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INTEGRATED QUALITATIVE ASSESSMENT OF WETLAND HYDROLOGICAL AND LAND COVER CHANGES IN A DATA SCARCE DRY ETHIOPIAN HIGHLAND WATERSHED

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ABSTRACT

Wetlands are important sources of water for humans and livestock in the dry drought-prone northern Ethiopian highlands. Hydrological changes in these wetlands affect local populations and are indicators of change in the upstream catchments. In this paper, we present a case study of hydrological and land cover changes in Hara Swamp located southeast of Kobo in Amhara State, Ethiopia. An integrated approach used remote sensing images, limited hydrological measurements, climatic data, and a survey of residents to gain complementary insights into what changes have occurred, when and why they occurred, and the local perceptions of these changes. Aerial photos and satellite images from 1964, 1973, 1986, 2000, and 2001 indicated limited flooding and dense woody vegetation cover in the wetland 40 years ago and a trend towards the current condition of no living trees/bushes, extensive flooding, and heavy sedimentation. Rainfall records revealed no significant trends which could sufficiently explain the observed changes in the wetland. A simple water budget analysis based on hydrological measurements indicated higher wetland flood levels were a result of increasing runoff and sediment inflow from the surrounding watershed over time. Reasons for increasing amounts of runoff were higher population pressure on the land and creation of more impermeable surfaces including houses and road construction in the watershed. Local residents' perceptions of the wetland changes, which were collected first, validated the sparse biophysical data and provided supplementary details. An integrated watershed management strategy is required to reverse the recent trends and protect the wetland resources.

KEY WORDS: runoff; land cover; perception; wetland hydrology; remote sensing; rainfall; flood; Ethiopia

INTRODUCTION

Wetlands are important microenvironments within the landscape providing many ecological and socio-economic benefits in the Ethiopian highlands where water resources are unevenly distributed. Among the benefits from wetlands are water storage, sediment control, groundwater recharge, stream flow moderation, water filtration and purification, plant and fish products, biodiversity, and wildlife habitat (Wood, 2001; Dixon and Wood, 2003; Wondefrash, 2003). Ethiopia's wetlands make up an estimated 11 250 km^2, which is over 1% of the country's surface area, and comprise an estimated 3·7% of the surface area of Amhara State where the current study was conducted (Kindie, 2001). Ethiopia's wetlands are threatened by increasing human population pressure, agricultural encroachment, intensive livestock grazing, deforestation, and construction (Edessa, 1993; Zeleke and Hurni, 2001; Dixon, 2002; Abunie, 2003; Desta, 2003). Sustainable wetland management must consider linkages between wetlands, the hydrology of the catchment, and local human needs and perceptions (Abbot and Hailu, 2001;

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McCornick *et al*., 2003; Dixon, 2005). An integrated approach is appropriate to gather the information necessary for better management (Haack, 1996; Vogt *et al*., 2006).

In this paper, we present a case study examining recent hydrological and land cover changes in a small wetland in eastern Amhara Statein Ethiopia. The rationale for the study is to demonstrate a simple integrated approach that uses remote sensing images, historic rainfall records, limited hydrological measurements, and local residents' perceptions to better understand land resources trends and their causes in a watershed that has limited recorded information. The results provide illustrations of issues which planners and local communities can use for better and more informed watershed development.

MATERIALS AND METHODS

Site Description

Hara Swamp is a shallow seasonal lacustrine wetland situated in a subhumid drought-prone mountainous landscape. It is located 16 km east of Weldiya town in North Wello zone, Amhara State, Ethiopia (Figure 1). The wetland is within the town of Hara's watershed (11·47–11·54 N and 39·43–39·48 E; 1460–1730 m.a.s.l.). The area has a dry tropical climate (20–29°C) with a bimodal rainfall pattern. Mean annual rainfall is 830 mm with a seasonal distribution of about 210 mm during the belg season (March–May), 490 mm during the kremt season (July–September), and 130 mm during the periods between rainy seasons.

Hara watershed is located in the marginal graben of the northeast Ethiopian plateau escarpment in the Afar depression. The geology of the area is composed of varieties of trap series rocks from weathered basalt, graben fill quaternary sediments, and valley-floor later granite intrusions of probably tertiary age (Gizaw *et al*., 1999). Major soil types in the catchment are Regosols and Leptosols on the hillsides, Luvisols and Vertisols in the cultivated low areas, and Fluvisols in flat parts that receive alluvial sediments.

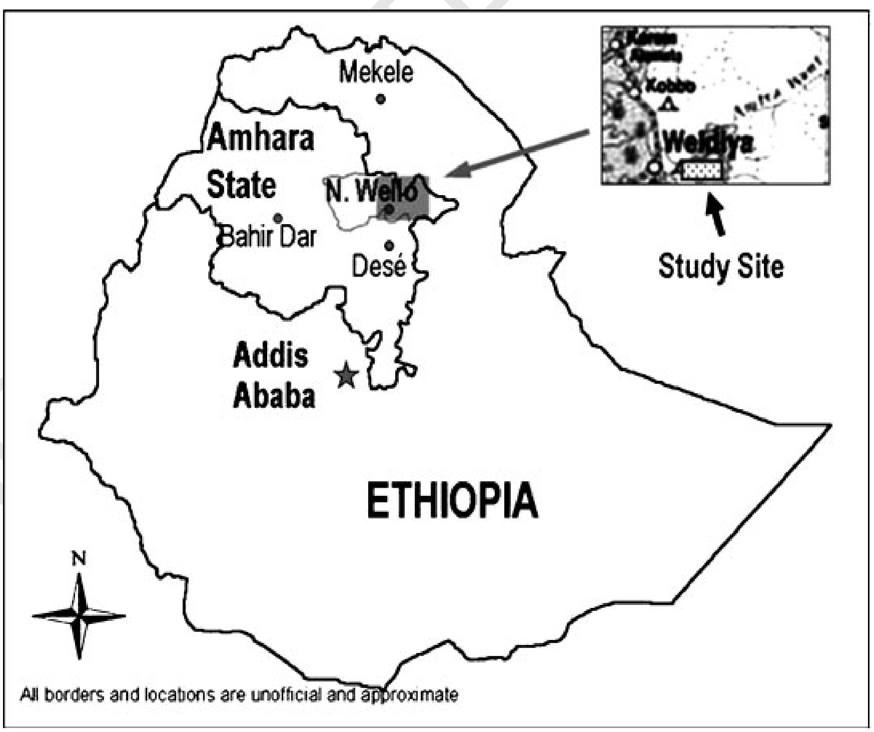

Figure 1. Location map of Hara watershed east of Weldiya, Ethiopia.

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Table I. Characteristics of Hara Swamp during 2004

Morphometric characteristics		Physiochemical characteristics	
Maximum depth (cm)	64	Daily temperature (°C)	18–36
Maximum flooded area (km^2)	2·1	Electrical conductivity (μS/cm)	254
Catchment area (km^2)	47·9		
Altitude (m.a.s.l.)	1462	pH	8·1
Latitude (°N)	11°50·6–11°51·6	Major water use	Livestock consumption
Longitude (°E)	39°45·4–39°46·7		

Hara Swamp is situated at the lowest point in Hara watershed (47·9 km^2) and has no surface water outlets. Table I presents some characteristics. Given the relatively flat and shallow bathymetry of the wetland, seasonal flooded area varies greatly from dry conditions to over 210 ha of flood. The chemical properties of the wetland (Table I) are similar to those measured in Lake Tana in central Amhara State (Kebede *et al*., 2006).

Hara watershed has a population of approximately 7500 people whose livelihoods depend mainly on mixed crop-livestock agriculture. Major crops are sorghum, teff, and chickpea and the most common livestock are cattle, donkeys, goats, and camel. The watershed is situated in a chronically food insecure zone and a majority of the population depends on external food assistance.

Survey Data Collection

A survey of 61 Hara watershed residents was conducted during September–October 2004. The primary objective of the survey was to understand the local population's perceptions of Hara Swamp and its changing conditions. Adult individuals over 30 years of age were selected at random from households in 18 villages surrounding Hara Swamp. Responses were recorded during formal interviews with a structured questionnaire composed of mostly open-ended questions. All formal interviews were conducted at or near the respondents' homes in the local language, Amharic, by Abdu Hussen, a native of Hara town who had a high school diploma-level of education. The interviewer was trained during pre-testing of the questionnaire. Group discussions and site visits were used to gather additional information and to explain findings of the structured survey.

Table II presents the survey respondents reported characteristics of themselves and their households. The respondents had lived on average 51 years in the Hara watershed. Eighty-three per cent were farmers and 97% owned livestock which indicate the respondents' intimate relationship with the land. The mean household size, land holdings, and livestock ownership are similar to those found in another study of the zone (Chapman and Desta, 1999).

Meteorological and Hydrological Measurements

Rainfall, evaporation, and ambient temperature were monitored in the Hara watershed during 2003–2004. Three recording rain gauges measured 15-min rainfall on the western and eastern sides of Hara Swamp. Two temperature

Table II. Characteristics of the survey respondents and their households

Respondent characteristics		Household characteristics	
No. of respondents	61	No. of households	61
Age[a]	52 ± 7	Household size[a,b]	5·4 ± 1·6
Gender	98% male	Cultivated area (ha)[a]	1·4 ± 0·6
Education	17% literate	Oxen owned[a]	1·8 ± 0·8
Occupation	83% farmers	Large livestock[a,c]	3·8 ± 1·9
Years living in Hara[a]	51 ± 7	Medium livestock[a,d]	1·0 ± 1·6

[a]Mean ± standard deviation.
[b]Number of people living in the home at time of interview.
[c]Cattle, donkeys, and camels.
[d]Goats and few sheep.

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loggers recorded hourly ambient temperature. Daily evaporation was measured manually with a US Class A evaporation pan at Hara town. Historic rainfall data (1955–2003) were obtained from the Ethiopian National Meteorological Services Agency in Addis Ababa, Ethiopia.

A water height recorder (TruTrack WT-HR 2000) monitored the Hara Swamp surface water level at 15-min intervals during the 2004 kremt rainy season (July–September). Daily wetland water level was also recorded manually with a reference tree trunk on the western edge of the wetland. All water level data are adjusted to elevation at the deepest part of the wetland.

The surface water area-depth relationship was determined by tracking (walking) the boundary of the flooded area with a global positioning system unit (Garmin GPS 72) and recording water depth at the deepest part of the wetland. Figure 2 presents the GPS traced water boundaries and the water depth—surface area data. Regression analysis fit a logarithmic curve ($R^2 = 0{\cdot}96$) to the water depth–surface water area relationship producing the equation

$$A_\mathrm{f} = 0.59\ln[D_\mathrm{dp}] + 2.33 \quad (1)$$

A_f is the area of floodwater ($m^2 \times 10^6$) and D_dp is the depth of water (m) at the deepest part of the wetland. The surface water volume–depth relationship was determined by integrating the area under the curve in equation (1) and adding the initial water volume stored in the wetland (the area under linear portion of the curve in Figure 2b) before July 14 (the first recorded depth–area data point) to obtain the equation

$$V_\mathrm{f} = D_\mathrm{dp}(0.59\ln[D_\mathrm{dp}] + 1.74) + 0.01 \quad (2)$$

V_f is the volume of floodwater in the wetland. The units are water depth (m) and flood volume ($m^3 \times 10^6$). Equation (2) was used to calculate wetland surface water volume during the season.

Land Cover Assessment

Aerial photos and multispectral satellite images provide accurate snapshots of recent and past land cover conditions (Dwivedi *et al*., 2005). False color composites created by combining images captured at different wavelengths enable better visualization of vegetation, soil, wetland flooded area, and settlements in the landscape. Composite images were produced using Landsat MSS 1973, Landsat TM 1986, and Landsat ETM + 2000 and 2001 images. The 1986, 2000, and 2001 false color composites were created using Band 4 in green, Band 5 in red, and Band 7 in blue. The Band 4 reflective infrared wavelength (0·76–0·90 μm) was selected because it is absorbed by water appearing dark and reflected by vegetation appearing bright. The mid-infrared Bands 5 (1·55–1·75 μm) and 7 (2·08–2·35 μm) contrast well revealing differences in types/condition of vegetation and soil. The 1973 composite was created using Band 4 in green, Band 2 in red, and Band 1 in blue because Landsat MSS does not record the

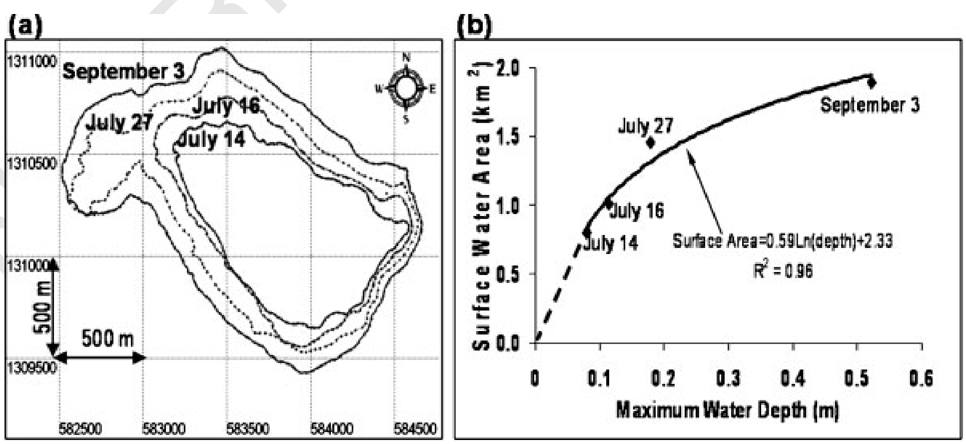

Figure 2. Hara wetland (a) GPS measured surface water boundary expansion during 2004 (coordinates in meters; UTM Zone 37) and (b) the water depth–surface area relation (equation and solid line—logarithmic regression fit; dashed line—linear fit).

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mid-infrared bands used for the other years. The green (0·5–0·6 μm) and red (0·6–0·7 μm) wavelengths of Bands 1 and 2 are absorbed by vegetation showing differences in vegetation health.

Panchromatic aerial photos taken in November 1964 and 1986 were acquired from the Ethiopian Mapping Authority. The scanned aerial photos were georeferenced using ground control points taken with a Garmin GPS72 unit.

A combination of field observations and computer terrain analysis of a digital elevation model (DEM) were used to delineate catchment boundaries. All computer analyses of land cover and terrain were performed in Manifold GIS System Release 6·50. Locations, elevations, and the catchment boundary were crosschecked with the Ethiopian Mapping Authority's 1:50 000 scale topographic maps of Weldiya and Dana (produced in 1994 based on 1986 aerial photographs).

RESULTS AND DISCUSSION

Local Perceptions of the Wetland

Residents of Hara watershed currently derive many benefits from Hara Swamp which is located centrally in the watershed. Table III presents reasons respondents liked the presence of the wetland in their watershed and Table IV presents their concerns. Ninety-two per cent of respondents liked having the wetland in the watershed. The primary reasons were the water and forage for livestock, the wood for cooking fuel, and the water for washing clothes that the wetland provides. Over a third of respondents said they would like to use the water the wetland stores to also irrigate crops.

The most commonly reported concern about the wetland was that it breeds mosquitoes (Table IV). Malaria is rampant in the area claiming lives yearly. A second common issue reported by three-fourths of respondents was the land it occupies could be used instead for crops or as livestock grazing grassland. The wetland including its immediate surrounding area is publicly owned communal land with no restrictions on grazing, but cropping in the area is prohibited. Some respondents were concerned with the general danger to human health and of children or

Table III. Primary reasons that the respondents liked Hara wetland

Reasons	Respondents (%)
Water for livestock	92
Water for crop irrigation[a]	41
Forage source for livestock	38
Fuel-wood source for home	31
Water for domestic use	11
Birds in/around the wetland	2
Don't like wetland	8

[a]Refers to potential use of water for irrigation; there was no crop irrigation in 2004.

Table IV. Primary reasons that the respondents did not like presence of the wetland in the watershed

Reasons	Respondents (%)
Too many mosquitoes	82
Livestock grazing area lost to flooding	72
Reduced cropland area in the watershed	72
Poor quality water source	33
Dangerous for humans	21
Dangerous for livestock	21
Public ownership of its resources	3

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livestock getting stuck in the mud and drowning. Despite their many concerns only 8% of respondents said they did not like the presence of the wetland in their watershed.

Remote Sensing Evidence and Local Perceptions of Wetland Changes

Satellite images and aerial photos from the past 40 years provide evidence of changing land cover and flood levels/area in Hara Swamp. Figure 3 presents aerial photos of the wetland in 1964 and 1986 and a panchromatic satellite image in 2000. It is quite apparent in these images which were all taken around the same time in the dry season that the wetland had dense woody vegetation cover in 1964 and 1986 but almost no vegetation in 2000. During the same time period the number of houses in Hara town greatly increased and a road was constructed (bottom left corner of Figure 3b,c). The wetland looked completely dry in 1964 (Figure 3a), very wet or possibly slightly flooded in 1986 (Figure 3b), and completely flooded in 2000 (Figure 3c).

Composite satellite images of the Hara watershed provide further evidence of recent hydrological and vegetation changes in the wetland. Figure 4 presents false color composites from 1973, 1986, 2000, and 2001 all taken in either December or January during the dry season. In these images vegetation appears green, water dark color, and soil a combination of red and blue. Within the wetland area at the center of the watershed there appears a large area of dense vegetation in 1973. The 1986 image appears to have the least vegetation cover of all images. This could be because 1984 was a drought year and 1985 had below average rainfall (rainfall is presented in the next section). In 2000 the wetland was completely flooded and there was little evidence of vegetation within it. The 2001 condition was similar to 2000 except for the reddish coloring to the west side of the wetland. This coloring suggests heavy sedimentation.

Local residents' perceptions of recent changes in Hara Swamp are in agreement with the information obtained from the remotely sensed images that were collected after the survey. Table V presents survey respondents perspectives of wetland changes. Eighty-four per cent of the respondents said that over the past 30 years the annual maximum flood levels have greatly increased and all respondents said that in the past the wetland used to have almost no flooding. When asked how long ago the flooded conditions started, the responses varied from 15 to 58 years ago with 81% of respondents saying 20–30 years ago. All respondents said that sedimentation has also greatly increased in the wetland during the past 30 years.

Hara watershed residents also reported recent drastic changes in the wetland vegetation cover (Table V). All respondents said there used to be dense trees, bushes, shrubs, and grass in and around the wetland 30 years ago. In 2004 when the survey was conducted there were no living trees or bushes within or near the wetland. Figure 5 shows the open water condition in 2004 as well as the numerous dead tree trunks which provide evidence of previous conditions. It is not known why all the trees are dead but a likely explanation are the longer and higher floods during recent years (Tiner, 1999). Although the wetland is officially classified on Ethiopian Mapping Authority maps as a swamp (i.e., wetland dominated by woody vegetation) based on past conditions it is more accurately described as a marsh (i.e., wetland dominated by grass and sedges) now. The northwestern part of the wetland had dense sedge (*Cyperus latifolius*) growth during kremt 2004.

The information obtained through the survey of local residents confirmed and supplemented what the satellite images suggested. Given the snapshot nature of remote sensing historic evidence and the lack of hydrological records in this small watershed, and in Ethiopia in general, the complementarity of the local perceptions input was important to better validate our understanding of recent environmental trends.

Rainfall Records

There is the possibility that rainfall variation could explain the trend and some of the interannual differences in wetland flooding and vegetation cover observed in the satellite images. Figure 6 presents rainfall records for Hara town, Kobo (45 km northwest of Hara), and Weldiya (16 km west of Hara). Rainfall records for Hara only include 1977–1981 and 2003–2004. During the years with gaps in the record Hara rainfall is predicted/estimated based on linear regression of Kobo and Weldiya rainfall records which together cover, except for a few gaps, the period of 1955–2003 (Figure 6).

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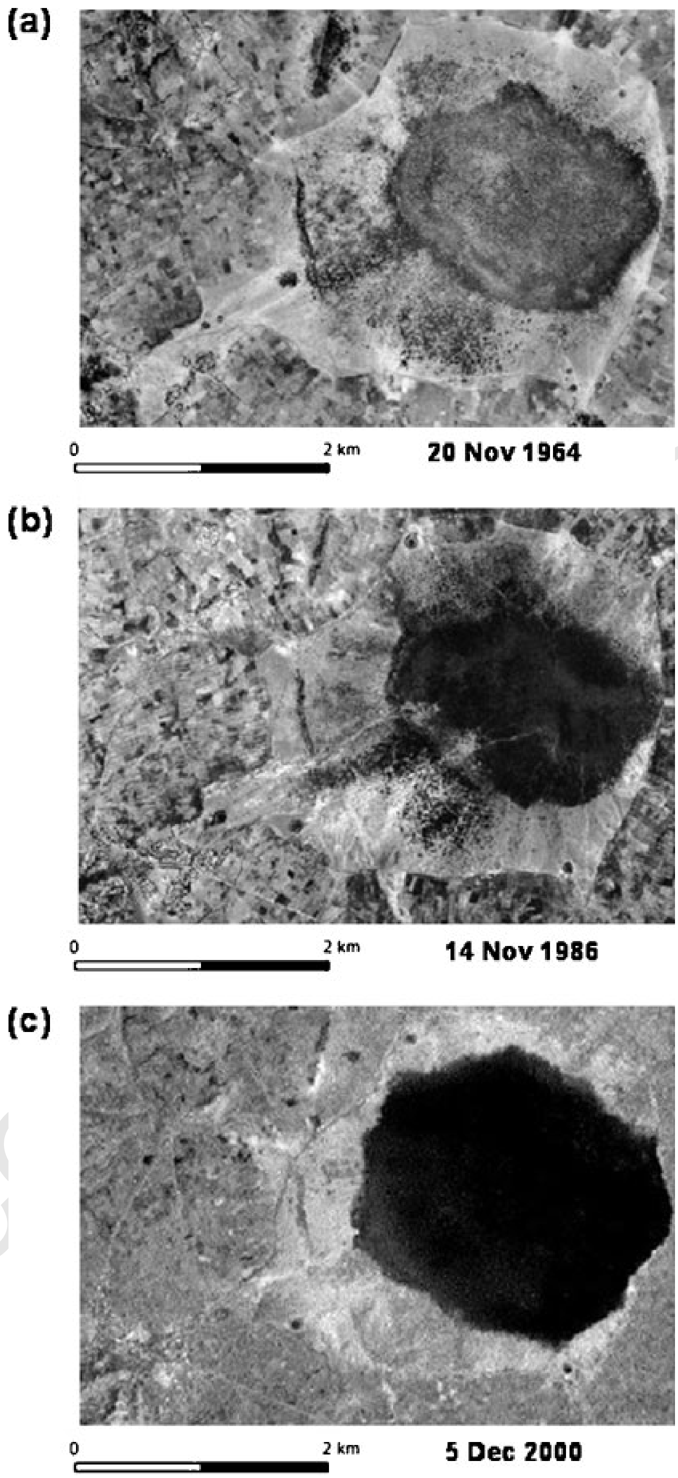

Figure 3. Aerial photos of Hara swamp (a) 20 November 1964 and (b) 14 November 1986, and panchromatic Landsat image (c) 5 December 2000.

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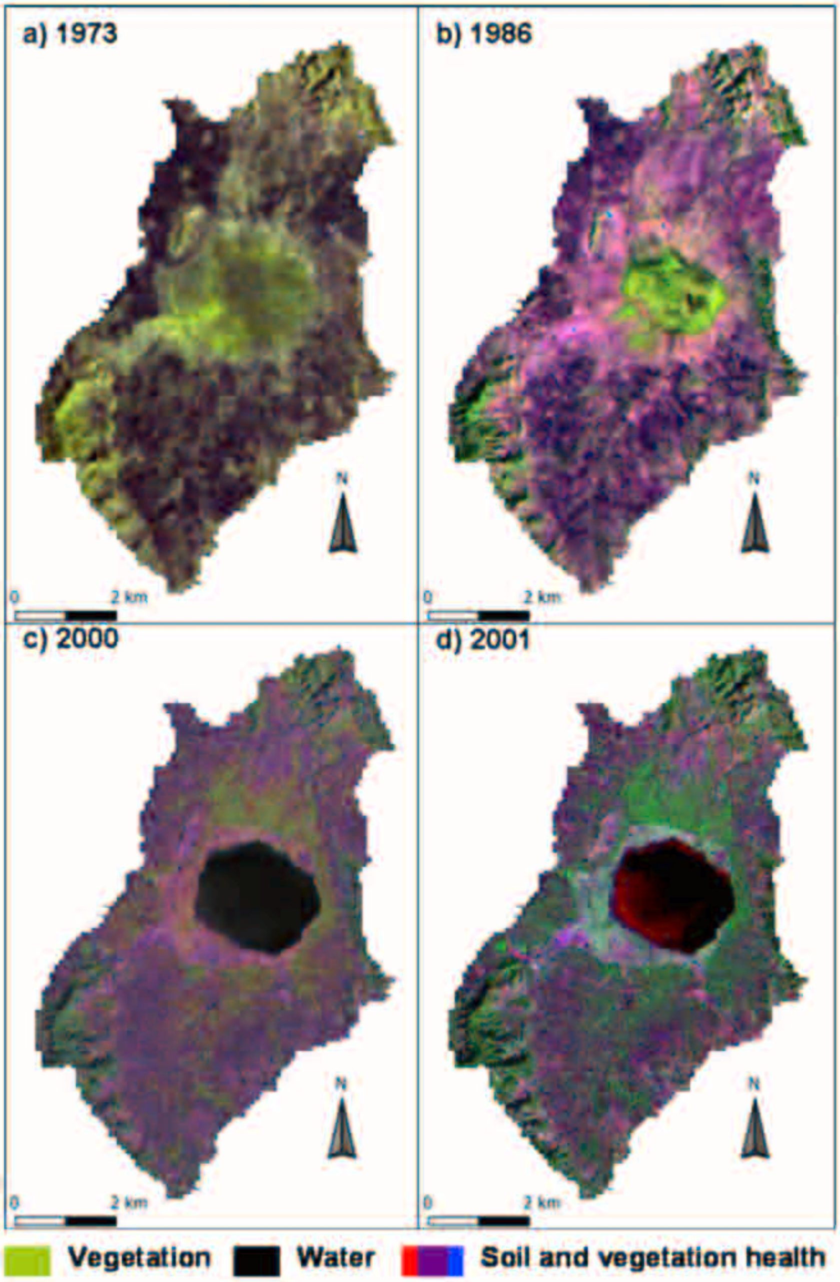

Figure 4. Landsat false color images (a) 31 January 1973, (b) 5 January 1986, (c) 5 December 2000, and (d) 5 December 2001.

Weldiya has more rainfall than Hara and Kobo due to its 500 m higher altitude of about 1950 m.a.s.l.. Annual rainfall depth at all stations was erratic, as is common in northern Ethiopia (Seleshi and Zanke, 2004), with coefficients of variation (CV) over 20%. There were no significant ($p < 0.05$) trends in rainfall depth at any of the rainfall recording stations (Figure 6). In addition, the slight statistically insignificant positive rainfall trend at Hara was too small to explain the rapid wetland flood area increases observed during the last 40 years. Although only 6%

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Table V. Perceptions of difference in current wetland condition compared to the past

	Now compared to	No. of respondents	Percentage of respondents (now compared to the past)				
			Much less	Little less	Same	Little more	Much more
Maximum wetland flood area	Last year	56	4	12	84	—	—
	5 years ago	54	13	15	2	59	11
	30 years ago	54	9	7	—	—	84
Water quality now compared to 30 yrs ago		58	97	—	3	—	—
Sedimentation now compared to 30 yrs ago		52	—	—	—	—	100
Vegetation now compared to 30 yrs ago	Trees	58	100	—	—	—	—
	Bushes	58	100	—	—	—	—
	Shrubs	49	100	—	—	—	—
	Grass	43	100	—	—	—	—
Bird population now compared to 30 yrs ago		57	100	—	—	—	—

Figure 5. Open water and numerous dead tree trunks are indicators of changing flood levels and vegetation cover at Hara Swamp (photo taken May 2004).

of survey respondents reported climate as a reason for wetland changes, 100% of respondents said that rainfall in the area has significantly declined during the past 30 years. However, the rainfall records do not support this perception. Similarly, Meze-Hausken (2004) in an intensive study in the neighboring regions of Afar and Tigray found a widespread perception of decreasing rainfall during the past 20–30 years although the available rainfall measurements did not show any declining trend. The author determined some possible reasons for the local perceptions of a downward rainfall trend were environmental changes which have caused decreased moisture/water availability in the landscape, declining land productivity, and people's changing needs for rainfall (Meze-Hausken, 2004).

Rainfall distribution within the year could also affect the level of floodwater. Figure 7 presents rainfall in Weldiya during the 12 months prior to when the satellite images in Figure 4 were captured. Total rainfall was not significantly different between the years except for 1985–1986 which had the lowest rainfall. The 1984 was a drought year with 48% below normal depth in Weldiya. This can explain why in the January 1986 satellite image there is relatively little vegetation cover in the Hara watershed (Figure 4b).

The seasonal distribution of rainfall was quite different between the years. A significant amount of rainfall in 1972 occurred during belg (April) while 2000 and 2001 had larger kremt seasons (Figure 7). The larger kremt season could possibly result in a higher flood level during the following dry season. Despite the difference in 2000 and 2001 rainfall depths the flooded areas were similar (Figure 4c,d).

Overall, rainfall variation cannot sufficiently explain the trend of increasing annual floodwater in the wetland. The long-term decline in wetland woody vegetation could be explained in part by the 1984/1985 drought period but

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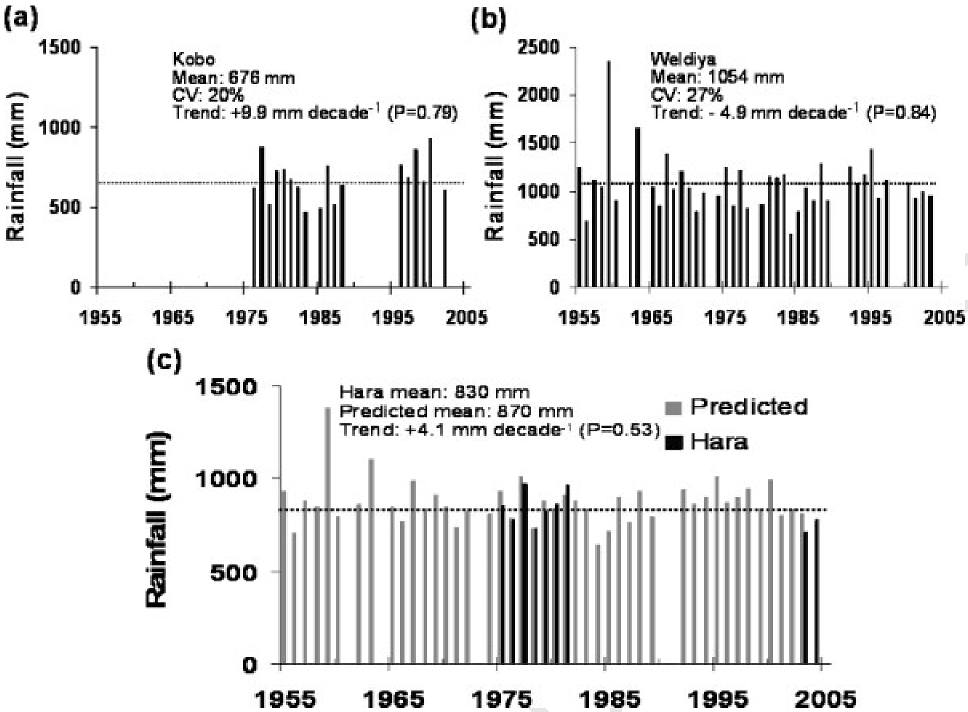

Figure 6. Annual rainfall records and trends: (a) Kobo 45 km northwest of Hara, (b) Weldiya 16 km west of Hara, and (c) Hara town actual and predicted based on linear regression of Kobo and Weldiya records ($R^2 = 0{\cdot}92$, $p = 0{\cdot}02$ for years with both Kobo and Weldiya records; $R^2 = 0{\cdot}52$, $p = 0{\cdot}07$ for Weldiya records only).

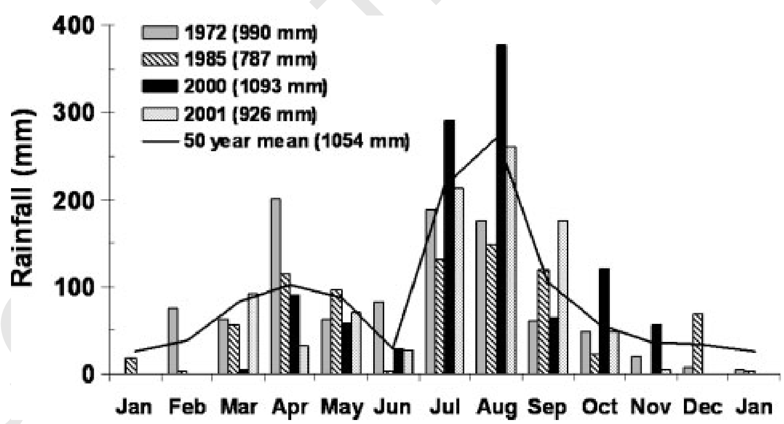

Figure 7. Monthly rainfall at Weldiya during the years prior to the satellite images.

this is unlikely a sole reason because the area previously had similar droughts in 1956 and 1971 (Figure 6b) which apparently did not decimate the extensive vegetation cover seen in 1973 (Figure 4a).

Hydrological Assessment of Wetland Floods

An assessment of the wetland hydrology is important to understand possible reasons for the drastic increase in the flood level/area. Given that rainfall amounts have not changed significantly, the observed trend of greater flood levels suggests that there are either increased surface runoff amounts entering from the catchment or more rainwater infiltration in the catchment raising the groundwater level. We explore these hypotheses using

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measurements of wetland water budget components during kremt 2004 to determine the relative contribution of runoff and groundwater inflow to the wetland flood levels. These results are then compared to local perceptions.

A simple approximation of wetland water budget components was computed based on the monitored rainfall, pan evaporation, and wetland water level. The components of the water budget were related by the equation,

$$\Delta V_{\mathrm{f}} = P_{\mathrm{f}} + R_{\mathrm{in}} - E_{\mathrm{f}} - R_{\mathrm{out}} + Q_{\mathrm{subsurface}} \quad (3)$$

where ΔV_{f} is change in wetland flood volume, P_{f} is rainfall directly over the wetland flood area, R_{in} is runoff inflow from the surrounding catchment, E_{f} is evaporation from the wetland flood area, R_{out} is surface outflow which was zero due to the topography of the surrounding catchment, and $Q_{\mathrm{subsurface}}$ is net subsurface water flow through the wetland bed soil below the flood area.

Figure 8 presents monthly rainfall, evaporation, and temperature in the Hara watershed during 2003–2004. Evaporation rates (E) were calculated from pan evaporation based on multiplication by the common lake coefficient factor of 0·70 (Haan *et al.*, 1994). Mean evaporation rates exceeded rainfall during all months except August 2003 with a daily average of over 5 mm day^{-1}. Although most months during the year received some precipitation, 83% of annual rainfall was concentrated during the two rainy seasons of belg (March–April) and kremt (July–September). Rainfall (P) during the study period of kremt 2004 (July–October) totaled 490 mm or 60% of the annual rainfall.

Hara wetland water level responded rapidly after the commencement of the kremt 2004 rains. Figure 9 presents the mean daily wetland surface water level and rainfall. The wetland water level varied from almost dry at the beginning of the kremt season to 64 cm water depth covering over 200 ha of land area during August. The surface water level responded rapidly to rainfall resulting in stepwise increases in water depth (rather than gradual increases) as the rainy season progressed. This type of rapid hydrologic response represents primarily surface runoff, and possibly limited rapid subsurface interflow (Brutsaert, 2005). During days without significant rainfall events the wetland water level declined rapidly suggesting relatively high evaporation losses and possibly downward percolation to the groundwater table (Figure 9).

The surface runoff (R_{in}) contribution to the wetland water volume can be estimated as the rapid change in wetland water volume during and for several hours immediately after storms. Figure 10 presents the stepwise depth increases observed for two storms and the method for estimating runoff volume for each storm. The surface water level started increasing shortly after the beginning of intense storms and often within 8 h after rainfall terminated, the water level stopped increasing and began to decrease gradually (Figure 10). Table VI summarizes the seasonal runoff contribution from all major storms during kremt 2004. Runoff varied greatly across events with 73% of the

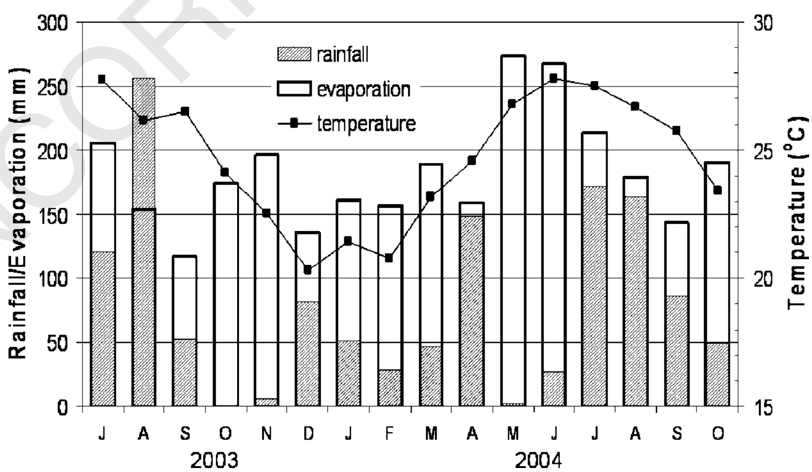

Figure 8. Monthly rainfall, evaporation, and ambient temperature in Hara watershed (2003–2004).

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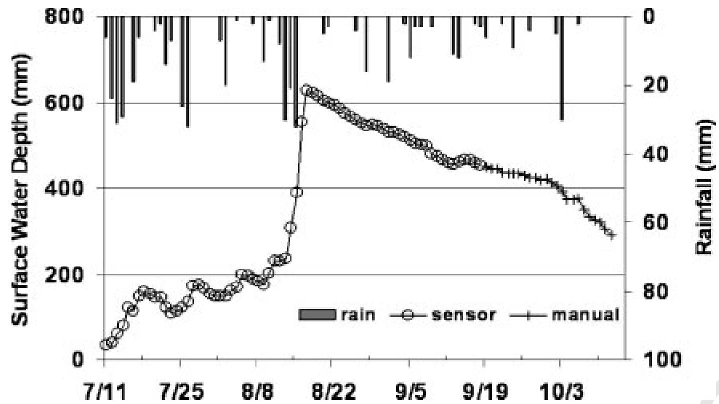

Figure 9. Mean daily maximum wetland surface water depth and rainfall during 2004.

seasonal runoff occurring over a 3-day series of storms during August 13–15. The mean runoff coefficient (runoff depth as a percentage of the event rainfall depth) for all storms (listed in Table VI) was 5%.

Using the estimated runoff contribution, the measured evaporation and rainfall, and the recorded wetland storage depth, the groundwater contribution ($Q_{subsurface}$) during the kremt season was estimated based on the relationship in equation (3). Table VII presents the water budget for the Hara Swamp during the kremt 2004 period. All budget components are expressed as the depth equivalent of water volume distributed over the entire catchment area. Direct rainfall (P_f) and evaporation over the wetland flood area (E_f) were calculated as volumes based on the daily rainfall depth (P) and daily evaporation (E), respectively, and the corresponding mean daily wetland flood area (A_f) determined with equation (1). Runoff (R_{in}) contributed 49% of total inflows. Given the shallow depth and large surface area of the wetland, it is not surprising to find that the remaining 51% of inflow was from direct rainfall onto flooded areas (P_f).

The major loss (outflow) was evaporation (E_f) accounting for 52%. There was an estimated minor net outflow to the groundwater ($Q_{subsurface}$) during the budget period (Table VII), but this is not very accurate as it includes all the errors in the other terms. Moreover, it is probably an underestimate because the runoff inflow calculation method does not account for initial water infiltration during wetting of the dry wetland bed. The wetland maintained 46% of the total inflow as surface storage at the end of the rainy season in October.

The wetland hydrologic response to rainfall and the simple water budget analysis demonstrated that the variability in annual wetland high flood level was controlled by the amount of surface runoff entering from the catchment. Considering that surface runoff is the primary inflow the increase in wetland flood area during the past 40 years indicates that changes in the catchment have resulted in higher runoff amounts. Also, higher sedimentation rates, which often accompany increased runoff, might have contributed some to increasing flood areas by filling in the wetland bottom changing the water depth-surface area relationship. The creation of more impermeable surfaces in the watershed, such as the large increase in the number of houses (in Hara town especially) and the construction of the main road (apparent in the 1986 aerial photo but not in the 1964 aerial photo) to Afar region (the Chifra-Mille highway) observed in the remote sensing images (Figure 3), can account for a large portion of the increased runoff and sedimentation over time. This is in accordance with Nyssen *et al*. (2002) who found that after construction of the Mekele-Adwa road in the adjacent region of Tigray increased runoff led to numerous severe gully formations offsite.

Local perceptions of reasons why the wetland has changed in recent years also confirmed the indications from the water budget analysis and remote sensing data (Table VIII). The reasons given by the residents included increased erosion/gullying and runoff from the watershed and from the hillsides and Hara town in particular. Watershed land cover changes to fewer trees and increased cropland area were also given as reasons. The61% of respondents said that the wetland changes are a consequence of human population increase. All respondents provided estimates of

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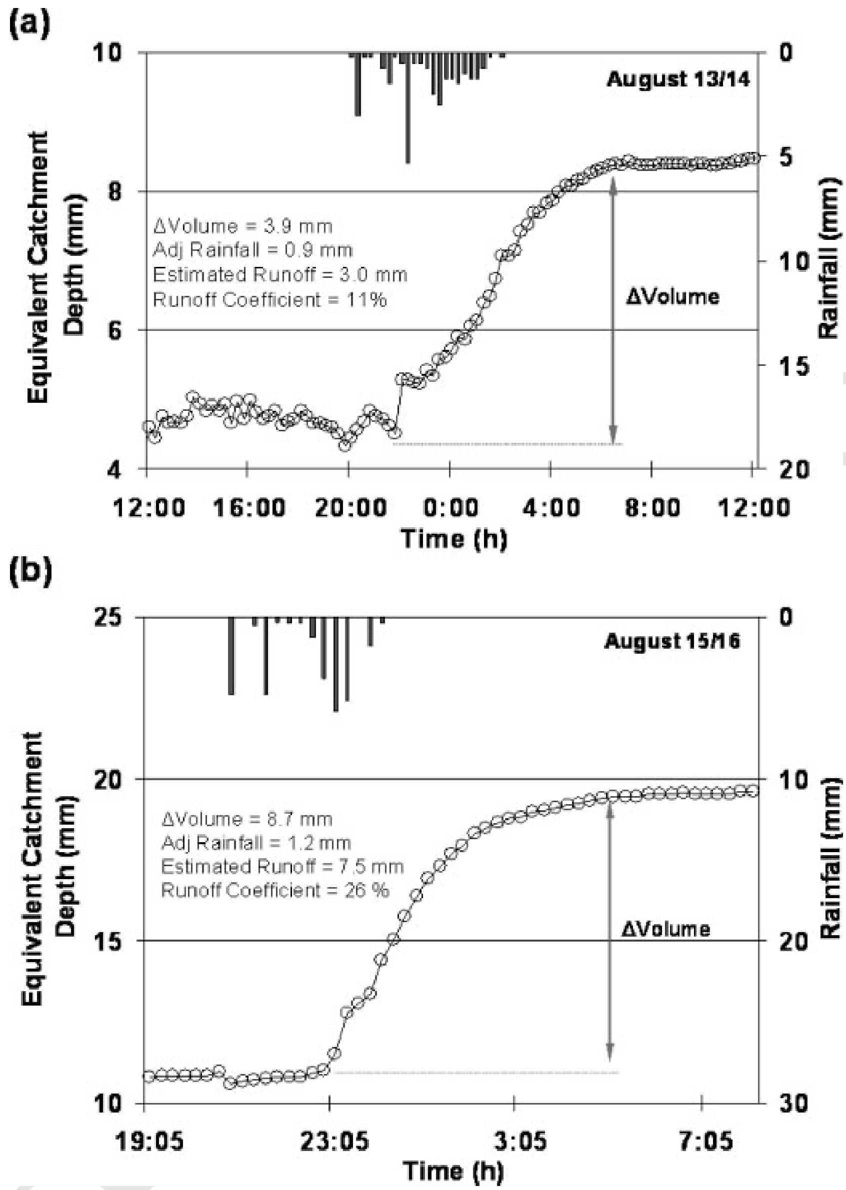

Figure 10. Storm runoff estimation based on wetland surface water volume increase during and for several hours after rainfall minus contribution from direct rainfall over the wetland flood area: (a) 13 August and (b) 15 August. Equivalent storage depth and rainfall are at 15-min intervals. (Adj rainfall is the total rainwater volume falling directly over the wetland flood area expressed as an equivalent depth over the entire catchment).

the watershed human population as more than doubling during the past 30 years. Except for the explanation of decreased rainfall (Table VIII), the residents' perceived reasons for changes in the wetland (which were collected first) were plausible and well supported by the hydrological assessment data and the remote sensing images.

Implications of Wetland Changes for the Local Communities

The changing condition of the wetland and its contributing catchment has direct impacts on the benefits and concerns enumerated by the local population (Tables III and IV). The expanding wetland flood area is reducing the

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Table VI. Runoff estimation (calculated as wetland surface water volume change during and for up to 8 h after major storms minus the contribution from direct rainfall over the wetland flood area)

Date	Δ Storage (mm)[a]	Rainfall[b] (mm)[a]	Runoff (mm)[a]	Coefficient of runoff (%)[c]
13/7/2004	0·6	0·3	0·3	1
14/7/2004	0·8	0·6	0·2	1
16/7/2004	0·9	0·5	0·4	2
17/7/2004	0·4	0·2	0·2	3
22/7/2004	0·4	0·2	0·2	3
25/7/2004	1·0	0·5	0·5	2
26/7/2004	1·5	0·8	0·7	2
9/8/2004	1·5	0·5	1·0	6
13/8/2004	3·9	0·9	3·0	11
14/8/2004	2·3	0·9	1·4	6
15/8/2004	8·7	1·2	7·5	26
29/8/2004	0·7	0·5	0·2	2
2/9/2004	0·4	0·3	0·1	1
13/9/2004	0·7	0·4	0·3	3
15/9/2004	0·8	0·5	0·3	2

[a]Water volume expressed as an equivalent depth over Hara catchment area.
[b]Volume of rainwater falling directly on wetland flooded area.
[c]Runoff depth as percentage of rainfall depth over the entire catchment area.

Table VII. Hara wetland estimated surface water budget during kremt 2004 (11/7/04–1/10/04)

Parameter	Direct rainfall inflow	Runoff inflow	Evaporation loss	Δ Surface storage	Subsurface flow
Equivalent depth over catchment (mm)	17·1	16·3	17·5	15·4	−0·5
% of total inflow	51	49	52	46	2

Table VIII. Primary reasons for changes in Hara wetland during the past 30 years

Reasons	Respondents (%)
Increased watershed erosion/gullying	79
Increased human population	61
Increased runoff from hillsides	46
Decreased number of trees in watershed	38
Increased runoff from Hara town	23
Increased cropland area	15
Increased livestock numbers	8
Decreased rainfall	6
Don't know	2

critically needed grazing area for livestock. The water quality deterioration with increased sedimentation is reducing the ability to use the water for domestic purposes. The remaining woody vegetation which a third of respondents depend for cooking fuel has been killed possibly by the increased floods and will soon completely disappear. The increased runoff from the watershed means less water is available for the rainfed crops upon which this food insecure population depends. The high sedimentation entering the wetland is a result of erosion degrading land productivity in the watershed. These are some of the major implications of the recent trends found in Hara Swamp and Hara watershed. An integrated watershed management strategy is required to address these issues and to reverse the current trend.

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CONCLUSION

Hara Swamp provides unique water and plant resources to the residents of Hara watershed who overall appreciate its presence in close proximity despite mosquito breeding and other concerns. Analysis of aerial photos and satellite image composites suggested that the current condition of the wetland is a drastic change from previous conditions of dense tree and bush cover and limited flooding 40 years ago. Rainfall records revealed no significant trends which could explain the changes observed in the wetland. Hydrological measurements and a simple wetland water budget suggested that increased surface runoff from the catchment produced the higher flood levels. Local residents' perceptions of the wetland in the past and reasons for changes to the present condition better validated and supplemented the information from the limited remote sensing and hydrological data. The integrated approach of understanding recent trends in the landscape through complementary methods provided better information for environmental planning in this data scarce area.

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REFERENCES

Abbot PG, Hailu A. 2001. Dynamics of wetland management: lessons for Ethiopia. EWRP—Ethiopian Wetlands Research Programme, Policy Briefing Notes, Issue 2, Huddersfield, UK.

Abunie L. 2003. The distribution and status of Ethiopian wetlands: an overview. In *Wetlands of Ethiopia*. Proceedings of a seminar on the resources and status of Ethiopia's wetlands, Abebe YD, Geheb K (eds). IUCN-International Union for Conservation of Nature and Natural Resources: Nairobi, Kenya; 116.

Brutsaert W. 2005. *Hydrology: An Introduction*. Cambridge University Press: New York, USA; 605.

Chapman C, Desta HK. 1999. *The North Wello East Plain Food Economy Zone: Baseline Report*. Save the Children-UK: Addis Ababa, Ethiopia.

Desta Z. 2003. Challenges and opportunities of Ethiopian wetlands: the case of Lake Awassa and its feeders. In: *Wetlands of Ethiopia*. Proceedings of a seminar on the resources and status of Ethiopia's wetlands, Abebe YD, Geheb K (eds). IUCN-International Union for Conservation of Nature and Natural Resources: Nairobi, Kenya; 116.

Dixon AB. 2002. The hydrological impacts and sustainability of wetland drainage cultivation in Illubabor, Ethiopia. *Land Degradation & Development* **13**: 17–31.

Dixon AB. 2005. Wetland sustainability and the evolution of indigenous knowledge in Ethiopia. *The Geographical Journal* **171**(4): 306–323.

Dixon AB, Wood AP. 2003. Wetland cultivation and hydrological management in eastern Africa: matching community and hydrological needs through sustainable wetland use. *Natural Resources Forum* **27**: 117–129.

Dwivedi RS, Sreenivas K, Ramana KV. 2005. Land-use/land-cover analysis in part of Ethiopia using Landsat Thematic Mapper data. *International Journal of Remote Sensing* **26**(7): 1285–1287.

Edessa S. 1993. The decline of forests and natural resources in Ethiopia. *Ekologia (Bratislava)* **12**(2): 215–222.

Gizaw S, Mekonnen K, Desta L. 1999. Lenche Dima integrated watershed development project feasibility study report. Amhara National Regional State, Bahir Dar, Ethiopia.

Haack B. 1996. Monitoring wetland changes with remote sensing: an East African example. *Environmental Management* **20**(3): 411–419.

Haan CT, Barfield BJ, Hayes JC. 1994. *Design Hydrology and Sedimentology for Small Catchments*. Academic Press: San Diego, USA; 588.

Kebede S, Travi Y, Alemayehu T, Marc V. 2006. Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia. *Journal of Hydrology* **316**: 233–247.

Kindie A. 2001. Wetland distribution in Amhara Region, their importance and current threats. In *Proceedings of the Wetland Awareness Creation and Activity Identification Workshop in Amhara National Regional State*, Dixon AB, Hailu A, Wood, AP (eds). Amhara Bureau of Agriculture, EWNRA and Wetland Action, 23 January 2001, Bahar Dar, Ethiopia.

McCornick PG, Kamara AB, Tadesse G. (eds). 2003. Integrated water and land management research and capacity building priorities for Ethiopia. In *Proceedings of a MoWR/EARO/IWMI/ILRI International Workshop Held at ILRI*, Addis Ababa, Ethiopia, 2–4 December 2002. International Water Management Institute, Colombo: Sri Lanka; pp. 267.

Meze-Hausken E. 2004. Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. *Climate Research* **27**: 19–31.

Nyssen J, Poesen J, Moeyersons J, Luyten E, Veyret-Picot M, Deckers J, Haile M, Govers G. 2002. Impact of road building on gully erosion risk: a case study from the northern Ethiopian highlands. *Earth Surface Processes and Landforms* **27**(12): 1267–1283.

Seleshi Y, Zanke U. 2004. Recent changes in rainfall and rainy days in Ethiopia. *International Journal of Climatology* **24**: 973–983.

Tiner RW. 1999. *Wetland Indicators: A Guide to Wetland Identification, Delineation, Classification, and Mapping*. CRC Press: Boca Raton, Florida; 392.

Vogt N, Bahati J, Unruh J, Green G, Banana A, Gombya-Ssembajjwe W, Sweeney S. 2006. Integrating remote sensing data and rapid appraisals for land-cover change analyses in Uganda. *Land Degradation & Development* **17**: 31–43.

Wondefrash M. 2003. Wetlands, birds and important bird areas in Ethiopia. In *Wetlands of Ethiopia*. Proceedings of a seminar on the resources and status of Ethiopia's wetlands, Abebe YD, Geheb K (eds). IUCN-International Union for Conservation of Nature and Natural Resources: Nairobi, Kenya; 116.

Wood AP. 2001. The role and importance of wetlands in Ethiopia. In *Proceedings of the Wetland Awareness Creation and Activity Identification Workshop in Amhara National Regional State*, Dixon AB, Hailu A, Wood AP (eds). Amhara Bureau of Agriculture, EWNRA and Wetland Action, 23 January 2001, Bahar Dar, Ethiopia.

Zeleke G, Hurni H. 2001. Implications of land use and land cover dynamics for mountain resource degradation in the northwestern Ethiopian highlands. *Mountain Research and Development* **21**(2): 184–191.

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