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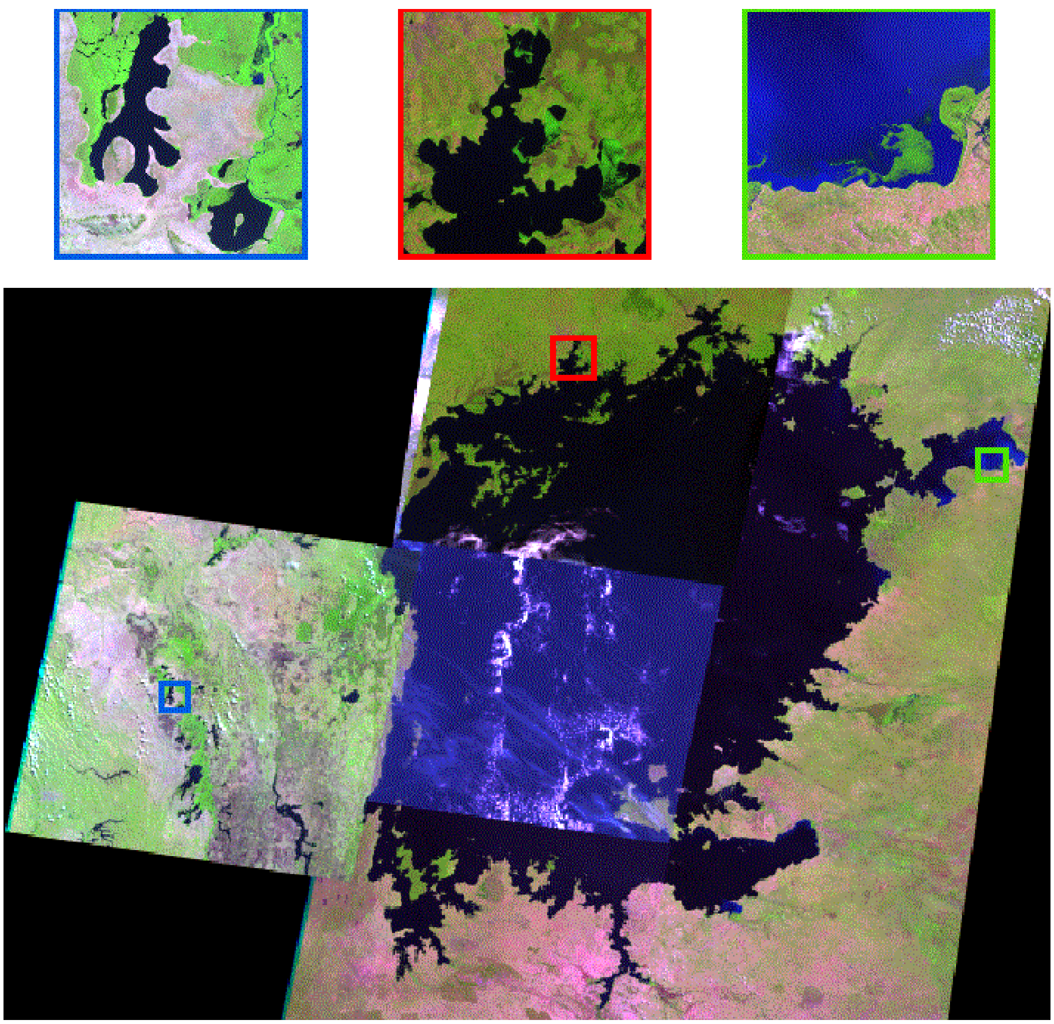
The Abundance and Distribution of Water Hyacinth in Lake Victoria and the Kagera River Basin, 1989-2001



About the cover: This graphic is from an image mosaic developed from a number of Landsat 5 TM and Landsat 7 ETM+ images acquired between 1995 and 2001. Bands 5, 4, and 3 are assigned to the red, green, and blue color channels, respectively. This color combination results in clouds being white, water being black, photosynthetically active vegetation, including water hyacinth, being green, and drier, less vegetated land being tan to pink. The magnified portions show areas of water hyacinth infestation in Rwanda, Uganda, and Kenya, respectively.

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The Abundance and Distribution of Water Hyacinth in Lake Victoria and the Kagera River Basin, 1989-2001

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Abstract: Water hyacinth (*Eichhornia crassipes* (Mart.) Solms) is an invasive aquatic macrophyte associated with major negative economic and ecological impacts to the Lake Victoria region since the plant's establishment in the 1980s. In order to assist the management and mitigation of this problem, Clean Lakes, Inc. and the U.S. Geological Survey's EROS Data Center have acquired and analyzed remotely sensed imagery, conducted field work, and compiled reports to document the abundance and distribution of this plant, from its establishment to the present day. Remotely sensed imagery was processed and analyzed to identify areas occupied by water hyacinth. Maps were produced and coverage was quantified for each of the riparian countries, as well as for numerous gulfs and bays. A similar procedure was carried out for selected lakes in the Rwanda-Tanzania borderlands lakes region in the Kagera River basin. Results confirm the severity of the water infestation – especially in the northern portions of the lake. A maximum lake-wide coverage of approximately 20,000 ha was attained in late 1998. Following this, a combination of factors, including management practices and probable changes in environmental conditions, contributed to a major decline in water hyacinth in the most affected portions of the lake. Recent data show that low levels of water hyacinth are present in most portions of the lake suitable for growth. Water hyacinth may remain approximately at these levels indefinitely if active management continues and environmental conditions are maintained. Results in the Kagera basin indicate that some lakes were severely infested in the late 1990s, but that the severity of infestation in most of these has decreased significantly since then. Non-remotely sensed estimates of water hyacinth coverage compiled from pre-existing published reports are highly inconsistent and should be used only with caution.

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[1] Work performed under U.S. Geological Survey contract 1434-CR-97-CN-40274.
[2] This paper is preliminary and has not been edited or reviewed for conformity with U.S. Geological Survey standards for nomenclature.
[3] This paper was made possible through support provided by the USAID/Uganda, Greater Horn of Africa Initiative (GHAI), U.S. Agency for International Development, under the terms of Cooperative Agreement No. 617-A-00-99-00008-00 with Clean Lakes, Inc. The opinions expressed herein are those of the author(s) and do not necessarily reflect the views of the U.S. Agency for International Development.

Introduction

Water hyacinth

Water hyacinth (*Eichhornia crassipes* (Mart.) Solms) has been described as the world's worst aquatic weed. It is native to the northern neotropics of South America; it spread to southern North America about 1860; in Africa it arrived first in Egypt about 1879; in Asia around 1888 in India, 1894 in Java, and about 1900 in Japan; in Australia it arrived in about 1890 (Cook, 1990). Water hyacinth is classified as a floating aquatic plant since its bulbous air-filled petioles allow the plant to freely float on water surfaces. When this exotic plant is introduced into uninfested areas, it may explode into large infestations causing serious disruption to environments, economies, and societies. Aquatic weed species have been defined as, "an aquatic plant (or group of plants) which is not desired by the manager(s) of the water body where it occurs, either when growing in abundance or when interfering with the growth of crop plants or ornamentals" (Pieterse, 1990).

Since officially being recognized in Lake Kyoga in May 1988 (Twongo, 1991), water hyacinth was soon reported in Lake Victoria, Uganda in 1989 (Twongo, 1991); Lake Victoria, Tanzania in 1989 (Bwathondi and Mahika, 1994), Lake Victoria, Kenya in 1990 (Mailu, Ochiel, and others, 1998), and the Kagera River of Rwanda in 1991 (Taylor, 1991).

Lake Victoria and the Lake Victoria basin

Lake Victoria measures over 68,000 km^2, making it the world's second largest fresh water lake in surface area (Figure 1). It is shared by Kenya, Tanzania, and Uganda, who control 6, 49, and 45% of the lakes surface waters, respectively. The lake is important for the region's inhabitants through the supply of drinking water, power generation, fisheries and food security, transportation, and ecological stability. The lake catchment is approximately 184,000 km^2 in size and supports a population of over 25 million people. The economy of the lake catchment has an estimated worth of US$ 3-4 billion annually, with the lake fishery benefiting the livelihood of at least 500,000 persons and having a potential sustainable fishery export value of $288 million (LVEMP, 1996). Economic benefits associated with power generation, tourism, clean drinking water, transportation, biological diversity, and other benefits add significantly to the value of the lake and Kagera River basin economies.

Effects of water hyacinth invasion in Lake Victoria

Unmanaged water hyacinth populations create serious impacts that ripple through infested areas. Effects of infestations in the region and worldwide are varied and well documented (Denny, 1991; Gallagher and Haller, 1990; Harley, 1991; Mailu, Ochiel, and others, 1998; Mitchell, 1990). These impacts include: impeding transport of irrigation and drainage water in canals and ditches; hindering navigation; interfering with hydroelectric schemes, increasing sedimentation by trapping silt particles, decreasing human food production in aquatic habitats (fisheries, crops); decreasing the possibilities for washing and bathing; and adversely affecting recreation (swimming, water-skiing, angling) (Pieterse, 1990). Additional impacts include hindering the processing and delivery of municipal and industrial water supplies, threatening structures such as low bridges and pipelines, creation/aggravation of human health hazards (harboring Bilharzia, venomous snakes, and possibly Cholera), the transformation of aquatic habitats into wetland or terrestrial habitats through succession by other plant species,

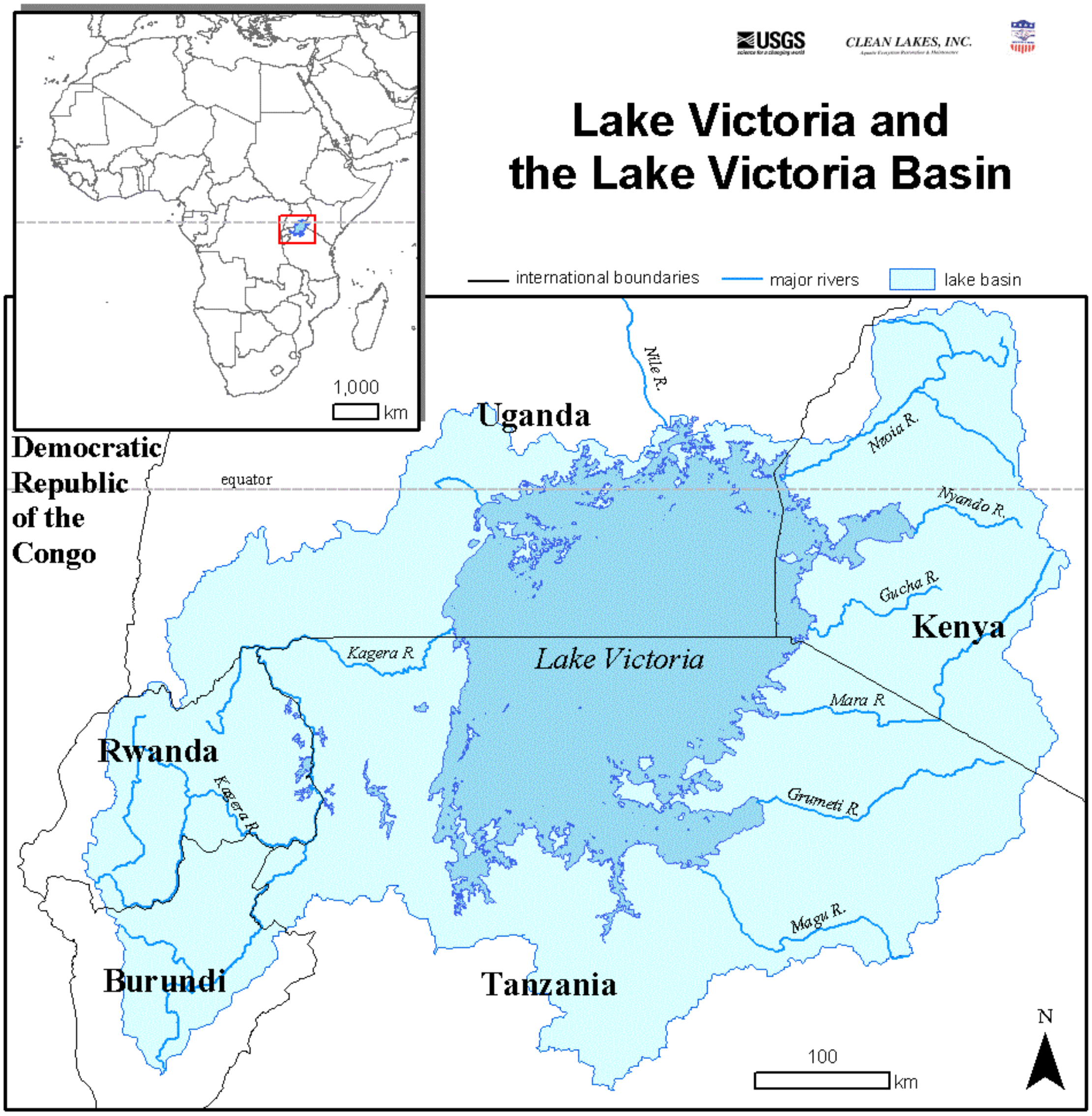

Figure 1. Lake Victoria, its catchment (shown in light cyan), and major rivers.

and displacement of native flora and fauna not able to compete or survive in infested environments.

Water hyacinth is distributed throughout the near shore portions of Lake Victoria and up to the headwaters of the Kagera River in the highlands of northern Rwanda. In Rwanda, water hyacinth has been identified in the upper reaches of the Mukungwa River, south of Ruhengeri town at an elevation of 1649 m above sea level. The Kagera Basin infestation spreads south along the Mukungwa River until the Nyabarongo River joins it. From this confluence, the Nyabarongo River continues in a south to southeasterly direction where it joins a small river leading out of Lake Rweru, a transboundary lake shared by Burundi and Rwanda, at which point the river becomes known as the Akagera River. The Akagera River then flows in an easterly direction passing over the Rusumo

Falls (approximately 15 m in height), which severely damages the water hyacinth. The Akagera River then takes a northerly course along the Rwanda/Tanzania border, passing through the lake and swampland valley of the Akagera National Park. Several lakes are infested with water hyacinth in this area – most significant among them is Lake Mihindi, at the northern end of the Park. As the river continues north it arrives at the Uganda border where it again turns primarily eastward, becomes known as the Kagera River, and passes mostly through Tanzania before discharging into Lake Victoria. Clean Lakes, Inc. (CLI) staff have visually estimated the amount of water hyacinth pouring into the lake. Within 1 km of Lake Victoria, the daily rate flowing down the Kagera River ranges from 0.2 ha/day to more than 1.5 ha/day (an average 0.75 ha/day or 300 ha/year), depending on seasonal river volume conditions (Moorhouse, Asiimwe, and others, 2002). In total, the Kagera river system is some 500 km in length with approximately 160 km of that total length flowing through the flatter waters of Tanzania.

Management programs/control efforts

Efforts to control water hyacinth in Lake Victoria and the Upper Kagera River of Rwanda during the early 1990s where primarily directed at manually removing water hyacinth and public awareness exercises. With water hyacinth weighing up to and even exceeding 400 tons/ha, manual removal efforts were limited in success. Upon successful trials of two *Neochetina* weevil species, Uganda commenced a biological control/release program on Lake Victoria in late 1995 through collaborative local and international efforts. Beginning in 1996, Uganda proceeded in earnest with mechanical removal operations, herbicide trial demonstrations, and environmental impact assessment (EIA) efforts through support from the United States Agency for International Development (USAID), the Dutch government, the United Nations Development Program, the Japanese government, and others in cooperation with various ministries and departments with management/control efforts led by the Water Hyacinth Unit of the Ministry of Agriculture, Animal Industries, and Fisheries. The outcome of the EIA process resulted in government approval for biological control using *Neochetina* weevil species, and mechanical control. The herbicide option was deferred pending further study and regional consensus. In 1997, the Lake Victoria Environmental Management Program (LVEMP) began supporting water hyacinth control at the country level (Kenya, Tanzania, and Uganda). Weevil releases began in Kenya in January 1997 (Ochiel, Mailu, and others, 1999). Tanzania began releases of *Neochetina* weevils in August 1997 in Lake Victoria (Mallya, 1999). A “chop and sink” exercise contracted under LVEMP Kenya between December 1999 and April 2000 was also employed with the goal of reducing the equivalent of 1500 ha of water hyacinth. Noticeable reductions around the lake began in late 1998 to early 1999. This reduction was coincident with a rapidly increasing population of weevils and followed the El Niño rains of late 1997 to early 1998. While the exact linkages between these events and the water hyacinth infestation are not certain, records indicate that lake levels rose 1.8 m and severe weather on the lake created high wind and wave action that supported the break down of weakened plants. A variety of pathogens have been isolated from the plants, which could also have had an important contributory role in reducing plant populations (Godonou, 2000). The East Africa Community (EAC), realizing the importance of this regional problem, established a Ministerial Committee on Water Hyacinth in 1998 and had prepared a Regional Strategy and Action Plan to further the management and coordination of control activities by mid 1999. The Kagera Agricultural and Environmental Management Program (KAEMP) of Tanzania began weevil rearing and followed with releases at several points in the middle Kagera River system beginning in

December 1999. Supported by USAID, Clean Lakes, Inc. supported efforts in Rwanda through a cooperative agreement that led to weevil rearing facility establishment and releases that began in September 2000.

Need for monitoring information

Information on the distribution and extent of water hyacinth is crucial in order to understand the evolution of the invasion, determine affected areas, relate water hyacinth abundance with environmental parameters, and to gauge efficacy of control measures and management actions. In support of water hyacinth management and control efforts, a monitoring program demonstration was established with USAID funding through Clean Lakes, Inc. and the U.S. Geological Survey's EROS Data Center (USGS). The two primary objectives of the monitoring program were to 1) assess the suitability of monitoring tools, including remote sensing and GIS, in the East African context, and 2) apply these tools to document the invasion of water hyacinth in terms of distribution and extent in Lake Victoria and select portions of the Lake Victoria basin. The first objective was addressed by research that is described in a report entitled, "Systems for Monitoring Water Hyacinth in the Lake Victoria Basin, East Africa" (USGS/CLI, 2000). This current report addresses the second objective of this monitoring program. The goal of this study is to provide quantitative and spatially explicit information on the distribution and extent of water hyacinth in Lake Victoria and select portions of the Lake Victoria basin from the early phases of the infestation to the present time, and to analyze this information in relation to potentially influential factors such as weather, water level fluctuations, and control measures.

Remote sensing

Remote sensing can be defined as "the acquisition of information about an object without being in physical contact with it" (Elachi, 1987). However, common usage of the term excludes ground observation (and ground photography) and visual inspection from the air or otherwise. Satellite and airborne remote sensing offer several key advantages for monitoring water hyacinth in East Africa. First, it affords a synoptic view, allowing large portions or even the entirety of the lake and its basin to be seen at once. Second, remote sensing offers a variety of sensors that obtain spatially and radiometrically characterized measurements of regions of the electromagnetic spectrum to which the human eye is not sensitive. Third, information obtained from remote sensing may be readily incorporated in geographic information systems, thus facilitating the measurement of areas, spatial analyses, comparisons among different dates, and creation of maps. Finally, the array of spaceborne sensors currently in orbit permits repeat measurements and consistent analyses.

Methods

The primary remote sensing task in this study was to discriminate water hyacinth from other image constituents such as open water, land, waves, and other types of vegetation. To accomplish this, a variety of spaceborne and airborne sensors were employed. Table 1 summarizes the key characteristics of the systems used in this study. The reader is referred to USGS/CLI, 2000 for a more detailed account of sensors and systems suited to monitoring water hyacinth.

Table 1. Characteristics of spaceborne sensors used

Sensor	Bands/ spectral regions	Ground sample distance	Scene dimensions (w x h)	Potential acquisition frequency	Period of availability	Other considerations
Landsat TM	6 bands optical, 1 band thermal	28.5 m 120 m	183 x 170 km	every 16 days at equator	1982 to present	• not currently recording images of East Africa
Radarsat	1 band C band radar, HH polarization	100 m (ScanSAR wide) 50 m (ScanSAR narrow) 25 m (standard) 8 m (fine)	500x500 km (ScanSAR wide) 300x300 km (ScanSAR narrow) 100x100 km (standard) 50x50 km (fine)	user scheduled acquisition, up to 3-4 x/week depending on mode.	1995 to present	• cloud penetration • many different resolutions, modes, look angles available • pointable • restrictions on distribution
Landsat 7 ETM+	7 bands optical, 1 band thermal, 1 band panchromatic	28.5 m 80 m 15 m	183x170 km	every 16 days at equator	1999 to present	• when cloud-free & available, efficient method of gathering data on water hyacinth distribution and coverage
JERS SAR	1 band L band radar, HH polarization	18 m	75 km x 75 km	every 44 days	1992-1998	• a 100 m resolution mosaic product was used for this study • cloud penetration
Ikonos	4 bands: blue, green, red, near infrared + panchromatic	4 m (multispectral) 1 m (panchromatic)	User selected (minimum size: 5 km x 5 km)	Revisit every 3 days at equator, acquisitions on request	1999 to present	• panchromatic and multispectral sold separately • restrictions on distribution • pointable

Selection of image data sets

Cloud-free or otherwise unimpeded imagery of the lake was sought from these sensors at a variety of time periods and at a variety of resolutions. In some cases, particularly during the historic period, suitable imagery at the desired time was not available. In the current time period however, (defined as 2000-2001 – the period during which the study was conducted) the possibility existed to request specific acquisitions for some of the sensors. Generally speaking, there is a trade-off between resolution and coverage, with coarse resolution sensors, defined for our purposes as having 50 m sized pixels or greater, offering large area and even lake-wide views and medium- to high-resolution sensors offering more detailed perspectives on limited areas. Regarding the selection of dates, with general knowledge of when the peak of infestation occurred in different parts of the lake, imagery was sought prior to, after, and especially during the peak. Thus, an attempt was made to balance these considerations and order imagery such that every portion of the lake was covered on a minimum of five dates, with additional imagery of sensitive areas, as indicated through discussions with stakeholders from the various countries, or where infestation was known to have been most acute (Table 2). Note that the 1997/04/19, 1997/07/26, and 2001/01/19 imagery, which was provided by Synoptics BV, was in a three-date composite RGB-clustered format, rather than raw imagery.

Table 2. Imagery used in study

Date	Sensor/mode	Cell size	Location
8 Oct 1994	Landsat 5 TM	30 m	Eastern third of Lake Victoria (path 170, rows 60-62)
19 Jan 1995	Landsat 5 TM	30 m	NW Lake Victoria (path 171, row 60)
8 Mar 1995	Landsat 5 TM	30 m	SW Lake Victoria (path 171 row 62)
Jan-Mar 1996	JERS (mosaic)	100 m	Lake-wide, Rwanda
Oct-Nov 1996	JERS (mosaic)	100 m	Lake-wide, Rwanda
6 Dec 1996	Radarsat ScanSAR Narrow B	50 m	SW Lake Victoria
19 Apr 1997	Radarsat ScanSAR Wide B	100 m	Lake-wide, Rwanda
4 Mar 1998	Radarsat ScanSAR Wide B (from RGB composite)	100 m	Lake-wide
29 May 1998	Radarsat Standard Beam 1	25 m	Winam Gulf
26 July 1998	Radarsat ScanSAR Wide B (from RGB composite)	100 m	Lake-wide except southern fifth
6 Nov 1998	Radarsat Standard Beam 4	25 m	Winam Gulf
12 Apr 1999	Radarsat Standard Beam 7	25 m	Emin Pasha Gulf
10 Jun 1999	Radarsat Standard Beam 7	25 m	Murchison Gulf
8 Jul 1999	Landsat 7 ETM+	30 m	Rwanda/Tanzania lakes (path 172, row 61)
12 Sep 1999	Landsat 7 ETM+	30 m	SE quadrant of lake (path 170, rows 61, 62)
5 Oct 1999	Landsat 7 ETM+	30 m	NW Lake Victoria (path 171, row 60)
17 Dec 1999	Landsat 7 ETM+	30 m	NE Lake Victoria (path 170, row 60)
12 Feb 2000	Radarsat Standard Beam 6	25 m	Winam Gulf
16 May 2000	Landsat 7 ETM+	30 m	SW Lake Victoria (path 171 row 62)
10 Oct 2000	Ikonos	1 m, 4 m	Lac Mihindi, Rwanda
20 Oct 2000	Ikonos	1 m, 4 m	Lac Mpanga, Rwanda
27 Jan 2001	Landsat 7 ETM+	30 m	Western 2/3 of Lake Victoria (path 171, rows 60-62)
5 Apr 2001	Radarsat ScanSAR Wide B (from RGB composite)	100 m	Lake-wide
10 May 2001	Landsat 7 ETM+	30 m	Rwanda/Tanzania lakes (path 172, row 61)
12 May 2001	Landsat 7 ETM+	30 m	Eastern third of Lake Victoria (path 170, rows 60-62)
27 Nov 2001	Landsat 7 ETM+	30 m	SW Lake Victoria (path 171 row 62)

The JERS imagery was obtained from NASA as part of the Global Rainforest Mapping Program's 100 m resolution mosaic. In addition to the imagery, reference maps for the region were acquired.

The extraction of information on water hyacinth extent and distribution from the imagery proceeded according to the accompanying flow chart (Figure 2).

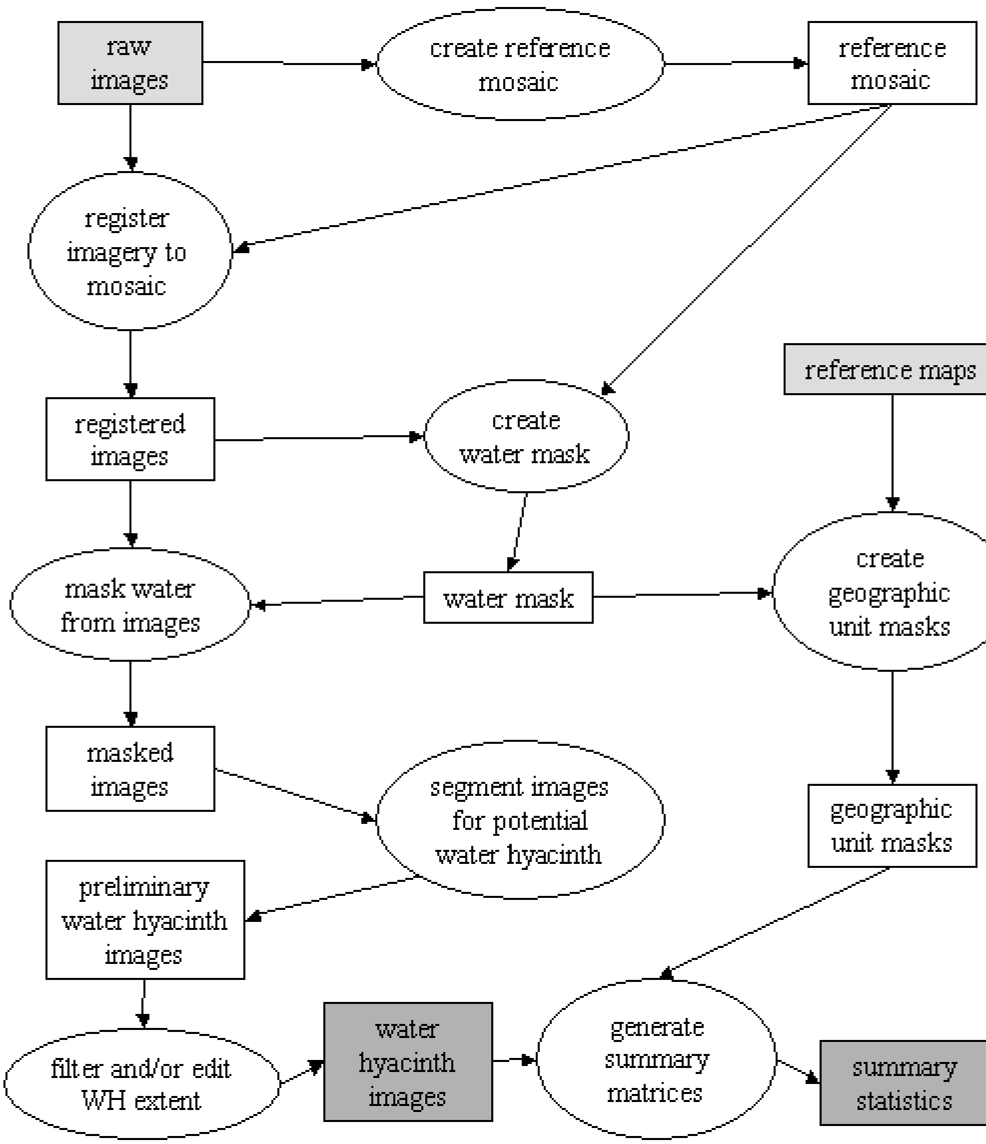

Figure 2. Outline of the procedure used for extraction of water hyacinth distribution and extent from remotely sensed imagery

Development of Lake Victoria mosaic and coregistration of imagery

While nearly all the imagery was received in UTM zone 36 projection (WGS84 datum), it was necessary to perform minor registration adjustments in order to ensure a high quality coregistration among all images. Recent Landsat ETM+ images, which are precisely geolocated, were selected as the reference projection.

The first image processing step was to produce from Landsat ETM+ imagery a reference mosaic, which merges adjacent and overlapping images into one image. The images were coregistered to eliminate minor differences in position and mosaicked using a simple overlay function with no resampling. All remaining imagery were then registered to the reference mosaic using either an X/Y offset adjustment or a 1st order polynomial transformation with nearest neighbor resampling.

Development and application of water mask

A key element to the monitoring effort was to develop a high-resolution map of the open water areas of Lake Victoria and selected lakes in the Rwanda-Tanzania borderlands area. There are many features on land as well as permanent wetlands with reflectance and backscatter characteristics that resemble water hyacinth. By removing these areas from consideration with a water mask, the task is simplified greatly. Existing maps of the lake proved to be of insufficient resolution and quality (for instance, not distinguishing open water from wetland areas) for such a task. The first step in creating a master water mask was to generate single-date water masks from the multiple dates of imagery available. To generate these, a combination of unsupervised classification and the identification of suitable intensity thresholds (thresholding) was performed. In the former, up to 250 statistically distinct spectral clusters were identified using an ISODATA algorithm on the ERDAS Imagine 8.4 software package. Clusters corresponding to open water were then identified and grouped to create a water mask. In some cases, clouds, land, vegetation, and other constituents were also identified. Thresholding was also performed on radar data and, in some cases, on ETM+ data on which a wetness index ((band 4 – band 5)/(band 4 + band 5)) had been calculated. The variety of techniques used was due to the variety of sensors used, the varying scene conditions, and to experimentation. The single-date masks were then used to identify maximum water extent such that if a pixel had been identified as water on any single date, it would be considered water for the purposes of the master water mask. There are some complications with this approach relating to fluctuating water levels, which may change the water extent on different dates and due to changes in aquatic vegetation, which may vary in coverage on different dates. Once the mask was complete, it was applied to the imagery and areas that were never occupied by open water were removed.

Preparation of geographic area definition masks

Lake Victoria is divided among three countries and can be further divided into numerous bays, gulfs, and sounds. A 1:1,000,000 scale country boundary vector data set was obtained and used to divide the water mask into Kenyan, Tanzanian, and Ugandan portions. Using locally available maps and charts, numerous bays, gulfs, and sounds were defined on the water mask by performing on-screen digitizing on the water mask image. A similar procedure was performed for the lakes of the Rwanda-Tanzania border region in the Kagera Basin. These units were used as a frame of reference for reporting the location of infestations and as reporting units upon which statistics were calculated and reported.

Extraction of potential water hyacinth from water-masked imagery

This section describes the process of spectrally determining the areas of potential water hyacinth in the images, the areas free of potential water hyacinth, and, when appropriate, the areas obscured by cloud cover and/or image noise. Clouds and noise that obscured observation were placed into the “no data” category since, as in areas with no data, it was not possible to discern the presence or absence of water hyacinth in these areas. This portion of the analysis varied according to the sensor employed, and is thus described separately. For the purposes of this discussion, potential water hyacinth was defined as areas having a spectral signature or high backscatter characteristic of aquatic vegetation that could include water hyacinth, but also other vegetation, and, in the case of radar data, waves, islands, ships and their wakes, and occasionally image noise.

TM/ETM+ imagery

All images analyzed included a minimum of bands 3, 4, and 5, with some also including other optical bands, according to analyst preference (Figure 3a). In some cases, when cloud cover was prevalent, clouds were removed using a masking procedure. In early stages of the analysis, experimentation incorporated band 8 (15 m panchromatic) and band 6 (thermal) in order to increase resolution (in the case of band 8) and aid in discrimination of water hyacinth. These bands were not found to improve the results significantly and were not included for subsequent areas. In some cases, the spectral clusters that were used to define the water mask were also used to discriminate potential water hyacinth from other scene constituents. In most cases this was not satisfactory and a second unsupervised classification was performed on the water-masked data set (Figure 3b). For the Rwanda-Tanzania lakes region, a wetness index was calculated and used as classification and/or thresholding input.

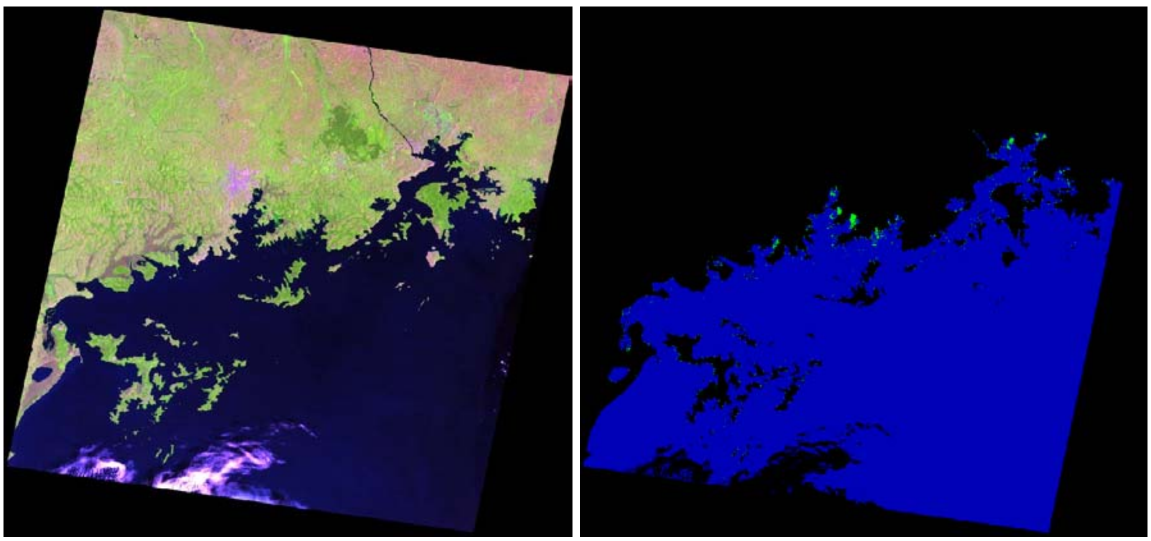

Figure 3. a) (at left) a coregistered 19 January 1995 band 5,4,3 ETM+ image of the NW Lake Victoria area (Uganda). b) (at right) Results of the unsupervised classification in which potential water hyacinth (green) is separated from open water (blue) and areas of cloud or no data (black). Land and permanent aquatic vegetation area, also in black, were removed prior to the unsupervised classification.

Ikonos imagery

The procedures for extracting potential water hyacinth from Ikonos imagery were largely the same as Landsat TM/ETM+ imagery, except that there was no equivalent to TM/ETM+ band 5, so instead, the green, red, and near-infrared bands were used. One other difference is that a spatial texture band was calculated from the 1 m resolution panchromatic band to be used as input in the unsupervised classification. The thought was that different spatial texture values captured by the high-resolution data might be associated with water hyacinth.

Radarsat standard beam imagery

Radar imagery is subject to highly variable image speckle, owing to the coherent nature of the backscatter returns. In order to minimize this, it is sometimes necessary to use a speckle reduction filter, which seeks to minimize this fine scale noise, while maintaining the detail inherent in the image. In addition or instead, the imagery can be “multilooked”

or resampled to a coarser resolution so that much of the noise is cancelled out. These techniques were performed on the Radarsat standard beam imagery. The radar images used in this study were all single band images. Thus, a threshold value for each image beyond which pixels were labeled as potential water hyacinth was identified.

Radarsat ScanSAR and JERS imagery
Speckle did not appear to be as significant an issue with the coarser resolution Radarsat ScanSAR imagery and with the JERS mosaic data. Further speckle reduction was not necessary, so the study proceeded to identify and apply a threshold value in order to identify potential water hyacinth.

Radarsat RGB clustered imagery
For the RGB-clustered ScanSAR imagery, clusters were identified that were associated with the presence of potential water hyacinth on each of the three dates, and on the various combinations of dates (Figure 4a). Separate image files were then created corresponding to the presence of potential water hyacinth on each of the dates included in the RGB cluster (Figure 4b-d).

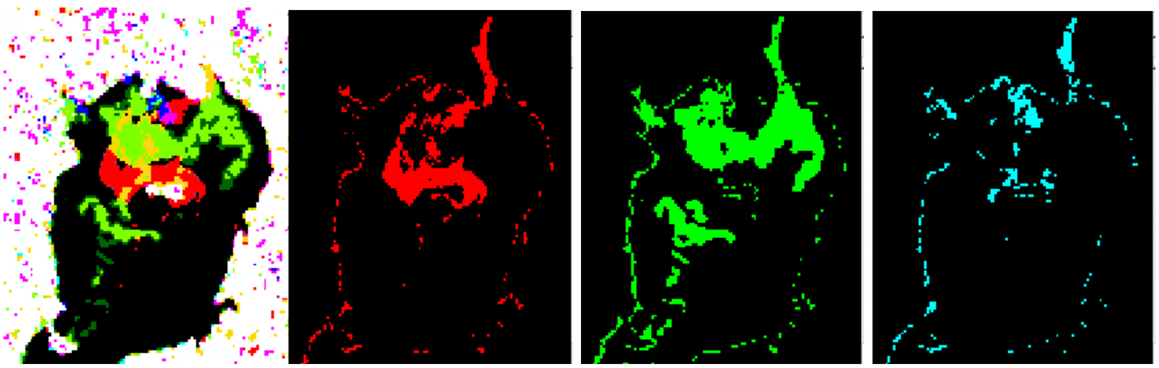

Figure 4. (from left) a) The Murchison Bay portion of the color-coded RGB-clustered Radarsat ScanSAR wide B image. b) The 4 March 1998 potential water hyacinth component. c) The 26 July 1998 potential water hyacinth component. d) The 5 April 2001 potential water hyacinth component.

Post-classification filtering and editing

While in some cases the results of the thresholding and classification were quite satisfactory, it was usually necessary to perform some spatial filtering and/or manual editing in order to improve the quality of the determination of areas covered by water hyacinth. Depending on scene characteristics, a 3 x 3 spatial majority filter was applied, or an elimination routine to generalize the data and eliminate extremely small specks that often correspond to noise. In the 3 x 3 majority filter, a moving window is applied to the data and, for each pixel, the value is defined as the value that has majority status in the 9 pixels defined by the 3 x 3 window. The elimination routine identifies isolated pixel clumps sharing a certain value. If the size of the clumps is less than a certain threshold, the pixels are reclassified as having the dominant background value. The motivation for these routines is to eliminate small, often noise-related, pixels spuriously misclassified. The primary benefit is in areas on the edge of the mask. Due to small variations in the coregistration of images and different pixel sizes used, there were frequently areas of shoreline on the initial classification that were misclassified as water hyacinth that were more likely land or permanent aquatic or wetland vegetation (Figure 5).

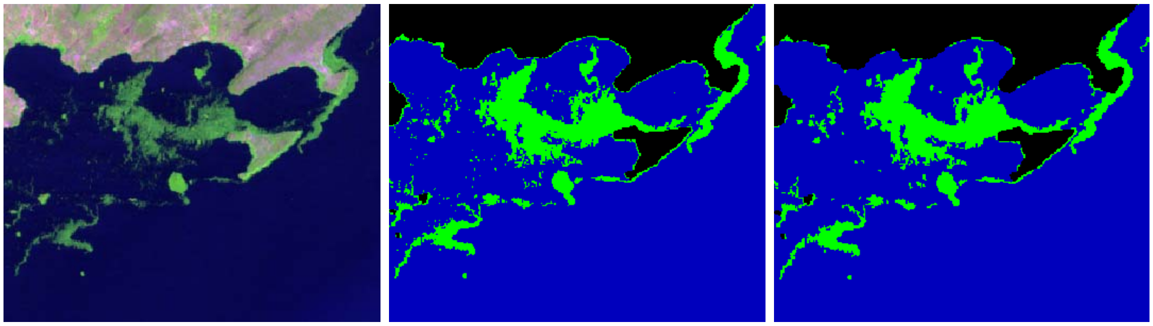

Figure 5. (from left) a) A portion of a 17 December 1999 band 5,4,3 ETM+ image in Winam Gulf, Kenya. b) After masking and unsupervised classification. c) After a 3 x 3 majority filter and after clumps of fewer than 3 pixels were eliminated. Note the disappearance of much of the shoreline fringe and some of the smaller speckled patches of water hyacinth.

Final determination of water hyacinth was made with manual editing. Sometimes, spectral means and filtering would not adequately identify water hyacinth. In these cases, “false positives” were removed or, in rare cases, pixels were reclassified as water hyacinth where “false negatives” had occurred. This was done by systematically viewing the image and classification and recoding the image map with screen digitized polygons. Such manual edits were especially crucial for extracting water hyacinth information from lower resolution satellite imagery, which is subject to significant error caused by coregistration and resolution issues (Figure 6). In addition to intensity and color, manual edits were based on context, texture, and other factors that the human eye and mind are better at identifying than most computer-based methods. Manual editing is facilitated by interactively overlaying coregistered images from multiple dates, allowing discrepancies and errors to be efficiently spotted.

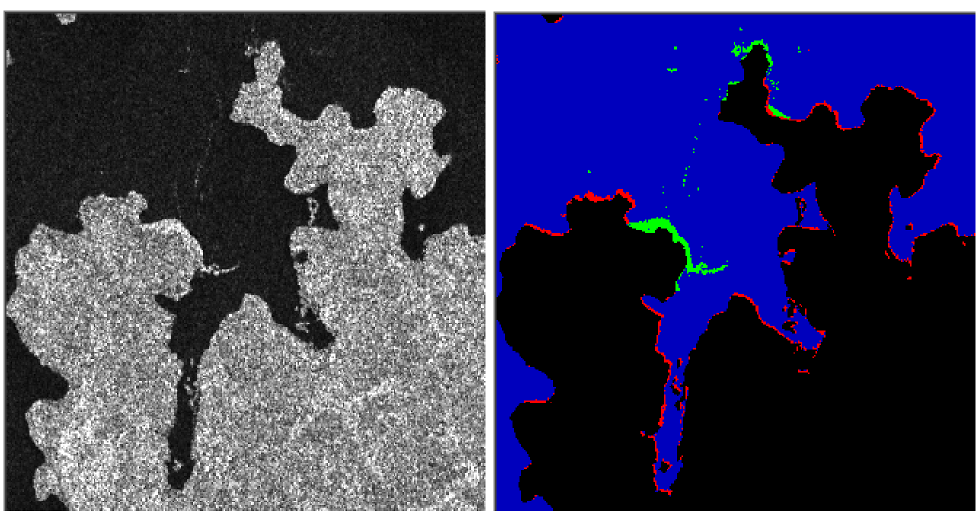

Figure 6. (from left) a) a Butundwi Bay (Emin Pasha Gulf, Tanzania) portion of a 6 December 1996 Radarsat ScanSAR narrow B image. b) The edited water hyacinth image, with manually confirmed water hyacinth shown in green. Red areas are those that were identified by thresholding and masking to be potential water hyacinth, but when examined manually, determined to be errors associated with the coarse resolution, changes in water levels, and imperfections in coregistration. Such editing is less necessary when using higher resolution data.

Compilation of area statistics

The area and fraction occupied by each of the three classes (water hyacinth, not water hyacinth, and no usable data) was determined in the various geographic unit zones defined (countries, gulfs, bays, and lakes). This was determined by performing a cross tabulation using the summary function of ERDAS Imagine for each of the water hyacinth classified images and each of the geographic area unit masks. The results of each cross tabulation were a matrix containing the number of pixels in each of the three classes in each of the geographic area units of interest. These matrices were imported into an Excel spreadsheet and developed the spreadsheet in order to convert the pixel information to fraction and area information according to the parameters of each image source. Furthermore, the area of each zone was tracked for which useable data was not available – that is, if part of the zone fell outside of the image or if it was impeded by cloud cover.

Compilation of published reports

In order to supplement, compare, and corroborate the image analysis, a small database of published water hyacinth reports and estimates (see Annex 1) was compiled for various portions of Kenya, Tanzania, Uganda, and Rwanda. The information is presented by day, month and year for the estimate; the number of hectares estimated, the location, and the source of the report. This collection of estimates is by no means exhaustive, but it does represent, for the most part, the more authoritative estimates made. While the reliability of these sources varies widely and is not always possible to assess, the authors feel that these represent a valuable resource, particularly when they are the only source of information available.

Most estimates were derived based on ground surveys by boat or from land. Some estimates were supported through aerial visual surveys and oblique 35 mm camera photography, while specific instance of satellite imagery where used by Synoptics. Though most these estimates lack the precise quantification available through remote sensing, professional level aerial photography, and GIS, these reported estimates, in many cases, provided the only means of documenting the extent of the infestation at that time. In some cases these ground-based surveys were fairly accurate, while others were much over or understated.

Results

Complete tabular results for the reporting units can be found in Annex 2. Summary results at a lake-wide scale are portrayed in Figure 7. This figure is meant as a general guide to the relative severity of the infestation in various portions of the lake. The relative severity index employed in the map was derived from all imagery used for each of the bays, gulfs, and sounds in the study and is defined as follows: *negligible* – never more than 0.5% of area of feature visible covered by water hyacinth; *slight* – at least one image showing more than 0.5%; *moderate* – at least two images showing more than 2%; *severe* – at least two images showing more than 7%. At least two images exceeding the threshold values were required to meet the definition of moderate and severe in order to reduce the effect of outlier observations.

It must be emphasized that the dynamic nature of water hyacinth and the time between image acquisitions of a given area mean that significant infestations of a specific area

may have been missed by the imagery altogether. Furthermore, the resolution of the sensors employed limit detection of water hyacinth to at least small to medium sized (> 0.1 ha for a 30 m resolution sensor) free-floating mats and very large (> 50 m in width for a 30 m resolution sensor) shoreline infestations. Thus, it is possible that local residents, researchers, and others may perceive an infestation of a specific area as having been quite significant even if it is in a bay that is labelled as having negligible water hyacinth. A more complete discussion on possible sources of error and their implications follows the presentation of results.

Infestation of the northern, Kenyan and Ugandan portions of the lake was more severe than in the southern, Tanzanian waters. This broad preference for northern portions of the lake may be linked to currents and weather patterns, which may push water hyacinth in this direction, but may also be associated with more suitable water hyacinth habitat and possibly higher levels of eutrophication associated with agricultural practices and the larger urban areas of these portions of the lake.

The evolution of water hyacinth extent between 1996 and 2001 is shown in Figure 8. Here, it can be seen that between 4000 and 6000 ha were present on the lake between 1996 and 1997. Then a large surge occurred in 1997 and 1998, followed by a decline to low levels at some time between 1999 and 2000. The peak amount of water hyacinth on the lake determined directly from the imagery was 17,374 ha on 4 March 1998. However, by November of the same year, 17,231 ha were present in Winam Gulf alone, which constitutes less than 5% of the entire lake. Thus, we infer that approximately 20,000 ha were present on the entire lake at this time. Previously published lake-wide estimates are highly variable and generally higher than the estimates provided in this study (Figure 9).

In the section that follows, more detailed findings are presented on a country by country basis by proceeding in rough chronological order of major infestation – that is: Uganda, Tanzania, and Kenya. This is followed by a presentation of findings for the Rwanda-Tanzania borderland lakes area in the Kagera river basin. Note that, for specific observations of a given geographic area to be included, at least 75% percent of the area of interest had to have been visible in the imagery, unless otherwise noted.

Severity of Water Hyacinth Infestation in Selected Bays and Gulfs of Lake Victoria, 1994-2001

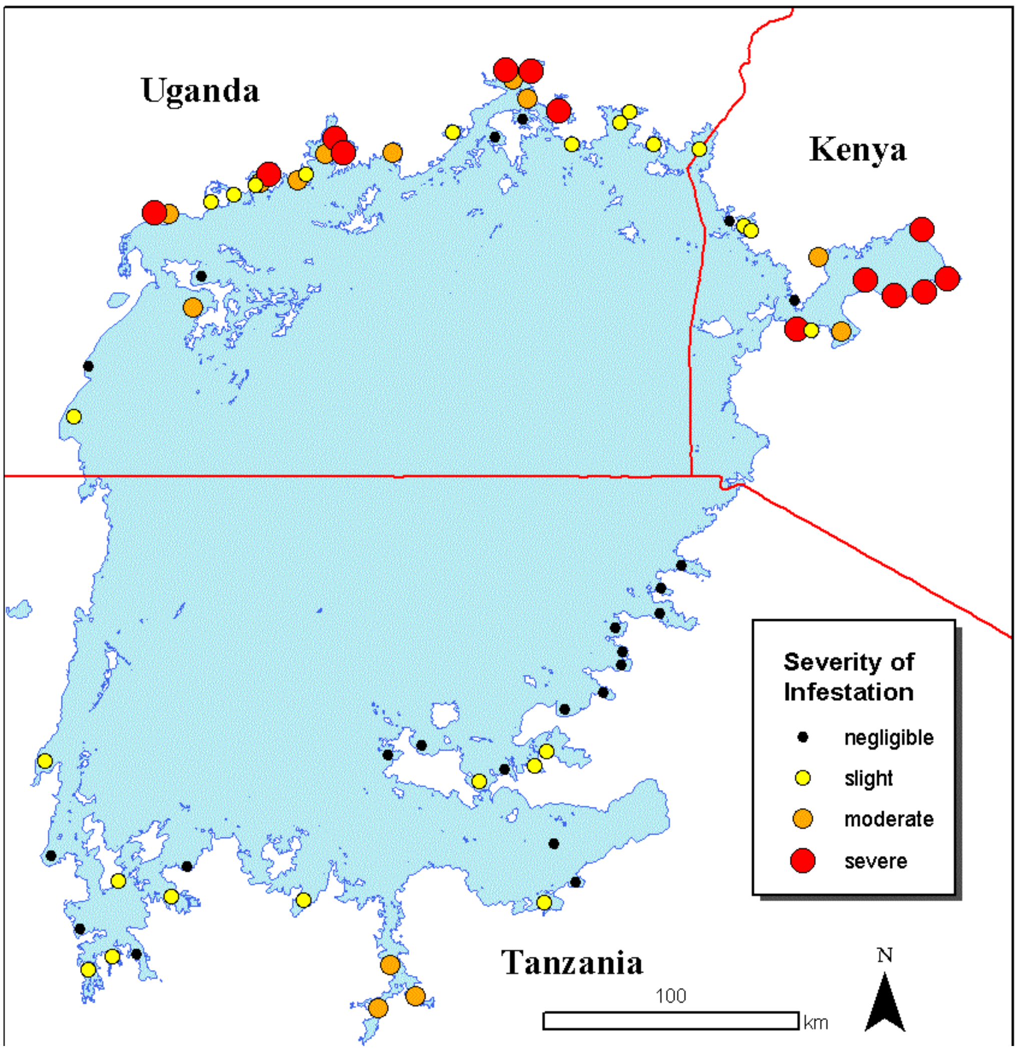

Figure 7. The observed relative severity of water hyacinth in selected bays and gulfs as detected by imagery collected between 1994 and 2001. Negligible – never more than 0.5% of area of feature visible covered by water hyacinth; slight – at least one image showing more than 0.5%; moderate – at least two images showing more than 2%; severe – at least two images showing more than 7%.

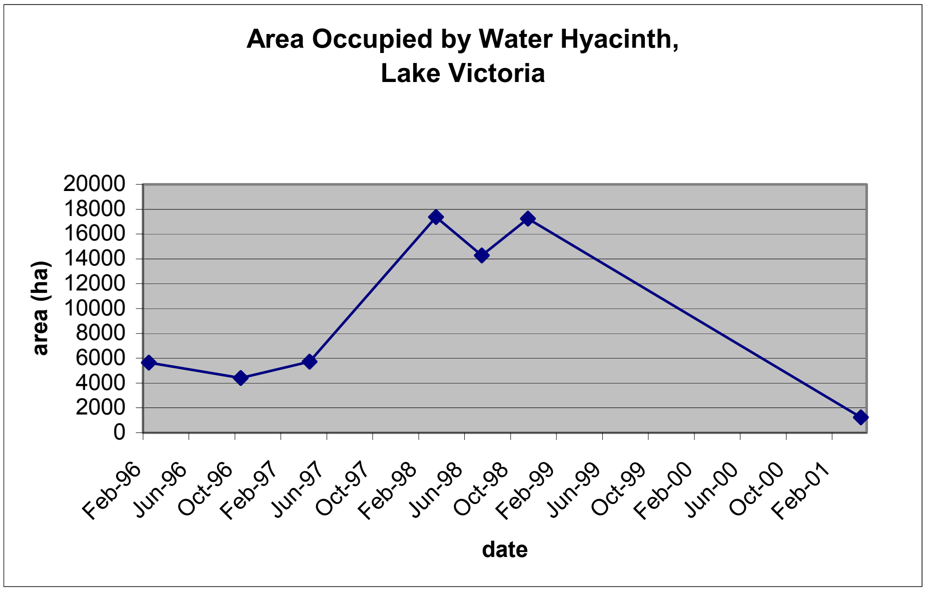

Figure 8. Area as measured from satellite imagery. For this and similar graphs, only data covering over 75% of the area are included. Lines interpolating between data points are meant only as a general guide.

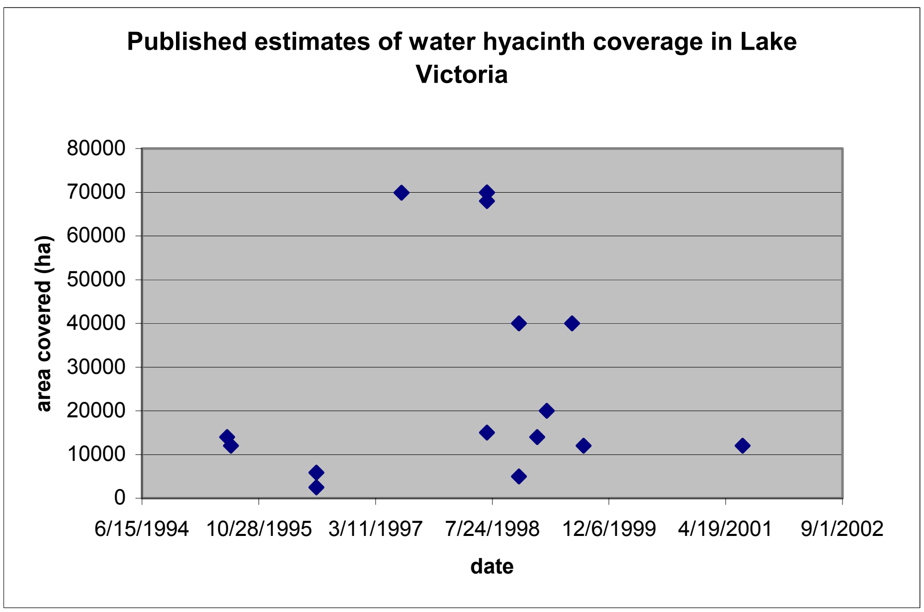

Figure 9. Previously published estimates of water hyacinth coverage in Lake Victoria. Note that these estimates were not derived from remote sensing.

Uganda

With its location at the mouth of the Kagera River, its numerous protected bays and gulfs, and the proximity of major population centers to the lake, the Ugandan portion of Lake Victoria (Figure 10) presents an environment that is both conducive to water hyacinth infestation and highly sensitive to its effects. In addition, prevailing winds tend to blow water hyacinth north into Uganda waters. The amount of water hyacinth identified in Uganda during the study is shown in Figure 11. In Uganda, large amounts

of water hyacinth (> 3000 ha) were present from the earliest countrywide image in February 1996 until a peak of 4732 ha on 4 March 1998. Following this was a sharp reduction to 2147 ha on 26 July 1998 and further reduction until a low of 53 ha was measured on 5 April 2001. Numerous bays and gulfs have experienced sizeable infestations and during some periods, large quantities of water hyacinth were found floating in open waters in Uganda. The Murchison Bay and greater Napoleon Gulf areas, however, distinguish themselves as among the most heavily infested and having generated the most concern among researchers, managers, government officials, and the general public.

Examination of published estimates of water hyacinth extent in Ugandan waters paints a less clear picture (Figure 12). The overall trend is not readily discernable and within 1995 alone, estimates range from 1300 ha to 10,000 ha.

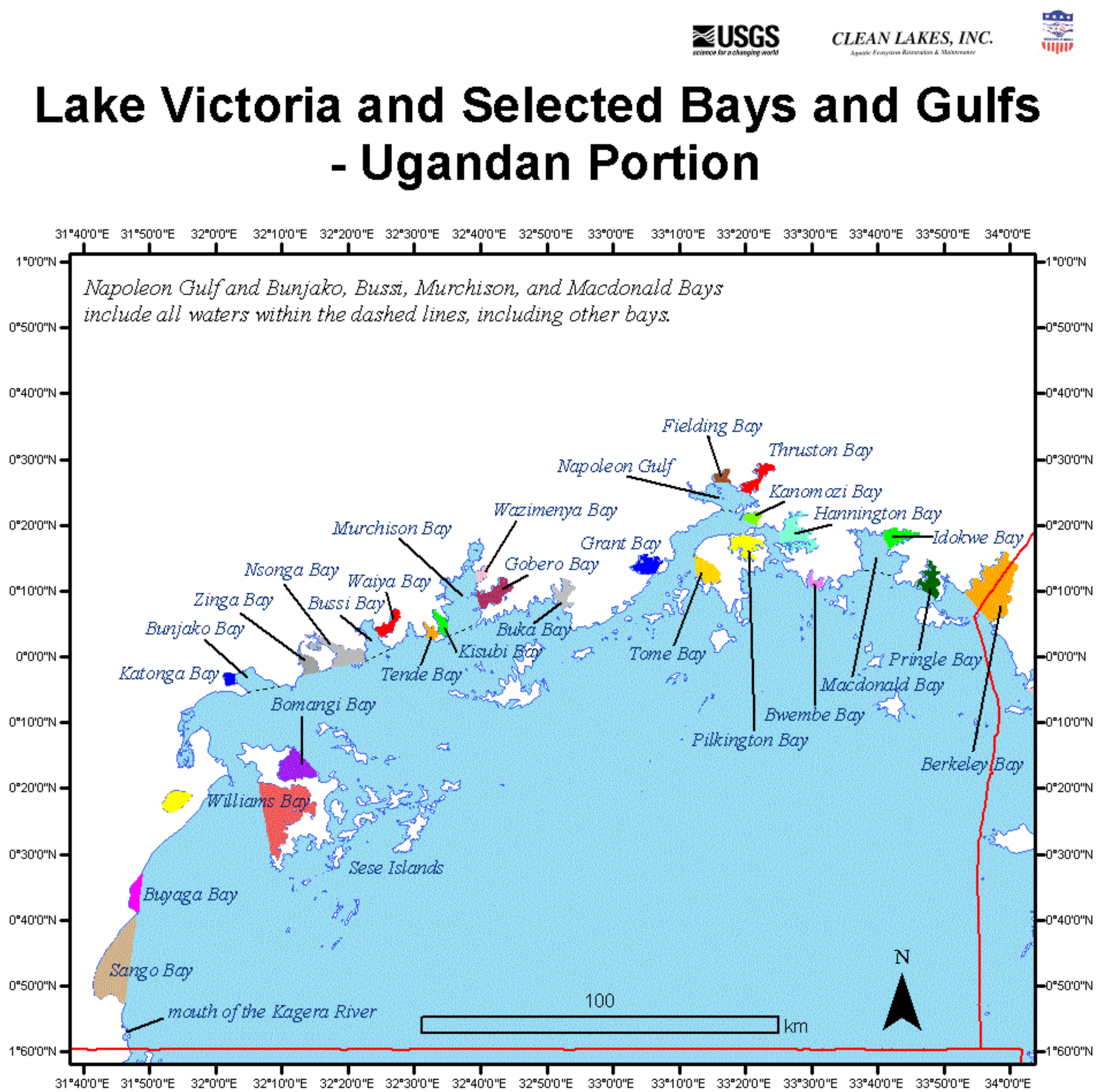

Figure 10. The Ugandan portion of Lake Victoria

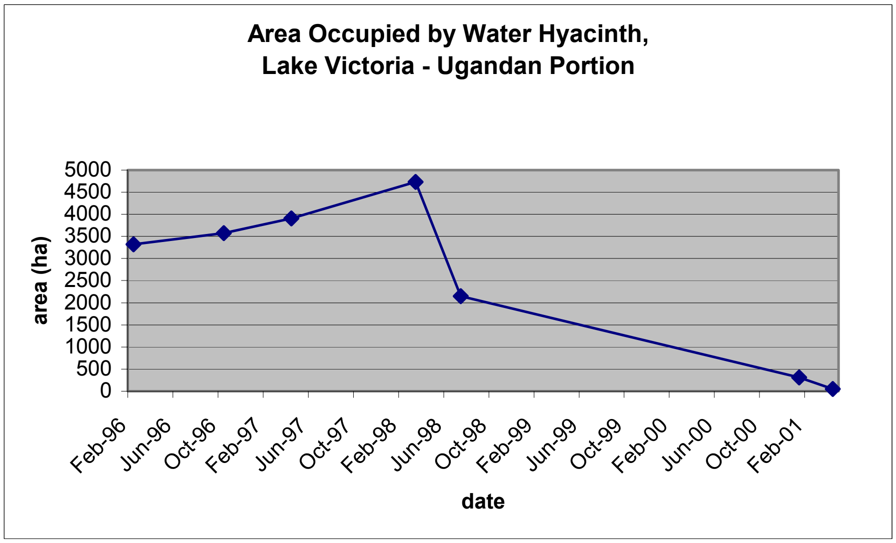

Figure 11. Area as measured from satellite imagery

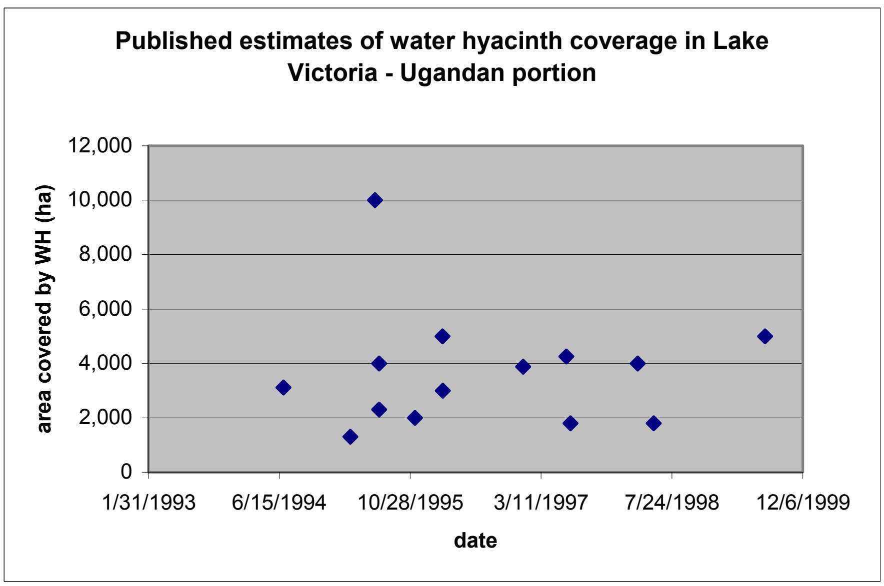

Figure 12. Published estimates of water hyacinth coverage for Ugandan waters

Murchison Bay

Figure 13 shows the evolution of water hyacinth distribution and coverage for Murchison Bay. The graph includes data from Schouten, van Leeuwen, and others (1999), which, unlike most of the other preexisting reports, are high-confidence estimates derived from remote sensing. The available imagery and reports indicate that a rapid increase in water hyacinth occurred during 1994, followed by a peak of 1974 ha (8.6% of bay) on 19 January 1995, and a period of abundant water hyacinth, ranging from 1140 ha to 1522 ha on dates observed between 1996 and 1997. During these periods of abundance, giant mats covering 100s of hectares could be found in inner Murchison Bay, Wazimenya Bay, and Gobero Bay. In 1997, a steady decline occurred until, in 1999,

there were only 15 and 1 ha detected in March and July, respectively. In 2001, there were reports of increased water hyacinth in Murchison Bay. Indeed, a slight increase to 35 ha was apparent in the data in January 2001. These quantities are the best estimates of water hyacinth present at the time the image was acquired. Due to strong winds and the highly mobile nature of water hyacinth (including even the largest of mats), estimates could differ greatly between morning and evening, and between seasons, due to changes in wind direction. The first four data points and the graph, for instance, were from two different times of day on two different dates and reveal how daily wind cycles can affect measured water hyacinth amounts. The significant "reduction" that occurred between 1995 and 1996 was thus most likely caused by a wind induced migration of water hyacinth out of Murchison Bay into other parts of the lake.

In late 1995, two species of *Neochetina* weevils were released into the Uganda portion of Lake Victoria. However it was not until February 1997 that weevil feeding activity became visible on plants in Murchison Bay. Weevils multiplied rapidly, attaining an average number of 13.8 weevils/plant in 1998, and 24.7 weevils/plant in 1999 on Lake Victoria in Uganda. By late 2001, weevil numbers had declined to an average of 8.8 weevils/plant (Uganda National Agriculture Research Organization, 2002). Weevil monitoring exercises carried out by Clean Lakes, Inc. within inner Murchison Bay indicate that weevil numbers had declined to 1.2 weevils/plant for stationary water hyacinth growing along the shoreline and to 2.3 weevils/plant for floating mats of water hyacinth by January 2002.

From the above, it is obvious that a decline in water hyacinth began in earnest with increasing weevil populations. Between 1997 and 1998, however, another event took place that is difficult to quantify as far as its impacts on water hyacinth. East Africa was hit by an El Niño weather phenomenon during the last quarter of 1997 that continued well into the first half 1998. In mid October 1997, prior to the beginning of the rains, the lake level was at near all time lows of 11.26 meters (datum level of 1121.65 a.s.l.). These lows had only been experienced at two other points in time (both low periods in 1994) during the previous 40 years. The lake level then climbed to 12.96 meters by mid May 1998 – a change of 1.70 meters in a period of seven months. This rapid rate of rise over the period was matched only once by an event that occurred in 1962/1963 as evidenced by a lake level monitoring table that exists showing data starting in 1899. Already in a weakened state due to insect attack, the water hyacinth also experienced heavy weather conditions that created wave action, which mechanically damaged large quantities of water hyacinth.

Several other factors are likely to have contributed to the decline as well. Pathogens have been isolated from water hyacinth plants in Lake Victoria that are capable of weakening plants (Godonou, 2000). These pathogens would have found an ideal environment with plants under attack by weevils and being damaged by severe weather conditions to become established and further weaken or destroy plants. Another factor influencing plant health is water quality. Though difficult to quantify at this time, it is possible that some change in water quality took place due to heavy rainfall and dilution of lake nutrients. Another possible factor in the reduction of abundance could have been the stranding of water hyacinth along shorelines and in low elevation areas of the lake as waters receded from their mid 1998 levels. Though no reports exist of large masses of water hyacinth entering inundated lakeside areas, it likely occurred in many areas around the lake and could have been responsible for a percentage of the decrease. In

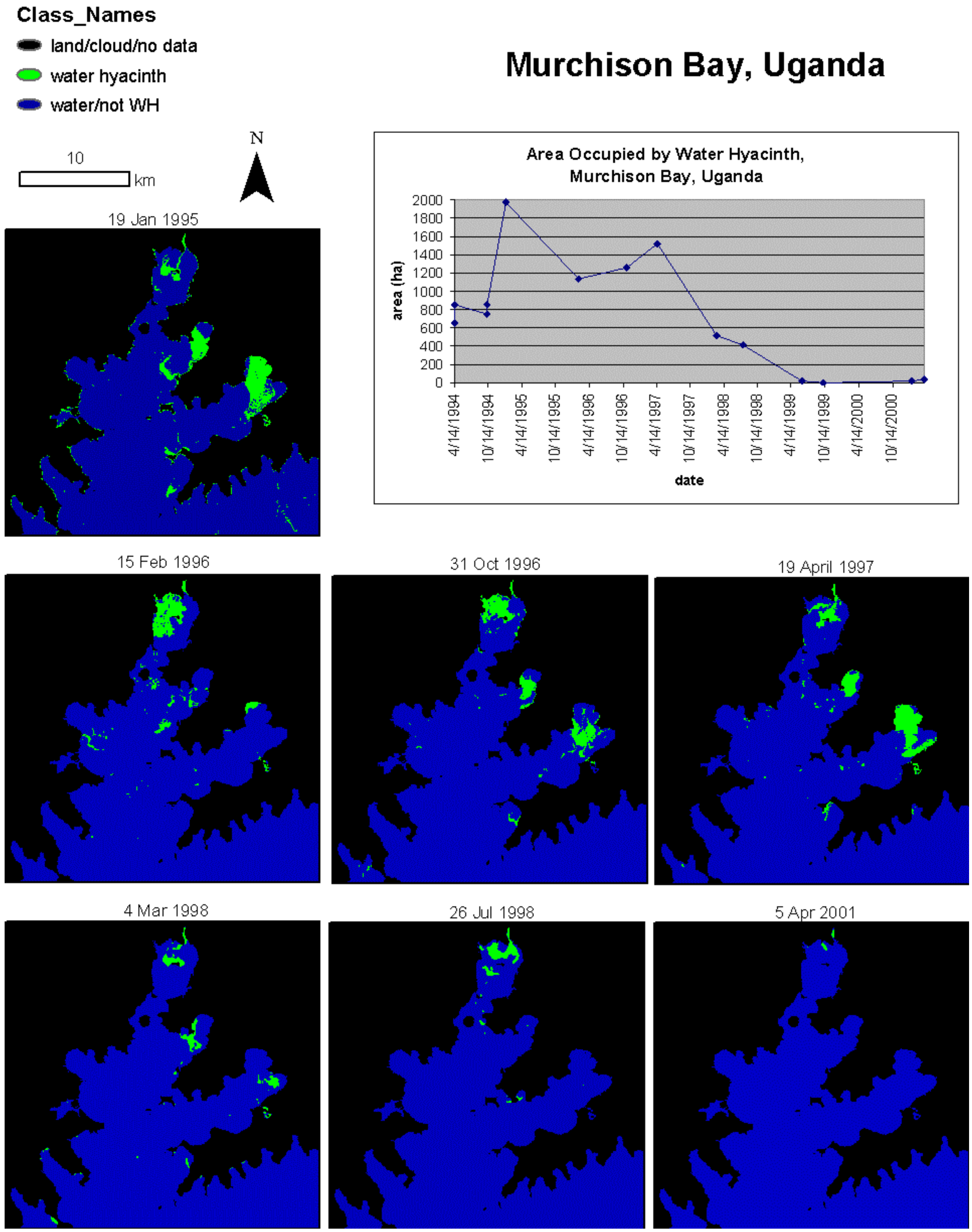

Figure 13. Evolution and distribution of water hyacinth coverage in Murchison Bay, Uganda. Note that the first four data points on the graph are estimated derived from Synoptics BV.

addition to the above factors, it would be remiss here not to mention the mechanical removal work that was occurring at Port Bell through the Japanese-funded and Uganda Water Hyacinth Unit-operated machinery during the period of 1998/1999. This equipment was rated at harvesting up to 40T/hr. Much of the above discussion related to declining populations is also applicable to the Kenya and Tanzania portions of the lake, but will not be repeated.

Greater Napoleon Gulf

The evolution of water hyacinth infestation differs slightly in Napoleon Gulf and neighboring Hannington Bay (Figure 14). In greater Napoleon Gulf (including Hannington Bay), elevated quantities were noted on 19 January 1995 and 15 February 1996, followed by an October-November 1996 observation of only 10s of hectares and elevated quantities again in 1997 and 1998. From 1999 onward, almost no water hyacinth was observed in this area.

Tanzania

While occupying nearly half of Lake Victoria, Tanzania (Figure 15) did not experience the same degree of extreme water hyacinth infestation as the other riparian countries. Levels between 825 ha and 2004 ha were observed in 1996 and 1997, followed by a peak of 4081 ha on 4 March 1998, a drastic decline to only 28.5 ha on 26 July 1998, and a slight resurgence to 117 ha on 5 April 2001 (Figure 16). It is important to note that the 26 July 1998 image did not cover the southern portions of Emin Pasha Gulf and Mwanza Gulf and is therefore likely responsible for a significant underestimate. Some areas, such as Speke Gulf, were spared of large infestations, with no water hyacinth evident on many of the images. On the other hand, Mwanza Gulf and Emin Pasha Gulf, which are more sheltered, experienced significant amounts of water hyacinth. We also note that large semi-stationary mats were less common on the southern, Tanzanian portion of the lake. This could again be due to the prevailing winds that tended to move water hyacinth to the northern portions of the lake. Results are relatively comparable with previously published estimates for Tanzanian waters (Figure 17).

Mwanza Gulf

In Mwanza Gulf, a bimodal evolution of water hyacinth was observed, with over 1000 ha in February 1996 and March 1998, separated by observations of less than half that amount in October 1996, December 1996, and April 1997 (Figure 18). These evolutions are likely related to wind regimes that would have forced water hyacinth into more open areas of the lake where they could have been severely damaged or destroyed by wave action. Weevil release in Tanzania began in August 1997 (Mallya, 1999), approximately 20 months later than in Uganda and 7 months after Kenya began releases. It is interesting to note, though, that by July/Aug 1998 water hyacinth had declined considerably in Tanzania waters and remained at low levels thereafter. If it is assumed that weevils alone were responsible for the large decline in water hyacinth abundance in Tanzania, then biological control acted in reducing the abundance within a period of only 11 months. We suspect that other influences were at work as described under the Uganda, Murchison Bay discussion presented above. Recent observations indicate that levels are significantly lower than in the late 1990s, with only 100-200 ha visible in any observations in the 2000s.

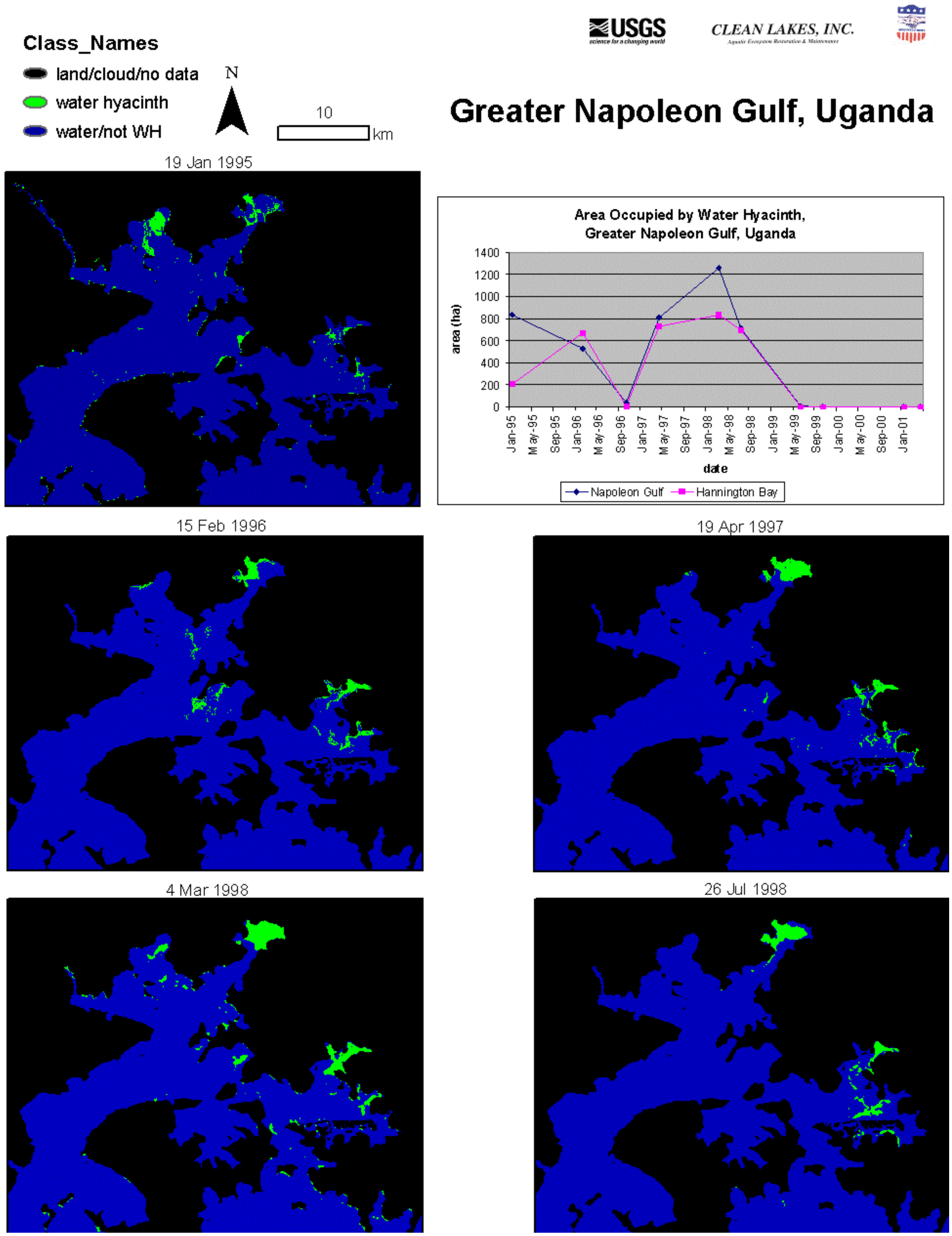

Figure 14. Evolution and distribution of water hyacinth coverage in greater Napoleon Gulf, Uganda.

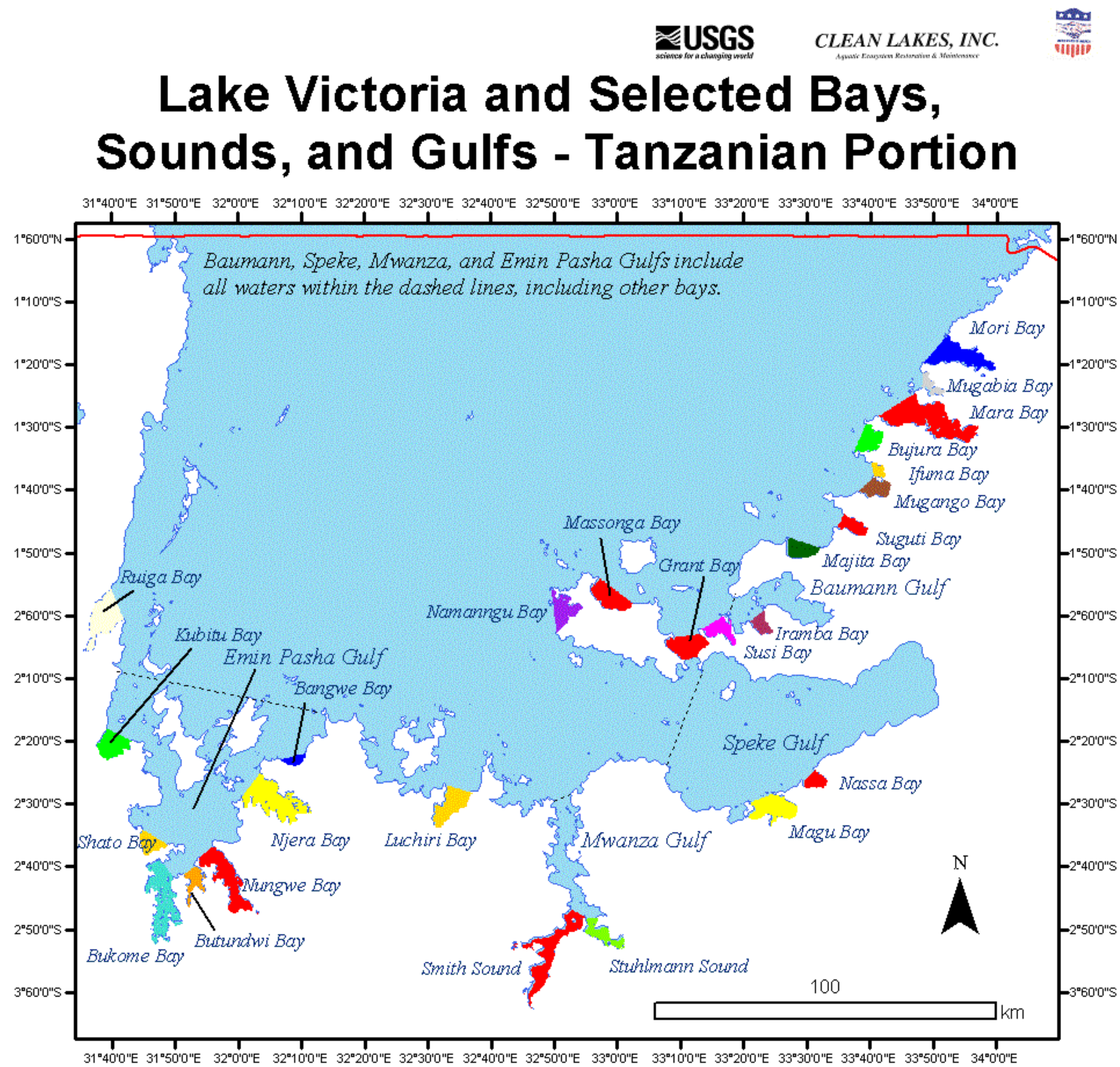

Figure 15. The Tanzanian portion of Lake Victoria.

Emin Pasha Gulf

Generally, our observations reveal lower amounts of water hyacinth in Emin Pasha Gulf relative to Mwanza Gulf (Figure 19). Most observations indicate less than 200 ha in Emin Pasha Gulf. The major exception is 4 March 1998, when 2177 ha were observed. This peak is coincident with one of the Mwanza Gulf peaks. This major peak is probably related to El Niño weather impacts and the associated rise in water level during that time. The rise in water level, together with wind, wave, and water current agitation along the shoreline, likely caused water hyacinth and other aquatic weeds thriving permanently along shorelines or in shallow protected swamp areas to have been lifted or broken away to drift with offshore based mats. It is also possible that large quantities that had been present in Mwanza Gulf were blown out and migrated into Emin Pasha Gulf. Consistent with observations of other areas in the lake is the slight increase noted in 2001. In general the decline in water hyacinth abundance followed the same pattern as the rest of the lake.

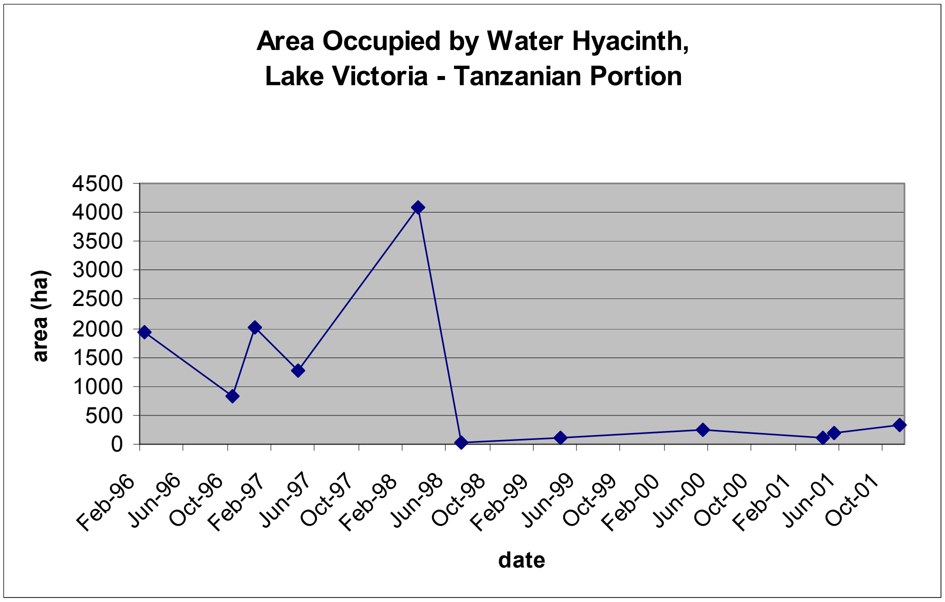

Figure 16. Area as measured from satellite imagery.

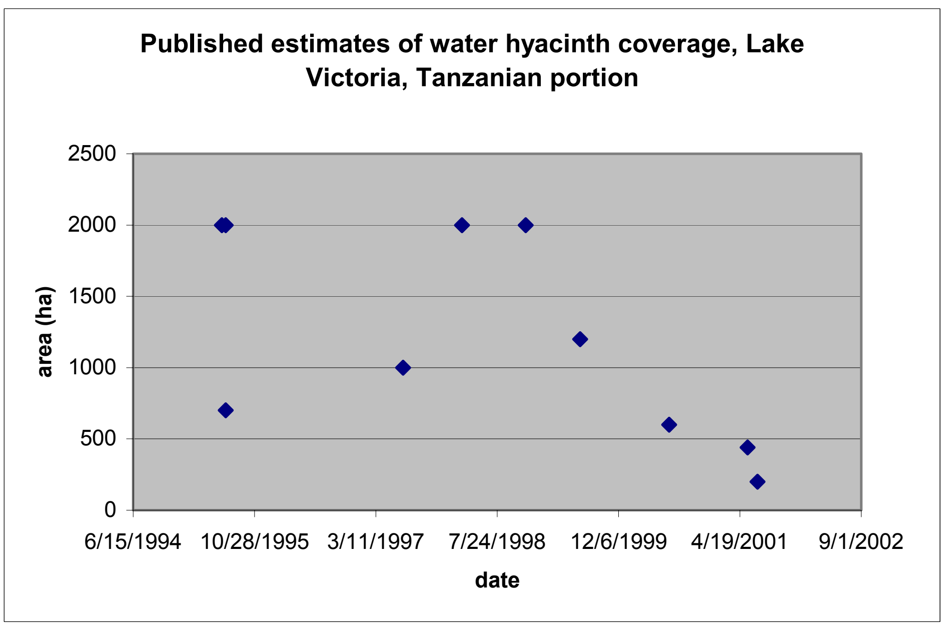

Figure 17. Published estimates of water hyacinth coverage for Tanzanian waters

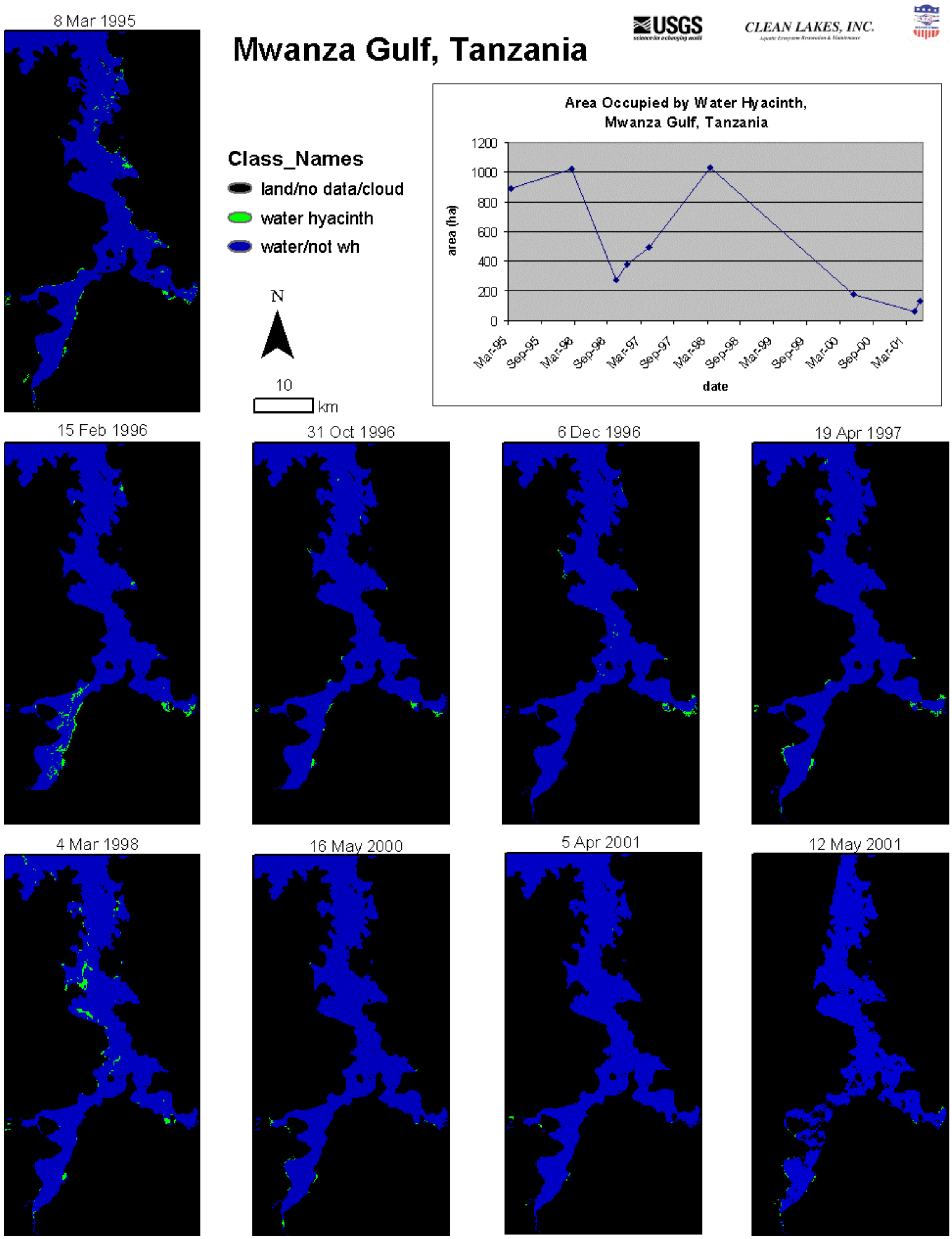

Figure 18. Evolution and distribution of water hyacinth coverage in Mwanza Gulf, Tanzania.

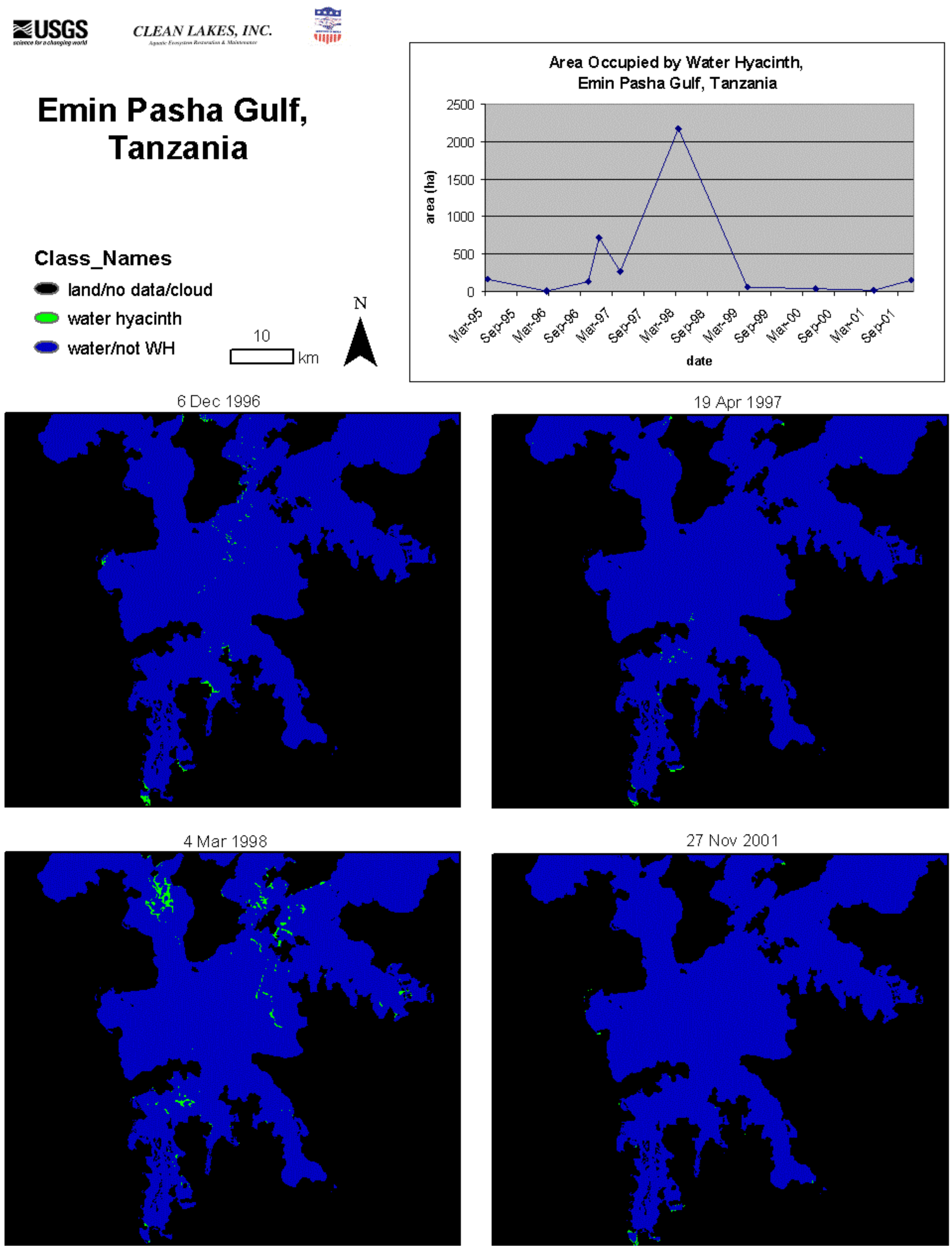

Figure 19. Evolution and distribution of water hyacinth coverage in Emin Pasha Gulf, Tanzania.

Kenya

In terms of shoreline and importance, the Kenyan portion of Lake Victoria is dominated by Winam Gulf (Figure 20), which is the site of the city of Kisumu and of several rivers that flow into Lake Victoria. Generally, Kenyan waters were late in being infested by water hyacinth (Figure 21). Published estimates are highly variable and, unlike in other countries, generally lower than results obtained from this study (Figure 22). Because the vast majority of water hyacinth in Kenyan waters resided in Winam Gulf, our discussion is focused on this important gulf.

Winam Gulf

Winam Gulf was the site of the largest quantities recorded in any location at any time during the study (Figure 23). After small amounts observed in 1994 and 1996, 8504 ha, 4846 ha, 12,091 ha, and 17,218 ha were observed in March, May, July, and November of 1998, respectively. This relatively late infestation of Winam Gulf strongly suggests that water hyacinth originally came from the Kagera River system and migrated to the Uganda and Tanzania sides of the lake first. The large amounts of aquatic vegetation seen during 1998 were not entirely composed of water hyacinth, though the vast majority is believed to be water hyacinth and opportunistic native invasive weeds growing on top of water hyacinth. The large increases of water hyacinth through 1998 are likely the result of self propagation and inflows from shoreline infestation that were freed from shorelines and swamps by high water levels associated with the 1997/1998 El Niño and the accompanying strong wind, wave, and water current action. Note that the reduced amount observed in May 1998 is due, at least in part, to the fact that a large portion of heavily infested Nyakach Bay was outside of the imaged area on this date. A large reduction to 3134 ha in December 1999 and 532 ha in February 2000 was observed, although data from this last date did not cover the southeastern portion of Winam Gulf and therefore this estimate is probably low. Weevil release in Kenya began about 13 months later than in Uganda, starting in January 1997 (Ochiel, Mailu, and others, 1999). The peak in water hyacinth and other aquatic vegetation occurred in November 1998 followed by a bottoming out in February 2000 at approximately 500 ha, a period of about 15 months, with the low population level occurring about 25 months after weevil introduction. This can be described as a fast response to weevil attack, if weevils alone are responsible for the decline. During the period 1999/2000 a water hyacinth mechanical “Chop and Sink” exercise was carried out under contract with the Kenyan Lake Victoria Environmental Management Program. Pathogens, weather conditions, and other factors, as outlined in the Uganda, Murchison Bay discussion probably also played some contributory role in this massive decline. This overall decline is consistent with declines in the rest of the lake. However, the Kenyan experience occurred many months after the declines in Uganda and Tanzania. Most recently and consistently with other portions of the lake, a slight increase in water hyacinth was observed in 2001.

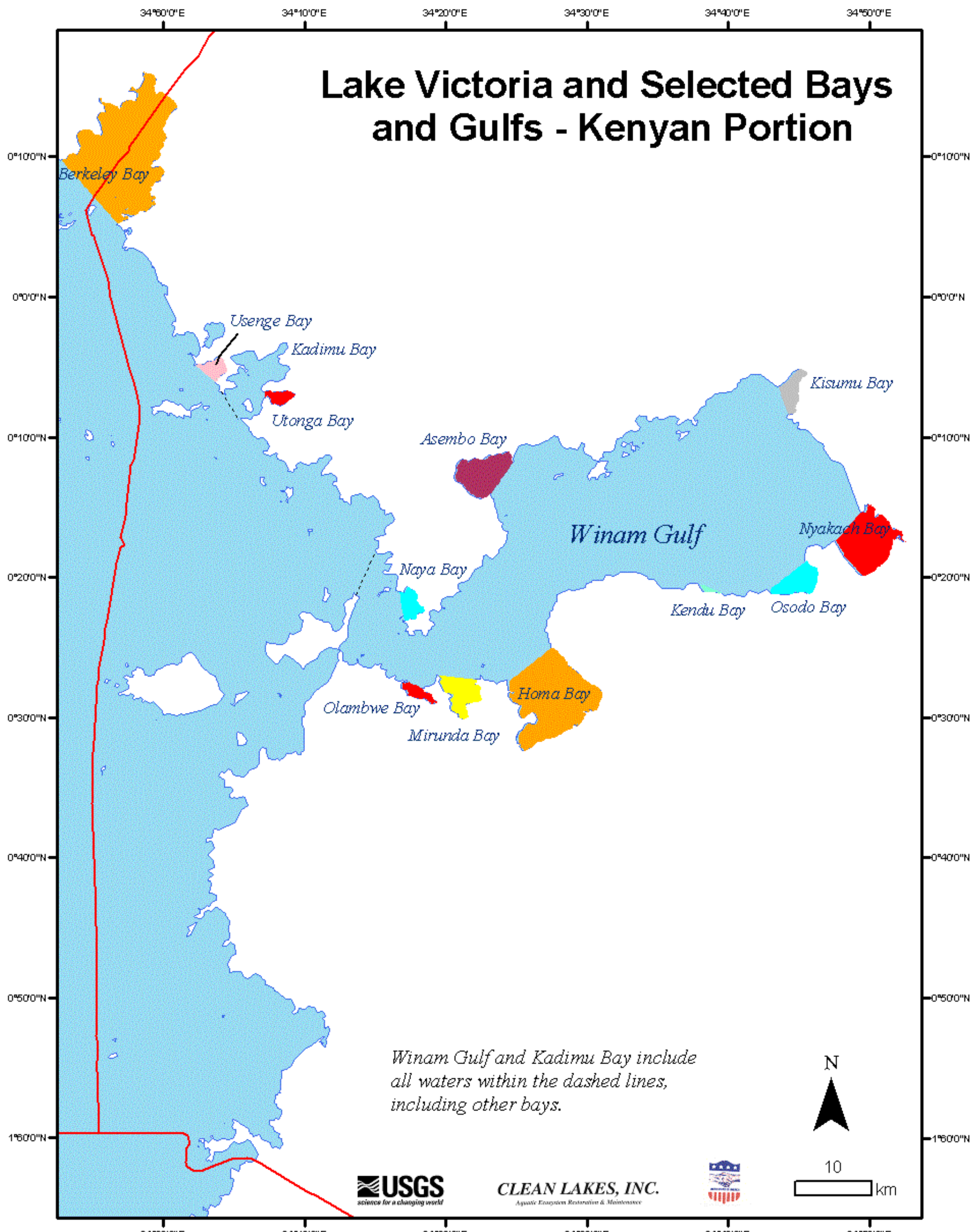

Figure 20. The Kenyan portion of Lake Victoria.

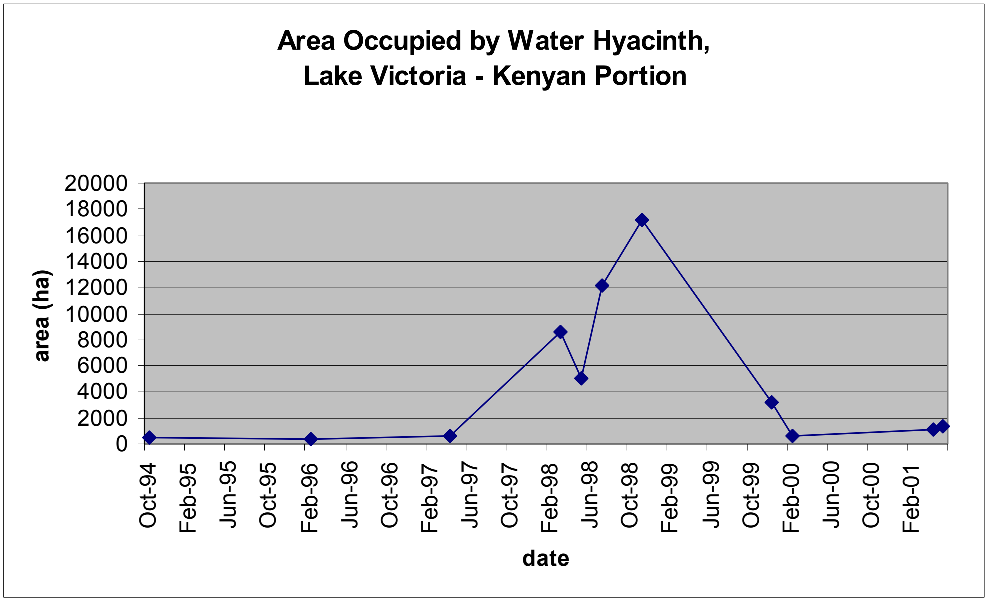

Figure 21. Area as measured from satellite imagery.

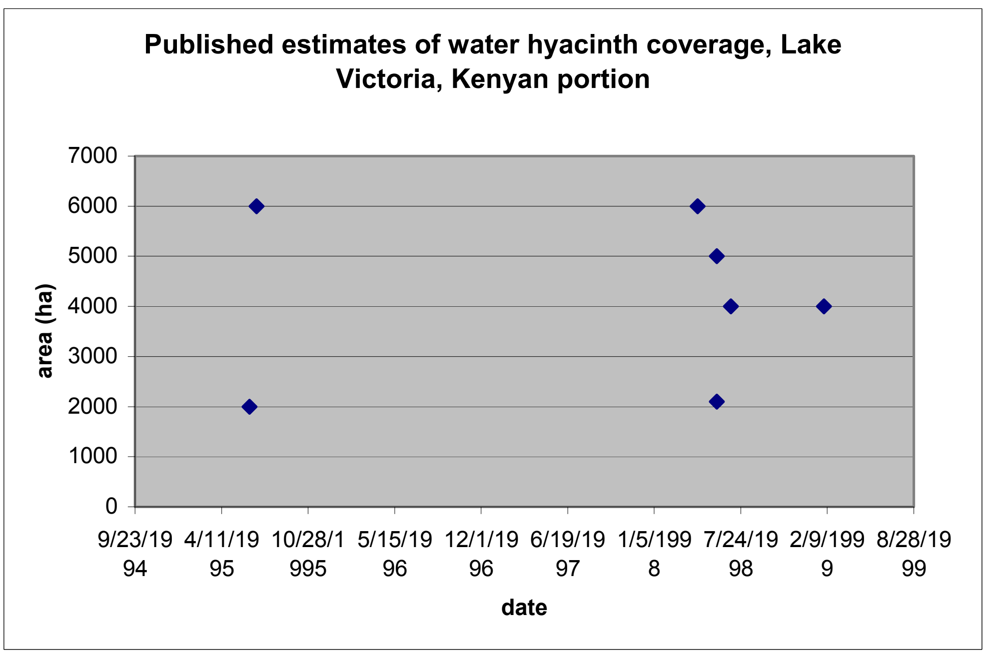

Figure 22. Published estimates of water hyacinth coverage for Kenyan waters.

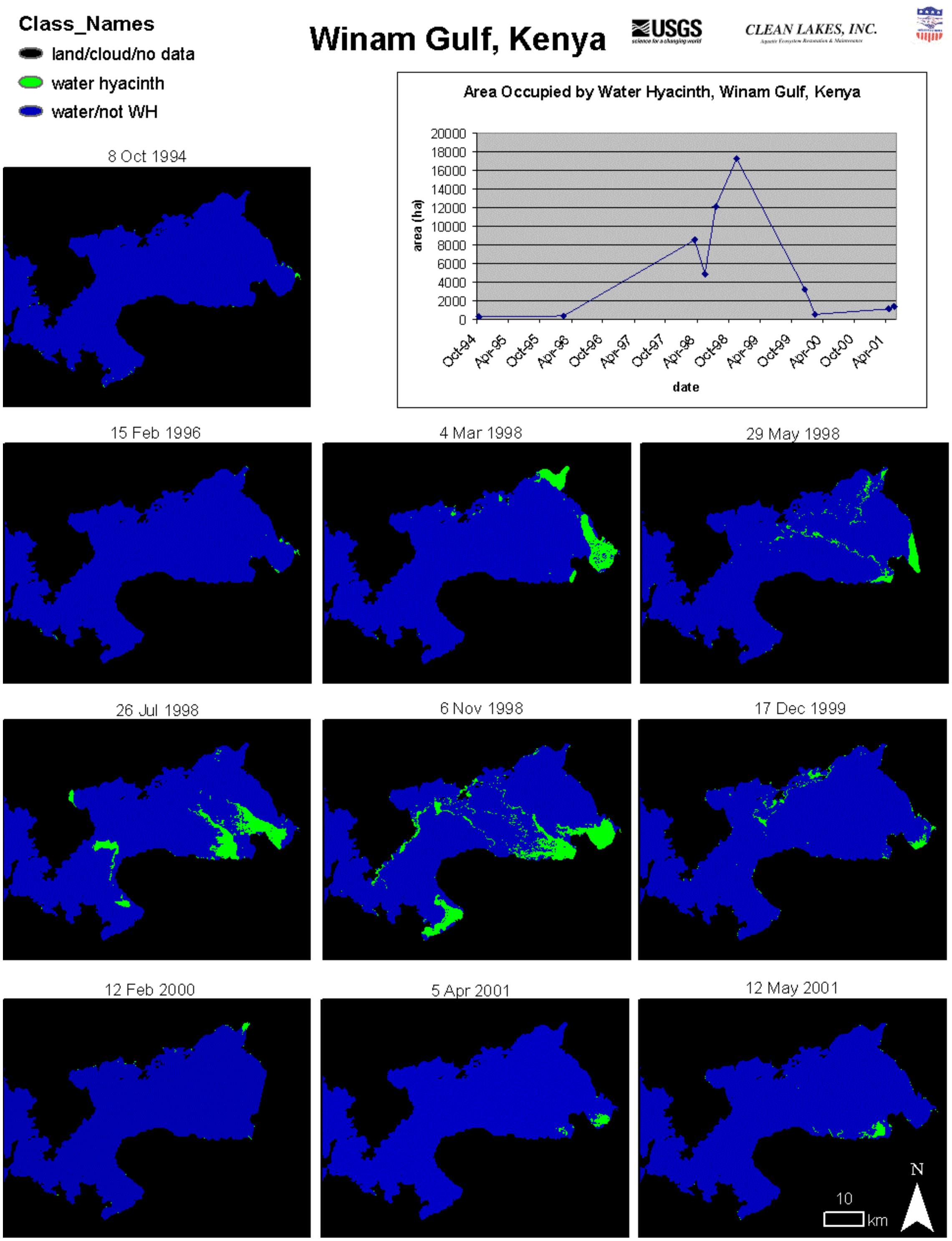

Figure 23. Evolution and distribution of water hyacinth coverage in Winam Gulf, Kenya.

Rwanda-Tanzania borderland lakes

This region near the Kagera River at the border between Tanzania and Rwanda contains a large number of small to medium sized lakes (Figure 24). In general, those lakes that are close to and/or connected to the Kagera River are more likely to have experienced water hyacinth invasion than those that are farther away and/or not connected. For instance, water hyacinth was observed on Lakes Nasho, Cyambwe, Ihema, and Mpanga, but not on Lakes Lwelo, Bisongu, or Rwanyakizinga.

Lac Mihindi, in particular has had a large amount of water hyacinth associated with it for many years (Figure 25). After the first observation of 270 ha in December 1996, a peak of 610 ha – well over half the lake – was observed in April 1997. Our most detailed observation, using the high resolution Ikonos satellite, revealed 200 ha in October 2000. This quantity appears to be relatively stable through our final May 2001 observation. Biological control implementation started in the Rwanda portion of the Kagera River in September 2000 along with some intermittent manual control. We suspect that the large reduction in water hyacinth that occurred between 1997 and 1999 was due, at least in part, to flood waters associated with the El Niño event breaching the blocked outlet of Lake Mihindi allowing water hyacinth to spill out of the lake and into the river system. Alternatively, other plant health changes may have occurred as a result of weather conditions associated with El Niño or increased pathogenic activity leading to the decline in abundance, though this is admittedly speculative. The declines in Lac Mihindi are consistent, however, with declines that occurred in Lake Victoria. The declines are quite dramatic, and do, more importantly, coincide with times of highs and lows seen in Kenya, Tanzania, and Uganda despite weevil releases not having been initiated in Rwanda until September 2000.

The river system itself is infested to varying degrees in Rwanda from the uppermost point of infestation near Ruhengeri to south of Kigali where it is considered light; the middle portion of the river to the border with Tanzania, where it is considered moderate; and the lower portion that encompasses most of the Akagera National Park, where it is considered heavy.

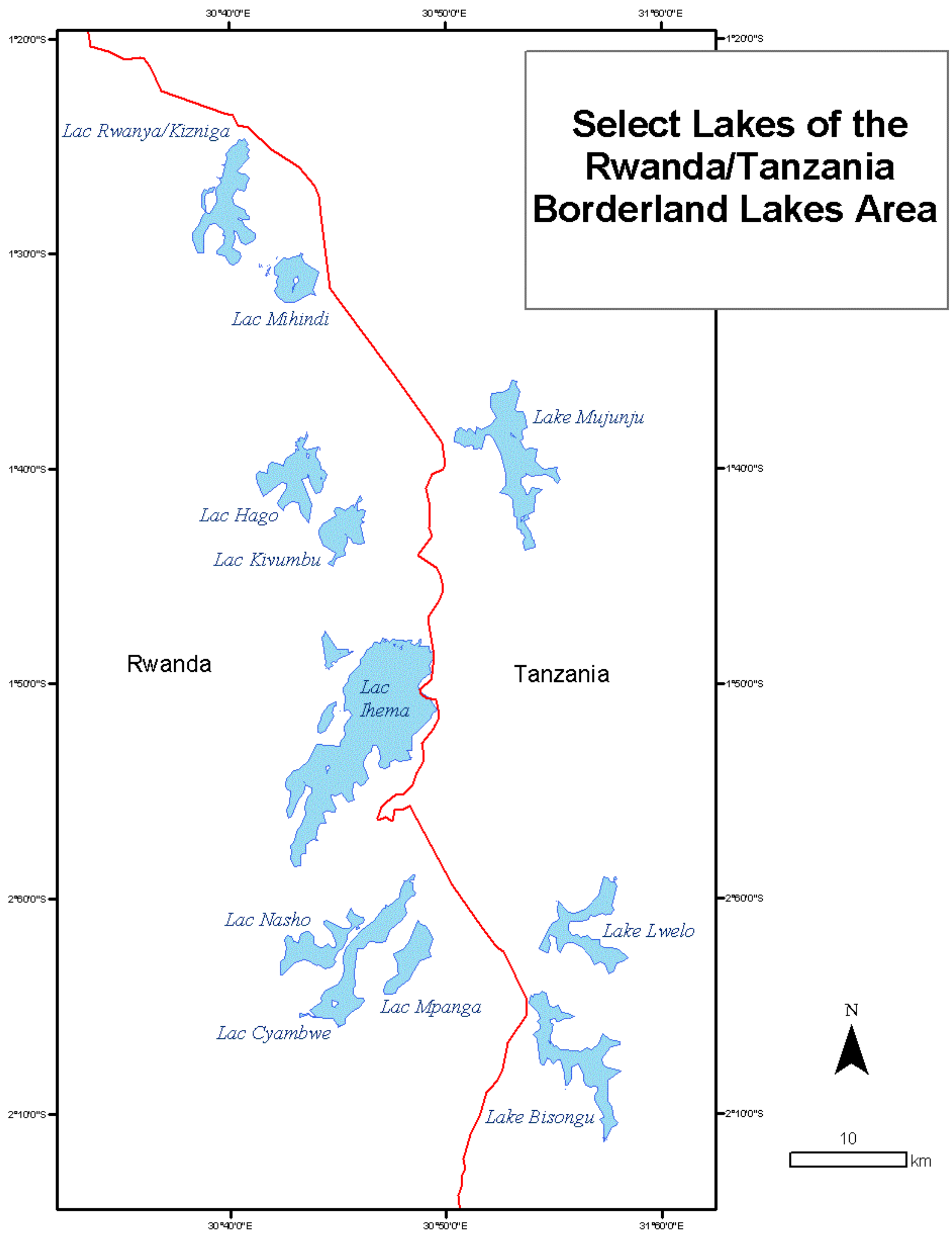

Figure 24. The Rwanda/Tanzania borderland lakes area. Note that the international boundary is generally defined by the Kagera River.

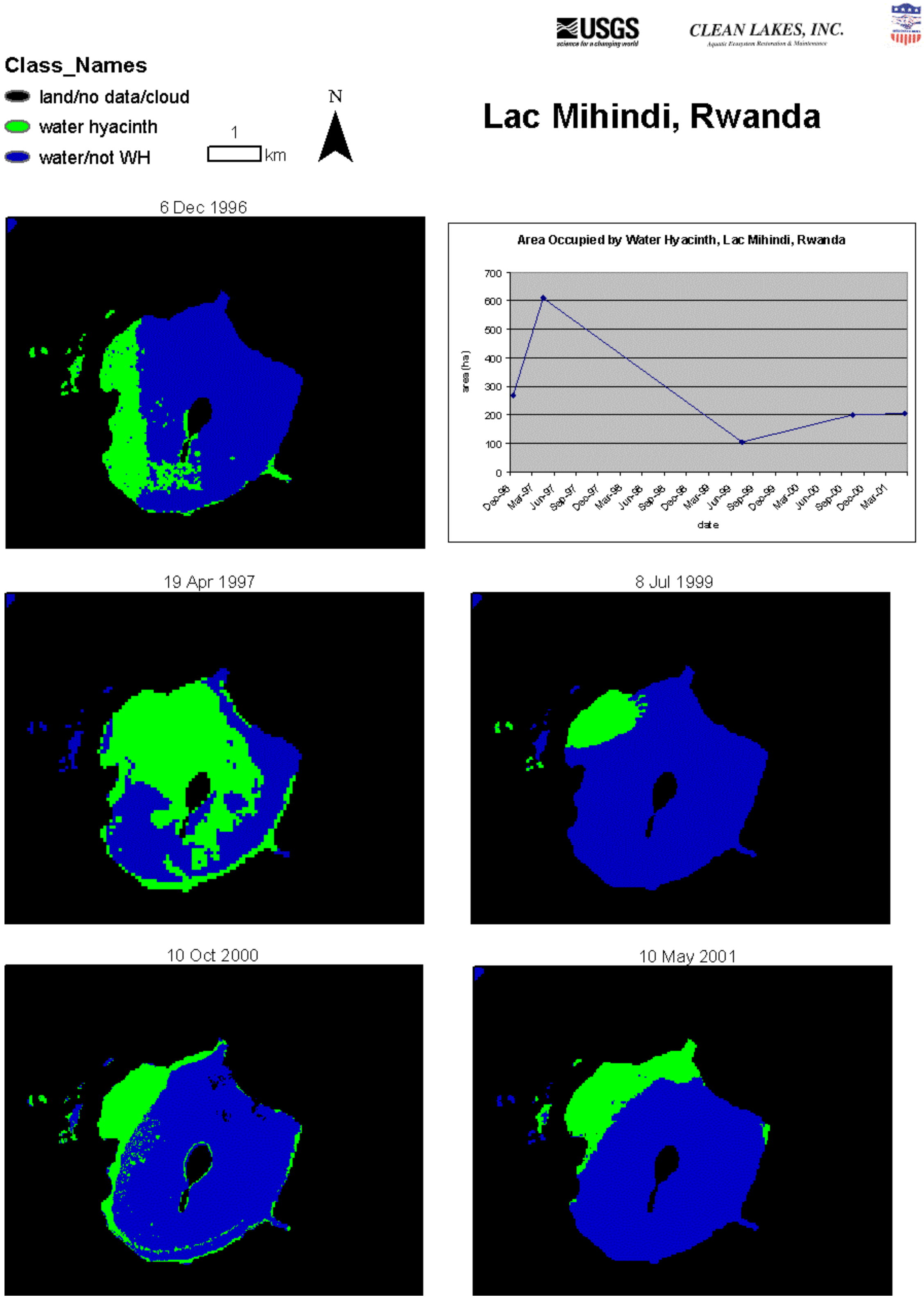

Figure 25. Evolution and distribution of water hyacinth coverage in Lac Mihindi, Rwanda.

Discussion

Possible sources of error in water hyacinth mapping

Before proceeding with conclusions, one must consider the degree to which these estimates and maps are subject to error. One can consider three types of error in mapping water hyacinth: confusion, resolution-related error, and definitional error.

Confusion occurs when one type of surface is mistakenly identified as another. There are many surfaces, objects, and or land covers that, when imaged using spaceborne and airborne remote sensing instruments, may resemble water hyacinth. Prominent examples of these include other aquatic and wetland vegetation such as hippograss (*Vossia cuspidata*), papyrus (*Cyperus papyrus*), a variety of sedges and other plants and, at times, extreme densities of algae. Confusion with other aquatic macrophytes can be greatly reduced by analysis of imagery over several dates (as was done in this study), allowing separation of aquatic vegetation that is static in extent (more likely to be hippograss and papyrus) verses that which is more mobile (more likely to be water hyacinth). As for confusion with extreme densities of algae, frequently the shape of these features can be quite distinct, with algae being more amorphous and sometimes exhibiting a spatial frequency that corresponds to boundaries of Langmuir spirals, which are turbulent features on lakes that can concentrate algae in zones of downwelling. Radar-based remote sensing of water hyacinth is subject to confusion with other aquatic vegetation, ships and their wakes, and waves. In most of these cases, the context, pattern, and shape of these features allows discrimination between these features and water hyacinth.

Resolution-related error is linked to the fact that the resolution of sensors available for use is not always ideally suited for mapping the highly spatially variable water hyacinth. For instance, small "ribbons" of water hyacinth are frequently observed in the field along shorelines. If these shoreline fringes of water hyacinth do not exceed some width threshold that is resolvable by both the sensor and the mapping algorithm, they will not be identified. The same can be said of small floating mats of water hyacinth. While these cases would favor an underestimation of water hyacinth, coarse resolution can also exaggerate estimated water hyacinth by mapping a partly occupied pixel as completely occupied. This problem is related to the classic "mixed pixel" problem of remote sensing and may include mixtures of water hyacinth with other aquatic and shoreline vegetation in addition to mixtures with open water.

Definitional error is not technically error, but rather arises from a difference in how a class is defined when it is being mapped verses how a user of the information may wish it were defined. This relates primarily to density in the case of water hyacinth. Two pixels occupied by and classified as water hyacinth may have a greatly varying quantity (biomass) of water hyacinth. Wind and waves may greatly vary the density of water hyacinth within the scope of hours by compressing or decompressing the amount found in a square meter. A pixel was defined as water hyacinth if the majority of the pixel was estimated to be occupied by water hyacinth, without respect to density or mixtures. Also related to this are changes in distribution over short time periods. In addition to compacting water hyacinth, wind and current may move water hyacinth, sometimes over large distances in a day and sometimes cyclically in accordance with daily wind regimes.

Thus, images may miss water hyacinth that has drifted outside of the area covered by the image.

While a rigorous and quantitative analysis of error in water hyacinth mapping is beyond the scope of this project, we can nonetheless speculate on the significance of these possible error sources. We begin by noting that many of the errors arising from the use of classification algorithms may be reduced through manual editing. The human eye is quite adept at identifying subtle variations in shape, pattern, and context that allow many errors to be eliminated through manual editing. Furthermore, of the errors that remain, many may be offsetting. There is no reason to suspect a systematic bias in our estimates. It should be noted that relative confidence in these estimates is higher in areas with large amounts of water hyacinth. This is because in any image, a certain amount of confusion is possible around shoreline areas. Images containing large amounts of water hyacinth have a relatively higher proportion of water hyacinth in the open water areas away from the shore. Regarding all error, we hope that by stating the limitations clearly, these results will be understood within the constraints to which they are subject.

Impact of weevil releases on water hyacinth populations

The cause of the rapid reduction in water hyacinth is complex, as many factors can contribute to a decline. As described earlier, weevils were released as a bio-control measure in all four countries, machinery was operated at several limited locations within Lake Victoria, manual removal was tried throughout the four countries, and plant pathogens are known to exist, and were isolated in water hyacinth plants in Lake Victoria. El Niño weather conditions caused heavy rainfall, changes in air temperature, humidity and wind patterns, and were primarily responsible for a rapid and large rise in water levels in Lake Victoria that changed water quality conditions, and thus could have caused large scale stranding as waters receded.

Table 3 compares initial weevil release dates and water hyacinth abundance at two points in time, and the percentage decrease in water hyacinth after weevil release. It is interesting to note that though Uganda and Tanzania experienced peak water hyacinth infestation at the same time (March 1998), Kenya did not experience a peak until 8 months later (November 1998), and Lake Mihindi, Rwanda peaked one year earlier (April 1997) than Uganda and Tanzania.

The percentage reductions seen post peak is variable and significant in quantity. Post peak images were used to measure the change in water hyacinth between the peak water hyacinth date and the next available and clear satellite image date. It can be seen, for instance, that at the peak date in March 1998, 4080 ha of water hyacinth were located in Tanzania's Lake Victoria waters. This peak occurred seven months after weevils were initially released in August 1997. By July 1998, water hyacinth extent was to 28 ha – a reduction of 99.3% from the peak only 11 months after initial release. This is an extremely rapid decrease that cannot be attributed to biological control alone. Uganda and Kenya show water hyacinth decreases of 54.6% and 81.4%, respectively, within a period 31 months and 36 months after *Neochetina spp.* release. Given that bio-control takes between two to five years to make an impact, these latter reductions are in line with expectations, though the speed with which these reductions occurred (4 months) makes it probable that other factors were also contributing to the decline.

Similar to the declining abundance seen in Lake Victoria, Lake Mihindi (Rwanda) also showed a decline between April 1997 and July 1999. The peak estimate of 610 ha occurred in April 1997, some 54 months prior to *Neochetina spp*. releases followed by a decline to 104 ha in July 1999, the next available and clear satellite image available for that lake. This amounts to a decrease of 83% between April 1997 and July 1999, some 27 months *before* biological control agents were introduced into Lake Mihindi, and 15 months before *Neochetina spp.* were introduced into floodplain ponds south of Kigali. This reduction is difficult to explain, but could be the result of El Niño flooding as described earlier, pathogens, native insect changes in the environment, or a combination of these.

Table 3. Comparison of country level water hyacinth abundance estimates as related to *Neochetina spp.* releases against peak infestation level and post peak infestation levels in Lake Victoria and Lake Mihindi, Rwanda between December 1995 and October 2001.

Country	Peak Water Hyacinth (WH) Estimate (ha) (a)	Peak (WH) Estimate Date (b)	Initial Weevil Release Date (c)	Period After Weevil Release (months) (b-c = d) (d)	Post Peak (WH) Image Date (e)	Post Peak WH Estimate (ha) (f)	Percentage Decrease (WH) (a-f/a *100 = g) (g)	Period After Weevil Release (months) (e-c= h) (h)
Uganda	4,732	Mar 1998	Dec 1995	27	Jul 1998	2,146	54.6	31
Tanzania	4,080	Mar 1998	Aug 1997	7	Jul 1998	28	99.3	11
Kenya	17,230	Nov 1998	Jan 1997	23	Dec 1999	3,200	81.4	36
Rwanda (Lake Mihindi only)	610	Apr 1997	Oct 2001	- 54	Jul 1999	104	83	- 27

Conclusions

Analysis of satellite imagery collected between 1994 and 2001 confirms the serious extent to which Lake Victoria and the Rwanda-Tanzania borderlands lakes have been infested by water hyacinth. The northern portions of the lake in Uganda and Kenya were most severely infested, with Winam Gulf having the most water hyacinth detected in the study. In most locations, the infestation reached a maximum in 1997 or 1998, with a lakewide maximum of approximately 20,000 ha in November 1998. By 2001, however, the severity of the water hyacinth infestation in Lake Victoria was much reduced relative to 1998.

This analysis corroborates some of the general trends suggested by the many reports estimating water hyacinth extent that have been published. However, comparison of the published reports to the results of this study reveals significant discrepancies and suggests that the reliability of many published estimates not derived from remote sensing is highly questionable.

The degree to which each of the control measures and environmental factors are responsible for the decline in water hyacinth cannot be determined from this study alone.

However, it does appear clear that biocontrol with weevils provided significant aid in reducing the abundance of water hyacinth, though this situation should be closely monitored. The decline in Rwanda's Lac Mihindi during the time of decline in Lake Victoria prior to the introduction of biocontrol agents highlights the need for vigilant monitoring over time to understand future developing trends and plan for modified approaches to control and management.

Finally, several rapid increases in different parts of the lake have been documented, which should serve as a reminder of the rapidity with which water hyacinth is capable of expansion. We therefore conclude that the region must continue with aggressive and active management strategies in order to reduce the possibility of resurgence to extremely high levels.

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Uganda: Ministry of Agriculture, Animal Industries and Fisheries – Water Hyacinth Unit and Department of Fisheries Resources, National Agriculture Research Organization – Fisheries Research Institution and Namalonge Agriculture Research Institution, National Environment Management Authority, Ministry of Lands, Environment and Water – Directorate of Water Development; Forest Department – National Biomass Study, Makerere University – Institute of Environment and Natural Resources, LVEMP – Uganda; Uganda Electricity Board

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Rwanda: Institut des Sciences Agronomique du Rwanda

Regional: East African Community Secretariat, Lake Victoria Fisheries Organization, Lake Victoria Environmental Management Program, Regional Centre for Mapping of Resources for Development, LVEMP - Regional.

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