DEVELOPMENT OF AN OPERATIONAL SYSTEM FOR MONITORING AND PREDICTING THE AQUATIC PLANTS PROLIFERATION IN THE LAKE VICTORIA

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ABSTRACT

This paper aims at presenting preliminary results of a project recently approved in the framework of the ESA-TIGER initiative. The project objective is the development of an operational monitoring system based on EO data useful to attempt the prediction of the environmental factors related to the occurrence of the abnormal aquatic plants proliferation in the Lake Victoria. The international projects concerning Lake Victoria [1], [2] emphasize how all derived by-products (distribution of the proliferation of floating vegetation, spectral identification of the weed, water quality and water compounds abundances estimation) have a potential usefulness in the management of the water resource [3].
The presence of macrophytes in the inland water of the Lake Victoria is related to the high concentration of some water constituencies like chlorophyll and suspended matter [4]. The monitoring of floating vegetation in the Lake Victoria will be useful to check the growing trend of the macrophytes. The objectives of this mapping phase will be to verify the efficiency of the data to derive valuable distribution of the weed units on the lake surface and to discriminate between the different floating species through their spectral characteristics.
Temporal variation of weeds and water compounds, obtained by analyzing time series of satellite images will be used to assess the correlation existing among water compounds concentration and aquatic plants proliferation trying to develop an alert system capable to indicate when the environmental pre-conditions for the weeds proliferation are reached.

1. INTRODUCTION

The Lake Victoria is the second largest freshwater lake in the world and the biggest in Africa. With an approximate surface area of 68,000 square kilometres the Lake supports approximately 20 million people distributed over Tanzania, Uganda and Kenya [5]. The relevance of the Lake Victoria for the economy of the riparian countries has been recognized by FAO, that promoted an international project named Lake Victoria Environment Management Project (LVEMP) in order to rehabilitating the Lake ecosystem via water pollution control, water catchments protection, enforcement of water quality, periodic monitoring and assessment of water resources.
The Lake Victoria drainage basin comprises several rivers that are heavily polluted by:
- high sediment load due to soil erosion and run-off from agricultural high populated areas;
- high agrochemical residuals that increase nutrients, which have resulted in eutrophication;
- discharge of untreated or semi-treated industrial as well as municipal effluents.

Environmental perturbations are raising concern for the future of the Victoria ecosystem [6]. Eutrophication resulting from increased nutrient concentration in the lake diminishes water quality by promoting the excessive growth of weeds and increasing suspended organic material. The aquatic weed Eichhornia crassipes (water hyacinth) began to appear in the lake during 1989 - 1990 and, since 1990, it colonized the whole lake. The problem has been particularly severe along the northern and eastern shorelines and islands (Uganda and Kenya). In particular, Kenyan sector of the lake had the highest reported infestation of water hyacinth in 1998 that caused significant socio-economic impact on riparian populations. A first attempt to quantify the total water hyacinth cover in Lake Victoria was done in 1994. The large increases of water hyacinth through 1998 are likely the result of self propagation and inflows from shoreline infestation due to high water levels associated with the 1997/1998 El Nino weather conditions [1]. The fact that the weed is found near shores and fish landing sites gives an indication of the interference it causes in the utilization and exploitation of this important natural resource.
In fact, the abnormal aquatic plants proliferation interferes with human activities such as fishing, and boating, stunts or interferes with a balanced fish population, causes fish kills due to removal of too much oxygen from the water, produces quiet water areas that are ideal for mosquito breeding, impedes water flow in drainage ditches, irrigation canals and culverts, causing water to back up.

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Troubles caused to fishery have a significant impact on the territory because, although fishery constitutes only a small percent of the Gross Domestic Product, it is an important source of livelihood for many riparian communities. Freshwater fisheries account for almost all the annual national production, and almost all the freshwater production derives from Lake Victoria. For this reason, national water management programs deserve particular attention to Lake Victoria, in accordance with its status as Kenya's leading fish producer.

Water resource assessment comprises the continuous measurement and recording of water quality data. The purpose of the collection of information is to provide a basis for management and planning of water resources. In this context an integrated approach based on multisensorial satellite remote sensed data (hyper/multispectral, radar), could provide an alternative means of water quality monitoring over a greater range of temporal and spatial scales in a timely and cost-effective manner.

2. DATA AND METHOD

The paper aims at showing how satellite-based observation of Lake Victoria can help in setting-up a monitoring/alerting system of the lake status. The main elements of this system are:

(a) the mapping of water hyacinth and associated macrophytes;

(b) the estimation of parameters related to water quality and composition, like concentrations of Chl a, CDOM and TSS,

(c) eutrophication indices related to the fast growing of floating weeds that have infested the area over the last few years and finally

(d) development of a early-warning system for the prevision of plants proliferation in the Lake Victoria.

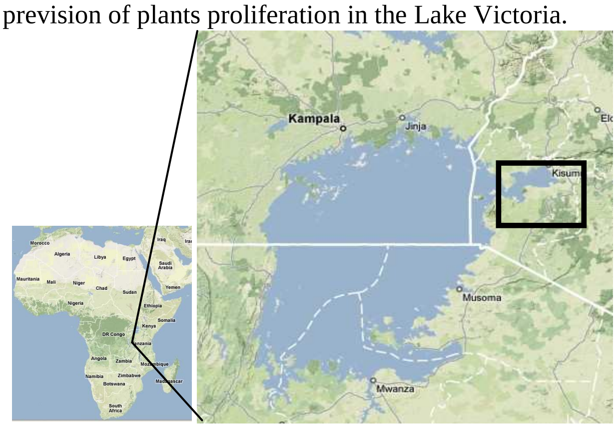

Figure 1 - Location of the study area.

If any correlation between these quantities can be established, it can help determining the main causes of the abnormal aquatic plants proliferation. This kind of information can result crucial in developing a management strategy of the Lake Victoria water resources

Several hyperspectral data (CHRIS) have been obtained through the opportunity provided by ESA via the Cat-1 project in the last 2 years. These images have been used to distinguish prevailing floating vegetation species by exploiting the spectral signatures gathered during a field campaign. They will be also used to estimate the characteristics of the substances flowing in the lake Victoria at the river mouths, that is: phytoplankton (associated to Chl a that represents its main pigment), CDOM, TSS (identified as a class of particulate) and pure water. Water compounds concentration maps will be built-up by using a bio-optical-model (that defines the optical properties of the main water compounds and connects them to the optical properties of the water body) and a radiative transfer model (that links the optical properties of the water to the radiometric field) already applied to the lower spatial resolution MERIS images [7].

A time series of MODIS images, covering a period of 10 years (from 2000 to 2009), has been used to monitor with an at least bi-weekly frequency the extension of the floating vegetation. In fact, a preliminary analysis carried out on Landsat/ETM+ images shows that the number of available data (see Tab. 1) is insufficient for revealing accurately (see next paragraph) the time when the plants proliferation starts or the period of peak or the decreasing phase.

Table 1 – Characteristics of the satellite images used for the study.

Sensor	Spatial Resolution (m)	Swath (Km)	Acquisition time	
ETM+	30	185x185	24/08/2004	**22/02/2007**
			21/04/2005	16/07/2007
			10/07/2005	04/10/2007
			03/02/2006	21/11/2007
			13/07/2006	
CHRIS	18	14x14	**22/02/2007**	
MODIS	250	Winam Gulf	2000 - 2009	

The utilizzation of the 250 m spatial resolution channels of MODIS poses some concerns regarding the capability to detect the floating plants and to distinguish water hyacinth from other floating weeds characteristics of the lake. The comparison with the results provided by applying unmixing techniques to ETM+ images [8], [9] can help in answering to this problems.

Further details, regarding the characteristics of the vegetation floating on the lake and the state of the lake water (water colour) have been obtained by exploiting the CHRIS/PROBA images.

Due to the high number of MODIS images to be

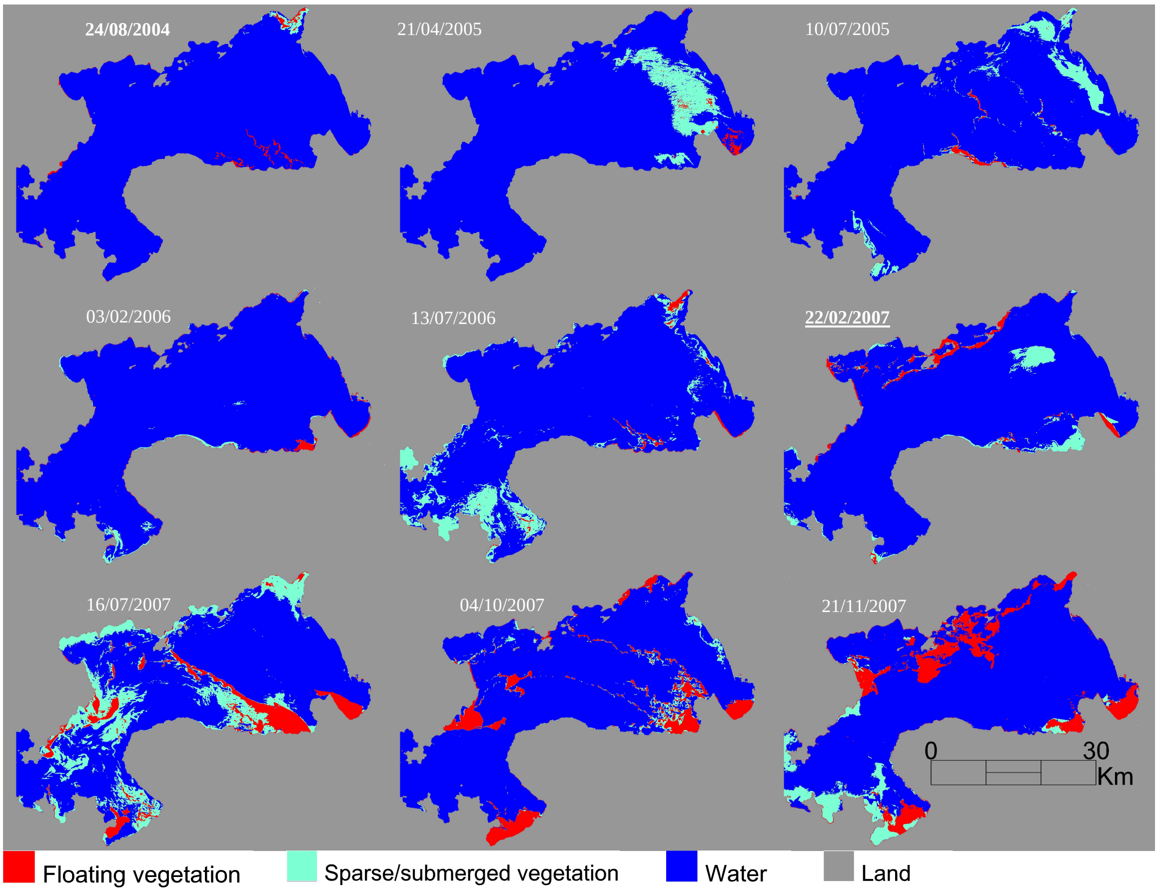

Figure 2 – Aquatic weeds dispersion map as attained from Landsat ETM+ temporal series classification.

analyzed, of the order of 2000, an automatic technique for the processing of them has been developed. The processing system, developed in IDL environment, applies a mask for defining the area of interest, a method to remove cloudy images and finally uses a NDVI based method for separating floating vegetation from submerged/sparse vegetation and water.

3. RESULTS

First of all, the time behaviour of the floating plants assessed by using Landsat/ETM+ images is shown in Fig. 2. The list of the used images is given in Tab. 1. It is clear as the number of available images (9 images for a period of 4 years) for the area of interest is enough to detect a certain periodicity in the evolution of the phenomena but insufficient to accurately determine the characteristic of such a periodicity. To the ETM+ images an unsupervised classification algorithm was applied. The selected surface units were recognized (taking into account the *in situ* observation made in 2004) as: (1) emerged riparian and floating vegetation; (2) sparse floating/submerged vegetation; (3) water; and (4) land. This segmentation process applied to Landsat ETM+ images allowed to isolate the floating macrophytes with the aim of highlighting the evolution of the weeds over the last 6 years, partially continuing the work done until 2001 [1].

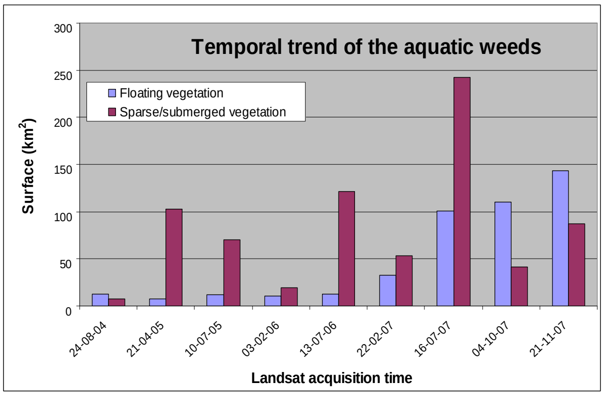

Figure 3 – Histogram of floating and sparse/submerged vegetation computed from ETM+ images temporal series.

The histogram shown in Fig. 3 gives an idea of the behavior of the aquatic weeds that, after being almost stable at around 10 km^2 from 2004 to 2006 undergone a rapid grow covering an area larger the 140 km^2 during 2007. As already said above, the lack of an adequate set of data hampers the possibility to clearly identify any seasonal dependence of the weeds presence in the lake. On the other side, the so called submerged/sparse vegetation apparently shows an higher frequency periodicity (annual or semi-annual) which cannot be suitability captured do to the already recalled lack of ETM+ data.

The contemporary availability of a hyperspectral image of the CHRIS sensor and an ETM+ image can be exploited to assess the error made when the simple classification scheme of Fig. 2 is applied, [10]. That is, when the floating vegetation is not distinguished in its different species (Water Lylium, Nile Cabbage, Water Hyacinth, etc.). In fact, the characteristics of the CHRIS image and the availability of the spectral reflectances of the vegetation species available in the Lake allows to discriminate the different species according to their spectral behavior as observed from the ASD field spectral feature analysis. To this purpose, a Spectral Angle Mapper (SAM) classification algorithm was applied to estimate the abundance of each species.

By the application of SAM classifier to the portion of the CHRIS image related to the floating vegetation (second classification step) it was possible to discriminate 3 different species: Water Hyacinth (58%), Nile Cabbage (25%), Water Lylium (17%). The relative abundances (reported in parenthesis) of the three classes referee to the area covered by the processed CHRIS images. In fig. 4 the two ETM+ and CHRIS images are shown with the corresponding classification results.

Table 2 – Results of the classification of the simultaneous ETM+ and CHRIS images.

ETM+	**22/02/2007**		
Veg. class	Npts	%	Km^2
Float. Veget.	3644	33.4	3.28
Subm. Veget.	7263	66.6	6.54
Total			**9.82**
CHRIS	**22/02/2007**		
Veg. class	Npts	%	Km^2
Water Lylium	2182	6.9	0.63
Nile Cabbage	3255	10.2	0.94
Water Hyacinth	7366	23.2	2.13
Subm. Veget.	18982	59.7	5.49
Total			**9.19**

This unique available example of simultaneous images of two different satellite sensor allows to highlight some of the limits of an analysis of the Water Hyacinth distribution of the Lake Victoria based on a multi-spectral sensor like ETM+. In fact, analyzing in detail the characteristics of the vegetation classified as floating vegetation on the ETM+ image it results that more than the 40% of the vegetation classified as floating vegetation and possibly as water hyacinth has been recognized to be made of other species like Nile Cabbage and Water Lylium. The other limit regards the effect of spatial resolution of the sensor that can cause an overestimate of the floating vegetation extend. However, due to the characteristics of the CHRIS images both in term of size of the image, unable to cover the whole area of interest and the revisit frequency unsuitable to capture the main temporal characteristics of the phenomenon under study a multi-sensor approach to the problem of determining the temporal evolution of the water hyacinth in the lake Victoria is required.

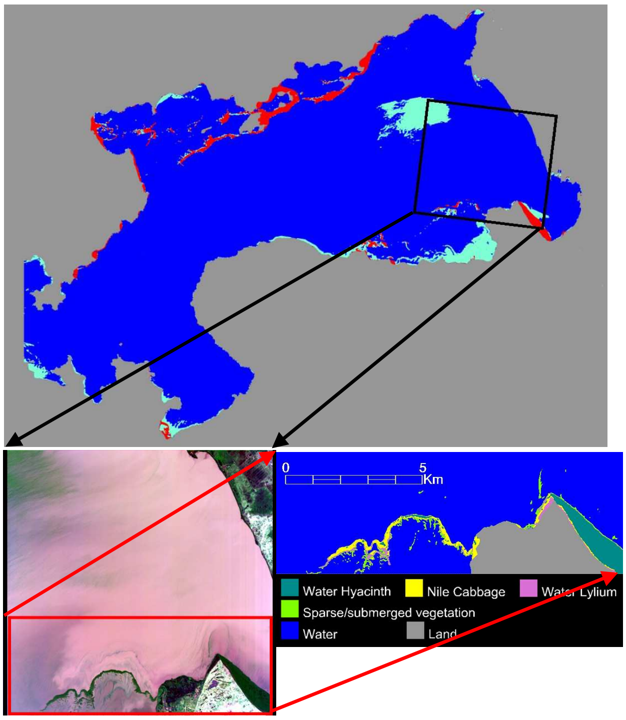

Figure 4 – Overlapping area of the ETM+ and CHRIS images of 22/02/2007. RGB combination of the CHRIS image(bottom left) and aquatic weeds classification map of the rectangular area (in red).

On the day 22 February 2007 an MODIS/Terra image of the lake Victoria is also available. Fig. 5 shows the map of the floating vegetation and submerged vegetation obtained by using the NDVI values computed by using the two MODIS sensor channels at 250 m spatial resolution. The comparison between the classification results for the ETM+ and MODIS images is reported in Tab. 3.

The results shown in Tab. 3 reveal, again, the difficulties encountered when a high revisit frequency is required. In fact, in this case the sensor capable to provide imagery with the required temporal frequency has a reduced spatial resolution unsuitable for allowing a correct classification of the area of interest.

Figure 5 – Classification map of of the MODIS/Terra image acquired on the 22/02/2007: = floating vegetation, = submerged vegetation.

As a matter of fact, even if the extent of the floating vegetation is only overestimated of about the 15% the extent of the submerged/sparse vegetation results noticeably underestimated as consequence of the spatial resolution of the sensor. This fact can hamper the possibility to develop hypotheses on the existence of precursors on which a prediction of an incipient weeds proliferation can be based.

Table 3 – Results of the classification, extended to the whole Winam Gulf, of the simultaneous ETM+ and MODIS images.

ETM+	**22/02/2007**		
Veg. class	N. pixels	%	Km^2
Float. Veg.	35889	31.7	32.3
Subm. Veg.	77333	68.3	69.6
Total			**101.9**
MODIS	**22/02/2007**		
Veg. class	N. pixels	%	Km^2
Float. Veg.	622	67.8	38.9
Subm. Veg.	296	32.2	18.5
Total			**57.4**

To further analyze the limits of the water hyacinth (floating vegetation) monitoring based on MODIS 250 m spatial resolution images the results obtained by the CHRIS and MODIS images acquired on the same days have been compared. Four cases are available, as reported in Tab. 4. The analysis has been carried out on the area of the Lake covered by the CHRIS imagery. Even if analyzed at the CHRIS spatial resolution (17 m) the floating vegetation estimate based on MODIS images results enough accurate. Of course, as already stated above, the estimate of the submerged/sparse vegetation results noticeable underestimated. Notwithstanding the accuracy of the floating vegetation estimate, the error made by assuming the whole floating weeds as composed of hyacinth can be large (see Tab. 4).

Table 4 – Results of the classification, extended to the small part of the Winam Gulf, covered by the CHRIS images, obtained by the simultaneous CHRIS and MODIS images. (WH% = Water Hyacinth percent).

CHRIS (Extension in Km^2)				
Acquisition Time	Water Lylium	Nile Cabbage	Water Hyacinth	Sparse/subm.
22/02/2007	0.63	0.94	2.13	5.49
03/03/2007	0.33	0.13	0.06	1.81
06/02/2008	0.93	2.34	1.70	9.87
31/01/2009	0.54	0.79	1.52	1.98
MODIS (Extension in Km^2)				
	Floating veg (*tot. veg CHRIS*), (WH %)			Sparse/subm. veg. (*Sparse CHRIS*)
22/02/2007	3.56 (*3.70*), (58%)			2.00 (*5.49*)
03/03/2007	0.56 (*0.52*), (11%)			0.75 (*1.81*)
06/02/2008	5.63 (*4.97*), (34%)			3.38 (*9.87*)
31/01/2009	3.00 (*2.85*), (53%)			2.00 (*1.98*)

4. CONCLUSIONS

This paper aims at describing the activity carried out by the authors in the framework of a project, that is part of the ESA initiative TIGER, focused on the Lake Victoria. The objective of the project is the development of an operational system, based on satellite images, capable to predict the aquatic weeds proliferation by monitoring the lake and assessing its state. The main result coming out from this preliminary study regards the necessity of a multi-sensors approach for suitably monitoring the temporal evolution of the vegetation weeds. In fact, the ETM+ sensor was able to easily monitor the extension of the total floating vegetation over the whole bay thanks to its wide swap (185 km) but the temporal frequency of available images is insufficient for an accurate estimate of the periodicity, if any, associated with its proliferation. Further, the CHRIS sensor, with it higher spectral resolution, allows the discrimination of the different species composing the floating vegetation (Water Hyacinth, Nile Cabbage, Water Lylium) and then the integration of the two sensors gives an accurate description of the phenomenon. The high revisit frequency of MODIS images, taking into account its limits in terms of spatial resolution and number of spectral channels could be adequate for accurately identifying the periodicity, if any, of the floating weeds proliferation, even if, an estimate of the preconditions for aquatic weed occurrence is made difficult by the sensor limits. Therefore, in order to develop an up-to-date decision support system MODIS data should be opportunely supported by the more precise information provided by the other two sensors (TM and CHRIS).

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