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Full Length Research Article

Water Hyacinth in the Rift Valley Water Bodies of Ethiopia: Its Distribution, Socioeconomic Importance and Management

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A survey was conducted in the Rift Valley water bodies of Ethiopia from 2009 to 2011 to (i) determine the prevalence, agro-ecological distribution and sources of infestation of water hyacinth, (ii) investigate the socio-economic impact of water hyacinth, and (iii) assess changes in its agro-ecological distribution. Water hyacinth was first introduced into the Rift Valley water bodies as an ornamental plant in the 1950s around the Aba-Samuel Dam. Eventually, it spread into Lake Koka, Lake Ellen, Koka Dam and Wonji site via the Awash River. Now it is common in various water bodies located at low, mid and high altitudes. At Lake Koka, Lake Ellen, Aba-Samuel Dam and Koka Dam, an increase in water cover was observed during the study period. Univariate as well as PCA analysis indicated that rainfall, intensity of wave action on the water bodies, water depth, N and P content of the water bodies were the factors representing the majority of correlations with water hyacinth coverage. Interviews revealed that the weed mats had an adverse socioeconomic impact on the local communities and enterprises. The present assessment also noted that no major management strategy had been employed in the infested water bodies except at Wonji and Koka Dam where a significant reduction (i.e., < 7% distribution) has been achieved. On the contrary, increasing trend of water hyacinth invasion had been observed in the upstream water bodies. Hence, effective management strategy should be implemented in the upstream water bodies so as sustain achievements in Wonji.

Key words: water hyacinth, *Eichhornia crassipes*, infestation level, agro-ecological distribution, economic significance**,** PCA, control measures

INTRODUCTION

Water hyacinth, *Eichhornia crassipes*, is considered as one of the world's worst weeds (Holm *et al*., 1977), invading lakes, ponds, canals, and rivers. Due to its extremely fast growth, the weed has become the major floating water weed of tropical and subtropical regions. In the absence of natural enemies, the weed quickly becomes invasive, colonizing slow moving waters resulting in thick and extensive mats (Edward and Musil, 1975) which degrade aquatic ecosystems and limit their utilization (Hill and Cotzee, 2008). The negative impacts of water hyacinth are due to its dense, impenetrable mats which restrict access to water. This mats affect fisheries and related commercial activities, functioning of irrigation canals, navigation/transport, hydroelectric programmes and tourism (Navarro and Phiri, 2000). Ecologically, benthic and littoral diversity is reduced (Masifwa *et al*., 2001; Toft *et al*., 2003; Midgley *et al*., 2006), while population of vectors of human and animal diseases such as bilharzias and malaria are increased with water hyacinth infestation as these plants interfere with pesticide application (Harley *et al*., 1996). Water hyacinth was introduced into Africa from South America in the early 1900s (Mitchell, 1985; Gopal, 1987), but since the 1950s it has become a problematical weed in Southern Africa, the Congo basin and the Upper Nile (Rzoska, 1974; Denny, 1984). In the East African region, the weed was first noticed almost simultaneously in Uganda, Tanzania and Kenya in 1987 (Ogwang and Molo, 2001). An exploratory survey was undertaken to assess the prevalence of water hyacinth on the different water bodies of Ethiopia.

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Results of this survey indicated that the weed infestation was small at that time and no subsequent action was taken. However, sporadic visits, including some clean-up attempts have been made during 1959, 1968, 1979 and 1988 (Stroud, 1994). There are also reports indicating the infestation of water hyacinth especially in Baro, Gillo, and Akobo Rivers in Western Ethiopia (Rezene, 2005). Recently, water hyacinth infestation has also been observed in Lake Tana (Y. Firehun 2012, personal observation).

At Wonji-Shoa Sugar Estate, the weed began to proliferate on reservoirs, irrigation and drainage structures since 1996 when the plantation was flooded by overflow of Awash River that crosses the Koka Dam (Firehun *et al*., 2007). As of 2005, the gravity of the situation was quickly realized and it was decided to embark a management strategy of the weed nationally. An action-oriented control program involving manual, mechanical, biological and chemical measures (Firehun *et al*., 2007; EIAR/UNEP-GEF, 2009) was launched; but only the manual, chemical and mechanical control programs were effectively implemented. Although in some of the infested areas these control programs were implemented (Dula *et al*., 2008, Taye *et al*., 2009), further spread of water hyacinth in the Rift Valley of Ethiopia was not stopped. However, to gauge the severity of the problem, reliable estimates of water hyacinth distribution and abundance are required. Knowledge of the weed community structure is an important component of weed management and is essential in setting priorities for weed management. Currently, to cope with the water hyacinth problems, the need for integrated use of manual, mechanical and biological control measures is widely recognized. Implementation of such control measures in an integrated manner requires reliable estimates of water hyacinth distribution, identification of water bodies that require management action and assessment of existing control measures and their efficacy. For effective management of this weed, identifying source of infestation and route of transportation is very crucial. Thus, the objectives of this study were to determine the prevalence, agro-ecological distribution of water hyacinth and sources of infestation; to investigate the socio-economic impact of water hyacinth; and to assess the change in distribution and impact of the existing control measures on the weed cover over the last three years in the Rift Valley of Ethiopia.

MATERIALS AND METHODS

Survey sites

A survey was done in and along Aba-Samuel Dam, Lake Bishoftu, Lake Koka, Lake Beseka, Koka Dam, Awash Dam, Lake Ellen, Lake Elletoke, Wonji-Shoa sugar estate, Metahara sugar estate, Melka-Sedi and Melka-Werer following the streams of the Awash River. Central Rift Valley lakes namely Beseka, Koka, Ziway, Langano, Abiyata, Shala, Abaya, Chamo and Awassa were also assessed. These sites are situated from low (< 1300 m a.s.l.) to high (> 1900 m a.s.l.) altitude and receive an annual rainfall ranging between 950 and 1500 mm. Geographic and bathymetric characteristics of Rift Valley Lakes and Koka Dam are indicated in Table 1.

Survey procedure

A survey was conducted twice per year between 2009 and 2011. In these surveys, hydro dams, lakes, irrigation and drainage structures found in the Rift Valley and in the Awash River down to Melka-Werer were examined for possible infestation by water hyacinth. Within the Rift Valley, survey sites were selected on the basis of the presence of water bodies and their accessibility. Water bodies were identified from the reports of the respective administrative zone agricultural office and preliminary assessment (EARO, 2003). In the surveyed water bodies, the existing aquatic environments were inspected for water hyacinth infestation. After identification of infested water bodies, the geographic coordinates (altitude, latitude and longitude) were recorded using a GARMIN 12X portable geographic positioning system (GPS). Extents of water hyacinth infestation were estimated by random sampling of plant population from different corners of the selected water bodies. For water bodies having limited infestation towards the shoreline, plant population count was made by throwing a one meter square quadrat in a zigzag fashion along the shore. For water bodies with infestations at the center, plant population count was made by throwing a quadrat ten times in a 'X' fashion systematically over an assumed square encompassing at least most of infested water bodies using local boats. The total number of sample varied depending on prevalence and infestation level of the water bodies to accommodate at least one tenth of the infested area (Coyne *et al*., 2007). For water hyacinth infestation starting from outside towards the center, the coverage was measured using a meter tape. A pair of binoculars was used to identify the edge or limit of the infestation. Finally, each infestation level of the weed was given an abundance score following the procedure described by Phillip (1992). These abundance score values were again categorized from high to low infestation level to simplify the distribution map as used by Firehun *et al*. (2007).

Change in infestation level

In order to determine seasonal change in water hyacinth infestation, observations were made between 2009 and 2011. The locations selected for this study were Aba-Samuel Dam, Lake Koka, Lake Ellen and irrigation and drainage structures of Wonji-Shoa sugar estate. During the assessment, observations were made from the shoreline and in the lakes using local boats. Point data were recorded about the number of plants per meter square, plant density and overall distribution of the weed. Besides, at each point, the geographic coordinates (altitude, latitude and longitude) were recorded using a GARMIN 12X portable geographic positioning system (GPS). While taking the geographical coordinates, the severity levels of the water hyacinth infestation were assigned by codes ranging from 0 to 5 based on their population density (cluster growth) in the water body as well as nearby water bodies (Phillip, 1992). During each season, visual observation and sampling was conducted to determine: presence of flowers, pH, level of wave action, water depth and level of N, P, K in the water.. These measurements and water samples were collected from the ten blocks of the respective severity level of water hyacinth and replicated six times at each site. For the wave action on water bodies and depth of the water bodies, measurements were taken at 12-20 points depending on the size of the block. For the water samples, three one liter samples were taken at each measuring point. After determining depth of the water bodies, the three water samples per measuring point were pooled and kept in a box at room temperature for water quality analysis. Change in infestation level analysis from year to year was made by developing time series distribution maps. In order to generate the water hyacinth severity map, the geographic coordinates of the water hyacinth taken by GPS were transferred to GIS environment using DNGarmin software, and then those ground control points were projected using the widely used datum geographic coordinate system of 1984 (WGS84). In order to classify the level of severity, those codes transferred into GIS environment were then reclassified into 0, tr-1, 2-3 and 4-5 which represent free, low, medium and heavy infestation of water hyacinth. While mapping the severity of the water hyacinth, the major water body and river network shape files were collected from the Central Statistics Agency of Ethiopia. Climatic data were also used to assess effect on change in the infestation level of the weeds at the respective water body.

Data processing of plant survey

Correlation analysis was conducted using PROC CORR procedure of SAS (SAS Institute, 2008) to identify associations between water quality parameters and climatic data with water hyacinth coverage of the respective water bodies. In order to group the correlated water as well as climatic variables to the smallest possible subsets representing the majority of variation, a principal component analysis (PCA) was conducted further using the PROC FACTOR procedure of SAS (SAS Institute 2008). The factors derived from the PCA are considered mutually orthogonal, uncorrelated, and successively explain the maximum residual variation. A factor, as an array variable, may hold contributions from all the nine variables. Total variance of each factor was defined as eigen value. Factors with eigen values >1 and those that explained at least 5% of the variation in the data were retained. Generally, variables with higher loading coefficients were included in each factor because they could be expected to have greater effect on water hyacinth area coverage variability. Variables with factor loadings >0.50 were selected to be included in each factor. If the loading coefficient of the variable was >0.50 in more than one factor, it was included in the factor having the highest coefficient value for that property.

Socio-economic impact of the weed

The socio-economic impacts of water hyacinth were assessed through interviewing the local communities and affected enterprise personnel's at Aba-Samuel Dam, Lake Ellen, Lake Koka, Wonji-Shoa Sugar Estate, Ethiopian Electric Power Authority (at Koka

Dam), and communities along Awash River. Structured questionnaires were designed and administered to 185 respondents in the respective sites. Data were also collected from other stakeholders such as governmental organizations, nongovernmental organization (NGOs), and urban dwellers. Secondary information was also collected from published and unpublished sources available from governmental, NGO and international organizations. The major issues posed in the questionnaires included: 1) awareness of the weed; 2) the time of introduction into the area; 3) rate of spread of the weed since its appearance; 4) impacts on crop and livestock production, on the operations of commercial farms, and on native plant species; 5) the costs incurred and labor required to control/minimize the impacts of the focal species; 6) measures taken so far (by the interviewee and other bodies); 7) success/failure of the measures taken to date; 8) other advantages and disadvantages of the weed. Finally, the questionnaires were coded and the data entered to computer for analysis. Statistical analysis software (SPSS) was used to summarize the information and analyze the data.

Case study: Impact of physical and herbicidal control measures

Assessment of the impact of physical and herbicidal control approaches implemented in the Rift Valley water bodies was evaluated taking Wonji-Shoa sugar estate as a case study. Wonji-Shoa irrigation and drainage structures were selected as a case study area because of its long history of water hyacinth control and because data on the cost and control success were available. The water bodies selected for the case study included reservoirs (”WR” and ”WZ”)1, irrigation supply canals (primary and secondary) and drainage structures (border and central drains) where physical (manual removal, removal with the use of machinery, and canal restructuring) and herbicidal control measures were implemented alone or in combination for the last 12 years (Firehun *et al*., 2007; Dula *et al.,* 2008). Efficacy of the implemented strategy was evaluated both qualitatively and quantitatively. For qualitative evaluation, visual rating of efficacy was made using the European system of the weed control evaluation scale (Burrill *et al*., 1976). For quantitative evaluation, percent weed control, percent reduction in dry weight and flower number following the application of control methods were calculated and the two sample t-test was conducted using SAS software (SAS Institute, 2008). Similarly, data on the plant population, cost of control and other aspect of water hyacinth management were obtained from Wonji-Shoa Sugar Factory Agricultural Operations Office (WSSFAO), from interviews with the relevant people at WSSFAO and from management staff of the Sugarcane Research Directorate Office located at Wonji. Evaluation of the cost incurred by the sugar factory to manage this weed was made by considering the impact of water hyacinth on a range of factors. All cost figures were adjusted for inflation using a consumer price index (CPI) with the year 2000 as the baseline.

RESULTS AND DISCUSSION

Distribution and status of water hyacinth in the Rift Valley of Ethiopia

Assessment result indicated that water hyacinth has become a major invasive alien weed in the Rift Valley of Ethiopia having successfully established and invaded the different water bodies. The present field assessment on the prevalence and severity of water hyacinth infestation showed that the weed prevails in most of the Rift Valley lakes, canals, reservoirs, irrigation water supplies and drainage structures with different magnitudes of infestation (Figure 2). Among the surveyed water bodies, the highest water hyacinth infestation (4 – 5 abundance scale) and visual area coverage (>90%) was recorded in Lake Ellen and Lake Elletoke. The lowest water hyacinth infestation level (tr -1) and area coverage (<2%) were recorded at Wonji-Shoa and Lake Abaya (Table 2). Moreover, 20 – 58% cover of water hyacinth mat area was recorded at Aba-Samuel Dam, Koka Dam, Awash Dam, Lake Koka, irrigation water supplies and drainage structures found in Melka Hida, Taree and Afer Gedeb. In all the three years of survey work, Lake Bishoftu, Lake Cheleka, Lake Ziway, Lake Langano, Lake Awassa, Lake Chamo and Lake Beseka were confirmed to be free of the water hyacinth problem. Previous assessment reports revealed that water hyacinth was prevalent in Aba-Samuel Dam, Lake Koka, Lake Ellen, Wonji-Shoa and Metahara sugar factory irrigation structures (Senayit *et al.,* 2004; Rezene, 2005; Taye *et al*., 2009). New records of water hyacinth infestation on Lake Abaya and Lake Elletoke wereobserved in the present survey. In all surveyed water bodies, there was a high degree of variability in water hyacinth infestation (Fig. 1). Most of the water bodies of Lake Ellen and Elletoke were predominated with high water hyacinth infestation and a few spots had low to medium infestation. These lakes are located near the farm lands and even part of them is cultivated when the water level decreases.

This might have created a high influx of nutrients into the lake which favored high reproduction rate of the weed. As a result, the weed forms mats covering all or part of these lakes. Severe water hyacinth infestation was also observed at Koka Dam, near Sire Robe peasant association (PA) and at the upper Koka near Tere PA in Koka Lake and on Awash River (to the side of Bora District). At Aba-Samuel Dam, the overall magnitude of water hyacinth infestation was relatively low (Table 2). However, as observed in the main rainy season assessment, the infestation was high during the months of August and September. In October, water hyacinth mats were broken and moved towards the shoreline. This dam had also high level of organic residues that might have come from the nearby factories and home waste disposal located in the capital city, Addis Ababa. In general, the majority of this aquatic plant was concentrated in the shoreline of the water bodies, on mud and sediments where disturbance by wind is relatively small. Part of the water bodies around the center remained clear with few floating plants which were detached as a result of the wind blown over the lake. In agreement to this result, many reports indicated that water level fluctuation, wave action, presence of suitable water hyacinth habitat, level of eutrophication associated with agricultural practice and the large urban areas would affect population dynamics of water hyacinth (Gopal, 1987; Wilson *et al*., 2001; Albright *et al*., 2004; Wilson *et al*., 2005; Kateregga and Sterner, 2007).

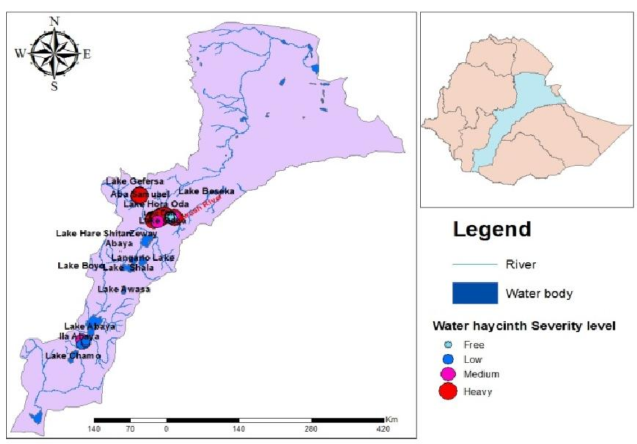
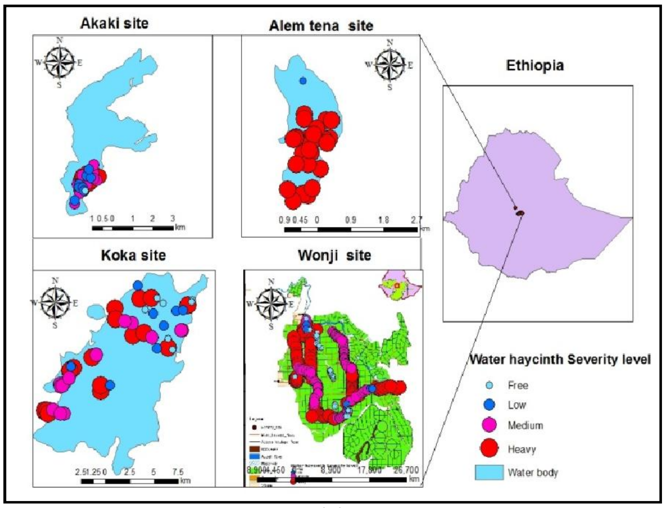
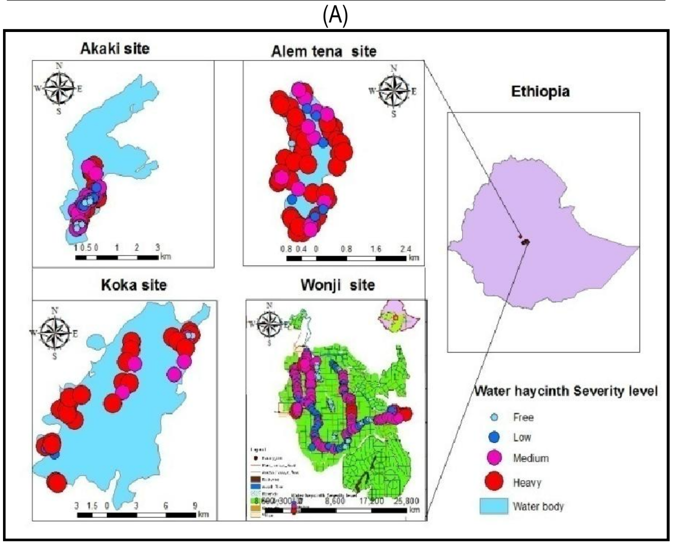


Figure 1. Distribution of water hyacinth in the Rift Valley water bodies of Ethiopia

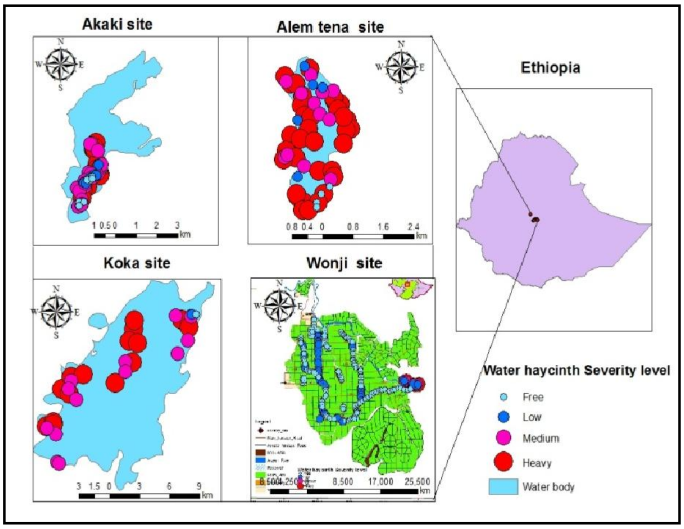
*[1] ‘WR’ and ‘WZ’ are local names of the reservoirs at Wonji



(A)



(B)



(C)

Figure 2. Change in distribution and extent of water hyacinth coverage in the Rift Valley water bodies, Ethiopia. [A] = Distribution in 2009, [B] = Distribution in 2010 and [C] = Distribution in 2011

Thus, the confined distribution of the weed to the shoreline of the surveyed lakes and dams could be attributed by the high wind current blown over the water bodies and reduced water level. The number of plants per meter square in these water bodies varied from none to more than 300; the highest plant population count (308 plants/m^2) was recorded in Koka Dam followed by Lake Koka (298 plants/m^2), Lake Ellen (274 plants/m^2), Lake Elletoke (268 plants/m^2), Afer Gedeb (261 plants/m^2), Tare and Awash (211 and 186 plants/m^2). Similarly, the highest weed density (> 40 kg/m^2, fresh weight) was recorded at Lake Ellen and Elletoke. Medium water hyacinth density (6 – 40 kg/m^2) was also recorded in the water bodies of Lake Koka, Aba-Samuel Dam, Koka Dam, Awash Dam, and irrigation water supplies at Tere and Afer Gedeb. In agreement with this result, reports indicated that outside its native range water hyacinth can grow quickly to a very high density, thereby completely clog water bodies (Frenandez *et al*., 1990; Julien *et al*., 1996). Wilson *et al.* (2005) also predicted a linear reduction relation between water hyacinth density (fresh weight) and specific growth rate. This indicates that it is not surprising to have variability in the weed density considering the reproduction rate of the weed outside its native area. Thus, the difference in extent of infestation within the infested water bodies of the Rift Valley water bodies indicates the relative clogging and expansion potential of the weed in the specific water body.

Table 1. Geographic and bathymetric characteristics of Rift Valley Lakes and Koka Dam in Ethiopia (After Tenalem 2004)

Lakes/Dam	Altitude (m a.s.l.)	Water body area (km^2)	Mean depth (m)	Volume (10^6 m^3)
Aba-Samuel	2050	20	2	-
Eltoke	1700	12	3	-
Elen	1700	28	2.5	-
Beseka	952	40	6	-
Koka	1584	177	-	1850
Ziway	1636	440	2.5	1466
Langano	1585	230	17	3800
Abiyata	1580	180	7.6	957
Shala	1550	370	8.6	37000
Abaya	1285	1162	7.1	8200
Chamo	1233	551	-	-
Awassa	1680	100	10.7	1340

Correlation analysis

Significant correlations were observed between water quality factors and water hyacinth coverage as well as between climatic factors and water hyacinth coverage (Table 3). Water hyacinth coverage was positively correlated with rainfall (RF), N, P, K and temperature (T) and negatively correlated with depth of the water bodies and altitude. Strong positive correlations were observed between the water hyacinth distribution, RF as well as T ($r = 0.57 – 0.97$, $P< 0.001$) in all the surveyed water bodies. N, P, and K ($r = 0.63 – 0.97$, $P< 0.001$) showed positive correlation with water hyacinth coverage at Aba-Samuel Dam, Lake Ellen, Lake Elltoke, Lake Koka and Koka Dam, and Melka Hida. Similarly, except at Wonji-Shoa, strong negative correlations ($r = 0.52 – 0.93$, $P< 0.001$) were observed between depth of water and the weed infestation in all the water bodies. The result also indicated that both the positive and negative associations between the weed infestation, water as well as climatic factors was mainly attributed to the nutrient influx (N, P, K), wave action and depth of the water bodies (W and WD). Among the water bodies, the strong association between the nutrient influx, wave action and depth of the water bodies was very apparent in Aba-Samuel Dam, Lake Ellen, Lake Elletoke and Lake Koka.

Furthermore, PCA was performed using the nine water quality and climatic variables selected from the univariate screening procedure. The factor analysis revealed that the main factors representing the majority of correlations were associated with five factors. Each of the first five groups or factors had eigen value > 1 and was retained for interpretation (Table 4). These five factors explained cumulative sample variance of 83%. The first and the most important factor, which explained 46% of the variation, had high factor loading (>0.50) for properties such as RF, K and T. Factor 2 had high loading from

Table 2. Mean water hyacinth infestation level and overall coverage in the Rift Valley water bodies, Ethiopia

Water bodies	Altitude (m a.s.l.)	Mean fresh weight (kg/m^2)	Mean plant population (plants/m^2)	Infestation level	Observed coverage (%)
Aba-Samuel Dam	2052	7	67	Low – High	46
Lake Ellen	1700	44	276	High	100
Lake Elltoke	1700	42	248	High	92
Lake Koka	1589	23	298	Free - High	37
Koka Dam	1580	21	308	Free - High	30
Wonji-Shoa Sugar Factory	1500	3	23	Free - Low	< 2
Metahara Sugar Factory	950	0	0	Free	0
Melka Hida	1450	6	58	Free - Low	20
Afer Gideb	1539	15	261	Free - High	55
Taree	1580	13	211	Medium - High	58
Awash	1460	10	186	Medium - High	42
Lake Abaya	1285	0.08	6	Free - Low	<1

Table 3. Correlation coefficients of water quality and climatic variables with water hyacinth coverage in the Rift Valley water bodies of Ethiopia

Water bodies	Water and climatic factors								
	AL	W	WD	pH	N	P	K	RF	T
Aba-Samuel Dam	-0.10	0.97	-0.93	0.29	0.92	0.93	0.97	0.97	0.77
Lake Ellen	-0.29	0.87	-0.77	0.30	0.98	0.88	0.73	0.98	0.75
Lake Elltoke	-0.29	0.80	-0.69	0.33	0.90	0.86	0.75	0.92	0.74
Lake Koka	-0.13	0.93	-0.91	0.02	0.80	0.80	0.74	0.89	0.81
Koka Dam	-0.18	0.55	-0.63	0.16	0.68	0.66	0.63	0.88	0.75
Wonji-Shoa Sugar Factory	-0.22	0.38	-0.09	0.16	0.48	0.47	0.39	0.63	0.69
Melka Hida	-0.37	0.63	-0.62	0.11	0.58	0.57	0.54	0.68	0.70
Afer Gideb	-0.20	0.53	-0.52	0.18	0.50	0.48	0.44	0.70	0.69
Taree	-0.05	0.64	-0.60	0.33	0.51	0.43	0.54	0.73	0.57
Awash	-0.43	0.56	-0.52	0.20	0.26	0.34	0.24	0.92	0.69
Lake Abaya	-0.16	0.58	-0.53	0.25	0.50	0.50	0.42	0.57	0.62

AL, altitude; W, wave action on the water bodies; WD, depth of the water bodies; pH, pH of the water; N, nitrogen content, P, phosphorous content, K potassium content; RF, rainfall; T, Temperature

Table 4. Factor analysis results based on nine water and climatic variables

Factors	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
Eigen value	4.55	1.65	1.24	1.10	0.99
Percent variance	45.50	13.50	10.40	8.00	5.90
Cumulative variance	45.50	59.00	69.30	77.30	83.20
Eigen vectors					
AL	0.02	-0.46	*-0.72*	-0.43	-0.12
RF	*0.85*	-0.06	-0.04	0.18	-0.18
pH	-0.18	*-0.61*	0.36	-0.07	-0.08
N	-0.34	*0.92*	-0.18	0.11	0.15
P	-0.39	0.38	-0.01	0.09	*0.77*
K	*-0.55*	-0.06	0.03	-0.19	*0.58*
W	-0.39	-0.21	*0.87*	0.06	-0.26
WD	0.19	-0.32	-0.35	*0.83*	0.14
T	*0.83*	-0.24	0.27	0.18	-0.44

pH and N and collectively they explained 13% of the sample variance. The highly weighted variables under Factor 3 were altitude (AL) and wave action (W). Water depth (WD) from Factor 4 and K from Factor 5 were selected as highly weighted variables. Correlation coefficients among RF, K and T under Factor 1 were strongly correlated (Table 4). The RF was selected as a representative from Factor 1 because it had the highest factor loading of 0.85. Under Factor 2, pH and N were significantly correlated. N with the highest factor loading of 0.92 was selected to represent Factor 2. Similarly, W and WD were selected as representatives from Factors 3 and 4, respectively. Only P was ranked as highly weighted from Factor 5, which was also added to the dataset. The final variables selected were RF, N, W, WD and P. In line with this, reports indicated that population dynamics of water hyacinth can be affected by the water level fluctuation and wave action (Gopal, 1987; Wilson *et al*., 2001). Reddy *et al*. (1990) reported that optimum growth of water hyacinth occurs in eutrophic, still or slowly moving water with high relative humidity, long sun exposure and a pH of 7 and a temperature range between 28°C and 30°C, and on abundant nitrogen, phosphorous and potassium.

Change in infestation level

A rapid change in the infestation levels of water hyacinth was recorded during the survey period, mainly at Akaki site (Aba-Samuel Dam), Alem Tena site (Lake Ellen), Koka site (Lake Koka and Koka Dam) and Wonji site (reservoirs, irrigation supplies and drainage canals) water bodies (Figure 2). The data showed a rapid increase in water hyacinth abundance during the 2011 survey followed by the 2010 survey conducted at Aba-Samuel Dam, Lake Ellen, Lake Koka and Koka Dam. During the 2011 survey period, the distribution map developed through GIS software revealed giant mats of water hyacinth covering large areas of the water bodies contrary to the mats formed in 2009. This aquatic weed infestation in the reservoirs, irrigation supplies and drainage canals located at Wonji site showed a rapid decline over the three years. In the interviews with the local communities, it was noted that no major management strategy had been employed in these water bodies except at Wonji and Koka Dam. A nutrient content of 2.8 – 3 mg/l N (mean = 2.9 mg/l N) and 1.2 – 1.5 mg/l P (mean = 1.3 mg/l P) had been recorded in all the infested water bodies. In line with this result, Heard and Winter (2000) reported a nutrient content of 3 mg/l N and 1.3 mg/l P to be high for water hyacinth growth and development. Hence, the giant mat covering in the water bodies of Akaki, Alem Tena and Koka sites could be associated with suitable habitat created for the weed growth and development.

Analysis of the change in infestation level over the last three years in these water bodies also indicated that stationary and mobile mats of water hyacinth were formed. The surface area of the water bodies covered by the mats varied from year to year. As shown in Fig. 2, during 2009, the mats located at Aba-Samuel Dam, Lake Ellen, Lake Koka and Koka Dam were sparse and more mobile than during the years 2010 and 2011. However, during 2010 and 2011, the mats recorded in these water bodies were stationary. In this regard, meteorological data of the study area during these periods indicated the presence of heavy winds and waves associated with heavy rain which might have physically damaged plants and dislodged mats (Table 3). Hence, the difference in mat type could be attributed to the difference in extent of wind, waves, extent of rainfall, and the water level. In line with this, Albright *et al*. (2004) reported that heavy winds and waves associated with heavy rain significantly contribute to the variation in extent of water hyacinth infestation and mat size in the Lake Victoria basin. Severity of water hyacinth infestation was also greater in the border parts of the lakes and dams compared to the central part (Figure 2). This might be linked to the water currents and weather patterns that push the weed to the shoreline. During the field assessment, flowering water hyacinth plants were observed in all the surveyed water bodies. Water aided movement of individual plants has been observed from Aba-Samuel Dam via Awash River down to Lake Koka, Lake Ellen, and Wonji sites. Therefore, these sexual and asexual reproduction mechanisms entail the water hyacinth to be a threat to the continued use of the affected water bodies as a resource.

Socio-economic impact of the weed

Water hyacinth was the most abundant aquatic weed on the water bodies studied and perceived as one of the most important noxious weeds (Table 5) showing high rate of spread within the last 60 years from its introduction. From the interviews conducted during the study, communities in Aba-Samuel generally believed that this aquatic weed was introduced to their area as an ornamental plant in the 1950s by foreign experts who were employed at the Dam site. Communities in Lake Koka, Lake Ellen, WSSF and EEPA have different views on its introduction such as by plant parts with running water and with flood, indicating its likely secondary dispersal from Aba-Samuel Dam. Field observation also confirmed that the weed found its way into the Rift Valley water bodies from Aba-Samuel Dam, which opens into the Awash River reroute to Lake Ellen, Lake Elletoke, Lake Koka, and Koka Dam. Consequences of infestation are often dramatic and now the weed is spreading to different water bodies located in the Rift Valley. Of the 185 interviewees, 93% in Aba-Samuel, 92% in Lake Koka and 90% in Lake Ellen were aware of the problem of water hyacinth on grazing and crop production activities, irrigation and drainage system and/or fishing. In WSSF and EEPC 100% of the interview were aware of the problem on irrigation and drainage system, power generation and/or proper water flow. Of the communities aware of the weed, 68% in Aba-Samuel, 75% in Lake Koka, and 60% in Lake Ellen considered water hyacinth to have a significant impact on grazing and crop production activities whereas 88% in WSSF and 84% in EEPA considered it to have an impact on irrigation and drainage system and power generation, respectively.

As reported by the communities living around the affected water bodies, impact of water hyacinth gets higher whenever there were mats. The most noticeable impacts that were reported by most interviewee include: restricting proper water flow, water loss through excessive evapo-transpiration, interference with fishing, grazing and crop production activities (accessibility to land water hindered), effect on power generation, increase siltation, flooding, increase cost of production and effect on native plants. Though vital epidemiological data pertaining to incidence of human diseases were not obtained during this study, there is a general increase in disease incidences as a result of provision of vector breeding grounds. Some of the human diseases reported include: skin rash, malaria, and bilharzias. These results showed that the impact of water hyacinth may be categorized into social, economical and environmental impacts. Fishers, riparian communities, Institute of Biodiversity, National Agricultural Research Institute, Ssugar corporation/sugar factories, Ministry of Energy and Water Resources, Ministry of Agriculture and Environmental Protection Authoritywere identified as the organizations and communities affected by this noxious weed. Similarly, other studies have indicated that the weed poses a great threat to agriculture, fisheries, transportation, hydroelectric power generation, health and the environment (Ding *et al*., 2001; Mailu, 2001; Center *et al*., 2002; Mildgley *et al*., 2006). Although no beneficial aspects of the weed were reported by the interviewees, 10% of them also reported its use as a feed for their animals. Following the remarkable spread and enormous impact of the water hyacinth at WSSF and EEPA, management strategy, namely, physical (manual removal, mechanical removal, drying and burning, reduction of water nutrient level) and herbicidal control measures alone or in combination were employed. Even though the application of herbicide proved to be effective in controlling this aquatic weed at WSSF (Firehun and Yohannes, 2008; Dula *et al*., 2008) its use is greatly discouraged because of health and environmental concerns. Moreover, manual removal and burning of the weed has been employed alone on grazing and crop lands located at Koka, Alem Tena and Aba-Samuel which resulted in limited success (Table 6). With integrated use of physical and chemical control measure in reservoirs, irrigation supplies and drainage canals of WSSF, it was possible to achieve successful control (Taye *et al*., 2009). Hence, the rapid proliferation of water hyacinth in Lake Koka, Lake Ellen, and Aba-Samuel Dams (upstream water bodies) could be the result of absence of effective control measures and the wide-spread availability of nutrients in fresh water bodies. Yet, sustainability of the success achieved at WSSF is not guaranteed as the upstream water bodies are still infested with the weed and its extent of invasion increased over years.

Impact of control measure: a case study of Wonji-Shoa Sugar Factory

Water hyacinth was first reported on the irrigation and drainage structures of WSSF in 1996 (Firehun *et al*.,2007; Taye, 2009). The high nutrient inputs from sewerage, factory waste and flooding of additional inputs from the surrounding areas created ideal conditions for the proliferation of the weed mainly on reservoirs, irrigation supply and drainage canals. By the year 2006, it covered about 116.4 ha of water bodies (Firehun *et al*., 2007). An integrated (physical and chemical) control strategy had been exercised in 2006/07 (Dula *et al*., 2008) and reduced water hyacinth to a significant level (> 50%) of its original area (Table 4). Following this control strategy, relatively small cost of weed management was incurred and the water hyacinth infestation had been maintained at approximately <7 % in 2011. The initial investment of the control strategy has played a significant role in reducing the water hyacinth infestation and maintaining its subsequent costs at minimum level. Currently, WSSF incurs a constant cost year to year just to maintain the cleared water bodies and proper water flow of irrigation and drainage canals. At WSSF, the cost of water hyacinth management varied from year to year (Table 7). From 1999/2000 to 2005/06 costs were increasing significantly together with the area of infestation. From 20006/07 to 20010/11 costs reduced significantly following the significant success rate in clearing and maintaining the water bodies. The low cost between 1999/2000 to 2004/05 corresponds with the period where only manual clearing and dredging of the weed were employed. During this period both the manual clearing and dredging of the weed had been employed mainly for canal restructuring purpose not as management of the weed. Hence, the control operations were performed at low-efficiency and focused on removal of the weed from the water bodies and left it on the edge of the irrigation structures and cost allocated was meant for canal maintenance instead of weed management.

Table 5. Respondents' view on water hyacinth in the Rift Valley of Ethiopia

Questions	Water bodies				
	Aba-Samuel Dam	Lake Koka	Lake Ellen	WSSF	EEPA
Awareness about the weed status (%)	(n=35)	(n=65)	(n=40)	(n=45)	(n=10)
Yes	93	92	90	100	100
No	7	8	10	0	0
Means of introduction (%)	(n=32)	(n=60)	(n=36)	(n=45)	(n=10)
With flood	0	13	6	97	45
By foreigners	95	0	3	0	0
With local fishing boats	0	0	3	0	0
With running water	5	87	88	3	55
Impact of the weed on (%)	(n=32)	(n=60)	(n=36)	(n= 45)	(n=10)
Grazing animals only	7	7	23	0	0
Both grazing animals and crop production	68	75	60	0	0
Fishing activities	0	18	0	0	0
Irrigation and drainage system	25	0	17	88	0
Proper water flow	0	0	0	12	16
Power generation	0	0	0	0	84

Table 6. Effect of the implemented management methods on percent weed control, weed count, fresh weight and flower number on selected water bodies

Parameters	Management methods				
	A	B	C	D	E
Percent weed control (%)	0	43.7*	57.5*	81.6**	93.1**
Weed count (No./m^2)	348	196**	148**	64**	24**
Fresh weight (g/m^2)	560	470*	304**	224**	104**
Flower number (No.)	96	56*	36**	20**	12**

Note: Two sample t-test assuming unequal variances was performed for physical control along with preventive measures [B], one time glyphosate application followed by physical control along with preventive measures [C], two times glyphosate application followed by physical control along with the preventive measures [D], and three times glyphosate application followed by physical control along with the preventive measures [E], against untreated check [A]; * and ** indicate significance at 5% and 1% probability level respectively;

Table 7. Area of water bodies infested by water hyacinth, cost for its management and success rate per year at WSSF, Central Rift Valley, Ethiopia

Year	Area infested (ha)	Cost (ETB)	Success rate* (ha of water bodies cleared and/or maintained)	Action taken
1999/2000	< 25	13,500	-	Physical control
2000/2001	ND	18,779	-	Physical control
2001/2002	< 35	25,017	(-15)	Physical control
2002/2003	< 50	25,103	(-25)	Physical control
2003/2004	70	26,485	(-45)	Physical control
2004/2005	116	42,582	(-91)	Physical control
2005/2006	116	189,668	0	Integrated management
2006/2007	66	392,966	50	Integrated management
2007/2008	28	62,716	88	Integrated management
2008/2009	10	9,579	106	Integrated management
2009/2010	7	8,574	109	Integrated management
2010/2011	< 7	7,890	>109	Integrated management
Total cost		822,859		

* = Success rate for the year 2002/03 and 2004/05 was calculated taking 1999/2000 as a base while for the remaining years taking 2004/05 as a base data

The cost of management increased significantly from 2005/06 to 2006/07 which corresponds with WSSF's integrated management strategy employed on the different water bodies based on the level of infestation. The total investment of this control strategy, including the cost of conventional physical control mechanism, was 822,859 ETB from 1999/2000 to 2010/2011. The present investigation indicated that the investment made for integrated control strategy during the period 2005/06 to 2007/08 (645,350 ETB) resulted in a successful management of the weed. It effectively and significantly reduced the level of infestation from 116.4 ha to less than 7 ha and then maintained more than 88 ha of water bodies free of this weed over the past five years. According to the assessment made in 2004/05 in the estate, it was noted that from the two highly infested water reservoirs a total of 393,660 to 2,945,160 m^3 water was lost via transpiration (Firehun *et al*., 2007). This amount of water could irrigate an additional 31 to 233 ha of land in a given cropping season. The drainage system blockage by the weed which contributes for the rise of ground water table and flooding problems were prevalent in the sugar estate. With the implementation of integrated management strategy, it was possible to reinstate the two highly infested water bodies, ensure proper drainage of irrigation and waste water, which consequently helped to alleviate the detrimental effects of the weed in the factory. As explained by the effect of water loss, flooding, ground water table rise and its associated cost of mitigation, the employed management strategy of water hyacinth in the factory delivered significant return and justified the investment. However, in order to ensure sustainability of the present success, it is vital to have effective management strategy on the site and the upstream water bodies.

Conclusion

Water hyacinth was introduced in the water bodies of the Rift Valley in the 1950s as an ornamental plant. After infesting Aba-Samuel Dam, it eventually spread in to Lake Koka, Lake Ellen, Koka Dam and Wonji-Site; where its proliferation was spectacular, resulting in an enormous socio-economic impact. Currently, the weed is distributed in the Rift Valley water bodies located in low, mid and high altitude. The low altitude water bodies infested by water hyacinth include Lake Abaya, Lake Koka, Koka Dam, irrigation and drainage structures along Awash River located at Koka and Awash. The mid and high altitude infested water bodies include the two lakes located in Alem Tena site (Lake Ellen and Lake Elltoke) and Aba-Samuel Dam, respectively. Extent of water hyacinth infestation showed the most massive coverage at Lake Koka, Lake Ellen, Aba-Samuel Dam and Koka Dam towards 2011. Univariate as well as PCA analysis indicated that the main factors representing the majority of correlations with water hyacinth coverage are associated with five factors (i.e., rainfall, N content, P content, wave action on the water bodies and depth of the water bodies). The estimates of hyacinth mats show reductions in the extent of hyacinth coverage during the last three years at Wonji-Shoa. A case study on the impact of control measure indicated that following the implementation of integrated management strategies at WSSF, it was possible to maintain proper water flow in irrigation and drainage canals. However, in order to ensure sustainability of the present success, it is vital to have an effective management strategy on the site and the upstream water bodies.

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