Bio-optical Model for Mapping Spatial Distribution of Total Suspended Matter from Satellite Imagery

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Key words: Bio-optical model, Inherent Optical Properties, Specific Inherent Optical Properties, Total Suspended Matter, Remote Sensing, Subsurface Irradiance Reflectance (R (0-))

SUMMARY

Decreasing water quality is a main problem in Indonesian coastal waters. One of the main parameter describing the condition of the water is turbidity, expressed as the total concentration of suspended matter (TSM). Most water management authorities measure this quantity on a regular basis. A drawback of this monitoring is that, only limited number of sampling points is visited. Utilization of satellite remotely sensed imagery offers the possibility to monitor in a large regions and to study the entire ecosystem over space and time.A case study of using remotely sensed data was done in Teluk Banten, Indonesia, applying bio-optical modelling approach. The main objective of the research was to estimate TSM concentrations of the coastal waters from remotely sensed data.The problem in Teluk Banten coastal waters deals with circulation patterns of the shallow bay water. The water is characterised by high concentrations of suspended sediment, which cause silting up of the bay.

Sets of Landsat TM 5 and SPOT images have been used in this study. Such images were processed to TSM maps according to the bio optical model which is developed by Dekker et al. (1999). The bio-optical model is based on the algorithm, developed from laboratory analysis data of Inherent Optical Properties (IOP) and its constituents. The average value of Specific Inherent Optical Properties (SIOP) is used as input of the model.

The research result shows that the application of red band of Landsat TM (band 3) and SPOT HRV (band 2) using exponential function are the most suitable algorithm for estimating TSM concentration. Several advantages of the use of bio-optical model are discovered in this research. The current study proved that such methodology can be used to map the spatial distribution of TSM with a sufficient accuracy. The advantage of this approach are: (i) it is applicable to all type of sensor as long as the appropriate SIOP are available for the spectral bands of the sensor, (ii) it allows the application of one algorithm based on the red band to a time series of image data from the same sensor for the same region, (iii) it allows error analysis of the error propagation, which enables to predict the error in the retrieved concentration, and (only initial measurements are needed to establish optical properties of the relevant waters in an area, requiring only a little in-situ measurements. This method has proved to be suitable for Teluk Banten and can easily be applied in other coastal area in Indonesia with sufficient accuracy.

Further development of this approach is expected to allow estimation in low cost and a litle in-situ measurements, in order to support Integrated Coastal Zone Management.

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1. INTRODUCTION

The problem addressed in Teluk Banten, a bay located near Jakarta, Indonesia, deals with the circulation patterns of the shallow waters that is characterised by high concentrations of suspended sediment reflected in it′s value of turbidity and Total Suspended Matter (TSM) concentration, which cause silting up of the bay.

Optical remote sensing is an alternative technique, which can be used for monitoring turbidity of coastal waters. One of the advantages of this satellite approach is that the data could be collected over large area and at regular time intervals.

Morel and Gordon (1980) pointed out three different approaches to determine spectral radiance or reflectance that can be used to estimate the concentrations of constituents in water. These are empirical approach, semi-empirical approach and analytical approach.
This research follows the analytical approach to retrieve TSM concentrations from the Landsat TM and SPOT. The analytical approach is based on a radioactive transfer approach for the atmosphere, for the air-water interface and for the underwater light field. The major advantages of the analytical approach are: (i) it needs only one algorithm to be applied to a time series of image data from the same sensor and same location, (ii) it could be applied by using archive image, (iii) it require a minimum *in-situ* measurement, and (iv) no *in-situ* measurements is required at the time of satellite images overpass at the study area.

2. MATERIAL AND METHODS

A series of satellite images of study area have been used for retrieving TSM concentrations. Those are Landsat TM 5 (May 27, 1995; June 14, 1996 and January 30, 1997) and SPOT HRV (June 12, 1990; April 14, 1996; and October 8, 1997). The water samples were collected in a field campaign, done in October 2001. The water samples are then analysed in IVM Laboratory in Vrije Universiteit, Amsterdam, The Netherlands in order to obtain the Inherent Optical Properties (IOP) and the concentrations of TSM and chlorophyll (CHL). Field spectral reflectance has been measured using Portable Spectroradiometer CE500.

2.1 Research Location

Teluk Banten (Banten Bay) is located in Banten Province, Indonesia at latitude of 05°50′00″ - 06°04′00″S and longitude of 106°05′00″ - 106°17′00″E. It has a total water surface of 150 km^2. The bay is situated in north coast of Java, about 60 km west of Jakarta.

2.2 General Approach

An analytical approach for water quality retrieval needs the use of a bio-optical model that relates the subsurface reflectance to the water constituent concentrations.

Pasterkamp *et al.* (1999) described the concentration of optical water quality parameter, which is linked to the R (0-) via the inherent optical properties (IOP) of the water. The IOPs are the total absorption (a) and backscattering (b_b) of the optical active constituents (suspended matter, Colour Dissolved Organic Material - CDOM and water itself). Absorption and backscattering depend on the wavelength (λ) and are expressed in (m^{-1}). Dekker *et al.* (1994) has found the equation that is the most appropriate bio-optical model for turbid water: $R(0-) = r \frac{b_b}{a + b_b}$ (Eq. 1). As the input value, the appropriate value for each of the IOPs are determined by equation below:

$$a = a_w + a^*_{pg}.TCHL + a^*_{tr}.TSM + a^*_{CDOM}.CDOM_{440}$$

(Eq.2)

$$b_b = 0.5.b_w + B.b^*_{tr}.TSM$$ (Eq. 3)

The Specific Inherent Optical Properties (SIOPs) are denoted by an asterisk as superscript. The value for the IOP in this model are: a_w (the absorption of pure water); b_w (the backscattering of pure water); a^*_{pig} (the specific absorption of phytoplankton pigment); a^*_{tr} (the specific absorption of tripton); 0.5 (the coefficient of backscatter to scatter ratio of pure water); a^*_{CDOM} (the specific absorption of CDOM); $CDOM_{440}$ **(**the CDOM absorption of 440 nm); and B^*_{tr} (the specific scattering of tripton).

The bio-optical model requires also other parameters that are not necessarily measured directly in the field. They are (1) the spectral shape coefficient (r), which depends on the geographic latitude and longitude and the volume of the scattering function; (2) the backscatter to scatter ratio (B) which is introduced here to convert the scattering coefficient into the backscattering coefficient. The backscatter to scatter ratio of tripton (B) is based on the tripton concentration and consequently on the water type

2.3 Methodology Extraction of TSM from Remotely Sensed Spectral Data

The bio-optical modelling deals with two sequences: forward analytical model and inverse analytical model (see Figure 1). The forward analytical model involved: (i) selecting a suitable bio-optical model; (ii) collecting a set of IOPs and its concentration (TSM and CHL); (iii) calculating SIOPs and including it into the bio-optical model; (iv) determining B and r coefficient (see Eq. 2 and 3); (iv) using the model to generate a series of R(0-) values as a function of a series of TSM concentration; and finally, (v) fitting a mathematical relationship to the series of combined TSM and R(0-) values.

The inverse analytical model deals with the processing of raw satellite images into maps of suspended matter. The first step is pre-processing the satellite images (geometric correction and image calibration) and creation of a series of mask map in order to consider only the seawaters part from the satellite image. The average field reflectance of red band of each sample from several locations and their Digital Number (DN) has been used for retrieving a linear regression of R(0-) algorithm. Using this algorithm, the subsurface reflectance of image could be obtained by applying the algorithm to entire image. Finally, the TSM algorithm from forward analytical model has been applied to the subsurface reflectance image in order to retrieve TSM concentrations map.

3. RESULTS AND DISCUSSION

3.1 Forward Analytical Model: Algorithm Development

Two optical water quality parameters that are taken into account in the bio-optical model are TSM concentrations and total chlorophyll-a (TCHL) concentrations. The TSM and TCHL were obtained from water sample, which is analysed based on the Dutch standard measurement (Pasterkamp, *et al*., 2001). The TSM concentrations in research area were ranged from 1.5 to 13.4 g/m^3. The lowest concentrations was found in the deep sea that was situated far away from river discharge, while the highest TSM concentrations was found in the Ciujung river mouth. The TCHL concentrations were ranged from 1 mg/m^3 (deep sea) to 8.53 mg/m^3 (turbid waters). The highest concentration of TCHL was found at the location close to the land.

In this model, the spectral properties of pure water have been derived from literature value. The average value of SIOP for CDOM absorption, tripton absorption, phytoplankton absorption and seston scattering (see Figure 1) has been used for the entire Teluk Banten, even it is known that individual measurements of samples in ten locations show some variations. This simplification of SIOPs will introduce some errors in the estimated TSM concentrations. The SIOPs were measured from the wavelength of 350 to 750 nm. This wavelength covers spectral band 1 and 2 of SPOT and band 1, 2 and 3 of Landsat TM.

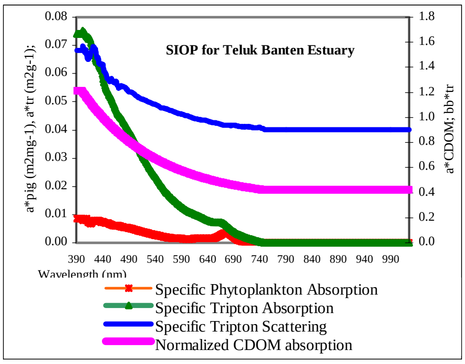

Figure 1. The average SIOP of Teluk Banten.

The R(0-) is calculated using the average of the SIOP dataset and measured concentrations. Figure 2 presents radiance reflectance spectra just below the water surface of Teluk Banten for ten points from different locations. The bio-optical model needs also some parameters that cannot be measured *in-situ*, such as B and r coefficients. Normally, these parameters are alternatively done by optimization (matching of simulated R(0-) using local SIOPs to measure R(0-) in the same location). In this research, literature values of B=0.019 and r=0.34 have been applied.

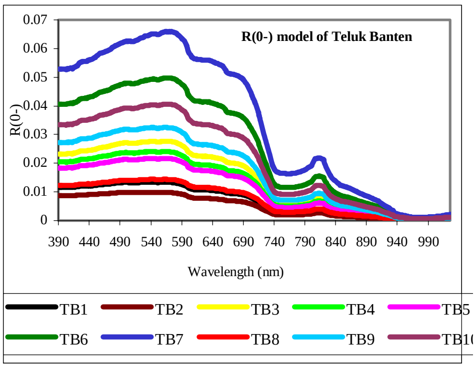

Figure 2. The R(0-) simulated of Teluk Banten

Figure 2 shows that the differences in water composition are clearly reflected in the modelled spectra (R(0-)) so that it is possible in turn to estimate the concentrations of the main water quality parameters. Figure 2 indicates also that the spectrals in the blue, green and red band do not have a linear relationship with TSM concentrations. The R(0-) of Teluk Banten coastal waters has a similar pattern to the R(0-) of the Banjarmasin coastal waters (Dekker *et al.*, 1999). They are characterised by quite high of CDOM concentrations and there is an evidence for this in the modeled spectra.

The algorithm building for TSM concentrations using the forward bio-optical model can be used to simulate a data set of R(0-) in each of the sensor band as a function of increasing concentration of TSM. Since the objective of this study is TSM retrieval only, a straightforward method would be an analytical inversion of the bio-optical model for one band. In this research, an exponential function has been applied for retrieving the TSM concentration from R(0-). Figure 3 show the relationship between R(0-) and TSM for Landsat TM and SPOT.

In this research, the algorithm has been recalculated for each SPOT and Landsat TM sensor separately. The sensitivity of curves differs per sensor.

The concentration of TCHL concentration and CDOM absorption has been fixed at 10 mgm^{-3} and 1.08 m^{-1} (Ambarwulan, 2002). This simplification produces some errors that give an impact to the accuracy of retrieval TSM concentrations. Table 1 presents the TSM algorithm for each band of SPOT and Landsat TM as the output of forward analytical model.In this research, the red band was chosen for some reasons: (i) it gives a good discrimination at lower TSM concentrations, (ii) it does not saturate too much at higher concentrations and (iii) red band is less affected by atmosphere than green and blue bands. For this reason, the algorithm resulting from forward model that have been applied in inverse model are based on the algorithm of red band (band 2) of SPOT and red band (band 3) of Landsat TM. The result of algorithm relating the simulated R(0-) to assumed TSM for SPOT HRV band 2 and Landsat TM band 3 the results are presented in Figure 4.

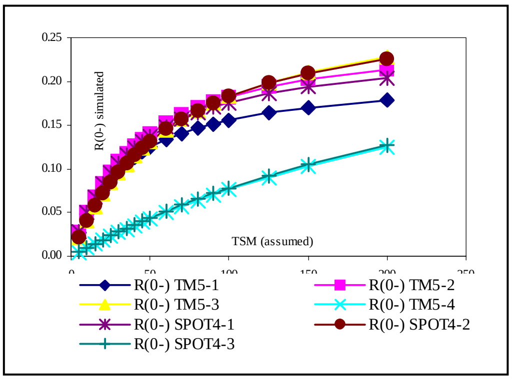

Figure 3. The analytical relationships between TSM concentrations and R(0-) for Landsat TM and SPOT.

3.2 Inverse Analytical Model

The series of TSM concentrations map retrieved from the image have been developed using the bio-optical model (Figure 4).

Satellite	Sensor	S	A	R^2
Landsat TM 5	Band 1	22.395	3.195	0.99
Landsat TM 5	Band 2	18.018	3.9652	0.99
Landsat TM 5	Band 3	16.073	5.6243	0.98
Landsat TM 5	Band 4	26.909	11.816	0.88
SPOT HRV	Band 1	19.082	3.682	0.99
SPOT HRV	Band 2	16.225	5.4743	0.98
SPOT HRV	Band 3	26.368	11.721	0.87

Table 1. The retrieval algorithm for the Landsat TM and SPOT sensors, coefficient are defined as TSM = A* Exp $^{S*R\ (0-)\ red}$

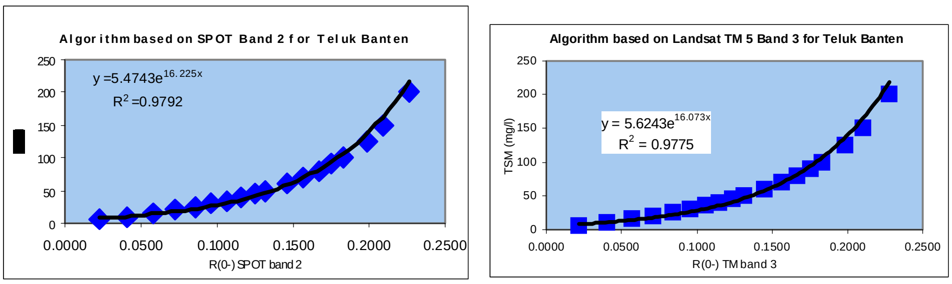

Figure 4. The Function Fitted over a Simulated Dataset of R(0-) Values in Band 2 of SPOT HRV (upper) and band 3 of Landsat TM (lower) as a Function of a Representative set of TSM Concentrations

The clearest distribution of TSM in the bay is shown for the six dates of the TSM concentration maps. The TSM statistics of those images (average value, standard deviation, and extreme values) have been calculated. This calculation can be used as an illustration of the power of remote sensing as a spatial analysis tool. The standard deviation varies between 2.06 to 42.88 mg/l. As comparison, the average of standard deviation of the entire bay, vary between 20 to 50%. The minimum values of TSM vary between 2 to 9 mg/l and the maximum values vary between 7 to 117 mg/l for all of the samples.

From the six images, it is shown that the Bay of Banten has a low concentration of TSM on June 14, 1996. At this time, the TSM concentration varies between 2 and 10 mg/l. It is possible that at this time, only little sediments came from the river, and the coastal dynamic was relatively stable (dry season).

4. ERROR ANALYSIS

The error analysis indicates that there are several sources of error in bio-optical modelling. This error is caused by some assumption and simplification of the bio-optical model of Teluk Banten. Rough estimation of overall error leads to a state in which such error is around 30 - 40%. The uncertainty in concentration retrieval depends mainly on the accuracy in R(0-) and SIOPs. The error in the R(0-) may be due to the chain of error in the process of obtaining R(0-) from the spectral signal at the sensor. In addition, some assumptions and simplifications have been made in the building of the retrieval algorithm. Errors in SIOPs occur due to the limitation in the experimental set-up for measuring absorption and scattering, as well as error in concentration measurements. In addition, when using average SIOPs, the variability in space and time may cause errors as well.

5. CONCLUSION

Bio-optical modeling, based on the knowledge of the *in-situ* inherent optical properties, leads to development of sufficient reliable multi-temporal algorithms for TSM retrieval for the data derived from SPOT and Landsat TM sensors. This methodology allows comparison of multi-temporal, multi-site (within this region) and multi-instrument TSM maps derived from satellite imagery.

The results indicate that a non-linear relationship exists between the satellite radiance image data and the suspended matter concentration. The relationship is an exponential relationship.
A bio-optical model has been presented in this research in order to develop and examine an analytical methodology to retrieve TSM concentrations by using remotely sensed data. Such methodology has proved to be suitable for Teluk Banten and can easily be applied in other coastal areas in Indonesia with sufficient accuracy (Ambarwulan, 2002). The bio-optical model was also previously tested in Indonesian (Banjarmasin) coastal water and in the Netherlands waters (Frisian waters and Vecht Lake waters).

6. RECOMMENDATION

The following points should be considered as guideline when using bio-optical model:

- It is applicable to all type of sensors as long as the appropriate SIOP are available for the spectral bands of the sensor
- It allows the application of one algorithm based on the red band to a time series of image data from the same sensor for the same region
- It allows error analysis of the error propagation, which enables to predict the error in the retrieved concentration
- Only initial measurements are needed to establish optical properties of the relevant waters in an area, requiring only a little *in-situ* measurement.

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BIOGRAPHICAL NOTES

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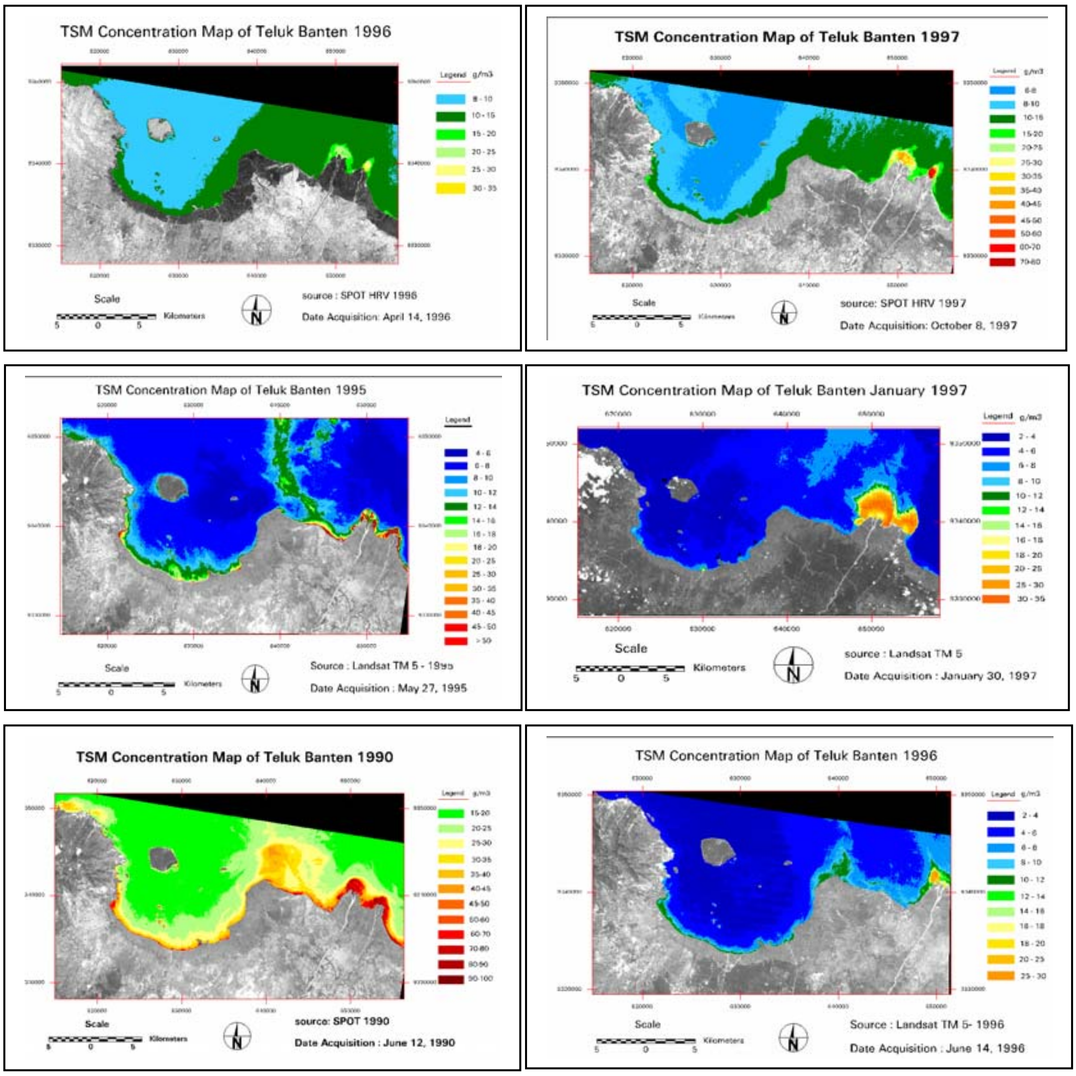

Figure 4. TSM Concentrations Map Retrieved from SPOT 1996 (upper left); SPOT 1997 (upper right); Landsat TM 1995 (Middle left); Landsat TM 1997 (middle right); SPOT 1990 (lower left) and Landsat TM 1996 (lower right)