Analysing the extent (size and shape) of Lake Basaka expansion (Main Ethiopian Rift Valley) using remote sensing and GIS

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Abstract

This study attempted to estimate the extent of the expansion of the area of Lake Basaka over the past 50 years (1960 to 2010), using LANDSAT images, field observations, local information and topographic maps. The analysis revealed that the lake has exhibited a dramatic expansion over the past five decades. An increase in the lake water level by 7.6 m over this period resulted in flooding about 45.8 km^2 of surrounding areas and an incremental lake volume of about 280 Mm^3. About 70% of the lake expansion was observed in the period between the 1970s and 1990s. This phenomenon coincides with the periods of remarkable land use/cover changes in the region. Furthermore, the beginning of the lake expansion coincided with the introduction of irrigated agriculture in the region, and construction of Koka Dam in the mid-1960s in the upper Awash River Basin. This study suggests that the observed expansion trend, if it continues unabated, could result in certain socio-economic and environmental consequences in the region in particular, and to Ethiopia in general. Groundwater inundation or salty water intrusion, for example, might occur in the area in the near future, thereby affecting the sustainability of regional irrigated agriculture. The lake has the potential to inundate the surrounding region (Matahara Sugar Estate; towns of Fantalle and Matahara) and might connect with the Awash River during the next 10–15 years. This would affect downstream irrigation developments in the Awash Basin and the livelihoods of people that depend on the basin's water resources. The overall findings of this study emphasize the need to adopt mitigation measures before the lake expansion results in irreversible damage to the region or the basin.

Key words

Awash Basin, Basaka Lake, ERDAS Imagine, expansion extent, indices, Landsat image.

INTRODUCTION

The surface area of Lake Basaka, unlike most of the other closed basin Main Ethiopian Rift (MER) Valley Lakes, is expanding at a rapid rate (Tessema 1998; Abebe 2000; Alemayehu *et al.* 2006; Ayenew 2007; Belay 2009; Goerner *et al.* 2009; Olumana *et al.* 2009; Olumana 2010). The total surface area of the lake was about 3 km^2 in 1957 (Abebe 2000; Alemayehu *et al.* 2006), but is estimated to be 43 km^2 in 2008 (Olumana *et al.* 2009). The lake was essentially a small (surface) pond before the establishment of Matahara Sugar Estate (MSE) in the 1960s (Oral communication, May 2008).

The expansion of Lake Basaka is a problem because of its poor water quality. The lake water is saline (EC~6.3 dS m^{-1}), sodic (SAR~300) or alkaline (pH~9.6), therefore being not usable for irrigation and drinking/consumption (Olumana 2010). The drastic expansion of the lake with its poor quality is expected to affect the surface- and groundwater dynamics and soil properties of the region. This is especially serious in regard to the sustainability of MSE and nearby villages (Matahara and Fantalle) and the Awash basin irrigation development in general. The expansion of the lake has already seriously affected the socio-economics of the indigenous (Karayyuu) people (Gebre 2004, 2009; Elias 2008) and might threaten the economic welfare of the society, depending on the water resources of the downstream basin. Figure 1 illustrates some of the effects of the lake

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Accepted for publication 9 February 2012.

Doi: 10.1111/j.1440-1770.2012.00500.x

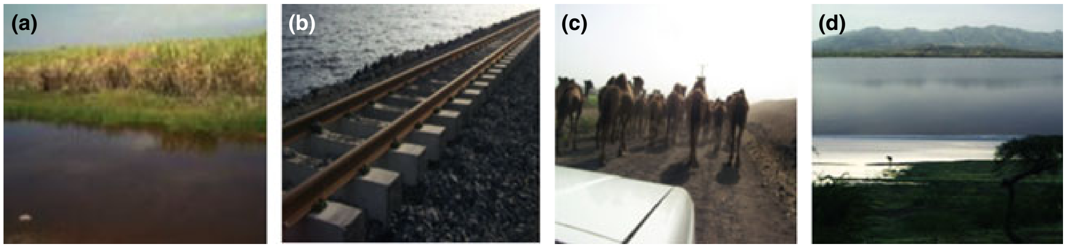

Fig. 1. Effects of the Basaka Lake expansion on: (a) irrigation development (MSE); (b) structures (railway and road); (c) pastoralism (Karrayyu people); and (d) ecosystem and grazing lands.

expansion on the environment, socio-economic situation, productivity, etc.

Identification of the differential vulnerability of the nearby areas to future inundation hazards because of the lake expansion is extremely important, in order that timely actions can be taken by the sugar estates, and other responsible institutions and decision-makers. Thus, quantification of the spatio-temporal expansion of the lake is extremely important to optimize and balance the interests of economical and ecological land uses. Different studies (local and international) were conducted on the expansion of Lake Basaka. Nevertheless, no profound scientific investigation has yet been made regarding the geometry (size and shape) of the lake from its formation (1950s) to the present time (2010). The lake is now getting more attention because of its dramatic change in size and shape, and the accompanying effects on the region's economy and environment.

This study was initiated to assess the expansion extent (size, shape) of the lake from time series of LANDSAT images and ancillary data (topomaps, field observations, local information). The specific objectives of this study were to: (i) estimate the spatio-temporal expansion extent of Lake Basaka; and (ii) predict possible future expansion of the lake, assuming that past trends will continue. The study results provide valuable information for national and international stakeholders (beneficiaries, researchers, irrigation managers, decision-makers, etc.).

METHODOLOGY

Study area

Lake Basaka is located in the Middle Awash Basin, Fantalle Woreda of Oromiya Region (8.5°1.5′N, 39°51.5′E, 950 m a.s.l.), about 200 km south-east of the Ethiopia's capital city, Addis Ababa, along the Addis–Dire Dawa–Djibouti or Addis–Harar–Jigjjiga highway road (Fig. 2). Matahara is situated on a nearly level plain stretching along the course of Awash River and surrounded by mountain chains with variable elevations in the south, south-east, south-west and north-west directions (Fig. 2),

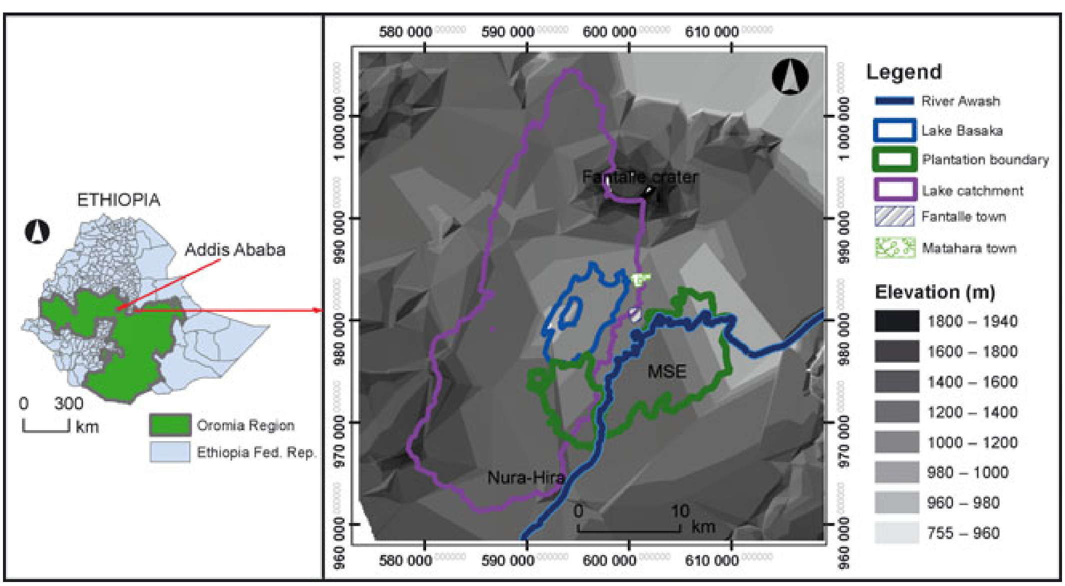

Fig. 2. The study area: location (left) and topographic view (TIN) extracted from digital elevation model (right).

being extensions of the Chercher (Hararghe) Highlands (Abejehu 1993). The area is delineated by Mount Fentalle (volcanic crater) and undulating plateaus in the north and north-east directions, respectively. Awash National Park also is situated in the flat plain of Matahara area (east of Lake Basaka). The area can be viewed physiographically as a topographic depression, where run-off and alluvial sediments overflow from the surrounding catchment areas (Mohr 1971; cit. Olumana 2010).

Being located in the upper part of MER, in the central rift valley region, Matahara is vulnerable to occurrences of tectonic and volcanic activities. As the result, the area is characterized by features of past and recent volcanic events, examples being vast lava extrusions at the foot slope of Fentalle Mountain (volcanic crater), dots of extensive scoriaceous hills in the locality (Mohr 1971), lava flows produced by the eruption in the northern part of the lake in the 1980s (Halcrow 1978), and the presence of a number of hot springs flowing into the lake (Olumana 2010). The area is bordered by older volcanoes and a rift margin in the east, by young Quaternary complexes of Fantalle Crater in the north and by Kone on the west side. The formation of common rock types in the area is the product of the recent volcano complexes, along with fissural basalt, rhyolite, alluvial and lacustrine sediments (Mohr 1971; Belay 2009).

The area is characterized by a bimodal and erratic rainfall distribution pattern, with the major rainy season being between July and September. Occasional minor rains can occur between March and May. Analysis of the area's long-year-average (LYA) weather data (1966–2010) indicates that the mean annual rainfall and temperature were about 543.7 mm and 26.5 °C, respectively. The LYA pan evaporation for the area was 6.92 mm day^{-1}, with the reference ET being about 4.65 mm day^{-1}. The general climate of the area is semi-arid.

Remote sensing image and ancillary data

Four LANDSAT images covering the study area and its surroundings were selected and acquired from the FREE Global Orthorectified Landsat Data via FTP (http://glovis.usgs.gov). All the images are cloud free, except for the year 2010 (Table 1). Furthermore, ancillary data (e.g. digital elevation model, DEM), digital plantation (base) map and topographic maps were obtained from different sources. The digital plantation base map (CAD format), illustrating all the roads, elevations, irrigation and drainage networks, field plots and River Awash, was obtained from the MSE (Civil Engineering Department, Haramaya University). The 1975 Matahara toposheet (scale 1:50 000) was purchased from the Ethiopian Mapping Authority, and detailed topographics for some parts of the lake catchment were obtained from MSE. The DEM (90 m resolution) was downloaded from the NASA Shuttle Radar Topography Mission (SRTM), via the National Map Seamless Data Distribution System site (http://www2.jpl.nasa.gov/srtm/).

Table 1. Details of satellite data used in the study

Sensor	Path/Row	Cloud Cover (%)	Resolution (pixel size)	Acquisition Time
Landsat–MSS	180/54	0	57 * 57 m	Jan, 1973
Landsat–TM	168/54	0	30 * 30 m	Jan, 1986
Landsat–ETM^+	168/54	0	28.5 * 28.5 m	Dec, 2000
Landsat–ETM^+	186/54	0	28.5 * 28.5 m	Feb, 2008
Landsat–ETM^+	186/54	9	28.5 * 28.5 m	Oct, 2010

Supplemental information on lake conditions, land use/cover (LUC) conditions, soil conditions and topographic features was obtained from field observation. Furthermore, information on the present and past conditions of the lake was obtained from interviews with the elders of the local indigenous peoples. The DEM resolution was increased to 15 m by the resembling technique available in GIS (ArcInfo v 9.2: ESRI (2006), ArcGIS 9.2. Redlands, California, USA) and subsequently processed for the study area and the surrounding features.

Satellite image processing

The LANDSAT images were registered with the topographic map of the project area by matching some identifiable features (e.g. road crossings, railways, rivers, irrigation canals, bridges, etc.) on both the base map and the satellite images. The images were then imported and processed with ERDAS Imagine 9.1 (ERDAS 2006) and ILWIS 3.4 Open (http://www.itc.nl/ilwis/) software. The image geometric corrections, layer stacking, sub-settings and image enhancements were carried out.

Different enhancement techniques utilizing indices were checked to delineate the lake's surface area. The spectral enhancement (indices) was adopted to delineate the lake area based on the LANDSAT Sensor type. The applied indices included Time Composite Normalized Difference Vegetation Index (TNDVI), Normalized Difference Salinity Index (NDSI) and Normalized Difference Water Index (NDWI). The NDWI and NDSI algorithms given by McFeeters (1996) and adopted by Gao (1996) were used in this study, being applied in ILWIS and the TNDVI, using the algorithms available in ERDAS. The adopted indices and algorithms are provided in Table 2.

Table 2. Spectral indices, algorithms and references adopted

Indices	Formulation/Algorithmes	Reference
NDVI	$\frac{\text{NIR} - \text{Re}d}{\text{NIR} + \text{Re}d}$	Rouse *et al.* (1974) Albert *et al.* (2000)
TNDVI	$\sqrt{\frac{\text{NIR} - \text{Re}d}{\text{NIR} + \text{Re}d} + 0.59}$	Albert *et al.* (2000)
NDSI	$\frac{\text{Re}d - \text{NIR}}{\text{Re}d + \text{NIR}}$	McFeeters (1996)
NDWI	$\frac{\text{Green} - \text{NIR}}{\text{Green} + \text{NIR}}$	McFeeters (1996)

NDSI, Normalized Difference Salinity Index; NDWI, Normalized Difference Water Index; TNDVI, Time Composite Normalized Difference Vegetation Index.

RESULTS AND DISCUSSION

Spatio-temporal dynamics of lake geometry

The lake geometry (sizes and shapes) for the different years is illustrated in Figure 3, with the individual shapes being superimposed in Figure 4a. The lake surface area and depth, and the adopted methods (indices) for the different years of interest, are tabulated in Table 3. The best-performing indices were applied for each LANDSAT image. NDSI was adopted for the 1973 and 2008 images, while NDWI and TNDVI were adopted for the 1986 and 2000 images, respectively. The incremental area of the lake in the early period (pre-1973), and in recent years (2000–2007), was relatively gentle. In contrast, the incremental areas were found to be very steep in the period between 1973 and 2000 and in the recent time (post-2007). This observation was indicative of the incremental area being exponential rather than linear in nature (Figure 5).

Expansion extent and patterns

The estimated incremental areas, depths and volumes for the considered periods are summarized in Table 4. The extent of lake expansion for the different periods is explained below in detail. LUC information (Table 5) during this period and topography (Figs 4b,6) are important factors for explaining the extent of expansion during different periods.

Period 1: 1960–1973

The annual incremental area and volume of the lake, compared to the other periods, were low. The exception was period 4, with lake expansion commencing during this period, mostly towards the south and the south-west directions, with minor expansion towards the west. Based on local information, there was a cotton farm in the Abadir area during this period, with the catchment being covered by thick forests. The MSE was established during this period (1965), which also led to the establishment of the Abadir sugarcane farm (1969). Moreover, the Nura-Hira irrigation scheme also was established almost at the end of this period.

Period 2: 1973–1986

The substantial expansion of all aspects of the lake was observed during this period, comprising about 53% and

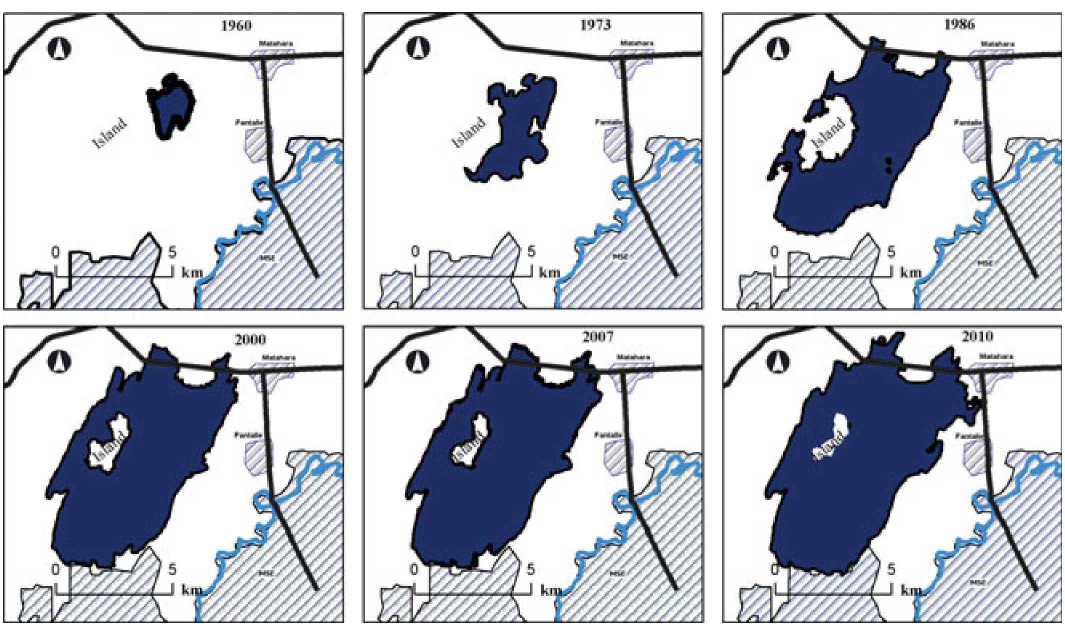

Fig. 3. Spatio-temporal dynamics of Basaka Lake (1960–2010).

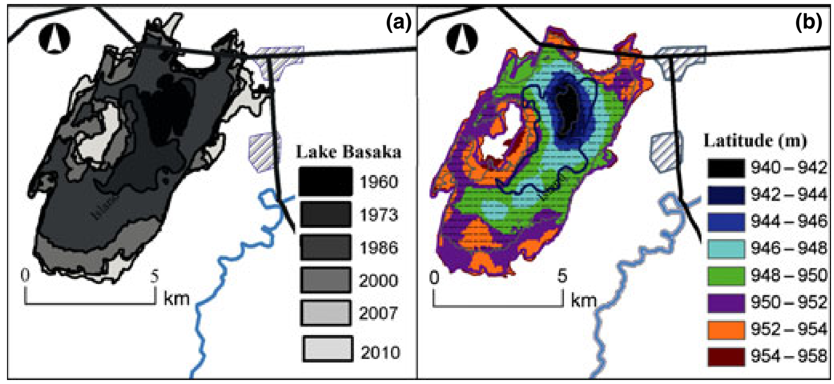

Fig. 4. (a) Expansion extents of Basaka Lake in the periods 1960–2008; (b) elevation of Basaka Lake bottom as extracted from digital elevation model superimposed by Lake level at different years.

Table 3. Estimated surface area and depth of the Lake Basaka and adopted indices

Year	Area (km^2)	Cumulative Incremental Area (km^2)	Average D epth (m)	Method Adopted
1960	2.7	0	0.5	*
1973	8.4	5.8	1.8	NDSI
1975	10.2	7.5	2.0	†
1986	29.5	26.8	4.9	NDWI
2000	41.5	38.8	6.3	TNDVI
2007	43.4	40.7	7.1	NDSI
2010	48.5	45.8	8.4	NDSI

NDSI, Normalized Difference Salinity Index; NDWI, Normalized Difference Water Index; TNDVI, Time Composite Normalized Difference Vegetation Index.
*From local information and topographic map of the area.
†Processed from 1975 toposheet.

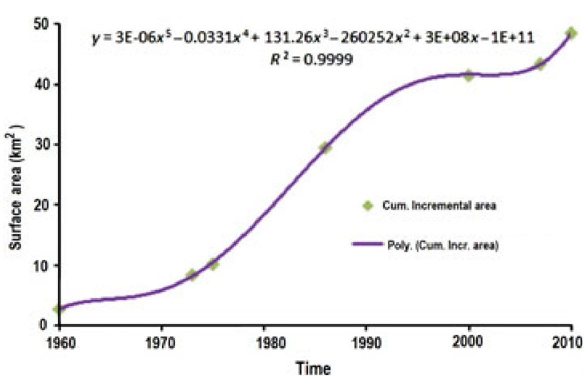

Fig. 5. Surface area of Basaka Lake in different periods.

46% lake area and volume expansions, respectively, over 38 years (1973–2010). During this period, although the lake expansion occurred in almost all directions, most of the surface area expansion was towards the south, south-west, north and north-east directions.

The highly significant incremental area and volume noted in this period might result from several factors, including (i) the introduction of irrigated agriculture (MSE and Nura-Hira), which discharged their excess irrigation water directly into the lake during this period (especially between 1976 and 1978); (ii) changes in the groundwater dynamics, particularly a rise in the water table, of the surrounding area as a result of the excess recharge from irrigation/rainfall; (iii) changes in the hydrogeology of the area as a result of tectonic activities; (iv) massive deforestation (Table 5) following the migration of people to the area to seek employment opportunities at the sugar estate, which resulted in increased run-off and sedimentation; and/or (v) a combination of all these possible factors. According to Olumana (2010), this period was characterized by severe LUC changes in the region (Table 5). Forested lands were changed to farmlands with the introduction of irrigated agriculture (furrows), consuming significant quantities of water. Furthermore, the significant surface area expansion may be a function of the topographic characteristics.

Period 3: 1986–2000

The direction of expansion that changed the shape of the lake was mostly restricted to the south (Abadir) and west directions, with the current shape of the lake being formed during this period. Although the extent of lake expansion also continued at a significant rate during this period, it was at a lesser rate than for period 2. About 26% of the total surface area expansion (periods 1–5) occurred during this period.

This period also coincides with significant LUC changes (Table 5) in the lake catchment (Olumana 2010). Forested lands were changed to farmlands, with the introduction of irrigated agriculture, and attendant water consumption. It can be suggested that the possible observed changes (e.g. deforestation, rise in groundwater table, increased groundwater recharge, etc.) that

Table 4. Summary of estimated incremental area, depth and volume for considered periods

		Incremental depth		Incremental area		Incremental volume	
Period	Years	m	m $year^{-1}$	km^2	km^2 $year^{-1}$	Mm^3	Mm^3 $year^{-1}$
1	1960–1973	1.20	0.10	5.8 (211*)	0.45	14.0	1.10
2	1973–1986	3.10	0.26	21.0 (251)	1.62	115.1	8.85
3	1986–2000	1.40	0.09	12.1 (41)	0.86	75.3	5.79
4	2000–2007	0.80	0.11	1.9 (5)	0.24	20.8	2.60
5	2007–2010	1.10	0.28	5.1 (12)	1.70	40.0	10.25
Total	1960–2010	7.60		45.8 (1696)		280.2	

*Values in parenthesis are percentage increment surface area; km, kilometer; Mm, million meter.

Table 5. Summary of areal change for different land use/cover units in Lake Basaka catchment (Source: Olumana 2010)

Period	Year	Water	Farmland	Forestland	Shrubland	Grassland	Open B. Woodland	Swamp/Lava
II. Total Change Rate (%)								
1	1973–1986	290.6	324.5	−49.9	−6.0	−31.3	156.4	109.9
2	1986–2000	41.6	−45.5	−64.8	4.9	−21.0	56.5	100.5
3	2000–2010	10.0	−6.3	−18.9	−5.3	−7.1	5.6	10.3
Total	1973–2010	342.2	272.7	−133.6	−6.4	−59.4	218.5	220.7

occurred in the area during the preceding period 2 also continued in period 3.

Period 4: 2000–2007

The extent of lake expansion was rather very slow during this period. The annual incremental area and depth were lower than during all the other periods. Moreover, excepting period 1, the annual incremental volume was less than during the other periods. The expansion direction was mostly restricted towards the Abadir Farm in the south, the town of Fantalle in the east and the town of Matahara in the north-east directions (Fig. 4a). Restriction of the expansion direction could be due to the area's topographic barrier. The relatively reduced extent of lake expansion in this period than in the other periods also could be attributed to the proportional draining of the lake water with Awash River, which was initiated by Ministry of Water Resources (MoWR) almost at the beginning of this period (1999) in recognition of the potential damaging effects of the lake on the Awash River Basin. The water mixing programme was actually initiated in 2004, although the diversion structure (pump) was totally submerged in the lake because of the extremely high rainfall that occurred in the area in summer 2008 (Oral information, May 2009). Another reason could be the reduced trends in LUC changes (Table 5), compared to the preceding two periods, and the relatively low rainfall.

Period 5: 2007–2010

The rate of lake expansion for all aspects was extremely high, compared to all the preceding periods (1–4). In addition to the possible reasons identified above regarding periods 2 and 3, this observation may be attributed at least in part to the establishment of the recent (2008) Fantalle irrigation project, which discharges some of the excess irrigation water directly to Lake Basaka. Another possible reason may be the occurrence of the extremely highest rainfall in the recorded history (1966–2010) of the area during the year 2008. The lake response to this extremely high rainfall was rapid and significant, resulting in inundation of significant cane fields on the Abadir-E side of the lake. Consequently, it was observed during fieldwork during May 2009 and 2010 that the sugar estate lost significant land resources, being forced to construct another long dyke (earth embankment) in the area to restrict further lake expansion. Based on eyewitness accounts during September 2008, personal observations of this author during 2007–2009 fieldwork and field visits during June 2010 and February 2011, an unusual depth increment of the lake occurred on the Abadir-E side, exerting pressures on the production and productivity of the area and infrastructures (major highway and railway lines). The lake inundated the dyke constructed by the sugar estate in the Abadir-E side in 2010, forcing the abandonment of more than 50 ha of productive fields on the adjacent site. A significant depth increment also was noted on the north side, where the lake inundated the railway and highway lines, forcing the government to construct a new railway line across the lake at certain elevations above the lake level. The lake expansion also has forced changes to the main road and railway lines three times to date. Based on the current lake expansion rate, the potential to inundate the new highway and railway lines in the near future continues to exist. The government is planning to change the main highway line (currently passing through the lake) beneath Mount Fantalle, which is a volcanic crater in a geologically unstable area.

Lake expansion trend – simple regime analysis

The recent expansion of the lake towards the south, east and north-east (Fig. 4a) was consistent with the topography of the area (Fig. 6), and it appears that the lake is in the process of trying to expand further in the east and north-east directions. The extent of expansion (both depth and direction) was estimated on the basis of the average elevation of the lake in 1975 (~944 m) and 2010 (~952.4 m). The lake has increased by at least a depth of 7.6 m (~0.152 m $year^{-1}$) over the past 50 years (1960–2010), with the average and maximum depth estimated to be 7.5 ± 0.5 and 13 ± 0.5 m (953–939.5 m), respectively. The depth ratio (i.e. ratio of mean depth to maximum depth) was estimated to be about 0.585. This ratio has implications for production and sediment accretion rates, thereby helping explain the limnology of different lakes (Carpenter 1983). The result agreed well with previous findings. Ayenew (2004), for example, reported that the average and maximum depth for the lake was 6 and 11 m, respectively, and Klemperer and Cash (2007) estimated the average annual lake level rise to be 0.15 m.

Ayenew (1998) suggested that the lake has a potential to pass the water divide line, joining the Awash River by the year 2008. This did not actually happen, however, and seems unrealistic as far as the past expansion trend is concerned. As noted earlier, future lake expansion can be predicted by considering the lake's expansion trend over the past 50 years (1960–2010) (Figs 3,4) and the topography of the area (Fig. 6). Assuming the prevalence of past conditions into the future, it can be expected that the lake would inundate parts of the town of Matahara over the upcoming 10–15 years. In the meantime, it may start flowing towards the east, probably passing through the village of Fantalle, towards the plantation through either the North or Awash section (see white arrows in Fig. 6). The lake has currently (2010) started flowing towards the East through the indicated arrow between the town of Matahara and the village of Fantalle (see year 2010 in Fig. 3), thereby inundating residents, Gudina Tumsa high school students and other offices in the area. Under extreme circumstances, the lake has the potential to join Awash River in the near future (i.e. by 2015). Accordingly, the lake may bring total devastation of MSE and inundation of nearby villages, thereby challenging the socio-economics of the area's population. It could also have negative impacts on irrigation developments in the middle and lower Awash Valleys.

Like most other terminal lakes, interactions between Lake Basaka and its surrounding groundwater (GW) systems are expected. Thus, groundwater inundations also are most likely to occur in some parts of plantation

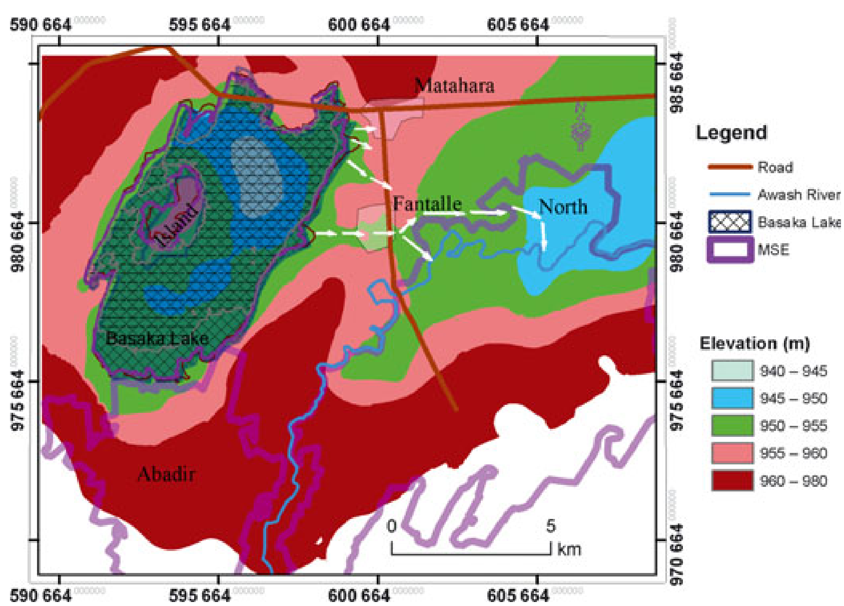

Fig. 6. Elevation map of the study area showing the future trends of lake expansion.

sections (Abadir-E, North, Riverlands, East and Awash) over the next 10–15 years. The groundwater table under the towns of Matahara and Fantalle is very shallow (< 2 m), further illustrating the rising trends of surrounding groundwater levels following the lake's phreatic levels. These towns might be inundated by rising groundwater prior to the lake level increase. Furthermore, another lake is most likely to emerge through the North and East sections of MSE, where the elevation is very low and the groundwater level extremely shallow (Olumana 2010).

Overall Synthesis

The incremental size of Basaka Lake was very high during period 5, followed in order by periods 2, 3, 4 and 1, respectively. The extent of the lake's expansion was slow and gradual during period 1, becoming fast in periods 2 and 3. About two-third of the total incremental areas and volume of the lake during 1960–2007 occurred during periods 2 and 3. The results revealed that a small rise in lake level resulted in the inundation of a greater surface area. This was evident from the additional 21 and 12 km^2 surface area of the lake observed in periods 2 and 3, because of the respective rise of the lake by 3.1 m and 1.4 m.

The root cause of the lake's expansion had not yet been fully identified. Different scholars have suggested differing views on the increment of the lake expansion, some being contradictory. The lake expansion is thought to be due to one or more of the following factors:

1. Introduction of the Abadir and Nura-Hira irrigation schemes, which are discharging their excess irrigation water directly into the lake (Halcrow 1978; Abebe 2000; Ayenew 2004; Ayenew *et al.* 2008);
2. Water transmission loss from Awash River because of its increased water level after construction of Koka Dam, and from direct recharges. Ayenew *et al.* (2008) pointed out that the water losses and recharges are facilitated by the presence of active terminal faults;
3. Decreased discharges owing to increased groundwater (GW) levels resulting from excessive downstream irrigation (Zemedagegnehu *et al.* 2009, cit. Klemperer & Cash 2007);
4. Increased recharge from submerged hot springs (Zemedagegnew and Egizabher 2004; Klemperer & Cash 2007) and/or from nearby irrigation fields (Ayenew *et al.* 2008). Klemperer and Cash (2007), based on 1973 chemical analysis data from the United Nations (Gizaw 1996), which suggested the possible cause, could be hot springs;
5. Increment in net groundwater flux into the lake (MoWR 1998; Tessema 1998; Belay 2009; Olumana 2010). The water balance analysis made by Belay (2009) and Olumana (2010) indicated that groundwater flux is currently contributing > 54% of the total inflow to the lake;
6. Lake neotectonism (Ayenew 1998, 2004; Tessema 1998; Ayenew & Becht 2008; Ayenew *et al.* 2008; Gebre 2009; Olumana *et al.* 2009; Olumana 2010). Ayenew and Becht (2008) reported strong signs of changes in the hydrological settings of the rift system by neotectonism (earthquakes and volcanic eruptions). Olumana *et al.* (2009) and Olumana (2010) also suggested the possibility of rift system influence on the lake because of its location in active parts of the MER. This idea has emerged on the basis of the changes happening in the Great African Rift Valley in general, and the MER in particular.

In addition to the above possibilities, some are also blaming the Fantalle irrigation project, which was recently established (2008) and is currently under development (personal communication, 2010). The rationale is that: (i) significant quantities of water (18 $m^3\ s^{-1}$) are diverted from the Awash River and are recharging the lake catchment at its upstream side; (ii) some of the excess irrigation water is directly discharged to Lake Basaka; and (iii) the natural drainage streams/patterns are disturbed. These arguments have not been justified or verified scientifically, however, thereby requiring due attention.

This study revealed that most (~70%) of the lake expansion was observed in the period between the 1970s and 1990s, which coincides with the periods of remarkable regional LUC changes (see Table 5). Furthermore, the beginning of the lake expansion coincided with the introduction of irrigated agriculture in the region, and construction of Koka Dam in the mid-1960s on the upper Awash River. It seems reasonable, therefore, to suggest that irrigation schemes have contributed directly or indirectly to the lake expansion. The direct effects may be the discharge of drainage waters into the lake at that time, and changes in the natural drainage system patterns in the area. The direct discharge of excess irrigation water into the lake by MSE was abandoned in the beginning of 1980s on the basis of recommendations by Halcrow in 1978. The indirect effect may be the LUC change occurring in the lake catchment because of demographic pressures and resulting changes in its hydrologic regimes (run-off, erosion, etc.).

Nevertheless, it is difficult to conclude that the irrigation/rainfall excess from the nearby farms was the only cause for the expansion of Basaka Lake. The comprehensive water balance analysis of Olumana (2010) indicated that the groundwater flux is mostly responsible for the existence and expansion of the lake, currently contributing about 56% of the total inflow. His study also revealed that the contribution from surface run-off and sedimentation is appreciable. Water run-off has exhibited a noteworthy increase since the 1970s. For unknown reasons, the groundwater flux in particular has exhibited a significant increment since the mid-1990s. Because the area is situated in the Ethiopian Rift Valley system, which contains active tectonic activities, this researcher believes that other natural factors (tectonism, faults, etc.) might have affected the lake expansion.

CONCLUSIONS AND RECOMMENDATIONS

The extent of Lake Basaka expansion over the past five decades was documented with use of LANDSAT images, topomaps, field observations and local information. Different satellite image enhancement techniques were utilized, namely NDSI, TNDVI and NDWI.

The results clearly indicated that Basaka Lake exhibited a remarkable and drastic expansion over the past five decades. Surprisingly, a small rise in lake level has resulted in the inundation of a greater surface area. The lake water level rise by 7.6 m over the past half-century (1960–2010) generally resulted in flooding of about 45.8 km^2 of surrounding areas and, an incremental lake volume of about 280 Mm^3. This was about a 15-fold incremental area increase since 1960s. These observations indicated the severity of the flooding problem in the area as a function of the rising lake level because of the flat topography of the area surrounding the lake.

If no management interventions are undertaken, the lake also will continue expanding in the future, mostly towards the east and north-east directions because of the area's topographic features. Past trends indicated that the lake has the potential to inundate the surrounding region (parts of MSE, and the towns of Fantalle and Matahara) and is anticipated to join the Awash River over the next 10–15 years. Moreover, groundwater inundation or salty water intrusions may occur in the area in near future, resulting in deleterious impacts on the environment and socio-economic characteristics of the region in particular, and the Awash Basin in general. Consequently, it influences all the downstream irrigation developments in the Awash Basin, affecting the livelihoods of people depending on the basin's water resources. The lake expansion, for example, has already begun to affect MSE in terms of waterlogging and salinization and/or sodification because of its intrusion towards the plantation.

The benefits obtained from the lake are very negligible or nil, compared to the damaging effects. Its drastic expansion is doubtless a great developmental challenge in the region. Thus, assessing the potential damage the lake causes to the environment and to the socio-economic characteristics of the basin, and understanding the measures needed to minimize this damage are extremely important to solve the practical problems and prevent the coming disaster. Managing the lake and its catchment is extremely important, not only to facilitate the sustainability of the nearby irrigation schemes, but also for pastoral livelihoods, towns and irrigation development in the Middle and Lower Awash Basin. Thus, all Lake Basin stakeholders, including beneficiaries of the basin, concerned institutions, decision-makers and scientists should seriously consider this situation and adopt mitigation measures before the lake expansion results in irreversible damage. Recognizing the damaging effects of the lake, the government has now (2011) established a committee of highly qualified and experienced professionals to study various means of reducing the lake expansion threats to the region. The effectiveness of any measures to be adopted obviously requires identification of the root causes for the lake expansion.

Notwithstanding the above observations, the exact cause of the expansion of Basaka Lake has not yet been fully identified. As previously noted, different views are suggested by different researchers on the possible cause(s) for the lake increment, including nearby irrigation schemes (MSE, Fantalle & Nura-Hira), submerged hot springs, groundwater inflows, surface run-off, siltation, Awash River flow conditions (Koka Reservoir) and tectonic activities. None of the previous studies considered all possible factors for lake expansion in a combined manner and produced convincing ideas. This situation of uncertainty is hindering the development and implementation of actions to minimize, if not prevent, the expansion of the lake and its possible threats to the region. Although Olumana (2010) undertook a comprehensive water balance analysis at different hydrologic periods, his study results do not fully explain all the factors responsible for the lake expansion.

This author shares the idea that most of the above-stated reasons have contributed directly or indirectly to the lake expansion. Thus, careful and detailed investigation considering all the parameters affecting the lake's expansion is needed to determine the potential/real causes. Moreover, this author recommends that more emphasis be given to the area's groundwater flow conditions and patterns. Consistent with this observation, delineating the sub-surface (groundwater) catchment for the lake, and mapping the groundwater system depths and flow patterns, is extremely important to identify the potential sources of the groundwater flux. This requires installation of piezometers and/or digging observation wells at representative sites.

ACKNOWLEDGEMENTS

The author acknowledges OeAD (Austrian Academic Exchange) for the scholarship, and the Ethiopian Sugar Development Agent (currently called Ethiopian Sugar Corporation), specifically Research Directorates, for their support during data collection. He is also thankful to all Matahara Breeding Station and Wonji Laboratory workers, and MSE supervisors for their valuable assistance during data collection.

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