J. Aquat. Plant Manage. 42: 73-84

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

THOMAS P. ALBRIGHT,[1] T. G. MOORHOUSE,[2] AND T. J. McNABB[2]

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 Uganda in the 1980s. Reliable estimates of water hyacinth distribution and extent are required to gauge the severity of the problem through time, relate water hyacinth abundance to environmental factors, identify areas requiring management action, and assess the efficacy of management actions. To provide such estimates and demonstrate the utility of remote sensing for this application, we processed and analyzed remotely sensed imagery to determine the distribution and extent of water hyacinth. Maps were produced and coverage was quantified using a hybrid unsupervised image classification approach with manual editing for each of the riparian countries of Kenya, Tanzania, and Uganda, 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 hyacinth infestation, especially in the northern parts of the lake. A maximum lake-wide extent of at least 17,374 ha was attained in 1998. Following this, a combination of factors, including conditions associated with the 1997 to1998 El Niño and biocontrol with water hyacinth weevils, appear to have contributed to a major decline in water hyacinth in the most affected parts of the lake. Some lakes in the Kagera basin, such as Lake Mihindi, Rwanda, were severely infested in the late 1990s, but the level of infestation in most of these decreased markedly by the early 2000s.

Key words: invasive plants, East Africa, *Eichhornia crassipes*, remote sensing, El Niño, biocontrol, aquatic weeds.

INTRODUCTION

Water hyacinth is native to the northern tropics of South America and has been described as the world's worst aquatic weed (Cook 1990). When it is introduced or colonizes a previously uninfested area, populations may rapidly increase causing serious disruption to environments, economies, and societies (Gopal 1990, Mitchell et al. 1990, Anderson and Steward 1990). After being recognized in Lake Kyoga, Uganda, in May 1988 (Twongo 1991), water hyacinth was reported in Lake Victoria, Uganda, in 1989 (Twongo 1991), Lake Victoria, Tanzania, in 1989 (Bwathondi and Mahika 1994), Lake Victoria, Kenya, in 1990 (Mailu et al. 1998), and the Kagera River of Rwanda in 1991 (Taylor 1991).

Lake Victoria is the world's second largest freshwater lake, with a surface area of 6,800,000 ha (Figure 1) (Horne and Goldman 1994). The lake is important for the region's inhabitants through the supply of drinking water, power generation, fisheries and food security, transportation, and provision of other ecological goods and services. The lake basin is approximately 18,400,000 ha in size and supports a population of more than 25 million people (Anonymous 1996). The economy of the lake basin has an estimated worth of 3 to $4 billion US annually, with the lake fishery benefiting the livelihood of at least 500,000 people and having a potential sustainable fishery export value of $288 million (Anonymous 1996).

The effects of invasive water hyacinth in the region and worldwide are serious, varied, and well documented (Gallagher and Haller 1990, Mitchell 1990, Denny 1991, Harley 1991). In the Lake Victoria area, these have included impeding shore access for fishing, hindering ferry transportation, interfering with hydroelectric power generation, blocking water intake for water supply and industry, and disrupting native aquatic plant communities (Mailu et al. 1998, Gichuki et al. 2001).

Water hyacinth is distributed throughout the near-shore areas of Lake Victoria and up to the headwaters of the Kagera River system in the highlands of northern Rwanda. Several lakes in the Kagera River system are infested with water hyacinth; the most significant among them is Lake Mihindi, at the northern end of the Akagera National Park, Rwanda. Moorhouse et al. (2000) estimated the rate of water hyacinth flowing into Lake Victoria from the Kagera River as being equivalent to contiguous floating mats covering between 0.2 ha/day and more than 1.5 ha/day (an average 0.75 ha/day or 300 ha/year), depending on seasonal river volume conditions.

Efforts to control water hyacinth in Lake Victoria and the Upper Kagera River of Rwanda during the early 1990s were of limited success and were primarily directed at manually removing water hyacinth and conducting public awareness exercises. In the mid-late 1990s, management to combat water hyacinth increased with efforts such as the Lake Victoria Environmental Management Program (LVEMP) and U.S. Agency for International Development funding for coordination efforts by Clean Lakes, Inc. (Martinez, CA, USA). Control actions included biocontrol using *Neochetina bruchi* and *N. eichhorniae* water hyacinth weevils, mechanical control using large harvesting and chopping boats, and herbicide trails (Ochiel et al. 1999, Mallya 1999). Operational water hyacinth control through the use of herbicides was not implemented in the region, however.

Currently available information pertaining to the extent, distribution, and status of water hyacinth in Lake Victoria dur-

[1]SAIC, USGS/EROS Data Center, and Department of Zoology, University of Wisconsin, Madison, WI 53706; talbrigh@usgs.gov. Work performed under U.S. Geological Survey contract 03CRCN0001.

[2]Clean Lakes, Inc., P.O. Box 3186, Martinez, CA 94553.

Received for publication August 25, 2003 and in revised form May 5, 2004.

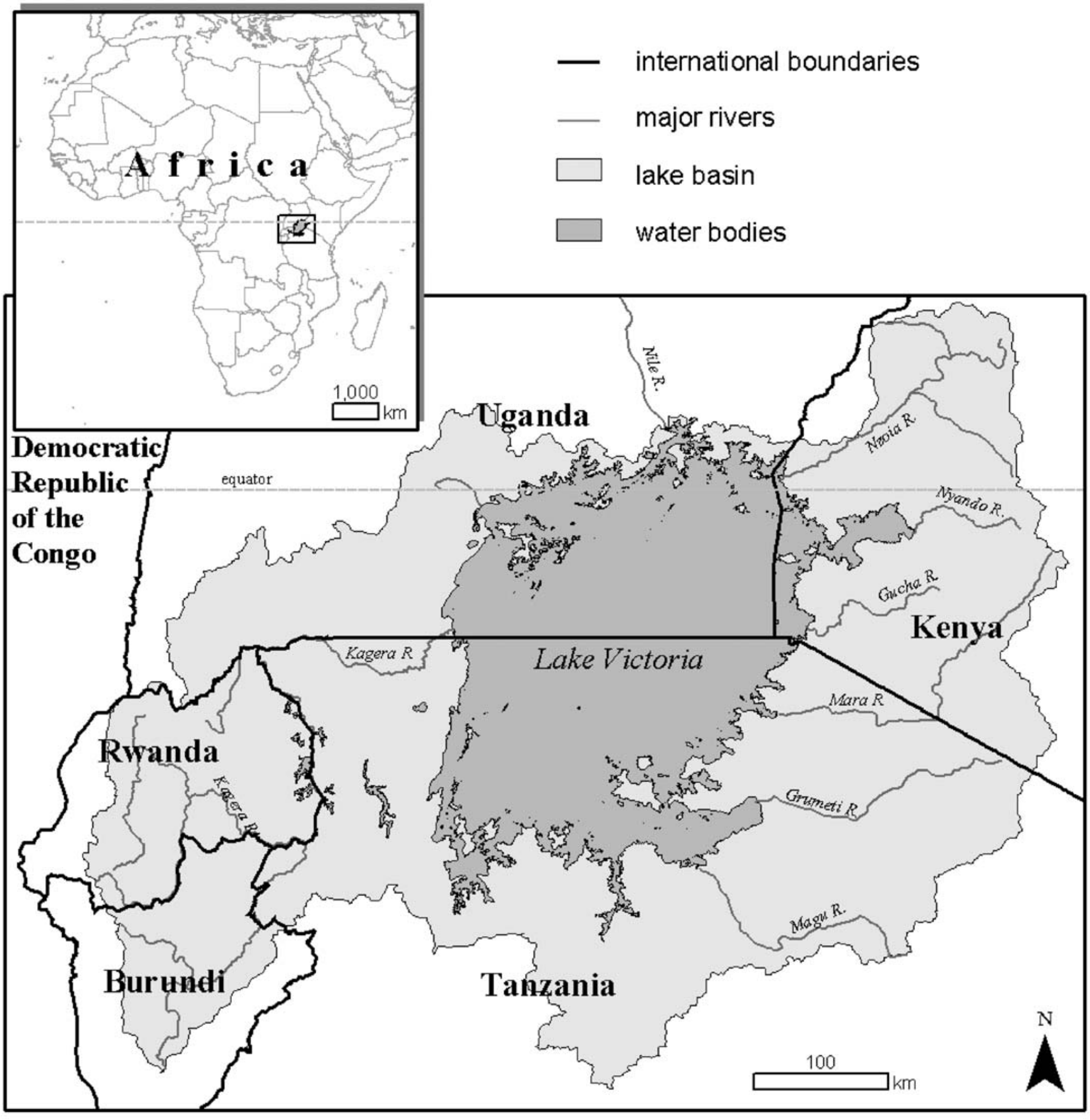

Figure 1. Lake Victoria, its basin, major rivers, and surrounding countries.

ing the 1990s and early 2000s is largely based on anecdotal accounts, local field observations, and rough estimates (McKinley 1996, Ochiel et al. 1999, and Twongo and Ondongkara 2000). Schouten et al. (1999) demonstrated the potential of synthetic aperture radar (SAR) imagery for estimating water hyacinth distribution and extent by providing estimates on three dates in 1998 for selected bays in Uganda and Kenya. Reliable information is required to gauge the severity of the problem through time, relate water hyacinth abundance to environmental factors, identify areas requiring management action, and assess the efficacy of management actions. Satellite remote sensing affords a consistent, repeatable, and synoptic view that is readily incorporated into geographic information systems for analysis. The goal of this investigation was to examine the progression of the extent and distribution of water hyacinth in Lake Victoria and parts of the Kagera River basin using remote sensing from the early stages of infestation until 2001, when data collection for the study ceased.

MATERIALS AND 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. We acquired 26 different date periods of satellite imagery from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Ikonos[3] (Space Imaging, Thornton, CO, USA), which are spaceborne optical instruments, and the Japanese Earth Resources Satellite (JERS) and Radarsat (Radarsat International, Richmond, BC, Canada), which are spaceborne SAR instruments. The optical instruments used in this study provide multispectral measurements of reflected energy from the sun and are very useful for discriminating objects based on their spectral signatures. SAR imagery is based on an active system in which the instrument emits microwave radiation and measures its return. SAR systems are capable of all-weather day and night operation and are useful for discriminating objects based on their structure, texture, and moisture content. Imagery was selected on the basis of time period availability, cost, spatial resolution, image area coverage, cloud cover, image quality, and effectiveness in discriminating aquatic vegetation. Since some of these factors are tradeoffs, we also sought balance among the factors so that some images favored one factor and others favored another. Our goal was to cover with cloud-free or otherwise unimpeded imagery every part of the lake on a minimum of five dates, with additional coverage, preferably at higher resolution, of sensitive and water hyacinth-prone areas (Table 1). Note that the 19 April 1997, 26 July 1997, and 19 January 2001 images, which were provided by Synoptics BV (Wageningen, The Netherlands), were in a three-date composite red-green-blue (RGB) clustered format, rather than being raw imagery with full radiometric resolution and fidelity. The JERS imagery was obtained from the National Aeronautics and Space Administration (NASA) as part of the Global Rainforest Mapping Program's 100-m resolution mosaic. We also included in our analysis water hyacinth extent data for Murchison Gulf, Uganda, from Schouten et al. (1999), which were derived from similar remote sensing techniques. In addition to the imagery, reference maps for the region showing local place names were acquired.

We produced an ETM+ image mosaic by merging recent adjacent images into one large image covering the entire study area. All remaining images were registered to overlay this mosaic, using either a simple X/Y offset or a 1st order polynomial transformation. We then removed land areas from consideration by generating a water mask. To accomplish this, we used a form of unsupervised classification based on the ISODATA algorithm available on ERDAS Imagine image processing software (Leica Geosystems, Atlanta, GA, USA) to identify spectrally distinct clusters that corresponded to water on individual dates of imagery. For data from radar-based sensors, we identified a backscatter threshold that cor-

[3]Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

TABLE 1. DATE PERIODS, SATELLITES/SENSORS AND MODES (WHEN APPLICABLE), CELL SIZE, AND APPROXIMATE LOCATIONS OF THE 26 IMAGES USED IN THE STUDY. TM IS LANDSAT 5 THEMATIC MAPPER, JERS IS JAPANESE EARTH RESOURCES SATELLITE, AND ETM+ IS ENHANCED THEMATIC MAPPER PLUS.

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	Lakewide, Rwanda
Oct-Nov 1996	JERS (mosaic)	100 m	Lakewide, Rwanda
6 Dec 1996	Radarsat ScanSAR Narrow B	50 m	SW Lake Victoria
19 Apr 1997	Radarsat ScanSAR Wide B	100 m	Lakewide, Rwanda
4 Mar 1998	Radarsat ScanSAR Wide B (from RGB composite)	100 m	Lakewide
29 May 1998	Radarsat Standard Beam 1	25 m	Winam Gulf, Kenya (NE Lake Victoria)
26 July 1998	Radarsat ScanSAR Wide B (from RGB composite)	100 m	Lakewide except southern fifth
6 Nov 1998	Radarsat Standard Beam 4	25 m	Winam Gulf, Kenya (NE Lake Victoria)
12 Apr 1999	Radarsat Standard Beam 7	25 m	Emin Pasha Gulf, Tanzania (SW Lake Victoria)
10 Jun 1999	Radarsat Standard Beam 7	25 m	Murchison Gulf, Uganda (N Lake Victoria)
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, Kenya (NE Lake Victoria)
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	Lakewide
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)

responded to the land/water interface. The single-date masks were then used to identify maximum water extent so that if a pixel had been identified as water on any single date, it would be considered water on the master water mask.

The next stage consisted of discriminating water hyacinth and cloud-covered or image noise areas from other areas free of water hyacinth. Clouds (in the case of the optical imagery) and noise that obscured observation were considered as "no data" since it was not possible to discern the presence or absence of water hyacinth in these areas. For most Landsat ETM+, TM, and Ikonos data, we used unsupervised clustering to identify water hyacinth and water hyacinth-free areas. Input bands included at least bands 3, 4, and 5 for ETM+/TM and the four multispectral bands for Ikonos. For ETM+ and TM imagery in the Kagera River area, we calculated a "wetness index" [(band 4 - band 5)/(band 4 + band 5)] as a basis for determining a threshold. For radar-based data, which were single-band intensity images, we applied speckle reduction filters and resampling as necessary to reduce coherent noise prevalent in radar imagery. We then identified a threshold value for each image to differentiate water hyacinth. The Radarsat RGB clustered imagery represented a special case; it was a multitemporal composite and we did not have access to the original data. For these data, we extracted three separate files corresponding to each of the original image dates, on the basis of the contribution of each date to the overall multitemporal composite image color. As necessary, we applied a 3 × 3 spatial majority filter or used minimum size threshold elimination techniques to eliminate small, often spuriously misclassified groups of pixels.

In some cases, spectrally based methods 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 (e.g., JERS mosaic, Radarsat ScanSAR), which were more sensitive to error caused by coregistration and resolution issues. In addition to intensity and color, manual edits were aided by field photos, notes, and experience, and were based on context and texture, which the human eye and mind are better at interpreting than most computer-based methods. Manual editing was facilitated by interactively overlaying coregistered images from multiple dates, allowing discrepancies and errors to be efficiently identified.

After water hyacinth and no-data areas were identified, we calculated statistics on the basis of various geographic units, which we derived from maps and a 1:1,000,000-scale vector GIS dataset. We divided Lake Victoria among three countries and further divided it into 73 bays, gulfs, and sounds. We also identified and separated the various lakes of the Kagera River system. The area and fraction occupied by each of the three classes (water hyacinth, not water hyacinth, and no data) were determined in the various geographic units defined (countries, gulfs, bays, and lakes). Furthermore, we calculated the area of each unit for which usable data were not available, i.e. if part of the unit fell outside of the image or if it was impeded by cloud cover or other no-data conditions. For specific observations of a given geographic unit to be included in figures and discussion in this report, at least 75% percent of the area had to have been visible in the imagery, unless otherwise noted. We also developed a classification of water hyacinth severity, which assigned each geographic unit to one of four categories. The categories were defined *a posteriori* as follows in order to provide clear and distinctive classes: negligible—never more than 0.5% of area 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%.

In this study, several factors prevented a comprehensive and quantitative assessment of accuracy. The study was largely retrospective and data acquired after project initiation were often collected on dates that were either not of our choosing or altogether not known in advance. Even when an image acquisition was known in advance, the large size of the lake, difficulty of access, and highly dynamic nature of free-floating water hyacinth mats made coincident reference data collection very difficult. Nonetheless, we corroborated remotely sensed estimates with field photographs and notes during several field visits. We also arranged for PhotoMap (Kenya) Ltd. (Nairobi, Kenya) to acquire 1:40,000 scale black/white aerial photographs of Winam Gulf on the morning of 12 February 2000, approximately two hours before the Radarsat image acquisition from the same date. The amount of detail visible on these photographs greatly exceeded that of any of the spaceborne remotely sensed images acquired for area. As an independent comparison, the amount of water hyacinth in Kisumu Bay, where water hyacinth was most abundant within Winam Gulf, was estimated using photo interpretation techniques from one frame of the photographs.

RESULTS

The extent of water hyacinth on Lake Victoria inferred from satellite observations between 1996 and 2001 is presented in Figure 2. Between 4,000 and 6,000 ha of water hyacinth

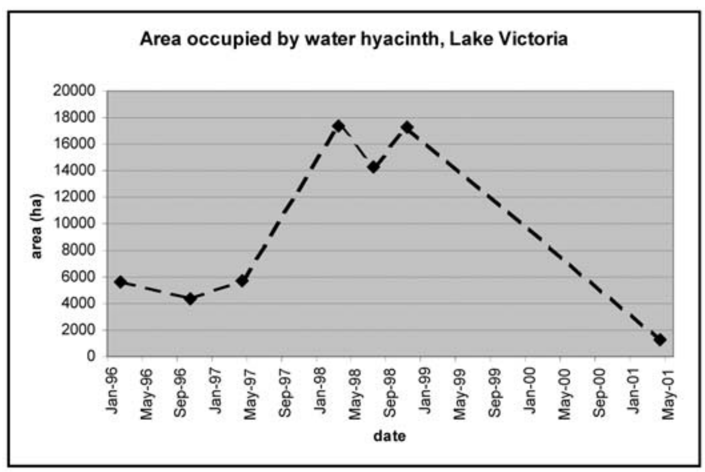

Figure 2. Area of Lake Victoria occupied by water hyacinth, as measured from satellite imagery. The reduction in water hyacinth for the July 1998 observation is related to the image for this date not covering the southern bays and gulfs in the Tanzanian portion of the lake. The graph includes data from a 6 November 1998 image, which did not cover 75% or more of the lake. In all other graphs, only data from images covering more than 75% of the area are included.

was present on the lake on dates sampled between January 1996 and April 1997. A large increase occurred in 1997 and 1998, followed by a decline to low levels by April 2001. 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 of water hyacinth was visible on an image covering primarily Winam Gulf (Kenya), which constituted less than 5% of the entire lake. Thus, it is likely that the amount present on the entire lake at that time exceeded this considerably. Generally, severity of water hyacinth infestation was greater in the north and in relatively protected bays (Figure 3). This may be linked to

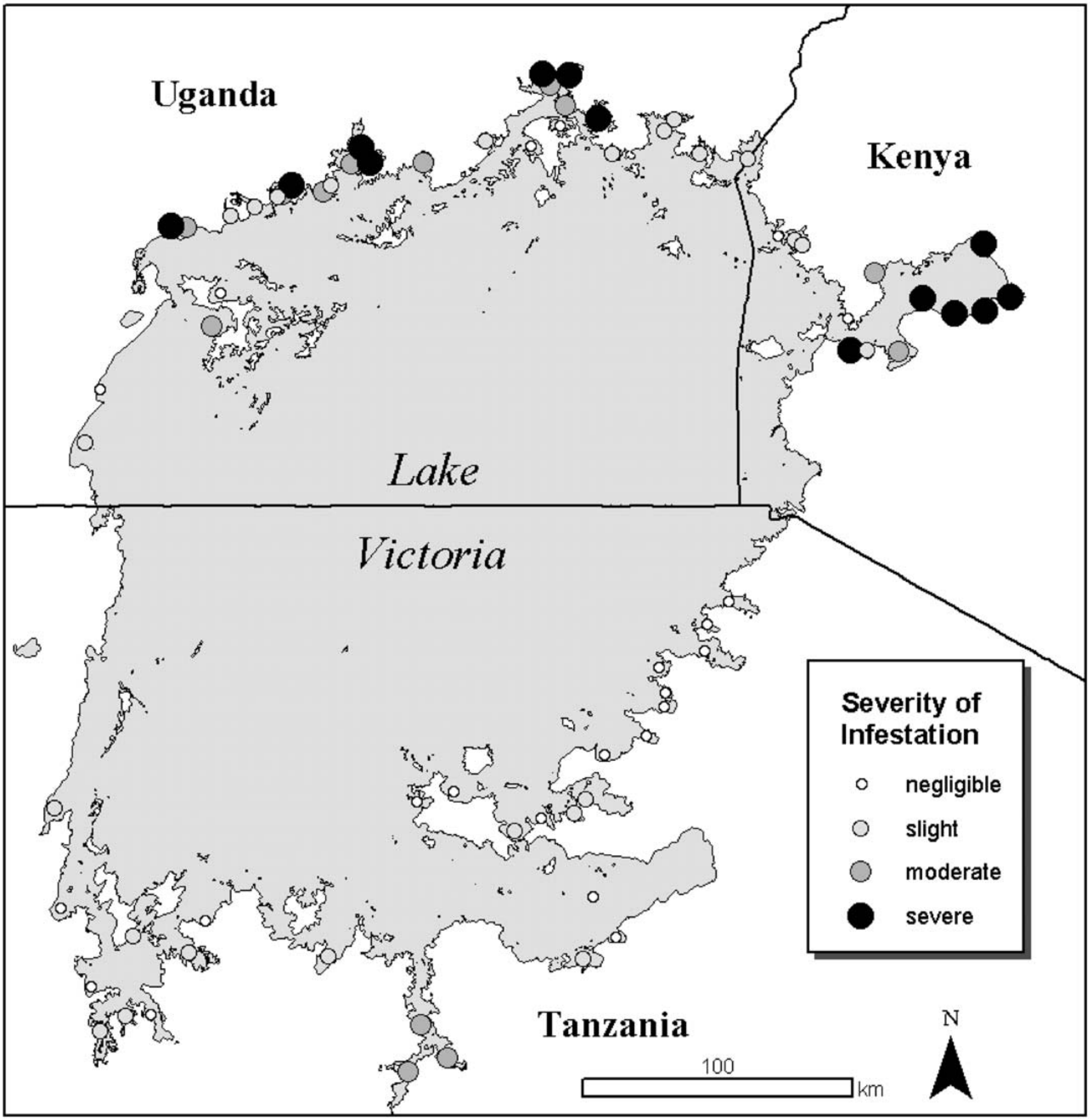

Figure 3. The observed relative severity of water hyacinth in selected bays and gulfs as detected by imagery collected between 1994 and 2001. Negligible–never more than 0.5% of area of feature visible covered by water hyacinth; slight–at least one image showing more than 0.5%; moderate–at least two images showing more than 2%; severe–at least two images showing more than 7%.

currents and weather patterns, which may have pushed water hyacinth to the north, but may also be due to the presence of more suitable water hyacinth habitat and possibly higher levels of eutrophication associated with agricultural practices and the larger urban areas of the northern parts of the basin.

Uganda

Large amounts of water hyacinth (>3,000 ha) were present in Uganda on all images from February 1996 until an observed peak of 4,732 ha on 4 March 1998 (Figure 4). Following this was a sharp reduction to 2,147 ha on 26 July 1998 and further reduction until a low of 53 ha was measured on 5 April 2001.

Murchison Bay experienced one of the most severe infestations on the lake (Figure 5). Because of strong winds and the highly mobile nature of water hyacinth (including even the largest of mats), estimates could differ markedly between morning and evening, and between seasons, owing to changes in wind direction. The earliest four points on the graph, from Schouten et al. (1999), were from two different times of day on two different dates and reveal how daily wind cycles can affect measured water hyacinth amounts. The data suggest that a rapid increase in water hyacinth extent occurred during 1994, followed by a peak of 1,974 ha (8.6% of bay) on 19 January 1995, and a period of abundant water hyacinth, ranging from 1,140 ha to 1,522 ha on dates observed between 1996 and 1997. During these periods of abundance, the imagery revealed giant mats covering hundreds of hectares in inner Murchison Bay and neighboring Wazimenya and Gobero Bays.

In late 1995, *Neochetina bruchi* and *N. eichhorniae* water hyacinth weevils were released into the Ugandan portion of Lake Victoria. However *Neochetina* spp. had been released as early as June 1996 at Katosi, Uganda (Ogwang and Molo 1997) and could have spread into Lake Victoria much earlier from a test trial pond located in Kajjansi less than 2 km from the lake where *Neochetina* spp. had been introduced in June 1994. It was not until February 1997 that we observed weevil feeding activity on plants in Murchison Bay. Weevils multiplied rapidly, attaining an average number of 13.8 weevils per plant in 1998 and 24.7 weevils per plant in 1999 on Lake Victoria in Uganda (pers. comm., Uganda National Agriculture Research Organization, 2000). Also during 1998 to1999, mechanical removal work was occurring at Port Bell. By 1999, there was only 15 and 1 ha of water hyacinth detected in March and July, respectively. By late 2001, weevil numbers had declined to an average of 8.8 weevils per plant (pers. comm., Uganda National Agriculture Research Organization, 2001). Our monitoring of weevil populations indicated that populations had declined to 1.2 weevils per plant for stationary water hyacinth growing along the shoreline and to 2.3 weevils per plant for floating mats of water hyacinth by January 2002 (unpubl. data). Perhaps associated with this decline in weevil density, a slight increase in water hyacinth to 35 ha was apparent in the image data in January 2001.

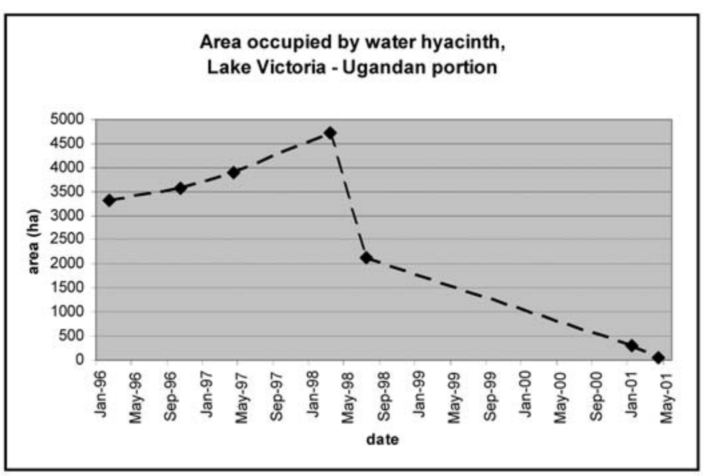

Figure 4. Area of the Ugandan portion of Lake Victoria occupied by water hyacinth, as measured from satellite imagery.

Tanzania

Although occupying nearly half of Lake Victoria, Tanzania did not experience the same degree of water hyacinth infestation as the other riparian countries. Levels of water hyacinth extent between 825 ha and 2,004 ha were observed in 1996 and 1997, followed by a peak of 4,081 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 6). It should be noted that the 26 July 1998 image did not cover the southern parts of Emin Pasha Gulf (extreme southwest) and Mwanza Gulf (extreme south) and was therefore probably responsible for an underestimation of extent. Weevil release in Tanzania began in August 1997 (Mallya 1999). Observations after 2000 indicated that extents of water hyacinth were less (100 to 200 ha) than those observed in the late 1990s.

Kenya

Kenyan waters were late in being infested by water hyacinth relative to the other countries, but experienced very large populations (Figure 7). The late onset of infestation supports the hypothesis that water hyacinth originally came from the Kagera River system and migrated to the Uganda and Tanzania sides of the lake first. In terms of shoreline length and economic importance, the Kenyan portion of Lake Victoria is dominated by Winam Gulf, which is the site of the city of Kisumu and of several rivers that flow into Lake Victoria. Winam Gulf was the site of the largest infestations recorded in any location at any time during the study. After small infestations were observed in 1994 and 1996, 8,504 ha, 4,846 ha, 12,091 ha, and 17,218 ha of water hyacinth mats were observed in March, May, July, and November of 1998, respectively. Note that the reduced amount observed in May 1998 was due, at least in part, to the fact that a large part of heavily infested Nyakach Bay was outside of the imaged area on this date. Because we rarely observed flowering, these drastic increases in water hyacinth extent were possibly due to a combination of rapid asexual reproduction and colonization of areas by individuals from other parts of the lake. Our 1998 field observations revealed that the large floating mats of water hyacinth also included opportunistic native

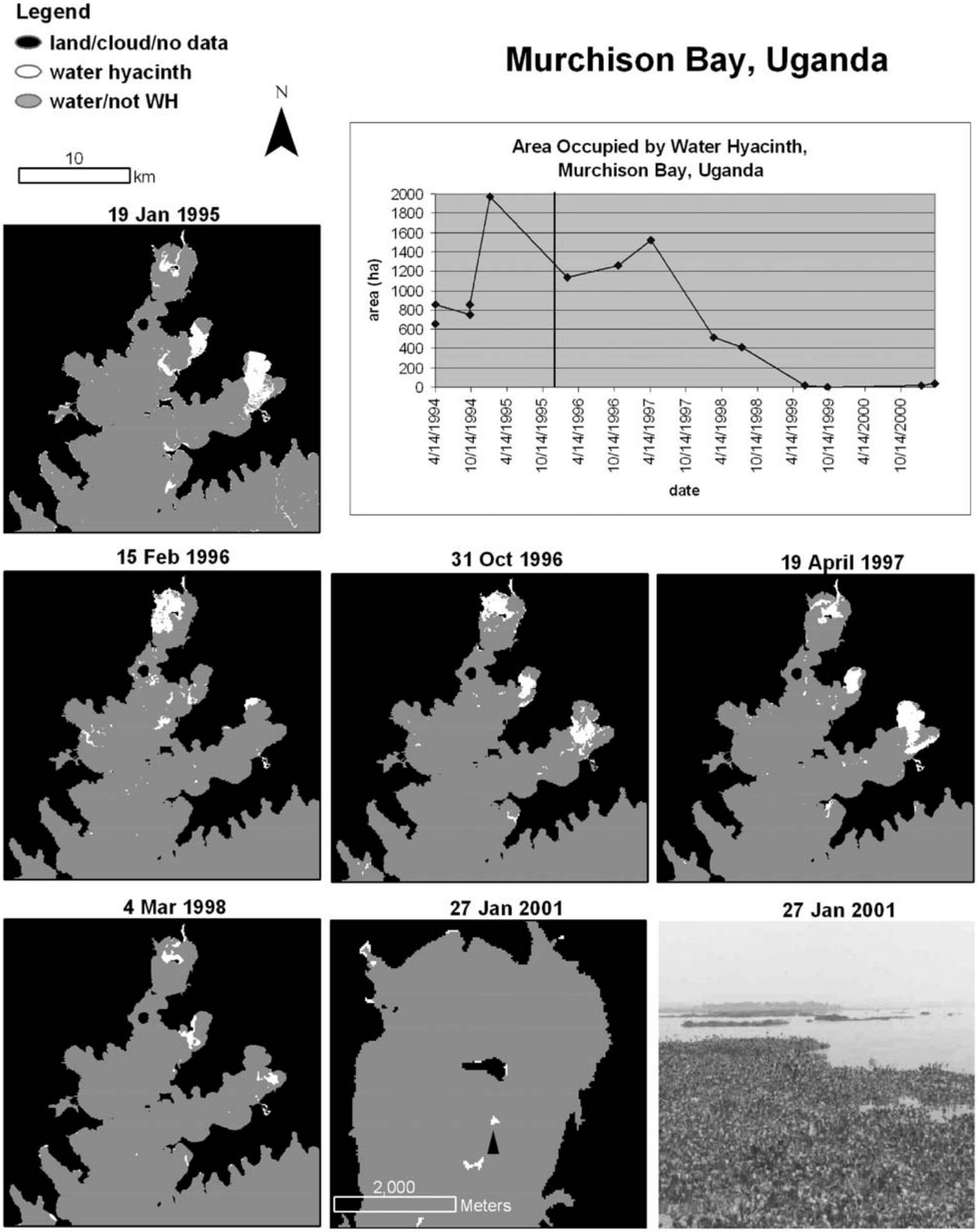

Figure 5. Changes in distribution and extent of water hyacinth coverage in Murchison Bay, Uganda. Note that the first four data points on the graph are from Schouten et al. (1999). Wazimenya and Gobero Bays are located within the east central and southeast parts of Murchison Bay, respectively. The vertical line on the graph indicates the approximate timing of weevil release on Murchison Bay. A lake level photograph taken within two hours of satellite image is shown for 27 January 2001. The black arrow on the adjacent image map indicates approximate photo position and direction.

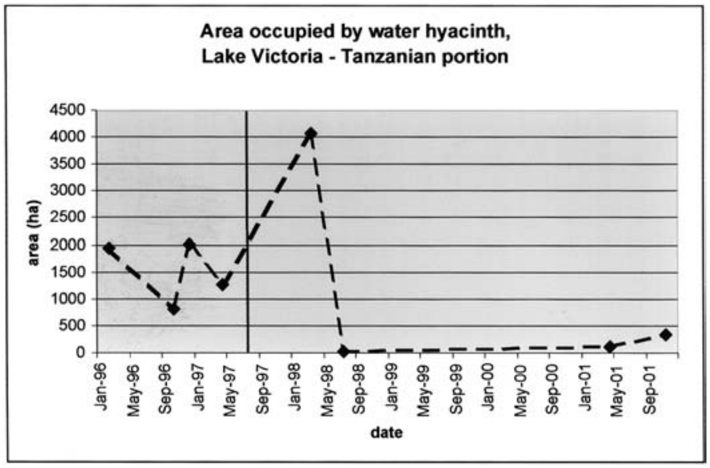

Figure 6. Area of the Tanzanian portion of Lake Victoria occupied by water hyacinth, as measured from satellite imagery. The vertical line indicates the approximate timing of weevil release.

plants, such as hippograss (*Vossia cuspidata* Roxb.) and papyrus (*Cyperus papyrus* L.), growing on top of water hyacinth. We did not witness these plants colonizing open water in absence of water hyacinth, suggesting that the presence of water hyacinth was required for their establishment in these new areas.

Weevil release in Kenya began in January 1997 (Ochiel et al. 1999) and the Kenyan LVEMP used a mechanical chopper between December 1999 and April 2000. A large reduction to 3,134 ha in December 1999 and 532 ha in February 2000 was observed. However, the 2000 image did not cover the southeastern part of Winam Gulf and therefore this estimate may have been lower than the actual extent. Manual interpretation of the aerial photograph frame of Kisumu Bay acquired on 12 February 2000 yielded an estimate of 313 ha of water hyacinth and associated aquatic vegetation (Figure 8). The comparable area measured from part of the Radarsat image from the same date was 290 ha (approximately 93% agreement). Even in the short time between the photograph and the image, shifting of floating mats of water hyacinth and associated aquatic vegetation is readily apparent. For this reason, we did not conduct a pixel-wise accuracy assessment, whereby corresponding pixels (scanned in the case of the photograph) from both the photo and the image would be compared. A field photograph taken on 23 February 2000 also clearly showed an expansive mat of water hyacinth, further confirming the validity of the satellite derived estimates. As with other parts of the lake, a slight increase in water hyacinth was observed in 2001.

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. Our analysis revealed that those lakes close to and/or connected to the Kagera River were more likely to have experienced water hyacinth invasion than those located farther away and/or not connected. Lake Mihindi, Rwanda, in particular, has had a large amount of water hyacinth associated with it for several years. After the first observation of 270 ha in December 1996, a peak of 610 ha, which covered over half of the lake, was observed in April 1997 (Figure 9). Our most detailed observation, using the high-resolution Ikonos satellite, revealed a decline to 200 ha in October 2000. This quantity appeared to be relatively stable through our final spaceborne observation in May 2001. However, a field visit in October 2001 revealed that water hyacinth coverage had increased greatly over the last image estimate (Figure 9). Based on the area that appears occupied in the photos from this visit and areas mapped from previous dates, between 350 and 550 ha of water hyacinth was present at this time. Biological control implementation started in the Rwandan portion of the Kagera River in September 2000 and in Lake Mihindi in October 2001 (Moorhouse et al. 2002).

Explaining the Decline in Water Hyacinth

Several factors may have contributed to the decline in observed water hyacinth extent in the Lake Victoria basin. East Africa experienced an El Niño associated weather phenomenon during the last quarter of 1997 and first half 1998 (Anyamba et al. 2001). During this time, the lake level climbed 1.70 m in a period of 7 months (pers. comm., Uganda Electricity Board, 2001). Since records began in 1899, such a rapid rise was matched only by an event that occurred in 1962 to 1963. Heavy winds and waves associated with a heavy rainy season may have physically damaged plants and a rapid rise in water level may have dislodged mats of macrophytes. For instance, Gichuki et al. (2001) implicated the 1962 to 1963 event, which was also associated with El Niño, in the destruction of wetlands in Winam gulf. The timing of the decline in water hyacinth extent in Tanzania from 4,080 ha in March 1998 to only 28 ha in July 1998 is consistent with the hypothesis that El Niño weather conditions contributed to a decline in water hyacinth there. Similarly, in Lake Mihindi, we suspect that the large reduction in water hyacinth that occurred between 1997 and 1999 was due, at least in part, to flood waters from a major rainfall event breaching the blocked outlet of Lac Mihindi and allowing water hyacinth to spill out of the lake and into the river system. The possible effects of the 1997 to1998 El Niño are complex, however. Rather than destroying water hyacinth, heavy rains and rising water levels may have dislodged and redistributed water hyacinth in some cases. This redistribution may have been the source of new populations in Winam Gulf after the 1997 to 1998 El Niño episode.

The timing of declines in observed water hyacinth with respect to the timing of weevil releases and observed populations and feeding scars strongly suggest that weevils played a role in the decline of at least some populations of water hyacinth on Lake Victoria. In Murchison Bay, Uganda, for instance, 1,522 ha of water hyacinth were observed on 19 April 1997, 16 months after the December 1995 weevil release in the area. By 4 March 1998, 27 months after weevil release, this amount had been reduced to 516 ha and weevil populations and feeding scars were visible during field visits in this period. Similarly, in Kenya, a reduction from 17,218 ha of water hyacinth on 6 November 1998 to 3,134 ha on 17 December 1999, occurred some 35 months after weevil release in Kenya. Such lags between weevil release and major impact are in the typi-

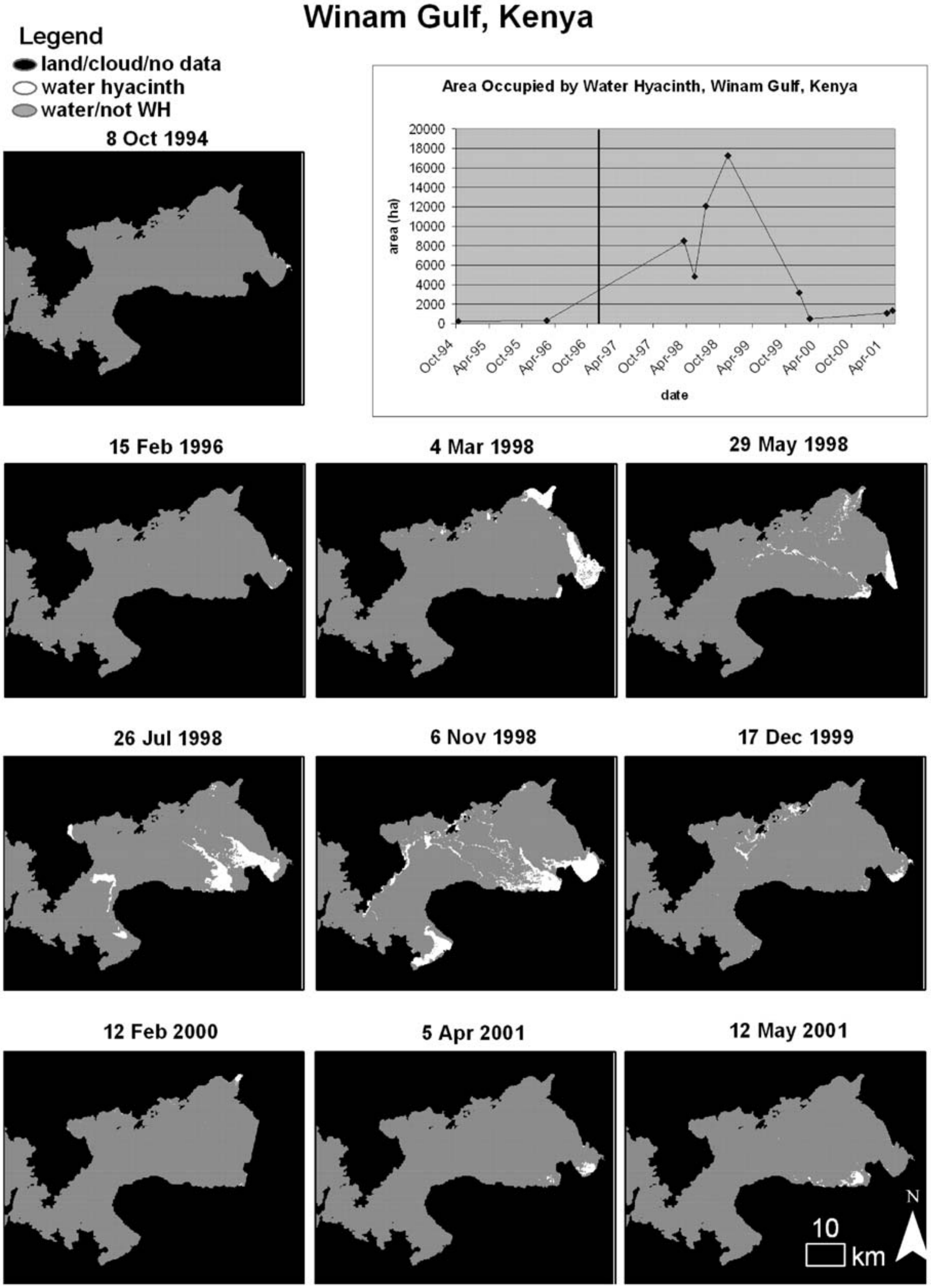

Figure 7. Changes in distribution and extent of water hyacinth coverage in Winam Gulf, Kenya. Note that the reduced amount observed in May 1998 is due, at least in part, to the fact that a large part of heavily infested Nyakach Bay, on the far eastern side of the gulf, was outside of the imaged area on this date. The vertical line on the graph indicates the approximate timing of weevil release in Winam Gulf.

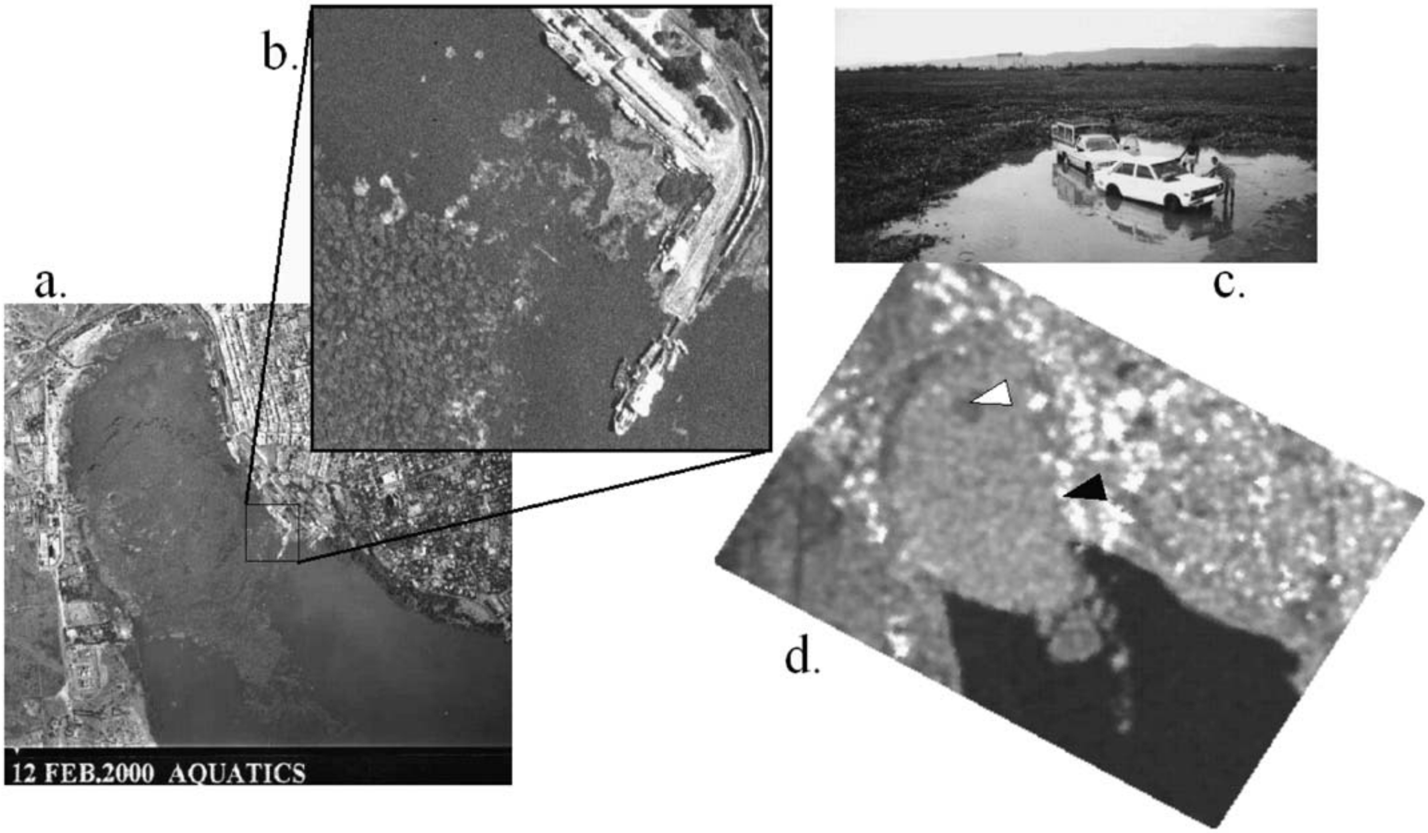

Figure 8. a) Scanned image of a portion of 1:40,000 aerial photography acquired 12 February 2000 by Photomap (Kenya) Ltd. b) blown up portion showing port of Kisumu. c) Field photograph taken on 23 February 2000. Vegetation in photograph and adjacent areas was identified as water hyacinth with mixture of hippograss and papyrus. Black arrow in d) indicates approximate position and direction of photo. d) Portion of 12 February 2000 Radarsat image of Kisumu Bay shown at comparable scale and orientation to aerial photograph. White arrow indicates an area of dominant papyrus, which is believed to have succeeded water hyacinth.

cal 2- to 5-year range (Julien et al. 1999). In Tanzania, the major reduction in water hyacinth extent between March and July 1998 occurred less than a year after weevils were released. Such a decrease appears to be too sharp and too soon after weevil release to be attributable to biological control alone. In the case of Lake Mihindi, Rwanda, it is clear that weevils played no role in the declines since they had not been released when the major decline occurred some time between April 1997 and July 1999. Because water hyacinth populations on Lake Mihindi appeared to be increasing again in October 2001 when weevils were released, subsequent imagery or field visits would likely prove useful in determining the effects of weevils on water hyacinth populations on this lake.

Several other factors may also have had an effect on water hyacinth populations. Various pathogens (*Alterneria* spp., *Phoma* spp., *Cladosporium* spp., *Myrothecium* spp., *Curvularia* spp., *Acermonium* spp., *Trichoderma* spp., *Fusarium* spp., and *Nigrospora* spp.) capable of weakening water hyacinth have been isolated from water hyacinth plants in Lake Victoria (Godonou 2000). In local areas, such as inner Murchison Gulf and Kisumu Bay, mechanical removal may have played a role. Plant health may also have been influenced by other weather and environmental conditions, such as water quality, nutrient supply, temperature, and humidity. Any and all of the above factors may have acted in combination or even synergistically with each other. For instance, with plants subjected to herbivory by weevils and damage by severe weather conditions, pathogens may have found an ideal environment to become established and further weaken or destroy the plants.

Analysis of satellite imagery collected between 1994 and 2001 confirms the serious extent to which Lake Victoria and the Rwanda-Tanzania borderlands lakes were infested by water hyacinth. The northern parts of the lake in Uganda and Kenya were most severely infested, with Winam Gulf, Kenya 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 at least 17,374 ha in 1998. By 2001, however, the severity of the water hyacinth infestation in Lake Victoria was much reduced relative to 1998.

The degree to which each of the control measures and environmental factors were responsible for the decline in water hyacinth cannot be determined from this study alone. However, it does appear that different factors predominated in different locations and may have acted in combination. Finally, the ability of water hyacinth to rapidly propagate, expand its extent, and colonize remote areas was clearly documented. This fact, together with the most recent remotely sensed and photographic evidence of expansions in water hyacinth extent, suggests that continued monitoring and management actions may be required to reduce the pos-

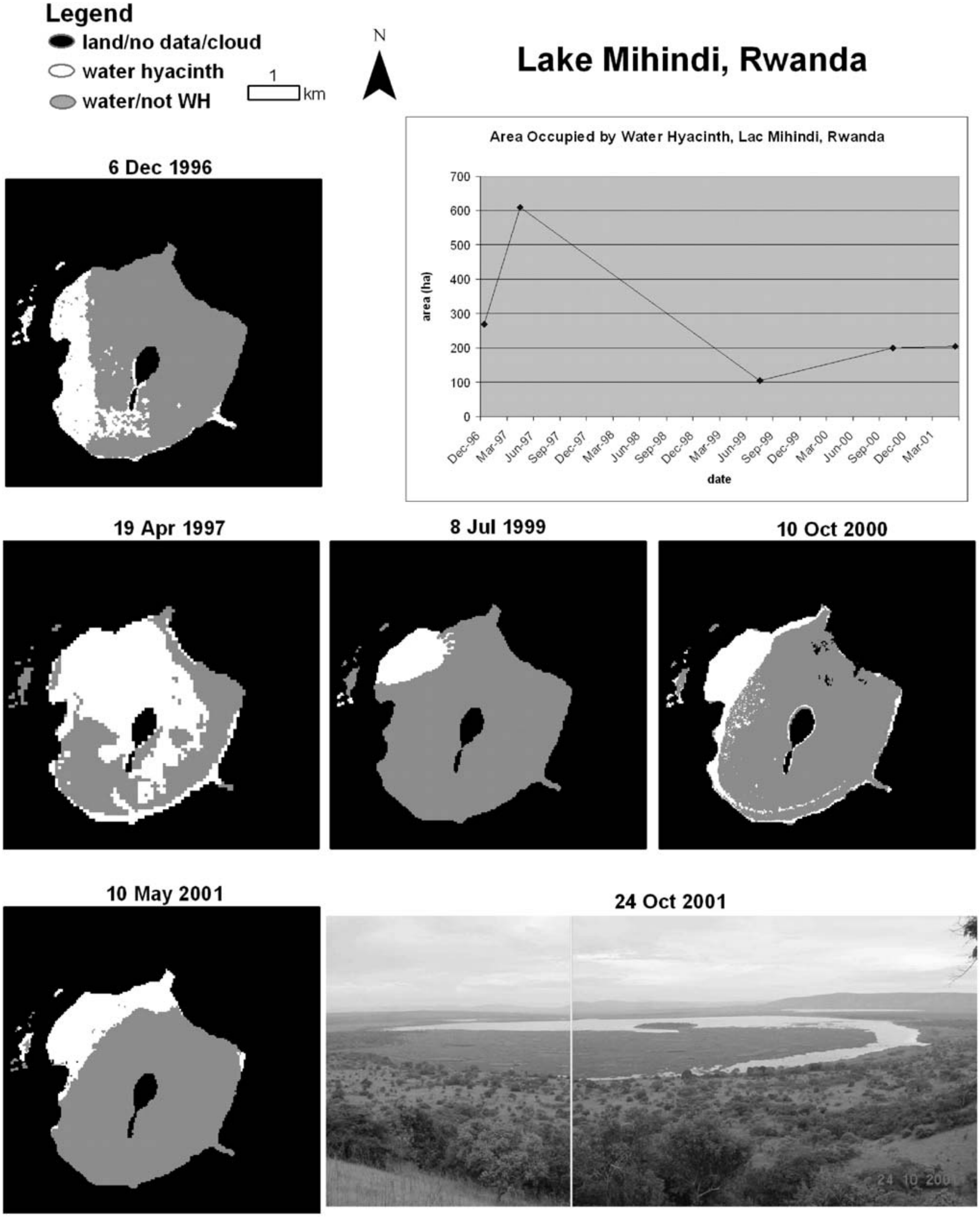

Figure 9. Changes in distribution and extent of water hyacinth coverage in Lake Mihindi, Rwanda. Field photos taken on 24 October 2001 were digitally stitched together to show a panoramic view of expended water hyacinth relative to satellite mapped coverage on 10 May 2001.

sibility of a resurgence to extremely high levels of water hyacinth in Lake Victoria and the Kagera River basin.

ACKNOWLEDGMENTS

This publication was made possible through support provided by the USAID/Uganda, Greater Horn of Africa Initiative (GHAI), under the terms of Grant No. 617-A-00-99-00008-00. The opinions expressed herein are those of the author(s) and do not necessarily reflect the views of USAID.

Special thanks go to Synoptics, BV for making their processed data available through funding provided to them by the Dutch Remote Sensing Board, and to NASA's Jet Propulsion Laboratory for provision of the Global Rainforest Mapping Program data. We acknowledge the contributions of Russell Rykhus and Michael Coan of the USGS/EROS Data Center who participated in parts of the data processing and analysis. We acknowledge Larry Tieszen of the USGS/EROS Data Center for early project development and vision. Thanks also to Chandra Giri, William Haller, and two anonymous reviewers for helpful suggestions on the manuscript.

We also wish to acknowledge the numerous national and regional institutions, and projects in Kenya, Rwanda, Tanzania, and Uganda as well as numerous institutions that fall outside the region for their discussions, suggestions, input, interest, or encouragement. Kenya: Kenya Agriculture Research Institute, Ministry of Environment and Natural Resources—Department of Resource Surveys and Remote Sensing, LVEMP—Kenya, PhotoMap (K) Limited. 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. Tanzania: Ministry of Agriculture—Plant Protection, Ministry of Natural Resources and Tourism, Department of Environment, National Environment management Council, University of Dar es Salaam-Natural Resources and Environment/Institute for Resource Assessment, University College of Lands and Architectural Studies—Geo Information Centre, LVEMP—Tanzania. 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.

LITERATURE CITED

Andersen, L. W. J. and K. K. Steward. 1990. Aquatic weed problems and management in North America, p. 371-405. *In:* A. H. Pieterse and K. Murphy (eds.). Aquatic Weeds: The ecology and management of nuisance aquatic vegetation. Oxford University Press, Oxford, England.

[Anonymous]. 1996. Lake Victoria Environmental Management Project. Global Environment Division, Environment Department, World Bank, Project document 15541-AFR.

Anyamba, A., C. J. Tucker and J. R. Eastman. 2001. NDVI anomaly patterns over Africa during the 1997/98 ENSO warm event. Int. J. Remote Sensing 22:1847-1859.

Bwathondi, P. and G. Mahika. 1994. A report of the infestation of water hyacinth (*Eichhornia crassipes*) along the Tanzanian side of Lake Victoria. National Environment Council, Dar es Salaam, Tanzania.

Cook, C. D. K, 1990. Origin, autecology, and spread of some of the world's most troublesome aquatic weeds, p. 31-38. *In:* A. H. Pieterse and K. Murphy (eds.). Aquatic Weeds: The ecology and management of nuisance aquatic vegetation. Oxford University Press, Oxford, England.

Denny, P. 1991. Africa, p. 115-148. *In*: M. Finlayson and M. Moser (eds.). Wetlands. International Waterfowl and Wetlands Research Bureau. Gloucester, UK.

Gallagher, J. E. and W. T. Haller. 1990. History and development of aquatic weed control in the United States. Reviews of Weed Science 5:115-191.

Gichuki, J., F. Dahdouh Guebas, J. Mugo, C. O. Rabour, L. Triest and F. Dehairs. 2001. Species inventory and the local uses of the plants and fishes of the Lower Sondu Miriu wetland of Lake Victoria, Kenya. Hydrobiologia 458:99-106.

Godonou, I. 2000. Surveys in Kenya, p. 7-8. *In:* R. Murphy and M. Hill (eds.) Water Hyacinth News, CABI Bioscience, United Kingdom. Vol. 2.

Gopal, B. 1990. Aquatic weed problems and management in Asia, p. 318-340. *In:* A. H. Pieterse and K. Murphy (eds.). Aquatic Weeds: The ecology and management of nuisance aquatic vegetation. Oxford University Press, Oxford, England.

Harley, K. L. S. 1991. Floating Aquatic Weeds: What are they? Where are they? How should we manage them? p. 111-124. *In:* A. Greathead and P. de Groot (eds.). Control of Africa's Floating Water Weeds. Commonwealth Science Council, Zimbabwe.

Horne, A. J. and C. R. Goldman. 1994. Limnology, 2nd Edition. McGraw-Hill, Inc. p. 29.

Julien, M. H., Griffiths, M. W. and A. D. Wright. 1999. Biological control of water hyacinth. The weevils *Neochetina bruchi* and *N. eichhorniae*: biologies, host ranges, and rearing, releasing, and monitoring techniques for biological control of *Eichhornia crassipes*. ACIAR Monograph No. 60, 87 pp.

Mailu, A. M., G. R. S. Ochiel, W. Gitonga and S. W. Njoka. 1998. Water Hyacinth: An Environmental Disaster in the Winam Gulf of Lake Victoria and its Control, p. 101-105. *In:* M. Hill, M. Julien and T. Center (eds.). First IOBC Global Working Group Meeting for the Biological Control and Integrated Control of Water Hyacinth.

Mallya, G. A. 1999. Water hyacinth control in Tanzania, p. 25-29. *In:* M. Hill, M. Julien and T. Center (eds.). First IOBC Global Working Group Meeting for the Biological Control and Integrated Control of Water Hyacinth.

McKinley, J. 1996. In Lake Victoria, Amazonian weed wreaks havoc. 5 August 1996, New York Times, New York, NY.

Mitchell, D. S. 1990. Aquatic weed problems and management in Africa, p. 341-354. *In:* A. H. Pieterse and K. Murphy (eds.). Aquatic Weeds: The Ecology and Management of Nuisance Aquatic Vegetation. Oxford Univ. Press, Oxford, England.

Moorhouse, T. G., P. Agaba and T. McNabb. 2001. Recent efforts in biological control of water hyacinth in the Kagera River headwaters of Rwanda, p. 152. *In:* M. H. Julien, M. P. Hill, T. D. Center and J. Ding (eds.). Biological and Integrated Control of Water Hyacinth, *Eichhornia crassipes* - Proceedings of the Second Meeting of the Global Working Group for the Biological and Integrated Control of Water Hyacinth, Beijing, China, 9-12 October 2002. ACIAR Proc. No. 102.

Ochiel, G. S., A. M. Mailu, W. Gitonga and S. W. Njoka. 1999. Biological Control of Water Hyacinth on Lake Victoria, Kenya, p. 115-118. *In:* M. Hill, M. Julien and T. Center (eds.). First IOBC Global Working Group Meeting for the Biological Control and Integrated Control of Water Hyacinth.

Ogwang, J. and R. Molo. 1997. Biological Control of Waterhyacinth in Uganda, p. 287-293. *In:* 16th East African Biennial Weed Sci.Conf. Proc. Weed Sci. Soc. of East Africa.

Schouten, L. S. M., H. J. C. van Leeuwen, J. G. M. Bakker and T. Twongo. 1999. Water Hyacinth Detection in Lake Victoria by Means of Satellite SAR. USP-2 report USP-2 98-28, Netherlands Remote Sensing Board, Delft, The Netherlands.

Taylor, A. R. D. 1991. Floating water-weeds in East Africa, p. 111-124. *In:* A. Greathead and P. de Groot (eds.). Control of Africa's Floating Water Weeds. Commonwealth Sci. Council, Zimbabwe.

Twongo, T. 1991. Status of Water Hyacinth in Uganda, p. 55-57. *In:* A. Greathead and P. de Groot (eds.). Control of Africa's Floating Water Weeds. Commonwealth Sci. Council, Zimbabwe.

Twongo, T. and O. K. Ondongkara. 2000. Invasive water weeds in Lake Victoria basin: proliferation, impacts, and control. Lake Victoria 2000. Lake Victoria Fisheries Organisation.