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Rapid assessment of water eutrophic state in Tien Yen-Ha Coi Bay by estimating Chlorophyll-a concentration using geostatistical interpolations and MODIS data

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Abstract. Eutrophication is a natural process of enrichment of water by nutrients, however in many case is considered as one of the major factors of water pollution affecting coastal ecosystem. Selection and application of suitable indicator and method to assess sea eutrophication is utmost important. This study aims at clarifying water eutrophic state in Tien Yen – Ha Coi Bay using geostatistical methods of 40 in situ sites data and auxiliary information from MODIS/Terra image. Resultant predicted chlorophyll-a concentration distribution map in Tien Yen – Ha Coi Bay produced by cokriging and eutrophic possibility map computed by indicator kriging identified clearly that the bay is classified as natural eutrophic waters. By this study, MODIS offers the possibility to support auxiliary information for assessment eutrophic state in large water areas. Cokriging and indicator kriging was proved to be effective for rapid environmental quality assessment and coastal water management.
Keywords: Eutrophications, cokriging, indicator kriging, estimation map, probability map.

1. Introduction

Eutrophication of coastal waters has been considered one of the major threats to the health of marine ecosystems. The different processes and effects of coastal eutrophication are well known and documented [1-4]. The main cause of eutrophication in coastal waters is nutrient over-enrichment (nitrogen, phosphorus and silica) leading to: an increase in the frequency of harmful algal blooms, shellfish contamination, anoxic and hypoxic events and fish kills; a loss of ecosystem integrity, aquaculture production, fish stocks and amenity value; and changes in biodiversity [5]. Therefore, identifying the most efficient way to diagnose the eutrophic state of coastal waters is indispensable task to protect coastal environment and preserve ecosystem health.

However eutrophication of coastal waters has been considered for a long time and many related researches have been carried-out worldwide, one important question is still to be answered: "How should primary production of eutrophication be measured or estimated?". Such question requires thorough scientific

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analyses as well as coordination, new methods and approaches in assessment of coastal water eutrophic state need be developed and demonstrated. Chlorophyll-a (Chl-a) concentration is an effective measure of the trophic status of sea and land waters, because it is related strongly to aquatic phytoplankton abundance and biomass. Estimating Chl-a concentration is one of the most traditional and significant applications of remote sensing for evaluating aquatic ecosystems and monitoring eutrophication [6-10]. This study develops a method for rapid assessment of water eutrophic state in Tien Yen – Ha Coi Bay by using various geostatistical interpolations of *in situ* Chl-a concentrations and auxiliary information from MODIS/Terra image. Resultant probability map of water eutrophic state and potential based on Chl-a concentrations of this study helps delimiting zones of high and low eutrophication. Since no other data of similar nature is available at the present time, the obtained results were considered as a first baseline for coastal water environmental analysis and management of Tien Yen – Ha Coi Bay on eutrophication assessment.

2. Materials and Methods

The study area

Tien Yen – Ha Coi Bay is adjacent to China - Vietnam border and connected to the South China Sea by five channels (Fig. 1). The most remarkable feature of the bay is its shallowness: the sea depth generally ranges from 2 to 5 m. Another feature is that the bay has a strong diurnal tide regime with maximum tidal amplitude of 5 m [11]. Therefore, aquatic ecosystem and environment of the bay are dominated mainly by oceanographic factors such as tide, waves, and near-shore currents.

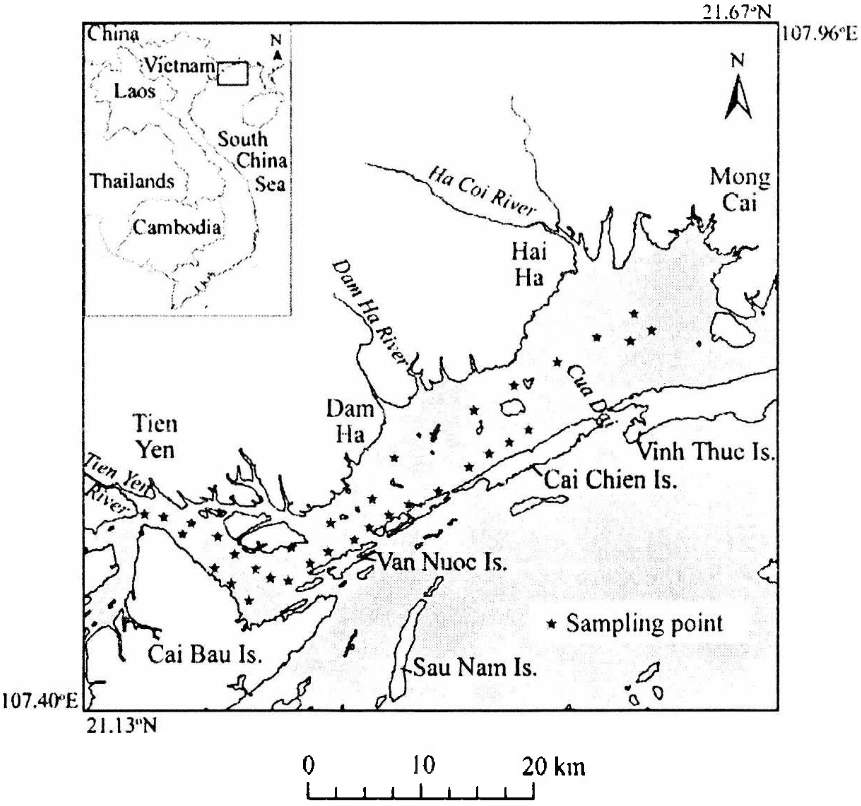

Figure 1. Location of Tien Yen - Ha Coi Bay and positions of 40 sampling points for water sampling.

A decline in the environmental and ecological systems in Tien Yen – Ha Coi Bay has been reported, including loss of seagrass meadows, phytoplankton abundance and water contamination [12]. One of serious environmental threats on the bay water environment is eutrophication process: its state and cause. Therefore, assessing water eutrophic state in Tien Yen – Ha Coi Bay is an indispensable task to protect the bay environment and preserve ecosystem health.

Water sampling and analysis

Sea water in Tien Yen – Ha Coi Bay was sampled at 40 points using a speed-board on 6 July 2010 with a Global Positioning System (GPS) receiver to locate the points. These points, shown in Fig. 1, were selected to investigate the environmental conditions all over the bay. The samples were taken at 50 cm water depth using Van Dorn water sampler, filled in 1 liter cleaned bottles at the constant temperature of 4^{0}C storage and transported to a laboratory. Water sampling was carried out within 10 hours before/after time of image acquiring on 6 July 2011. Speed-boat was used for fast data collection.

Concentration of Chl-a in water was determined by standard Spectrophotometric measurement method [13]. Firstly, water samples were filtered by a pre-washed 47mm glass fiber filter and then extracted into 90% acetone. The Chl-a and phaeophytin concentrations in the extract were determined by spectrophotometer at 750 nm and 664 nm before acidification, and 750 nm and 665 nm after acidification. Descriptive statistics of the resultant Chl-a concentrations of the 40 samples are summarized in Table 1.

MODIS data

The Terra spacecraft passes over Tien Yen – Ha Coi Bay at about 3:20 GMT (10:20 local time) each day. This time is suitable for acquiring satellite imagery to compare with *in situ* water quality. MODIS/Terra level 1B image data acquired on the same date as the water sampling (6 July 2010), which were calibrated at-aperture radiances for the 36 bands and geo-located for WSG-84 N48 of the UTM system, were used to estimate Chl-a concentration. According to Ha and Koike (2011) [14], it was identified that dark-object subtraction (DOS) by Chavez (1988) [15] was a suitable atmospheric correction method for the MODIS data of Tien Yen – Ha Coi Bay. Therefore, this study used obtained reflectance after DOS as data for cross-estimation.

Geostatistical methods

Co-Kriging

Co-Kriging (CK) is a form of kriging that involves multiple variables. It is considered a 'hybrid' Kriging technique (i.e. non-stationary geostatistical method). In fact, the method is a multivariate extension of Kriging that allows inclusion of more readily available and inexpensive attributes in the prediction process [16]. CK uses auxiliary variables and takes into account additional correlated information between variables to improve spatial prediction, which requires an estimation of cross-variograms. With CK the estimated value at an unsampled location is a linear weighted sum of all of the variables being examined (i.e. two or more). For two variables, the models are:

$$Z_a(x) = \mu_a(x) + \varepsilon_a(x) \quad (1)$$

$$Z_b(x) = \mu_b(x) + \varepsilon_b(x) \quad (2)$$

Where μ_a and μ_b are unknown mean values (constants) and ε_a and ε_b are random errors. Each of these sets of random errors may exhibit autocorrelation and cross-correlation between the datasets, which the procedure attempts to model. Co-Kriging uses this cross-correlation or covariance to improve the estimation of $Z_a(x)$. The covariance is calculated according to the following formula:

$$C(s_i, s_j) = \mathrm{cov}(Z(s_i), Z(s_j)) \quad (3)$$

where *cov* is the covariance of two random variables. Covariance is a scaled version of correlation. So, when two locations, s_i and s_j, are close to each other, you expect them to be similar and their covariance (a correlation) will be large. As s_i and s_j get farther apart, they become less similar, and their covariance becomes zero.

Indicator Kriging

Indicator Kriging (IK) is a non-parametric geostatistical method for estimating the probability of exceeding a specific threshold value, z_k, at a given location. In indicator Kriging, the stochastic variable, $Z(u)$, is transformed into an indicator variable with a binary distribution, as follows:

$I(u; z_\downarrow k) = \{$ (1, *if* $Z(u) \le z_l k$, k = 1, 2,…m@0, otherwise) (4)

The expected value of $I(u; z_k)$, conditional to *n* surrounding data, can be expressed as:

$$E[I(u; z_k \mid (n))] = Prob \{Z(u) \le z_k \mid (n)\} = F(u; z_k \mid (n)) \quad (5)$$

$$P(u; z_k \mid (n)) = 1 - F(u; z_k \mid (n)) \quad (6)$$

Where $F(u; z_k|(n))$ is the conditional cumulative distribution function of $Z(u) \le z_\downarrow k$, and $P(u; z_k|(n))$ is the probability that $Z(u) > z_\downarrow k$. At an unsampled location, u_o, estimation must use indicator kriging and the indicator estimator, $I^*(u_0; z_k)$, according to:

$$I^*(u_0; z_k) = \sum_{j=1}^{n} \lambda_j(z_k) I(u_j, z_k) \quad (7)$$

where $I(u_j, z_k)$ represents the values of the indicator at measured locations, u_j, j = 1,2,..,n, and $\lambda_j(z_k)$ is the weighting factor of $I(u_j, z_k)$ in estimating $I^*(u_0; z_k)$.

Results and Discussion

The atmospheric correction methods, DOS, were applied to the MODIS 36 bands data to obtain surface reflectance $(R_\downarrow rs(\lambda))$of the Tien Yen - Ha Coi Bay water surface entire. Table 1 summarizes descriptive statistics of obtained $R_{rs}(\lambda)$at two bands: visible green band (band 12, at 551 nm) and blue band (band 9, at 443 nm), using MODIS/Terra image at 1 km pixel size with total number of pixels is 392.

Table 1. Descriptive statistics water samples datasets of Chl-a concentrations (mg/m^3) and obtained reflectance of bands 9 and 11 MODIS/Terra Image after DOS

Parameter \ Item	Chl-a (mg/m^3)	R_{rs}(443) (MODIS band 9)	R_{rs}(551) (MODIS band 12)
Number of data	40	392	392
Average	12.5	0.045	0.047
Median	12.7	0.043	0.047
Maximum	16.5	0.090	0.095
Minimum	8.1	0.025	0.014
Standard deviation	1.8	0.011	0.015
Range	8.4	0.066	0.081

Fig. 2 shows a strong relationship between Chl-a concentrations of water samples and ratio of two reflectances at MODIS band 12: $R_{rs}(551)$, versus band 9: $R_{rs}(443)$ (correlation coefficient r = 0.78). This relationship confirmed a high possibility of cokriging in prediction Chl-a concentrations from MODIS/Terra image data ($R_{rs}(551)/R_{rs}(443)$).

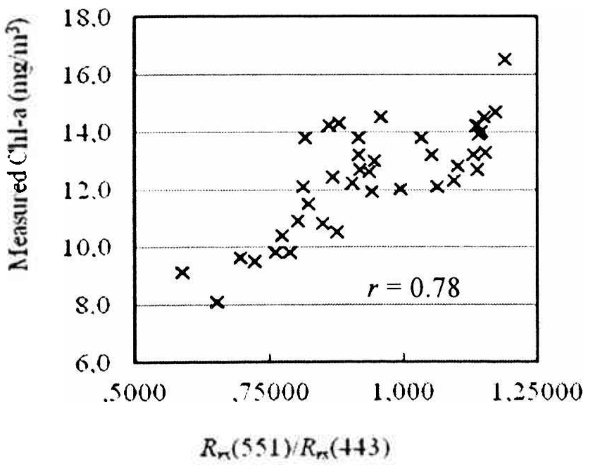

Figure 2. Relationship between Chl-a concentration of water sample and ratio of two reflectances at MODIS band 12 (551 nm) versus band 9 (443 nm).

Experimental covariance produced from these two datasets was approximated best by the exponential model with a nugget effect of 0.12 mg/m^3, a sill of 16.6 mg/m^3, and a range of 17 km (Fig. 3A). To check the spatial estimation accuracy of CK with a cross-validation, a scattergram that represents the relationship between the *in situ* C_{Chla} - value and the predicted CK value using the C_{Chla} data was produced (Fig. 3B). The resultant mean error of the prediction is close to 0 (0.005 mg/m^3) and the RMSE is relatively low (0.99 mg/m^3), which confirms the high capability of CK. The resultant CK distribution of Chl-a concentration and the kriging variance map are depicted in Fig. 4 and 5. The kriging variances are negligible over the entire bay. Only a small zone outside the bay, where no *in situ* data was collected, has a relatively high variance, but its value is under 10% of the estimated C_{Chla}. Such variance trend also supports the correctness of the CK estimation.

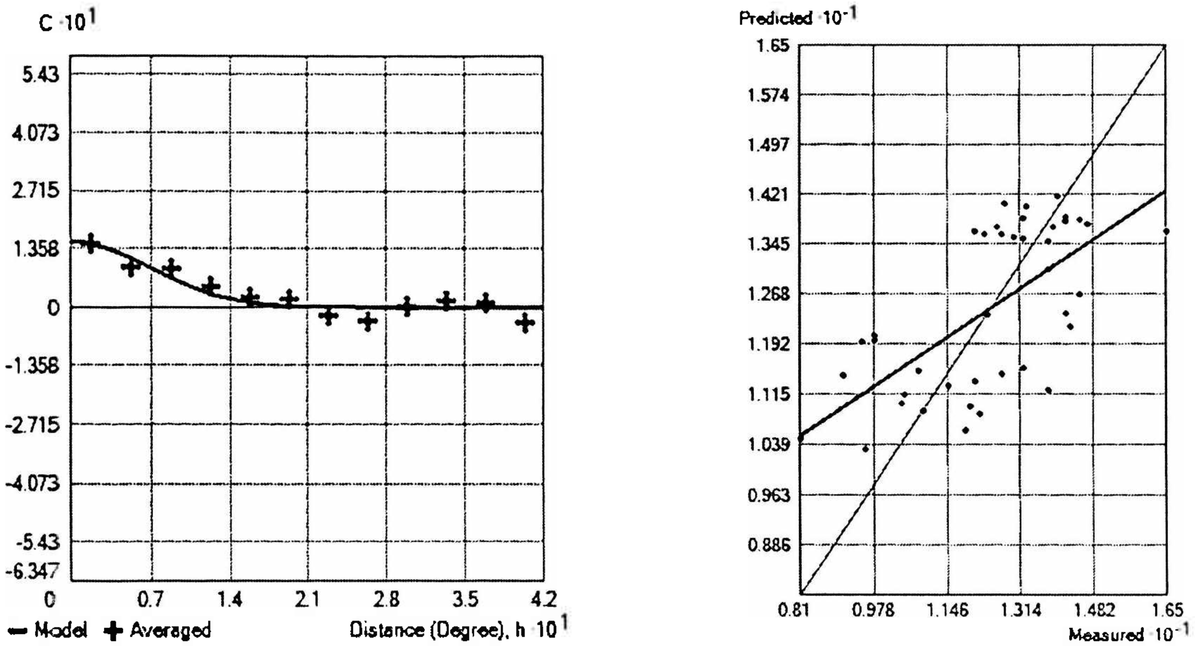

Figure 3. (A) Covariance and exponential model (curve) of the *in situ*Chl-a concentrations and$R_{rs}(551)/R_{rs}(443)$. (B) Scattergram for cross-validation of cokriging prediction. The 45-degree line is superimposed.

Prediction Chl-adistribution map produced by CK

The spatial distribution of Chl-a concentrations within Tien Yen - Ha Coi Bay was predicted by CK interpolation (Fig. 4). Basing on the map, Chl-a concentrations on 6 July 2010 ranged from 8.1 to 16.5 mg/m^3, which are 4 to 7.5 times of the eutrophic level, 2.21 mg/m^{3}of Simboura et al. [17]. Generally, concentrations of Chl-a over 14.3 mg/m^3 occur in local estuaries at the mouths of the Ha Coi and Dam Ha Rivers and along the coast from Mong Cai to Hai Ha. The middle bay also contains high Chl-a from 13.8 to 14.3 mg/m^3 from Cai Chien to Hai Ha districts. On the contrary, the concentrations become low toward the west near Cai Bau Island with a minimum of 8.1mg/m^3 in the channels connected with the outer sea.

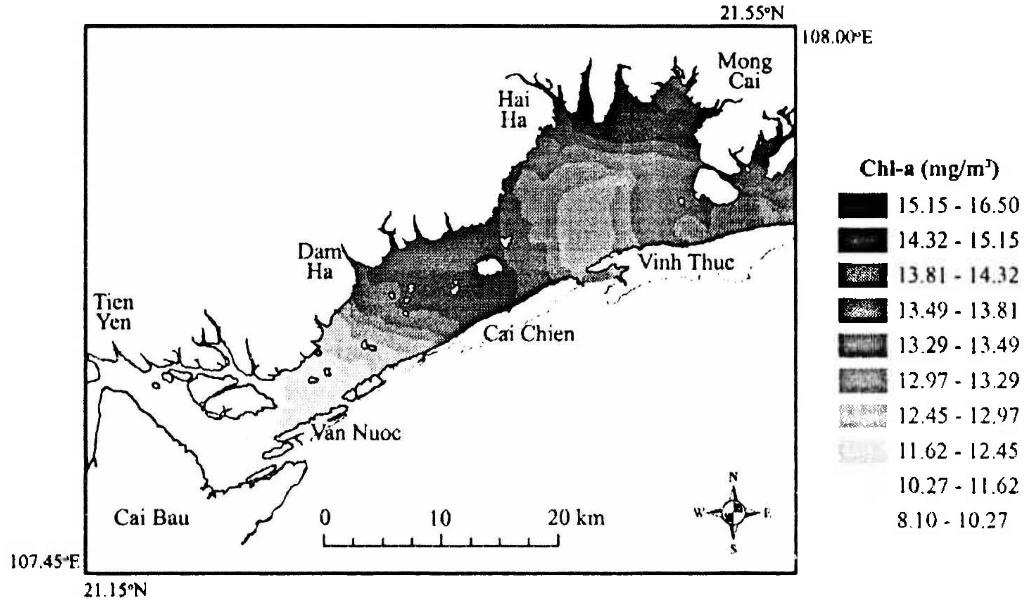

Figure 4. Spatial distribution of Chl-a concentrations produced by cokriging.

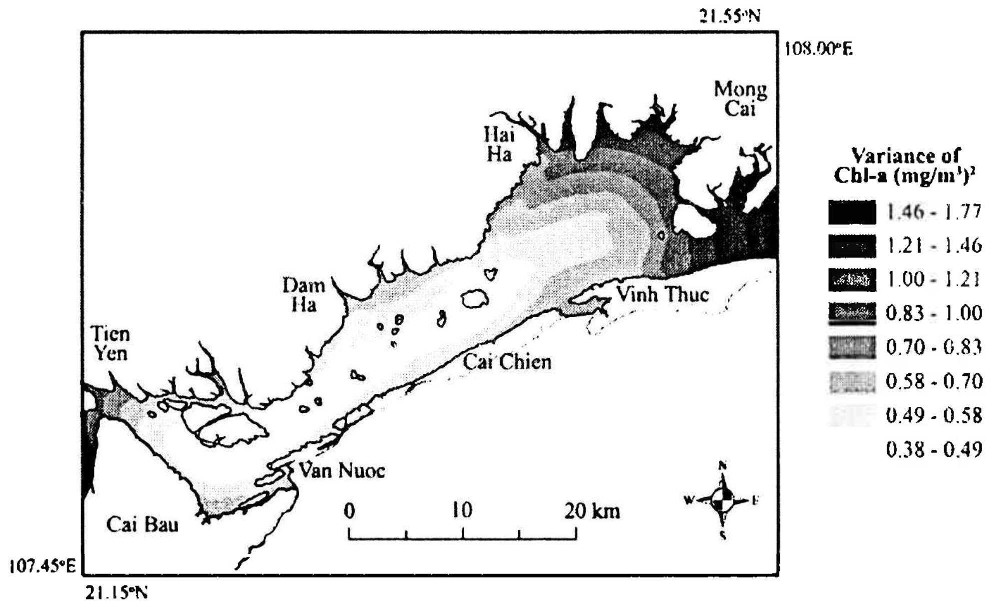

Figure 5. Kriging variance for representing uncertainty of estimation of Chl-a concentrations by cokriging.

Those spatial characteristics of Chl-a concentrations conformed to the hydrodynamic system in the bay that is generated by the interaction of regional surface currents, tides and waves. The local river estuaries and central bay are shielded by the islands (Van Nuoc, Cai Chien, and Vinh Thuc) and the tortuous coastline, and therefore the hydro-energy related to currents and waves is weak there. Under such conditions, phytoplankton, the main source of high Chl-a concentrations, accumulate and grow. In contrast, in the connection channels and the largely movable waters affected directly by the outer sea, the hydro-energy is strong. These waters contain abundant amounts of re-suspended material, which prevent the accumulation and growth of phytoplankton. Thus, Chl-a concentrations become low in such high-energy zones.

Water eutrophic state probability map

CSTT[18] defined 10 mg/m^3 of Chl-a as the Environmental Quality Standard (EQS) for coastal waters. If the Chl-a concentration of a water body frequently exceeds this criterion in summer, it is regarded as having a eutrophic condition. Based on this criterion, the waters of Tien Yen - Ha Coi Bay were considered to be eutrophic.

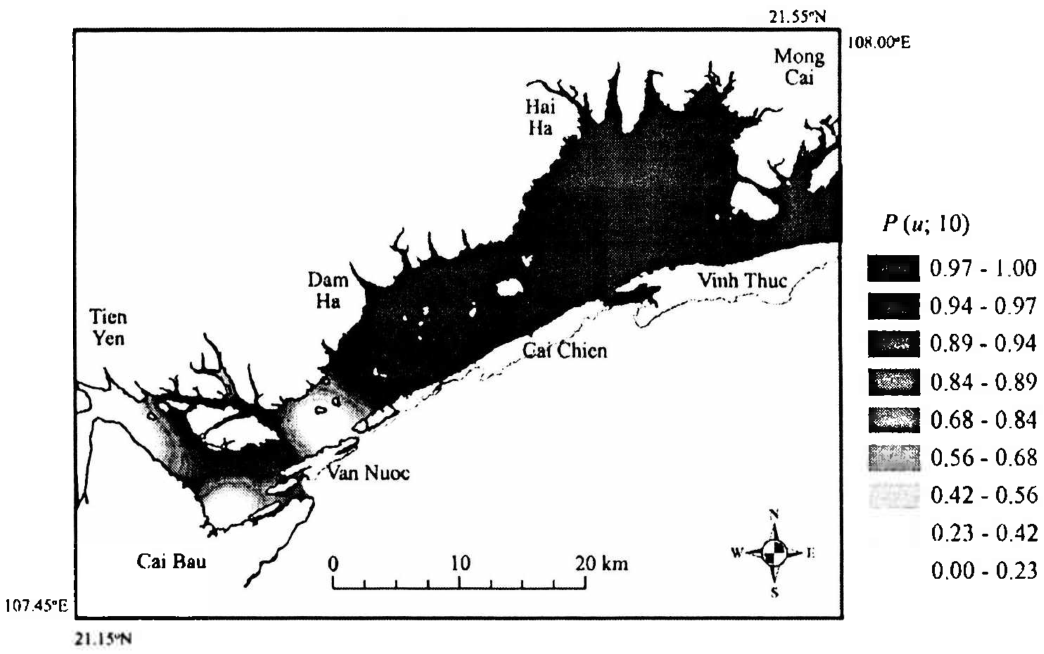

Figure 6. Probability map of water eutrophic state and potential in Tien Yen – Ha Coi Bay by IK.

Figure 6 shows probability of water eutrophic state and potential in Tien Yen – Ha Coi Bay by using IK and threshold of 10 mg/m^3. A high probability of eutrophication ($P(u;10)$ ranges from 0.97 to 1) was determined in the bay water entire except for the zones in front of Tien Yen Estuary or channel connected the bay with outer sea which located between Van Nuoc and Cai Chien islands. However, undesirable eutrophication disturbances, such as algae blooms, generated in the water with concentration of Chl-a over 100mg/m^3 [19] have not been observed in Tien Yen - Ha Coi Bay. This bay may be eutrophic by natural processes rather than by anthropogenic causes such as waste water, thereby maintaining a high ecological quality similar to other coastal areas [20].

Conclusions

This study demonstrates usefulness of two geostatistical methods, CK and IK, and auxiliary information for coastal water eutrophication assessment by considering the relationship between *in situ* data and MODIS image reflectance, analyzing the excess of Chl-a concentration against the environmental standard. A case study for Tien Yen – Ha Coi Bay clarified that Chl-a concentrations in seawater exceeded high eutrophic level [17] and the bay can be marked as natural eutrophic waters.

Another superiority of the combination between geostaitistical methods and remote sensing data was to provide rapidly database for good understanding of the spatial variation and distribution of Chl-a concentration. Consequently, that is easy to delineate high and low risk areas of eutrophic state and potential for regional water management.

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