SINET: Ethiop. J. Sci., 27(1):61–68, 2004

ISSN: 0379–2897

Short communication

BATHYMETRIC SURVEY AND ESTIMATION OF THE WATER BALANCE OF LAKE ARDIBO, NORTHERN ETHIOPIA

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ABSTRACT: Quantification of the water balance components and bathymetric survey is very crucial for sustainable management of lake waters. This paper focuses on the bathymetry and the water balance of the crater Lake Ardibo, recently utilized for irrigation. The bathymetric map of the lake is established at a contour interval of 10 meters based on depth measurements at 176 points. The depth-area relationship shows that only less than 25 percent of the area is greater than 50 meters deep. The maximum-recorded depth is 62.4 m. Input from direct rainfall and evaporation are the most important components of the water balance of the lake. The annual input from rainfall and inflow from surface runoff is 18.43 and 5.53 million cubic meters, respectively. The average annual open water evaporation, estimated from Colorado Class-A Pan records and Penman modified method is 23.49 million cubic meters. The net groundwater flux estimated as a residual of the other water balance components is -5.03 million cubic meters, indicating that groundwater outflow is greater than groundwater inflow. The recent abstraction for irrigation appears to affect the water balance and lead to grave environmental consequences on the fragile lacustrine ecosystem.

Key words/phrases: Bathymetry, crater lake, hydrology, irrigation, water balance

INTRODUCTION

Ethiopia contains numerous inland water bodies whose scientific interest is largely unexplored, not withstanding the role, which these waters might play in agricultural and tourism development. Most of these inland water bodies are located within the rift forming the spectacular lakes region and the largest lake Tana in the highlands. But, there are many crater lakes in the highlands and rift escarpments, which play important roles in the lives of millions of people. One such lake is Ardibo located near the edge of the northwestern rift escarpment, some 430 km north of Addis Ababa in southern Wollo Administrative Zone.

The hydrology and bathymetry of most of the major lakes in the Main Ethiopian Rift lakes have been studied for more than half a century (UNDP; 1973; Tesfaye Chernet, 1982; Dessie Nidaw, 1997; Tenalem Ayenew, 1998; Vallet-Coulomb *et al.*, 2001). Despite the importance of the various crater lakes scattered elsewhere in the country very few hydrological studies were carried out (Baxter and Golobitsh, 1970; Wood and Talling, 1988; Seifu Kebede, 1999; Molla Demellie, 2000).

Lake Ardibo is one of the most poorly studied scenic fresh lakes in Ethiopia. This lake has been recently used for irrigation. It also plays a significant role in local fishing activity and watering of animals. Irrigation aqueduct and canal were constructed for irrigation by the government at the northwestern shore of the lake some time in 1989 with a designed capacity of 300 liters per second, which is now irrigating some 1.5 km^2 of land (Molla Demellie, 2000). There is still a great interest of expanding the irrigation project including the nearby lake Hayq in the adjacent catchment by the Commission for Sustainable Agriculture and Environmental Rehabilitation in the Amhara Region (SAERAR). Despite the growing interest of irrigation development, there is no basic relevant data. The study of the bathymetry and hydrology of the lake has become a vital issue. Bathymetry refers to the systematic measurement of the depth of a water body and the establishment of contours of equal depth. Bathymetry of rivers and lakes provides important information on the configuration of the bed, which will be of great help for navigation purposes, for the study of rate of sedimentation, assessment of habitation of aquatic animals and plants, detection of geological structures, and above all for water management purposes.

The main objective of this work is to establish the bathymetry of the lake and to estimate the surface water balance components and quantify the groundwater fluxes as a residual of the other components of the hydrological cycle, all of which are essential elements for any development scheme of lake waters.

THE STUDY AREA

The centre of Lake Ardibo is located between 11° 14' N latitude and 39° 46' E longitude at an elevation of 2120 meters above mean sea level (m a.s.l) in northern Ethiopia. The surface area of the lake and its catchment is 15.8 km² and 52.6 km², respectively. The Lake Ardibo catchment is a closed drainage within the northwestern watershed of the Awash River basin, near the headwaters of the Mille River (Fig. 1).

The area is dominantly hilly and intensively cultivated. High altitude areas are characterized by scattered bushes and grazing fields. The climate is sub-humid with average annual temperature and rainfall of 18°C and 1158 millimetres (mm), respectively (Molla Demellie, 2000).

The present-day physiography of the region is the result of Cenozoic volcano-tectonic and erosional processes. Lakes Ardibo and Hayq are situated in two separate craters within a small graben bounded to the east and west by distinct NNW-SSE trending major fault systems. Unlike the typical circular shape of a crater lake, later modification by faulting gave an elongated shape to Lake Ardibo. There are many springs emanating along these faults. Sometime during the Quaternary Ardibo and the adjacent lake Hayq were connected by a channel through the Ankarka River. Currently there is no direct surface water connection between the two lakes. The only outflow is through the newly constructed irrigation canal.

The basin is covered with Trap Series volcanics. Figure 2 is a simplified geological map of the Ardibo catchment. According to Zanettin *et al.* (1978) the volcanics belong to the Aiba and Alaji fissural volcanism (32–15 Ma); which are dominantly basalts associated with rhyolites. There are also Quaternary sediments covering the flat low-lying areas. The simplified lithostratigraphic description from the oldest to the youngest unit is given below.

1. *Rhyolite and ignimbrite unit* – These are the oldest rock unit in the catchment, characterizing the slope of the major E-W trending main ridges on both sides of the lake. The ignimbrites are more dominant than the rhyolites. They show distinct flow structures and often form steep cliffs.
2. *Unwelded acidic volcanic pyroclastics* - The unit is composed of various volcanic ash and acidic fragmental extensively faulted volcanites. It is loose and incoherent and is underlain by degraded basaltic materials.
3. *Weathered basaltic unit* - is an extremely weathered rock covering most of the high altitude areas. They show spheroidal weathering. The major degraded basaltic unit is overlain locally by a thin fine-grained basaltic flow characterized by extensive jointing. The unit grades upward to a slightly lighter intermediate rock, which also shows extensive fracturing and weathering.
4. *Upper basaltic unit* - is fine-grained dark basalt characterized by columnar jointing. It is highly fractured and covers the top of hills; in places associated with rare tuffaceous and volcanic ash units. This unit forms the major recharge area of the catchment.
5. *Quaternary sediments* - Along the slopes and feet of hills they are colluvial, talus and scree deposits grading to alluvial type associated with lacustrine deposits in the plains around the lakes. It is the most dominant rock unit in the catchment.

There are distinctly visible fault systems. Most of the steep cliffs and saddles at the top of the hills are related to faulting. There are at least three sets of normal faults trending NNW-SSE, NE-SW and E-W. The former is manifested by major scarps and cliffs. In the Hayq cathment there are many E-W trending faults along which many springs emanate. Often gulleys, seasonal streams and springs are structurally controlled by faults. The movement and occurrence of groundwater appears to be strongly controlled by these fault systems.

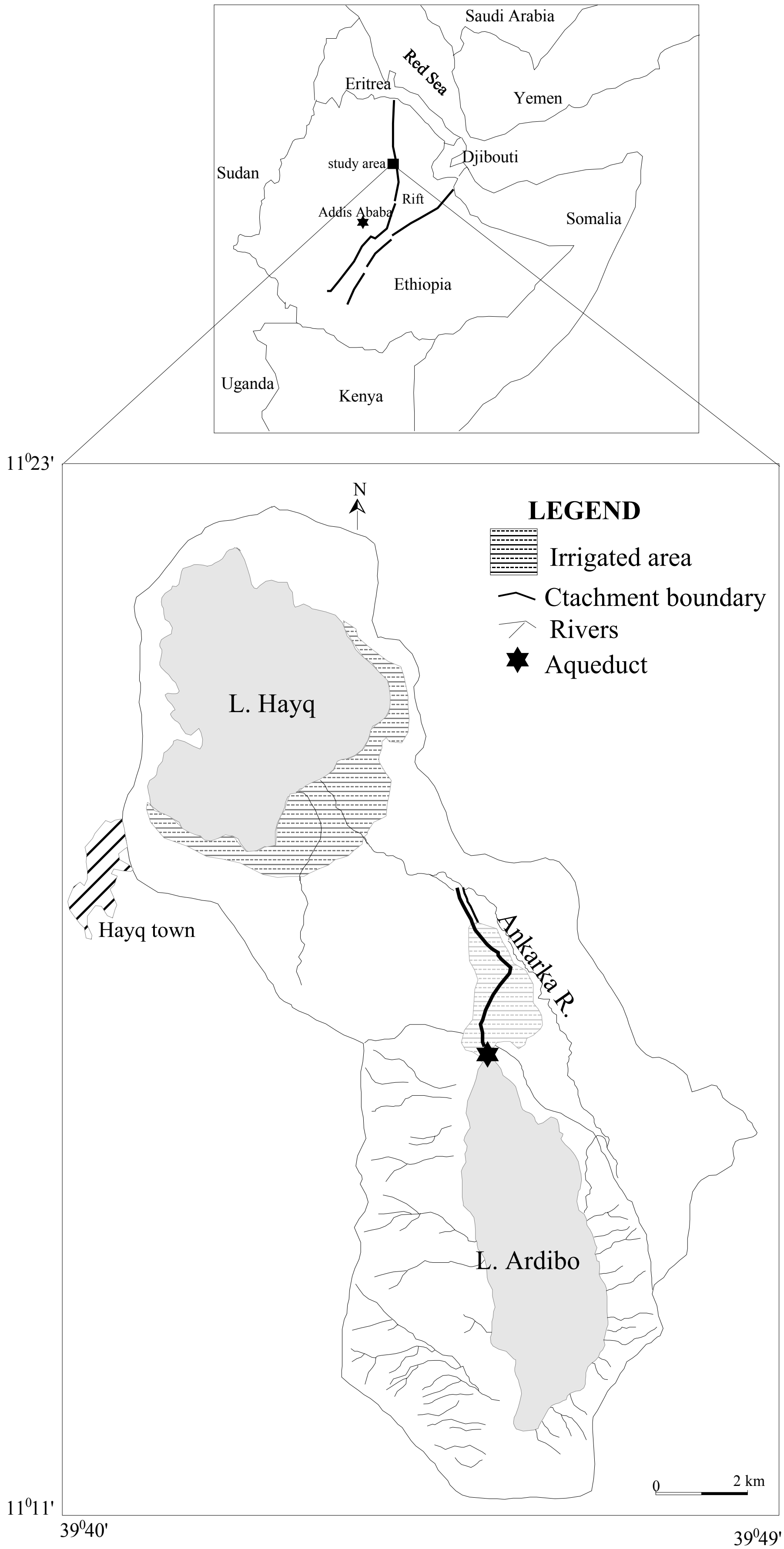

Fig. 1. Location map of the study area.

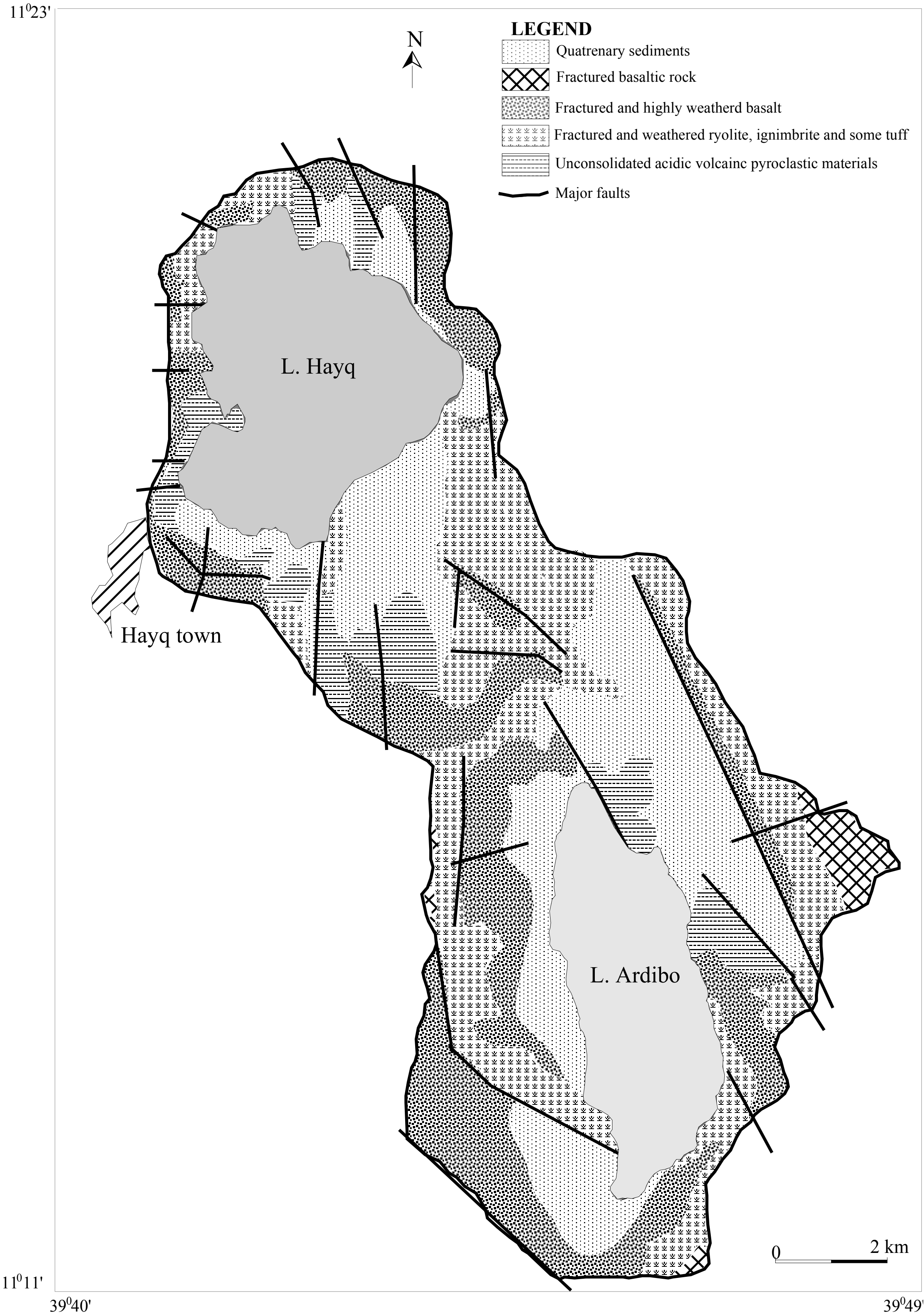

Fig. 2. Simplified geological map of the Hayq-Ardibo area.

METHODOLOGY

Field hydrogeological and bahymetric survey was carried out from February to March 2000. The geographical locations of depth measuring points were determined using high precision Global Positioning System (GPS). The depth is measured using graduated plastic rope. Measurements were taken at 176 points. Linear interpolation has been used to establish the bathymetric contours.

For the estimation of the water balance components relevant hydrometeorological data were collected from the Ethiopian Meteorological Services Agency. Extensive field hydrogeological mapping and discharge measurement of lake water outflow through the irrigation canal and the discharge of Ankarka River were made using current meter (SIAP model 601407). Low discharge springs were observed in the lake catchment. These springs are used for local community water supply and irrigation of small farm plots. As compared to the other water balance components, these springs have very limited importance. Therefore, all the groundwater components including springs are incorporated as a residual net flux (groundwater inflow minus groundwater outflow) in the water balance calculations.

Quantification of the water balance of any hydrologic system of a lake or watershed requires defining the inflow and outflow components of the hydrologic cycle. This can mathematically be represented as:

Inflow - outflow ± change in storage = 0.......... (1)

The water balance components of Lake Ardibo are given by:

$$P + Sr + Gi - E - Go - A \pm \Delta S = 0 \quad \text{.......... (2)}$$

where, P = precipitation on the lake; Sr = surface runoff from all the ungauged catchment; Gi = groundwater inflow; E = lake water evaporation; Go = groundwater outflow; A = abstraction from the lake for irrigation; ΔS = change in storage.

The rainfall record at the meteorological station of Hayq town (1965–1999) is used. There are no perennial rivers feeding Lake Ardibo; all surface inflow comes as overland flow. From surface water point of view, the Ardibo catchment can be considered as a closed system, except for outflows through the newly constructed irrigation canal.

The surface water inflow is estimated after quantifying the runoff coefficient. This is estimated based on field observations of land use, topography and geology using the method of Tripathi and Singh (1993). This method aerially weighs land use, soil type and slope classes. For this purpose six land use, five slope and two soil type units were used. The values were weighed using Geographic Information System (GIS) overlay operations. The weighted mean runoff coefficient value for the entire catchment is 0.3.

The groundwater inflow to the lake comes from springs and seepage zones, which all come from rainfall recharge. Molla Demellie (2000) estimated the recharge on the basis of Thornthwaite and Mather (1957) soil-water balance approach. The annual recharge in the catchment is 35.4 mm. On annual basis the change in storage can be fairly neglected. Therefore, the ΔS term in equation 2 can be replaced by the net unmeasured ground water fluxes (Gi-Go), including the incoming springs.

The open water evaporation is estimated based on seven years Colorado Class-A pan evaporation record (1985–1991) at Hayq town (NMSA, 2000). A pan receives larger quantity of energy for radiation than a lake, and hence the evaporation from the pan is greater than the lake. Therefore, the pan evaporation value has to be multiplied by a pan coefficient (usually less than 1). In the adjacent Ethiopian rift a pan coefficient ranging from 0.75 and 0.83 were adapted for lake water evaporation estimation (Makin *et al*., 1976; Tenalem Ayenew, 1998; Zemenu Geremew, 2000). Dune and Leopold (1978) proposed different pan coefficients for various lakes under different climatic conditions. Taking the geographical location and the hydrometeorological condition of the area and the experience from the Ethiopian rift a medium pan coefficient of 0.8 is used for this marginal lake located at the edge of the rift valley.

An independent Penman-modified method is also used to estimate the open water evaporation. The method can be expressed as:

$$E_0 = \frac{\left[\left(\frac{\Delta}{\gamma}\right) \times H + E_a\right]}{\left[\frac{\Delta}{\gamma} + 1\right]} \quad \text{.. (3)}$$

where, E_0 = open water evaporation expressed in centimeter per day; H = net radiation in centimeter per day; Δ = slope of the curve relating saturation vapour pressure to temperature, γ = psychrometric constant, E_a = a term describing the contribution of mass transfer to evaporation.

The quantities H and E_a are determined based on the following relations:

$$H = \frac{[Q_s(1-\alpha) - Q_l]}{\lambda} \qquad (4)$$

$$E_a = \frac{(0.013 + 0.00016V_a)}{(e_{sa} - e_a)} \qquad (5)$$

where, Q_s = the mean daily solar radiation of the month under consideration (cal/cm^2); Q_l = net long-wave radiation estimated from empirical relation developed by Chang (1968 cited in Dune and Leopold, 1978) (cal/cm^2); V_a = wind speed (km/day); ∝ = albedo; λ = latent heat of vaporization of water (590 cal/cm^2); e_{sa} = saturation vapor pressure of the lake (millibar) and e_a = actual vapor pressure (millibar).

For the water balance calculation the average evaporation from the pan and the modified Penman method is used.

RESULTS AND DISCUSSION

The bathymetric map of Lake Ardibo, prepared for the first time in this study, is shown in Fig. 3. Table 1 summarizes the depth-area relationship. More than 50 per cent of the lake area lies below 25 m depth. The maximum-recorded depth is 62.4 m. The depth increases in all directions towards the center. The eastern shore has very steep gradient, while the western has gentle gradient. The surface area of the lake, as calculated from the 1992 topographic map prepared by the Ethiopian Mapping Authority, is 15.8 km^2. The area of the lake was much larger in the early 1950s (Molla Demellie, 2000). There is no clear information on the cause of the reduction of the size of the lake, either due to irrigation or climatic change. In the Main Ethiopian Rift, both factors have influenced the level of lakes substantially (Tenalem Ayenew, 1998).

Table 1. Depth-area relation of Lake Ardibo.

No.	Depth range (m)	Area (Sq. km)	Area (%)
1	> 60	0.84	5.3
2	50–60	3.29	20.8
3	40–50	2.48	15.7
4	30–40	2.31	14.6
5	20–30	1.43	9.1
6	10–20	1.95	12.3
7	< 10	3.50	22.2

The bathymetric map and observation of local geological features clearly indicate that lake Ardibo lies in volcanic crater later modified by parallel/sub-parallel normal faults. Sites of the maximum depth represent the volcanic vent, probably later filled partly by sediments derived from the surrounding hills.

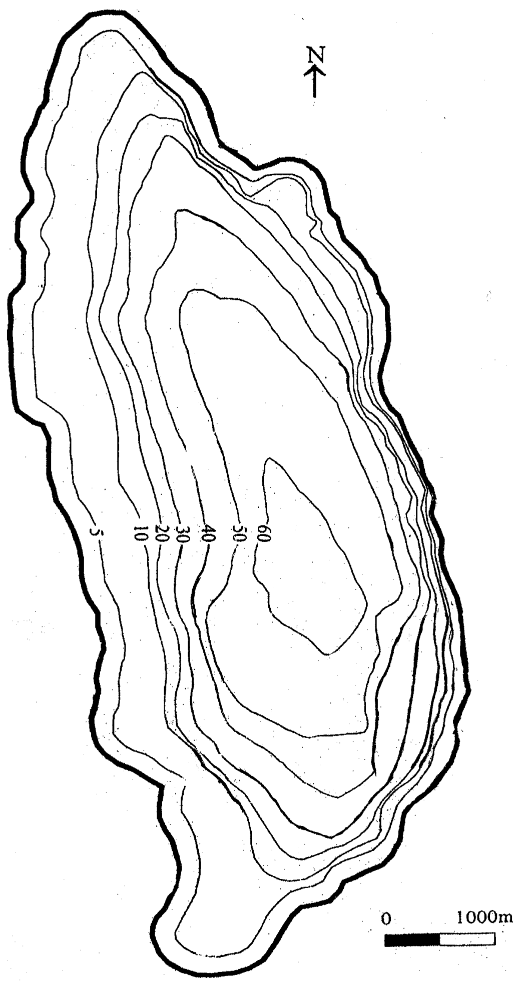

Fig. 3. Bathymetric map of Lake Ardibo (contours in meters).

Table 2 summarizes the water balance components of the lake. Input from rainfall and evaporation are the most important components of the water balance. The annual inflow from rainfall and surface runoff is 18.42 and 5.53 million cubic meters (mcm) respectively. The average annual open water evaporation, estimated from Colorado Class-A Pan record and Penman-modified method is 23.49 mcm. The abstraction for irrigation is 3.15 mcm. This value is in good agreement with the discharge measurements made from the open irrigation canal, estimated at 3.27 mcm.

Table 2. Estimated water balance components.

Parameters	Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Temperature	1965–1999	15.5	16.7	18.1	18.9	19.6	20.7	20.3	19.7	18.8	16.8	15.6	14.9	18 (mean)
Precipitation	1965–1999	31.5	71.0	104.0	113.0	81.6	31.6	261.5	262.0	118.0	47.0	21.0	24.0	1167.0
Pan evaporation	1985–1991	128.7	112.0	120.0	116.0	125.0	125.0	120.6	116.0	117.0	124.0	125.0	127.0	1456.0
Penman evaporation	1992–1999	112.3	114.0	137.0	138.0	153.0	133.0	116.3	125.0	125.0	133.0	119.0	111.0	1516.0
Average evaporation	–	120.5	113.0	128.5	127.0	139.0	129.0	118.6	120.5	121.0	128.5	122.0	119.0	1486.0
Surface runoff	1965–1999	9.5	21.3	31.2	33.9	24.5	9.5	78.5	78.6	35.4	14.1	6.3	7.2	349.9

The net groundwater flux (Gi-Go) estimated as a residual of the other water balance components is -5.03 mcm. The negative value indicates that groundwater outflow is greater than the inflow. Under steady state conditions, the total inflow must be the same as the total outflow. In the absence of abstraction of water for irrigation, it appears that the steady-state water balance is reasonable. Because, the residual value treated as groundwater outflow, is more or less similar to the annual abstraction for irrigation. This means that the natural steady-state condition will be maintained in the absence of abstraction.

The water balance calculation revealed that the abstraction of water for irrigation, without considering short-term variations and lake level changes, would certainly result grave consequences. If we consider the 3.15 mcm abstraction annually, it will result in 19.9 cm reduction of lake level. This requires serious consideration of the temporal variation of all the inputs and good water management and irrigation scheduling. The reduction in lake level minimizes the groundwater outflow that directly goes to the adjacent Lake Hayq. This intern affects the water balance of Lake Hayq.

CONCLUSIONS AND RECOMMENDATIONS

From this study the following conclusions and recommendations were drawn. The most important component of the water balance of the lake is input from rainfall and outflow by evaporation. The groundwater inflow appears to be higher than the inflow. The bathymetric map shows that much of the surface area of the lake is shallow accommodating many aquatic biotas. The abstraction of water and consequent reduction in lake level will certainly affect this important portion of the Lake.

More vigorous assessment of spring discharge measurements, abstraction rates, and quantification of groundwater fluxes using seepage meters along the shore of the lake may lead to more detailed water balance assessments. Installation of lake level recording gauge will give a better picture of the temporal variation of inputs and abstraction in the future. Irrigation activity should consider all the changes of the level and hydrochemical and limnological changes.

ACKNOWLEDGEMENTS

The authors are grateful to the Department of Geology and Geophysics, Addis Ababa University, for the field logistic support. The Ethiopian Meteorological Services Agency is highly appreciated for providing the relevant meteorological data. Thanks are also due to the Commission for Sustainable Agriculture and Environmental Rehabilitation in the Amhara Region for providing some basic information.

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