

Impact of water overexploitation on highland lakes of eastern Ethiopia

Tamiru Alemayehu · Wagari Furi ·
Dagnachew Legesse

Received: 9 March 2006 / Accepted: 10 August 2006 / Published online: 13 September 2006
© Springer-Verlag 2006

Abstract The eastern Ethiopian highland is endowed with large potential of water resources in terms of rainfall, groundwater and surface water. Yet, due to overpumping of lake water and groundwater and environmental degradation, Lakes Haromaya and Adele have completely dried up. The environmental degradation, due to deforestation and clearing of land for farming, has increased the rate of siltation in the lakes that dramatically decreases the lakes' volume and surface albedo, which increased the rate of evaporation. The impact of these factors is aggravated due to decreasing net recharge to the lake and the alluvial aquifer. Over the last 35 years, pumping of lake water for irrigation, mainly for subsistence farming, domestic and industrial use shows an increasing trend. Hence, the available water for drinking and industrial purposes decreased drastically. In this research, classical Penman aerodynamic combined energy budget, Penman nomogram methods, conventional soil moisture water balance method and Penman–Monteith model were adopted to estimate free evaporation, actual and potential evapotranspirations. The results indicate that evaporation is the dominant factor for the loss of water and water abstraction is 316% higher than the effective precipitation, which is 110 mm/year. Therefore, over-exploitation of the available resources has played an aggravating role for the loss of the lakes in the area.

The main cause for such resource depletion is the lack of integrated water resources management strategies. The current water shortage in the area has mainly affected urban residents of Harar, Awoday and Alemaya towns and the surrounding villages, which depend heavily on the two lakes. To alleviate the current crises interbasin water transfer and rainwater harvesting would be possible alternatives besides ameliorating environmental situation of the basin.

Keywords Groundwater · Evaporation · Surface water · Water resources

Introduction

Natural lakes are environmental resources with substantial importance to human being by regulating climate, making environment favorable for life to sustain and enhancing development. Once these precious resources are lost due to misuse, uncomfortable and challenging environment would complicate life and enhance poverty.

Community water resources could be derived from perennial water bodies like lakes, rivers and groundwater. The unsustainability issue arises when demand and supply mismatches lead to the overexploitation of a single resource. Due to hydraulic linkage, surface and groundwater are always in a continuous interaction through geological media. The interaction between surface and groundwater could be considered as a complex recharge–discharge process where the system is viewed as a linked component of a hydrologic continuum leading to sustainability issues (Sophocleus 2002). Hence, the imbalance on recharge–discharge process could lead to perturbation on water system.

T. Alemayehu (✉) · D. Legesse
Department of Earth Sciences, Addis Ababa University,
P.O. Box 1176, Addis Ababa, Ethiopia
e-mail: tamalem@geol.aau.edu.et

W. Furi
Oromiya Water Well Drilling Enterprise,
Addis Ababa, Ethiopia

One of the areas where population pressure affected the perennial water resources is East Hararghe zone in eastern Ethiopia. The East Hararghe highlands are one of the most populated areas in the Oromiya Regional State in Ethiopia (Fig. 1) and show rapid development both from agricultural and industrial activities point of view. The Haromaya and Adale Lakes are located on this highland and naturally closed lakes with a surface area of 33.2 and 28.2 km² and catchment area of 140 and 48 km², respectively. These lakes were formed within the erosional depression constituted by Mesozoic sedimentary rocks and crystalline basements. The depression is aligned NE–SW direction and collects natural recharge exclusively from rainfall. For the past many centuries, Lakes Haromaya and Adele were the source of life for the area and played very important role in environmental regulation. In this work, Lake Haromaya will be discussed in detail since it was the main source of drinking water for the nearby towns for a population of more than 150,000, besides the availability of data for the required analysis. However, due to the similarity in the impact, both lakes have gone dry.

Large water demand for domestic supply, industrial and irrigation uses has brought a burgeoning pressure on Lake Haromaya. Numerous hand pumps and bore holes are sunk in the alluvial aquifer and around 20 boreholes are pumping water over 24 h from the lakes basin that has contributed to the continuous decrease in the groundwater level due to the hydraulic connection with the lake water. The observed pumping test results show that all wells are pumping in an unsteady state, which could facilitate the rapid lowering of water table. Water shortage in the area substantially affected the economy of the local people and is the root cause for poverty and hunger of the community. In general,

high population pressure has affected the natural dynamics of the hydrological and hydrogeological environment of the lakes basin.

The loss of Lake Haromaya has worsened the water shortage of the area and is creating population displacement due to the increase in water demand. Therefore, this paper is addressing the potential factors that have contributed to the loss of water from Lake Haromaya and suggests alternative water resources management strategies.

Climate and hydrogeology

The altitude in the basin ranges from 1,980 m above sea level (a.s.l) on the lakes floor to 2,343 m a.s.l at the peak of the recharging hills. The rainfall pattern is bimodal with the mean annual precipitation of 751 mm. Maximum precipitation occurs in April, August and September with the highest peak in August (mean 149 mm) while the minimum is in December (mean 10.2 mm). The mean ambient temperature of the area is 16°C (maximum in June, 19°C and minimum December, 13°C) and is classified as semihumid and semiarid climate. The mean monthly relative humidity before the year 2003 falls between 53 and 75%. Due to the drying up of the lakes in the area, the relative humidity is expected to be low that could be related to dry environmental condition. The surface drainage is characterized by radial pattern, forming a closed drainage system whereby water drains from the surrounding hills into the central plain land.

The bed rock of the lake basin is made of Precambrian crystalline rocks dominantly represented by granitic gneiss and pegmatite. These rocks constitute very poor aquifer in the area and the sole water re-

Fig. 1 Location map of the Lake Haromaya (*star*)



source for the people was coming from the lakes. Currently due to the absence of surface water, there is overexploitation pressure on the shallow alluvial aquifers that overlay the crystalline rocks. From the hydrogeological point of view the most important aquifer is represented by alluvial deposits with the thickness that ranges from 20 to 50 m and characterized by silt and clay deposits. There are few seasonal springs such as Bate worq that discharges 0.5 l/s and is a contact type between the lower sandstone and limestone formations. The inventory of the wells that tap water from the Haromaya basin shows that there are more than 20 operational boreholes near by the lakes with the discharge that varies between 0.5 and 17 l/s. Due to the closed nature of the basin, hydrological outlet from the basin is mainly through evapotranspiration and artificial abstraction while inflow to the basin is only from precipitation falling in the lake catchment.

High population increase over the limited land area resulted in the indiscriminate forest clearings, overgrazing around the lakes. The absence of soil conservation practice and encroachment of people into the lake for the need of extra land for tillage accelerated siltation processes. Vegetation in the lake basin is entirely cleared off and former vegetated lands such as those on Haromaya highlands in the southwest of the lake and the Ifa bate and Ambo highs in east and northeast are cleared off and the land is changed into agricultural lands since two decades.

The current status of Lake Haromaya is shown in Fig. 2, where dead trees, bare soils and the absence of trees are the characteristic features that imply the consequence of the drying up of the lake and impact on the natural environment.



Fig. 2 The Lake Haromaya: dried up since 2005

Estimation of water loss from the Lake Haromaya

The amount of water that is extracted for use and evaporated from the lake depends on its availability and the recharge condition. If extraction and loss exceed the rate of natural recharge, depletion of the resource is an inevitable phenomenon. Rainfall is the principal source of recharge in the lakes basin that feeds directly the lakes and the alluvial aquifer. The amount of recharge depends upon the duration and amount of rainfall and degree of evapotranspiration. The effect of recharge is characterized by a decreasing trend in the area in the last few years due to increasing evaporation facilitated by deforestation. Considering various inflow and outflow components as indicated in Fig. 3, the basic water balance equation for the lakes could be

Input = output, which is given by

$$G_{in} + P_{eff} = ET_{out} + Ab_I + Ab_d + G_{out}$$

where:

- G_{in} groundwater input
- P_{eff} effective precipitation
- ET_{out} evapotranspiration
- Ab_I abstraction for Irrigation
- Ab_d abstraction for drinking
- G_{out} groundwater output

G_{in} represents groundwater input derived from adjacent basin, while G_{out} designates groundwater that moves out of the basin. Since the hydrographic basin is a closed basin, G_{in} and G_{out} can be considered zero. Therefore, the only input variable in the basin is rainfall (751 mm/year), which is not uniformly distributed over a year. After subtracting the actual

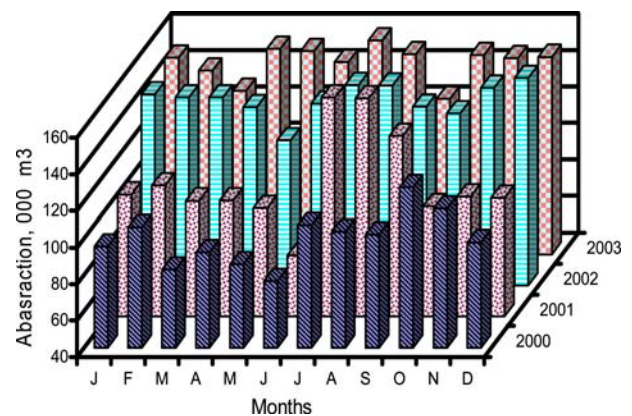


Fig. 3 Abstraction from the Haromaya Lake for drinking (000, m³)

evapotranspiration component, the effective precipitation in the basin is around 110 mm/year.

The outgoing components (ET , Ab_I , Ab_a) are considered as a water loss from the basin. Lake water abstraction can be affected in many ways but three major types are considered in this special case for the Lake Haromaya. Water loss through natural processes (free water evaporation), artificial abstraction both for drinking and irrigation are considered as the primary factors. Siltation is considered as an indirect or secondary factor to reduce the lake volume by decreasing the amount of water contained in the lake.

Evaporation

Evaporation is one of the main components of the hydrologic processes through which water is naturally lost from a basin. Free water evaporation occurs from an open water surface in the absence of advection and changes in heat storage and depends only on regionally continuous meteorologic or climatic conditions (Dingman 1994). The evaporation rate from the Lake Haromaya is computed taking into account the available energy, the net radiation, air temperature and wind speed measured at the meteorological stations of Haromaya and standard tables as indicated in Shaw (1988). Penman aerodynamic energy budget combined method and Penman nomogram (Wilson 1983) are used to estimate free water evaporation from the lake water. Accordingly, the estimated annual rate of evaporation is 1,264 and 1,274 mm, respectively, with the mean value of 1,269 mm. Therefore, the direct evaporation rate from the lake is estimated to be 42 Mm^3 /year.

The evaporation rate has been estimated using the soil moisture water balance method of Thornthwaite and Mather (Dunne and Leopold 1978) taking into consideration the type of soil and vegetation cover in the basin. Accordingly, the annual potential and actual evapotranspiration are 715 and 641 mm, respectively (Table 1). While, using the Penman–Monteith model the potential evapotranspiration is 980 mm, which is higher than the previous method. From this analysis it can be seen that using the actual evapotranspiration result, effective precipitation in the basin is around 110 mm/year, which is equivalent to 15.4 Mm^3 .

Abstraction

Domestic and industrial water supply

The Lake Haromaya was the only source of water supply for the three big towns of east Hararge Zone (Harar, Alemaya and Awoday) as well as for the communities of the lakes region. Information from Harar town water supply office shows that the lake had been providing drinking water for a population of nearly 150,000 for the past 35 years. Initially the lake was abstracted at a rate of 35 l/s over 24 h a day for 25 years when the population was about 60,000. Later this rate was raised to 60 l/s in order to cope up with the increased water demand due to the increased population. The daily volume of water withdrawn from the lake for water supply (during the initial period of 35 l/s) was 3,024 m^3 /day with an annual abstraction rate of 1.1 Mm^3 /year. Similarly, the daily volume of water withdrawn from the lake during the later time with 60 l/s was 5,000 m^3 /day with an annual abstraction rate of 1.8 Mm^3 /year. Considering the first 25 years during which the lake was abstracted at a rate of 35 l/s, the volume was 27.5 Mm^3 and considering the later 10 years during which it was abstracted at a rate of 60 l/s, the volume was 18 Mm^3 with the total abstraction of 45.5 Mm^3 . The measured monthly abstraction pattern from the Lake Haromaya for 4 years is given in Fig. 4, which shows increasing trend in the past years. Due to the extensive water utilization, the lake level declined rapidly (Fig. 5), which had a water level of 8.5 m in the year 1975. For the comparison purpose, the exhaustion pattern of the Lake Adele is given in Fig. 6, which was dominantly used for irrigation and dried up in the year 2003.

Currently due to the disappearance of the lake, for both drinking and irrigation, the local people excavate wide wells at the center and around the dry lake basin and pump water (Fig. 7). Such wells are quite unfriendly to the environment and are distributed all over the basin. All of the wells have wide opening with a depth that reaches 8 m. The local people also pump water from these wells for small-scale horticulture irrigation.

Table 1 Monthly evapotranspiration from the Lake Haromaya basin in millimeters

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
P	11.7	19.95	65.8	102.75	94	45.35	98.75	149.3	103.65	37.55	12.2	10	751
PET	43	51.7	63.3	70.3	74.4	77.6	68.3	67.9	65.3	51.3	44.4	37.5	715
AET	20.9	25.5	63.3	70.3	74.4	68.8	68.3	67.9	65.3	54.3	38.6	23.3	641

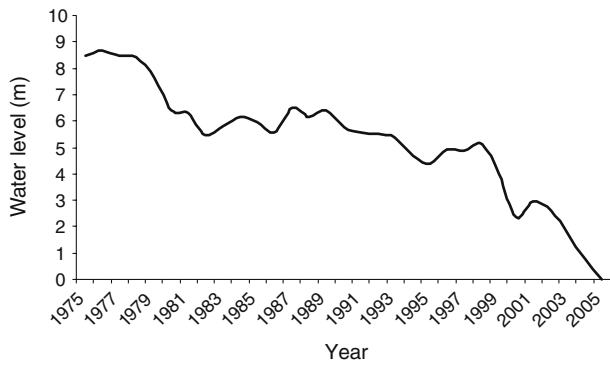


Fig. 4 Yearly mean lake level fluctuation for the Lake Haromaya: dried up in 2005

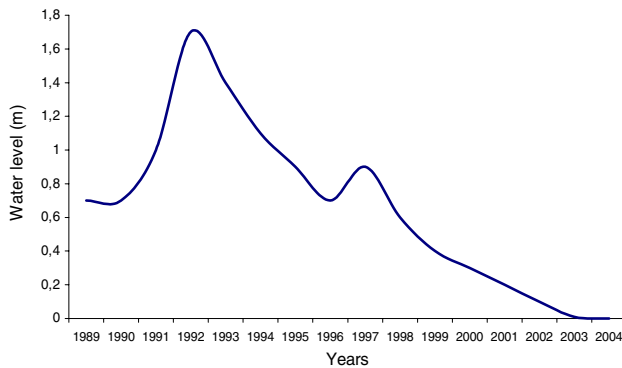


Fig. 5 Yearly mean lake level fluctuation for the Lake Adele: dried up in 2003



Fig. 6 Dug well at the center of dry lake basin. The water level is at the depth of 6 m

Groundwater pumping

To provide water for the Alemaya Agricultural University, Harar town and industries in the region, more than 20 boreholes have been drilled in the unconfined alluvial aquifer that was recharged from the Lake

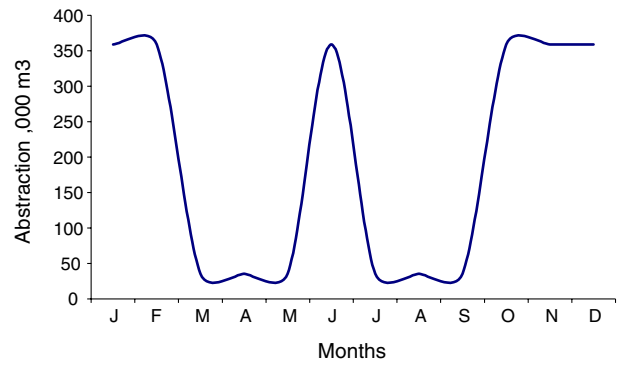


Fig. 7 Monthly mean abstraction from the Lake Haromaya for irrigation

Haromaya. The wells operate over 24 h in unsteady state with variable yield (0.5–17 l/s). According to Furi (2005), the estimated overall abstraction from groundwater located in the unconsolidated aquifer is at a rate of 115 l/s, which is equivalent to 3.6 Mm³. Due to an unbalanced recharge with respect to the abstraction in the area, excessive groundwater pumping could invite the lake water, through hydraulic connection within the alluvial sediments, as a potential recharge and eventually reduce the lake water. Most of the boreholes are located within the close proximity to the lake and, therefore, the groundwater overdraft could be considered as supplementary and important factor for the loss of the Lake Haromaya. From field survey it has been observed from the open dug wells (Fig. 7) that the water level is located at about 6 m below the lake surface.

Irrigation

The Lake Haromaya has been intensively used for irrigation. Even though there is no recorded data that show clearly the amount of water abstracted from the lake for irrigation, during the field investigation it has been known that there are more than 80 surface pumps with a discharge rate of 16.7 l/s, around the lake that were pumping lake water for a minimum of 5 h/day. Therefore, considering 80 operational pumps at a time for 5 h/day from the lake, the amount of water abstracted from the lake for the irrigation purpose would be 23,760 m³/day. Crop irrigation by the lake water was mainly practiced exclusively during the dry months and a very small amount of water is used during the rainy months. Considering eight dry months and small pumping during rainy months, the annual extraction amounts to 0.19 Mm³. Taking into consideration the intensive irrigation activity in the area for the last 35 years the total amount of water extracted could be

6.65 Mm³. The general lake water abstraction pattern for irrigation is presented in Fig. 8 and it shows two extreme peaks characterized by seasonal pumping and abstraction decreases during rainy months (March, April, May, June). There is a large demand of water for irrigation by local people to irrigate vegetables all over the year.

The calculated total loss through evaporation, domestic and industrial water supply and irrigation would be 48.69 Mm³/year. If we assume the last 35 years as a time frame both for evaporation and abstraction except groundwater (only 15 years), the total loss will be 1,576.15 Mm³. The compiled results are given in Table 2 where the primary factors are presented. The result obtained is much higher than the effective precipitation in the area on an annual basis. Therefore, the abstraction is 316% higher than effective precipitation.

Siltation

Siltation process is mainly one of the major man-made factors that can cause negative impact on the lake ecosystem. In the Lake Haromaya, large volumes of soil have been deposited and hence contributed to the decrease in the storage volume. From the repeated soil profile measurement in the field taken from six pits, the annual average deposition rate was estimated to be 10 cm/year. Hence, the total lake volume occupied by the silt was estimated to be 3.32 Mm³/year. In the last 35 years the total deposition could be 116.2 Mm³. The absence of control measures and poor soil handling practice around the lake has enhanced the entry of soil into the lake that ultimately caused the decrease of lake volume. This indicates that annually the volume of the lake is decreasing by around 1.2%.

Discussion

The complete loss of the Lake Haromaya has generated drinking and irrigation water crises in the region

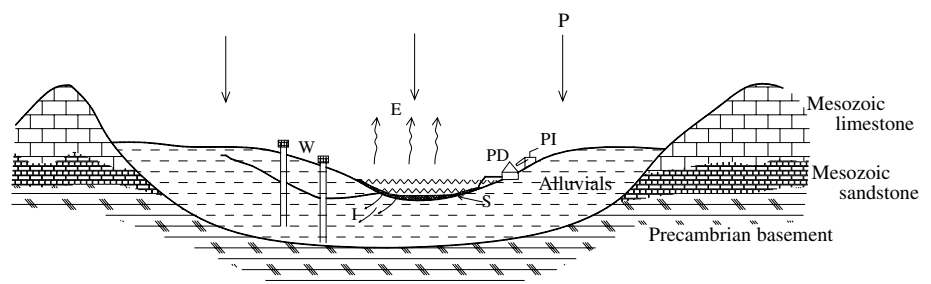
Table 2 Major losses from the Lake Haromaya

Parameters	Annual (Mm ³)	Percentage	For 35 years (Mm ³)
Evaporation	42	86.26	1,470
Drinking water—lake	2.9	5.96	45.5
Drinking water—groundwater	3.6	7.39	54
Irrigation	0.19	0.39	6.65
Total	48.69	100	1,576.15

that has affected the socio-economic condition of the people. Lake water pumping for drinking and industrial supply, evaporation and abstraction are important factors for the drying up of the Lake Haromaya. Additional very important factors that might have contributed for the decrease in the lake volume are excessive groundwater pumping and siltation processes. Deforestation of the catchment for the expansion of agricultural area, improper settlement adjacent to the lake, excavation and land tillage near and adjacent to the lake enhances soil erosion and deposition in the lake reservoir which decreases the lake level. Part of the old lake water pumping station has been immersed in the sediment, which could be an indicative of the impact of siltation. The high evaporation rate of the lake is due to the deforestation that has increased albedo, the increase of evaporative parameters such as temperature and wind speed that are aggravated by environmental degradation and alteration of lake basin such as clearing of vegetation in watershed and urbanization.

According to Furi (2005), there is a continuous borehole drilling operation undertaken in the area by government institutions, which was witnessed during the fieldwork that depleted the available groundwater resources where the groundwater level might have been encroached with the lake water. Hence, to avoid the risk of groundwater depletion, it should be utilized safely and the current trend of overabstraction of groundwater beyond the recharging rate should be limited to within the bearing capacity of the unconfined aquifer. Furthermore, recharge to groundwater should

Fig. 8 Conceptual model for the parameters that constrained loss of the Lake Haromaya (*P* precipitation, *E* evaporation, *PI* pumping for irrigation, *S* siltation, *PD* pumping for drinking, *W* Boreholes, *I* Infiltration from the lake to the wells)



be enhanced through artificial means such as land terracing on hillsides and construction of recharging ditches or ponds.

Both on the plateau and Rift valley, lakes are suffering from overexploitation and environmental changes; however, climatic changes play important role in changing the lake level (Coulomb et al. 2001; Legesse et al. 2003, 2004; Alemayehu et al. 2006). The main impact of climate change in the Haromaya area could be excessive evaporation and minimized precipitation that affects direct recharge to the lakes. The decrease in the lake level due to evaporation could concentrate the salt at the lake bottom. The most dangerous activity is overpumping that could cause a complete loss by leaving behind white calcite precipitate, as it was observed on the dry lake surface. The impact of abstraction of water for irrigation purpose is equally responsible for the decreasing trend of water in the lakes of Rift valley. However, like the lakes considered in this study, most of the lakes in the country are largely affected by improper water utilization. The loss of the Lake Haromaya has critically affected the life of the community. Among many, the following factors have contributed for the scarcity of water resources in the area.

- Limited regional groundwater flow system from adjacent basins
- Exposure of the nonwater-bearing basement rocks that act as a barrier for infiltration
- Extensive deforestation
- Overabstraction of the limited local groundwater reservoir
- Poor land use practice, which is mainly represented by manual ploughing and lack of terracing to control erosion
- Decreasing trend of rainfall
- Long dry period
- Increase in population

The ongoing water shortage caused the depletion of the existing limited water reservoirs, which cause a chronic water shortage in the area. Therefore, at least to minimize future adverse effects on the available groundwater, the available water resources should be conserved and wise use of the resource should be practiced and other alternative sources should be sought. This includes the effective use of water including rainwater. Suggested strategies for the effective use of water resources in the basin are: roof catchment, conservation of overland flow, infiltration galleries or channel flow for possible aquifer recharge and land terracing and afforestation. Effective means

of utilizing rainfall is the promotion and construction of terraces across the hills and steep escarpments which are prone to soil erosion. Terraces can enhance infiltration into groundwater. For successful water management, technical solutions alone could not mitigate the problem, but political and administrative solutions should be integrated. In the study area and in similar regions where water scarcity is a problem, integrated water resources management (IWRM) should be adopted where different uses of water resources are considered together. In Ethiopia IWRM principles are being practiced through participatory decision making for environmental protection and to solve water use conflict. IWRM has not been practiced so far in the Haromaya area, which has caused pressure on single resource. The main actors should be local farmers, industries, higher education centers and town dwellers. Rehabilitation of the lakes is a long process that requires dedication of the local people and policy makers and can be achieved through integrated approach that needs more than two decades. This is estimated on the basis of land closure method to regenerate trees to the required level.

Conclusions

The Lake Haromaya became dry due to a large water demand, misuse of the natural resources, strong evaporation, overpumping, deforestation and siltation. It is obvious that such practices could harm natural ecosystem and hence, restoration could be difficult or basically impossible. Rehabilitation of lake environment through vegetating the lake catchment, planting native grasses and trees near and adjacent to the lake, protection and management of lake watershed such as avoiding land tillage near the lake, illegal settlements and human encroachment adjacent to the lake are some of the envisaged strategic actions to be taken in order to regenerate the lost lakes. This can be achieved through the involvement of all stakeholders, principally the community in lakes basin, through government coordination. Destruction of an ecosystem is a rapid action as compared to rehabilitation, which needs cooperation, patience and finance. Alternative water sources such as interbasin water transfer should be considered by policy makers as an innovative plan and implemented to avoid the water resource crises and the related environmental hazard and to facilitate the regeneration process.

References

- Alemayehu T, Kebede S, Ayenew T (2006) Hydrogeochemical and lake level changes in the Ethiopian Rift. *J Hydrol* 316(1–4):290–300
- Coulomb CV, Legesse D, Gasse F, Travi Y, Tesfaye C (2001) Lake evaporation estimates in tropical Africa. *J Hydrol* 245(1–4):1–18
- Dingman SL (1994) *Physical hydrology*. Printice-Hall Inc., Englewood Cliffs, p 575
- Dunne T, Leopold BL (1978) *Water in environmental planning*. Freeman, San Fransisco, pp 815
- Furi W (2005) *Groundwater productivity and the hydrology of the dry lakes basin in the north central sector of east Hararghe zone*. Unpublished MSc. thesis, Addis Ababa University
- Legesse D, Coulomb CV, Gasse F (2003) Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *J Hydrol* 275(1–2):67–85
- Legesse D, Coulomb CV, Gasse F (2004) Analysis of the hydrological response of a tropical terminal lake, Lake Abiyata (Main Ethiopian Rift Valley) to changes in climate and human activities. *J Hydrol Processes* 18:487–504
- Shaw EM (1988) *Hydrology in practice*, 2nd edn. Chapman and Hall, New York, pp 539
- Sophocleus M (2002) Interactions between groundwater and surface water: the state of the science. *Hydrogeol J* 10:52–67
- Wilson EM (1983) *Engineering hydrology*, 3rd edn. Macmillan Publisher's ltd., Hong Kong, pp 309