Assessment of the abnormal growth of floating macrophytes in Winam Gulf (Kenya) by using MODIS imagery time series

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A B S T R A C T

The objective of this research study is to assess the capability of time-series of MODIS imagery to provide information suitable for enhancing the understanding of the temporal cycles shown by the abnormal growth of the floating macrophytes in order to support monitoring and management action of Lake Victoria water resources.

The proliferation of invasive plants and aquatic weeds is of growing concern. Starting from 1989, Lake Victoria has been interested by the high infestation of water hyacinth with significant socio-economic impact on riparian populations.

In this paper, we describe an approach based on the time-series of MODIS to derive the temporal behaviour, the abundance and distribution of the floating macrophytes in the Winam Gulf (Kenyan portion of the Lake Victoria) and its possible links to the concentrations of the main water constituencies.

To this end, we consider the NDVI values computed from the MODIS imagery time-series from 2000 to 2009 to identify the floating macrophytes cover and an appropriate bio-optical model to retrieve, by means of an inverse procedure, the concentrations of chlorophyll a, coloured dissolved organic matter and total suspended solid.

The maps of the floating vegetation based on the NDVI values allow us to assess the spatial and temporal dynamics of the weeds with high time resolution.

A floating vegetation index (FVI) has been introduced for describing the weeds pollution level.

The results of the analysis show a consistent temporal relation between the water constituent concentrations within the Winam Gulf and the FVI, especially in the proximity of the greatest proliferation of floating vegetation in the last 10 years that occurred between the second half of 2006 and the first half of 2007. The adopted approach will be useful to implement an automatic system for monitoring and predicting the floating macrophytes proliferation in Lake Victoria.

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1. Introduction

Aquatic weeds are a kind of water “biological pollution” and a major component of global change due to human impacts. Aquatic weed species can be defined as aquatic plants (macrophytes) not desired by the managers of water bodies, either when growing in abundance or when interfering with the growth of crop plants or ornamentals (Pieterse and Murphy, 1990). Like conventional pollutants, aquatic weeds can lead to environmental and economic impacts. In particular, invasive aquatic plants affect drainage for agriculture and forestry, fishing, drinking water quality, fish and wildlife habitat, flood control, habitats for other plants, human and animal health, hydropower generation, irrigation, navigation and land values (Rockwell, 2003). The numbers of aquatic weeds and invasive species impacting on ecosystems are ever more increasing. Water hyacinth (Eichhornia crassipes) has been described as the world’s worst aquatic weed. When this exotic plant is introduced into uninfested areas, it may explode into large infestations causing serious disruption to environments, economies and societies.

Starting from 1989s Lake Victoria has been interested by a most severe infestation of water hyacinth with significant socioeconomic impact on riparian populations. The relevance of Lake Victoria for the economy of the region has been recognized by FAO so much so that it promoted an international project named Lake Victoria Environment Management Project (LVEMP, Kloh and Andjelic, 1997) in order to rehabilitate the Lake ecosystem via water pollution control, water catchments protection,
enforcement of water quality, periodic monitoring and assessment of water resources.

Kenya as well as the other countries surrounding Lake Victoria are facing a number of serious challenges related to water resource management, including population growth, water scarcity, climate variability and water resource degradation, invasive species, rivers water pollution (agricultural and agrochemical residuals, discharge of industrial/urban waste). The infestation of the water hyacinth has been particularly severe along the northern and eastern shorelines and islands (Uganda and Kenya). In particular, the Winam Gulf, located in the Kenyan sector of the Lake, was interested by the highest infestation of water hyacinth in 1998 resulting in significant socio-economic impact on riparian populations. Troubles caused to fishery have a significant impact on the territory because, although fishery constitutes only a small percentage 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 programmes reserve particular attention to Lake Victoria, in accordance with its status as Kenya’s leading fish producer. Aggressive efforts to fight the plant, including manual removal and the introduction of the plant’s natural predator (Neochetina weevil), combined with favourable environmental conditions helped reduce the weeds by 2000 (Wilson et al., 2007). Subsequently the problem of water hyacinth was relatively low and in the years 2004/2005 seemed to have almost disappeared. However, in February 2007 NASA disclosed some images acquired by the satellite MODIS sensor in December 2005 and December 2006 (http://earthobservatory.nasa.gov/IOTD/view.php?id=7426) and the comparison showed a massive proliferation of water hyacinth in the Winam Gulf. According to NASA, this abnormal event could possibly be related to unusually heavy rains seasons that occurred in Kenya between 2006 and 2007 and that flooded the rivers that feed into the Winam Gulf. The rain and floods raised water levels of the lake and swept agricultural run-off and nutrient-rich sediment into the water.

In this context, satellite remote sensing offers the capability to rapidly and synoptically monitor large water ecosystems and detect vegetation cover dynamics over time (Coppen et al., 2004). The importance of remote sensing for wetland and inland water inventory and monitoring at all scales was emphasized several times by the Ramsar Convention on Wetlands and by EU projects like SALMON and ROSALMA, e.g. by Finlayson et al. (1999) and Lowry and Finlayson (2004).

The most common method to investigate the temporal behaviour of the vegetation is by means of satellite time series imagery. The temporal domain of satellite imagery holds plenty of information on ecosystem behaviour and could be very important as another tool in vegetation mapping and monitoring (Justice et al., 1985; Malingreau, 1986).

Although the value of remotely sensed time-series data for monitoring vegetation seasons has been firmly established (Malingreau, 1986; Tucker et al., 1986), only a limited number of methods for exploring and extracting seasonality parameters from such data series have been developed. Therefore, developing methodologies to detect the spatial and temporal distribution of aquatic weeds is of high priority. It is essential to know where infestations occur in order to manage them and to understand their causes and consequences (Cavalli et al., 2009).

The use of medium resolution satellite images like MODIS products offers the opportunity to create a wide set of time-series data that allows the analysis of floating vegetation dynamics over a long temporal range. From this point of view, the goal of this study is to assess the capability of the time-series MODIS imagery to provide information suitable to understand the temporal behaviour of the macrophytes growth in order to support the monitoring and management action of Lake Victoria water resources.

We processed 10 years (2000–2009) of MODIS imagery in order to examine the seasonal and inter-annual variability of NDVI within the Winam Gulf test area for deriving the fluctuation of the floating vegetation with at least weekly frequency and identifying the areas more affected by the weeds occurrence. Moreover, we assessed the concentration of the water quality parameters, retrieved by using an appropriate bio-optical model and an inverse procedure, in order to find some evidence (precursor) with some environmental variable (rainfall, temperatures, lake height fluctuation, etc.) and the floating vegetation proliferation.

The floating vegetation cover and its variations can be evaluated by means of the Normalised Difference Vegetation Index (NDVI). MODIS NDVI time-series have been successfully applied to quantify vegetation activity and to measure vegetation dynamics (Ahl et al., 2006; Jaccquen et al., 2010; Zhang et al., 2003). Furthermore some indicators related to water quality and composition, like concentrations of chlorophyll a (Chl a), coloured dissolved organic matter (CDOM) and total suspended solid (TSS) can be obtained by a physics based approach. If any correlation between floating vegetation distribution and water quality parameters can be established, it could help determine the main causes of the “explosive” growth of the aquatic weeds that have infested the Winam Gulf over the last few years. This kind of information can result useful to develop an operational system for monitoring and predicting the floating macrophytes proliferation and crucial to develop a management strategy of Lake Victoria water resources. Of course, this methodology can be generalized to other areas of concern.

These results, whenever related to ancillary hydrological information (e.g. the rainfall), have shown that the synergy of MODIS images time-series with lower temporal frequency time series imagery is a powerful tool to monitor the Lake Victoria ecosystem, to follow the floating vegetation extension and even to foresee the possibility to setting up a model for the abnormal vegetation growth.

2. Study area

Lake Victoria is the second largest freshwater lake in the world and the biggest in Africa. With an approximate surface area of 68,000 km², the Lake supports approximately 20 million people distributed over Tanzania, Uganda and Kenya (Romero et al., 2005). The Lake Victoria basin comprises several rivers that are heavily polluted by high sediment load due to soil erosion and run-off from agricultural areas highly populated and discharge of untreated or semi-treated industrial effluents. Eutrophication resulting from increased nutrient concentration in the lake worsens water quality by promoting the excessive growth of weeds and increasing suspended organic material; indeed, the Secchi transparency index (water clarity/quality) has declined from 5 m in the 1930s to less than 1 m in the 1990s (Klohn and Andjelic, 1997).

In particular, the Winam Gulf, located in the Kenyan sector of the Lake (Fig. 1a) and characterized by a relatively shallow bottom (av. 10 m depth, Romero et al., 2005) and an area of 1350 km², was interested by the highest infestation of water hyacinth (Fig. 1b and c). The appearance of this weed was first reported in 1989. In 1994 the first attempts to quantify the weed coverage were made, with an estimated 270 ha, while the peak of infestation occurred in 1998 and was estimated to be 17,218 ha (Albright et al., 2004).

From a climatic point of view, this area is characterized by an equatorial climate with two rainy seasons which occur in March to May (long rainy season) and November (short rainy season), followed by a relatively dry season; the yearly average temperatures range from 17.4 °C to 29.9 °C (Fig. 2).
3. Materials and methods

3.1. Data

A time-series of MODIS multispectral images covering a period of 10 years (from 26 February 2000 to 15 January 2010) equivalent to 3605 days of data acquisition, has been used to monitor with at least weekly frequency the floating vegetation extension over the water surface of the Winam Gulf. A preliminary analysis (Lane et al., 2010) carried out on Landsat images showed that the number of available data is insufficient for revealing accurately the time when the abnormal plants proliferation starts or the peak period or the decreasing phase. To this end the TERRA MODIS spectral bands 1 (620–670 nm) and 2 (841–876 nm) with a 250 m spatial resolution (MOD02QKM, level 1B, collection 5, see Table 1) have been used to distinguish the floating vegetation from water and land by calculating the NDVI.

In addition, AQUA MODIS spectral bands 1–4, with a 500 m spatial resolution (MYD02HKM, level 1B, collection 5), were also used to analyze the optical properties of the water column to retrieve the water constituent concentrations (Chl a, TSM, CDOM), in order to establish a correlation between aquatic weed proliferation and water quality parameters, if any. The time availability of these data ranges from 2002 to 2009.

Furthermore, AQUA MODIS clouds mask (MYD35_L2 – level 2) was used to automatically remove MODIS images with cloud cover greater than 10% of the lake surface defined by the coastline of the Winam Gulf (Fig. 1a).

All MODIS standard products were ordered directly from the LAADS website (http://ladsweb.nascom.nasa.gov/data/) and retrieved from the LAADS ftp site (ftp://ladsweb.nascom.nasa.gov/).

For this study, additional data were analyzed to determine if other factors may have contributed to the fast growth of the macrophytes. In particular, we have taken into account the averages of the monthly rainfall and temperatures recorded at the meteorological station of Kisumu (courtesy of the Kenya Meteorological Department) and the relative Lake Victoria height variations computed from the TOPEX/POSEIDON (T/P), Jason-1 and Jason-2/OSTM altimeters (http://www.pecad.fas.usda.gov/lakes/images/lake0314.TPJO.1.txt), produced by the U.S. Department of Agriculture’s Foreign Agricultural Service (USDA-FAS), in cooperation with the National Aeronautics and Space Administration (USDA/NASA, 2006).

3.2. Methodology

Changes in the vegetation seasonal behaviour can be assessed by means of the NDVI, derived from time-series of MODIS imagery or from other satellite sensors (e.g., NOAA/AVHRR, SPOT/VEGETATION, etc., Ahi et al., 2006; Jacquin et al., 2010; Zhang et al., 2003). The NDVI is a measure of the amount and health conditions of the biomass on the land surface and maps based on this vegetation index are developed to distinguish more easily green vegetation from other not-photo-synthetically active surfaces (Rouse et al., 1974; Tucker, 1979). Indirectly, NDVI has been used to estimate the cumulative effect of rainfall on vegetation over a certain time period, rangeland carrying capacity, crop yields for different crop types, and the quality of the environment as habitat for various animals, pests and diseases.

NDVI is calculated by subtracting the red spectral channel from the near-infrared (NIR) spectral channel and dividing their difference by the sum of the two channels. In other words, for MODIS sensor it can be expressed as:

$$\text{NDVI} = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

where \(\rho_1\) and \(\rho_2\) are MODIS red and near-infrared reflectance bands, respectively. NDVI values range from –1.0 to 1.0, with negative values indicating clouds and water, positive values near zero indicating bare soil, and higher positive values of NDVI ranging...
from sparse vegetation (0.1–0.4) to dense green vegetation (0.5 and above).

Such an index has been used to estimate the amount of floating vegetation infesting the Winam Gulf. In fact, time series of MODIS NDVI data have been applied to monitor the fast vegetation dynamics within the lake.

In particular, a floating vegetation index (FVI), defined as the ratio between the surface interested by floating vegetation and the Winam Gulf surface, has been introduced

\[ FVI = \frac{N_{FV}}{N_{A0I}} \]  

where \( N_{FV} \) is the pixels number defined as floating vegetation and \( N_{A0I} \) is the pixels number of the area of interest, depicted by Winam Gulf surface.

The FVI, computed over the time series, represents a useful index for describing the weeds pollution level.

In order to look for a precursor of the abnormal growth of floating vegetation, we retrieved information related to the water constituents possibly associated with that (Lung'ayia et al., 2001).

A previous work carried out on the area (Cavalli et al., 2009; Santini et al., 2007) showed the capability of a physically based approach to estimate the abundances of phytoplankton (associated with its main pigment, chlorophyll – Chl), coloured dissolved organic matter (CDOM) and a class of particulate (TSS – identified as total suspended solids). In said work the water constituent concentrations were built-up by using an appropriate bio-optical model and an inverse procedure developed in the IDL language starting from MERIS Rs (remote sensing Reflectance) signal (Santini et al., 2010; Mobley, 1994)

\[ Rs(\lambda_i) = F \frac{b_b(\lambda_i)}{a(\lambda_i)} + \frac{b_b(\lambda_i)}{a(\lambda_i)} \]  

where \( \lambda_i \) is the ith band, \( b_b \) and \( a \) represent the absorption and backscattering water properties, respectively, and \( F \) is a parameter that takes into account water light field anisotropies and the reflectance and transmittance properties of the water surface (mainly due to wind speed). A linear composition, with respect to single constituent optical properties, was assumed for \( b_b \) and \( a \) (Alberotanza et al., 2010; Santini et al., 2010). In this work we follow the same procedure for processing the whole set of MODIS images. The need of elaborating a great number of data imposed a less accurate parameterization with respect to what done in Cavalli.
et al. (2009). The $F$ parameter was, in fact, considered constant and equal, for the whole set of data, to the main value of 0.65. Considering this lower accuracy as well as the limited number of bands taken into account and the lack of an appropriate set of in situ measurements for validation purposes, the results of the model application have to be regarded as a qualitative indicator of the trend of the water constituent abundances.

In order to understand if the concentration trends returned by the model application could be considered as a precursor of the abnormal weeds proliferation, a preliminary statistical analysis was carried out to find correlations among the different constituent concentrations (mean values computed on the whole Winam Gulf), then a cross-correlation as a function of the lag $L$ was applied to every single constituent and the FVI time series (Fuller, 1996)

$$P_{c<FVI}(L) = \begin{cases} \frac{\sum_{k=0}^{N-L-1} (C_{k+i+1} - \bar{C}) (FVI_k - FVI)}{\sqrt{\sum_{k=0}^{N-L-1} (C_{k+i+1} - \bar{C})^2 \cdot \sum_{k=0}^{N-L-1} (FVI_k - FVI)^2}} & L < 0 \\ \frac{\sum_{k=0}^{N-L-1} (C_{k+i+1} - \bar{C}) (FVI_k - FVI)}{\sqrt{\sum_{k=0}^{N-L-1} (C_{k+i+1} - \bar{C})^2 \cdot \sum_{k=0}^{N-L-1} (FVI_k - FVI)^2}} & L \geq 0 \end{cases}$$

where $C_{k+i+1}$ represents the $i$th mean value of the constituent concentration ($i=$ Chl, CDOM, TSS) related to the $k+i$th MODIS image; $FVI_k$ is the FVI related to the $k$th MODIS image; $\bar{C}$ and $\bar{FVI}$ are the mean values over the time series of the constituent concentrations and of the FVI, respectively.

The $P_{c<FVI}(L)$ values range in the $-1, 1$ interval and indicate the correlation level between the $i$th constituent concentration and the FVI.

The absissa value corresponding to the maximum represents the lag of the reaction, i.e. the time interval occurring between the increase of the precursor and the FVI response. Negative lag indicates that the variation of the constituent concentrations precedes the floating vegetation variation.

The high number of MODIS images to be analyzed (see Table 1) involves practical issues to data management and processing. To this end an IDL procedure for the automatic processing of MODIS data has been developed. The processing procedure (see Fig. 3) involves: a water mask for defining the area of interest (Winam Gulf), an automatic method to remove images that are incomplete (if lacking more than 10% of the area of interest), saturated (more than 1% of the image) and cloudy (more than 10% of the area of interest). At the end of this procedure, the starting dataset decreased from the original 3948 multispectral images to only 1370, corresponding to about 2.66 images for week.

Finally, the NVI-based method was applied for separating floating vegetation from sparse-submerged vegetation and water with subsequent evaluation of FVI. A careful comparison between a Landsat image (acquired on 11 June 2009) and a MODIS image acquired on the same day (see Fig. 4) allowed us to define a suitable threshold NDVI value greater than 0.4 and discriminate in the best way possible the floating vegetation.

4. Results and discussion

The analysis based on MODIS imagery dataset make it possible to highlight the trend of the floating vegetation growth (see Fig. 5) within the Winam Gulf, in the time range from March 2000 to January 2010.

By analysing the graph shown in Fig. 5, we can see that before October 2006, the growth rate remains relatively weak, with a cycle in accordance with the local climatic conditions; in fact, the growth cycle of the floating vegetation is correlated to the two rainy seasons (long and short rainy season, March–May and November, respectively) characterizing this area.

In particular, during the years 2002–2004 the phenomenon of the weeds proliferation seems almost absent. However, during 2005 and 2006 the phenomenon shows some signs of resurgence. After October 2006, the proliferation of the floating vegetation exhibits an abnormal growth rate. Indeed, during the abnormal growth cycle, it is possible to detect when the weeds proliferation...
becomes very sudden. The floating vegetation maps based on NDVI values provide an accurate temporal vision of the weeds evolution with a time resolution of at least half-week. The time sequence of this maps, shown in Fig. 6, highlights the rapid growth of the floating weeds occurred from March to April 2007, when the weed surface increased from about 40 km² to over 400 km² (about 33% of the Winam Gulf surface). This event can also be expressed as FVI values, in this case equivalent to 0.33. It is also interesting to note that this rapid growth is preceded (2–3 weeks) by an increase of sparse/submerged vegetation. This event reaches its peak, in terms

Table 2
Monthly rainfall (mm) at the meteorological station of Kisumu city (courtesy of the Kenya Meteorological Department).

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<tbody>
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<td>January</td>
<td>65.3</td>
<td>317.2</td>
<td>128.0</td>
<td>54.9</td>
<td>158.8</td>
<td>92.0</td>
<td>82.6</td>
<td>100.6</td>
<td>27.9</td>
<td>114.2</td>
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<td>82.6</td>
<td>100.6</td>
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<td>114.2</td>
<td>114.2</td>
<td>79</td>
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<tr>
<td>March</td>
<td>105.5</td>
<td>116.7</td>
<td>253.3</td>
<td>170.4</td>
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<td>113.2</td>
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<td>143.5</td>
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<td>–</td>
<td>70.8</td>
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<tr>
<td>August</td>
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<td>113.5</td>
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<td>117.5</td>
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<td>149.7</td>
<td>–</td>
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<td>115.8</td>
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<td>203.1</td>
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<td>121.6</td>
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<td>143.4</td>
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<td>62.2</td>
<td>133.8</td>
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<td>284.0</td>
<td>59.1</td>
<td>37.7</td>
<td>–</td>
<td>111.9</td>
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Fig. 5. Temporal comparison between the floating vegetation evolution, water constituents, rainfall, lake height variations and temperatures, for the decade 2000–2009.
of surface extent, in April 2007 and ends around January–February 2008 (see Fig. 5).

This abnormal proliferation may be related to the unusual heavy rainfall that occurred in Kenya at the end of the 2006, swelling the rivers that flow into the Winam Gulf. As a matter of fact, in the time range 2000–2009, the Kisumu meteorological station recorded that during November and December 2006 the rainfall was 346 and 284 mm, respectively. The first value is the highest value of this decade and both values were 2.5 times larger than the ten-year average (see Table 2). However, this meteorological trend does not continue in 2007, according to the meteorological data recorded at the Kisumu station, even if the rainfall pattern is very different from the averaged behaviour of the last ten years. Unfortunately, the rainfall data from other stations (Eldoret, Kakamega, Kericho, etc.) inside the Kenyan portion of the Lake Victoria basin were not available; therefore it was not possible to assess the effective rain amount in the areas surrounding the Winam Gulf.

The rains and floods swept agricultural runoff and nutrient-rich sediment into the lake. The influx of fertilizer and sediments could have stimulated a new outbreak of the floating vegetation and, in particular, of the water hyacinth. Though other water plants may be contributing, water hyacinth is certainly the principal (or most abundant) macrophyte of the weeds mass.

The hypothesis that the abnormal proliferation of the weed is linked to the heavy rainfall and to the massive presence of the nutrients and sediments that flowed into the water body appears to be confirmed by the behaviour of water constituents retrieved by the model described in Section 3.2.

In fact, one month after the unusual rainfall of the November/December 2006, a large increase of the Chl (see Fig. 4), which precedes by about 7 weeks the weed proliferation, can be observed. As regards the statistical analysis, although we are concerning with very turbid Case 2 waters, the results show high temporal correlation between the different constituent concentrations with correlation indexes generally over 0.8. This high correlation is partially due to the limited number of MODIS bands used in the model that appear to be unable to completely discriminate between the three constituents.

Anyhow, we are looking for a precursor of the abnormal weeds proliferation. In this concern, the results of the physics based model application have to be considered as a qualitative indicator of the water constituent abundances. Nevertheless, they appear to be compatible with the values reported in Cavalli et al. (2009) and congruent with respect to the meteorological trend (Figs. 5–7).

By analyzing Fig. 7, it seems that the increase of the constituents concentration precedes the weeds bloom that occurred in the 2007. This analysis confirms the results, providing a consistent correlation in particular between FVI and TSS. According to Fig. 7d, the increase of the constituent concentrations precedes the FVI growth trend by about 7 weeks.

Also the lake level fluctuations could have played a role in the weed proliferation. In fact, in the early months of 2006 the water levels (see Fig. 5) monitored by satellite radar altimeters (USDA/NASA, 2006) reached the lowest level since September 1961 (Reynolds, 2005) of about 1.2 m lower than mean level of the last twenty years. This could have brought about an environmental stress on the lake ecosystem, thus creating the favourable preconditions for the occurrence of the phenomenon.

With respect to the air temperature, the trend shows no anomalies that can suggest any effects on growth rate of the weed.

After this abnormal event the growth rate of the floating vegetation decreases to the levels before 2007 until December 2009. The large amount of images (1370) used for this study provided an excellent statistic sample to assess the areas within the Winam Gulf more affected by the weed occurrence. This kind of hazard analysis of the phenomenon, is based on how many times the weeds were found, in other words how many times the pixels were classified as floating vegetation.

The map depicted in Fig. 8 shows the areas with the highest frequency of weeds. They are mainly the bays, gulfs and areas near the coastline, where water circulation is reduced. The cause could be related to the local environmental conditions, shallow and stagnant waters, that promote the increase of the nutrients and at

The integrated use of the available data (satellite, rainfall, lake height variations, etc.) allowed to better understand some mechanisms that could have caused the abnormal proliferation of the floating vegetation: in the last few months of 2006, an unusual heavy rainy season removed large amounts of nutrient-rich sediments from agricultural lands into the lake ecosystem already under stress after a long water-deficit period, by creating the favourable environmental conditions, such as the increase of the water constituents (Chl, CDOM and TSS), for the occurrence of the weed infestation.

Our analysis highlighted, with a good temporal precision, when the weeds began to proliferate quickly and the spatial and temporal extent of the event. In particular, a very abnormal proliferation began after October 2006, reached its maximum extension in April 2007 and ended in January 2008.

The hypothesis that the abnormal proliferation of the weed is linked to the heavy rainfall and to the massive presence of the nutrients and sediments that flowed into the water body appears to be confirmed by the behaviour of water constituents retrieved by the model that provide consistent correlation in particular between FVI and TSS. The results of the correlation analysis showed, in fact, that the water constituents can be considered a good predictor of the abnormal macrophytes bloom as well as they precede by about 7 weeks the weed proliferation.

Furthermore, the high number of MODIS images allowed us to identify the area most affected by the occurrences of floating vegetation. The highest frequency areas are the bays, gulfs and generally the areas near the coastline.

The future works will continue the acquisition and analysis of MODIS data for the years 2010 and 2011 in order to further validate this challenging method and be confident of the attained results.

In order to develop an up-to-date decision support system, a multi-sensor approach is required, that is, MODIS data should be opportunely supported by the more precise information provided by traditional data sets.

5. Conclusions

This study showed the potentiality offered by the MODIS imagery time series in providing information useful for supporting a water management decision system.

The method adopted here made it possible to monitor the growth trend of the floating vegetation within the Winam Gulf from 2000 to 2009, with a frequency of at least half week. In particular, we focussed our analysis in the time range 2006–2007.
by other satellite sensors (i.e., Landsat, ASTER, CHRIS, etc.) and in particular the synergetic use of the optical and SAR data (COSMO-Sky-Med).

The information provided by satellite can play an important role in supporting a decision system for the management of the water resources allowing also an easy and inexpensive way of monitoring the environment response to any action that might be undertaken to contrast its degradation.

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References


