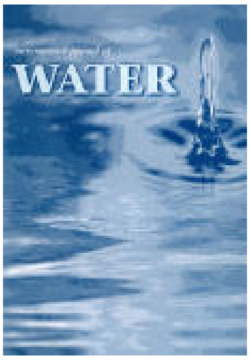


International Journal of Water

ISSN online: 1741-5322 - ISSN print: 1465-6620
https://www.inderscience.com/ijw

Examining sediment accumulation pattern and storage capacity loss of Lake Ziway, Ethiopia

Alemu O. Aga

DOI: 10.1504/IJW.2023.10057450

Article History:

Received:	05 August 2022
Accepted:	30 May 2023
Published online:	09 October 2023

Examining sediment accumulation pattern and storage capacity loss of Lake Ziway, Ethiopia

Alemu O. Aga

Faculty of Civil Technology,
Department of Water Works Construction Technology,
Ethiopia Technical University (FTVTI),
2RGF + MHJ, Addis Ababa, P.O. Box 190310, Ethiopia
Email: alemu.osore@hu.edu.et

Abstract: To estimate Lake Ziway (Ethiopia) sedimentation and life time of reservoirs, multi-year, repeated acoustic surveying techniques were applied. The lake's old bathymetry of the year 2005 and new 2017 lake bathymetry were generated by collecting lake depth. The sediment distribution pattern between the years was analysed by subtracting their raster maps and the sediment thickness was generated by subtracting the old bottom elevation from the new by using ArcGIS 10.2. From this, the total amount of sediment deposited in 12 years was 17.75 million cubic metres, which gives an average thickness of 4.2 cm. After 12 years, the lake has lost about 1.12% of its volume. Assuming a constant rate over the period, the annual sedimentation is 1.479 million cubic metres or 1.81 million ton/year. Based on the calculated sediment rate, the lake will lose its volume by 0.093% annually and its half-life is estimated as 519.5 years.

Keywords: bathymetry; reservoir capacity; sedimentation; capacity curve; Lake Ziway.

Reference to this paper should be made as follows: Aga, A.O. (2023) 'Examining sediment accumulation pattern and storage capacity loss of Lake Ziway, Ethiopia', *Int. J. Water*, Vol. 15, No. 3, pp.232–247.

Biographical notes: Alemu O. Aga is currently an Assistant Professor in the Department of Water Works Construction, Ethiopia Technical University (FTVTI), Ethiopia. He received his BSc and MSc in the field of Water Resources Engineering from Haramaya and Hawassa University, Ethiopia in 2009 and 2012, respectively. He earned his PhD in Civil (Hydraulic) engineering from Addis Ababa University in 2019. Prior to joining Ethiopia Technical University (FTVTI) in 2022, he was an assistant professor and researcher at Hawassa University Institute of Technology, Ethiopia.

1 Introduction

Reservoir sedimentation is reducing a significant proportion of the original storage capacity of many lakes in different parts of the world (Mahmood and Mundial, 1987; Petts and Gurnell, 2005; Rãdoane and Rãdoane, 2005; Dechasa et al., 2022). Today, the rate of annual capacity loss of the world's reservoirs due to sedimentation is estimated as 1–2% (Yoon, 1992; Abdallah and Stamm, 2012). Hence, sediments accumulation in the reservoirs is resulting in crucial storage loss and affecting the operation and functionality of the reservoirs, such as abrasion in hydropower facility, energy loss, delta deposition (Rãdoane and Rãdoane, 2005; Rahmani et al., 2018); and an excessive sedimentation in reservoirs is leading to loss of their biogeochemical and ecological cycles (Wood and Armitage, 1997; Cheng et al., 2013; Wang et al., 2015).

Reservoir sedimentation is an ill effect of catchment erosion (Reusser et al., 2015). Some of the sediment transported within a basin will be deposited in the reservoir due to stagnant water velocity in the reservoir; and hence, it is reducing its lifetime and service. Therefore, estimation of reservoir sedimentation is an important issue to improve the catchment management and the system operation of the lake and reservoirs. Generally, that can be achieved by four main approaches:

1 predicting from suspended sediment data at gauging stations (sediment rating curve) (Ulke et al., 2009; Sadeghi and Saeidi, 2010)

2 estimating gross soil erosion and sediment delivery ratio by applying models (Ayenew and Demellie, 2004)

3 estimating with sediment transport formulas (Demissie et al., 2004)

4 using storage-level relationship to predict the capacity change (bathymetric difference) (Awulachew, 2006; Dost and Mannaerts, 2008).

The first three approaches are more attractive to indicate the basin sediment yields. For example, predicting sediment yield by model will provide both sediment yield and decision-making tool in the uses of appropriate watershed management techniques and development of reservoir operation techniques aimed at limiting and controlling sedimentation in reservoirs (Awulachew, 2006; Setegn et al., 2009, 2010a, 2010a, 2011; Mekonnen and Melesse, 2011; Dessu and Melesse, 2012, 2013; Maalim and Melesse, 2013; Dessu et al., 2014; Grey et al., 2014; Msaghaa et al., 2014; Yesuf et al., 2015). Similarly, by applying the relations of stream flow and sediment concentration equations, the volume of sediment flux and catchment sediment yields can be estimated. But, all the soil eroded from the contributing basin area as well as the sediment available in the river channels will not reach the outlet or lakes (Wang et al., 2008; Anwar et al., 2015). Some part of the sediment will be dropped in the floodplain and more will be lost on river conveyance structures. To estimate the net amount of sediment deposited and its effects on the lake and reservoir, the repeated bathymetric surveying technique is the most appropriate (Abdallah and Stamm, 2012). Additionally, to assess indicators for lake environmental changes like sedimentation, lake ecosystem functionality, lifetime and pattern of sediment deposition, the bathymetric surveying method (Dost and Mannaerts, 2008; Yesuf et al., 2012, 2013; Giordano et al., 2016; Moges et al., 2018) is the most preferable method.

Sediment transport in the river and deposition in a reservoir depend on sediment consolidation, flood frequency, river regime, reservoir geometry and land management practices over time (Borland and Miller, 1960; Aga et al., 2018; Dananto et al., 2022; Ayele et al., 2023). Hence, to reduce lake sedimentation rates and to develop a sound management strategy understanding the nature of sediment transport and deposition, is an important factor (Belete, 2013). To do this, the following two approaches can be used to illustrate sediment distributions inside the lake (Aga, 2019):

i sediment distributed by longitudinal profile

ii sediment distributed by depth.

To assess the sediment distribution patterns and nature of sedimentation within a reservoir, the repeated bathymetric surveys can provide a significant instigation method (Rahmani et al., 2018). By repeated bathymetric surveying technique, a sediment accumulation will be determined by developing a reservoir's current volume and subtracting this from its original stated volume derived from previous volumetric surveys (Abdallah and Stamm, 2012; Rahmani et al., 2018; Moges et al., 2018). The original water storage volumes of reservoirs can be estimated from topographical contour maps (McAlister et al., 2013).

Based on sedimentation rate and deposition pattern, no sediment deposition study was carried out on Lake Ziway. Moreover, the basin is classified as one sediment data limited area of Ethiopian rift valley lake basin. By chance, for the Lake Ziway, the old lake bathymetric survey of the year 2005 is available in Federal Ministry of Water Irrigation and Electricity. Hence, to determine the actual sediment deposition rates and its distribution pattern inside the lake, using the bathymetric differencing approach could be an attractive and judicious method because of the existence of earlier bathymetry maps to compare with the new one. Therefore, the main objective of the study was to examine the sedimentation rate and its deposition pattern in the Lake Ziway by applying bathymetric differencing techniques. The specific aims were to

1 produce a new bathymetry map of 2017 and to compare it with the 2005 old map

2 determine sediment accumulation rate and patterns in the Lake Ziway

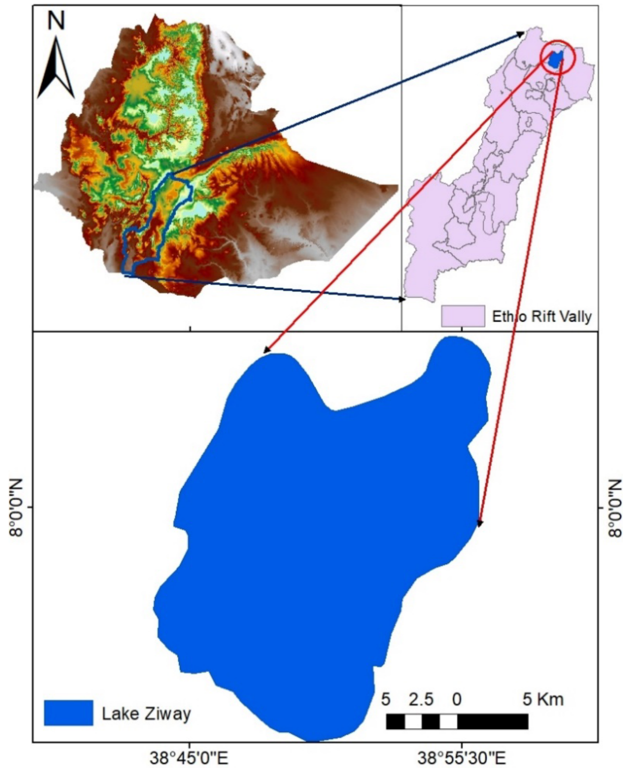
3 to establish a surface for comparison of future surveys of the lake.

2 Study area

The study area, Lake Ziway and its basin, is located in Ethiopia Rift Valley (Figure 1). The lake basin has a total surface area of 7285 km^2 and geographically lies between latitudes 7°20′54″ to 8°25′56″ North and longitudes 38°13′02″ to 39°24′01″ East. Topographically, the lake basin shows variation with altitude ranging from around 1637 m at lake surface to about 4256 m above mean sea level on mountain areas. The total surface area of the lake is estimated as 423 km^2 (Aga et al., 2019) and based on the water quality, it is the fourth largest freshwater lake in the country, Ethiopia.

Regards to climate, the Lake Ziway watershed is characterised by dry to sub-humid or humid. The highlands areas of the basin is sub-humid to humid and lowland area surrounding the lake is arid (dry) or semi-arid. The long-term (1987–2016) mean annual-rainfall analysed by Aga (2019) indicates as the basin has the mean annual precipitation of 620 mm to 1225 mm and as the mean annual temperature ranges from 15°C and 25°C. In the basin, there are three seasons based upon the rainfall pattern. Short rainy season which extends from March to May, the wet summer (longest rainy season) that extends from June to September and the dry period which extends from October–February (Aga, 2019).

Figure 1 Location of Lake Ziway basin in Ethiopia (see online version for colours)



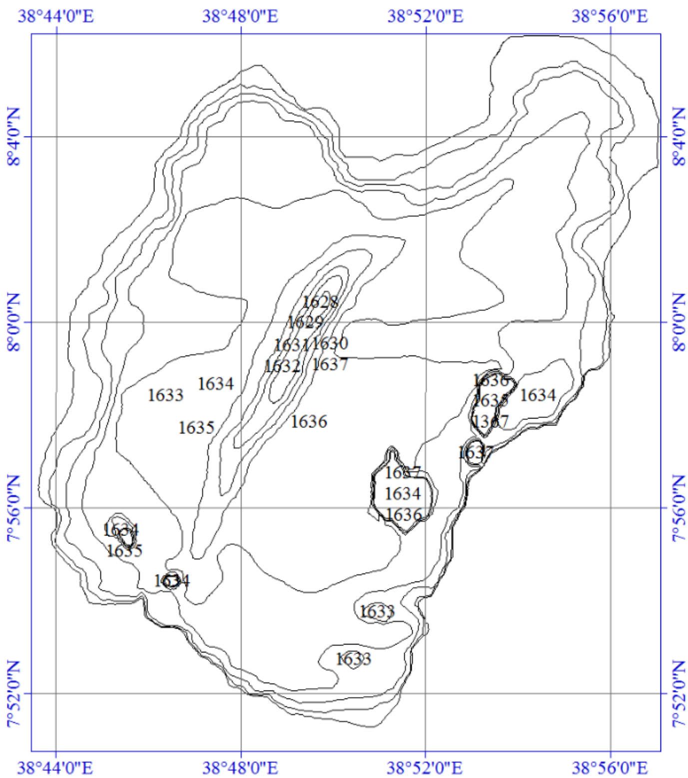
Hydrologically, the lake is fed by two main rivers , Rivers Katar and Meki, and has an outlet through the River Bulbula which flows in the south direction to Lake Abiyata (Aga et al., 2020). From the Lake Ziway, there is a possibility for the groundwater to flow into other Ethiopia Rift Valley lakes since the elevation of the Lake Ziway is 1636 m while the other lakes such as Langano, Abiyata and Shalla are 1585 m, 1578 m and 1550 m.a.s.l respectively.

3 Methodology

3.1 The 2005 Lake Ziway bathymetric map

The first intensive Lake Ziway bathymetry survey was done by Ethiopia Ministry of Water Irrigation and Electricity in 2005 using Bathy 1500 echo-sounder. The lake bottom contour map (image) produced from 2005 bathymetry was obtained in soft copy from Hydrology and Water Quality Directorate of Federal Ministry of Water Irrigation and Electricity (MoWIE). To process the image, it was georeferenced (Figure 2) using the standard georeferencing technique available in ArcGIS 10.2, and the storage capacity of the lake in the year 2005 was computed for each contour by creating TIN (Triangulated Irregular Network) using polygon volume calculation technique available in ArcGIS 10.2.

Figure 2 The geo-referenced contour map of the year 2005 (see online version for colours)



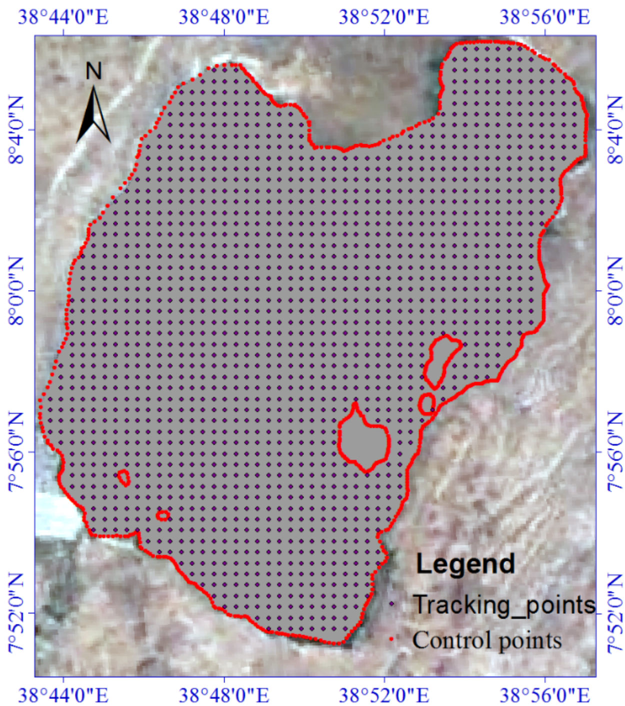
3.2 *The new reservoir bathymetric surveying*

A portable echo-sounder was applied to develop a geostatistical bathymetric model of the Lake. To collected the data, a regular grid of 500 m by 500 m (Figure 3) points were generated by using GIS 10.2 Fishnet Tool. The lake shore was digitised from Spot 5 satellite images in GIS10.2 and the coordinates obtained from the digitised image were crosschecked by collecting zero depth coordinates from accessible lake shores.

By following the points generated on Figure 3, the data was collected at December 02, 2016 to February 08, 2017, during the driest season of the basin. Due to its shortest path, east to west direction was selected during bathymetric surveying. In areas of marine grass and shallow depths of less than 1 m, where sounding was difficult, the depth was measured by using a standard measuring rod.

To minimise the error on the measurements, the data was collected during the time with low water waves. Since the measured depth in echo-sounder depends on a number of factors like salinity, temperature, frequency as well as the quality of the transducer, it was calibrated by staff (measuring rod) measured data. Hence, before and after the measurements, the sample water depths were measured by using staff, and the data recorded by eco-sounder were calibrated and adjusted for each measurement for every measurement days.

Figure 3 Boundary of the lake and sampling locations (see online version for colours)



3.3 Data adjustment

During the period of bathymetry survey, the level of the lake water was not constant. At the time of surveying, the lake depth varied between 2.06 m and 1.62 m. Accordingly, for every measurement day, the collected data were adjusted to account for these variations by using a reference value of lake water level. To adjust the measured lake depth (bathymetry) data, the investigation period maximum lake water level was collected from the hydrologist who records the daily lake level and every day bathymetric data were adjusted by using the corresponding day's record.

3.4 Data analysis

Surfer 8.01 Golden software was used to interpret the measured bathymetric data. Through Surfer worksheet, three-dimensional XYZ data file was created and a grid file was produced using point kriging gridding method, and a series of maps (three-dimensional (3D) surface map) were formed in the Surfer plot document. To detect the sediment deposition rate and its pattern in the lake, the depth measurements are converted into a GIS layer for analysis.

The 'Topo to Raster' tool in ArcGIS is implemented to creating DEMs. Given the small size of the reservoir area and the accuracy required, a triangulated irregular network

(TIN) based analysis is preferred and hence, the reservoir topography (digital elevation model, (DEMs)) is converted into a TIN, using polygon volume calculation technique available in ArcGIS10.2. From the generated TIN surface, the contour lines of the lake bottom were generated with a certain elevation.

To determine the deposited sediment rate of the lake between the years 2005 and 2017, a volume and area of the reservoir at every 1 m of elevation difference were determined for both maps. The sediment distribution pattern between the years 2005 and 2017 was analysed by subtracting the two different years raster's maps in GIS 3D analyst tools of raster-to-raster math function. In the same procedure, the sediment thickness map was generated by subtracting the old values from the new bottom elevation.

3.5 Morphometric parameter generation

Area and volume calculations were achieved by generating a grid file, which defines the lake bottom surface that represents the water level as a negative *Z*-axis value. The upper surface was defined as a horizontal planar surface that defines the uppermost surface of the lake water with a constant *Z* value ($Z = 0$). Accurate area and volume calculations were done by using the three arithmetic integration algorithms, equations (1)–(3), developed by Press et al. (1988).

1 *Trapezoidal Rule*

$$V = \frac{h}{2} * (A_o + A_n + 2(A_1 + A_2 + A_3 + A_4 + \cdots + A_{n-1})) \tag{1}$$

2 *Simpson's Rule*

$$V = \frac{h}{3} * (A_o + A_n + 4 * A_1 + 2 * A_2 + 4 * A_3 + 2 * A_4 + 4 * A_5 + \cdots + 2 * A_{n-1}) \tag{2}$$

3 *Simpson's 3/8 Rule*

$$V = \frac{3h}{8} * (A_o + A_n + 2(A_3 + A_6 + A_9 \ldots) + 3(A_1 + A_2 + A_4 + A_5 + A_7 + A_8 \ldots)) \tag{3}$$

where V = reservoir volume, h = the grid spacing; and A_1, A_2, A_3, A_4 are planar areas at interpolation points; A_{n-1} = grid area (prisms, successive columns of lake part) and n is the grids total number.

The differences in the lake capacity calculations with these three different methods (trapezoidal, Simpson's and Simpson's 3/8 rules) will afford a quantitative measure for precision of the volume calculations. When the calculated volumes of water in the lake by the three methods are close to each other, the true volume is believed to be close to these values. If the volumes calculated by three methods have a significant different value, a new denser grid file production will be needed and the volume should be calculated again. In this study, to check for the closeness in the estimated volumes, the relative error (RE) of the volumes obtained from the three methods was determine using equation (4). When RE is less than 0.9, the variation is considered as insignificant (Yesuf et al., 2012, 2013).

$$RE = \left(\frac{LR - SR}{\text{Aver}}\right)*100 \tag{4}$$

where RE is the relative error (%); SR is the smallest result from the three approaches; LR is the largest result from the three approaches; and Aver is an average of the three approaches.

4 Results and discussion

4.1 Sediment distribution and thickness in the lake

The average sediment thickness between 2005 and 2017 was determined as 4.2 cm and its thicknesses ranged from 1 cm to 45 cm. It is higher at the western and eastern ends of the lake and becomes lower while approaching the southern end where the city of Ziway is located. The maximum deposition occurred at the end of western and eastern parts of the lake. The inlet location of Rivers Katar and Maki shows comparatively higher sediment accumulation than the rest of the areas. If a constant annual rate is assumed in the period, the sedimentation rate would be 0.35 cm/year.

4.2 The deposed sediment rate in the lake between 2005–2017

Lake sediment volume calculation has been done by differencing 2005 and 2017 volume for each elevation. According to the calculation, the total accumulated sediment between 2005 and 2017 is estimated to be 17.75 MCM and if distributed evenly over the depositional area of lake bottom (423 km^2) would give an average thickness of 4.2 cm after 12 years, which is about 1.12% of the total volume of the lake. When assuming a constant rate over the period, the annual sedimentation is 1.479 million cubic metre. By taking the average bulk density of the basin soil as 1.22 ton/m^3, the annual sediment yield is estimated as 1.81 million ton/year. As per this rate, annually the lake will lose its volume by 0.093%. The calculated sediment deposition results of Lake Ziway are much less than global average (1%) (Douglas et al., 2001). Similarly, the estimated annual capacity loss of Lake Ziway is much lower compared with Ethiopian largest Lake, Tana (Lemma et al., 2017) and Lake Hawassa (one of Ethiopian rift valley lakes) (Belete, 2013).

By using modelling approach, Aga et al. (2019) estimated the capacity loss of the Lake Zaway due to sedimentation as 0.106% per year. This is similar to what was detected in this approach for lake sedimentation. By looking at its physical magnitude only, one may decide that the effect of sedimentation for Lake Ziway is minimum, but the truth is that this sediment conveys chemicals from the basin, which can severely affect the overall function of the lake. So the result determined in this study should not be considered as discounting the devastating effect of the sedimentation process on the lake ecosystem.

As per this annual storage capacity reduction rate, the half-life of the lake is estimated as 519.5 years and which is almost similar what was determined by Aga et al. (2019) as 474 years.

4.3 Estimation of Lake Basin sediment yield

The sediment yield from a catchment can be determined by measuring the accumulation of sediment in a lake/reservoir of known age and adjusting for losses over the spillway, or by periodic sampling of the stream flow. Accordingly, for the total basin of 6863.6 km^2, the long-term annual average sediment load is estimated as 287.2 ton/km^2/year. This is low when compared with Ethiopia's average sediment yield rate. Moreover, the average sediment yield predicted from the lake sedimentation may underestimate the actual erosion rate of the lake basin. Lake Ziway has an outlet on its southern direction through River Bulbul. Hence there is an opportunity for sediment to leave from the lake.

Globally, the minimum sediment yield lies below 2 ton km^{-2} $year^{-1}$. Maximum of 10^3 ton km^{-2} $year^{-1}$ were reported for River Lo Ho in China (Walling et al., 1985) and 23700 ton km^{-2} $year^{-1}$ for River Geleda Basin in Ethiopia (Gashaw et al., 2017). For the country Ethiopia, an average soil loss rate of 42 ton ha^{-1} $year^{-1}$ for cultivated agricultural lands and 35 ton ha^{-1} $year^{-1}$ for other lands is estimated by Hurni (1993). Hence, the estimated sediment yield of Lake Ziway lies well below the maximum range, but above the low sediment yield estimated globally.

4.4 Morphometric characteristics of Lake Ziway

Lake morphometry parameters provide invaluable information to assess lake residence time, sedimentation rate, life expectancy, sustainable water abstraction, and water balance and to derive volume-stage curves. These parameters include: lake bed depth and its topographic nature, elevation–area and stage-storage curves.

4.4.1 Bed topography

The 3D map produced from the bathymetric survey in 2017 (Figure 5) illustrates the minimum elevation, being 1628 m.a.s.l. in the central part of the lake. In the eastern part, its topography is undulated due to the existence of islands. The western lake bottom has gentler slope towards the centre of the reservoir and from north to south direction, it has relatively uniform curve shape with steep slopes in southern parts. Hence, the developed 3D map for the lake can offer full background information for recreation and fishing purposes and to evaluate the long-term temporal lake morphological changes.

4.4.2 Updated lake stage-storage relationship

With the knowledge of the lake bed topography (Figure 4) and the lake shoreline the volume and area of the lake were computed in the Arc GIS 10.2 environment. Three classical numerical integration algorithms were adopted for the volume estimation. By these three methods, namely: trapezoidal, Simpson's and Simpson's 3/8 rules, the volume of the Lake Ziway was calculated as 1582.88, 1572.19 and 1573.03 MCM, respectively. From these values, a relative error (RE) of 0.6 was calculated which shows that the variation is considered insignificant (Yesuf et al., 2012, 2013).

Figure 4 Sediment accumulation pattern of the Lake Ziway from 2005 to 2017 (see online version for colours)

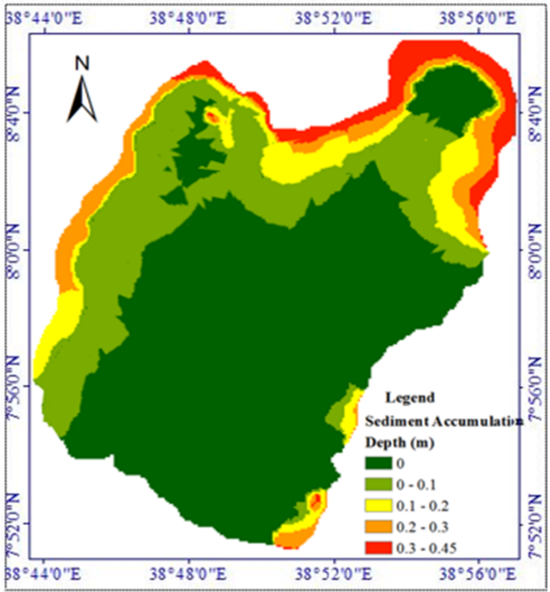
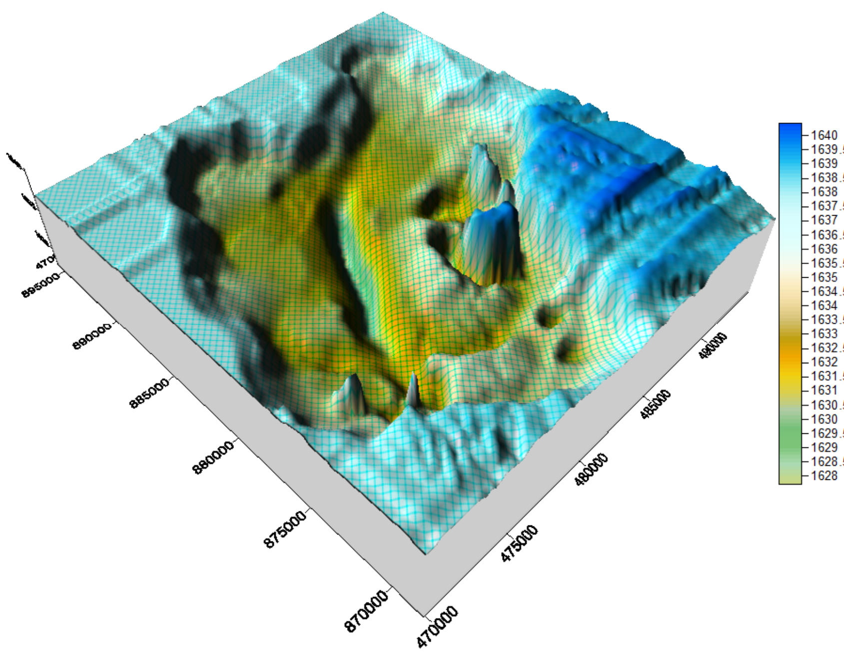


Figure 5 Lake Ziway three-dimensional (3D) map (see online version for colours)



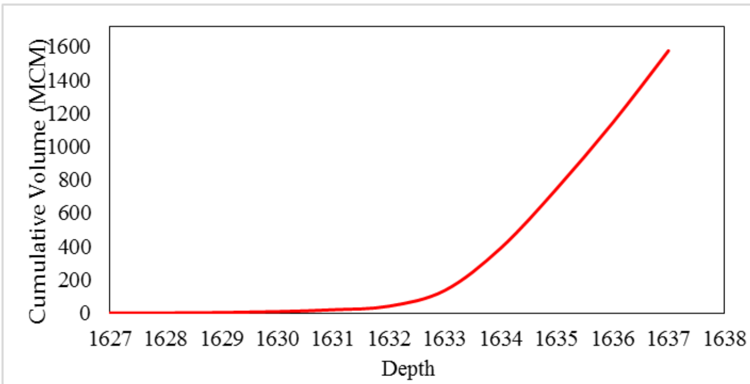
The elevation–volume curve fitting the lake volume is derived as:

$$V = -0.1428x^5 + 2.4478x^4 - 9.1877x^3 + 6.7185x^2 + 10.957x - 2.0645, \text{ with } R^2 = 0.9996 \quad (5)$$

where x is the water depth (m) measured from a lake level and V is volume in MCM.

Stage and capacity curves (Figure 6) were determined with respect to a reference lake level. Stage-storage curves can be used to assess the temporal variations in the lake capacity and area at different lake water levels and vice versa. The quantification of depth and calculation of area and volume helps us to detect the relationship between such variables.

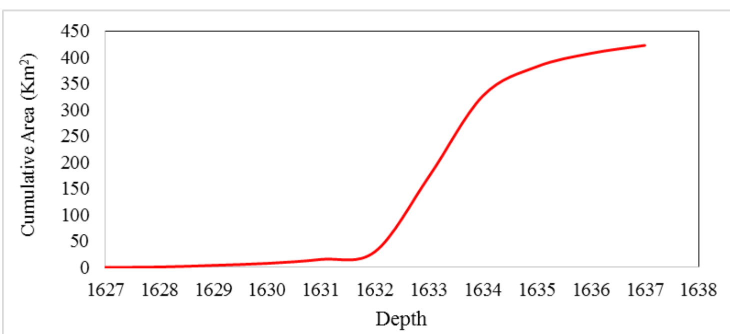
Figure 6 Stage-storage curves of Lake Ziway (see online version for colours)



4.4.3 The updated lake elevation–area relationship

Based on the surveying benchmark (referenced lake level), an elevation–area relationship curve of the lake is derived as follows (Figure 7).

Figure 7 Elevation–area curve of Lake Ziway (see online version for colours)



The fitted elevation–area polynomial curve shown in Figure 8, is computed as:

$$A = -0.492x^4 + 6.4437x^3 - 12.821x^2 - 3.3006x + 6.8974, \text{ with } R^2 = 0.9807 \quad (6)$$

where x is the water depth (m) measured from a lake level and A is area in km^2.

For further lake ecosystem assessments, the developed lake bottom topography and stage-volume-area curves can be used by investigators/researchers and the concerning authority to estimate the water balance of the lake and can be employed to develop sound lake management activities within the basin.

Figure 8 Flower greenhouses and its effluents at the shore of Ziway Lake (see online version for colours)

4.5 Lake Ziway shores existing physical conditions

On the shore of Lake Ziway, large scale floriculture and horticulture greenhouse complex has been developed. Activities of these industries have been putting stress on the water quality of the lake through discharging of effluents having toxic chemicals directly into the lake. Effluents (back flow) from farms are promoting the growth of algal blooms around the outlet of the greenhouse which is driven by the application of excessive nitrate and phosphate residues (Brook and Hayal, 2016).

Each farm has a water way channel from the greenhouse to the Lake Ziway as effluent drainage channel while roof runoff from the farms also makes its way to the lake (Figure 8). In addition, fertiliser and pesticide residues and leakages from the vacuum house are directly discharged into the lake via the water way channel without any waste water treatment measures to minimise the concentration of the contaminants. Specially, due to the existence of many development activities, like those of the floriculture industries, large scale irrigation farms and urban settlements, the western part of the lake is more exposed to several sources of pollutants. Thus, the applications of excessive agrochemicals in these areas are increasing (Derege et al., 2012), especially by the floriculture industries (Hengsdij and Jansen, 2006). Berhan et al. (2016) reported that the nutrient and physicochemical levels in this part of the lake have exceeded both the national and international standards.

Another problem faced on the shore of the lake is the expansion of nearby agricultural fields. Almost all of the circumference of the lake is under irrigation. Different Non-Governmental Organizations (NGOs) are donating water pumps to poor farmers for extensive irrigation purpose and this is resulting in extra water abstraction from the lake surface. Moreover, there are no demarcated buffer zones and buffer zone protection rules in the country to protect the lake shoreline areas from human impacts (agricultural irrigation) and investment projects. Currently, there is a misuse of the lake’s resources, which is causing resource degradation and ecosystem disturbances of lake environments. The high levels of fertilisers and pesticide residues in the farm effluents are promoting growth of aquatic vegetations and algae. Moreover, the lake water near the farms is becoming less suitable for water supply and sanitation purposes. In general, because of the activities of the flower farms and irrigations around the lake, the water quality of the lake may be seriously degraded and the number (quantity) of fishes will decline on the shores of the lake. Hence, I would like to recommend that the lake water dextrorotation should be considered by the concerning body to prolong the useful life of the lake.

5 Conclusion

The sediment deposition pattern and its rates were assessed by differencing the two bathymetry maps. From this, the total amount of sediment deposited in 12 years was 17.75 MCM and if spread evenly over the depositional area of lake bottom (423 km^2) would give an average thickness of 4.2 cm. After 12 years, the lake has only lost about 1.12% of its capacity. Assuming a constant rate over the period, the annual sedimentation is 1.479 MCM. By taking the average bulk density of the basin soil as 1.22 ton/m^3, the annual sediment yield is estimated as 1.81 million ton/year. As per this rate, annually the lake will lose its volume by 0.093% and the half-life of the lake is estimated as 519.5 years.

To investigate bathymetric characteristics of the lake, the water depth and bottom profiles were surveyed with state-of-the-art technology, using rapid surveying, portable equipment and geostatistics at low cost. A kriging interpolation approach was used to develop digital data at sampled points. From the developed regular grids, various physical morphometric parameters: namely bed topography, stage-volume relation curves and stage-area relation curves were developed. Hence, these physical morphometric parameters can be used for different water related and water resource management studies around the lake basin. The results will also provide ample chances for further assessments related to lake basin hydrology, lake hydrodynamics, water balance and for consumptive water use impact analysis.

The shore of the lake environment is highly distorted by many development activities, such as floriculture industries and irrigation farms. To minimise the deterioration of lake water quality, all industries should treat their effluent before releasing to the lake and buffer zone areas of lake should be developed by concerning authorities like Ministry of Water, Irrigation and Electricity and Ethiopian Rift Valley Lake Basin Authority.

Acknowledgements

I would like to thank the Ethiopian Ministry of Water and Energy (MoWE) for providing an old lake bathymetry map.

References

Abdallah, M. and Stamm, J. (2012) 'Evaluation of Sudanese eastern Nile reservoirs sedimentation', *Dresdner Wasserbaukolloquium*, Vol. 35, pp.285–297.

Aga, A.O. (2019) *Modeling Sediment Yield, Transport and Deposition in The Data Scarce Region of Ethiopian Rift Valley Lake Basin*, PhD Dissertation, Addis Ababa Institute of Technology.

Aga, A.O., Chane, B. and Melesse, A.M. (2018) 'Soil erosion modelling and risk assessment in data scarce rift valley lake regions, Ethiopia', *Water*, Vol. 10, pp.1–17.

Aga, A.O., Melesse, A.M. and Chane, B. (2020) 'An alternative empirical model to estimate watershed sediment yield based on hydrology and geomorphology of the basin in data-scarce rift valley lake regions, Ethiopia', *Geosciences*, Vol. 10, No. 17, pp.1–17.

Aga, A.O., Melesse, A.M. and Chane, B. (2019) 'Estimating the sediment flux and budget for a data limited rift valley lake in Ethiopia', *Hydrology*, Vol. 6, No. 1, pp.1–22.

Anwar, AA., Seifu, A.T. and Essayas, K.A. (2015) 'Climate change impact on sediment yield in the upper Gilgel Abay catchment, BlueNile basin, Ethiopia', in Melesse, A.M. and Abtew, W. (Eds.): *Landscape Dynamics, Soils and Hydrological Processes in Varied Climates*, Springer International Publishing, Switzerland, pp.615–644.

Awulachew, S.B. (2006) 'Investigation of physical and bathymetric characteristics of lakes Abaya and Chamo, Ethiopia, and their management implications', *Lakes and Reservoirs: Research and Management*, Vol. 1, pp.133–140.

Ayele, HA., Aga, AO. and Belayneh, L., Wanjala, T.W. (2023) 'Hydrological responses to land use/Land cover changes in Koga watershed, upper Blue Nile, Ethiopia ', *Geographies*, Vol. 3, pp.60–81.

Ayenew, T. and Demellie, M. (2004) 'Bathymetric survey and estimation of the water balance of Lake Ardibo, northern Ethiopia', *Ethiop J. Sci*., Vol. 27, pp.61–68.

Belete, M. (2013) *The Impact of Sedimentation and Climate Variability on the Hydrological Status of Lake Hawassa, South Ethiopia*, PhD Dissertation, Rheinischen Friedrich-Wilhelms-Universität Bonn, Germany.

Berhan, M.T., Amare, H. and Wiegant, D.A. (2016) 'Impacts of nutrients and pesticides from small-and large-scale agriculture on the water quality of Lake Ziway, Ethiopia', *Environ Sci Pollut Res*., Vol. 16, pp.13207–13216.

Borland W.M. and Miller, C.R. (1960) 'Distribution of sediment in large reservoirs', *Transactions of the American Society of Civil Engineers*, Vol. 125, pp.166–180.

Brook, L. and Hayal, D. (2016) 'Review of the natural conditions and anthropogenic threats on the Ethiopian rift valley rivers and lakes', *Res Manage*., Vol. 21, pp.133–151.

Cheng, P., Zhu, H. and Fan, J. (2013) 'Numerical research for contaminant release from un-suspended bottom sediment under different hydrodynamic conditions', *J. Hydrodyn*., Vol. 25, pp.620–627.

Dananto, M., Aga, AO., Yohannes, P. and Shura, L. (2022) 'Assessing the water-resources potential and soil erosion hotspot areas for sustainable land management in the Gidabo watershed, rift valley lake basin of Ethiopia', *Sustainability*, Vol. 14, pp.1–19.

Dechasa, A., Aga, A.O. and Dufera, T. (2022) 'Erosion risk assessment for prioritization of conservation measures in the Watershed of Genale dawa-3 hydropower dam, Ethiopia', *Quaternary*, Vol. 5, pp.1–19.

Demissie, M., Xia, R., Keefer, L.L. and Bhowmik, N.G. (2004) *The Sediment Budget of the Illinois River*, Contract Report, Illinois State Water Survey.

Derege, T., Tsunekawa, A. and Tsubo, M. (2012) 'continuing land degradation: cause-effect in Ethiopia's Central Rift Valley', *Land Degrad Dev*., Vol. 23, pp.130–143.

Dessu, S. and Melesse, A.M. (2012) 'Modelling the rainfall–runoff process of the Mara River basin using the soil and water assessment tool', *Hydrol Process*, Vol. 26, pp.4038–4049.

Dessu, S. and Melesse, A.M. (2013) 'Impact and uncertainties of climate change on the hydrology of the Mara River basin, Kenya/Tanzania', *Hydrol Process*, Vol. 27, pp.2973–2986.

Dessu, S., Melesse, AM., Bhat, M. and McClain, M.E. (2014) 'Assessment of water resources availability and demand in the mara river basin', *CATENA*, Vol. 115, pp.104–114.

Dost, R.J.J. and Mannaerts, C.M. (2008) 'Generation of lake bathymetry using sonar, satellite imagery and GIS', in Dangermond, J. (Ed.): *ESRI 2008: Proceedings of the 2008 ESRI International User Conference: GIS, Geography in Action*, 4–8 August, San Diego, Florida. ESRI, Redmond, 5p., ESRI.

Douglas, B., Michael, S. and Stephen, P. (2001) 'Sea level rise: history and consequences', *International Geophysics*, Vol. 75, pp.1–232.

Gashaw, T., Tulu, T. and Argaw, M. (2017) 'Erosion risk assessment for prioritization of conservation measures in Geleda Atershed, Blue Nile Basin, Ethiopia', *Environ Syst Res.*, Vol. 6, pp.1–14.

Giordano, F., Mattei, G. and Parente, C. (2016) 'Integrating sensors into a marine drone for bathymetric 3D surveys in shallow waters', *Sensors*, Vol. 16, No. 4, pp.1–17.

Grey, O., St, F. and Webber, D. (2014) 'Application of the soil and water assessment tool (SWAT model) on a small tropical island (Great river watershed, Jamaica) as a tool in integrated watershed and coastal zone management', *Int. J. Trop Biol Conserv.*, Vol. 62, pp.293–305.

Hengsdijk, H. and Jansen, H.C. (2006) *Agricultural Development in the Central Ethiopian Rift Valley: A Desk-Study on Water-Related Issues and Knowledge to Support a Policy Dialogue*, Note; No. 375, Plant Research International, Wageningen.

Hurni, H. (1993) 'Land degradation, famine, and land resource scenarios in Ethiopia', in Pimentel, D. (Ed.): *World Soil Erosion and Conservation*, Cambridge University Press, Cambridge, pp.27–62.

Lemma, H., Admasu, T., Dessie, M., Dessie, M., Fentie, D., Deckers, J., Frankl, A., Poesen, J., Adgo, E. and Nyssen, J. (2017) 'Revisiting lake sediment budgets: how the calculation of lake lifetime is strongly data and method dependent', *Earth Surf Process Landforms*, Vol. 43, pp.593–607.

Maalim, F.K. and Melesse, A.M. (2013) 'Modelling the impacts of subsurface drainage on surface runoff and sediment yield in the Le Sueur Watershed, Minnesota, USA', *Hydrological Sciences Journal*, Vol. 58, pp.570–586.

Mahmood, K. and Mundial, B. (1987) *Reservoir Sedimentation: Impact, Extent and mitigation*, International Bank for Reconstruction and Development, Washington DC, USA.

McAlister, R.J., Fox, I., Wilcox, B. and Srinivasan, R. (2013) 'Reservoir volumetric and sedimentation survey data: a necessary tool for evaluating historic sediment flux and appropriate mitigation response', *Lakes and Reservoirs: Research and Management*, Vol. 18, pp.275–283.

Mekonnen, M. and Melesse, A.M. (2011) *Soil Erosion Mapping and Hotspot Area Identification Using GIS and Remote Sensing in Northwest Ethiopian Highlands, Near Lake Tana*, Nile River Basin, Springer, Dordrecht, pp.207–224.

Moges, M.M., Abay, D. and Engidayehu, H. (2018) 'Investigating reservoir sedimentation and its implications to watershed sediment yield: the case of two small dams in data-scarce upper blue Nile basin, Ethiopia', *Lakes and Reservoirs: Science, Policy and Management for Sustainable Use*, Vol. 23, pp.217–229.

Msaghaa, JJ., Melesse, A.M. and Ndomba, P.M. (2014) *Modeling Sediment Dynamics: Effect of Land Use, Topography, and Land Management in the Wami-Ruvu Basin, Tanzania*, Nile River Basin, Springer, Cham, pp.165–192.

Petts, G.E. and Gurnell, A.M. (2005) 'Dams and geomorphology: research progress and future directions', *Geomorphology*, Vol. 71, pp.27–47.

Press, W., Flannery, B., Teukolsky, S. and Vetterling, W. (1988) *Numerical Recipes in Fortran*, 2nd ed., Cambridge University Press, Cambridge.

Rãdoane, M. and Rãdoane, N. (2005) 'Dams, sediment sources and reservoir silting in Romania', *Geomorphology*, Vol. 71, pp.112–125.

Rahmani, V., deNoyelles, F. and Jakubauskas, M.E. (2018) 'Examining storage capacity loss and sedimentation rate of large reservoirs in the central U.S. great plains', *Water*, Vol. 10, pp.1–17.

Reusser, L., Bierman, P. and Rood, D. (2015) 'Quantifying human impacts on rates of erosion and sediment transport at a landscape scale', *Geology*, Vol. 43, pp.171–174.

Sadeghi, S.H. and Saeidi, P. (2010) 'Reliability of sediment rating curves for a deciduous forest watershed in Iran', *Hydrological Sciences Journal*, Vol. 55, pp.821–831.

Setegn, S., Srinivasan, R., Dargahi, B. and Melesse, A.M. (2009) 'Spatial delineation of soil erosion vulnerability in the lake tana basin, Ethiopia', *Hydrological Processes*, Vol. 23, pp.3738–3750.

Setegn, S., Dargahi, B., Srinivasan, R. and Melesse, A.M. (2010a) 'Modeling of sediment yield from Anjeni-gauged watershed, Ethiopia using SWAT model1', *JAWRA Journal of the American Water Resources Association*, Vol. 46, pp.514–526.

Setegn, S.G., Srinivasan, R., Melesse, A.M. and Dargahi, B. (2010b) 'SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia', *Hydrol Process*, Vol. 24, pp.357–367.

Setegn, SG., Rayner, D. and Melesse, A.M. (2011) 'Impact of climate change on the hydroclimatology of lake tana basin, Ethiopia', *Water Resour Res*, Vol. 47, pp.1–13.

Ulke, A., Tayfur, G. and Ozkul, S. (2009) 'Predicting suspended sediment loads and missing data for Gediz river, Turkey', *Journal of Hydrologic Engineering*, Vol. 14, pp.954–965.

Walling, D.E., Hadley, R.F. and Lal, R. (1985) *Recent Developments in Erosion and Sediment Yield Studies*, UNESCO, International Hydrological Programme, Paris.

Wang, F., Mu, X. and Li, R. (2015) 'Co-evolution of soil and water conservation policy and human–environment linkages in the yellow river basin since 1949', *Science of the Total Environment*, Vol. 508, pp.166–177.

Wang, X., Whitney, M., Yang, W. and Melesse, A.M. (2008) 'Prediction of sediment source areas within watersheds as affected by soil data resolution. in: prediction of sediment source areas within watersheds as affected by soil data resolution', in Paul, N. (Ed.): *Environmentalmodelling: New Research* (Findley; ISBN: 978–1–60692–034–3), Ch. 7, Nova Science Publishers, Inc., Hauppauge, NY, pp.151–185.

Wood, P.J. and Armitage, P.D. (1997) 'Biological effects of fine sediment in the lotic environment', *Environmental Management*, Vol. 21, pp.203–217.

Yesuf, H., Alamirew, T., Melesse, A. and Assen, M. (2012) 'Bathymetric Mapping for Lake Hardibo in Northeast Ethiopia Using Sonar', *International Journal of Water Sciences*, Vol. 1, pp.1–9.

Yesuf, H., Alamirew, T., Melesse, A. and Assen, M. (2013) 'Bathymetric study of lake Hayq, Ethiopia', *Lakes and Reservoirs Research and Management*, Vol. 18, pp.155–165.

Yesuf, HM., Assen, M., Alamirew, T. and Melesse, A.M. (2015) 'Modeling of sediment yield in maybar gauged watershed using SWAT; northeast Ethiopia', *CATENA*, Vol. 127, pp.191–205.

Yoon, Y.N. (1992) 'The state and the perspective of the direct sediment removal methods from eservoirs', *International Journal of Sediment Research*, Vol. 7, pp.99–115.