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Water hyacinth detection in Lake Victoria by means of satellite SAR

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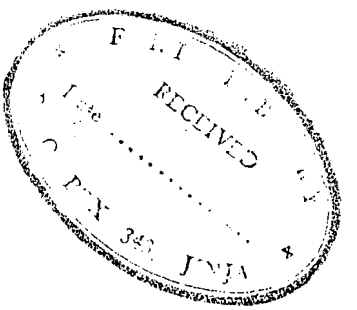

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This report describes a project, carried out in the framework of the National Remote Sensing Programme (NRSP-2), under responsibility of the Netherlands Remote Sensing Board (BCRS).

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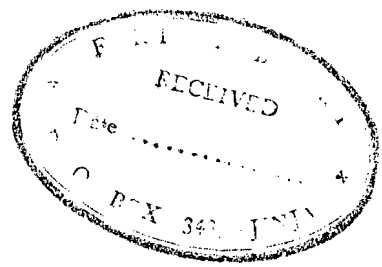
ABSTRACT

Water hyacinth *(Eichhornia crassipes)* is a notorious weed that can be found in large parts of the tropical world. It infested East African fresh water lakes in the 1980's, soon causing major problems on notably Lake Victoria. Mats consisting of water hyacinth blocked ports along the shoreline of the lake, the generation of hydro-electricity was hampered and the already disrupted ecosystem was further affected. A control program has been initialised, that requires objective and efficient information. The ways to get information about the exact location and the size of the water hyacinth mats need to be improved. The application of remote sensing techniques can realise this improvement.

SYNOPTICS and FIRI have carried out a project to investigate the potentials of spaceborne Synthetic Aperture Radar to detect water hyacinth mats on Lake Victoria. ERS, Radarsat and SIR-C data were acquired to evaluate the different sensors. The evaluation showed that in particular Radarsat data are well suited to identify and map the mats. New sensors, both in the optical range and the microwave range, make the perspective of a monitoring program based on remote sensing techniques even better.



SUMMARY

During the last century water hyacinth *(Eichhornia crassipes)* has colonised large parts of the tropical zones. On the African continent it was first introduced in Egypt and from the 1930's onwards it appeared in many of the fresh water lakes and rivers of Africa. In the 1980's it reached Ugandan waters and in the early 1990's it started a rapid proliferation in Lake Kyoga and Lake Victoria. Scientists of the Ugandan Fisheries Research Institute (FIRI) have studied water hyacinth infestations and impacts. Because of the international interests and the economical meaning of Lake Victoria the attention has been focussed on this lake.
Water hyacinth is a nuisance for fishermen and other navigators on the lake. The water hyacinth plants cause problems to the generation of hydro-electricity and to water abstraction. In addition the water hyacinth affects the ecosystem of the lake, which was already disrupted by an increased input of nutrients, a change in the regional climate and by species stocking of the Nile perch and Nile tilapia. Development of (biological) control mechanisms has been given top priority. It is however acknowledged that objective and efficient information about the distribution of the water hyacinth is essential. Current methods to map its distribution are time consuming and results of these methods are occasionally received with scepticism by policy makers. Therefore the development of techniques based on remote sensing and GIS technology to identify, map and quantify provides a practical and more reliable measure of the magnitude of the water hyacinth problem. Data based on these techniques would be an essential input into policy decisions on water hyacinth management.

As clouds often cover the area the use of optical sensors is less opportune. Synthetic Aperture Radar (SAR) can be applied notwithstanding clouds. In addition previous studies, carried out in Bangladesh have demonstrated the ability of microwave sensors to detect water hyacinth. SYNOPTICS Integrated Remote Sensing & GIS Applications and FIRI set up a project to further explore the potential of spaceborne SAR to determine the presence of water hyacinth particular on Lake Victoria. It aims to develop a practical and applicable technique that can provide data required by the policy makers.

After an extensive analysis of available SAR systems and of conditions on the lake an acquisition scheme for SAR imagery was set up. Eventually four Radarsat products were obtained and two ERS-2 scenes. The Radarsat images existed of ScanSAR Wide B images and of one Fine Beam image. In addition to these SAR products special imagery recorded by the two Space Radar Laboratory (SRL) missions in 1994 was acquired.

The results clearly demonstrate the potential of SAR imagery to map water hyacinth distribution. A simple technique has been developed that enables a swift estimation of the surface of the water hyacinth mats. This technique can be applied on both dedicated software and relatively simple software. The analysis of the SRL data learnt that short wavelengths (X-band) are the most optimal to monitor water hyacinth, but that medium (C-band) and to a less extent long wavelengths (L-band) can be used as well.
Preliminary results that were presented to the National Task Force on Water Hyacinth were well received. It has a concrete interest to find out if similar projects can prove the presence of water hyacinth on other fresh water lakes in Uganda.
The results also show that Radarsat provides more suited imagery than ERS, mainly because of its polarisation and overpass time. It has also been shown that estimations of the size of water hyacinth mats are affected by the degree of compactness. Winds can increase the compactness and thus decrease the surface by more than 25%. Winds are also capable of translocating water hyacinth mats several kilometers a day.

In the future a monitoring program can be based on new SAR systems of which ASAR onboard the Envisat satellite is an example. Envisat is currently being developed by the ESA and will be launched in May 2000. For detailed monitoring ASAR will offer an attractive alternative for Radarsat, but the latter will still be favoured for broad scale monitoring because of its ability to capture the entire lake with one image. Newly launched optical sensors make it worthwhile to further explore the potential of these sensors as well.

ACKNOWLEDGEMENTS

This project would not have come about without the support and the efforts of Mr. Martin van der Knaap, the coordinator of the Lake Victoria Fisheries Research Project (LVFRP) in Jinja. He provided the means to communicate and exchange data and proved to be essential in many other ways.
Professor Mukiibi and Mister Tizikara of NARO are thanked for their willingness to discuss the project proposal and to agree in the participation of FIRI in the project. Also we acknowledge the interest of Dr Orach Mesa of the Lake Victoria Monitoring Panel.
From KMFIRI we would like to thank Mr. Kelemba and Mr. Getabu for their measurements and their general interest in the project.
We also have to mention Sam Small who went through quite some trouble in providing us with meteorological data collected at Jinja Kimaka Airfield.

Finally all the employees of FIRI who assisted in the study need to be thanked. We'd like to name the people in the field who collected data about the distribution of the weed in Thruston Bay, the master of the vessel Mputo who managed to keep the vessel sailing despite the opposition of the water hyacinth mats and notably Fred Wanda and Hannington Ochieng for their respective contributions to the project.

1.2 PROJECT OBJECTIVES

Lake Victoria measures well over *68,000* km², which is slightly less than the surfaces of the Netherlands and Belgium put together. Due to the enormous size of this area the application of spaceborne sensors provides the best objective monitoring technology to identify and map water hyacinth on Lake Victoria. In principal a technique to monitor water hyacinth should indicate whether or not the weed is present at a certain location (space) at a certain moment (time). Spaceborne systems qualify for two reasons to this monitoring need:

1. The size of the area is so vast that other monitoring techniques need a lot of time to gather data. For instance it takes several weeks to complete the entire Ugandan portion of Lake Victoria mapping weed distribution and cover with canoe and outboard motor.
2. To observe the dynamics of water hyacinth along the bays is complicated and difficult due to the inaccessibility of the areas.

It took the scientists at FIRI several years to map the seasonal weed movement patterns on the lake. Accurate determination of weed cover requires long-term experience relating to diurnal and seasonal movements of the weed. Also knowledge of plant densities at various times of the day is essential to understand the actual extension of the mats; multi-layering effects may result in a misinterpretation of the actual magnitude of the coverage. Due to the complicated matter the information on water hyacinth dynamics can not be relied on. It is expected that the use of remote sensing information as a mapping and monitoring tool will improve the determination of water hyacinth coverage as well as to understand the mobility of the huge floating mats.

To monitor water hyacinth from space one can avail over optical and microwave sensors. Water hyacinth plants make up large mats of green vegetation. Sensors that are sensitive for infrared radiation are able to detect water hyacinth as has been demonstrated in the past (Neuville et al. 1995, see also Plate 1d). However, it proved to be difficult to distinguish with these sensors water hyacinth from other vegetation zones like papyrus. An additional problem for using optical sensors is the frequent presence of cloud cover in the Lake Victoria region during daytime. An average of 40 to *50%* cloud coverage throughout the year hinders the application of optical sensors in a continuous monitoring program (see Table 1)

Table 1 *Average cloud coverage values during daytime in the period 1931-1960 for Entebbe, Uganda*

	I	II	III	IV	V	. VI	VII	VIII	IX	X	XI	XII
% **Cloud coverage**	35%	38%	43%	49%	47%	47%	45%	46%	44%	44%	43%	141 %1

Microwave sensors (SARI) on the other hand, have the possibility to observe the earth notwithstanding the presence of cloud coverage. This enables the set up of a continuous monitoring program, which is necessary for studying the extension, the movements and the spatial distribution of the water hyacinth. As the water hyacinth mats have a clear, relatively homogenous texture it is likely that microwave sensors can detect water hyacinth mats. In fact, this has been demonstrated by recent studies carried out in the floodplains of Bangladesh with Radarsat (EGIS, 1997). In this study the potential of Radarsat imagery to distinguish water hyacinth from other water plants was hindered due to strongly varying open water bodies and the presence of various crops in the area. The area covered by open water in the Lake Victoria region is more stable. This makes the area well suited to carry out the current study, since it can focus on a positive differentiation between water hyacinth and

ı *SAR: Synthetic Aperture Radar. More about SAR application canbefound in Oliver ond Quegon (1998).*

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other water elements, especially when the shorelines of the Lake can be brought into the processing and classification procedures.

The main objective of the current project is to explore the potential of spaceborne SAR to determine the presence of water hyacinth, to map distribution and migration in time and to estimate the extent of water hyacinth mats in order to support environmental management decisions in wetland areas in particular around Lake Victoria. A second objective is to develop a relatively simple satellite SAR-based technique for monitoring water hyacinth. This technique should be applicable, even if basic image processing packages are used.

1.3 PROJECT SET-UP

The project has been set up with the explicit intention to operate in a practical and applicable manner to ensure that the findings are relevant for the management of Lake Victoria. It means that some scientifically interesting questions remain unanswered if they do not have any practical value. The report reflects this intention.
The next chapter looks in more detail at the ecosystem of Lake Victoria. Also some of the major movement patterns of water hyacinths on the Lake will be discussed. Chapter 3 describes the existing SAR systems and the relevant data sets. It starts with a technical paragraph (3.1) discussing the prerequisites of the various SAR sensors that are currently available to support decision-making policy. In the next chapter the methods used to carry out the project are described, including the set-up of the applied image acquisition scheme and a description of acquired imagery.
Chapter 5 describes the results implying data pre-processing and processing. In chapter 6 the conclusions and recommendations are discussed as well as an outlook to other disciplines that may benefit from the availability of SAR imagery. If indeed SAR imagery will be acquired in the framework of a general management system for Lake Victoria, it is obvious that the images can be used for more than just one purpose.

1.4 ROLES OF DIFFERENT INSTITUTIONS INVOLVED

For the kind of study presented here two types of expertise are essential. The first one is expertise about the water hyacinth and about the ecosystem in which this plant grows. The *Fisheries Research Institute (FIRI)* in Jinja (Uganda) provides this kind of expertise. The second kind of expertise is about SAR systems. *SYNOPTICS Integrated Remote Sensing and GIS Applications BV* (Wageningen, the Netherlands) provides this kind of expertise. Although FIRI and SYNOPTICS are the main organisations involved in this study, two other organisations played an important role as well: the Kenya Marine and Fisheries Research Institute (KMFIRI) and the Lake Victoria Fisheries Research Project (LVFRP).

SYNOPTICS
SYNOPTICS Integrated Remote Sensing and GIS Applications BV is active in various fields of remote sensing applications and in projects based on the implementation of Geographical Information Systems (GIS). An example of one of its activities is flood monitoring by means of satellite SAR in the Ganges/Brahmaputra floodplain in Bangladesh. In this project it was shown that certain Radarsat modes have potential to distinguish between water hyacinth and open water areas (EGIS I, 1997 and Van Leeuwen et al., 1997).

FIRI
FIRI is one of the seven research institutions under the National Agricultural Research Organisation (NARO) In Uganda. FIRI undertakes research on the water environment, fishery biology and ecology; and on fish stock dynamics, impact of fishing gears and methods, as well as on post harvest technology and aquaculture. FIRI is therefore mandated to generate sound

scientific knowledge base, technology packages and policy recommendation towards optimal development and utilisation of fisheries resources while concerning the resources base.

KMFIRI

KMFIRI is responsible for the research into fisheries related subjects of both freshwater ecosystems and marine ecosystems of Kenya. It has two major branches, one in Mombasa for the marine ecosystems and one in Kisumu for the freshwater ecosystems. With the branch in Kisumu agreements were made during the course of the project to exchange data. Officially the KMFIRI has not been a partner in the project. As the nuisance caused by water hyacinth in Kisumu Bay and Winam Gulf has been notorious, the contributions of KMFIRI are well appreciated.

LVFRP

The LVFRP is a collaborative research project between a consortium of European research institutions and the fisheries research institutes of Kenya (KMFIRI)·, Uganda (FIRI) and Tanzania (Tanzania Fisheries Research Institute, TAFIRI) that is sponsored by the European Development Fund (Bugenyi & Van der Knaap, 1997). In brief the Research Project aims to harmonise the collection of data, to analyse the data and present results in forms useful for fisheries managers.

The LVFRP will not deal with the water hyacinth problem, which is one of the reasons why the LVFRP has not been a partner in the project. But in the scope of the project the LVFRP contributed with logistics and facilities, which were essential for communication between Synoptics and FIRI and for progress of the project.

TAFIRI, the counterpart of FIRI and KMFIRI in Tanzania did not participate in this study for logistic reasons. An additional reason for not including the TAFIRI in this exploratory study is that along the Tanzanian borders of the Lake the problems caused by water hyacinths are still relatively modest.

2 WATER HYACINTH ON LAKE VICTORIA

2.1 LAKE VICTORIA

Lake Victoria is the largest lake of Africa with an open water surface of 68,500 km². The lake is characterised by its relative shallowness (average depth of 40 m), its long shoreline (3,440 km long) and its altitude of 1136 m above sea level. The Lake is split between three countries. 51% of the Lake is situated in Tanzania, 43% in Uganda and 6% in Kenya. The border between Uganda and Tanzania follows the 1-degree latitude line south of the Equator. The catchment area of the Lake is 184,000 km². The Lake has several inlets, of which some are seasonal, but it has only one outlet: the Victoria Nile at Jinja in Uganda. Some of the major topographical features of the Lake are indicated in Figure 1.

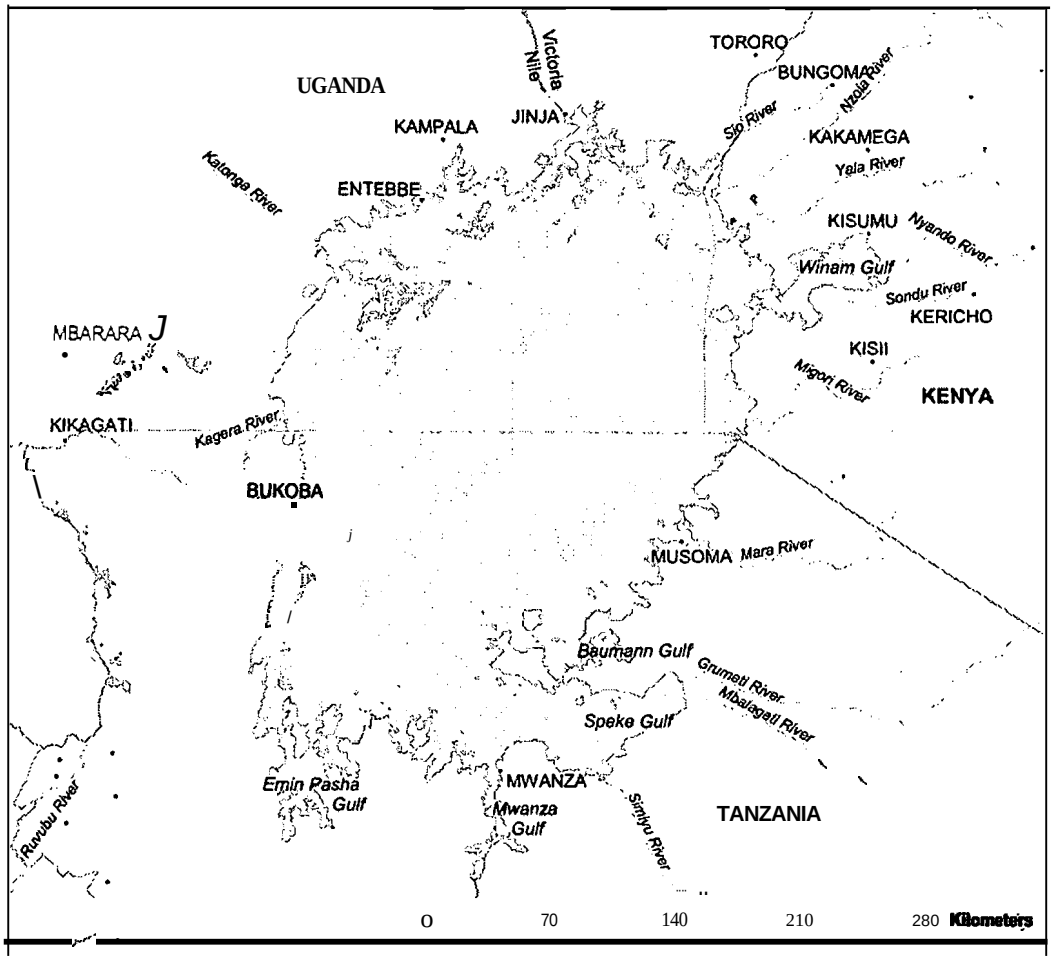


Figure 1 Lake Victoria with some of the major rivers, Gulfs and towns indicated.

The ecological balance of the Lake has been disturbed since several decades due to (Balirwa, 1998):

1. an increased input of nutrients from external sources, particularly from the atmosphere, but also from run off;
2. a change in the regional climate associated with an increase in temperature leading to prolonged periods of thermal stratification and anoxia at the bottom of the water column;

3. species stocking of the Nile perch and Nile tiLapia, which have led to a disruption of energy, flow patterns.The introduction of the Nile perch has had far reaching consequences. It has been welcomed by fishermen and the fishery industries of the three riparian states, but ecologists feared a complete disruption of the ecosystem (Goldschmidt, 1996).

From the early 1990's a fourth cause brought further disruption to the ecosystem: the proliferation of water hyacinth. It is assumed that water hyacinth has been introduced to Lake Victoria through the Kagera River. Though the first report in which the presence of the weed was mentioned was not published until 1989, the first observations of the weed in the lake date back to the early 1980's. In 1991 it reached Kampala and the following year the first plants were observed in the Jinja area. From these observations it is clear that the long-term spread has been in an eastern direction. The presence of water hyacinth causes several problems:

- water hyacinth fringes along the shores make up a physical obstruction of fishing areas;
- fishing activities are disrupted;
- landing sites become less accessible;
- certain parts of the lake start to smell badly;
- a number of dangerous reptiles find a shelter in the water hyacinth mats.

The presence of water hyacinth is not just a nuisance. Recent research has indicated that the weed may alter the ecology of shoreline wetlands of the lake. For instance Balirwa (1998) found that the extension of water hyacinth coincides with an increase of hippo grass *(Vossia cuspidata)*, a native emergent macrophyte, and with a strong decline of water plants like *Nymphaea, Ceratophy{{um* and *Pistia.* Most researchers believe that water hyacinth will become a permanent part of the ecosystem of the lake. Though the proliferation may be kept under control, it is expected that it won't be possible to ever get rid of the weed. The impact of the introduction and proliferation of water hyacinth in Lake Victoria needs to be studied carefully. On a scientific seminar held in July 1997 by staff of FIRI some important recommendations for future, research were made. Amongst others the FIRI staff recommended (Mikenga, 1997):

- to include basic limnological parameters in studies on water hyacinth, especially the nutrient dynamics of the fresh water lakes involved
- the study the impact of the water hyacinth on socio-economic conditions of the communities around the lake
- to determine the actual magnitude of the lake infestation of water hyacinth with higher accuracy.

A monitoring program based on remote sensing techniques can provide the higher accuracy FIRI staff would like to have. A long-term program provides ways to follow the magnitude of the infestations throughout the years.

2.2 CURRENT CONTROL MECHANISMS

Since the problems around the presence of water hyacinth arose, both the local people and the governments of the riparian are concerned in finding solutions. In general three different methods can be applied to combat the proliferation of water hyacinth. They are the physical removal of the plants, the use of herbicides and biological control. The physical removal of water hyacinth is the most direct way and can either be done manually or mechanically (see Plate 1c). During the last few years several experiments were carried out on Lake Victoria to verify the effects of mechanical removal. These experiments were done at amongst others Owen Falls Dam near Jinja (Uganda) and at Port Bell near Kampala (Uganda). In 1998 a tender was issued to remove the weed by mechanical means from Winam Gulf (Kenya). Initially it was thought that the American company that won the bid would start the harvesting in January 1999. Within a period of three months it was going to harvest 1,500 hectares of the weed. But until April 1999 the actual launch of the campaign has been put off three times. The

manual removal of water hyacinth is often done in an unorganised way, for instance by fishermen who are directly affected by the presence of water hyacinth.

The use of chemical herbicides has often been considered, but currently none of the three countries has authorised the use of herbicides to control water hyacinth. Nobody seems to question the effectiveness of chemicals, but many people fear the consequences from applying chemicals. The exact effect of the chemicals on people and fish is un known and in addition there is a threat of economic sanctions the EU may impose on the import of fish from Lake Victoria if herbicides are applied.

The third way to control the water hyacinth is by biological means; natural enemies of the water hyacinth are being released to keep it under control. So far two different species of weevils have been released: Neochetina eichhornia and Neochetina bruchi. The release of a third insect, a may fly, is being considered. Characteristic for these insects is that they are plant specific. Extensive research has been done prior to their release, in order to prevent an other uncontrollable distortion of the ecosystem. The Task Force established under the East African Co-operation arrangement regards biological control as a sustainable control strategy, which is environmentally friendly. During the scientific seminar held by staff of the FIRI the following future strategies with respect to the biological control of the water hyacinth were proposed (Mikenga, 1997).

- to extent the current biological control programs by introducing new insect species, notably may flies of the *Povilla* genus
- to extent the im pact of weevils on water hyacinth by introducing virulent strains that can be brought to the plants by the insects
- to extent the current control programmes with micro-biological research to find out why the plants start to rot after attack by weevils

Table 2 summarises the current stand of the management of water hyacinth in the three riparian states.

Table 2 Practical manifestation of the management of water hyacinth in East Africa

Country	Current status
Kenya	Limited manual removal of water hyacinth. Biological control turns out to be the most promising solution. The intended mechanisation of physical control has not yet taken off.
Tanzania	Manual removal and biological control, the latter is still in an early stage but catching on very fast.
Uganda	A combination of manual removal at small landing sites; mechanical removal at strategic locations e.g. the Owen Falls bridge across the Nile River; and biological control, which appears the most successful solution so far.

2.3 WATER HYACINTH AND ITS DYNAMICS

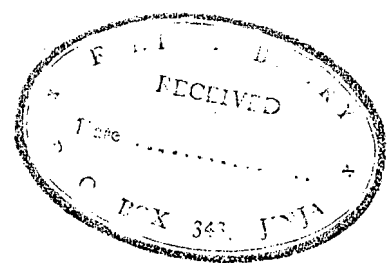
Research on water hyacinth identifies two modes of distribution, namely the stationary fringe along shorelines of lakes and rivers, and mobile mats of variable dimensions resident in sheltered bays most of the year. Stationary mats along Lake Victoria range between 5 and 15m in width and by 1995 they covered about 80% of the shoreline with an estimated cover of 2,200 ha. The rate of increase in the mobile component of water hyacinth in Lake Victoria, Uganda peaked between 1994 and 1995. Cover estimates of 1.112 ha, 1.673 ha and 1.793 ha were made in 1994, 1997 and 1998, respectively.

Two wind patterns can be identified on the lake: a diurnal pattern and a seasonal pattern.
The diurnal pattern is related to the heating of the air above the earth during the day. The air above land is heated faster than the air above water bodies. Warm air rises and as a consequence the local air pressure decreases. The air pressure above water bodies is therefore higher than above land and wind will start to blow from the water body towards the land. After sunset the temperature of the air above land will drop faster than the temperature above the water body. During the night the exact opposite situation will occur and an offshore wind will start to blow. In theory each day has two periods with calms, one at the end of the night and one at the beginning of the evening. The diurnal winds cause a daily oscillating movement pattern of water hyacinth mats resident in a given bay from and towards the shoreline.

The seasonal pattern is related to changes in rain and prevailing wind conditions. In general the area north of the lake has four seasons. The long wet season starts in the middle of March and lasts until June. The short dry period runs from July to mid-September. This period is followed by a short wet period that lasts until November. The final long dry season runs from December until mid-March. However it should be stressed that the 1997/1998 season was an exceptional year as a result of the El Nino effect. Early 1998 the water level of the lake was 1 meter higher than average!
The main wind conditions during these seasons have an important influence on the distribution of the water hyacinth. During the second half of the year, particularly between September and November, seasonal wind regimes often associated with thunderstorms intermittently migrate mobile water hyacinth cover from sheltered areas across the open lake (see Figure 2) in a systematic pattern. From the main production bays the weed is being redistributed to three 'collection bays'; Thruston and Hannington Bay to the north east of the lake and Waiya Bay west of the Entebbe peninsular (see Figure 6 for the location of these bays). Since 1992 large quantities of water hyacinth accumulated in these bays as only a small fraction of the cover can reach the open water area again. During the last three years large quantities of water hyacinth have been accumulated in Winam Gulf, in the north east of the lake, too. From these observations it is clear that:

1) the lake should be monitored at different moments in the year, with at least one image during the period when southern winds prevail and one image in the period when northern winds prevail;
2) specific bays where large quantities of water hyacinth accumulate, need to be paid more attention to.

As the current project seeks to explore the potential of SAR to detect water hyacinth, it is not required to cover the whole lake with high-resolution imagery. Therefore high-resolution images were ordered only for two areas that are known for their water hyacinth infestations; Thruston Bay, east of Jinja, and Winam Bay, a large bay west of Kisumu, Kenya. These areas are situated near research institutes which ease the performance of field observations.



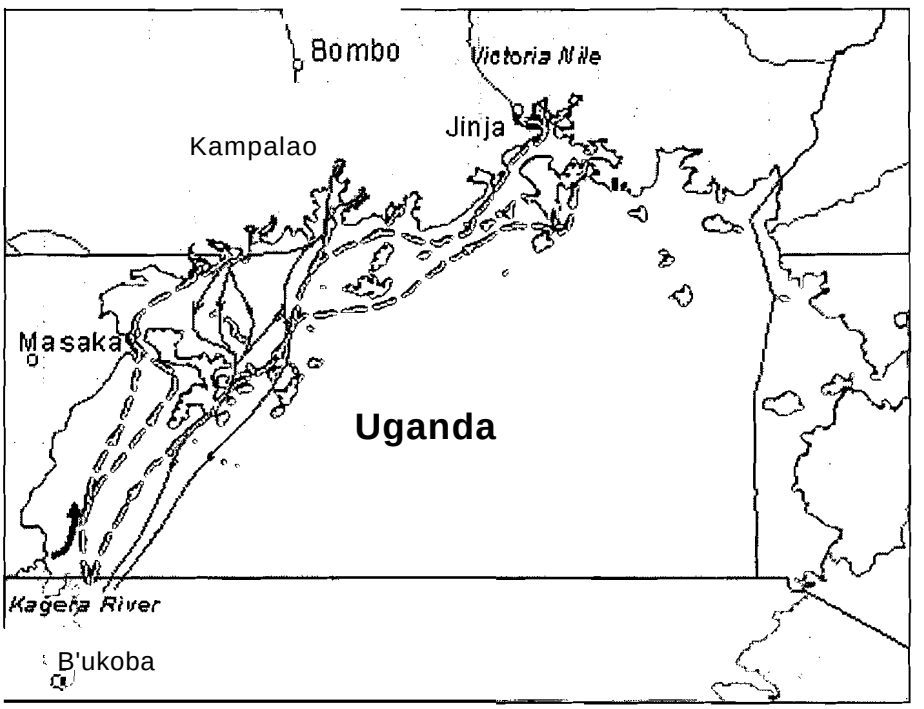


Figure 2 Seasonal movements of water hyacinth in Lake Victoria, Uganda. The dark blacke arrow indicates fringing water hyacinths, coming out of the Kagera Rivers; the thin greene arrows indicate the north-heading movements of water hyacinth and the black arrows the south-heading movements.

3 MATERIALS

An important issue in this study is the search for the most dedicated remote sensing tool(s) that are available or might become available in the near future. The study not only envisages the challenge what sensor is technically capable to detect water hyacinth but also if this sensor can be put into force as an operational instrument in a monitoring programme and at what costs. In the following three paragraphs the available data sets and sensors will be discussed.

3.1 PREREQUISITES OF A SATELLITE SAR-BASED DETECTION TECHNIQUE

This paragraph is about the technical prerequisites of satellite SAR to monitor water hyacinth. To develop a satellite SAR-based technique it is necessary to assess which SAR system has to be chosen. At the one hand this means that an analysis of the optimal configuration has to be made and at the other hand one needs to take into account which systems are currently available. The circumstances have to be analysed under which the system should operate and conditions have to be set accordingly to make the application successful. On the basis of these prerequisites the general objectives are refined.

3.1.1 Relevant properties of SAR

A SAR system consists of a fixed antenna mounted on a platform (a satellite or the Space Shuttle). As the platform tracks its orbit, the sensor transmits and receives a microwave signal (or microwave signals, in the case of the Space Shuttle) with a certain wavelength. The microwave signal is sent downwards with a specific angle. Both the sent signal and the received signal can be in different modes of polarisation. After a fixed time interval the received signals can be combined to create a SAR image. The swath of the sensor determines the width of an image. From this brief overview its is clear that SAR systems may differ in several ways, notably:

a) the wavelength of the microwave signal;
b) the angle under which the signal is sent (depression angle);
c) polarisation of the microwave signal;
d) the swath of the sensor.

Apart from these four factors that are connected with intrinsic properties of the sensor, other factors that proceed from the characteristics of the platform are relevant too:

e) the repeating cycle and
f) the time of overpass.

a. The wavelength

For spaceborne systems only radar is used with a wavelength of a few centimetres up to a few decimetres. In practice this means that three classes of wavelengths are relevant: the X-band, the (-band and the L-band (Table 3). As a rule of thumb only objects larger than the wavelength can be detected. In the case of water hyacinth this means that leaves, with an average size of ca. 5-8 cm across, will be detected by sensors operating in the X- and (-band, but probably not by sensors operating in the L-band. Water hyacinth mats make up large vegetation zones with a typical homogenous structure (Plate 1b) that may consist of thousands of individual plants representing a substantial biomass. For these reasons it can be expected that sensors that operate in the L-band will be able to detect water hyacinth mats, but there is likely to be some difference compared to sensors that operate in X- or (-band.

Table 3 Overview of three relevant wavelengths for spaceborne SAR

Band	Frequency Range in GHz.	Wavelength Range in cm
X	5.20-10.90	2.75-5.77
C	3.9-6.2	3.8-7.6
L	0.39-1.55	19.3-76.9

b. Polarisation

The out- and incoming microwave signal can be filtered in such a way that the electrical wave vibrations are reduced to a single plane perpendicular to the direction of wave propagation. The possible planes are either horizontally or vertically orientated (Lillesand & Kiefer, 1994). These planes are referred to as polarisation. Four combinations of polarisation are possible:

the signal is sent in horizontal mode and received in horizontal mode (HH polarisation)
the signal is sent in horizontal mode and received in vertical mode (HV polarisation)
the signal is sent in vertical mode and received in horizontal mode (VH polarisation)
the signal is sent in vertical mode and received in vertical mode (VV polarisation)

The HV and VH polarisations are most suited to act as discriminators, because volume scattering causes the signal to be depolarised.

c. Depression angle

The depression angle is platform dependent and varies roughly between 45^0 and 67^0. The incidence angle is the angle with which the microwave beam 'hits' the target and is important for the extent in which the signal is returned towards the receiver. The smaller incidence angle, the less signal will return to the receiver. So, a large incidence angle should be preferred.

d. Swath of the SAR

The swath is the area on the ground that is covered by that part of the microwave beam that is used for building up the image. With the aid of the depression angle and the angle of the microwave beam itself the swath can be determined. A typical swath width is in the order of 100 km, but can significantly vary depending on the sensor.

e. Visiting freguency

Each platform follows a certain orbit characterised by an altitude, an inclination angle and a visiting frequency. The inclination angle represents the angle of the path or track of the platform with respect to the Equator. The visiting frequency concerns the time lapse between two successive images of the same sensor that can be obtained of the same area. This sensor specific property is also known as the temporal resolution and is particular important for monitoring activities. In this respect it may be worth mentioning that spaceborne SAR systems can operate during daytime and night-time and observe the earth surface twice during overpass by means of the descending mode and ascending mode. If a phenomenon on earth is likely to change quickly, a high frequency of images is needed to monitor the changes that take place. In this study the required repeating frequency has to be studied for monitoring the water hyacinth dynamics.

f. Time of overpass

The time of overpass can be important if certain conditions are likely to change in the course of the day and these conditions affect the state of the features that has to be observed or monitored. Examples are the tidal effects on water levels along coasts, or diurnal wind patterns that cause waves on the water surface.

These factors brought up the following question:

i. What configuration of a SAR system is best suited to monitor water hyacinth?
ii. When should SAR images be acquired?
iii. What is the best time to record the SAR data?

The answers to these questions determine to a large extent the SAR-based technique that needs to be developed. However, the SAR systems presently available make up a pre-selection that not necessarily complies with the answers on these questions.

3.1.2 Available SAR systems

At the start of the project three SAR based satellites were operational: the ERS-2, JERS-l and Radarsat. On October 11th 1998 the JERS-l satellite came to an end. In this paragraph the specifications for these three systems that will be of importance in the development of a SAR-based technique are presented. Their main characteristics are listed in Table 4.

Table 4 Overview of the characteristics of the SAR systems in operation. A complete overview of possible Radarsat modes can be found in Appendix I.

SAR system	Platform	Wavelength	Polarisation	Incidence angle	Swath
AMI	ERS-2	5.66 cm	VV	23°	100 km
SAR	JERS-1	23.51 cm	HH	35.21°	75 km
SAR	Radarsat	5.6 cm	HH	35-49° (Fine Beam mode) 20-45° (ScanSAR Wide)	50 km 500 km

The AMI sensor of ERS and Radarsat both operate in the (-band, but with different polarisations. The SAR system of ERS was designed with oceanographic applications in mind. In fact, this was one of the reasons why the SAR system of ERS has been fitted with a VV polarised sensor. This makes the AMI sensor especially useful for oceanographic studies, because it is likely to give more information about water surfaces than other polarisations. The use of this sensor however is not restricted to oceanographic applications as it proofed to provide valuable information for land applications as well. The distinction of water hyacinth from the water surface will be enhanced if the later will give a return signal to the receiver as little as possible.
In the table only two of the many types of Radarsat modes are presented. Appendix I shows an overview of the possible modes Radarsat offers. For a discussion of the different types one is referred to literature, like Kramer (1996) or Radarsat International (1997).

The three satellites have different repeat cycles. Radarsat reaches the same orbit after 24 days, JERS-l after 44 days and ERS after 35 days. As has been shown in chapter 2, the dynamics of water hyacinth follow a seasonal pattern. So a repeat cycle of even 44 days will be able to monitor this pattern. Yet a repeat cycle of one and a half months introduces some risks making it less suitable for this specific monitoring activity; If for some reason one acquisition fails, the interval between two acquisitions becomes too long[2]. Table 5 gives an indication of the passing times of the three SAR systems in their descending and ascending passes. From the description of the diurnal wind patterns in chapter 2.3 it is clear that the overpass times of Radarsat coincides best with the periods of calms.

2 This project experienced that the failure of an acquisition is not just a hypothetical possibility.

Table 5 Approximate overpass times of SAR based satellites operating in C-band over Lake Victoria.

Sensor	Mode	Local time
ERS	Ascending	10:59 - 11:12
	Descending	23:22 - 23:33
JERS-1	Ascending	10:30 - 11:00
	Descending	22:25 - 22:55
Radarsat	Ascending	18:53 - 19:18
	Descending	06:19 - 06:27

Besides the above described technical characteristics of the sensor it is of equal importance how these systems transmit their recorded information to earth. A sensor can only transmit information directly to earth if the satellite is in the reach of a ground receiving station. If this is not the case, the data have to be stored temporarily on a tape device. Once the satellite passes over an area that is covered by a ground receiving station the sensor can transmit its tape stored data. Ground receiving stations in or near Africa are scarce; only two stations are in permanent operation: Maspalomas, on the Canary Islands and Johannesburg in South Africa. Occasionally a transportable station is installed in Libreville (Gabon), but this station is removed after completion of campaigns (see e.g. Husson and Harms, 1996 and Malingreau et al., 1997). Both the Johannesburg and Libreville stations are capable of receiving data of Lake Victoria, but lies in the outer ranges of the respective receiving areas. In 1997 a ground receiving station has been installed in Malindi (Kenya). Unfortunately this station has only been in operation for about one month, from early September 1997 till October 1997.

The ERS-2 does not have a tape device on board and is therefore is not capable of storing data temporarily. If the ERS-2 is not in the reach of a ground receiving station, a recording attempt of a certain area is futile. The SAR system on board of the JERS-1 was initially equipped with a tape recorder. In August 1997 it had to be taken out of operations. From then on operations were restricted to real-time acquisitions over areas covered by ground stations. As only the northern part of Africa was within the reach of one of the ground receiving stations data, most of the African continent could not be recorded any more by JERS-1. In October 1998 the existence of the JERS-1 satellite came to an end due to malfunction. An operational SAR-based technique to detect water hyacinth in Lake Victoria using L-band is therefore not available. Radarsat has an On-board Recorder (OBR) that can be used to store data when real time data transfer to earth is not possible. Because of bandwidth limitations of the On-board Recorder some beam products will have reduced swath coverage. The ScanSAR Wide A is restricted to direct data transfer. Tape recorder data rate restrictions dictate the use of the ScanSAR Wide B mode when on-board data storage is necessary (Radarsat International, 1997).

From the above the following can be concluded:

- Only SAR systems that operate in C-band are available to perform a pilot study into the potential of SAR systems to monitor water hyacinth in Lake Victoria;
- C-band seems an appropriate wavelength to be use in this pilot study;
- Radarsat imagery may produce better results than ERS imagery because of the available polarisation directions;
- For the development of a reliable monitoring program a short repeat cycle is preferred, though not required. This favours Radarsat over ERS.

The above analysis relates to current operational spaceborne SAR sensors. The question about what SAR configuration is actually most suited for monitoring water hyacinth still remains unanswered. To answer this question it is necessary to fall back on previously recordings of the area during the two Space Radar Laboratory (SRL) missions in 1994. During this mission a total of 6 strips were recorded covering a part of the north-western area of Lake Victoria. The data offered a unique opportunity to expand the SAR data set with data of April and October 1994. It provided data in X-, C- and L-band. For the later two in different polarisations. This data set has been analysed to determine which SAR configuration is best qualified for monitoring water hyacinth. It has also been used to study the effects of wind on the compactness and the size of water hyacinth mats. As the first mission recorded the area on four consecutive days in April and two consecutive days in October it was possible to determine changes in surfaces caused by winds.

3.2 DATA ACQUISITION

This paragraph provides an overview of the remote sensing data and of other geo-information used in this study. It contains meta-data of the imagery, presented in the form of tables. Four data types are distinguished: (1) Satellite radar imagery; (2) Satellite optical imagery; (3) SRL imagery and (4) Maps

1. Satellite radar imagery

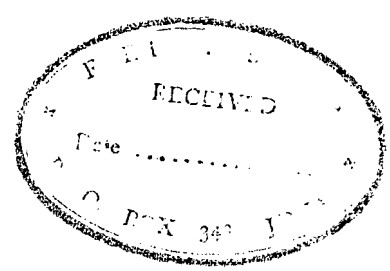
Table 6 lists the images that have been acquired and which are all in the C-band (see paragraph 3.1.2).

ERS data

To obtain a good fit over Thruston Bay the ERS scene Buvuma has been shifted six nodes backward with respect to reference frame 3609. The two ERS scenes were recorded within the short period the Malindi ground receiving station was operating. The ERS scenes were ordered in SLC format and in-house transformed to PRI-like images. Figure 3 shows the coverage of the scenes with respect to the two areas of interest.

Table 6 Overview of the used satellite radar imagery.

ERS	Orbit	Frame	Date	Local Time	Name
	12514	3609	1l-SEP-97	11:00:13.731	Kisumu
	12557	3603	14-SEP-97	11:05:52.946	Buvuma
Radarsat	**Mode**	**Orbit**	**Date**	**Time**	**Name**
	ScanSAR Wide B	12156	4-MAR-1998	06:27:44.937	Lake Victoria
	SAR Fine 4 Beam	12256	11-MAR-1998	06:23:48.577	Jinja
	ScanSAR Wide B	14214	26-JUL-1998	06:27:29.048	Lake Victoria
	ScanSAR Wide B	14221	26-JUL-1998	19:03:39.567	Lake Victoria



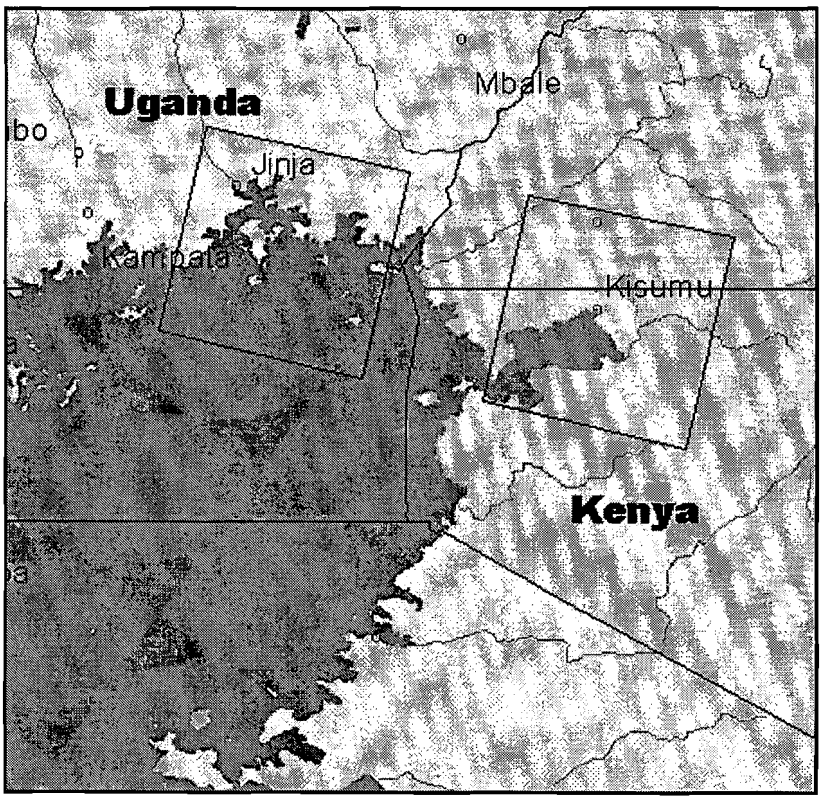


Figure 3 *Coverage of the two ERS-2 scenes* Kisumu *and* Buvuma.

Radarsat data

With the Radarsat ScanSAR Wide mode it is possible to capture the entire lake by one image. For Lake Victoria Radarsat needs to use its on-board tape recorder, which means that it can only produce ScanSAR Wide B (SWB) images (see paragaph 3.1.2). Only during its descending pass Radarsat can cover the entire lake; during its ascending pass it misses the extreme south-western part of the lake. The fact that the entire lake can be captured instantly is a major advantage above high-resolution imagery that will take several days to cover the entire lake. With SWB the location of all major mats on the lake are registered undisputedly. However SWB imagery has two minus points. The first point is its resolution of 100 meters, which implies that small water hyacinth mats will be missed. The second point is the radiometric 'depth' of the images. Single beam imagery comes in 16-bits format, but ScanSAR imagery comes in 8-bits format only. So, the information content of a pixel in a ScanSAR image is less than in a single beam image.

To get insight in the performance of SWB images it was decided to acquire one Fine Beam image for comparison. With a resolution of 6 to 7 meters the Fine Beam mode is the highest resolution any SAR system can currently offer. The selected area to be covered by Fine Beam images is Thruston Bay.

Two SWB images were foreseen in the project; one during a period with dominating southern winds and one during a period with dominating northern winds. After ample consideration it was decided that the images had to be acquired in the period February-March and June-July, respectively. Eventually requests were made for recordings of SWB images on March 4th and on July 2nd 1998. The first acquisition was successful, but the latter failed. Due to the repeat cycle of the satellite the recording had to be put forward another 24 days to July 26th. The acquisition on that day was successful, but as it had been shifted northwards, it missed the

southern strip of the lake. To make up for the incomplete coverage, the image in the ascending pass was also recorded. This left the extreme south-western part of the lake uncovered, as can be seen on Figure 4. This explains the presence of two images of July 26th in Table 5.

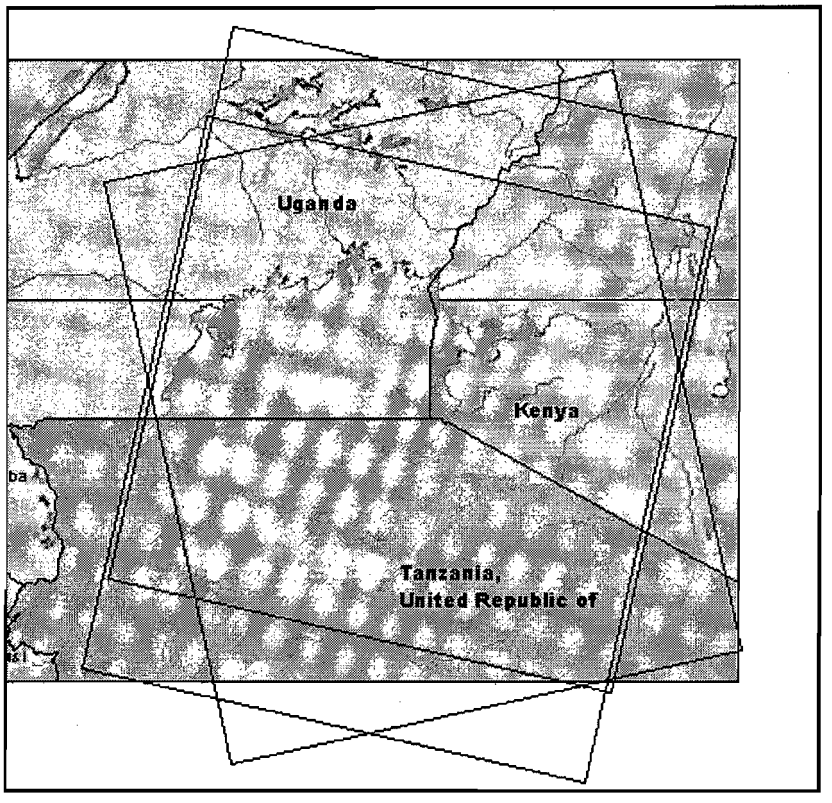


Figure 4 Coverage of the acquired SWB images of Lake Victoria

2. Satellite optical imagery

To validate the interpretation of the first sets of radar images it was decided to acquire optical satellite images. During the first two acquisition periods of radar imagery (September 1997 and March 1998) only a limited number of optical sensors was available'. Landsat 5 and SPOT 3 can not dispose any longer of their respective tape facilities, implying that these satellites can not provide images of Central Africa during these two periods. Satellites that can provide imagery of Central Africa are - among others - IRS-1C, IRS-1D and NOAA satellites. Both IRS satellites have an operational on-board tape recording device, while the Kenya Meteorological Department is capable of receiving NOAA imagery for East Africa.

IRS data

The IRS-1C and IRS-1D differ in their orbital characteristics. The IRS-1C performs at an altitude of 817 km and it follows a circular polar orbit. It has a repeat cycle of 24 days. The IRS-1D performs at 780 km altitude from a near-circular polar orbit and a repeat cycle of 25 days.

The two IRS satellites were the only satellites capable of delivering high-resolution optical data of Lake Victoria during the 1997/1998 season. Initially it had been considered that this

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, SPOT 4 has become operational shortly after its launch on March 24th 1998 and has a working tape recorder on board. With the successful launch of Landsat 7 (that is also equipped with a recorder) on April 15th 1999, the possibilities to acquire optical data of this region will increase further from July 1999 onwards.

kind of data was necessary to validate the interpretation of SAR images. A combination of reasons made us abandon the plan to purchase IRS imagery. Main reasons had to do with the price of the images, the timing of possible acquisitions and conditions set by the National Remote Sensing Agency (NRSA) in Hyderabad. For a proper coverage of the areas of interest at least two full scenes were needed. Although a few quarter scenes could also give an adequate coverage but if the tape recorder has to be used to store the data of a scene NRSA charges the full price ($ 3,500.00). Furthermore, NRSA requested an advance payments of the scenes. With the possibility that the areas of interest are covered by clouds and the fact that IRS scenes would always be recorded a few days before or after the March radar imagery, it was decided not to use IRS scenes.

NOAA-AVHRR data

Due to the low geometric resolution of the NOAA-AVHRR images (ca. 1.1 kilometer) these images were used to validate the Radarsat SWB images. To a less extent they can be used to validate the ERS scenes, but a comparison between NOAA imagery and the Fine Beam image falls short. Yet, NOAA imagery was considered useful for the following reasons:

- NOAA images are made on a more than daily basis. This means that it is possible to order at least one NOAA image that is only a few hours apart from the moment the SWB image was recorded. One still needs daylight and a cloud-free sky, but it offers the possibility of a good validation for large water hyacinth mats.
- The NOAA images cover the entire lake, so major water hyacinth mats can be noticed over the entire lake.
- By ordering the morning and the afternoon image of both NOAA 12 and 14 it will be possible to monitor the diurnal dynamics of the large mats on the lake, provided the light and cloud conditions allow a good analysis of the respective images.
- Due to the low price of a NOAA scene (ca. $ 100.-) there were no budgetary restrictions to purchase some scenes and study there potential added value.

Requests were made to the Kenya Meteorological Department (KMD) for NOAA images of the following dates: September 10th 1997, September 14th 1997, March 3'd 1998 and March 4th 1998. Due to technical problems the imagery of March 3'd was omitted. Other images were made at the end of the afternoon and had to be rejected because of unfavourable light conditions. Eventually only three NOAA images were acquired, as is shown by table 7.

Table 7 Overview of the ordered NOAA images.

Satellite No.	Orbit	Date	Time
14	13898	10-SEP-97	12:01
14	13954	14-SEP-97	11:18
14	16367	4-MAR-98	11:48

3. SRL imagery

During the two Space Radar Laboratory (SRL) missions in 1994 a total of 6 strips were made covering a part of the north-western area of Lake Victoria. Since the bays near Kampala are known for their water hyacinth infestations the recording made by the SRL missions offered an opportunity to expand the SAR data set with data of four consecutive days in April 1994 and two consecutive days in October 1994. Figure 5 shows the approximate location and width of the SLR strip.

For nearly all days full polarisation data is available in (- and L- band, while X band data is available for all 6 days. The (-and L-band data will be called SIR-(data, thus complying with the general naming conventions and the X-band data X-SAR. Table 8 lists the SIR-(data and

Table 9 the different characteristics between mode A and B. Table 10 shows which X-SAR data were requested.

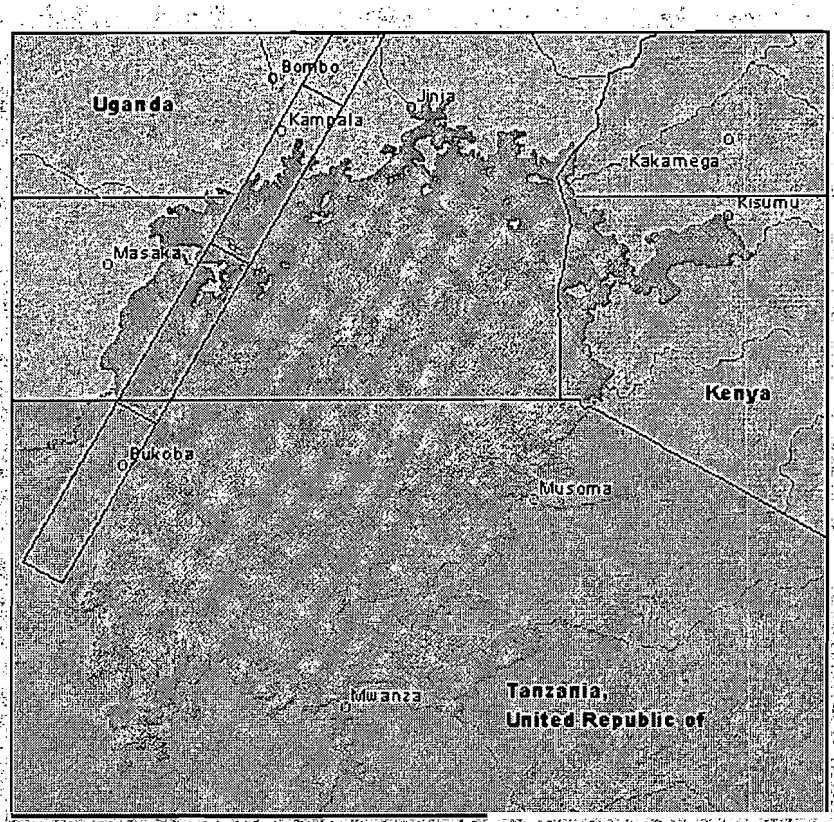

Figure 5 Location of the strip of 1994 SIR images in the Lake Victoria region. All tracks follow' cover approximately the same strip.

Table 8 Overview of the requested SIR-C imagery

Mission ID	Data track	Segment	Date	Local Time	Mode
SRL-1	075.40	8	14-APR-94	03:45:50.7	B
SRL-1	.075.40-,	9	14-APR=94	03':46:04;4	B
SRL-1	091.10		15-APR-94	03:14:45.6	8
SRL-1	091.10	'13	15-APR-94	03:14:59.3	,8
SRL-1	107.10	29	16-APR-94	02:54:21.0	8,
SRL-1	123.11	14	17-APR-94	02	
SRL-1 -	123.11	15	17-APR-94	02	
SRL-2	075.40	8	05-OCT-94	03:45:50.7	B
SRL-2	107.10	31	06-OCT-94	03:05:59.5	B
SRL-2	107.10	32	06-OCT-94	03:06:13.2	B

TabLe 9 Characteristics of the reLevant modes of the SIR-Ç imagery

Mode	Channell	Channel 2	Channel 3	Channel 4	Notes
A	LHH	LHH	CHH	CHH	Double swath
B	LHH, LVH	LHV, LVV	CHH, CVH	CHV, CVV	Reduced swath

TabLe 10 Overview of the requested X-SAR imagery

Mission ID	Data track	Date	Local Time
SRL-1	123.11	17-APR-94	02:33:34.6
SRL-2	075.40	5-0CT-94	03:45:50.7

4. Maps

Besides the remote sensing data other geo-information has been acquired including analogue and digital maps. The maps were used as a reference for geo-coding the remote sensing data and as a source for determining the land-water interface. Appendix III shows a complete overview of the maps that were acquired and used for this study. For the entire area two so-called Tactical Pilotage Charts were bought. The scale of these maps is 1:500,000. They are produced with an aeronautical objective, meaning that special attention has been paid to information relevant for pilots (like elevation figures). Topographical features like lakes, islands and rivers are presented accurately. For Uganda both digital and paper maps of the National Biomass Study (NBS) were obtained. Basically these are thematic maps, comprising land use information, to which some topographical annotation has been added. The NBS produces a small-scale version and a large-scale version of the map. The first is a nation-wide map on a scale of 1:1,000,000. The latter are sheets on a scale of 1:50,000 that cover an area of approximately 23 x 23 km. The NBS sells the large-scale maps in both digital and printed format. The available information is stored in five separate Arc/Info layers (NBS, 1996):

1. Land cover / land use stratification,
2. Administrative boundaries,
3. Protected areas,
4. Infrastructure,
5. Rivers and waterways.

Atotal of four paper and five digital sheets has been purchased. The paper sheets cover the area around Jinja. Two of these sheets covering the main bays near Jinja have also been purchased in digital format. The three remaining digital sheets cover the area between Entebbe and Kampala. The five digital sheets contain just two of the five Arc/Info layers, notably layers 1 and 5.

For Kenya five copies of old topographical maps were purchased. These maps date from the early 1960's and 1970's, but were the only large-scale maps that could be found. The scale of the maps is 1:50,000 and they cover the eastern part of Winam Gulf. From information found on the World Wide Web it is known that the Survey of Kenya and the French institute IGN are involved in a project to update topographic maps in Kenya with SPOT imagery. Attempts to get more information about this project from the Survey of Kenya remained however unanswered.

4 METHODS

To detect and map water hyacinths with SAR images several data processing steps have to be followed. These steps can be divided into pre-processing and processing steps.

4.1 PRE-PROCESSING

The pre-processing steps consist of the handling of the images prior to the actual analysis of the images. The first step in the pre-processing phase is importing the images in an image-processing package. The package used at SYNOPTICS is Erdas Imagine (version 8.3.1). As FIRI did not dispose of an image processing package prior to this project, SYNOPTICS introduced IORISI for Windows (version 2.007) at FIR!.

Radar waves can interact to produce light and dark pixels in the SAR images that are known as speckle noise. Before SAR data can be used well the speckle noise has to be reduced. This can be achieved by applying a filter. Dedicated speckle filters have been developed like the Gamma MAP filter. In Erdas this filter has been used to reduce the speckle. In IORISI no dedicated speckle filters have been incorporated, but other filters, like the median filter are also able to reduce some of the speckle noise. For ScanSAR images that are a combination of several single beam images, no speckle filter is needed. For the other SAR imagery a speckle filter has been applied to enhance the image. Subsequently the images need to be geo-referenced and re-sampled. To allow comparison with the data of the National Biomass Study conversion to the UTM projection was chosen. This UTM grid has been slightly adapted for the Ugandan situation by giving all the latitude values an offset of 200,000 meters. This offset lifts the whole country virtually above the Equator. After geo-referencing, all SAR data have been resampled to this adapted UTM grid.

4.2 IMAGE PROCESSING

The processing steps make up the actual analysis of the images. The first step is to identify the presence of water hyacinth in the images. Then the mats need to be outlined. After the determination of the shape of the mats they can be mapped and their surface can be estimated. In this paragraph the necessary processing steps are described.

4.2.1 Identification of water hyacinth

A SAR-based technique to detect water hyacinth mats on the lake is based on the idea that a signal is not or hardly returned from water. So, if a return signal (backscatter) is received from an area covered by the lake, this backscatter should come from a feature that does produce a return signal, like floating or other emergent vegetation on the water surface. In the context of Lake Victoria this means that the vegetation either exists of the exotic water hyacinth, native water plants like Nile cabbage *(Pistia stratiates),* water lilly *(Nymphaea caerulea)* and water fern *(Azalia* ssp.), or a mixture of these species. The composition of the observed vegetation can not be determined solely on the basis of the radar images. Even when areas with clearly deviating levels of backscatter can be distinguished, additional information is needed to identify and classify specific vegetation zones. Additional information may consist of:

- ground truth data, consisting of field observations, varying from observations from the shore or from boats to GPS' surveys on the lake
- knowledge of people who thoroughly know the ecosystem (expert's knowledge)

GPS surveys were. carried out in March 1998 in the same mornings the two Radarsat images were recorded. The objective was to encircle several water hyacinth mats on the lake while

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‘ *GPS: Global Positioning System. For more information about GPS, see Seeber (1993).*

doing GPS measurements. This would result in a series of positions that marked the boundaries of water hyacinth mats indicating their location, form and measure. As the mobile water hyacinth mats in the open water could not be reached it was decided to focus on the mats that are locked inside collection bays. A more precise description of the way the surveys were carried out is presented in Appendix IV. For the summer period no GPS measurements were made. In stead a number of bays were observed around the supposed day of the Radarsat recording: July 2nd. Observations were made in Thruston Bay, Port Bell (near Kampala), Waiya Bay (west of Entebbe), Kisumu Bay and Napoleon Gulf. In the end these observations were rather futile, as the Radarsat recording of July 2nd could not be processed (see paragraph 3.2). Some observations were repeated at the end of July, roughly coinciding with the recording of the Radarsat image of July 26th.

The most important source of additional information is the knowledge of people who are familiar with the ecosystem. The relevance of this knowledge was clearly demonstrated by the interpretation of the ERS recording of Buvuma Island. The waters near Buvuma Island appeared in very dark and medium grey tones (see Plate 2). Initially it was assumed that these medium grey tones might be caused by backscatter from water hyacinth mats but local experts assured that water hyacinth does not occur in these areas. Obviously the weather circumstances at the time of the recording were such that some parts of the waters near Buvuma Island produced higher backscatter levels than other parts of these waters (see next paragraph). The exact cause for this difference in backscatter levels is not known, but is has probably to do with differences in the 'roughness' of the waters (see paragraph 4.2.2).

4.2.2 Outline of mats and estimation of surfaces

The successful recognition and discrimination of water hyacinth by means of remote sensing depends on the specificity of its radiometric properties. Changes in the compactness of the mats, the state of the water hyacinth plant (vegetative versus generative) and the extent in which the water hyacinth mats are impaired by weevils may all affect the radiometric characteristics. In many bays the mats are attached to papyrus dominated vegetation zones. Since papyrus vegetation has a clear and distinct structure compared to (homogenous) water hyacinth vegetation it should be possible to separate these two vegetation types. The extent in which this is possible depends on the outline of the water hyacinth mats and the adjoining vegetation zone and their respective widths. Especially if the outline is irregular and the zones are narrow the chance of confusion increases as the area covered by a single pixel will include different types of vegetation (so-called mixels). This will make it difficult to determine the outline of the water hyacinth mats. According to local aquatic ecologists the possible confusion of floating indigenous water plants with water hyacinth mats in open water is very small. The floating indigenous water plants make up mats that tend to be stable and are located at close range from the emergent fringe along the shoreline. Also the size of these mats is in general too small to be confused with water hyacinth.
A comparison between the ScanSAR Wide image - with a resolution of 100 m - and the Fine Beam image - with a resolution of around 7 m - should indicate the possible restraints of geometric resolution on the determination of water hyacinth mats. Problems in the discrimination of water hyacinth mats with its surroundings can be twofold:

1. The water hyacinth mat can not be distinguished from the surrounding water; The studies carried out in the floodplain of Bangladesh have shown that it is possible to distinguish between water hyacinth from surface water on Radarsat imagery. In this study the water hyacinth mats produce significant higher backscatter than the surface water, thus enabling a positive discrimination. However, under windy conditions surface water can also produce high backscatter values due to the presence of water ripples. Depending on the 'roughness' of the water surface, the incidence angle and the polarisation of the microwave signal the successful discrimination between open water and water hyacinth can become difficult as both can produce high backscatter values. It is therefore

important to perform SAR recording under relative calm weather conditions. In paragraph paragraph 3.1.2 it has already been stated that the AMI sensor on board ERS has been designed with oceanographic applications in mind. This means that this sensor is sensitive for ripples on water surfaces. Hence, confusion between water and emergent water vegetation is imminent if the SAR data is recorded by AMI.

2. The mat can not be distinguished from other adjacent vegetation types; To distinguish water hyacinth mats from other vegetation zones along the shore can be troublesome, particularly if these zones have similar structures as water hyacinth mats. Mats of water hyacinth are often attached to the shoreline of the lake. If the vegetation on the shore has a similar structure as the water hyacinth mat both produce backscatter levels in the same range. In that case other information, like topographical maps or additional remote sensing data is needed to determine the border between land and water hyacinth. If maps are available, the shoreline can be adopted from it. If additional remote sensing images are used the shoreline may appear after the creation of multi-temporal imagery. Especially when water hyacinths drift to other locations the position of the shoreline may eventually become clear.

For Uganda thematic land use maps were consulted that are available in digital and paper format (see paragraph 3.2). The discerned unit boundaries in these maps are principally based on SPOT XS imagery that was recorded from early 1989 to early 1993 (National Biomass Study, 1996). It is assumed that the occurrence of water hyacinth is restricted to the areas which are classified as water. Masks that are created on the basis of this assumption may include some errors as a result of natural changes along the shoreline (e.g. expansion of zones with papyrus), digitising inaccuracies, and small deviations in the geo-referencing process. Most of the SPOT data were recorded during a period that many bays in Uganda (and Kenya) were only slightly or not infested by water hyacinth, enabling the establishment of well-defined shorelines.

Once the outline of the water hyacinth mats has been established the area covered by the mats can be estimated. The accuracy of the estimation depends on the resolution of the image. A water hyacinth mat with a size less than one hectare is too small to be visible on the SWB image, while a mat measuring about 1/400 of a hectare may still appear on a Fine Beam image. For ERS images the critical size is approximately 0.3 hectare. For a clear identification the mat should be larger than the geometric resolution of the respective sensor. Water hyacinth coverage has been estimated for a number of sites (Figure 6). As this study seeks to determine the potential of SAR imagery for the detection and mapping of water hyacinth an estimation of its total surface on Lake *Victoria* is out of the scope. In stead only estimations were made of those sites that seemed relevant, either from a management point of view or because of the apparent dynamics in that particular area. To reduce the calculation time an artificial area of interest around each site was drawn. The size and location of these areas is given in Table 11.

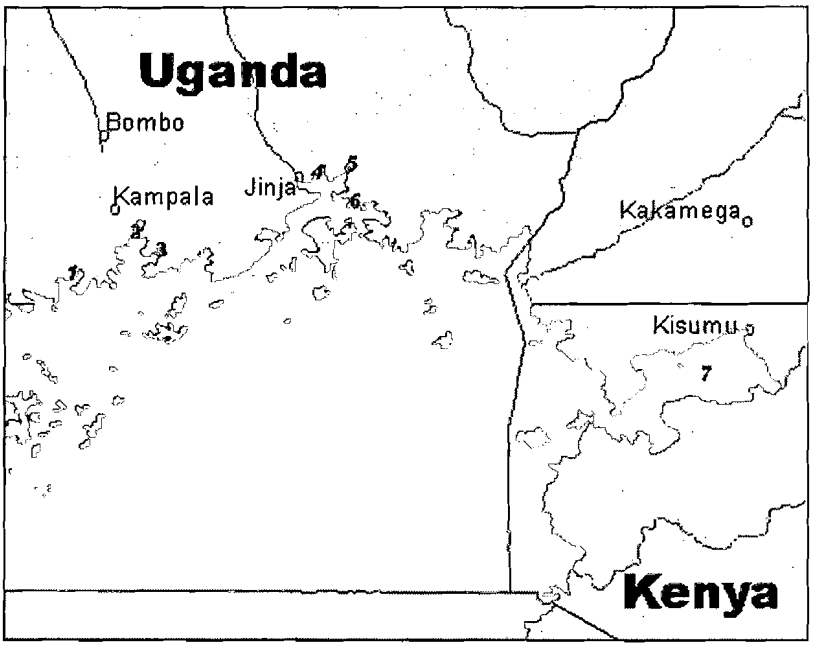


Figure 6 *Location of the bays and gulfs for which the water hyacinth coverage has been estimated:* 1. *Waiya Bay;* 2. *Murchison Bay;* 3. *Gobero Bay; 4 Napoleon Gulf;* 5. *Thruston Bay; 6. Hannington Bay and* 7. *Winam Gulf*

Table 11 *Location and size of squares around bays of interest in Uganda and Kenya.*

Bay	X-centre	V-centre	Width in km	Height in km
Waiya Bay	437961.8	208434.3	12.38	13.23
Murchison Bay	460950.7	227783.8	10.10	12.19
Gobero Bay	465320.2	217849.1	13.18	11.01
Napoleon Gulf	526849.6	248134.4	12.71	11.65
Thruston Bay	541610.2	250525.5	9.54	9.29
Hannington Bay	550721.4	238341.3	9.54	9.29
Winam Gulf	666926.1	161039.9	97.95	77.10

Basically two methods were used to estimate the size of the mats. With the first method the land use vector maps of the Kampala and Entebbe and the Jinja area are rasterized. The information of the maps is reduced to two units: land and water. The unit land is masked out on the SAR imagery leaving the pixels that make up either water or water plants. As has been stated in paragraph 4.2.1 it is assumed that these mats are dominated by water hyacinths. Applying a threshold will be an adequate way to make a distinction between water and water hyacinth. This implies that all pixels with a value below a certain critical value (threshold) are classified as open water and all pixels whose value is above this threshold are classified as water hyacinth. The exact value of this threshold can be determined empirically. Plate 3 (see Annex) illustrates the application of this method. Thruston Bay is displayed twice. On the left the original Fine Beam image is shown and on the right the same image overlaid with the classified image. The rectangular that was drawn around Thruston Bay can still be seen in one corner of the bay. The area covered with land in this rectangular has been kept transparent. The area covered with water has been classified as either 'water hyacinth' or 'open water'. The

second method was used for those areas for which no detailed digital maps are available. It consists of digitising relevant areas on screen. Relevant areas are parts of the lake that contain mobile or stable water hyacinth mats. The accuracy with which the digitising has to be carried out depends on the location of the mat. For mats that are attached to the shoreline the digitising has to be done very precisely, but for mats that are out on the open water this can be done more coarsely. After the digitising of a polygon in which the water hyacinth is enclosed a threshold can be set to classify water hyacinth and water.

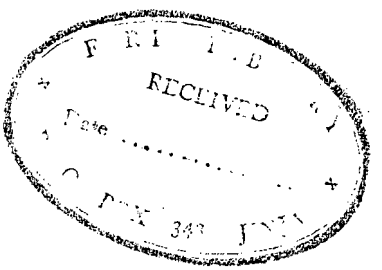
The first method implies the use of large-scale digital maps. If these maps are not available the second method was used. The two described methods are deliberately kept simple. A third and more complex method is texture analysis. This method calculates new values for each element in the picture that represent the texture around that element. Since water hyacinth mats are very homogenous, these values can prove to be a good basis for determining size and location of the mats. As this method requires dedicated and expensive software it has not been used.

4.3 VALIDATION OF SAR IMAGERY INTERPRETATION USING OPTICAL IMAGERY

The results of the Radar Remote Sensing images interpretation was validated by local expertise and experience (see paragraph 4.2.1) and to a certain extent through field observations and in addition with other type of remote sensing data. It may however be difficult to differentiate between different vegetation zones in a single image. By comparing several images the location of water hyacinth can become more visible.

As described in paragraph 3.2 three NOAA images are acquired to validate the interpretation of the SAR images. The main purpose is to see whether the location of the water hyacinth mats can be confirmed by a second information source. Because of the low resolution of the NOAA data only large mats can be detected. As all three images showed substantial cloud coverage over parts of the shoreline of the lake, the actual usefulness of the NOAA images was reduced; it does underline the limitations of optical images in this area. As a NOAA image covers a large part of the earth, the resolution decreases near the edges of a NOAA scene. This is inevitable because the earth curves away from the sensor. As Lake Victoria was near the edge of the image of September 14th 1997, the lake was recorded with an even lower resolution than the normal 1-kilometer resolution. Therefore, the images were first geometrically corrected in order to give all grid cells the same geometrical dimensions. The images were converted to Normalised Difference Vegetation Index (NDVI) images and subsequently geo-referenced. Water hyacinth mats represent a massive green vegetation zone, which lead to a high NDVI value (Lillesand & Kiefer, 1994). Water has a very low NDVI value, which should allow a clear distinction of the water hyacinth mats. No atmospheric corrections were carried out prior to the calculations of the NDVI images, because on the basis of the 10-bits data the NDVI images were clear enough.

The SIR-C and X-SAR data were also used to verify the results in combination with the various observation campaigns that FIRI performed along the Ugandan shoreline of the lake in 1994. Retroactively these campaigns validate the interpretation of the SIR-C and X-SAR data. It proved that identification of water hyacinth on Lake Victoria with SAR imagery was feasible.



5 RESULTS

This chapter deals with the results achieved by each of the studied sensors. To begin with, the pre-processed images will be described briefly (see also the Annex Plates).

5.1 THE ACQUIRED SAR IMAGES

ERS-2 scenes

The ERS-2 image of Buvuma Island is presented in Plate 2 by the image on the left. Remarkable are the grey tones produced by the open water of Lake Victoria. It indicates that the backscatter levels of the water are high. Especially in the south-eastern corner of the Buvuma scene the water has very bright grey tones, making it difficult to identify the islands that are situated in this area. Even if one knows where to look for water hyacinth it is still hard to distinguish the mats.

In the morning of September 14th it was cloudy and it was dry.s No information about the wind conditions is available. Considering the sensitivity of ERS-2 for 'roughness' of surface water, it would have been interesting to know the wind conditions at the moment the image was recorded.

On the ERS-2 scene of Winam Gulf the surface water also shows various grey tones. In general the contours of the Gulf are distinct. In the south and in the extreme east of the Gulf the contours are less distinct. As can be seen in Plate 1b these are exactly the areas where huge water hyacinth mats were present in October 1997.

Radarsat Fine Beam mode

The part of the Fine Beam mode image covering Thruston Bay is shown on Plate 3. The amount of detail catches the eye. Striking is the black appearance of surface water throughout the image. This allows an unambiguous identification of water. The contours of Thruston Bay are clear, even where the surface water is covered by a big water hyacinth mat. The clear identification of the water hyacinth mat is supported by the fact that a zone with dark grey tones borders it. This zone consists of a different vegetation type (possibly papyrus). Only in the extreme north of the bay this darker zone is missing. Here the exact border of the water hyacinth mat is more difficult to distinguish. A few scattered hazy patterns can be discerned on the surface water. The nature of these patterns is unknown. Table 12 lists some meteorological data that were recorded on the morning of March 11th. It is obvious from these figures that the wind dies down in the night, but that soon after sunrise the wind gains in force. This means that the mats and especially the water hyacinth tufts may start drifting again after sunrise.

Table 12 *Meteorological data recorded at Jinja Kimaka Airport in the night of March 10th to March 11th 1998.*

Date	Local Time	Temp	Wind Direction	Wind Speed	Precipitation	Rel. Humidity	Cloud coverage
March 10th	24:00	20.9	290	06	NIL	90%	4/8
March 11th	03:01	19.4	360	02	*NIL*	94%	3/8
March 11th	06:00	19.2	CALM	--	NIL	96%	4/8
March 11th	09:00	22.8	180	02	1.4 mm	84%	3/8
March 11th	12:00	22.4	140	08	NIL	66%	4/8

, Meteorological data recorded at Jinja Kimaka Airfield (0 °27' N 33 °12 E). All these data are kindly provided by Sam Small, Airport manager Jinja.

Radarsat ScanSAR Wide images

The Radarsat ScanSAR Wide image that was recorded in a descending pass on March 4th 1998 is partially shown on Plates 2 (the right-hand figure). Due to the coverage of the images some geometric distortions are introduced when projecting them to a conformal projection. These minor errors have been ignored in the further elaboration of the data. From Plate 2 it is clear that the visual distinction between land and open water is easier on the Radarsat image than on the ERS image. On the image of March 4th no water hyacinth mats can be identified visually. The image of July 26th shows some large mats in the middle of Winam Gulf. In the northern half of the lake some large hazy patterns are visible. It is not clear whether these hazy patterns are of the same nature as the haze in the Fine Beam image.

From the Jinja meteo data recorded in the morning of March 4th the rapid rise in temperature between 9:00 and 12:00 is striking (see Table 13). In the same period the wind speed increases substantially.

Table 13 *Meteorological data recorded at Jinja Kimaka Airport Airport in the night of March 3rd to March 4th 1998.*

Date	UT Time	Temp	Wind Direction	Wind Speed	Precipitation	Rel. Humidity	Cloud coverage
March 3"	24:00	20.3	260	02	NIL	97%	5/8
March 4th	03:01	19.5	CALM	--	*NIL*	98%	5/8
March 4th	06:00	19.7	180	02	NIL	97%	4/8
March 4th	09:00	22.6	180	01	12.4 mm	83%	1/8
March 4th	12:00	28.1	190	06	NIL	56%	6/8

SIR-(images

An example of the SIR-(data is given in the left-hand figure of Plate 4. The recording is of April 14th 1994 and covers Murchison Bay. It shows a composite consisting of (-band VV polarisation (in red), L-band HH polarisation (in green) and L-band HV polarisation (in blue). The chosen channels partly coincide with the operational spaceborne SAR systems; the (-band VV polarisation is also used by ERS, while JERS-1 used to operate in the L-band HH polarisation. As a final channel one of the two available cross polarisations has been chosen. Because of the different incidence angles this composite is only a limited simulation of ERS and JERS-1. The water hyacinth mats are characterised by a reddish colour indicating high backscatter values in the (-band. Parts of the open water in the eastern parts of Murchison Bay appear red, indicating relative high backscatters in (-band. This seems to confirm the assumption made in paragraph 3.1.2 that VV polarisation is particularly sensitive for ripples on the water surface.

X-SAR images

The X-SAR images contain the data recorded in X-band with VV polarisation. Plate 4 (the right-hand figure) shows an example of an X-SAR image. The bright grey tones (almost white) of water hyacinth near Kampala are the most striking features on this image. The microwave in the X-band is reflected from practically every part of the plant. Longer wavelengths than X band will, to some extent, penetrate the foliage, but X band is not able to do so and practically all interactions with the plants will lead to backscatter. Especially if the leaves are pointed perpendicular to the direction of the microwave signal, one can expect high backscatter values. Though not obvious from the presented images, it is expected that X-band in general and the VV polarisation in particular is sensitive for 'roughness' of the surface water. (om pared to the (- and L-band, the short wavelength of the X-band is particular sensitive for the detection of low ripples.

5.2 ESTIMATION OF SURFACES

The sites for which the water hyacinth surfaces have been estimated were introduced in paragraph 4.2.2. They are Waiya Bay, Murchison Bay, Gobero Bay, Napoleon Gulf, Thruston Bay, Hannington Bay and Winam Gulf (see Figure 6). The estimations are based on the Radarsat imagery acquired in 1998. The figures are presented in table 14 and table 15. Each site will be discussed briefly.

Table 14 Absolute and relative surface of water hyacinth mats for 6 bays in Uganda.

	Surface in ha			Relative surface		
	March 4th	July 26th	March 11th	March 4t	July 26'h	March 11th
Waiya Bay	888	551		100.0	62.1	
Murchison Bay	694	731		100.0	105.5	
Gobero Bay	412	320		100.0	77.7	
Napoleon Gulf	556	301	254.26	100.0	54.1	45.7
Thruston Bay	1055	912	948.71	100.0	86.5	89.9
Hannington Bay	985	796		100.0	80.8	
Total	4590	3611		100.0	78.7	

Table 15 Absolute and relative surface of water hyacinth mats in Winam Gulf, Kenya

	Surface in ha		Relative surface	
	March 4th	July 26th	March 4'h	July 26'h
Winam Gulf	9,371	10,627	100.0	113.4

1. Waiya Bay is situated just north of the two major runways of Entebbe airport. In the northern part of the bay a major water hyacinth mat is detected. In March the size of this mat was clearly bigger than in July. By personal observations from the shoreline along Waiya Bay in early July it is known that the water hyacinth mat occasionally drifts towards the south. If the mats move beyond the southern tip of the peninsular, parts of the mats can be cut off and move along the eastern shoreline of the peninsular. This can explain the difference in size between the March and July recordings.
2. Dispersed water hyacinth mats can be seen on the Radarsat imagery throughout Murchison Bay. In July water hyacinth was present in the extreme north of the Bay, near Port Bell. In March most of the mats were found in the bay located between Port Bell and Gobero Bay. The narrow cove just north-east of Port Bell can not be identified as open water. As this cove is very narrow (250 to 300 meters), it is possible that on SWB imagery only mixels cover this area. In this case it seems premature to conclude that the cove was covered by water hyacinth in March and July. The estimates of the total surface of water hyacinth are almost the same for both recordings.
3. Gobero Bay is basically a part of Murchison Bay. In March several free-floating mats were present in the bay and were absent in July. The applied mask suggests the presence of a strip of water hyacinth along the southern shoreline from March to July. There is no ground truth data to confirm whether this strip is indeed a fringe of water hyacinth or a small zone of another vegetation type. The maps from the NBS are based on data from the early 1990's and local developments that have occurred since can have made the maps less accurate. Observations on the ground will have to provide the definitive answer.
4. Napoleon Gulf lies in front of the Victoria Nile, south of Jinja. Though some mats were present in the early 1998, they had all disappeared by July. In March the presence of the mats was confined to the north and north-eastern parts of the Gulf. The area in front of Owen Falls Dam was relatively free of water hyacinth. The two small islands in the Gulf as well as the

southern shoreline were surrounded by a strip of water hyacinth. The Fine Beam image reveals that one week after the recording of the SWB image most mats had drifted out of Napoleon Gulf with the exception of some small spots in the north, the Victoria Nile and a narrow strip along the southern shoreline.

5. Hannington Bay is located just north of Buvuma Island. The eastern part of Hannington was covered with water hyacinths in both March and July. Except from the extreme northern part in March the western part of the bay was almost completely covered by the weed in March. In July the water hyacinth mat in this part of the bay had disappeared, except for a narrow strip along the shoreline. The decrease of the surface taken by water hyacinth in Hannington Bay is caused by the drop in the western and southern parts of the bay. Not included in the figures of Hannington Bay are the mobile mats in the 'strait' between Hannington Bay and Buvuma Island. It is interesting to compare the location of these small mats with the seasonal movements as indicated on Figure 2. The location of these small mobile mats seems to confirm that water hyacinth mats move from south of Buvuma Island to the northern coastline of the lake.

6. Thruston Bay is situated east of Jinja. In March and in July the area north of the narrow in Thruston Bay was largely covered by water hyacinths (see the Fine Beam Mode image displayed in Plate 3). In March the weed was more concentrated in the eastern parts of the bay, while in July the western parts were covered. The total surface of water hyacinth slightly drops from March to July. The reason for this decline can possibly be derived from the Fine Beam image and also from the SWB recording of July, as some water hyacinth mats seem to move out of the bay along the western shoreline south of the narrow.

7. Winam Gulf: Plate 5a shows a composite of Winam Gulf. The red channel is the SWB recording of March 4th 1998, the green channel is the SWB recording of July 26th 1998 in its descending pass and the blue layer the SWB image that was recorded in the afternoon of that day. In March the weed was primarily found in the eastern part of the gulf. The harbour of Kisumu was fully blocked by a huge mat of water hyacinth, while a large mat also covered Nyakach Bay and Osodo Bay (the location of these bays is indicated in Figure 7). In July the main mats were situated in the middle of Winam Gulf. The harbour of Kisumu could again be reached by boat and Osodo Bay was also free of water hyacinth. In Nyakach Bay some major mats remained, probably because they were kept there by the peninsular west of the bay. By July a fraction of the weed has accumulated in Asembo Bay to build a new relatively small mat. The general impression is that the mats have moved from north-eastern and eastern parts of the bay towards southern and western parts.

In general terms the water hyacinth mats show remarkable changes in surface with reductions up to 50%. Only in Winam Gulf the coverage of the mats shows a clear increase that is likely to be ascribed to a decrease in the compactness of the weed; In March most water hyacinth mats were firmly pressed against the eastern border of Winam Gulf, especially near Kisumu and in Osodo Bay. By July the mats were blown into the open areas of the Gulf causing a decline in the compactness and hence an increasing surface. The effect of the compactness on the surface will be discussed in more detail below. The pattern of the movements of the mats in Winam Gulf suggests a migration of the. weed towards the west and the southwest. If the direction of this migration can be applied to other bays it comes as no surprise that bays with a northeast-southwest orientation (like Waiya and Gobero Bay) show a sharp decrease in surface of water hyacinth; Surfaces in these bays have declined with almost 40% and 25% respectively. The narrows in Thruston Bay and to a less extent Hannington Bay prevent the mats from. being blown out of the bay.

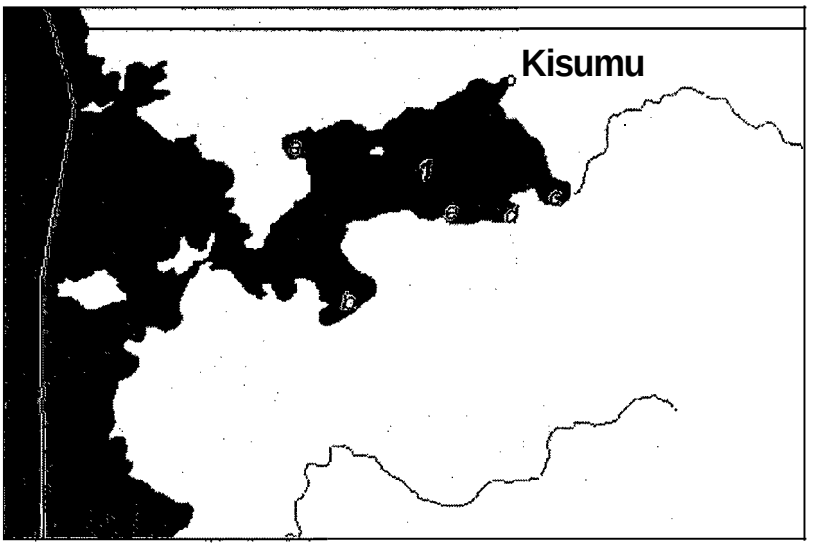


Figure 7 Locations of bays in Winam Gulf (1). *a) Asembo Bay, b) Homo Bay,* c) *Nyakach Bay, d) Osodo Bay and* e) *Kindu Bay.*

A further analysis of the SWB images shows that more bays than the ones listed in TabLe 14 contained water hyacinth mats. EspecialLy the March image shows several of these mats, for instance in Mwanza and Baumann Gulf in Tanzania and west of the Sese Islands (see Figure 1 for the location of these areas). Their surfaces are reLatively small, but to understand the migration patterns they are interesting. The location of the smalL mat west of the Sese Islands is an indication of the validity of the movements of water hyacinth as have been depicted in Figure 2. The size of this mat is about 491 hectares and the location suggests that it has not moved any further to the north. By the end of July the mat had disappeared probably due changing wind directions.
The two bays in the Tanzanian part of the lake are also of interest as it seems that water hyacinth starts to infest the southern part of Lake Victoria as well. In Mwanza Gulf, dispersed mobile mats with an estimated surface of (at least) 386 hectares were found in March. In July the mobile mats are absent. It is unclear whether these mats aggregated with the shoreline or if they floated away in northern directions. The same applies for the mats in Baumann Gulf in the southeast of the lake. In March mobile mats with an estimated surface of 244 hectares were present in this gulf whereas in July they had disappeared.

The estimations of the surfaces in Winam Gulf already mentioned the effects of compactness on the extent of water hyacinth mats. If mats are pushed against the shoreline, strong winds press the water hyacinth mats together and decrease the surface of the mats. The SIR-C images of April and October 1994 demonstrate the effects of winds on the compactness of the mats. In April 1994 the SRL recorded four strips of Murchison Bay with an interval of almost 24 hours. In October two strips were recorded with a similar interval. It is assumed that changes in the size of the mats during these periods are only related to changes in the compactness and that the possible natural growth or the effects of ,migration can be ignored. As the recording of April 17th was made with a different mode (see Table 8), the data of this day was skipped in order to work with comparable source data. The estimations of the water hyacinth coverage in Murchison Bay in April and October 1994 are shown in Table 16.

Table 16 *Estimation of the water hyacinth coverage in Murchison Bay and Gobero Bay in 1994 based on SIR-C images.*

Date and (time)	Surface in ha	Surface relative to 1" day of period.
14 April 1994	661.22	100.0
15 April 1994	853.70	129.1
16 April 1994	858.25	129.8
5 October 1994	755.94	100.0
6 October 1994	851.72	112.7

Especially the figures for April demonstrate the effect of wind, but it is also obvious by comparing the shape of the water hyacinth mats presented in Plate 4. The left-hand image on Plate 4 shows the mats on April 14th with a strong wind blowing from the south-southwest. Though there are no meteorological data to substantiate this, it can be derived from the shape of the three visible mats. Their lakeside borders are short and directed perpendicular to the (assumed) wind direction. The right-hand image on Plate 4 shows the same mats three days later loose and partly dispersed in the bays. The wind conditions clearly deviates from the conditions on April 14th. The size of the three mats increases with 30% as a result of the decreased compactness of the mats. In October the mats changed less dramatically. They were spread throughout the bays in several, almost wave-like patterns. Yet, the total surface of these mats is of the same order of magnitude as the surface of the three mats in April. Since the mats in October were not attached to the shoreline but scattered throughout the bays their compactness - and as a consequence their surface - is likely to change more easily than the mats that were present in April along the shoreline.

The figures presented for April 1994 show the relative value of estimations based on scattered areas since the compactness of the mats may vary strongly. Whatever accuracy the estimations may be, it is still difficult to substantiate a growth of water hyacinth on the basis of a particular location. Between two estimations the compactness of the mats may have decreased and hence the size of the mats increased. The cause of the increasing size of the mat can be ascribed to actual growth or migration on the one hand and to a decreasing compactness on the other, or a combination thereof. The actual cause is difficult to determine on the basis of satellite remote sensing. Though the shapes of the mats can give an indication, the extent of compression is impossible to quantify. Only long-term monitoring can smoothen out effects caused by differences in compactness.
The effects of wind are shown in Plate 5a. The SWB images of July 26th are both displayed in this plate, with the morning image in the green layer and the afternoon image in the blue layer. Many mats have moved within the twelve hours that separates them. The most western mat for instance has moved two to three kilometers in a southern direction. It emphasises the relative value of area estimates of water hyacinth on the ground as the same mats can easily be counted twice whereas other mats can be missed.

5.3 SUITABILITY OF ERS SCENES

On the ERS image of Winam Gulf it is possible to detect some water hyacinth mats, but it is not possible to make a proper estimation of their surface. Mats can be seen near Homa Bay (in the south of Winam Gulf), near Nyakach Bay (in the south east corner of Winam Gulf) and near Asembo Bay (in the northwest corner of Winam Gulf). For the ERS image of Buvuma this applies even stronger. At the most western edge of Napoleon Gulf a water hyacinth mat may be present, but this pattern does not seem to deviate from patterns that can be observed just north of Buvuma Island, where certainly no water hyacinth mats were present at the time of

the ERS recording. The water produces too much backscatter to make a reliable distinction between water hyacinth and water.

The problems in distinguishing water from other features in the ERS imagery is illustrated by comparing the histograms of the ERS image of September 14th 1997 with the Radarsat image of March 4th 1998 for exactly the same area (see Figure 8). Both histograms consist of two peaks; The pixels in the water make up the first peak while the non-water pixels make up the second one. The peak for the water pixels on the ERS histogram is clearly less pronounced than the one in the SWB histogram. Since the area covered by water in both images is almost identical, the variation in backscatter values produced by water must be much higher on the ERS scene. This implies that it will be more difficult to distinguish water from other features.

For Winam Gulf the histograms show similar patterns. The histograms of the respective recordings (for ERS a major part of the September 11th 1997 scene has been taken and for ScanSAR Wide a small part of the recording of March 4th) are presented in Figure 9. It is hardly possible to distinguish a peak for water areas on the cut of the ERS scene, so the distinction between water and non-water features is difficult to make on radiometric properties. For the ScanSAR Wide recording a peak for water areas can be distinguished, though not as clear as in the previous example.

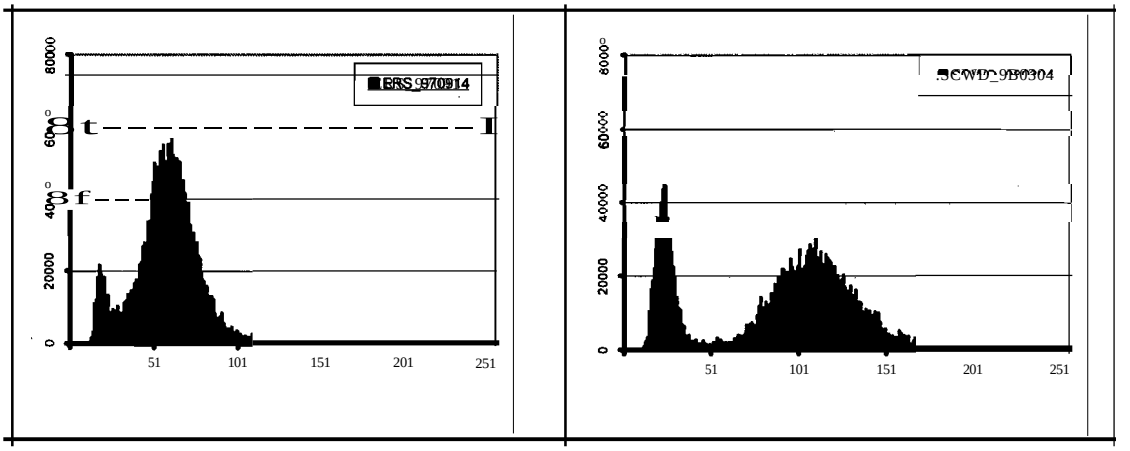


Figure 8 Histograms of ERS (left) and SWB (right) for the area of Napoleon Gulf, Thruston Bay and Hannington Bay.

For Winam Gulf the histograms show similar patterns. The histograms of the respective recordings (for ERS a major part of the September 11th 1997 scene has been taken and for ScanSAR Wide a small part of the recording of March 4th) are presented in Figure 9. It is hardly possible to distinguish a peak for water areas on the cut of the ERS scene, so the distinction between water and non-water features is difficult to make on radiometric properties. For the ScanSAR Wide recording a peak for water areas can be distinguished, though not as clear as in the previous example.

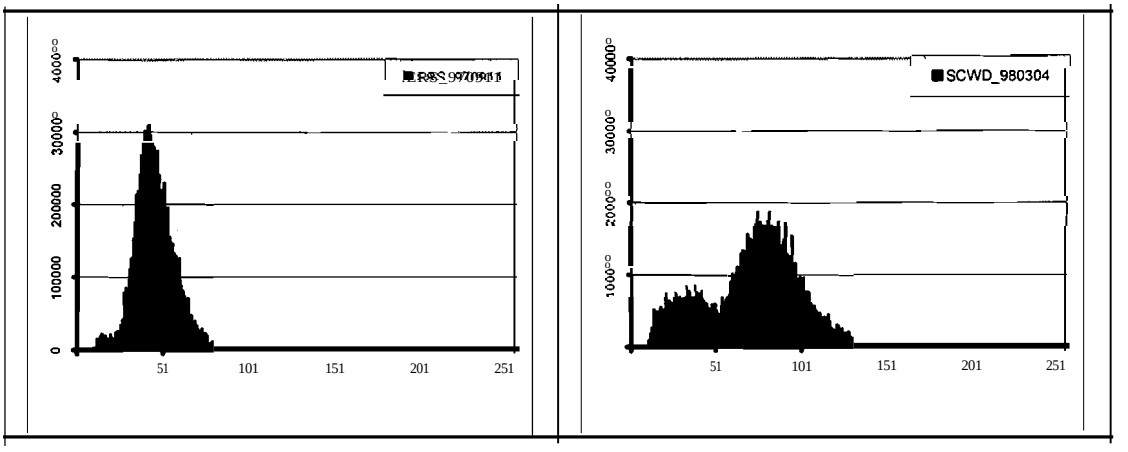
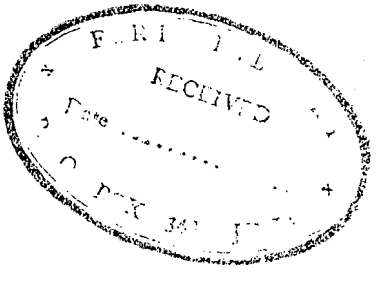


Figure 9 Histograms of ERS (Left) and SWB (right) for the area of Winam Gulf.

5.4 VALIDATION WITH NOAA IMAGERY

The meaning of NOAA imagery for validation of the interpretation of SAR data is limited (paragraphs 3.2 & 4.3) and *de facto* restricted to Winam Gulf as for only this area NOAA images are available without cloud coverage and large water hyacinth mats are present. Nonetheless, the mats in Winam Gulf are presented by only a confined number of pixels on the NDVI images. To emphasise these pixels a colour composite has been made of the NDVI images of the two most relevant NOAA recordings, notably those of September 10th 1997 and of March 4th 1998. This composite also allows the display of more than one NDVI image at the same time. In the composite the red layer has been assigned to the September NDVI image, the green layer to the March NDVI image and the blue layer to the absolute difference between these two NDVI images. A part of this composite is presented in Plate 5b. The NDVI value of water hyacinth mats is high and the NDVI value of water is practically zero. Migrated mats will ideally appear in either magenta (red and blue) or cyan (green and blue) while immobile mats ideally appear in yellow (red and green). For instance, Homa Bay and Kendu Bay (Figure 7) appear magenta, because these bays were (partly) covered with water hyacinth in September 1997 and clear in March 1998. The small bay near Kisumu appears as bright green, because in September 1997 this bay was free of water hyacinth while in March 1998 it was covered by it. The findings for Winam Gulf confirm the results obtained by the SAR data.

For other bays, like the ones near Kampala or Jinja the composite does not give a decisive answer if these bays were covered with water hyacinth or not. The size of these bays are actually to small compared to the geometric resolution of the NDVI image and in some cases cloud coverage hinders the interpretation.



6 CONCLUSIONS AND FUTURE OUTLOOKS

A SAR-based technique to monitor presence of water hyacinth needs to fulfil two major functions: a signal function and a control function. For the signal function the technique has to provide the responsible managers of Lake Victoria and its environment with accurate information about the location of water hyacinth at a certain moment. It should also give a rough estimation of the size of the water hyacinth mats. Especially the prospect that the magnitude and dynamics of the water hyacinth problem is quantifiable will be a direct benefit. The data would be an essential input into policy decisions on water hyacinth management.
The monitoring of the long-term spread is the object of the control function. Based on the analysis of the images of different seasons and years the proliferation or the decline of water hyacinth can be determined objectively. In this respect it is interesting to note that according to observations from the coastal area around October 1998 the cover of mobile water hyacinth mats in Uganda showed a dramatic decline. This decline may be due to biological control and other ecological impacts. A reliable monitoring mechanism could answer the question whether this is a general or a local decline.

In this paragraph the objectives of the study are evaluated. We also look at other conclusions that can be drawn on the basis of the study. Some of these conclusions lead to practical recommendations for future monitoring programs. As new sensors will be operational within a number of years, the possible consequences of these new sensors is discussed too. Finally some attention is paid to other application fields.

6.1 CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of the study is that SAR has a high potential to determine the presence of water hyacinth. On the basis of SAR imagery, especially multi-temporal imagery, it is well possible to map distribution and migration in time and to estimate the extent of water hyacinth mats. The effects of winds influence the size of the mats as winds can migrate and compress the mats. From the analysis of the SIR-C images it is obvious that the size of the mats can increase more than 25% in 24 hours. The two ScanSAR Wide images of July 1998 show that water hyacinth mats are very mobile and can migrate within 12 hours is well over 2 km. The consequence of the effects of the wind on water hyacinth mats is twofold. Firstly, the need to monitor the distribution of the weed is emphasised because of its ability to move rapidly. By monitoring water hyacinth at the ground the plants may drift out of sight. This problem can be overcome by using remote sensing techniques. Secondly, an accurate estimation of the size of water hyacinth mats is not essential since it can vary from day to day. This implies that short-term growth of water hyacinth mats is difficult to determine.

Other questions that were raised in this project deal with the configuration of the optimal SAR system and timing of the SAR images. SAR systems that operate in X-, C- or L-band are all capable of detecting water hyacinth mats. In principal short wavelengths are best suited to detect water hyacinth. Short wavelengths however, are more sensitive for ripples than longer wavelengths. Thoug h X-band systems are best suited to monitor water hyacinth, the C-band is a good alternative as it can still detect water hyacinth and is less sensitive for backscatter produced by ripples. For this reason one should prefer to work with HH or a cross polarisation. Radarsat imagery gives better results therefore than ERS imagery. This is illustrated in paragraph 5.3 where the class 'water' shows a considerable overlap with the class 'water hyacinth'. An additional reason for the better performance of Radarsat compared to ERS is the time of overpass of the two satellites. Radarsat comes over as diurnal winds have generally died down while ERS comes over as they are (generally) blowing.

Multi-temporal imagery consisting of two input images with a resolution of 100 meters already gives a good impression of water hyacinth coverage. On the basis of migration and changes in the compactness most of the mats can be identified. As a minimum requirement the size of the mats should coincide with the geometric resolution of the used satellite images. For ScanSAR Wide B images of Radarsat the size of the mats needs to be more than 1 hectare. High-resolution imagery like the Fine Beam mode of Radarsat is well suited to detect small sized mats of about 0.05 hectares.

The months March and July are suitable moments for monitoring water hyacinth movements due to the opposite seasonal wind directions in these months (see paragraph 2.3). Another period of interest is October when water hyacinth is directed from sheltered area into the open lake. Especially the developments in the autumn of 1998 seem to justify this acquisition scheme. Diurnal movements can be monitored by acquiring images in both the descending and ascending pass of the satellite. Because of the costs involved (see paragraph 6.1.1) the monitoring of diurnal movements should be considered carefully.

Depending on the areas that are selected for the monitoring program the appropriate resolution should be chosen. For a monitoring the entire lake the ScanSAR Wide B images of Radarsat will yield good results. If only parts of the lake have to be included in a monitoring program other modes that operate in higher resolution are preferred. Currently, the areas with the highest priority covers the area between the mouth of the Kagera River in Lake Victoria and Winam Gulf and the entire northern and north-western part of the lake. The latest coincides with the area where water hyacinth mats migrate on a seasonal basis (see Figure 2). The next important area on the priority list lies in the eastern and south-eastern part of the lake (roughly between Winam Gulf and Mwanza Gulf). In this area small water hyacinth mats already occur as has been shown by the SWB images. The area between Mwanza Gulf and the mouth of the Kagera River has - at this moment - the lowest priority.

During a brief presentation of the preliminary results at FIRI in the summer of 1998 the results were received well by the National Task Force on Water Hyacinth.. The members of the Task Force were excited about the possibilities the technology offered. Currently the main interest of the NTFWH is however focussed on Lake Kyoga that is situated north of Lake Victoria. A more extensive presentation of the final results to the Task Force is foreseen in 1999.

The study has shown that GPS measurements to provide ground truth data have little relevance. Only if these surveys are carried out from several places and at the time the SAR data are recorded the measurements might be meaningful. The results count for little to the efforts. Expert's knowledge is a reliable alternative. In general the contribution of local experts is essential for a successful application of the SAR-based technique.

Another objective of the project is the development a relatively simple satellite SAR-based technique for monitoring water hyacinth. The technique should be applicable with relative cheap and basic image processing software. To test the methods that have been developed under Erdas Imagine most of the imagery has been analysed in IORISI too. The results are positive and show that satisfying results can be obtained with simple techniques. SYNOPTICS already gave a basic training in IORISI at FIRI, but it is clear that this should be given a follow-up if FIRI is to benefit fully of the available data and the software. To fully capitalize this technique it is necessary therefore that local training on the use of remote sensing and GIS will be continued. The extension of this kind of training to for instance KMFIRI should also be considered to obtain a regional impact.

6.1.1 Monitoring in the future

In the future the use of Envisat, the successor of ERS-2, can be considered. The launch of Envisat is foreseen in May 2000. The Advanced SAR (ASAR) on board of this satellite can be regarded a second-generation SAR sensor of the European Space Agency (ESA). Typical characteristics of second generation SAR systems are the different modes of operations and polarizations. ASAR will operate in the same band as the AMI sensor onboard the ERS satellites. The main modes of ASAR are the image mode and Wide swath mode. The swath width of the image mode is up to 100 km with a geometrical resolution of ca. 30 meters. The swath width of the Wide Swath mode is at least 400 km and its resolution is about 150 meters. ASAR will allow scenes to be imaged in vertical and horizontal polarisation (ESA, 1997). Based on the results of this study the HH polarisation of ASAR can become an alternative for Radarsat products. In this respect it is interesting to see how the ASAR products compare to the Radarsat products. Both sensors can record imagery on a resolution of about 30 meters and dispose of a Wide swath mode. For a broad-scale monitoring program of entire Lake Victoria the SWB mode of Radarsat is still the best option. It can cover the lake with one recording in a resolution of 100 meters. The Wide swath mode of Envisat will need 4 frames to cover the lake (see Figure 10), but with a lower resolution. Currently a Radarsat ScanSAR Wide image costs $ 4,000.- (about ECU 3,450.-). The prices for products of Envisat are not known at this stage, but the prices for ERS products may be indicative; The used ERS product costs ECU 1,200.- so a first calculation of the cost for four Envisat Wide swath images to cover the entire lake is well over ECU 4,500.-.

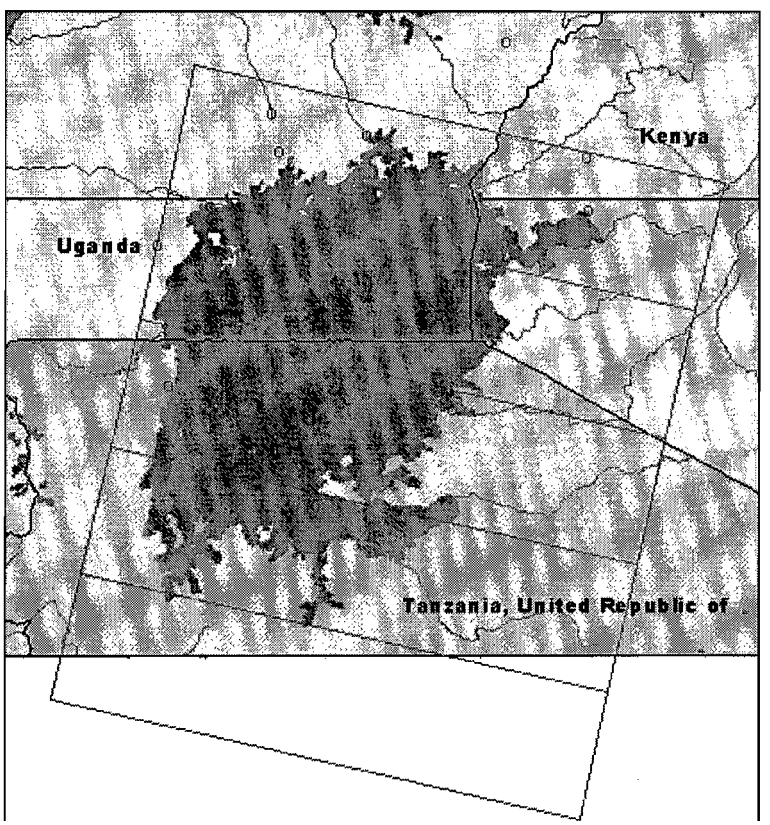


Figure 10 Coverage of Envisat Wide swath mode of Lake Victoria. The possibility to use four Wide swath images is ensured by the application of a small node shift.

If it comes to imagery with a resolution of approximately 30 meters, the situation is different. To cover the Lake with Radarsat products of this resolution one could choose the Wide Beam mode (see Appendix I). Atotal of 9 images are needed to cover the lake which amounts up to . The price to $31,500.-. To cover the lake with Envisat Image mode products 16 images are required against a total price of ca. ECU 19,200.-. This makes the use of Envisat images very appealing. Yet, one has to keep in mind that less images also means less elaboration of the images.

It is also possible to use archived SAR imagery that dates from a period before the major water hyacinth proliferation. This is particularly interesting for multi-temporal analysis. As Radarsat was launched in December 1995 it is not possible to use Radarsat imagery as a reference for the non-infested period. It is however possible to use JERS-1 SAR imagery. A SAR image of JERS-1 costs YEN 125,000.- which makes about ECU 900.-. The favourable price compared to other SAR products might be somewhat misleading though as a SAR product of JERS-1 covers an area of 75 x 75 km.

In the years to come more SAR systems will be brought into operations. LightSAR is under construction and may be launched in 2001 or 2002. LightSAR will be equipped with an L-band sensor and with either a C- or X-band sensor (Evans and Moghaddam, 1998). The L-band will be fully polarised. The Japanese prepare the launch of the successor of JERS-1, ALaS, which will carry a SAR sensor called PALSAR. This will also operate in the L-band, in either HH polarisation or VV polarisation. PALSAR is scheduled to be launched in early 2003. In 5 years time SAR data in different wavelengths, in different polarisations and in different modes (image mode versus ScanSAR mode) will be available. Depending on the mode the resolution may alter too. These future SAR systems will guarantee high quality data for years to come, of which the proliferation of water hyacinths in for instance Lake Victoria can be adequately monitored.

Finally from 1998 onwards it has become easier to use optical data to monitor the proliferation of the water hyacinth. Though strictly speaking this development falls outside the scope of this research, it is interesting for those who are involved in the management of the lake. As has been mentioned in paragraph 3.2 both SPOT and Landsat have new satellites in orbit. To cover the lake with SPOT data one would need a lot of scenes, but depending on its final orbit Landsat 7 could cover the lake with six scenes. As it is foreseen that the central archive of Landsat will contain at least one cloudless image per year of every part of the world (if possible), this archive can become an interesting source for monitoring programs that are based on annual data. The meaning of NOAA data is limited; Though the use of NOAA imagery is tempting because of the visiting frequency and the price, the resolution is too coarse and only allows information retrieval on the location of the major water hyacinth mats. Water hyacinth mats of the size that could be observed in Baumann and Mwanza Gulf on the March image of the SWB image will be overlooked completely.

6.2 OTHER POSSIBLE DISCIPLINES AND FIELDS OF APPLICATION

The SAR imagery also provides an opportunity to analyse other features. For instance it would be possible to monitor wetlands along the shores of the lake, and to monitor forest stands on islands in the Lake and sites on the main land. In this respect it is noteworthy to cite the National Policy for the Conservation and Management of Wetland Resources of the Republic of Uganda, which states:
"Those [new wetland developments] which have been subjected to EIAs [Environmental Impact Assessment] will continuously be monitored to assess their impact on the environment and where the impact is detrimental, Government will require that such a development be halted." (Ministry of Natural Resources, 1995).

Because of the interesting prospects SAR imagery offers for monitoring wetlands some of the results of the current project have been demonstrated during the second international conferen'ce on wetlands and developments held in Dakar in November 1998.
Agricultural purposes could be served as well. Especially on the Fine Beam image of Jinja and surroundings large-stale arable lands with sugar cane, tea and coffee can be identified.

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Appendix I Different modes of Radarsat

Radarsat can offer different types of images, depending on the mode of operation. In general it has two major modes: Single Beam mode and ScanSAR mode (see Figure 11). In the study presented here both modes have been used. The Fine Beam is an example of a Single Beam mode and the ScanSAR Wide B is an (obvious) example of the ScanSAR mode.

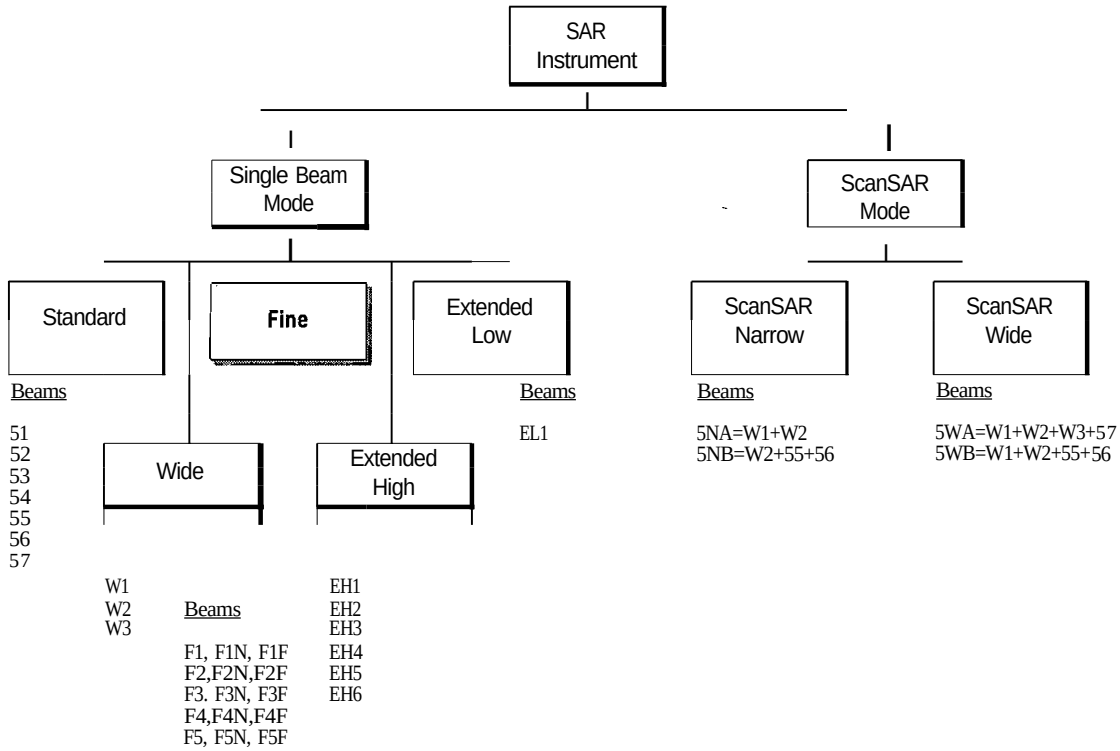

Figure 11 *Scheme with the modes that the SAR instrument of Radarsat can offer (Radarsat International,* 1997)

The following is derived from Radarsat International (1997):

Fine Beam

The Fine beam mode is intended for applications, which require the best spatial resolution available from the RADARSAT system. The azimuth resolution is 8.4 m, with range resolution 9.1 m to 7.8 m from Fl to F5. Since the radar operates with a higher sampling rate in this mode than in any of the other beam modes, the ground swath coverage has to be reduced to a nominal 50 km in order to keep the downlink signal within its allocated bandwidth. Originally, five Fine beam positions, Fl to F5, were available to cover the far range of the swath, the incidence angle range from 37 to 47 degrees (see Figure 12). By modifying timing parameters, 10 new positions have been added with offset ground coverage. Each original Fine beam position can either be shifted closer to or further away from Nadir. The resulting positions are denoted by either an N (Near) or F (Far). For example, Fl is now complemented by FiN and F1F.

Wide Beam

Wide beams are similar to the Standard beams except that the swath width achieved by this beam is 150 km rather than 100 km. As a result, only three Wide beams, Wi, W2 and W3 are necessary to provide coverage of almost all of the 500 km swath range (see Figure 12). They provide the comparable resolution as the standard beam mode although the increased ground swath coverage is obtained at the expense of a slight reduction in overall image quality. Wi and W2 are available for single beam products. W3 is used as one of the beams to form SWA product but not recommended for individual image because it contains a nadir ambiguity (narrow white vertical strip in the image).

ScanSAR Wide

The ScanSAR Wide mode (SeW) provides coverage of either 500 km (for SWA) or 450 km (for SWB) nominal ground swaths (see Figure 12), with spatial resolution 100 m in general. Two combinations of single beams (SWA and SWB) can be used:

- SWA: Wi + W2 + W3 + S7
- SWB: Wi + W2 + S5 + S6

The first combination SWA covers the full 500 km swath incidence angle range of 20 to 49 degrees. The second combination SWB provides 450 km of coverage over the incidence angle range 20 to 46 degrees.

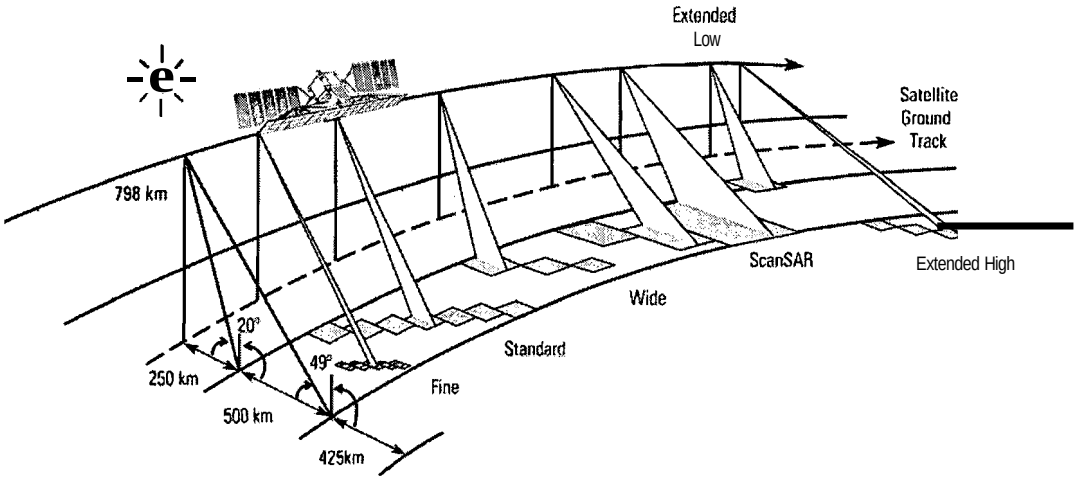

Figure 12RADARSAT SAR Beam Modes, taken from Radarsat International (1997).

Appendix II Acquired maps

The most important maps used in this project are listed in Table 17. In addition to these maps copies of two other maps have been used:

- A map of Jinja at a scale of 1:10,000 published by the Department of Lands and Surveys Uganda in 1963 (Series U.S.D. 2; Edition 3 U.S.D).
- Sheet 72/1, named Jinja from the Uganda 1:50,000 series (Series Y732) published by the Department of Lands and Surveys, Uganda, 1965

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Table 17 Overview of the used analogue maps

Area	Name	Sheet	Map ID	Edition	ScaLe	Year	Publisher
Lake Victoria	Tactical Pilotage Chart		M-5A	1	1:500;000	1982	Defense Mapping Agency Aerospace Center
	Tactical Pilotage Chart		L-5D (G)	I-GSDS	1:500,000	1974	Director of Military Survey
Kenya	Y731	Asembo	115/2	5-0.0.5. 1970	1:50,000	1970	Directorate of Overseas Surveys Published by D.O.s. for the Kenya Government
	Y731 (D.O.S. 423)	Kisumu West	116/1	6-0.0.5. 1970	1:50,000	1970	Directorate of Overseas Surveys Published by 0.0.5. for the Kenya Government
	Y731 (D.O.S. 423)	Kisumu East	116/2	6-0.0.5. 1971	1:50,000	1971	Directorate of Overseas Surveys Published by 0.0.5. for the Kenya Government
	Y731	Kendu Bay	116/3	4-0.0.5.	1:50,000	1963	Directorate of Overseas Surveys
	Y731	Nyakach	116/4	4-0.0.5.	1:50,000	1962	Directorate of Overseas Surveys
Uganda	Land Cover (Land Use) Stratification Map	Jinja	72/1	1	1:50,000	1996	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda
	Land Cover (Land Use) Stratification Map	Ikulwe	72/2	1	1:50,000	1997	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda
	Land Cover (Land Use) Stratification Map	Bwema	72/3	1	1:50,000	1997	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda
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	Y731 (0.0.5.423)	Kisumu West	116/1	6-0.0.5. 1970	1:50,000	1970	Directorate of Overseas Surveys Published by 0.0.5. for the Kenya Government
	Y731 (0.0.5. 423)	Kisumu East	116/2	6-0.0.5. 1971	1:50,000	1971	Directorate of Overseas Surveys Published by 0.0.5. for the Kenya Government
	Y731	Kendu Bay	116/3	4-0.0.5.	1:50,000	1963	Directorate of Overseas Surveys
	Y731	Nyakach	116/4	4-0.0.5.	1:50,000	1962	Directorate of Overseas Surveys
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	Land Cover (Land Use) Stratification Map	Ikulwe	72/2	1	1:50,000	1997	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda
	Land Cover (Land Use) Stratification Map	Bwema	72/3	1	1:50,000	1997	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda
	Land Cover (Land Use) Stratification Map	Magyo	72/4	1	1:50,000	1997	The National Biomass Study, Forest Department Min. Natural Resources - Government of Uganda

Appendix III GPS surveys on Lake Victoria

In order to gather ground truth data two GPS surveys were carried simultaneously with the Radarsat recordings of March. The type of receiver used for the measurements was a Garmin 12 XL. This relatively simple and cheap instrument indicates the positions with an accuracy of about 50 meters. The main reason for the inaccuracy is the Selective Availability (Seeber, 1993). Differental GPS receivers can be used to eliminate this artificial inaccuracy, but these receivers are expensive. An alternative is found by using a second Garmin 12 XL as a base station. This instrument is kept at the same spot during the actual survey and its measurements are the basis for the calculation of the Selective Availability (SA). As long as the distance between the base station and the field GPS instruments remains within certain boundaries (Garmin Corporation, 1996) the two receivers use the same satellite configuration. The SA is then equal for both receivers and the determined SA can be subtracted from the measurements of the field instrument. .

For the GPS surveys six instruments were available. On March 4th two sets of three instruments were made. Each set was switched on simultaneously, the first set on time *T* and the second set on time *T+15 seconds*. Both sets were set with a fixed time interval of 30 seconds. This means that every other set determined a position after 15 seconds. From each set one instrument remained at FIRI in Jinja as a base station. The other four instruments were taken into the field. By keeping two instruments with a mutual measure interval of 15 seconds together a long series of points is obtained. As the vessel towed a canoe it was possible to make two independent series of points. The goal of the survey was Thruston Bay and possible other water hyacinth mats that were spotted along the way.

On March **11th** day this method could not be applied for several reasons. The first reason was that the vessel left the landing place near FIRI institute the evening prior to the measurements. Therefore it was not possible to install a base station at the institute. The second reason was that the time interval between measurements had to be reduced since the geometrical resolution of the Fine Beam image was much higher than the geometrical resolution of the ScanSAR Wide image. The interval of successive GPS measurements had to be adjusted accordingly. Apart from Thruston Bay, Hannington Bay was also chosen for the GPS measurements. For each bay a set of just two instruments was used. The instruments of each set were switched on simultaneously with a time interval of 5, respectively. 6 seconds. Just before the measurements in a bay actually started one of the instruments was brought ashore and functioned as a base station.

Plates



Plate 1a. Flowering water hyacinth



Plate 1b. Picture of a water hyacinth mat near Kisumu (Kenya) in October 1997 that demonstrates the vast and homogenous nature of these mats.

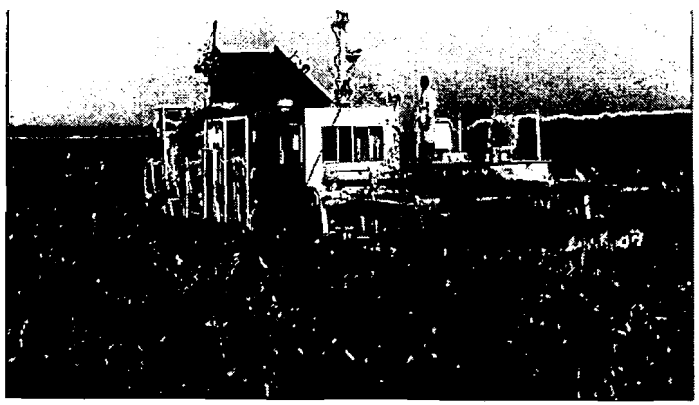

Plate 1e. Mechanical removal of water hyacinth near Kampala (Uganda) in June 1998.

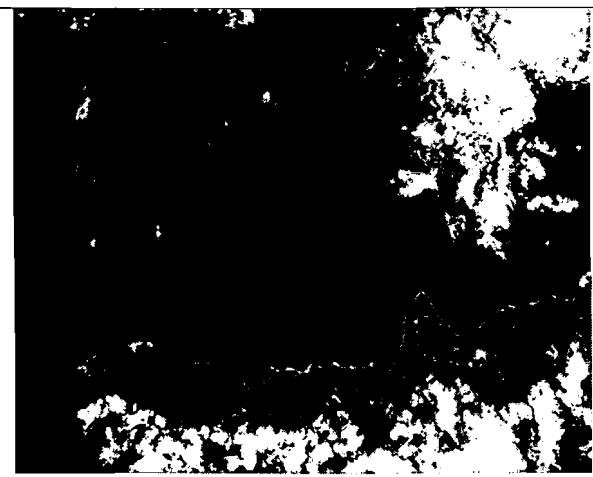

Plate 1d. Picture taken on July 12th 1997 by an astronaut on board of Space Shuttle, mission STS-94.

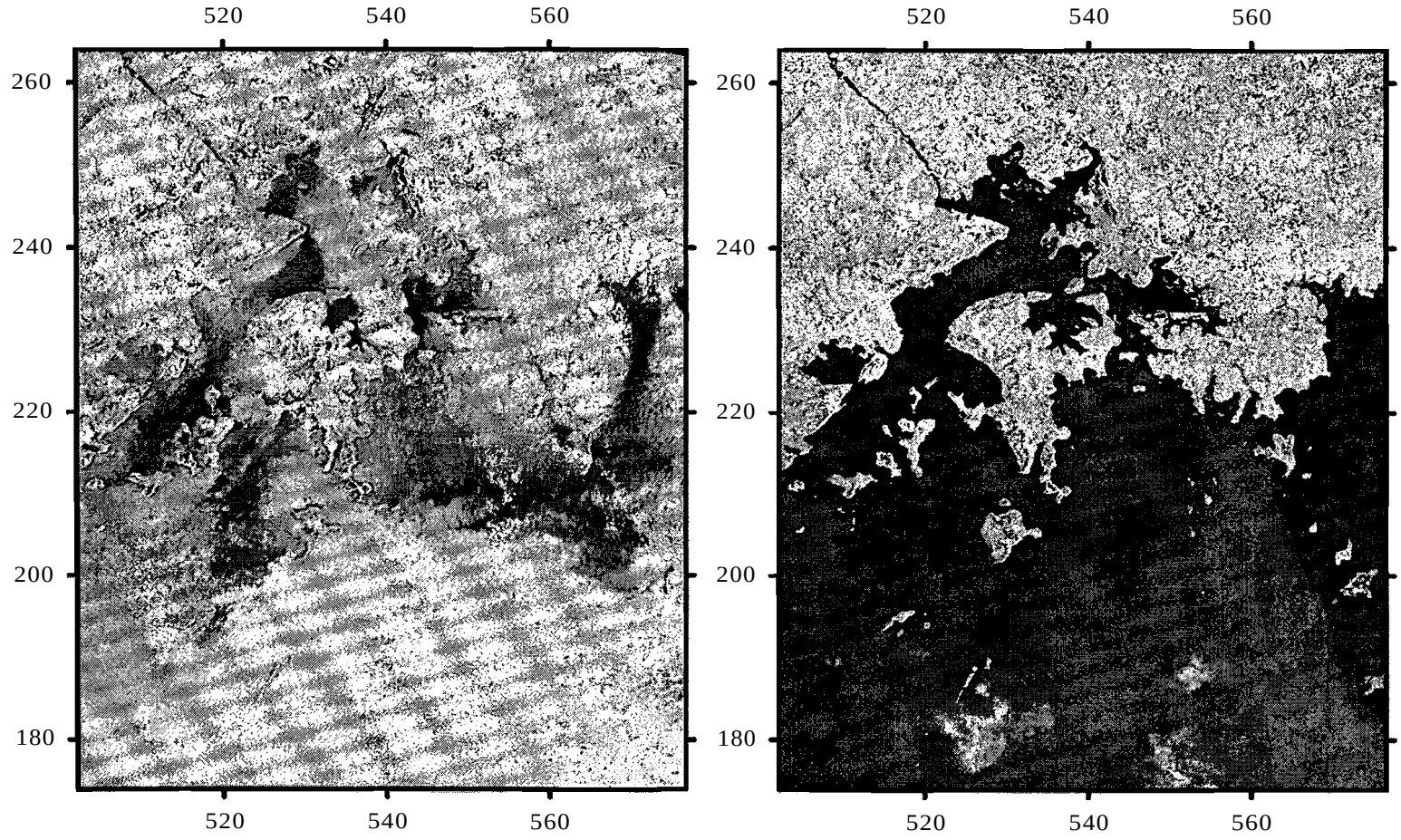

Plate 2 The area of Buvuma Island (Uganda) as recorded by ERS-2 and by Radarsat SWB. The ERS-2 recording was made on September 14th 1997 and its geometric resolution is around 25 meter. The Radarsat recording SWB was made on March 4th 1998; its geometric resolution is around 100 meter. Only a part of each image is displayed (see figures 3 and 4).

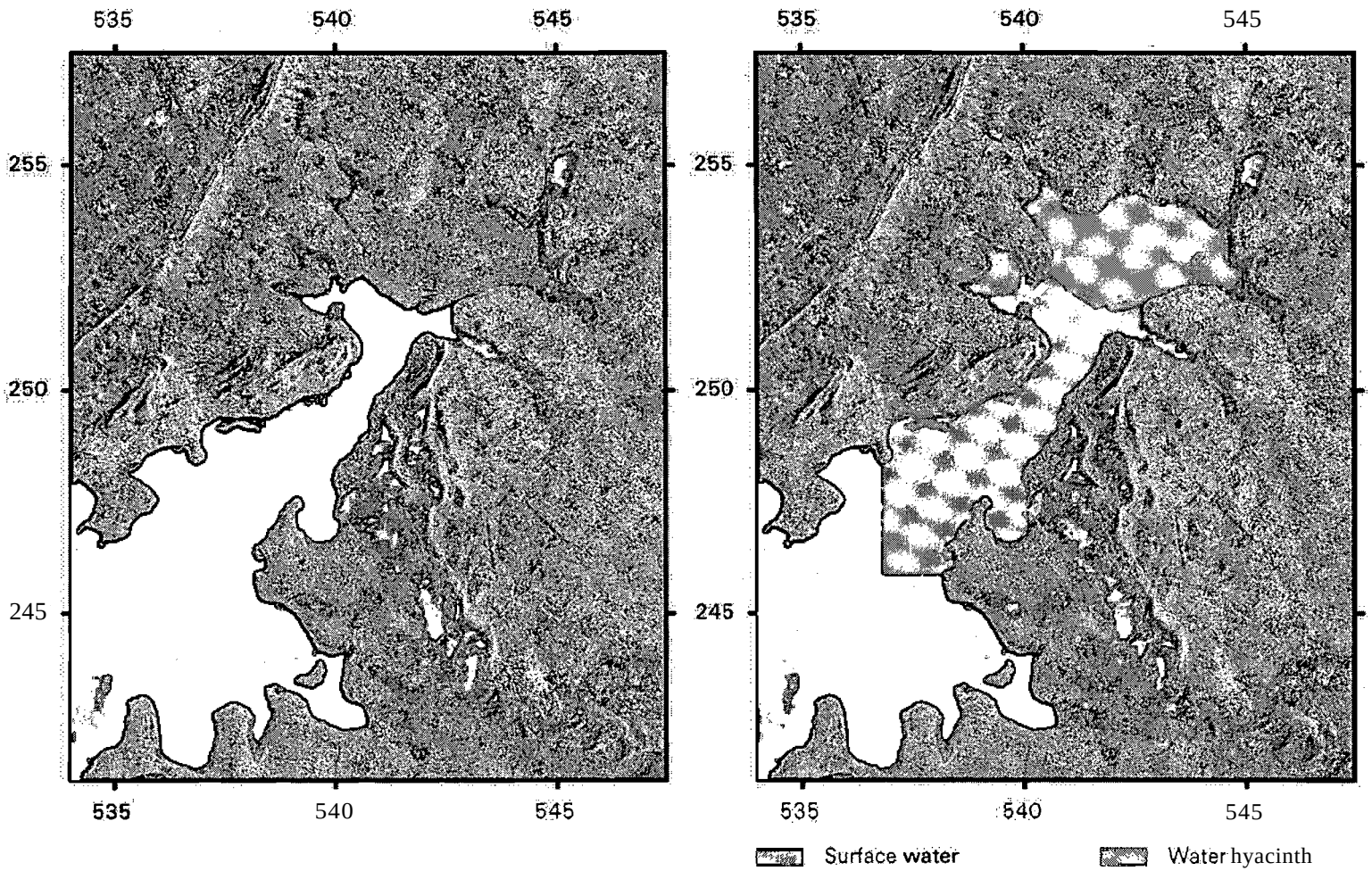

Plate 3 Thruston Bay recorded by Radarsat Fine Beam Mode, dd. ll-MAR-1998 (Gamma MAP filtered). A part of Fine Beam image has been classified and the result has been draped over the SAR image (figure on the right). The total surface of water hyacinth is almost 950 hectares.

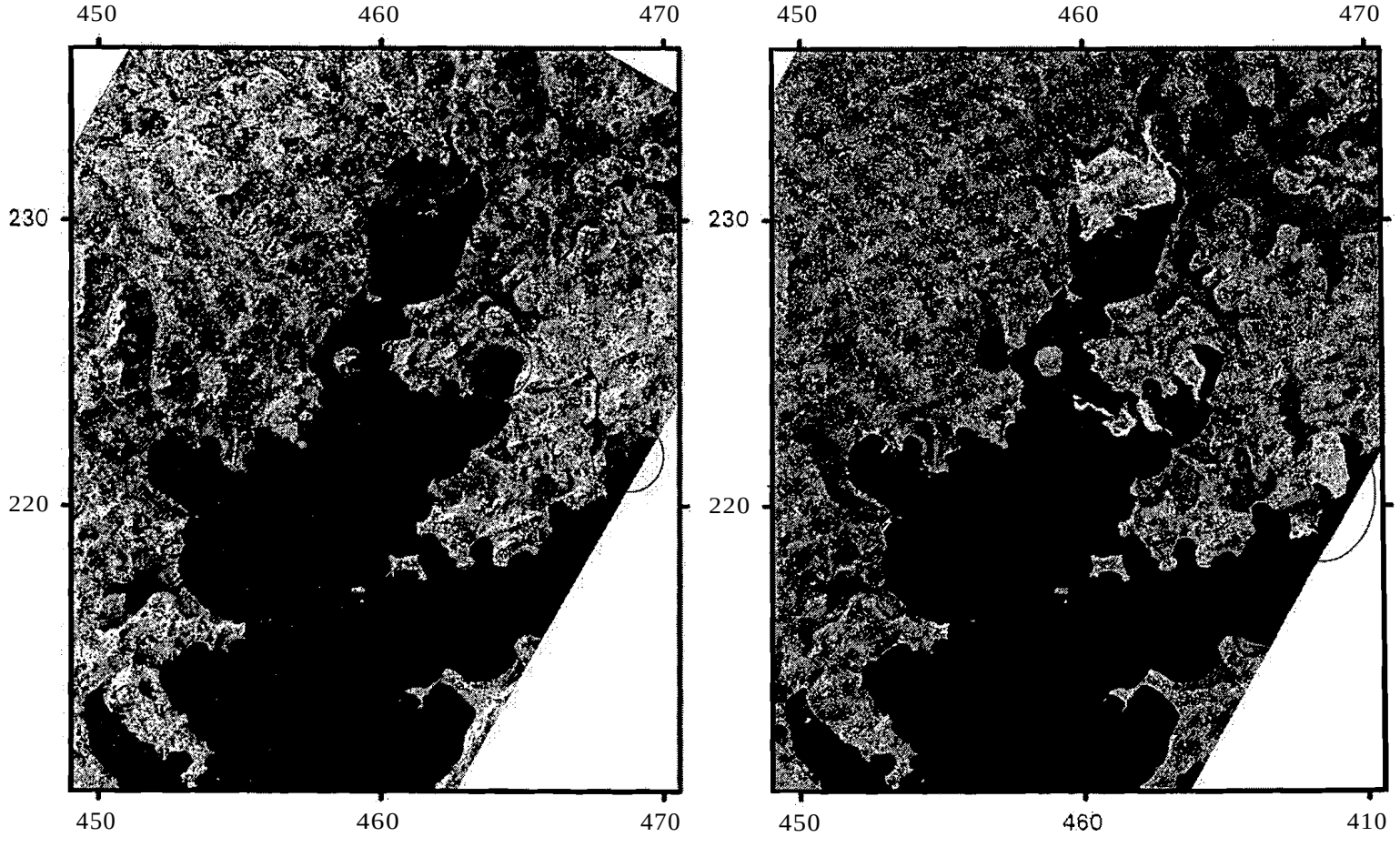

Plate 4 SIR-C and X-SAR recordings of Murchison Bay near Kampala (Uganda). On the left the SIR-C recording from April 14th 1994, displayed are the channels C-VV (in red), L-HH (in green) and L-HV (in blue). The right-hand figure is the X-SAR recording of April 17th 1994. The red circles and ovals mark the location of the major water hyadnth mats. Though only recorded 72 hours after one another the size of the mats has changed substantially due to changes in the (ompactness.

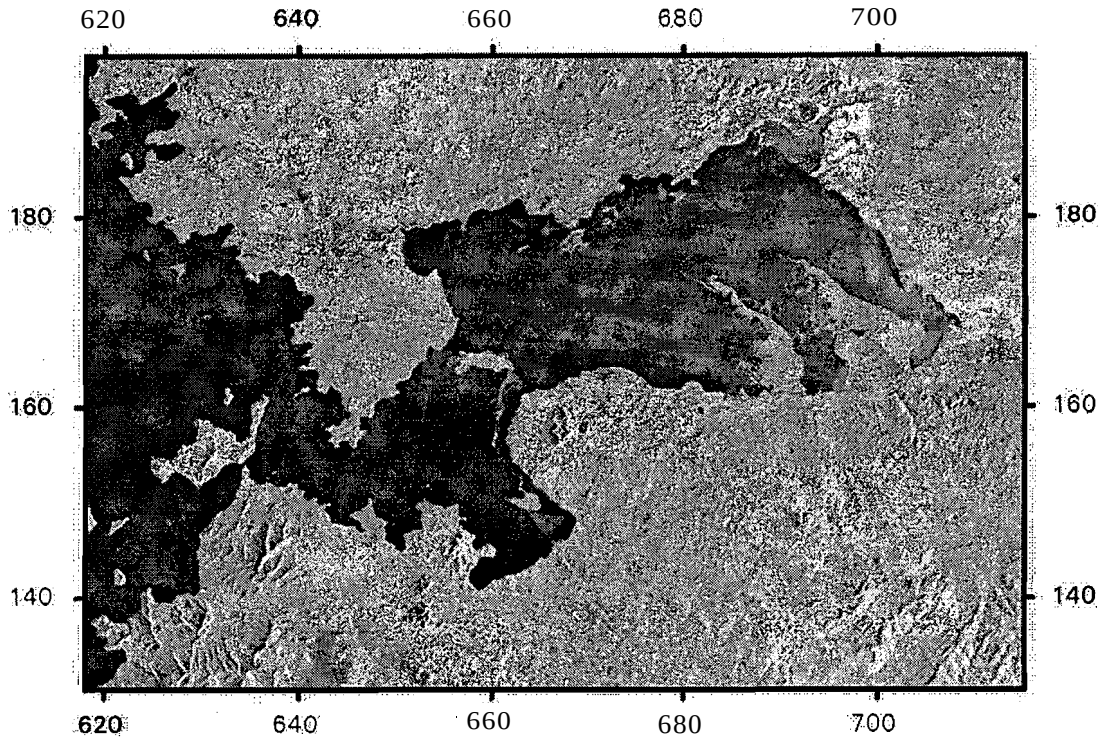

Plate 5a. A multi-temporal composite of Winam Gulf (Kenya) consisting of three Radarsat SWB recordings: in red the SWB recording of March 4th 1998, in green the SWB in descending mode of July 26th 1998 and in blue the SWB recording of the same date in ascending mode (ca. 12 hours later).

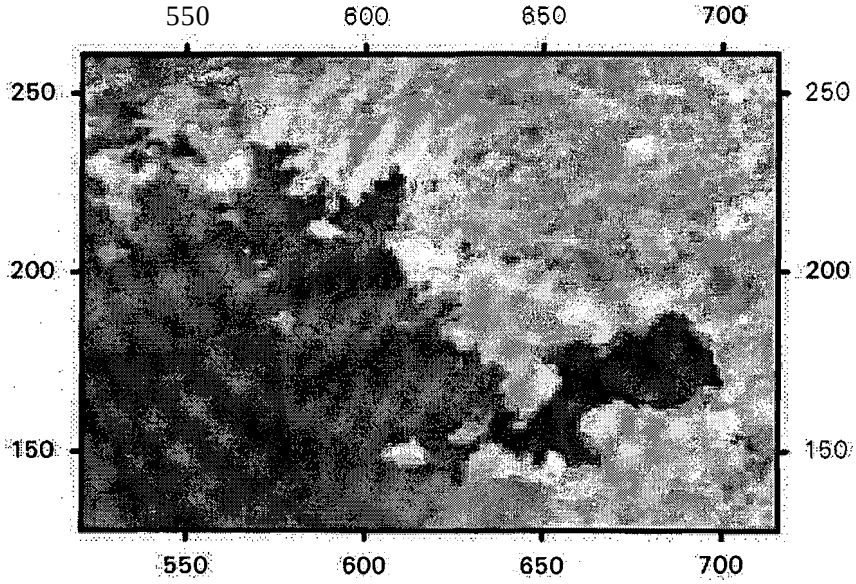

Plate 5b A NOAA NDVI composite of Winam Gulf (Kenya) and wider vicinity,. Displayed are: the NDVI image based on NOAA data of 10-Sep-97 in red, the NDVI image based on NOAA data of 4-Mar-98 in green and the absolute difference of these two layers in green.