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Bathymetric Mapping for Lake Hardibo in Northeast Ethiopia Using Sonar

Hassen M. Yesuf¹*, Tena Alamirew², Assefa M. Melesse³ and Mohammed Assen⁴

1 Wollo University, Dessie, Ethiopia
2 Haramaya University, Dire Dawa, Ethiopia
3 Florida International University, Miami, USA
4 Addis Ababa University, Addis Ababa, Ethiopia

* Corresponding author E-mail: hassennmohammed2008@gmail.com

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Abstract Lake Hardibo is a remarkable feature in the northeast Ethiopian highlands, with a rich endowment of resource values that need a series of scientific studies. This study adds multi-temporal bathymetric information on the lake, which is of paramount importance, to indicate environmental changes and understand the effect of land processes on hydrology and sediment development of the lake and its basin in the future. Physical parameters, including depth, volume, area, width and length, were derived. The maximum depth measured was 65.20m, located almost at the geographical centre of the lake. A contour map, composite map, and three-dimensional map were produced. Plot profile curves were drawn. These findings can provide valuable information for lake protection initiatives and can be utilized for various water related resource management systems and environmental impact assessment studies. The bathymetric survey was carried out using a combination of the SonarLite Portable Echo Sounder and Global Positioning System (GPS), to generate XYZ hydrographic data points. Surfer 8.01 and ArcGIS 9.3 computer software were used to finalize data evaluation.

Keywords Lake Hardibo, Bathymetry, Echo Sounder, Morphometry, Ethiopia

1. Introduction

Mountains occupy 24% of the global land surface area and are home to 12% of the world’s population. About 10% of the world’s population depends directly on the use of mountain resources for their livelihoods and wellbeing and an estimated 40% depends indirectly on them for water, hydroelectricity, timber, biodiversity, niche products, mineral resources, recreation and flood control [1].

Ethiopia is a country of many lakes and rivers that are comprised of diverse aquatic ecosystems of great scientific interest and economic importance. The total area of inland waters in Ethiopia is 8,800km², representing 0.72% of the total surface area of the country [2; 3]. According to these authors, the total surface area of open waters, including wetlands, is 7,444 km². The Ethiopian Rift Valley is particularly endowed, containing
a chain of permanent lakes lying in what is known as the lakes district, located within the main Ethiopian Rift.

Most of the inland water bodies are confined within the Ethiopian Rift Valley, forming the spectacular lakes region, with the exception of the largest lake, Lake Tana, in the highlands. There are also quite a number of crater lakes in the highlands and the rift escarpments. One such lake system is Hayq and Hardibo situated in an elongated intermountain graben near the edge of the western escarpment of the Afar Rift in north-eastern Ethiopia [4].

Lake Hardibo is an outstanding and fascinating feature surrounded by elongated chains of mountains. The Lake sustains human livelihoods, supports economic activities, provides habitat for biodiversity and affords buffering capacities against hydrologic and climate fluctuations. Despite its importance, enhanced and inappropriate human activities exacerbate excessive sediment deposition and the decline of stream flow into the lake.

Different studies [5; 6; 7; 4] have indicated that there might be an intensive cultivation of the drainage basin of Lake Hayq and Hardibo, regardless of the slope steepness and without sound soil and water conservation measures. Improper farming practices in the periphery of the lake caused degradation, as was the case in most parts of the highlands of Ethiopia [8], further contributing to a high rate of runoff and silt accumulation in the lake in the rainy seasons, reduction of ground water recharge and interruption of base flow into the lake in dry seasons.

Personal communication with prominent elders (Adem Bushra, age 79 and Mohammed Ahmed, age 70, 2009) who live around the lake explained that Lake Hardibo, which is situated 7km southeast from and 231m higher than Lake Hayk, was once used for overflow to Lake Hayk sometime before the last few decades (until 1962), through Ankerkah stream. From this date onwards, the lakes have been hydrologically disconnected, at least by surface water and the watershed split into two independent closed drainage basins. This indicates the diminishing nature of surface and subsurface inflows into the lakes.

The data from the first bathymetric study on Lake Hardibo was collected in 2000 [4]. The authors used the technique involving lowering of a heavy rope of known length over the side of a locally made, non-motorized boat (personal communication with Ayenew, 2009). This method is tedious and frequently inaccurate; usually measuring the depth at only a single point, rather than a continuous measurement, which results in less dense grid data formation, producing rough interpolated maps that affect depth, volume and area estimations at various depth profiles [9].

This crater highland mountain lake has not received sufficient attention in the local and regional discourse on Lake Basin management policy and is not studied adequately.

The objectives of this study were therefore, intended firstly, to study the bathymetry with a more satisfactory approach using an echo-sounder, which is widely used today. Secondly, to make bathymetric data available to compare and contrast multi-temporal results between successive bathymetric surveys to indicate changes driven by multitude of anthropogenic and natural factors. Environmental interpretation of the lake’s determined physical parameters will presuppose a detailed understanding of the negative impacts thereof and help develop integrated watershed management practices for the lake in the future.

2. Materials and methods

2.1 Description of the study Lake

Lake Hardibo is situated in South Wollo in the northeast escarpment at the western margin of the Afar triangle, 447km by road northeast of Addis Ababa (Fig. 1). Geographically it is bounded by 39.75° to 39.78° E longitudes and 11.20° to 11.27° N latitudes within the Awash River Basin. The lake basin has closed drainage with no surface outflow.

There exists a paleo-channel slightly above the present lake level that was used to drain Lake Hardibo (where the outlet was located at around 39.771° E and 11.261° N in the northeast, with seasonal variation in location) to the northwest of Lake Hayk. Currently all streams contributing runoff to Lake Hardibo are ephemerals.

The total dissolved solids (TDS) are less than 780 mg/litre [4]. From the hydro-chemical analysis result, the lake water is fresh. That is why both human and livestock population use the lake for drinking purposes. Water with total ionic concentration <3g/litre is considered fresh [10]. Water with TDS <1500mg/litre is believed to be fresh [11].

Figure 1. Location map of Lake Hardibo and its drainage basin.
The lake has no algal outbreaks or growth of aquatic weeds and the water clarity seems in good condition due to reduced non-point nutrient sources in the basin, owing to limited use of fertilizers by the farmers and limited effluents from animals in the drainage basin. The area is characterized by a sub-humid tropical climate of bimodal rainfall pattern, with a mean annual rainfall of 1141mm and mean annual temperature of 18.2°C.

2.2 Materials

Recent advances in marine born sonar technology provide a cost-effective way to map precisely the bathymetry of lakes. In this study a SonarLite Portable Echo Sounder (Fig. 2), a state-of-the-art underwater surveying instrument, was applied to Lake Hardibo. The SonarLite uses a digital active transducer and microprocessor to synthesize transmitted frequencies of sound and to interpret the return signals.

![Echo sounder equipment with accessories.](image)

**Figure 2.** Echo sounder equipment with accessories.

A Personal Computer was connected to the SonarLite through a serial data cable to access the operating system of the instrument and to download the data for post-processing applications. Geographical Positioning System (GPS) was connected to the SonarLite using a standard data cable, so that GPS readings were generated in conjunction with instrument’s echo sounding functions to create full XYZ hydrographic data using Sonar2000 software package.

2.3 Methods

The hydrographic data was collected from June 16th to 18th 2009, during the dry season. No benchmark of known coordinate and elevation points were available. Therefore, the surface elevation of the lake level during the survey was measured with hand held GPS, recorded as 2134m and used as a reference level.

Before the survey was started, the transducer was connected to the echo sounder, mounted and screwed to the boat by inserting a measured length into the water. After selecting the right datum and projection, the GPS time was synchronized with the SonarLite internal clock and the motorboat was taken for a short run at known depth profiles while watching the SonarLite LCD. It was decided that the device was well functioning.

Then, after a continuous record of lake floor topography was measured with the echo sounder mounted on a motorboat at a constant speed of 5km/hr along predefined narrow traverse lines at 210m from east to west. Surveying within the narrow spacing was to compensate for measurements that were not taken in a north-south direction. With this small width, all the lake area was thought to be well covered by the survey. Simultaneously, zero depth coordinates were taken with a hand held GPS along the shoreline of the lake at shorter distances to complement the dataset produced by the echo sounder. The shoreline coordinate readings were taken from June 17th to 18th, 2009, at the edge of the lake periphery. There were not any obstacles, so the real size of the lake was not under or overestimated during mapping using these border coordinates. The extent of the lake area drawn using zero depth coordinates was crosschecked and confirmed by digitizing Spot 5 satellite images of 5m resolution taken in 2007.

2.4 Data validation

The XYZ database generated by the echo sounder was a continuous record, where the difference between magnitudes of two consecutive depth values was insignificant, which resulted in an enormous number of data points. Duplicate data and data gaps caused by infrequent malfunctioning of the GPS receiver were omitted from the dataset. Zero depth coordinates taken along the shoreline were merged with the dataset generated by the echo sounder and a total of 4011 data points were organized for analysis.

2.5 Data analysis

2.5.1 Data file creation and map production

The data was analysed with Surfer 8.01 Golden Software. An XYZ data file was created in Surfer worksheet, a grid file was produced using Point Kriging Gridding method and a series of maps were formed in Surfer plot document. The relationship between XYZ data files, grid files and maps are illustrated in Figure 3. The negative Z values were used in the data file so that the lake appeared as a basin rather than a hill because the lake bottom is defined as the depth of the water.

2.5.2 Interpolation techniques

Cross validation was used as an objective method of assessing the quality of interpolation techniques, including Kriging, Inverse Distance to a Power, Natural Neighbour, Nearest Neighbour and Triangulation with
Linear Interpolation. The relative quality of the five methods was determined by computing the gridding errors in Surfer.

| Method                                      | $R^2$ |
|---------------------------------------------|------|
| Kriging                                     | 0.9981 |
| Inverse Distance to a Power                 | 0.9884 |
| Natural Neighbour                           | 0.9984 |
| Nearest Neighbour                           | 0.9952 |
| Triangulation with Linear Interpolation     | 0.9985 |

*Table 1. Grid interpolation method accuracy assessment.*

3. Results and discussion

3.1 Bathymetric maps

A composite map (contour map) and three-dimensional (3D) meshed surface maps were drawn based on XYZ data and grid files created previously. A contour map was created from the grid file. The contour map is a two-dimensional representation of three-dimensional data. The first two dimensions are the XY coordinates, and the third dimension, $Z$, is the depth that is represented by lines of equal value. Contour lines were labelled every 15m, starting from the zero contour line at the shoreline to the 60m contour line. The relative spacing of the contour lines indicated the relative slope of the lake surface. The area between two contour lines contains only grid nodes with $Z$ values within the limits defined by the two enclosing contours. The difference between two contour lines is 5m, made as the contour interval. The highest contour line displayed on the map is 60m and is located at the centre of the lake. The maximum depth measured was 65.20m (Table 2), located almost at the geographical centre of the lake.

The XY data points were posted and overlaid on a grid-based contour map to show the spatial distribution and density of the original data surveyed. The composite map (Fig. 5) indicates XY locations with (dot marks) and contour lines. This is often a means of presenting a qualitative measure for the accuracy of the contour lines on the map. The traverse lines are clearly seen on the post map, following the outline of grid points.

A three-dimensional perspective view shaded rendering map was created from a grid file (Fig. 6). The height of the surface corresponds to the $Z$ value of the associated grid node. The upper cyan colour in the colour scale represents the lake surface, while the lower deep blue colour depicts the deepest layer of the lake. Greater detail on the surface is ascribed to the denser grids. The surface morphology of the lake floor was also analysed using the surface analysis tool of GIS.

About 71% of the area of the lake floor is represented by 0 to 5% flat to gentle slope (Table 2). The three-dimensional map can provide valuable information for fishing and recreation purposes and for long-term temporal morphological changes.
Table 2. Morphometric parameters of Lake Hardibo.
* Durations of data collections, not year of publication nd – no data
amsl – above mean sea level
** Day of measurement was on June 17, 2009.

| Parameter                                      | Demlie, et al. 2000* | This study 2009* |
|------------------------------------------------|----------------------|------------------|
| Drainage area, ha, including lake surface area | nd                   | 5214.57          |
| Lake surface area, ha                         | 1580                 | 1582.82          |
| Volume, km³                                    | 0.5683               | 0.5722           |
| Maximum depth, m                              | 64.00                | 65.20            |
| Mean depth, m                                 | nd                   | 25.45            |
| Maximum length (north-south), km              | nd                   | 8.21             |
| Maximum width (east-west), km                  | nd                   | 2.72             |
| (measured perpendicular to maximum length)     | nd                   |                  |
| Perimeter/shoreline length, km                | nd                   | 19.84            |
| Minimum slope, %                              | nd                   | 0.00             |
| Maximum slope, %                              | nd                   | 89.00            |
| Mean slope, %                                 | nd                   | 5.14             |
| Surface elevation, m, amsl (at zero lake depth)** | nd                   | 2134             |

Figure 5. Composite map of Lake Hardibo.

The maximum depth measured was 65.20m, located almost at the geographical centre of the lake. A bathymetric survey data collected in 2000 in Lake Hardibo [4] reported a maximum depth of 64.00 m, 1.20 m less from this study, but at the same location. The probable reason for this is the technique they employed, which involved the lowering of a heavy rope, which could not necessarily travel straight to the bottom, but instead might be deflected by subsurface currents or movements of the non-motorized boat.

Figure 6. 3D meshed surface map of Lake Hardibo.

Although the two bathymetric studies were carried out within a relatively short time span, the former study would have resulted in a depth exceeding the present day result because of the declining nature of the quantity of discharge from upstream watersheds into the lake due to watershed degradation. Ephemeral streams transport sediment-laden runoff during rainy season from the steeper range of mountains surrounding the lake and ceased to flow immediately after wintertime.
3.2 Morphometric characteristics

Lake morphometric parameters provide helpful information to assess the lake residence time, life expectancy, rate of sedimentation, water balance and sustainable abstraction of water and also to derive stage-volume/area curves.

The most significant parameters of the lake’s morphometry studied during the two bathymetric events, including volume, area, depth, maximum length, width, shoreline length etc., are summarized in Table 2.

In this study, volume and area of the lake were computed with Surfer Golden software. Volume calculations were performed by creating a grid file, which defines the lake bottom and represents the depth of the water as a negative Z value, so that the lake appears as a basin.

The other surface was defined as a horizontal planar surface that defines the water upper surface of the lake with a constant value, Z = 0. Having fulfilled those requirements, the software reported volume and area calculations, where volume and area of the lake were reported as the positive volume and positive area.

The accuracy of volume and area calculations was tested using three classical numerical integration algorithms [15].

i. Extended Trapezoidal Rule

\[
V \approx \frac{\Delta y}{2} \left[ A_1 + 2A_2 + 2A_3 + \cdots + 2A_{nCol-1} + A_{nCol} \right]
\]

\[V_f = 526847889 \text{ m}^3\]

ii. Extended Simpson’s Rule

\[
V \approx \frac{\Delta y}{3} \left[ A_1 + 4A_2 + 2A_3 + 4A_4 + \cdots + 2A_{nCol-1} + A_{nCol} \right]
\]

\[V_s = 526993488 \text{ m}^3\]

iii. Extended Simpson’s 3/8 Rule

\[
V = \frac{3\Delta y}{8} \left[ A_1 + 3A_2 + 3A_3 + 2A_4 + \cdots + 2A_{nCol-1} + A_{nCol} \right]
\]

\[V_{3/8} = 526762131 \text{ m}^3\]

Where:

- \(V\) = volume
- \(\Delta y\) = the grid row spacing,
- \(A\) = area,
- \(V_f\), \(V_s\), and \(V_{3/8}\) are total volumes calculated with the respective rule.

\[
RE = \frac{(LR - SR)}{Aver} \times 100
\]

Where,

- \(RE\) = relative error, \(LR\) = largest result among the three methods, \(SR\) = smallest result among the three methods, \(Aver\) = average volume of the three methods.

\[Total\ \text{volume} = 1580603508 \text{ m}^3\]

\[Aver\ \text{volume} = 526867836 \text{ m}^3\]

\[LR - SR = 231357 \text{ m}^3\]

\[RE = 0.04\]

The relative error was estimated and used as an indicator whether the three total volume calculations were close together or not. As a rule of thumb if RE does not exceed 0.9, the variation is insignificant; therefore, the computed lake volume and area calculations were acceptable.

Lake parameters, such as, length, width, perimeter and slope were determined in ArcGIS 9.3 environment by exporting the contour lines with associated Z values to an AutoCAD DXF file. Drainage area was also processed with the ArcGIS surface hydrology tool.

Similarly, like the depth, the volume and area of Lake Hardibo computed by Demile et al. [4] in 2000 were less than the size of volume and area computed by this study. The methods they adopted in calculating the lake’s physical parameter were not explained.

3.3 Storage characteristics

Curves can be used to evaluate and note temporal variations in the lake water volume and area at different water levels and vice versa. The measurement of depth and computation of volume and area enabled us to show the relationship between such variables [4; 13; 16; 17; 18]. Stage and capacity curves (Fig. 7; Fig. 8; Fig. 9) were drawn with respect to a reference lake level. The elevation points were organized by subtracting the depth values from 2134m, because this was the reference lake level at zero depth of lake during the time of the survey.

Volume and area at 5m elevation intervals were determined with the same procedure as lake volume, but instead of defining the upper surface with \(Z = 0\) constants -5, -10, -15 etc., -65.20m was inputted and the resulting volumes and areas were recorded. Coefficient of determination, \(R^2\), and the regression lines portrayed on the graphs show the strength of the responses of the area to depth profile and show that they have positive relationships when the line goes up from lake floor to water surface (Fig. 7; Fig. 8). The size of the area to storage volume also has a positive association (Fig. 9).
Figure 7. Elevation versus volume, stage curve.

Figure 8. Elevation versus area, stage curve.

3.4 Seasonal variation of lake parameters

The bathymetric survey discussed above was carried out in the dry season, from June 16th to 18th 2009, where the lake level receded to the maximum. To recount the changes in some of the lake’s morphometric parameters in the wet season in the same year, a levelling staff gauge was installed and recording of zero depth coordinates around the shoreline was once again conducted (from September 22nd to 24th 2009), immediately after the rainy season came to an end.

![Graph representing seasonal variation of lake parameters](image)

Table 3. Comparison of some morphometric parameters of Lake Hardibo in dry and rainy seasons.

| Parameter          | Dry season (June 12 - 15/2009)* | Wet season (Sep 22-24/2009)* | Average |
|--------------------|---------------------------------|--------------------------------|---------|
| Surface area, ha   | 1582.82                         | 1632.33                        | 1607.58 |
| Volume, km³        | 0.5722                          | 0.5797                         | 0.5760  |
| Maximum depth, m   | 65.20                           | 65.67                          | 65.44   |
| Maximum length     | 8.21                            | 8.40                           | 8.31    |
| Shoreline length, km | 19.84                         | 22.60                          | 20.22   |

*Range of data collection period, not duration of seasons.

Figure 9. Area versus volume, capacity curve.

A maximum depth increment of 47cm was recorded on September 23rd 2009. The corresponding volume and area calculations were performed in Suffer Golden software with the same procedure as stated in article 3.2, by defining the upper (level) surface with Z = 0.47. The results were summarized in Table 3. The maximum width and length of the lake advanced up to 80m and 190m, where gentle slopes (2-5%) made up the landmass bordering the lake in the east-west and north-south coasts respectively. The recession of the lake was mainly due to evaporation. There had been water abstraction for irrigation for some years from the lake, currently it is interrupted due to drawdown of the water from the diversion structure. The drawdown of the lake in these shallow areas in the dry season has brought about the loss of spawning grounds of certain fish species caused by silt accumulation and shoreline erosion during the wet season.

Mapping bathymetric charts and figures of the results of the wet season were not carried out in this paper because they have been tested and did not bring about distinct differences from what was drawn in the dry season, due to the small-scale nature of the maps and figures.
4. Conclusion

Lake Hardibo is a remarkable feature in northeast Ethiopian highlands with rich endowment of resource values that requires scientific research owing to its low ionic concentration, high depth and absence of eutrophication. It sustains human livelihoods, supports economic activities, provides habitat for biodiversity and offers buffering capacities against hydrologic and climate fluctuations. While it provides indispensable goods and services, it has not received adequate consideration and is often undervalued or even ignored, especially by Ethiopian Ministry of Water Resources.

The present day bathymetric maps and morphometric characteristics were generated with state-of-the art technology, with rapid surveying, portable equipment and ease of use at low cost. These findings will provide valuable information and can be utilized for various water related resource management systems and environmental impact assessments.

Physical parameters of the lake, including depth, volume, area, width and length were derived. The maximum and mean depths measured were 65.20m and 25.45m respectively, occurring in the dry season. The lake gradually diminishes in size despite the fact that it was once an overflow to Lake Hayq, before the last four decades, through its outlet in the northeast corner. One of the causes for the lake shrinkage could be the declining quantity of discharge from streams flowing out of the upstream watersheds into the lake, due to watershed degradation and environmental changes. Perennial streams have become seasonal, which transport sediment-laden runoff during rainy season and become dry during summer time.

To complement the scientific information on the lake, it is recommended to study further the water balance of the lake, and the rate of sediment deposition into the lake.

Moreover, studies of soil erosion processes, land use and land cover changes and climate variability in the lake’s drainage basin play an important role in proposing, implementing and using the lake’s resources sustainably because there is an intimate link between what happens in the lake with what is happening in its drainage basin.

The lake has the potential capacity for fishing, recreation and small-scale orchard irrigation as a key resource for promoting sustainable human livelihoods and protection and development of the lake and its basin by lake basin communities, as long as sound lake basin management is planned and implemented in a systematic way.

Establishment of a meteorological station, including lake level recording gage, is imperative to monitor temporal variations of climate elements and to use as a databank for future studies of water and natural resource monitoring and evaluation of the lake and in its drainage basin.

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