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A sensitive suspended sediment sensor for the detection of total suspended solids (TSS)

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A novel optical sensor has been designed and developed to measure light through water samples for the retrieval of total suspended solids (TSS) concentrations. Light-emitting diodes (LED) were used as light sources of this sensor. In case 1, light was transmitted through the sample when the angle between light source and photodiode was 180°, and for case 2, light was scattered by small particles in the sample when the angle between light source and photodiode was 90°. An algorithm equation was developed and used to determine the relationship between measured TSS and predicted TSS.

Keywords: light emitting diode (LED), total suspended solids (TSS).

1. Introduction

Solid particles suspended in water absorb or reflect light and cause the water to appear cloudy or show up as dirty sediments. In view of the current problem of pollution of local waters, we designed a simple sensor for the detection of such pollution. The proposed optical system uses light emitting diodes (LEDs) to transmit light through the total suspended solids in water samples. LEDs have considerably lower cost and higher reliability than conventional sources. Progress in these sources has attracted global attention and has been extensively reviewed by many researchers [1]. LEDs have relatively narrow bandwidths and consequently may not require the use of filters. Their scattering and absorption are not mutually independent processes [2]. Based on the features mentioned above LEDs are very suitable to use as components of active sensor systems. The major advantages of using LEDs as the light sources are their relatively low power consumption and ability to be modulated electronically at rapid rates [3]. In case 1, light was transmitted through the sample when the angle between light source and photodiode was 180°, and for case 2, light was scattered by small particles in the sample when the angle between light source and photodiode

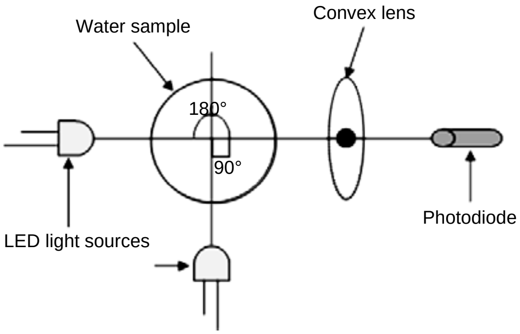

Fig. 1. A schematic diagram of the proposed optical sensor.

was 90°. Figure 1 shows a schematic diagram of experiment. In this study, the seawater samples of the Penang Straits, Malaysia, were also collected at the selected points (at the depth of about 3–4 cm from the surface) on 9th March 2006. The water samples were then analyzed in laboratory using a technique proposed by STRICKLAND and PARSONS (1972) [4]. As the intensity of light transmitted through the sample decreases, the voltage produced increases.

2. Optical model of water

An algorithm developed was used to determine the relationship between TSS concentration and reflectance. The development of the algorithm was based on the spectral reflectance model. The spectral reflectance (R_{rs}) is given by [5]

$$R_{\mathrm{rs}}(\lambda) = 0.33 \frac{b_b(\lambda)}{a(\lambda)} \tag{1}$$

where λ is the spectral wavelength, $b_b(\lambda)$ and $a(\lambda)$ are the backscattering and absorption coefficients, respectively [6]. The inherent optical properties are determined by the contents of the water. The contributions of the individual components to the overall properties are strictly additive [7]. The total absorption coefficient at wavelength λ, $a(\lambda)$, can be considered to be the sum of absorption due to water, $a_w(\lambda)$, phytoplankton, $a_c(\lambda)$, non-chlorophyllous particles of biological and terrestrial origin, $a_p(\lambda)$, and dissolved organic matter or yellow substance, $a_y(\lambda)$ [8]. Thus,

$$a(\lambda) = a_w(\lambda) + a_c(\lambda) + a_p(\lambda) + a_y(\lambda) \tag{2}$$

The absorption of pure seawater is practically the same as that of the pure water in the visible region (400–700 nm). Absorption by dissolved salts is known to be negligible in this region [7]. The absorption related to each substance is expressed as the product of its concentration of C (phytoplankton), P (non-chlorophyllous particles), or Y (yellow substance) and its corresponding specific absorption coefficients $a_c^*(\lambda)$, $a_p^*(\lambda)$ and $a_y^*(\lambda)$, respectively. Therefore, the total absorption

$$a(\lambda) = a_w(\lambda) + a_c^*(\lambda)C + a_p^*(\lambda)P + a_y^*(\lambda)Y \tag{3}$$

Similarly, for the backscattering coefficients [8]

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bc}(\lambda) + b_{bp}(\lambda) \tag{4}$$

where $b_{bw}(\lambda)$, $b_{bc}(\lambda)$ and $b_{bp}(\lambda)$ are the backscattering coefficients of water, chlorophyll and suspended matter, respectively. It is reasonable to assume that the effects of the backscattering due to yellow substance are negligible [8]. Then,

$$b_b(\lambda) = b_{bw}(\lambda) + b_{bc}^*(\lambda)C + b_{bp}^*(\lambda)P \tag{5}$$

where asterisk denotes specific coefficients. The magnitude of $b_{bw}(\lambda)$ is $0.5b_w(\lambda)$ because the molecular volume-scattering function of pure sea water, $b_w(\lambda)$, is symmetrical [9, 10].

For a case involving three water quality components, *e.g.*, chlorophyll C, suspended sediment P, and yellow substance Y, the simultaneous equations using Equations (1) to (5) for the three channels of three different wavelength (λ_1, λ_2 and λ_3) can be expressed as:

$$R_{rs}(\lambda_1) = R_1 = \frac{c}{Q}\,\frac{0.5b_{bw}(\lambda_1) + b_{bc}^*(\lambda_1)C + b_{bp}^*(\lambda_1)P}{a_w(\lambda_1) + a_c^*(\lambda_1)C + a_p^*(\lambda_1)P + a_y^*(\lambda_1)Y} \tag{6}$$

$$R_{rs}(\lambda_2) = R_2 = \frac{c}{Q}\,\frac{0.5b_{bw}(\lambda_2) + b_{bc}^*(\lambda_2)C + b_{bp}^*(\lambda_2)P}{a_w(\lambda_2) + a_c^*(\lambda_2)C + a_p^*(\lambda_2)P + a_y^*(\lambda_2)Y} \tag{7}$$

$$R_{rs}(\lambda_3) = R_3 = \frac{c}{Q}\,\frac{0.5b_{bw}(\lambda_3) + b_{bc}^*(\lambda_3)C + b_{bp}^*(\lambda_3)P}{a_w(\lambda_3) + a_c^*(\lambda_3)C + a_p^*(\lambda_3)P + a_y^*(\lambda_3)Y} \tag{8}$$

where: $b_{bw}(\lambda)$ – water backscattering coefficient, $b_{bc}^*(\lambda)$ – chlorophyll specific backscattering coefficient, $b_{bp}^*(\lambda)$ – sediment specific backscattering coefficient, $a_w(\lambda)$ – pure water absorption coefficient, $a_c^*(\lambda)$ – chlorophyll specific absorption coefficient, $a_p^*(\lambda)$ – sediment specific absorption coefficient, $a_y^*(\lambda)$ – yellow substance specific absorption coefficient.

TSS concentrations can be obtained by solving the simultaneous Equations (6), (7) and (8) to yield the series consisting of the terms in R_1, R_2 and R_3 (ignoring higher order terms):

$$P = e_0 + e_1R_1 + e_2R_2 + e_3R_3 + e_4R_1R_2 + e_5R_1R_3 + e_6R_2R_3 + \\ + e_7R_1^2 + e_8R_2^2 + e_9R_3^2 \qquad (9)$$

where the coefficients e_j (j = 0, 1, 2, …) are the functions related to the coefficients used in Equations (6), (7) and (8) which are to be determined empirically from multiple regression analysis. This equation is used to relate reflectance values from the image bands to the observed TSS concentrations.

In this study, we used detected radiation, φ, instead of reflectance values, R. The relation of polluted water in terms of suspended particles with the detected radiations was derived as

$$\mathrm{TSS} = \alpha_1\varphi_1 + \alpha_2\varphi_2 + \alpha_3\varphi_3 + \alpha_4\varphi_1\varphi_2 + \alpha_5\varphi_1\varphi_3 + \alpha_6\varphi_2\varphi_3 + \\ + \alpha_7\varphi_1^2 + \alpha_8\varphi_2^2 + \alpha_9\varphi_3^2 \qquad (10)$$

where: TSS – pollutant (total suspended solids) concentrations; φ_i – detected radiation (LED, I – blue, white, red, yellow and green); α_i – coefficients, with i = 1, 2 , ..., 9, determined empirically.

3. Results and discussion

The proposed multi-spectral sensor system consisting of (1) two pairs of LEDs (yellow, red, green, blue and white), (2) a silicon photodiode as a detector, and (3) an electronic circuit was designed to perform the algorithm implementation and standard polluted samples were prepared for sensor calibration. In this paper, a multispectral sensor gave reliable and accurate readings for suspended solids concentration in the range of 0 to 500 mg/l. Light scattering occurs when light interacts with suspended particles in the water. When light is emitted by light emitting diode, LED, and it is passed in the water sample, the incident light is absorbed or scattered with reducing or increasing respectively the intensity of transmitted light. As the concentration of total suspended solids, TSS, was increased, the intensity of the scattered radiation decreased. This decreased or increased the reading of the multimeter for case 1 and case 2, respectively. The transmitted intensity decreases negative-exponentially as a function of the TSS concentration of the solid for a fixed path-length of case 1 (Fig. 2**a**). On the other hand, the scattered light intensity is directly proportional to the TSS concentration for the diluted suspension from which the single scattering is generated and the proportionality relation breaks down by the multiple-scattering effect as the concentration increases, case 2 (Fig. 2**b**). The level of the photocurrent was negative-exponentially or linearly proportional to the pollutants concentration as shown in Figs. 2**a** and 2**b** for case 1 and case 2, respectively.

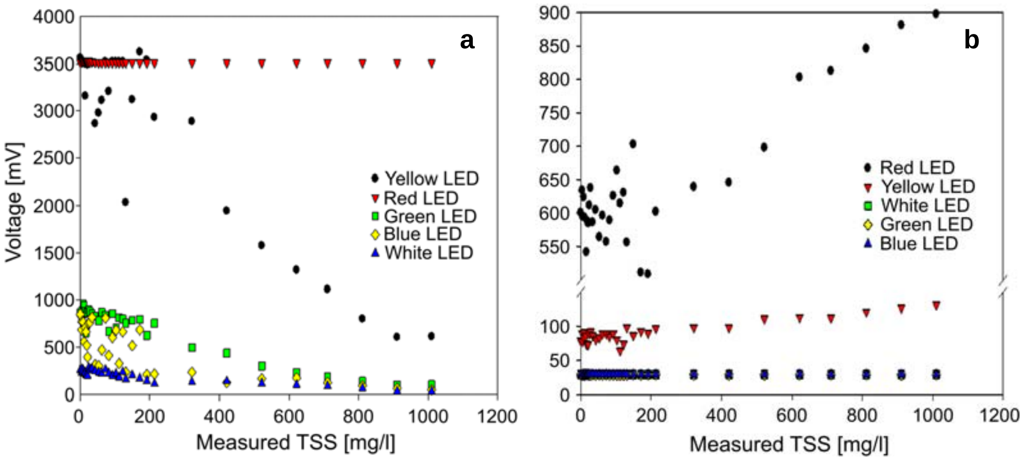

Fig. 2. TSS concentration versus voltage for case 1 (**a**) and case 2 (**b**).

The optical multispectral sensor gave reliable and accurate readings for total suspended solids concentration in the range of 0 to 400 mg/l. The optical geometry of the optical sensor was fixed. The angle between the sources and detectors was 180°. The higher the concentration of total suspended solids in the water sample, the higher the amount of transmitted light absorbed by suspended particles in water sample. Therefore, low amount of transmitted light was recorded in the direction of the detector. As the concentration of total suspended solids (TSS) was increased, the intensity of the transmitted radiation decreased. This increased the reading of the multimeter. The relationship between the estimated TSS using the proposed algorithm and measured total suspended solids concentration is shown in Figs. 3 and 4 for case 1 and case 2, respectively. The optical algorithm developed produced

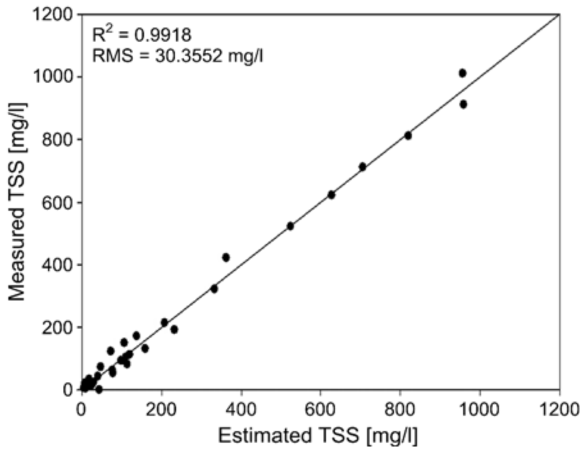

Fig. 3. The measured TSS and estimated TSS concentration (mg/l) combination of white, red and green LED for case 1.

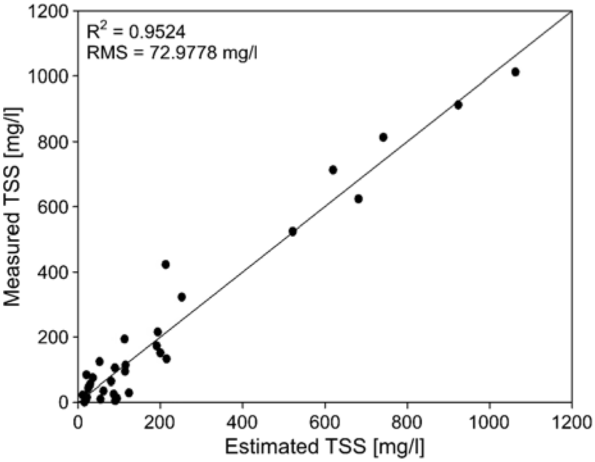

Fig. 4. The measured TSS and estimated TSS combination of red, yellow and green LED concentration (mg/l) for case 2.

a high degree of accuracy with the high correlation R^2 and low root mean square (RMS) error values. For case 1, a combination of white, red and green LED produced the highest R value of 0.9918 and low RMS value of 30.3552. For case 2, a combination of red, yellow and green LED produced the highest R value of 0.9524 and low RMS value of 72.9778. The results obtained in this study indicated that the combination of three different visible wavelengths LED gave the highest accuracy compared to that of using a single visible wavelength LED for predicting the TSS values.

4. Conclusions

This study has proven that the visible LEDs can be used as sources for the optical sensor for measuring total suspended solids concentration. This suspended sediment sensor produced a high degree of accuracy with high correlation coefficient (R) and low root mean square error. The main advantage of this optical sensor is its low cost. This optical sensor system is very useful for measuring suspended sediment concentrations of polluted water.

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