1997

Monitoring of Polluted Water Bodies by Remote Sensing

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Remote Sensing and Geographic Information Systems for Design and Operation of Water Resources Systems (Proceedings of Rabat Symposium S3, April 1997). IAHS Publ. no. 242, 1997

Monitoring of polluted water bodies by remote sensing

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Abstract The purpose of this study is to evaluate a remote sensing method for real time monitoring of wastewater effluent. Reflectance in the range from 400 to 950 nm with a spectral resolution of 2 nm, simultaneously with turbidity, chlorophyll and total suspended matter contents were acquired in two wastewater systems: R"m and Naan, Israel. The reflectance spectra of wastewater effluent were investigated in order to develop algorithms for remote estimation of wastewater quality expressed as chlorophyll-*a*, bacteriochlorophyll-*a*, non-organic and total suspended matter concentrations. Reflectance height at 720 nm and an area above the base line from 670 to 950 nm were used in algorithms for chlorophyll-*a* assessment. An area under the base line, through 780 to 900 nm, was found to be a measure of bacteriochlorophyll-*a*. Reflectance around 570 nm and reflected light in the range 400 to 950 nm were used to assess total suspended matter concentration. For the first time quantitative remote assessment of waste waters quality is reported.

INTRODUCTION

Deep wastewater reservoirs are extensively used in Israel, providing means for sewage disposal and advanced treatment, while supplying water for irrigation of industrial crops. Conventional methods to analyse the effluent quality are time consuming and quite expensive. An effective technology for monitoring water quality in ponds and wastewater reservoirs could be remote measurements of water radiance, that depends on the concentrations of wastewater constituents, absorbing and scattering light. Information on optical properties of the wastewater stored in ponds and reservoirs is scarce. Braude *et al.* (1995) used SPOT images for classification of clean water and wastewater reservoirs. Whereas major changes in the chemical conditions of the water can be detected, this technique is not likely be able to differentiate between different levels of pollution of wastewater reservoirs. Oron & Gitelson (1996) used the algorithms, developed for inland waters (Gitelson *et al.*, 1994; Yacobi *et al.*, 1995), for qualitative estimation of chlorophyll (Chl) and total suspended matter (TSS) in the R"m wastewater system. The purpose of this work is to develop a technique for quantitative estimating the quality of wastewater ponds and reservoirs, expressed as Chl-*a* in phytoplankton, bacteriochlorophyll-*a* content in bacteria and TSS concentrations.

MATERIALS AND METHODS

The possibility of using radiometry as a tool for real time monitoring of the quality of wastewater in stabilization ponds was examined at a domestic sewage treatment plant of the city of Beer-Sheva, south of Israel, and in the Naan reservoir situated in central Israel. R"m wastewater plant consists of four settling ponds, two facultative ponds, two maturation ponds, and a large open surface reservoir. Total retention time in the ponds is between 10 to 15 days. During the winter months and towards beginning of spring (November to April) the reservoir is practically full, due to reduced effluent withdrawal for agricultural reuse. The effluent from the reservoir is gradually used up towards the end of August every year.

The Naan reservoir is situated in central Israel. It collects wastewater effluent from the city of Ramla, which constitutes the major source of the reservoir water. After the primary and secondary treatments, effluents enter two shallow oxidation ponds adjacent to the reservoir. Both oxidation ponds collect wastewater effluent from Ramla, but while pond 1 is fed exclusively from this source, pond 2 also receives the manure effluent from kibbutz Naan, as well as clean water. The filling cycle begins in September and lasts until June. During this period, wastewater enters the reservoir continuously via the oxidation ponds where retention time is around 48 h in pond 1 and around 72 h in pond 2. From June, the filling is discontinued and the water is pumped for irrigation until the reservoir is almost empty towards the end of August.

The field measurements in R"m were conducted on an annual basis, seven experiments were made from March 1995 to January 1996. The field measurements in Naan were conducted on May 1995 and 1996. The radiometric measurements were collected from all the treatment ponds along the wastewater treatment course and the reservoir. The measurement stations were situated so that in each place, measurements were taken near the inlet and outlet.

A surface grab sample was taken from the scan site to the laboratory for analyses. Among parameters characterizing wastewater quality, turbidity, Chl concentration, nonorganic suspended matter and TSS, were selected. Measurements were carried out according to the standard methods for the examination of water and wastewater by APHA (American Public Health Association *et al.*, 1992). The above water quality variables constituted the groundtruth for the remote sensing assessment.

Radiometric measurements were made by a portable LICOR LI-1800 radiometer in the spectral range 400 to 950 nm with a spectral resolution of 2 nm. To measure upwelling radiance of water (L_w), the radiometer was attached to a telescope with a field of view of 15°, which was positioned over the water at a height of about 2 m. The 15° optic resulted in an instantaneous field of view of about 50 cm by 50 cm on the water surface. Downwelling irradiance (E_{dn}) was measured by a remote cosine receptor. Each reading took approximately 25 s. A microcomputer initiated spectroradiometer scanning and stored the data. Then in the laboratory, data were fed into the computer and each measured radiance spectrum of the water was normalized to the appropriate downwelling irradiance spectrum, yielding the reflectance as $R = L_w/E_{dn}$. To measure attenuation coefficient for downwelling irradiance, water samples were taken to a wide bowl; E_{dn} was measured by cosine receptor just above the water (E_0), and at depth z (E_z). The attenuation coefficient was calculated as $k_d = \log(E_0/E_z)/z$.

RESULTS AND DISCUSSION

Although the spectral reflectance features were similar for all water bodies studied, variations in magnitude of the reflectance were found all over the spectrum. The reflectance of the ponds in the entire visible and near infrared regions of the spectrum was much higher than in the reservoir. This is caused by higher scattering by suspended matter in the ponds. The reflectance spectra and the attenuation coefficient have several distinguishing spectral features (Fig. 1(a) and (b)):

(a) Minimum reflectance in the blue region of the spectrum (400-500 nm) due to maximum absorption by photosynthetic pigments and by dissolved organic matter.

(b) Maximum reflectance in the green region of the spectrum (around 570 nm) due to minimum absorption by all photosynthetic pigments of phytoplankton.

(c) A minimum around 580 nm, probably due to absorption by chlorophyll-*a* and -*c* (Goedheer, 1970).

(d) A small minimum near 624 nm, corresponding to phycocyanin absorption by cyanobacteria (Malinsky-Rushansky & Berman, 1991; Dekker, 1993; Gitelson *et al.*, 1996). The depth of the minimum is a measure of phycocyanin which defines the cyanobacteria. Despite the fact that cyanobacteria were not identified in the water samples, minimum at 624 nm, indicating phycocyanin (the dominant

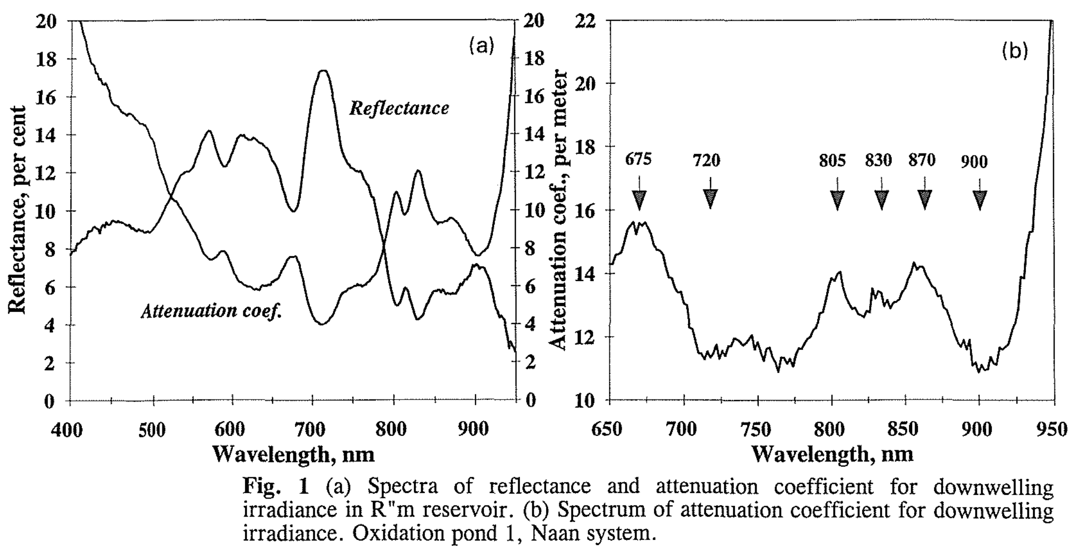

Fig. 1 (a) Spectra of reflectance and attenuation coefficient for downwelling irradiance in R"m reservoir. (b) Spectrum of attenuation coefficient for downwelling irradiance. Oxidation pond 1, Naan system.

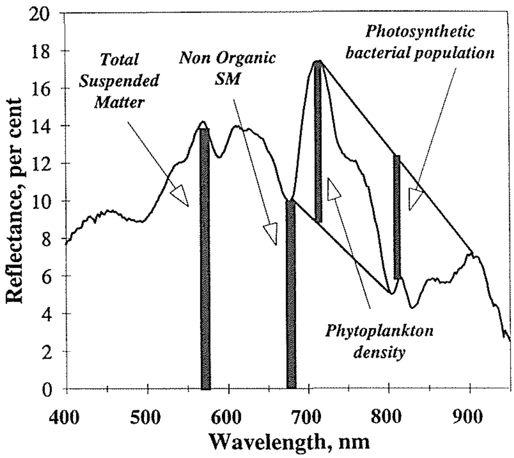

Fig. 2 Reflectance spectrum typical for waste water reservoirs. Spectral bands and characteristics of spectral features, sensitive to variation in constituent concentration are shown.

cyanobacteria pigment), was found in all reflectance spectra of the reservoir and the ponds.

(e) A gap at 676 nm is caused by chlorophyll-*a* absorption.

(f) A peak near 720 nm, caused by combined absorption of Chl-*a* and pure water (Gitelson 1992). In the spectra of the attenuation coefficient for downwelling irradiance of the reservoir (Fig. 1(a)), a minimum near 720 nm can clearly be seen. It produced a corresponding peak in the reflectance spectrum. This peak represents scattering by phytoplankton cells and other particular matter (Gitelson *et al.*, 1996).

(g) A gap in the range from 800 to 870 nm in the reflectance spectra of the ponds

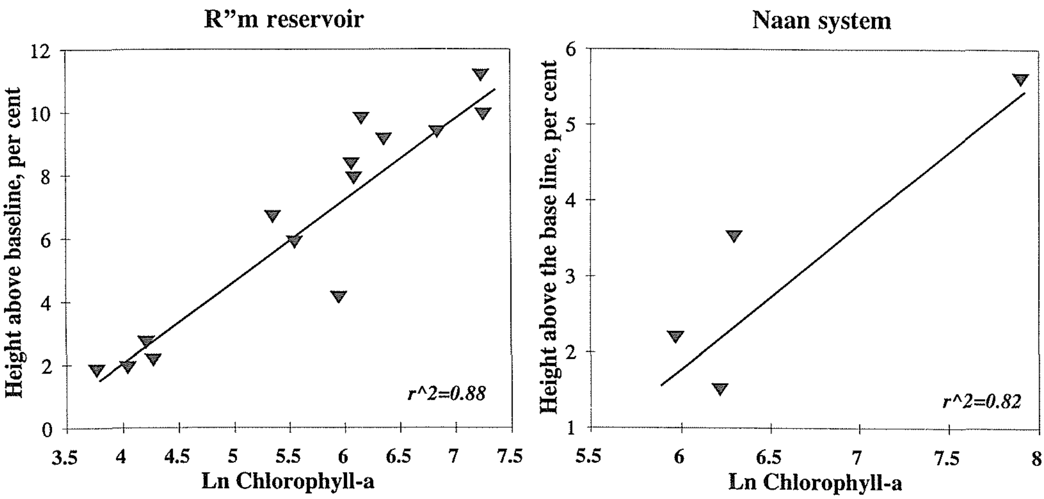

Fig. 3 Height of the peak near 720 nm above the base line through 670 to 950 nm plotted versus logarithm of chlorophyll content as actually measured in the laboratory, for both the R"m reservoir and for the Naan system.

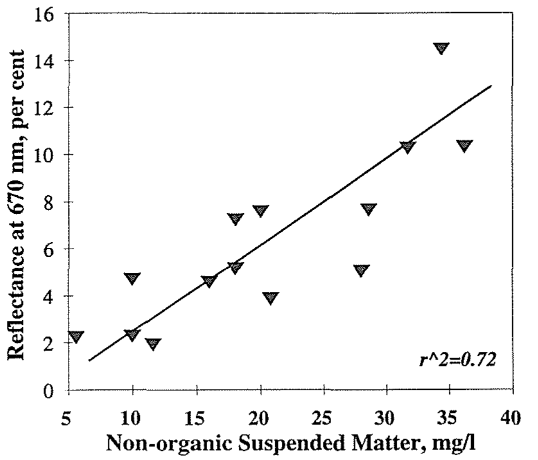

Fig. 4 Reflectance around 670 nm plotted versus nonorganic suspended matter concentration as actually measured in lab for the R"m reservoir.

(Fig. 1). Several absorption bands are present in this range: they are quite narrow near 805, 830 nm and there is a wide one around 860 nm. They form the gap of reflectance between 800 and 870 nm. Bacteriochlorophyll-*a* is dominant pigment in the Thiocapsa bacteria, that was found in the ponds. Therefore, absorption by bacteriochlorophyll-*a* is responsible for the gap between 800 and 900 nm.

(h) A peak around 900 nm. It is the result of absorption by bacteriochlorophyll-*a* at wavelengths shorter than 780 nm and absorption by pure water at longer wavelengths (Fig. 1). The minimum in the absorption spectra manifests itself in the reflectance spectra as a pronounced peak. The magnitude of the peak primarily depends on scattering by all suspended matters.

Dissolved organic matter, tripton and the "blue" Chl-*a* absorption peak yield effective light absorption. As in inland productive waters, the combined absorption effect of these constituents at wavelengths shorter than 500 nm, and the increase in scattering at shorter wavelengths make it very difficult to differentiate between the contribution of each of them to reflectance in this spectral region. Thus, as revealed in this study, only spectral features in the green, red and near infrared ranges of the spectrum, are suitable for remote sensing of wastewater reservoirs.

It was found (Gitelson *et al.*, 1994; Yacobi *et al.*, 1995), that in the wide range of Chl concentrations, the height of the peak at 700 nm above the base line through 670 nm and wavelength in near infra-red range (Fig. 2) and also an area above this base line, are linearly proportional to Chl-*a* content. For wastewater studied, reflectance height above the base line at 720 nm correlated with Chl content, measured analytically, with the determination coefficient $r^2 > 0.88$ (Fig. 3). For the sum of reflectance above the base line r^2 was higher than 0.80.

Absorption by bacteriochlorophyll-*a* in the range from 800 to 870 nm can be used to assess Thiocapsa bacteria population. The magnitude of the gap under the base line through 780 to 900 nm primarily represents photosynthetic bacterial population.

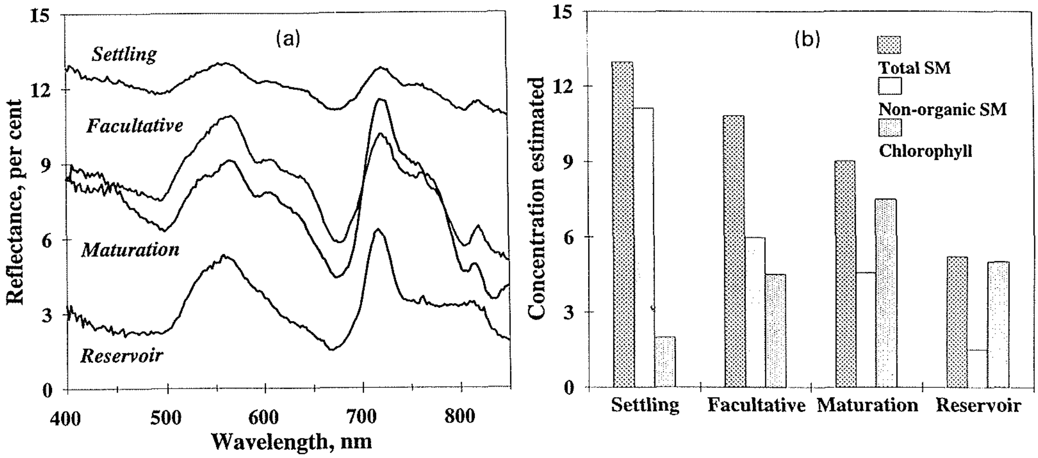

Fig. 5 R"m system, (a) reflectance spectra of ponds and reservoir and (b) quality of treatment, expressed as concentrations of "optically-active" constituents.

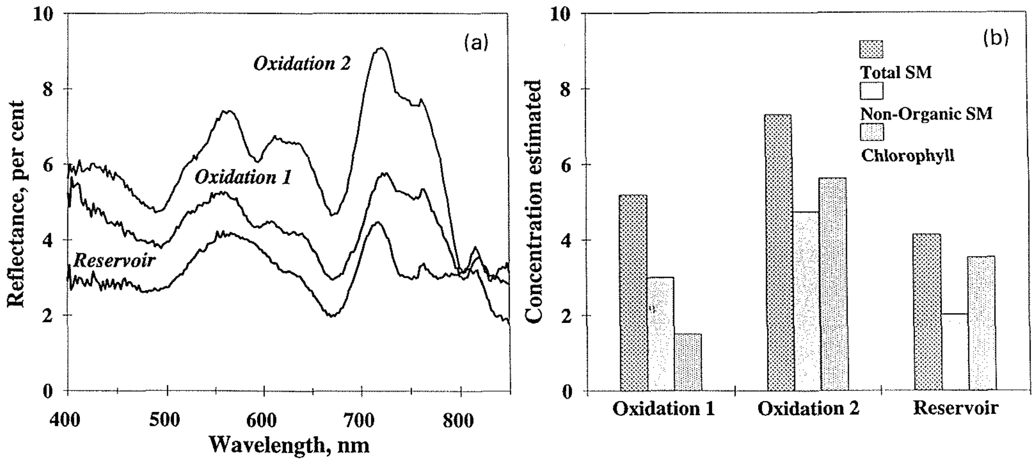

Fig. 6 Naan system, (a) reflectance spectra of ponds and reservoir and (b) quality of treatment, expressed as concentrations of "optically-active" constituents.

Nonpigmented suspended matters do not have specific spectral features. Increase in suspended matter causes an increase in back-scattering and, thus, the reflectance goes up over the whole visible spectrum. Therefore, sum of reflectance below the curve can be used for TSS assessments. Reflectance near 570 nm is relatively insensitive to phytoplankton pigments and, thus, is appropriate for the estimation of TSS. When the sum of reflectance below the curve was compared to analytical measurements of TSS, r^2 was 0.68, and when reflectance around 570 nm was compared, r^2 was 0.71. It was revealed that reflectance near 670 nm remains almost insensitive to Chl-*a* concentration (Gitelson *et al.*, 1994; Yacobi *et al.*, 1995). Thus, the magnitude of the gap is primarily dependent on non-organic suspended matter concentrations and can be used for determination of its content. When reflectance

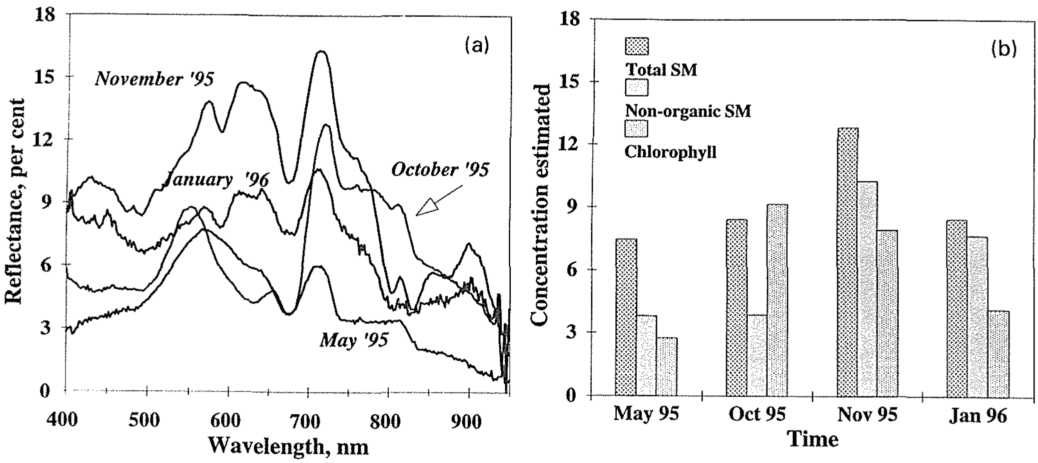

Fig. 7 R"m reservoir, (a) temporal variation of reflectance and (b) constituent concentrations. Significant differences indicate a change in water quality in reservoir.

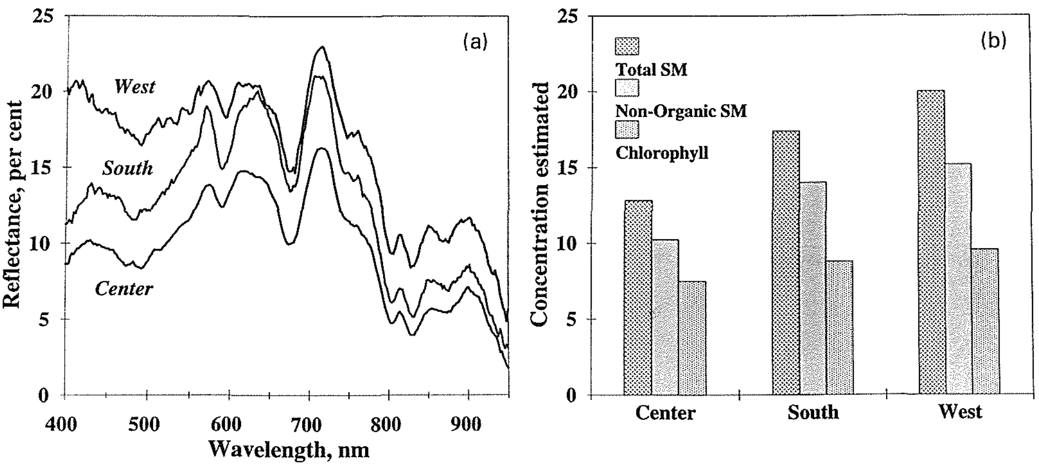

Fig. 8 R"m reservoir, (a) spatial variation of reflectance and (b) constituent concentrations. While spectral features of reflectance remain the same, variation in magnitude of reflectance is noticed.

around 670 nm was compared to the laboratory measurements of non-organic suspended matter, r^2 was 0.72 with an estimation error less than 5.42 mg l^{-1} (Fig. 4).

On the base of these findings, the quality of treatment can be assessed quantitatively from reflectance spectra measured remotely. Figures 5 and 6 show the quality of treatment in R"m and Naan reservoirs. In R"m reservoir chlorophyll content increased sharply from very low values in settling pond to the highest in maturation pond. In reservoir it was lower, remaining nevertheless, quite high. Both suspended matter concentrations were maximal in settling ponds decreasing to minimal values in reservoir. In Naan system, suspended matter concentrations were minimal in the reservoir.

Changes in the quality of water can be sensed by differences in the reflectance spectrum. Spatial distribution of reflectance in the reservoir is nonhomogeneous (Fig. 7). Temporal variation also occurred (Fig. 8), and can be used for studying the behaviour of the reservoir on an annual basis.

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