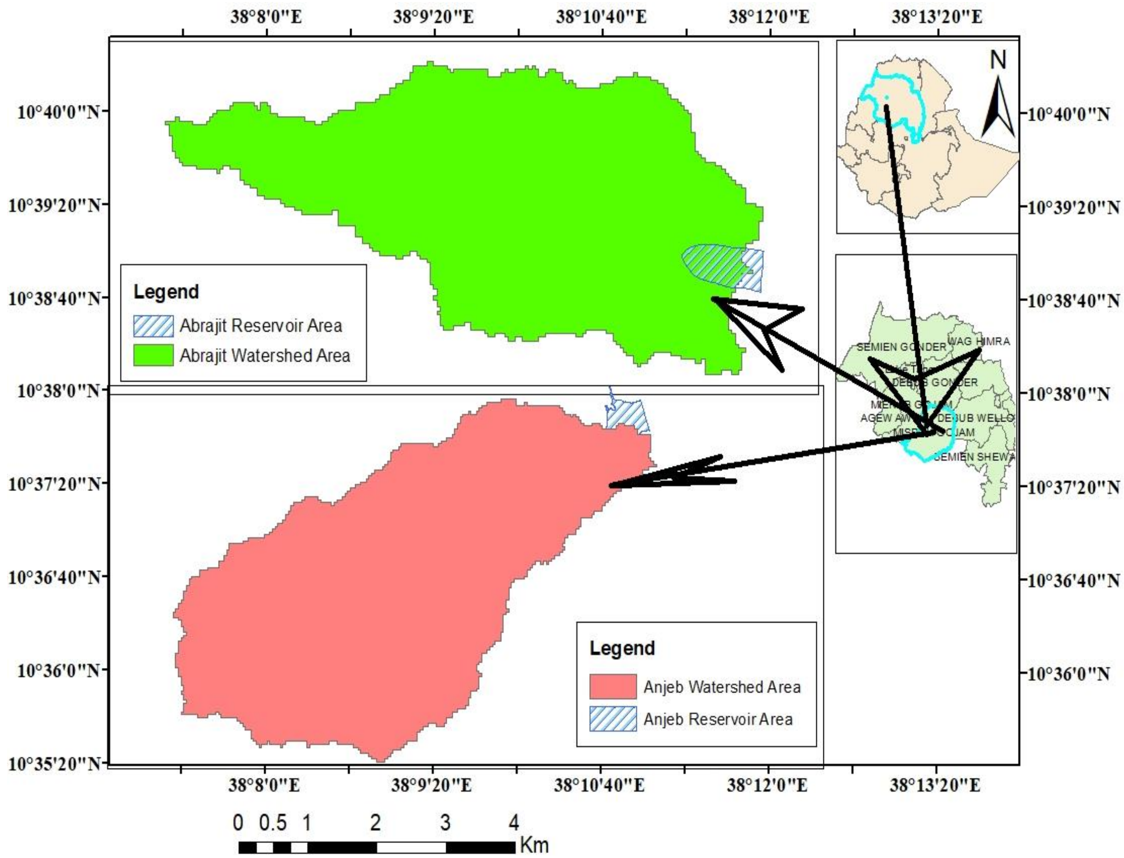

Figure 3 1:-Location map of Anjeb andAbrajit study watersheds

2.2 Topography, Soil and Land use

The slope of a watershed is a crucial factor influencing soil erosion. The slope map of the study area was generated from a 30-meter DEM, processed using ArcGIS. The landforms in the Anjeb and Abrajit watersheds include flat plains, rolling and undulating plains, hills, and a small portion of mountainous terrain. Abrajit watershed is mainly characterized by undulating plains, flat plains, hills, and rolling plains. The dominant soils in the area are Eutric Vertisols and Haplic Alisols, with black cotton soils being the most prevalent. Various land use and land cover types in the Anjeb and Abrajit watersheds have also been identified.

Table 2-1 : Watershed Slope classification for Anjeb and Abrajit dams (*FAO*, 1989) .

			ANJEB		**ABRAJIT**	
NO	Slope %	Description	Area ha	Area %	Area ha	Area %
1	0-3	Flat plain	31.99	3.01	96.08	12.8
2	3-8	Rolling plain	230.43	21.69	415.82	55.4

3	8-15	Undulating plain	442.15	41.62	214.32	28.56
4	15-30	Hills	352.18	33.15	24.29	3.24
5	30-50	Mountain	5.62	0.53	0	0
SUM			1062.36	100	750.51	100

3. METHOD OF DATA COLLECTION

3.1 General

The Abrajit and Anjeb dams began operations in 2011 and 2010, respectively. The reservoirs were studied through bathymetric surveys of the water bodies and total station (TS) surveying to collect data from the reservoir areas. The research methodology involved conducting bathymetric surveys and utilizing GIS software to create triangulated irregular network (TIN) surfaces for generating ArcMap results. Bathymetric analysis, including maps of current data and pre-impoundment topography of Anjeb and Abrajit reservoirs, was used to estimate sediment volume by comparing the differences between two TIN surfaces(Ferrari, 2011). A 2-meter contour interval was applied to capture the details of both reservoirs.

3.2 Climate, Topography, Soil and Land use

The study area receives an average annual precipitation of 972.01 mm, with approximately 77% of the rainfall occurring during the main rainy season ("Kiremt"), which lasts from June to September. The average maximum and minimum temperatures are 27°C and 11.2°C, respectively.The slope of a watershed is a key factor influencing soil erosion. A slope map of the study area was created using a 30-meter DEM and processed with ArcGIS. The landforms of the Anjeb and Abrajit watersheds include flat plains, rolling and undulating plains, hills, and a small proportion of mountainous terrain. The Abrajit watershed is primarily characterized by undulating plains, flat plains, hills, and rolling plains. The study area is predominantly covered by Eutric Vertisols and Haplic Alisols, with black cotton soils being the dominant soil type. Land use and land cover types in the Anjeb and Abrajit watersheds have been identified.

3.3 Method of Data Collection

3.1.1 General

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3.1.2 Bathymetry and Total Station Survey

We used the Garmin Bathymetric tool, Total Station, and Hand GPS to collect reservoir field data. The Garmin Echo sounders, a type of sonar, measure water depth (Z) and detect X and Y positions (EchoMAP TM CHIRP 40/50/70/90 Series, 2016). The Garmin Bathymetric GPS receiver quickly acquires satellite signals and provides precise location data. The touch screen menu made it easy to set up depth measurements. Echo sounding, a sonar method, determines water depth by transmitting acoustic waves into the water. The time interval between the emission and return of a pulse is recorded to determine water depth and position, factoring in the speed of sound in water at that time. Survey-grade echo sounders and differential GPS receivers were used to collect water depth and position data (Gary L. Wilson and Joseph M. Richards, 2001). A bathymetric surface model, contour map, and area/capacity tables were created from the GIS database. An accuracy assessment was performed on the collected data, bathymetric model, area/capacity tables, and contour map. accuracy assessment was completed on the collected data, bathymetric surface model, area/capacity table, and contour map product.

The non-water reservoir area was surveyed using a Leica Total Station (model 1200 and set 230) to complete the bathymetric study. The bathymetry and total station surveys shared the same benchmark stations, with the reservoir spillway crest levels (from ADSWE's as-built drawing) serving as reference points. A total station combines electronic transit and distance measurement (EDM) for user convenience, utilizing high-efficiency electronic tachometers. Angles and distances were measured, and coordinates (X, Y, Z) of surveyed points were calculated using trigonometry. Data was downloaded to a computer, where ArcGIS and AutoCAD Civil 3D were used to compute results and generate maps and TIN surfaces.

3.1.3 Method of Analysis

ArcGIS was the primary digital data processing tool used in this study. A 30x30 resolution digital elevation model (DEM) was utilized to quantify the land surface characteristics. ArcGIS 10.3 supports raster and TIN surface models and provides analysis tools through Arc Hydro Tools, Spatial Analyst, and 3D Analyst extensions. These tools help create, analyze, and extract information from surfaces, which represent phenomena with values at every point. Surface analysis was conducted using direct measurements, such as elevation values, and interpolation (IDW), along with extraction by mask to create raster and TIN models. Most surface analysis in ArcGIS 10.3 was performed using raster or TIN data. ArcGIS was used to calculate the differences in each cell between the "before" and "after" rasters of the same reservoir area, along with the volume of sediment that must be moved from the construction site. This tool operates on two rasters, and the results are presented as a raster showing the difference between the two layers. Primary data was collected through bathymetric surveys on the reservoir water body using a 10m x 10m grid and total station surveys on the dry part of the reservoir using a 20m x 20m grid. These data were used to analyze the required reservoir volume using ArcGIS 3D Analysis Tools.

3.1.4 Estimation of sediment and Specific Sediment Yield

To compute the sediment yield (SY) and specific sediment yield (SSY) of the Anjeb and Abrajit watersheds, average dry sampling and bulk density were determined in the laboratory, with field weights measured using a core sampler (5 cm diameter, 5 cm height). The sediment yield (suspended and deposited) was then calculated. In this study, the estimation of sediment yield and specific sediment yield was performed using the relevant formula.

$$SY = \frac{SV * dBD}{TE * \Delta T} * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.1$$

$$SSY=SY/A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. 3.2$$

Where, SY is Sediment yield (ton/year), SSY is Specific sediment yield (ton/km2y-1), SV is the measured volumetric sediment of the reservoir (m3), TE is the sediment trap efficiency (%), ΔT is the time interval (years) between two successive reservoir surveys, DBD are the average dry bulk density of the sediment (ton/m3), and A is the watershed area (km2).

3.1.5 Reservoir Trap efficiency estimation

To determine the average sediment yield from the contributing watersheds, the weight of deposited sediment must be adjusted for the reservoir's sediment trap efficiency (TE). This adjustment accounts for sediment that may exit the reservoir, preventing potential underestimation of sediment deposition. The reservoir trap efficiency for the Anjeb and Abrajit reservoirs is calculated using the following equation(Verstraeten & Poesen, 2000).

$$TE=100\left(1-\frac{1}{1+0.0021D*\frac{C}{A}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

Where, TE, Trap Efficiency. D, Drainage density and A, Area of watershed.

4. RESULTS AND DISCUSSION

4.1. Reservoir Data points and Mapping

A water bathymetry (400 points) and a land total station survey data (500 points) analysis results over Abrajit (Figure 4.1) and Anjeb (Figure 4.2) micro earth dam’s reservoirs produced promising and significant results on sediment accumulation in the reservoirs. The reservoirs survey data were put together and plotted using ArcGIS for simple visual observation at this preliminary result display section (Figure 4.1 and 4.2). The data sparsely populated part of the map near uppermost reservoir (Figure 4.1) was a denied access for both surveys for Anjeb due to the reservoir was marsh area. However, some reservoir points were taken and TIN was investigated very well if there was a different sediment distribution pattern. The double direction red-colored arrow in Figure 4.1 and Figure 4.2 showed the dam axis for the schemes. In Abrajit reservoir, the reservoir was relatively full during survey period and almost all points (95%) shown here (Figure 4.2) were collected using bathymetry survey and land survey using total station was not conducted, rather some additional points were collected using RTK GPS system.

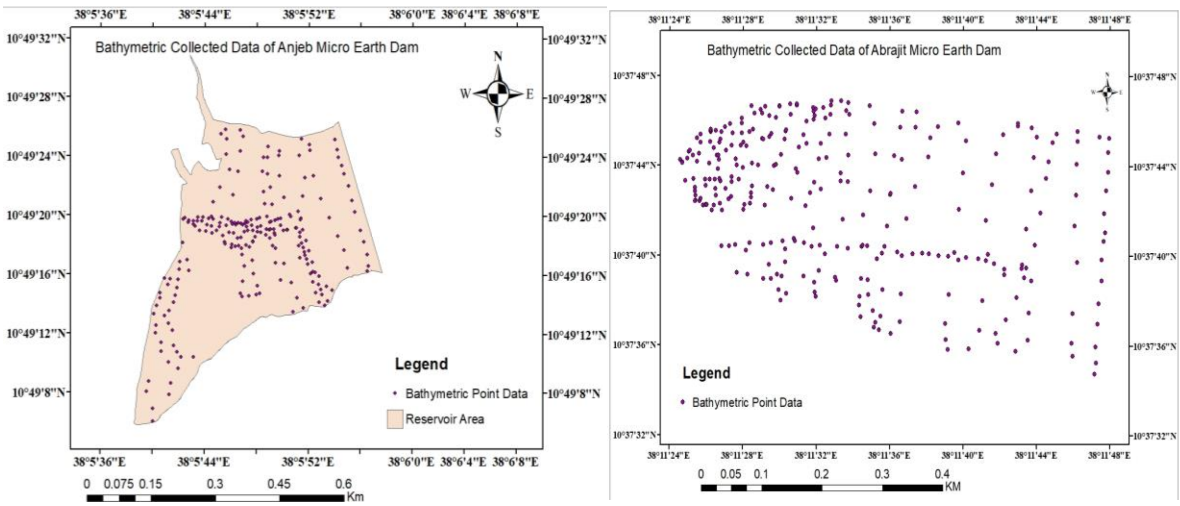


Figure 4-1: Bathymetry and total station land survey points generated using ArcGIS over the reservoir area of Anjeb and Abrajit micro reservoirs

4.2. Reservoir Sediment Analysis results

Reservoir TIN computation results for Anjeb showed that about 42.8% of the sediment (Table 4.1) was found over the point ID of 3 (Figure 4.4b) which was also followed by PID 4 (21.7%) and in the third rang over the PID =5 (19.7%) as shown Figure 4.4b). PID 3 in Figure 4.3b is the furthest distance from the outlet and the sediment distribution seems high at the middle and lowest at the lower. The result showed that there were significant bed loads impounding in to the reservoir and the trap efficiency for this dam is high.

Table 4-1: Reservoir sediment volume and depth and affected area of Anjeb

PID	Reservoir Area (ha)	Depth (m)	Volume (x1000 m^3)	Volume (%)	Remark
1	0.45	-0.39	22.77	2.39%	Erosion

2	0.00	0	0.00	0.01%	Unchanged
3	8.06	2.65	408.14	42.81%	Sediment Gain
4	4.09	6	206.88	21.70%	Sediment Gain
5	3.72	9.5	188.13	19.73%	Sediment Gain
6	2.52	16.65	127.50	13.37%	Sediment Gain
	Total		953.42	100%	

The analysis also showed that there is an erosion process over previously sediment area which fits the reality for most silted up reservoirs in the tropics (Haregeweyn et al., 2015) .

Reservoir sediment was calculated using raster analysis of these two TIN surfaces. Reservoir TIN computation results for Abrajit showed that about 97% of the sediment (Table 4.4) was found over the point PID of 2 (Figure 4-10b) which was also followed by PID 1 (1.1%). PID 4 in Figure 4-10b is the furthest distance from the outlet and the sediment distribution seems high at the apex of the reservoir. The result showed that there were significant bed loads impounding in to the reservoir and the trap efficiency for this dam is higher. This also shows that the catchment area to reservoir area ratio is very low as shown in the design documents. The analysis also showed that there is an erosion process over previously sediment area which fits the reality for most silted up reservoirs in the Ethiopian highlands.

Table 4-2: reservoir sediment volume and depth and affected area of Abrajit.

PID	**Reservoir Area (ha)**	**Depth (m)**	**Volume (x1000 m^3)**	**Volume (%)**	**Remark**
4	0.03	5-8	1.28	0.16%	
3	0.15	1.5-5	6.35	0.79%	
2	18.1	1-1.5	781.99	97.9%	
1	1.22	0.8-1	9.07	1.13%	
	Total		798.63	100%	

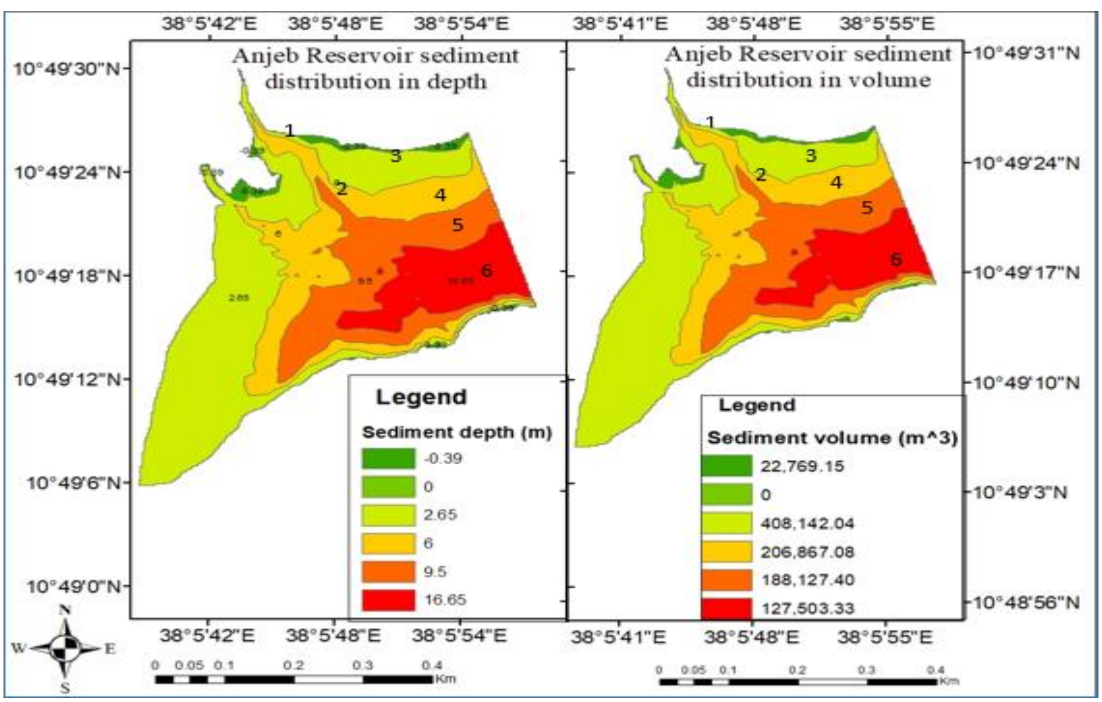
4.3. Net gain and loss of reservoir sediment volume.

The sediment space (dead storage capacity) for Anjeb was 0.443 Mm^3 in 2013, and the estimated sediment volume for 2021 was 0.953 Mm^3, indicating sediment accumulation in the dead storage area. The live storage capacity for Anjeb was 1.0720 Mm^3 (design capacity) in 2013, with a silted volume of 0.9534 Mm^3 in 2021. After subtracting the current sediment storage (0.953 Mm^3), the remaining live storage capacity is approximately 0.119 Mm^3. This is the available volume for irrigation practices in 2021. Over eight years, the accumulated sediment yield was 12,889.61 tons/km²/year, indicating a moderate to high annual storage loss due to sediment impoundment.

In case of Abrajit, the sediment space (dead storage capacity) was 0.029 Mm³ in 2008, with the estimated sediment volume for 2021 reaching 0.798 Mm³, indicating sediment accumulation in the dead storage area. The live storage capacities, calculated by subtracting the dead storage from total capacity, were 1.3425 Mm³ in 2008 and 0.542 Mm³ in 2021. The long-term average annual sediment accumulation rate was calculated by dividing the accumulated sediment volume by the reservoir's age (13 years for Abrajit). The accumulated sediment yield over 13 years was 9,362.29 tons/km²/year, indicating an average annual storage loss due to sediment impoundment.

The sedimentation rates for both reservoirs is relatively high compared to other regions and exceeds the global average annual loss of 1%. Additionally, 36% (202.1 ha) of land is classified under moderate to high erosion risk, which is several times the maximum tolerable soil loss (11 tons/ha/year) proposed by Ayalew & Selassie (2015). (Ayalew & Selassie, 2015). Although there is limited quantitative data on reservoir siltation in Ethiopia, storage losses up to 4% have been observed in the north (Haregeweyn et al., 2011), (Lee et al, (2022). The previous study, which only used the RUSLE method, underestimated the results. Sedimentation rates depend on the accuracy of both current and original bathymetric data.

The elevation –capacity –area curves in this study showed that there was a wider shift of elevation-capacity curve and elevation area curve towards outside indicating that most of the lower elevations were silted-up and the live storage was significantly taken up by critical sediment impoundment.



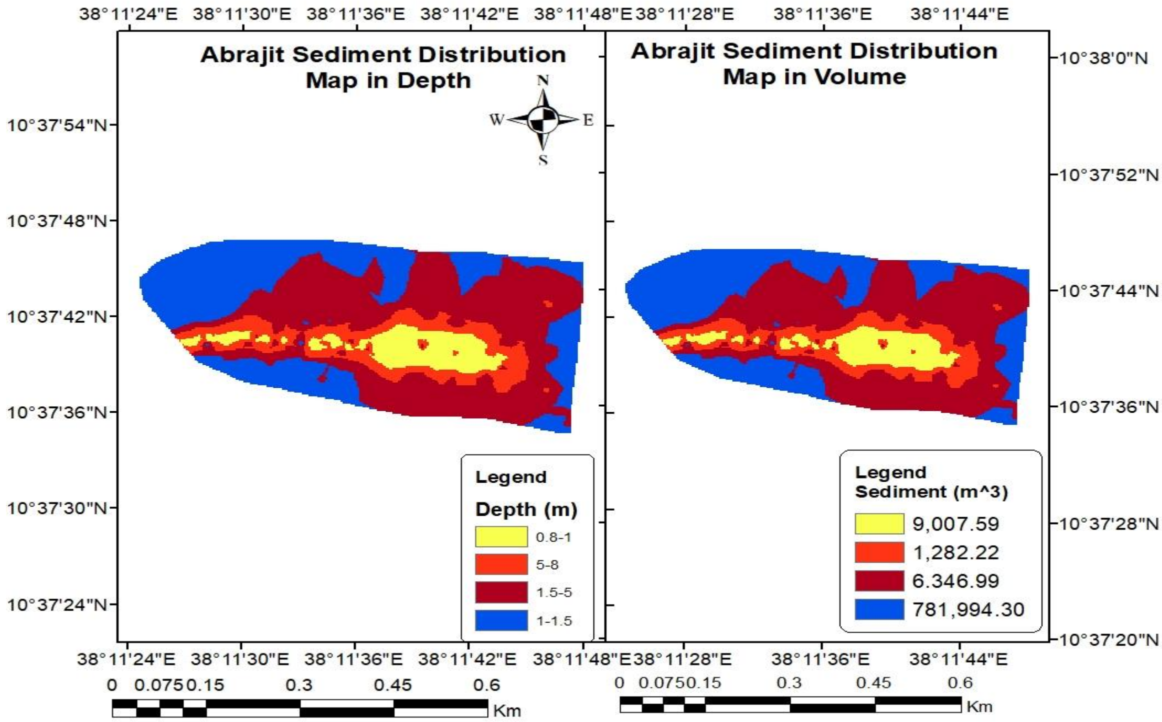


Figure 4-2: Anjeb (above) and Abrajit (bottom) reservoir depth in meter (a) and reservoir sediment volume in m3 (b) map as leveled in PID numbers.

4.4. Reservoir Trap efficiency

The Reservoir Trap efficiency of Anjeb and Abrajit reservoirs was 98.3% and 99% respectively Taking the watershed area, drainage density (D) estimated and reservoir capacity respectively as 10.624 km^2 , 0.27 and 1.072000Mm^3 for Anjeb and 7.55 km^2,0.26 and 1.3425Mm3 for Abrajit. the trap efficiency was computed (Verstraeten & Poesen, 2000) as show in Equation

$$TE=100\left(1-\frac{1}{1+0.0021D*\frac{C}{A}}\right) \qquad \text{...3.4}$$

4.5. Specific Sediment Yield

The average dry bulk density and trap efficiency was estimated to be 1.13 ton/m^3 and 98.3% respectively. Then SY and SSY of Anjeb reservoir were calculated using the total sediment volume (SV) of 0.953 Mm^3. Taking eight (8) years as the age of reservoir; the sediment yield (SY) and specific sediment yield (SSY) were then computed as (Haregeweyn et al., 2011). Using Equation (3.1) and (3.2), the SY and SSY values becomes 136,939.22 ton/ha/year and 12,889.61ton/km^2/year, respectively.

The specific sediment yield outflow from the watershed to the reservoir was 3,703 ton/km^2/y (calculated by RUSLE using arc GIS raster map algebra it average annual soil loss Table 4-3page 55 or Figure 4-3 page53 on map) is much less than the specific sediment yield we computed above (12,889.61ton/km^2/y). This showed that our results were found logical and at least sediment reaching the reservoir should be less than that generated in the watershed.

But the bathymetric study sediment result in the reservoir high. This indicated that there was severe erosion in the watershed area. When compare the result of specific sediment yield in a regional context this study found in similar order of specific sediment yield Tamene,(2020) reported that the specific sediment yield value is within the range from 345 to 4935 ton/km2 /year the highlands. Haregeweyn et al., (2015) reported SSY for Angereb reservoir in the range of 1200 to 3500 ton/km2/y. The previous study uses only RUSLE method that is underestimate the result.(Abrajit

To compute the sediment yield (SY) and specific sediment yield (SSY) of Abrajit the average dry bulk density and trap efficiency was estimated to be 1.14 ton/m^3 and 99% respectively. Then SY and SSY of Abrajit reservoir were calculated using the total sediment volume (SV) of 0.798 Mm^3. Taking thirteen (13) years as the age of reservoir; the sediment yield (SY) and specific sediment yield (SSY) were then computed (Haregeweyn et al., 2011). Using Equation (3.1) and (3.2), the SY and SSY values will become 70,685.31ton/year, and 9,362.29 ton/km^2/year, respectively.

The specific sediment yield flow from the watershed to the reservoir was 3,197 ton/km^2/y is much less than the specific sediment yield we computed above (9,362.29 ton/km^2/y). This showed that our results were found logical and at least sediment reaching the reservoir should be less than that generated in the watershed for the watershed. But the bathymetric study sediment result in the reservoir high. This indicated that there was severe erosion in the watershed area. When compare the result of specific sediment yield in a regional context this study found in similar order of specific sediment yield.(Ayalew & Selassie, 2015) reported that the specific sediment yield value is within the range from 345 to 4935 ton/km^2 /year the highlands. Haregeweyn et al., (2015) reported SSY for Angereb reservoir in the range of 1200 to 3500 ton/km^2/y.

5. Conclusion

Conclusions were drawn after analyzing reservoir sedimentation using bathymetry, TS survey data, and the RUSLE model. The study assessed capacity loss, sediment distribution, useful life, and sediment mass in Anjeb and Abrajit reservoirs. Changes in reservoir volume due to sedimentation were computed using ArcGIS software and TIN maps based on 2008 topographic data and 2013 and 2021 bathymetric surveys for Abrajit and Anjeb, respectively. Erosion risk identification using the RUSLE model prioritized Micro-Watersheds 3, 2, 1, 7, and 4 for Anjeb, while Micro-Watersheds 3, 1, and 2 were most critical for Abrajit to reduce siltation.

The bathymetry survey revealed that Anjeb and Abrajit reservoirs have lost 88.94% and 58.20% of their capacity due to sedimentation over 8 and 13 years of operation, respectively. The average sedimentation rate is estimated at 12,889.61 t/km²/year, with an annual loss of 11.12% for Anjeb, and 9,362.29 t/km²/year with a 4.5% annual loss for Abrajit. This indicates that the dead storage and live storage zones have lost 100% and 46.46% (total 88.94%) of their capacity in Anjeb, and 100% and 54.53% (total 58.20%) in Abrajit. This study provides a foundation for implementing conservation measures to extend the reservoirs' lifespan.

Author contribution statement

The authors conceived and designed the experiments, performed the experiments, analyzed and interpreted the data, contributed reagents, materials, analysis tools, or data, and wrote the paper.

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