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Dynamic estimation of water hyacinth area using fusion of satellite and GPS sensors

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Abstract. The interaction of water hyacinth area with growth is known to be strongly influenced by area size, but little is known about the interdependent role that size and time have on dynamic estimation of water hyacinth area. We report on the fusion of satellite and GPS sensor data into area growth model as a function of area and time. We employ a multi-sensor fusion technique that is able to generate uniform data of fitting area growth model with complete control of area and time. Evidence of an overall Goodness of Fit Index of 0.9753 was obtained by using conventional statistic analysis. These findings suggest that the multi-sensor fusion technique readily supports area growth model development with highly resolution. The differential equation is good at describing the spatial spread of water hyacinth. Moreover, it was found that area growth model enjoy an appreciable advantage when it comes to harvesting water hyacinth.

1 Introduction

Dynamic estimation of water hyacinth area (DEWHA) in environmental phytoremediation has received much attention in recent years due to water hyacinth low cost and flexibility, which offer important ecological and economic benefits [1]. DEWH involves the use of water hyacinth for removing pollutants from environment [2]. In DEWH, the estimation of water hyacinth area is the key factor that affects the quality of phytoremediation [3]. However, it has been found to be too weak in modeling water hyacinth area to be used commercially [4].

One way to estimate water hyacinth area is to incorporate a logistic model and there has been extensive research regarding water hyacinth growth with logistic biomass model [5]. For example, Mahujchariyawong et al. showed that the estimation of water hyacinth biomass could be implemented using a logistic biomass model [6] and more recently, Reisinger et al. established the application of such model [7]. However, although the effect of the logistic biomass model was demonstrated over several years, little attention has been paid to the research on DEWHA with satellite and GPS sensors.

The present paper presents a logistic model of DEWHA using satellite and GPS sensors, which provides an efficient way to estimate water hyacinth area in eutrophic river in order to attain DEWHA. By this model, we can remove an amount of nutrient from the river and simultaneously remove the water hyacinth to use in beneficial ways.

2 Material and methods

The water pollution of Taihu Lake is characterized by the severity of eutrophication and high frequency of algae bloom. Zhushanhu is one of the most seriously polluted areas of Taihu Lake. Thus,



this study was undertaken in Zhushanhu, Taihu Lake, China, from August-October 2009. The site's coordinates area are 31°27' Latitude N and 120°04' Longitude E. Water hyacinth covered an initial area of 54250 square meters.

The GPS sensor consists of a Mobile Mapper, which is a differential global positioning system (DGPS) made by Magellan Navigation Inc. It uses a combination of an Ashtech MobileMapper Pro as a roving receiver and an Ashtech Promark 500 for the reference station. The DGPS enables the recording of points, lines and areas with sub-meter accuracy.

Table 1: Characteristics of Alos satellite sensor

Number of Bands	4
Wavelength	Band 1: 0.42 to 0.50 micrometers Band 2: 0.52 to 0.60 micrometers Band 3: 0.61 to 0.69 micrometers Band 4: 0.76 to 0.89 micrometers
Spatial Resolution	10 m (at Nadir)
Swath Width	70km (at Nadir)
S/N	>200
MTF	Band 1 through 3 : >0.25 Band 4 : >0.20
Number of Detectors	7000/band
Pointing Angle	-44 to +44 degree
Bit Length	8 bits

(<http://www.eorc.jaxa.jp/ALOS/en/about/avnir2.htm>)

Remote sensing for identification of water hyacinth has many advantages when compared to GPS survey methods. For example, it is able to record data and information widely and repeated, can use multi-temporal for detecting changes in community structure of water hyacinth, can reach difficult areas visited by GPS, and may be relatively less expensive to obtain the area data of water hyacinth. The satellite sensor used here consists of an ALOS Satellite with sensor AVNIR-2. To give you a better notion of the wide applicability of AVNIR-2, we list some characteristics of AVNIR-2 in Table 1. Note the diversity of the number of bands and the wavelength in the first two rows. The third row identifies the spatial resolution. The last six rows indicate the swath width, S/N, MTF, number of detectors, pointing angle and bit length, respectively. This sensor has 3 visible spectrums i.e. band1 (blue), band2 (green) and band3 (red). They have the ability to differentiate water hyacinth. The sensor is a visible and near-infrared radiometer for observing land and water zones and provides better spatial resolution. It will be useful for monitoring aquatic resources and water quality.

Taihu Lake environments are characterized by erratic climate conditions, challenging the applicability and robustness of remote sensing technologies. The high humidity in Taihu Lake areas makes difficult to obtain cloud-free images. Thus, cloud was a particular problem over the water hyacinth. It was especially heavy during August 2009 to October 2009. Further, the limitation of the study is the non-availability of enough multi-spectral remote sensing images during August 2009 to October 2009 because of cloud cover. An area of water hyacinth at a key growing stage would have been advantageous for identifying the area growth model of water hyacinth. But then higher humidity, or actual clouds, would certainly have resulted in poorer image quality.

Three nearly cloud-free ALOS images that covered the study area were acquired only. The coverage dates of these images were 17 August, 3 September and 2 October 2009. In other words, the three-date cloud-free ALOS images were used to generate the water hyacinth maps. The procedure includes creating a geo-referenced, registered multi-date image. That is, after each ALOS image was examined for sensor errors, the digital numbers were converted to reflectance and rescaled to values between 0 and 100. The reflectance values were then adjusted for atmospheric scatter using the Improved Dark Object Subtraction technique. The images were corrected for geometric error by first transforming the September image to a Universal Transverse Mercator (UTM) projection. The geometric transformation equation was computed using 18 ground control points. The August and

October images were then georegistered to the ground-rectified September image. The spectral values for each pixel were interpolated using a nearest neighbour resampling approach and the data were output to a 10×10m pixel size. Supervised classification was carried out to generate the water hyacinth maps. The temporal area of the three dates was created to analyze the growth pattern of water hyacinth in this period. Otherwise, GPS guided field surveys were also conducted to acquire lake truth for classification scheme design and accuracy assessment.

The water hyacinth mapping has presented numerous challenges to the field of remote sensing. Given the regular occurrence of thunderstorms in summer months, cloud free days are rarely found during the growing season of water hyacinth. GPS, however, holds a lot of potential for monitoring water hyacinth communities of water bodies as it has the ability to penetrate cloud cover. GPS can therefore provide valuable insight into temporal changes in the area of water hyacinth by enabling water hyacinth cover monitoring at all times of the year. Thus, four-date GPS data acquired during August 2009 to October 2009 were used to derive the area of water hyacinth, as cloud-free data from optical sensors is rarely available during this period. In such cloud-covered study area, GPS is a prime source of area information about the water hyacinth. Such information is essential to developing the area growth model of water hyacinth in such ecologically sensitive areas. The all weather capability is one major advantage of GPS with respect to optical systems. Furthermore, GPS provides information that is complementary to that of visible to infrared imagery. The benefit of combining optical and GPS data for improved land cover mapping was demonstrated in several studies. In general, the data fusion process can be performed on the area measurement level.

Data fusion has been extensively used in remote sensing studies related to vegetation studies. There are a number of potential benefits resulting from the fusion, one of these might be the improvement in acquiring a satellite-based high spatial resolution temporal sequence. The fusion method adopted in this study proved to be more suitable for the water hyacinth mapping. Data fusion from two different sensors can improve water hyacinth mapping and analysis. Three-date ALOS and four-date GPS data were analyzed to derive the water hyacinth maps. They were used to compute acreage of water hyacinth crops. The satellite and GPS sensors were fused in DEWHA, shown in Table 2. The first column summarizes two methods for measuring area of water hyacinth. The second column then introduces the fusion date. The last column indicates the number of growth days of water hyacinth on the date.

Table 2: Sensor fusion for measuring area of water hyacinth

Method for measuring area	Date	Growth days
Sub-meter accuracy GPS sensor	2009-08-04	0
Alos satellite sensor	2009-08-17	13
Alos satellite sensor	2009-09-03	30
Sub-meter accuracy GPS sensor	2009-09-18	45
Sub-meter accuracy GPS sensor	2009-09-28	55
Alos satellite sensor	2009-10-02	59
Sub-meter accuracy GPS sensor	2009-10-15	72

In situations where the area growth rate of water hyacinth population is determined primarily by the population's reproductive rate, exponential model may be adequate tools for forecasting the likelihood of population establishment, the probability of local population extinction and population density. In the following an exponential model is based on a mathematical formulation of logical rules and equations and can describe a water hyacinth system in a simplified form using input data and parameter values. The exponential model that is defined in this way is considered as deterministic model. The model assumes that the area growth is a function of the total population area and there is the maximum equilibrium population area at which the average change in population area is zero. The exponential model assumes also an exponential rate of area growth of water hyacinth population and is mostly represented by the differential equation. That is, the area growth of water hyacinth was analyzed by using a differential equation as followed.

$$\frac{dS(t)}{dt} = r_s S(t) \left(1 - \frac{S(t)}{K_s}\right) \quad (1)$$

where t is a given time in day, $S(t)$ is area of water hyacinth at time t , r_s is area growth rates of water hyacinth in day, and K_s is area capacity of water hyacinth.

The stable solution of the differential equation was obtained by algebra and integral method as followed.

$$S(t) = \frac{K_s}{1 + \left(\frac{K_s}{S(0)} - 1\right)e^{-r_s t}} \quad (2)$$

where:

$$S(0) = \text{area of water hyacinth at time } t = 0, \quad (3)$$

$$K_s = \max\{K_{si} \mid i = 1, 2, \dots, n\}, \quad (4)$$

$$K_{si} = \frac{1 - e^{-r_{si} \times (t_i - t_j)}}{\frac{1}{S(t_i)} - \frac{1}{S(t_j)}} \times e^{-r_{si} \times (t_i - t_j)}, \quad (5)$$

$$r_{si} = \frac{S(t_i) - S(t_j)}{(t_i - t_j) \times S(t_j)}. \quad (6)$$

Table 3: Measuring area of water hyacinth

Item	Year-Month-Date	Observed value(m^2)
0	2009-08-04	54250.34
1	2009-08-17	68780.34
2	2009-09-03	78288.71
3	2009-09-18	95624.84
4	2009-09-28	103446.63
5	2009-10-02	112173.77
6	2009-10-15	135525.66

The areas of water hyacinth in different growth stages were measured by using the satellite and GPS sensors, shown in Table 3. The second column identifies the seven measure dates. Despite the advancements in remote sensing, the area analysts of water hyacinth preferred less automated tools, and concentrated on visual interpretation and manual digitization to outline the maps of water hyacinth on the supervised images. These maps were used to measure the areas of water hyacinth on 17 August, 3 September and 2 October 2009. Similarly, the GPS was used also to generate the maps of water hyacinth. These maps were used then to measure the areas of water hyacinth on 4 August, 18 September, 28 September and 15 October 2009. The last column indicates that these measurements resulted in the areas of water hyacinth. The seven measured areas are $S(0) = 54250.34$, $S(13) = 68780.34$, $S(30) = 78288.71$, $S(45) = 95624.84$, $S(55) = 103446.63$, $S(59) = 112173.77$ and $S(72) = 135525.66$, respectively. These area data were then fitted to the differential equation.

Table 4: Area growth rates and area capacities of water hyacinth

Growth days	Area growth rates	Area capacities
0		
13	0.0206	537575.31
30	0.0081	1159331.20
45	0.0148	896738.10
55	0.0082	2564316.39
59	0.0211	2697210.03
72	0.0160	1348793.42

3 Results

The area growth rates and area capacities of water hyacinth (WH) in different growth stages were interpreted by using the areas from Table 3, shown in Table 4. The first column identifies the number of growth days of water hyacinth on the measure date. The second column then introduces the area growth rate or of water hyacinth. The six area growth rates of water hyacinth in day are followed.

$$\begin{aligned} r_{s1} &= \frac{S(t_1) - S(t_0)}{(t_1 - t_0) \times S(t_0)} = \frac{S(13) - S(0)}{(13 - 0) \times S(0)} = 0.0206, \\ r_{s2} &= \frac{S(t_2) - S(t_1)}{(t_2 - t_1) \times S(t_1)} = \frac{S(30) - S(13)}{(30 - 13) \times S(13)} = 0.0081, \\ r_{s3} &= \frac{S(t_3) - S(t_2)}{(t_3 - t_2) \times S(t_2)} = \frac{S(45) - S(30)}{(45 - 30) \times S(30)} = 0.0148, \\ r_{s4} &= \frac{S(t_4) - S(t_3)}{(t_4 - t_3) \times S(t_3)} = \frac{S(55) - S(45)}{(55 - 45) \times S(45)} = 0.0082, \\ r_{s5} &= \frac{S(t_5) - S(t_4)}{(t_5 - t_4) \times S(t_4)} = \frac{S(59) - S(55)}{(59 - 55) \times S(55)} = 0.0211, \\ r_{s6} &= \frac{S(t_6) - S(t_5)}{(t_6 - t_5) \times S(t_5)} = \frac{S(72) - S(59)}{(72 - 59) \times S(59)} = 0.0160. \end{aligned}$$

$r_{s1}=0.0206$, $r_{s2}=0.0081$, $r_{s3}=0.0148$, $r_{s4}=0.0082$, $r_{s5}=0.0211$ and $r_{s6}=0.0160$, respectively. The growth rate is also called below the intrinsic rate of growth. It depends on nutrient level and water temperature of water hyacinth. The water temperature and nutrient concentration were readily included in the differential equation through simple relations to the intrinsic rate of growth. Based on these relations, the differential equation accurately describes the results of this study. That is, the differential equation is good at describing the spatial spread of water hyacinth invasions. The last column indicates that these measurements typically resulted in the area capacities of water hyacinth on the measure dates. The six calculated area capacities of water hyacinth are $K_{s1}(13)= 537575.31$, $K_{s2}(30)= 1159331.20$, $K_{s3}(45)= 896738.10$, $K_{s4}(55)=2564316.39$, $K_{s5}(59)= 2697210.03$ and $K_{s6}(72) = 1348793.42$, respectively. The area capacity of water hyacinth is followed.

$$\begin{aligned} K_s &= \max\{K_{si} \mid i = 1, 2, \dots, 6\} \\ &= \max\{K_{s1}(13), K_{s2}(30), K_{s3}(45), K_{s4}(55), K_{s5}(59), K_{s6}(72)\} \\ &= K_{s5}(59) \\ &= 2697210.03 \end{aligned}$$

After the data in Tables 3 and 4 were fitted with the SPSS software program, the area growth model of water hyacinth in general form was solved as followed.

$$S(t) = \frac{2697210.0317}{1 + 47.5041e^{-0.0124t}} \quad (7)$$

The differential equation has two parameters, the area growth rate and the area capacity of water hyacinth. It may be expected that if a factor affects the area growth rate then it will affect the area capacity. However, we have been unable to derive general rules to predict the area capacity. Thus temperature and nutrients, although they do not directly affect the area capacity in the differential equation, will be expected to have a significant effect on the area of water hyacinth. The result of area growth model is consistent with the data in Table 3.

The plot of the area of water hyacinth against the growth days is given in Figure 1. The model fits the data with an overall Goodness of Fit Index of 0.9753.

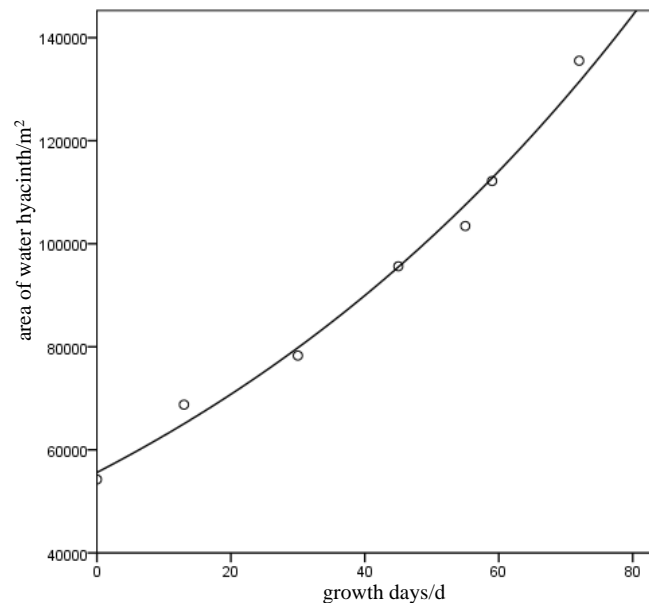


Figure 1: Comparison of the measured area with the estimated area for the water hyacinth

4 Conclusion

We have developed a common theoretical framework for dynamic estimation of water hyacinth area and showed that many existing biomass schemes can be not considered as the dynamic estimation where all satellite and GPS sensors are used jointly to make the dynamic estimation of water hyacinth area. We have demonstrated that under different assumptions and using different sensors we can derive a logistic area growth model for the dynamic estimation of water hyacinth area. A surprising outcome of the study was that such a model can give results which are in agreement with the observed experimental data from satellite and GPS sensors. Further researching work will have to be done to solve the problems such as optimal decision of harvest strategy and management of water hyacinth in environmental phytoremediation.

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