Coastal Suspended Sediment Concentration Estimation using THEOS Satellite Imagery on the Chao Phraya River Mouth, Thailand

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Abstract
Water quality monitoring is important to environmental control and ecosystem studies, which are not only scientifically relevant but also legally binding in several countries (e.g. the Water Framework Directive and the European Marine Strategy Framework Directive). Suspended sediment concentration (SSC) is one of the main parameters for water monitoring and can be roughly detected from satellite. In the present study, the Chao Phraya River mouth was used as a case study to assess measurement of levels SSC using spectral indices and THEOS satellite imagery. The THEOS satellite image of the Chao Phraya River mouth was taken on the same day with sea surface leaving radiance measured by spectrometer and water sampling for SSC determination. Sea surface radiance was converted to reflectance values to determine the relationship with SSC by applying to fourteen spectral indices from previous studies. The ratio ofRrs798 and Rrs532 was the spectral index with the best correlation to the observed SSC (R^2 = 0.7598).THEOS satellite image was used in the estimation of SSC by applying the best spectrometer index to the satellite data. The ratio of Band4/Band2fromTHEOSbands provided the best estimation for this SSC parameter by R^2 =0.6189.

1. Introduction

The Chao Phraya River is the largest river located in the northern and central part of Thailand. It accounts for about half of the river flow to the Gulf of Thailand (Cheevaporn and Menasveta, 2003). The river and estuary is the main sea artery to Bangkok. Its water flow is influenced by domestic and industrial activities before it discharges into the Gulf of Thailand. Agricultural and maricultural activities in the basin also affect the estuary by contributing to the load of suspended sediment (SS) (Doydee et al., 2010). Each year, a significant amount of SS is released into the Inner Gulf of Thailand, most of which comes from rivers which discharge into the sea in the delta area and near the shore. There are 6 main rivers that flow into the Inner Gulf; the Chao Phraya, Maeklong, Thachin, Phetchaburi, Pranburi and Bangpakong Rivers. During the rainy season, each river lets off water with a large amount of suspended sediment (Buranapratheprat et al., 2009). Deposited sediments alter the estuary and coastal properties (OurLake, 2009), especially in the Chao Phraya river mouth due to high suspended sediment concentration (SSC) (Cheevaporn and Menasveta, 2003). The sediment might also be available for resuspension and subsequent transport during periods of increased stream discharge (OurLake, 2009). Moreover, SSC is also important for both ecological and water quality reasons (Zhang et al., 2010b). High SSC degrades optical water quality by reducing water clarity and decreases light available to support photosynthesis. In previous studies, SSC was correlated to water surface reflectance (Pierson and Strombeck, 2001). Many studies carried out around the world have used remote sensing techniques and have focused on parameters such as turbidity and suspended solids or sediments, for example; the Columbia River estuary (Fain et al., 2001), the Winyah Bay (Patchineelam and Kjerfve, 2004), USA; the Elbe Estuary (Kappenberg et al., 1996), the Weser Estuary (Grabemann and Krause, 2001), Germany; the Scheldt Estuary (Fettweis et al., 1998), Belgium; the Sado Estuary (Vale et al., 1993), the Tagus Estuary (Vale and Sundby, 1987), Portugal; the Tamar Estuary (Tattersall et al., 2003), the Tay Estuary (McManus, 2005), UK; the Yangtze (Changjiang) Estuary (Chen et al., 2006; Shi and Kirby, 2003; Shi and Zhou, 2004), the Hangzhou Bay (Chen, 2001; Huang and Huhe, 2009) and the Bohai Bay (Zhang et al., 2009), China (Zuo et al., 2012). In this study, the existing spectral indices from previous studies have been verified by the field data from Chao Phraya River mouth area and the suitable indices will be applied with satellite imagery technique for estimated SCC. Thailand Earth Observation System (THEOS) satellite, Thailand's first Earth observation satellite, acquired images for this study. THEOS was established in June 2004 by Geo-Informatics and Space Technology Development Agency (Public Organization) namely, GISTDA of Bangkok, Thailand in cooperation with the Ministry of Science and Technology, Thailand and European Aeronautic Defence and Space company, EADS Astrium, in France. The Ministry of Science and Technology, Thailand has been operating agency and EADS Astrium has been primary contractor. This program has involved the design, development, testing, launch, and control of the THEOS satellite and the ground facilities for data exploitation (Kaewmanee et al., 2006). THEOS satellite imagery can be applied to agriculture, land use, forestry, cartography, water resources, environmental monitoring, coastal zone and natural disaster management (Singhasneh and Charoenrath, 2009). THEOS has four multispectral sensors of visible to near infrared wavelength range with a spatial resolution of 15 m (GISTDA, 2009 and Kaewmanee et al, 2006). It is suitable to investigate the study location, into which the Chao Phraya River mouth releases a lot of sediment. Moreover, THEOS has an orbital "revisit period" of 26 days (GISTDA, 2009), so that there is the possibility to acquire datasets from THEOS every month, facilitating a more effective analysis of coastal suspended sediment change in the Inner Gulf of Thailand. In this study, the suitable spectral indices have been applied to THEOS satellite imagery. The data from satellite imagery can significantly increase the body of information available on the suspended sediment, which has already been under inspection. The suitable spectral indices can also be applied to any satellites that have spectral band ranges that correlate to index spectral reflectance parameters. The parameters can be measured using satellite data and present the concentration by visual mapping of wide areas. This study aimed to investigate the suitable indices for SSC estimation for Chao Phraya River mouth and applied to the satellite technique by using THEOS imagery application. It is also possible that the results of the study could be used for SSC estimation in other areas of the Inner Gulf of Thailand or can be an area based dataset for the further studies.

2. Material and Methods

2.1 Location of the Study

Water Sampling was conducted in the Chao Phraya River mouth, Samuthprakarn province Thailand. The sampling time was June 10th, 2012, because the Southwest monsoon started from May to September make it high SSC from the Chao Phraya watershed, which is the largest watershed, covers approximately 35% of the nation's land, and drainage area of 157,924 square kilometers. The watershed of Chaophraya and tributaries is divided into the basin and discharges high SSC fresh water into the inner gulf of Thailand at the Chaophraya River mouthas shown in the figure 1(Buranapratheprat et al., 2002).

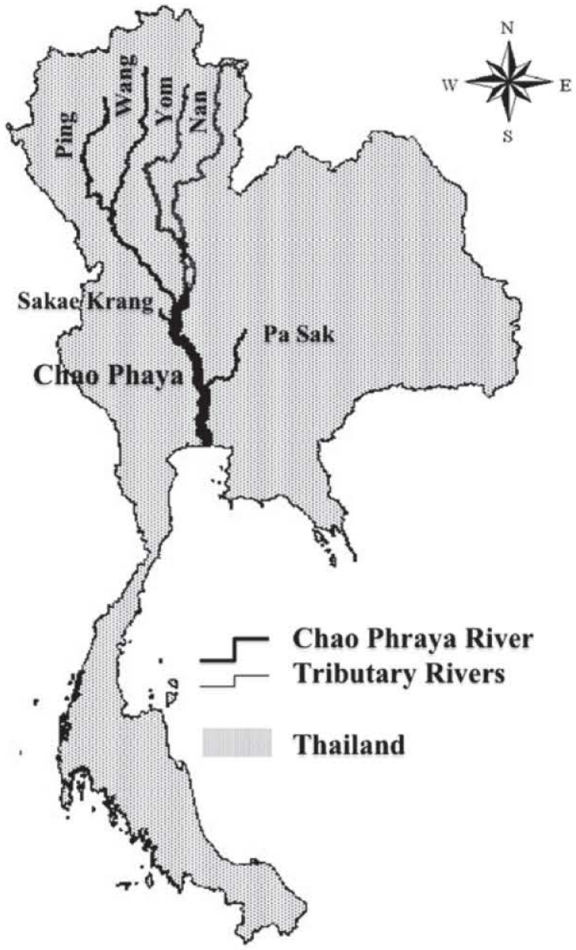

Figure 1: Map of the Chao Phraya drainage basin

2.2 Water Sampling and Analysis

The ground truth sampling was scheduled according to the satellite or bit over the sampling sites in order to get an image at the time the samples were collected. The Kemmerer, a vertical transparent cylinder made of plexi glass using for water sampling in specific desired depth, was used to collect water samples in this study. The water sampling was conducted within the same day that the THEOS satellite orbit passed over the sampling site. The sampling time was limited from 8 a.m. to 1 p.m. to cover the satellite visiting time, at about 10.30 a.m. Samples were collected at mid-level light transparency levels using the Secchi disk. In all, thirty-four samples were collected within the sampling time limit. The stations were about 200 meters apart, within 10 kilometers from river mouth. The distance between the sampling stations was maintained by measuring coordinates using GPS receiver, Garmin 76 CSx, and the display of the coordinates on the estuary map via ArcView 3 software on board the boat at the sampling site. Sampling and preservative methods in this study followed Standard Methods, Section 2540 A(Eaton et al., 2005).The water samples were contained in 1000 ml. plastic bottles and refrigerated in an ice bucket, at about 4°C to minimize microbiological decomposition of solids. The samples were analysed in the same day as the water sampling at the Mahidol University Laboratory following Standard Methods, Section 2540 D. (Eaton et al., 2005)

2.3Radiance Measurement

The sea surface leaving radiance had been measured on site using a Field Spec Handheld, ASD Inc., following the Mahasandana methodology. (Mahasandana et al., 2009)The wavelength rage of the spectrometer was 325 to 1075 nm which covered the rage of visible wavelength (Blue 400 to 500 nm, Green 530 to 580 nm and Red 620 to 680 nm). The measurements were at the same stations where water were collected, with angle of 90 degree between spectrometer probe and sea surface and the probe was about 10 centimeters above sea surface. Meanwhile, leaving radiance from a whiteboard was also collected to represent as a 100% of radiance for native water. The percentage of reflectance was calculated using the following formula:

$$F = \frac{N\ x\ 100}{W}$$

Equation 1

Where F is the reflectance (%), N is the radiance for the native water, W is the radiance from the whiteboard.

2.4 Existing Spectral Indices

Fourteen spectral indices of spectral reflectance, i.e. the ratio of reflected energy to incident, from previous studies, 1998 to 2012, are shown in the table 1. The remote sensing reflectance spectra (Rrs) is the spectral reflectance of specific wavelength. The number after Rrs indicates the wavelength number which provided specific reflectance value. The reflectance from the study area was added into the existing spectral indices to investigate the correlation with the observed SSC.

Table 1: Existing spectral indices from previous studies

Author	Year	Spectral Index	Satellite/Sensor
Avinash et al.	2012	(Rrs555+Rrs670)x(Rrs490/Rrs555)	Hyper spectral airborne
Mantas et al.	2011	Rrs496/Rrs555	LANDSAT7 ETM+ and MODIS
Xi and Zhang	2010	Rrs629 / Rrs671	MERIS
Chen et al.	2010	(Rrs555+Rrs670+(Rrs670/Rrs555)	MERIS
Zhang et al.	2010a	(Rrs555+Rrs645)+(Rrs488/Rrs555)	MODIS
Fang et al.	2009	Rrs680 / Rrs520	EO-1
Lui et al.	2009	Rrs620 / Rrs520	MODIS
Hu et al	2004	Rrs645 - Rrs859	MODIS
Doxaran et al.	2003	Rrs865 / Rrs555	Hyper Spectral Airborne
Turdukulov	2003	Rrs810 / Rrs536	HyperSpectral Airborne
Turdukulov	2003	Rrs798 / Rrs532	
Turdukulov	2003	Rrs798 / Rrs532	
Doxaran et al.	2002	Rrs850 / Rrs550	Spot, LANDSAT and IRS
Althuis	1998	Rrs630 - Rrs750	MODIS

2.5 Satellite Imagery

THEOS has four multi-spectral bands with fifteen meters spatial resolution, the visible bands are Band1 (blue; 420nm – 550nm), Band2 (green; 530nm – 620nm) and Band3 (red; 620nm – 690nm), including Band4 which is a near-infrared band (770nm – 900nm)(GISTDA, 2009). The THEOS image was acquired on 10th June 2012. The THEOS data was processed using Envi® 4.7 software. The Level2A images were converted to Top of Atmosphere (TOA) reflectance. The process was initiated with the conversion of the digital numbers to radiance and conversion of radiance to reflectance respectively, and calculated using the equations equation 2 – equation 4. (Chander and Markham, 2003):

Radiance calculation:

$$L_{\lambda} = (L_{Max\,\lambda} - L_{Min\,\lambda})/255\text{DN} + L_{Min\,\lambda}$$

Equation 2

Where L_{λ} is the spectral radiance at the censor aperture (W/ (m²·sr·µm)), $L_{Max\,\lambda}$ is the radiance corresponding to 255DN (W/ (m²·sr·µm)), $L_{Min\,\lambda}$ is the radiance corresponding to 0DN

Reflectance Calculation

$$\rho_{\lambda} = \pi L \lambda\, \text{d}2/(E \lambda \cos \theta)$$

Equation 3

Where ρ_{λ} is the unit less planetary reflectance, E_{λ} is the mean solar exoatmosphereic, θ is the solar zenith angle in the degrees, and *d* is the Earth-Sun distance in astronomical units as calculated from the following equation (Chander and Markham, 2003).

$$d = 1 + 0.033 \cos \theta \frac{2\pi\ (\text{DOY})}{365}$$

Equation 4

Where DOY is the day of the year. After all conversion, satellite DN was converted to reflectance datasets.

3. Results and Discussion

3.1 SSC and Spectral Reflectance of Water Samples

The optical water condition in the area of sampling stations showed color of water was brown on the sampling day. Water light transparency depth was measured, the greatest visible depth was found only to 30cm. It indicated to high SSC and turbidity. The samples were determined for SSC in laboratory, the results of SSC from 34 stations varied from 33 mg/l to 117 mg/l, the average was 74.45 mg/l. ArcView 3 software plotted the water sampling stations, as shown in Figure 2. A high concentration of suspended sediment was found at the sampling stations close to the river mouth and near shore. The concentrations decreased as the distance into the sea increased, due to sea water dilution and deposition of suspended sediment. Meanwhile, water surface leaving radiance was measured and converted to be percentage of wavelength reflectance. Figure 3 shows spectral reflectance of the thirty-four sampling stations calculated from leaving radiance. The reflectance peak was found around 580 nm which was in the range of visible wavelength and decreased gradually from 600 nm to 700 nm which was in the range of visible wavelength (Red) but the percentage of reflectance was still high. The curves decreased sharply after 700 nm. The percentages of reflectance from all stations were different but the patterns of reflectance curves were relatively similar.

3.2 The Relationship between SSC and Spectral Indices

Fourteen indices from previous studies were applied to the Chao Phraya River mouth reflectance data. The indices values investigated the correlation with SSC. They were plotted using different types of correlation, such as linear, logarithmic, exponential and power. .The best correlation gave the maximum of R^2 as shown in the table 2. There is a group of indices which had significant correlation to SSC providing $R^2 > 0.7$, such as Rrs810/Rrs536, Rrs810/Rrs538, Rrs798/Rrs532 and Rrs680/Rrs520. Another group of indices which had good correlation with SSC, giving $R^2 > 0.6$, such as Rrs630 – Rrs750, Rrs645 – Rrs859 and Rrs629/Rrs671. The remaining of indices provided $R^2 < 0.5$. The best correlation was found by using the ratio of Rrs798/Rrs532. The regression analysis of this ratio and SSC from in situ measurement provided the good linear relation calculate as $R^2 = 0.7598$, the plot of regression is shown in Figure 4. The Chao Phraya river mouth's SSC (CSSC) model can be expressed as follows:

$$CSSC = 1.5181 \left(\frac{Rrs798}{Rrs532}\right) - 13.873$$

Equation 5

Where CSSC is suspended sediment concentration in mgl^{-1}, Rrs798 and Rrs532 are % reflectance.

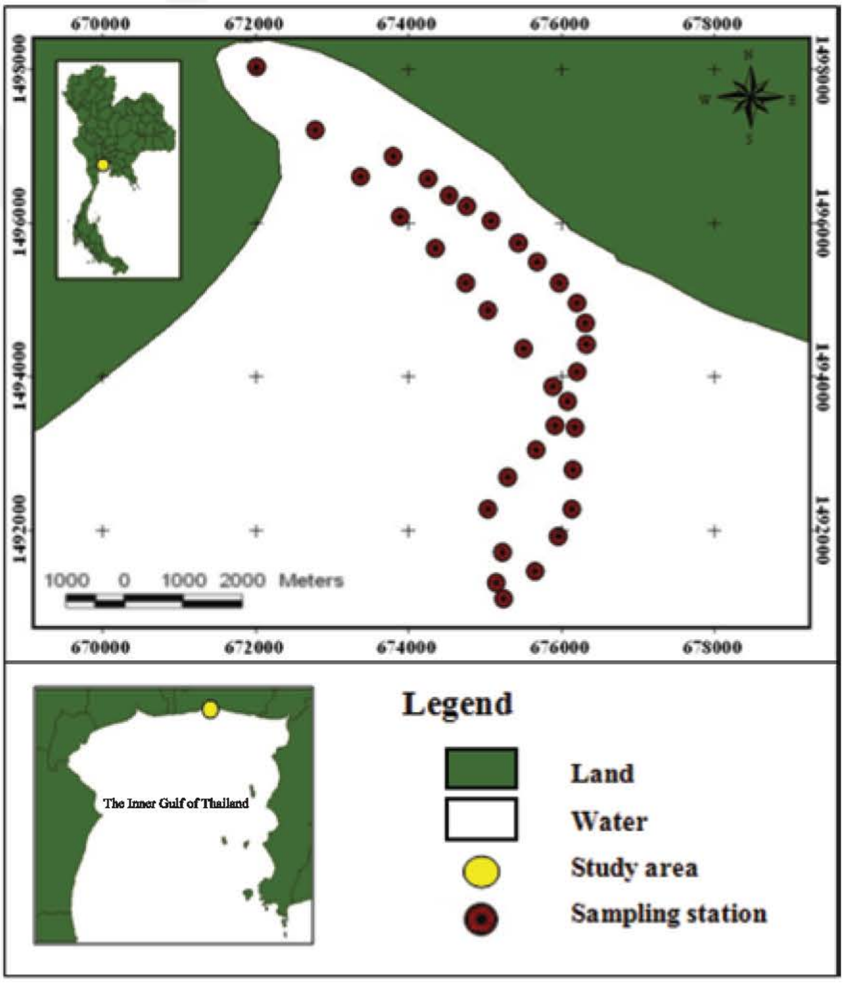

Figure 2: Sampling stations in Chao Phraya River mouth

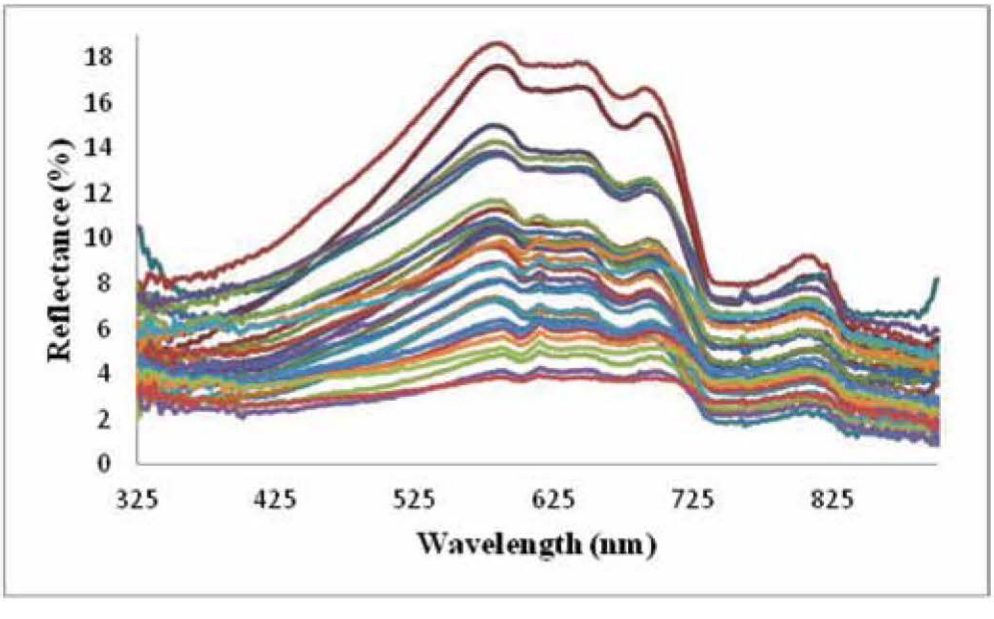

Figure 3: Spectral reflectance curves of sampling stations in Chao Phraya River mouth

Table 2: Correlations between existing reflectance indices and observed SSC

No	Index	Equation	R^2
1	Rrs798 / Rrs532	$y = 249.61x - 83.277$	0.7598
2	Rrs810 / Rrs536	$y = 238.03x - 75.533$	0.7421
3	Rrs810 / Rrs538	$y = 238.6x - 74.619$	0.7410
4	Rrs680 / Rrs520	$y = 0.1538e^{5.7154x}$	0.7082
5	Rrs630 - Rrs750	$y = -60.54\ln(x) + 161.24$	0.6739
6	Rrs629 / Rrs671	$y = 183.99x^{-11.01}$	0.6643
7	Rrs645 - Rrs859	$y = -71.98\ln(x) + 192.94$	0.6210
8	Rrs850 / Rrs550	$y = 254.91x - 34.748$	0.5192
9	Rrs865 / Rrs555	$y = 233.92x - 20.443$	0.4598
10	Rrs496 / Rrs555	$y = 645.21x - 428.73$	0.4157
11	(555+645) + (488/555)	$y = 638.88x^{-0.785}$	0.3963
12	Rrs620 / Rrs520	$y = 20.309x^{6.3419}$	0.3200
13	(555+670 + (670/555)	$y = 568.08x^{-0.757}$	0.3580
14	(Rrs555+Rrs670)*(Rrs490/Rrs555)	$y = 332.65x^{-0.645}$	0.2842

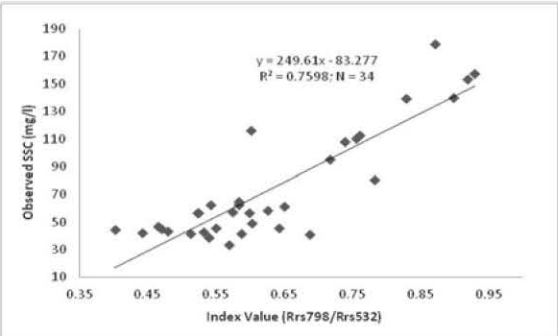

Figure 4: Relationship between Reflectance Ratio, Rrs798/Rrs532 and Field Sampling SSC

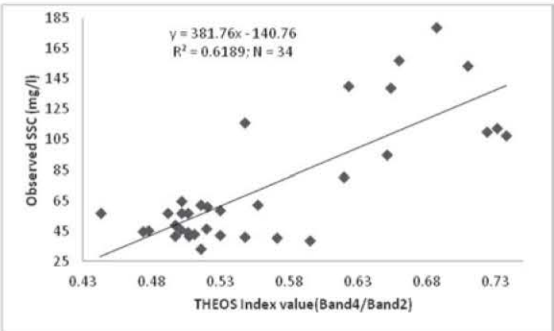

Figure 5: Relationship between THEOS Index Values, Band4/Band2, and Ground Truth SSC

3.3 Application of THEOS Imagery

There was an image from THEOS acquired on 10th June 2012. The multi-spectral digital number (DN) from four sensors were converted to be reflectance and analyzed. The best reflectance index from 3.2 was compared to the wavelength range of THEOS spectral bands.

Based on the best result from existing indices, Rrs798/Rrs532 correlated to SSC providing maximum $R^2 = 0.7598$. When the index compared to THEOS spectral bands, Rrs798 was in the range of Band4 and Rrs532 was in the range of Band2. However, the other existing indices were also compared to THEOS band ranges. The group of existing indices, which provided good correlations with SSC, was in the range of ratio Band4/Band2. The THEOS DNofBand2 and Band4 were read from thirty-four sampling coordinates and converted to be reflectance values. The reflectance ratio values of Band4/Band2were calculated and correlated to SSC giving maximum $R^2 = 0.6189$ by linear correlation. Linear correlation was plotted as shown in the Figure 5.

The CSSC model for THEOS imagery can expresses as follows:

$$CSSC_{THEOS} = 381.76\left(\frac{\text{Band4}}{\text{Band2}}\right) - 140.76$$

Equation 6

Where $CSSC_{THEOS}$ is suspended sediment concentration in mgl^{-1} and Band4 and Band2 are reflectance values derived from THEOS image. The $CSSC_{THEOS}$ model (equation 6) was applied to THEOS image on Chao Phraya River mouth taken on 10th June 2012 processed by using ENVI 4.4 software. The SSC was classified into 5 levels, based on SSC in mg/l as shown in Figure 6. The dark brown area indicates the highest SSC level, which was higher than 80 mg/l. The high level of SSC near shore and those diluted out to sea in the map indicate a good correlation to the ground truth R^2=0.6189.

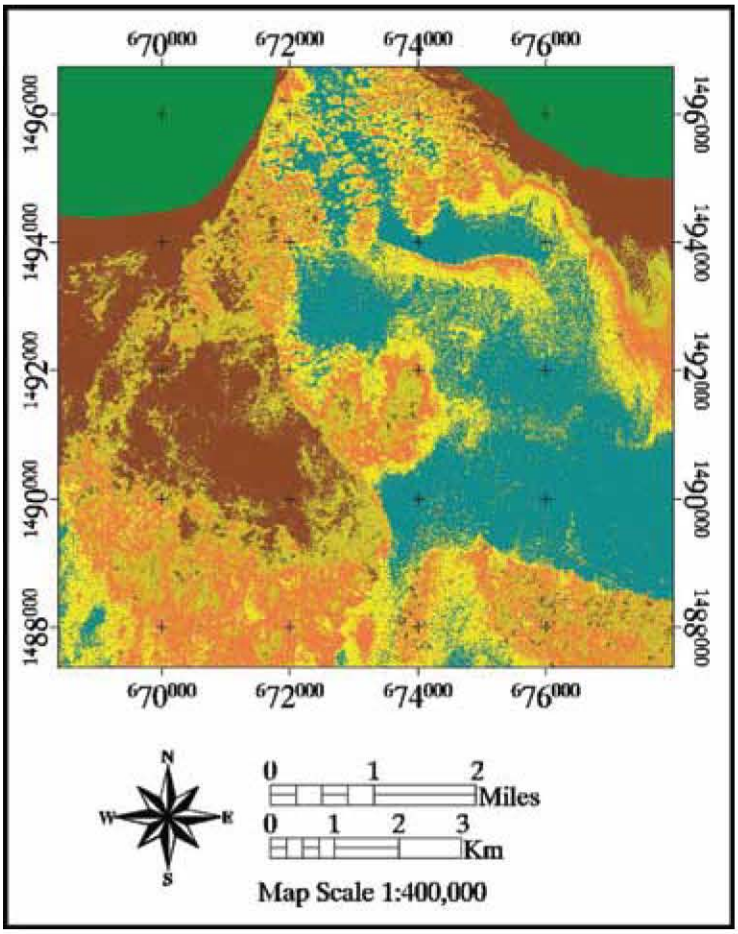

Figure 6 : Map of suspended sediment concentration (SSC) on June 10th, 2012, at Chao Phraya River mouth, Thailand

4. Summary and Conclusion

The current study characterized the spatial variability of the important water quality parameter, suspended sediment in river mouth water columns, by field-measured spectra and remote sensing imagery in the Chao Phraya River mouth area. The in situ SSC and the ratio of Rrs798/Rrs532 correlated as the CSSC, eq.5, with the highest R^2 of 0.7598. The other reflectance indices were Rrs810/Rrs536, Rrs810/Rrs538, Rrs798/Rrs532 and Rrs680/Rrs520 gave good correlations, the correlations provided maximum $R^2 > 0.7$. The Rrs798/Rrs532 index was compared to the range of THEOS spectral bands and THEOS index was Band4/Band2. The Band2 and Band4 DN values from satellite image were converted to provide reflectance values for the index application. The maximum correlation between reflectance index values of Band4/Band2 and SSC found $R^2 = 0.6189$. The regression correlation model was $CSSC_{THEOS}$ as equation 6. The $CSSC_{THEOS}$ model was applied to THEOS image provided the map of SCC in the Chao Phraya River mouth area as Figure 5.

The CSSC model could be used for further Chao Phraya SSC estimation by specific wavelength reflectance while the $CSSC_{THEOS}$ model could be used for the SSC estimated by THEOS satellite. The ratio of Rrs798/Rrs532 could be applied to other satellite images of Chao Phraya river mouth area for SSC estimation. In other coastal areas which have similar high turbidity, the SSC could be estimated by using the indices in table 1 to verify with the local coastal SSC and sea surface leaving radiance data. The methodology to apply spectrometer spectral index to THEOS satellite index was proved by ground truth data and satisfied with the good correlation for sea surface monitoring. This method could be applied on another land cover types. This study produced the SSC mapping from the THEOS satellite with 15 meter resolution. The SSC map with this high resolution has expanded information on Chao Phraya River mouth SSC and can be useful in SSC monitoring and sediment studies in the future.

Acknowledgement

This study is a part of a Mahidol University master thesis and the research project on "Coastal Suspended Sediment Estimation Using satellite Imagery in The Inner Gulf of Thailand" supported by Office of Naval Research Global, US., Geo-Informatics and Space Technology Development Agency (Public Organization) and Mahidol University, Thailand. The study was supported for publication by the China Medical Board (CMB), Faculty of Public Health, Mahidol University, Bangkok, Thailand.

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