Cent. Eur. J. Geosci. • 6(1) • 2014 • 67-78
DOI: 10.2478/s13533-012-0161-4

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Central European Journal of **Geosciences**

Trophic State Index derivation through the remote sensing of Case-2 water bodies in the Mediterranean Region

Research article

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Received 16 September 2013; accepted 11 November 2013

Abstract: The main goal of this study is the derivation of Carlson's Trophic State Index (TSI) through the remote sensing of four different Case-2 waters in the Mediterranean region such as Cyprus and Greece. TSI_{SD} is derived through extensive field ground campaign of Secchi Disk Depth measurements for the Asprokremmos Dam, located in Paphos District in Cyprus; Alyki Salt Lake, located in Larnaca District in Cyprus; and in Karla Lake, located in Volos District in Greece; and finally to three coastal water areas in the Limassol coastal area. Several regression models have been applied in order to develop the best regression model between the TSI_{SD} and in-band reflectance values for Landsat TM/ETM derived from spectroradiometric measurements using a GER-1500 field spectroradiometer over the main case study area in Asprokremmos Dam in Cyprus. Finally, we apply several regression models for Asprokremmos Dam for retrieving the suitable Landsat TM/ETM band or band combinations (obtained from field spectroradiometric measurements) in which TSI_{SD} can be determined. Indeed, the best regression model has been obtained by correlating 'TSI Versus Band2/Band3', with R^2=0.89. All field TSI_{SD} and in-band reflectance values from the four different water bodies have been used to develop the best fitted model for the established TSI_{SD} Versus Band2/Band3 model. We find that the exponential regression model provides the best fitted equation over the four different water bodies.

Keywords: trophic state index • optical properties • inland water • coastal water • field spectroscopy

1. Introduction

The European Water Framework Directive (WFD) establishes a framework for the protection of groundwater, inland surface waters, estuarine waters, and coastal waters. The WFD constitutes a new view of water resources management in Europe, based mainly upon ecological elements; its final objective is achieving at least 'good ecological quality status' for all water bodies by 2015. The analyses of pressures and impacts must consider how pressures would be likely to develop, prior to 2015, in ways that would place water bodies at risk of failing to achieve ecological good status, if appropriate programs of measures were not designed and implemented [1]. Future scenarios for water resources in the Mediterranean region suggest (1) a progressive decline in the average

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streamflow (already observed in many rivers since the 1980s), including a decline in the frequency and magnitude of the most frequent floods due to the expansion of forests; (2) changes in important river regime characteristics, including an earlier decline in high flows from snowmelt in spring, an intensification of low flows in summer, and more irregular discharges in winter; (3) changes in reservoir inputs and management, including lower available discharges from dams to meet the water demand from irrigated and urban areas and (4) hydrological and population changes in coastal areas, particularly in the delta zones, affected by water depletion, groundwater reduction and saline water intrusion. These scenarios enhance the necessity of improving water management, water prizing and water recycling policies, in order to ensure water supply and to reduce tensions among regions and countries [2].

Reliable, spatially covering and cost-efficient monitoring techniques of lakes and coastal waters are generally growing in importance as a consequence of increasing symptoms of the on-going eutrophication process. Remote sensing offers a potentially significant source of information, and methods are being developed for operational large-scale monitoring of water quality [3]. At the same time, additional in situ samples and reference field spectra can aid in finding new methods and test not only the accuracy of the final image analysis output, but also the intermediate steps in that process and estimate the accuracy of the remote sensing or image processing technique under development. As a result, "ground-truth" or validation data are required to Support Remote Sensing Research and Development as is used to assist with (1) image analysis and interpretation (e.g. image classification) of remotely sensed imagery, (2) remote sensor calibration, and (3) accuracy assessment of image analysis results [4–7].

Protecting and monitoring lake water quality is a major concern for many local and state agencies [8]. Environmental researchers have been making efforts to monitor, simulate and control eutrophication for more than two decades. Various mathematical models have been developed and applied to rivers, lakes and estuaries [9–11]. Satellite and aircraft remote sensing systems has been used to monitor inland water by using the correlation between broad-band reflectance and other properties of the water column, including Secchi disk depth, turbidity, total suspended solids (TSS), Chl-a concentrations, temperature and water quality data analyzed in a laboratory [12–18].

The water quality is known to be affected by suspended sediment, phytoplankton biomass (Chl-a concentration) and dissolved organic carbon. These three components are also the major factors that control the spectral signatures of water bodies [19, 20]. Since the 1960-70s, a number of attempts have been made to quantitatively evaluate the trophic state of lakes using single-variable trophic indices or multi-parameter approaches [21]. The trophic condition of a freshwater lake is linked to densities of algal pigments, or algal biomass, which are indicative of overall productivity, as wel1 as concentrations of certain nutrients, such as nitrogen and phosphorus [22, 23]. Carlson proposed a trophic state index (TSI) [24] that retains the expression of the diverse aspects of the trophic state found in three multi-parameter indices yet also has the simplicity of a single parameter index, for water quality assessment of impounded water bodies. Carlson's trophic state index can be computed from any of the three interrelated water quality parameters: Secchi Disk (SD), Chl-a concentration, and Total Phosphorous measurement (TP). The index has since then been widely accepted owing to its calculation simplicity and ability to communicate between researchers, government agencies, and local community residents [24]. The use of remote sensing for lake trophic index formulation is based on the fact that the consequences of eutrophication and an increase in productivity will be associated with a change in the optical properties of the water mass [25].

Secchi Disk Transparency (SDT) is a standard indicator of water clarity, which is strongly correlated with biomass and annual productivity of suspended algae and is influenced by the abundance of organic and inorganic particulate and dissolved matter [26, 27]. SDT measurements are the most consistently collected data and have been found to correlate well with Landsat data [28]. Turbidity is a unit of measurement quantifying the degree to which light traveling through a water column is scattered by the suspended organic (including algae) and inorganic particles. The light scattering increases with a greater suspended load. Turbidity is commonly measured in Nephelometric Turbidity Units (NTU).

During our research, field campaigns were established in four different water bodies. The Asprokremmos Dam, located in Paphos District area in Cyprus; the Larnaca main Salt Lake, located in Larnaca District area in Cyprus; the coastal areas of Zugi Harbour; Vassiliko Cement Works and Limassol Old Harbour, located in Limassol District area in Cyprus; and Karla Lake, located in Volos District area, in Thessaly, Greece. During the field campaigns, in-situ spectroradiometric measurements and measurements of the SD and turbidity were acquired. Samples were collected for laboratory water quality analyses. The project's main objective was the comparison of the water spectral signatures of different water bodies, under various trophic conditions. In this work, characteristic spectral signatures of each water body for several turbidity values are presented and discussed. Furthermore, the TSI values based on SD field measurements are calculated and used for the development of a simple algorithm which aims to estimating the TSI_{SD} directly from the Landsat ETM+ spectral bands.

2. Materials and methods

In this section the overall methodology and the resources used during the field studies are described. The main objective of this project is to examine the spectral characteristics of several water bodies. The examined water bodies refer to sites with different productivity levels such as oligotrophic (coastal sites), mesotrophic/eutrophic (Asprokremmos Dam and Larnaca Salt Lake) and eutrophic/hypertrophic (Karla Lake). The specific coastal sites were selected as potential point sources (harbors and cement works) are located at those areas.

2.1. Study areas

Four study areas were selected for our research field campaigns, representing four different categories of water bodies. The intense modification of their characteristics increases the range of the performed measurements/data, extending the validity of the concluding results, as will be shown. Special attention was given in choosing sites with ecological interest and/or those that contain water that is under pressure. Three sampling sites are located in Cyprus and one is in Greece. Specifically, as shown in Figure 1, in Cyprus we selected (1) the Asprokremmos Dam in Paphos District, and (2) the Larnaca main Salt Lake in Larnaca District area, both of which are coastal sites. The third area refers to (3) the coastal area of Limassol with three sampling points across the coastline at (3.1) Zugi, (3.2) Vassiliko Cement Works and (3.3) Old Harbor, all facing distinct tensions. The fourth selected area is (4) Karla Lake, located in Volos District area in Thessaly, Greece (Fig. 3). This area was selected as it shows much higher values of nutrients concentration compared to the respective observations in the Cyprus water bodies.

Asprokremmos Dam, located in Paphos District in Cyprus, was the main pilot study area in which extensive sampling campaigns were performed. Asprokremmos Dam is built at an altitude of about 80 m above sea level and is located 16 km east of the city of Paphos. The construction was completed in 1982 and is the second largest reservoir in Cyprus with a maximum capacity of 52,375,000 m^3. It is an earth fill dam consisting of the main embankment, spillway, tunnels and galleries and geotechnical works. Due to the relatively poor rainfall the dam rarely overflows. The Xeros River which flows directly into the dam runs only during winter and spring. The dam's water is used for both potable and irrigation purposes. Figure 2 presents the two areas of the reservoir where extreme conditions are observed (Outlet Area: lower turbidity values & Inlet Area: higher turbidity values). In-situ campaigns were carried out with the collaboration of the Cyprus Water Development Department, Paphos, Cyprus [30].

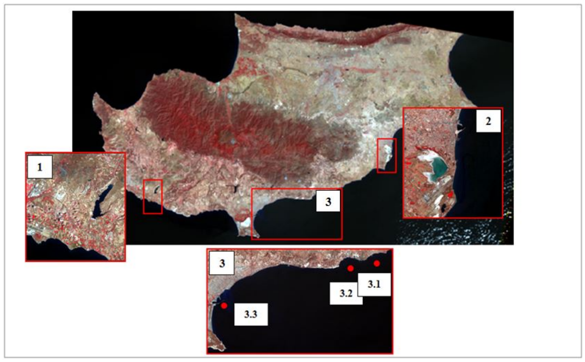

Figure 1. Examined water bodies located in Cyprus, (1) Asprokremmos Dam, Paphos District; (2) Larnaca main Salt Lake (Alyki), Larnaca District and (3) coastal area of Limassol District (3.1 Zugi, 3.2 Vassiliko Cement Works & 3.3 Old Harbor).

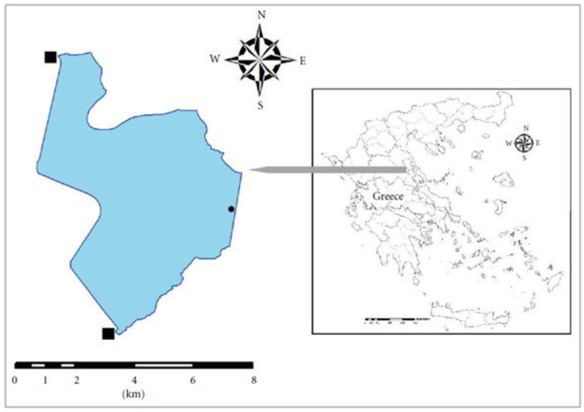

Figure 2. Map of Lake Karla, located in the Volos District area, Thessaly, Greece. Black squares show points of inflowing water for reconstruction purposes. Centre of the lake is at 39°29′00″ N, 22°49′00″ E. (Reproduced from Oikonomou *et al.*, 2012 [29]).

2.1.1. *Larnaca main Salt Lake (Alyki)*

The Larnaca Salt Lake Complex is one of the most important natural standing water bodies in Cyprus and is of international ecological significance (declared a pro-

Figure 3. Picture of Asprokremmos focused in the (a) Outlet Area & (b) Inlet Area of the Dam.

tected area by a decision of Council of Ministers (1997), Ramsar Site, Natura 2000 Site, Special Protected Area under Barcelona Convention, Important Bird Area). It consists of four main lake water bodies, the main Salt Lake (Alyki), Orphani, Soros and the small so-called Airport Lake, which was part of the Orphani Lake but was cut off when the airport runway was constructed [31]. This wetland area in southeastern Cyprus is in one of the driest parts of the island. The three most important climatic factors determining the development of salt lakes are temperature, net evaporation and precipitation [32]. The wetland area includes extensive halophytic communities on the shores of the lakes and in the area between the lakes and the sea. Two small forests - one by the western bank (Tekke), and the other on the east bank of Alyki - add bio-diversity to the area.

Our research field campaigns focused on Alyki, which is the main salt lake, having a very high salinity regime, hence its use in the past for salt collection [31]. The hypersalinity of Larnaka's salt lake makes it inhospitable to many life forms and only some specialized adapted forms can survive [33]. The alga that forms the basis of the food chain here is Dunaliella salina, a brick red unicellular alga, which is a very salt tolerant species. On this alga feeds Artemia salina, the Brine shrimp. These shrimps are the main food of the Flamingo and of other birds in these lakes. On average, about 1000-2000 Flamingo overwinter here each year, though in peak years, such as 1995 and 2005, there may be as many as 7000 [34, 35].

2.1.2. Coastal Areas in Cyprus (Limassol District Area)

Cyprus is the third largest island in the Mediterranean (after Sicily and Sardinia) with an area of 9,251 square km and has 772 km of shoreline of which 404 Km are in the occupied areas, 72 km within the Sovereign British Base areas, and only 296 km within the area controlled by the Government of Cyprus. The most serious coastal-planning problems today relate to the sudden expansion of the main coastal urban centers of Limassol, Larnaka and Paphos and have mostly been caused by the type and the speed of development. From a survey [36] of a coastal stretch of 181 km, in 1973 development along the coastal zone was only 22 km urban, 9 km suburban/tourist and 150 km pristine. This picture changed completely in 1991 with 31 km urban, 48 km suburban/tourist and only 102 km pristine coastline. Serious problems started to appear also in the coastal zone outside from the urban areas, mainly due to the rapid encroachment of development of tourism facilities and holiday homes in natural/pristine areas [36].

The Ministry of Agriculture, Natural Resources and Agriculture is responsible for the control of the pollution of water and soil, which is a result of human activities. Continuous studies are conducted dealing with the impact of pollution on marine ecology, as well as with the impact of aquaculture on marine biodiversity. For the assessment of the ecological status of coastal waters, a relevant monitoring is being implemented within the Water Framework Directive (2000/60/EC). Furthermore, within the MED POL Program, a monitoring of the coastal water quality including the assessment of pollutants (heavy metals etc.) in sea-life is carried out. It is a fact that excessive use of fertilizers has resulted in high nitrate levels in the aquifer in specific areas, leading in some cases to higher nutrient concentration. This factor, combined with other synergistic mechanisms, has resulted to the occasional occurrence of the ephemeral macroalgae Cladophora at a few beaches [37]. The study areas are located in the Limassol District on the southern part of the island of Cyprus. Three different sampling stations were selected as Figure 1 indicates (3.1 is the area of the Zugi Harbour, 3.2 is the area of the Vassiliko Cement Works and 3.3 is the area of the Old Harbour); all are under relatively strong anthropogenic pressure.

2.1.3. Lake Karla (Thessaly, Greece)

Lake Karla, is located in the plain of Thessaly, in the Volos District area, in Greece (see Fig. 2) and was selected as a case study because it shows high values of nutrients concentrations (such as chlorophyll-a and phosphates) compared to those observed in Cyprus water bodies. Lake Karla was also chosen because notably, until 1962, it was a natural lake sustained by Pinios River winter flood flows and basin runoff. That period, the natural lake Karla was covering most of the eastern part of Thessaly plain in central Greece. It was one of the most important wetlands in Greece and a natural reservoir which provided significant water storage. The basin surface runoff and the overflowing floodwaters of Pinios River sustained Lake Karla. The lake area was fluctuating from 40 to 180 km^2 due to the very gentle land slope and the inflow-outflow balance. For this reason, a significant area of the surrounding farmland was often inundated, facing soil salinity problems [29, 38–40]. The lake was drained through an ambitious reclamation project, mainly for agricultural purposes. Quite shortly after the reclamation project's completion, it became evident that it was a failure. In fact it created bigger problems than the ones it was supposed to solve. The decision to restore part of the former lake has only recently been made by the Greek government, although numerous studies advocoating the construction of a reservoir have been made throughout the period following the lake's drainage. Currently a project for a partial restoration of the Karla Lake is under progress. According to the current scheme, a water reservoir with a size of 3,800 Ha will be created in the lowest part of the old lake bed [29, 40, 41].

2.2. Resources

The sampling campaigns started in April 2010 and lasted until October 2010 including eighteen sampling campaigns at the Asprokremmos Dam. Five sampling campaigns were performed in open sea, ten in the Karla Lake and five in the Alyki. The main resources used during the field campaigns will be described in this section. A power-engine boat was used to support the in-situ campaign in the main study area at Asprokremmos Dam in Paphos. A small boat was used to support the in-situ campaign in the Karla Lake in Thessaly region, in Volos, in Greece. A canoe boat was used in order to carry out the sampling campaigns in Larnaca main Salt Lake (Alyki) in Larnaca District, in Cyprus. Finally, a ship was used in order to carry out the sampling campaigns in Limassol District coastal areas, in Cyprus. A Global Position System (Garmin GPS72) and a differential Leica Viva GPS, utilized in order to track the locations of the selected sampling stations during all the campaigns.

A hand-held GER-1500 field spectroradiometer (which has a spectral range extending from 350 nm to 1050 nm and 512 channels with a sampling bandwidth of 1.5 nm) equipped with a fibre optic probe was occupied in order to retrieve the water spectral signatures just below the water surface of the examined water bodies. Reflectance values were calculated as the relative reflectance which is determined as the ratio of the target radiance (upwelling radiance from the water body) to the reference radiance (upwelling radiance measured on the white reference panel with approximately 100% reflectance across the spectrum). McCloy [42] describes the technique for measuring the reflectance factors using a control stable surface with known characteristics. This is the method that was followed in this research for the spectroradiometric measurements. For the aims of the current study, a commercially available "Labsphere" compressed "Spectralon" white panel was used as the control stable surface. Spectralon diffuse reflectance targets are ideal for field applications which are performed in order to collect remote sensing data since they appear high reflectance. Spectralon diffuse reflectance targets appear typical reflectance values range from 95% to 99% and are spectrally flat over the UV-VIS-NIR spectrum. Stability of the light field is always an issue in field measurements because sky conditions are not always stable. For this reason a reflectance measurement was always taken over the "Spectralon" white panel shortly before every single reflectance measurement acquired over a water body during the field campaigns [43, 44]. Reflectance data were collected from a boat at a depth of approximately 10 cm below the water surface in the vertical downward direction. The relative reflectance measures were oriented to the boat side within the light propagation to minimize sun glint from waves, but far enough not to be affected by the boat shadow [45]. Also, the in-situ determination of water turbidity was achieved using both a portable turbidity meter (Palintest Micro950) and a Secchi Disk. Secchi Disk depth measurements were taken over the shady side of the boat [46]. In addition, water surface samples were collected and laboratory analyses for the estimation of chl-a, phosphates and total suspended solids concentrations were established.

3. Results and discussion

We use a combination of TSI_{SD} measurements and spectral characteristics of the water bodies to explore the effectiveness of simple algorithms relating directly TSI_{SD} to common spectroradiometric measurements. Specifically, SD measurements of the Asprokremmos Dam were used to calculate the Carlson's TSI_{SD} through the relation (1).

$$TSI_{SD} = 60 - 14.41 Ln(SD) \qquad (1)$$

All the spectral measurements were processed in order to calculate the respective mean in-band reflectance values using the relative spectral response filters given by the U.S. Geological Survey (USGS) including the spectral characteristics of the Landsat ETM+ sensor as shown in [47]. All the TSI_{SD} values were correlated with the corresponding mean in-band reflectance values and several tests were done to achieve the best correlation sets. Several regression models between TSI_{SD} and different band combinations were examined in order to retrieve the most effective relation in order to monitor the TSI_{SD} using Landsat ETM+ sensor data. Results of one- and two-band linear regression were applied, based on the measurements acquired during the extended sampling campaign that took place during 2010 at the main study area of the Asprokremmos Dam covering the entire reservoir surface. Eighteen field campaigns were performed with a total of 161 measurements. All the results are given in Figure 4, where the correlation between the TSI_{SD} measurements and several spectral-related values are shown. In most cases a linear relation represents the data reasonably well. In the cases of using spectral data from Band3 and Band4, a log-linear relation improves the correlation coefficients slightly. In all cases, the best correlation (R^2 = 0.87) was achieved between the TSI_{SD} and the Band ratio 2:3 of the Landsat ETM+ mean in-band reflectance values (see Fig. 4), resulting in a clear linear relation of the form (2).

$$TSI_{SD} = 86 - 12\text{Band2/Band3} \tag{2}$$

As noted, this result was derived during the sampling campaign of the Asprokremmos Dam indicating that the best correlation was given for the Band ratio 2:3. The result indicates that the maximum TSI_{SD} value should be around 86, when the Band ratio 2:3 vanishes. Admitting that the range of the measured data is relatively short, we may also try to fit an exponential curve, which could be approximately linear in the specific short range of the data. This is shown in Figure 5, where it is evident that the approximate linearity in the range of the data is not modified. However, the exponential relation allows for higher TSI_{SD} values at low Band ratios 2:3, estimating a maximum TSI_{SD} value around 93 as the Band ratio 2:3 vanishes. Taking into account that the maximum possible TSI_{SD} value should be 100 [41], we force the intercept to match this limit, obtaining, without any serious distortion to the correlation coefficient, the exponential relation (3).

$$TSI_{SD} = 100\exp(-0.24\text{Band2/Band3}) \tag{3}$$

Additional surveys were performed over the Larnaka's Salt Lake, the Karla Lake and the Limassol coastal area, aiming to collect additional SD and field spectroradiometric data in order to test the generality and the effectiveness of the above equation (3). Taking into account the results of all the examined water bodies, the exponential behavior becomes evident (Figure 6). Both the exponential and the linear models successfully describe the results derived from the Asprokremmos sampling campaign as both curves appear similar in that range. The inclusion of the rest of the data, however, promotes drastically the choice of the exponential fit. Specifically, Asprokremmos Dam TSI_{SD} values range from 40.0 to 77.3 with an average value of 54.4, while for the case of Larnaca's Salt Lake TSI_{SD} values range from 69.4 to 70.6 with an average TSI_{SD} value of 70. Both data sets are accurately described by the acquired equation (3). For the coastal water bodies, TSI_{SD} values range from 13.6 to 15.5 with an average TSI_{SD} value of 14.5. In that case, equation (3) slightly overestimates (by around 7%) the measurements. On the other side, for Karla Lake the TSI_{SD} values range from 73.9 to 90.5 with an average TSI_{SD} value of 80.3 which is underestimated (by around 15%) using equation (3). However, it is evident that the measurements over Karla Lake reveal a different pattern in comparison to the rest of the data; this is perhaps due the fact that Karla Lake is a severely hypertrophic lake with high concentrations of nutrients, contrary to the Asprokremmos Dam and the other sites. It is important to mention that in the case of the Asprokremmos Dam, the concentration of chl-a ranged from 4 to 40μg/L (average 14.9μg/L), contrary to the case of Karla Lake where concentrations of chl-a ranged from 5 to 311μg/L (average 73.4μg/L). Still, the divergence is considered reasonable.

Aiming to secure the validity of equation (3), the fitting procedure of the exponential relation was repeated, including the whole data set from all the measuring sites. As shown in Figure 7, in that case the two parameter exponential fitting reveals an intercept close to the limit of 100 (102). Forcing the intercept to match this limit results in exactly the same coefficient in the exponential (-0.24) that appears in (3). It is worth noted that in this case, where all the measurements are used, the overall correlation coefficient increases to 0.91. This result indicates that the acquired empirical equation seems trustful, and could be used as a first guide for the estimation of TSI_{SD} values from spectral characteristics, showing good overall performance with a smooth behavior between the limiting values of TSI_{SD} (0 - 100).

Still, further work is needed in order to strengthen and test the previous result with measurements at the range of high TSI_{SD} values (more than 70), and especially at the range of relatively low TSI_{SD} values (less than 40) where a clear gap in the data can be observed (Figs. 6-7). This is due to the fact that the coastal waters of Cyprus are classified among the poorest in nutrients of the world's oceans, and are characterized as ultra oligotrophic. Since the background values of nutrients are very low, the sea around Cyprus has low productivity resulting in very low TSI_{SD} values around 20. The inclusion of the missing information can be achieved either by performing field measurements over different seawater bodies in Cyprus, looking for areas (with the aid of remote sensing and satellite data) with highest TSI_{SD} values or by performing such measurements over other seawater bodies in other Mediterranean countries (such as Greece or Italy) where higher TSI_{SD} values have been observed. Also, due to the simplicity of the relation, the theoretical investigation and the link of

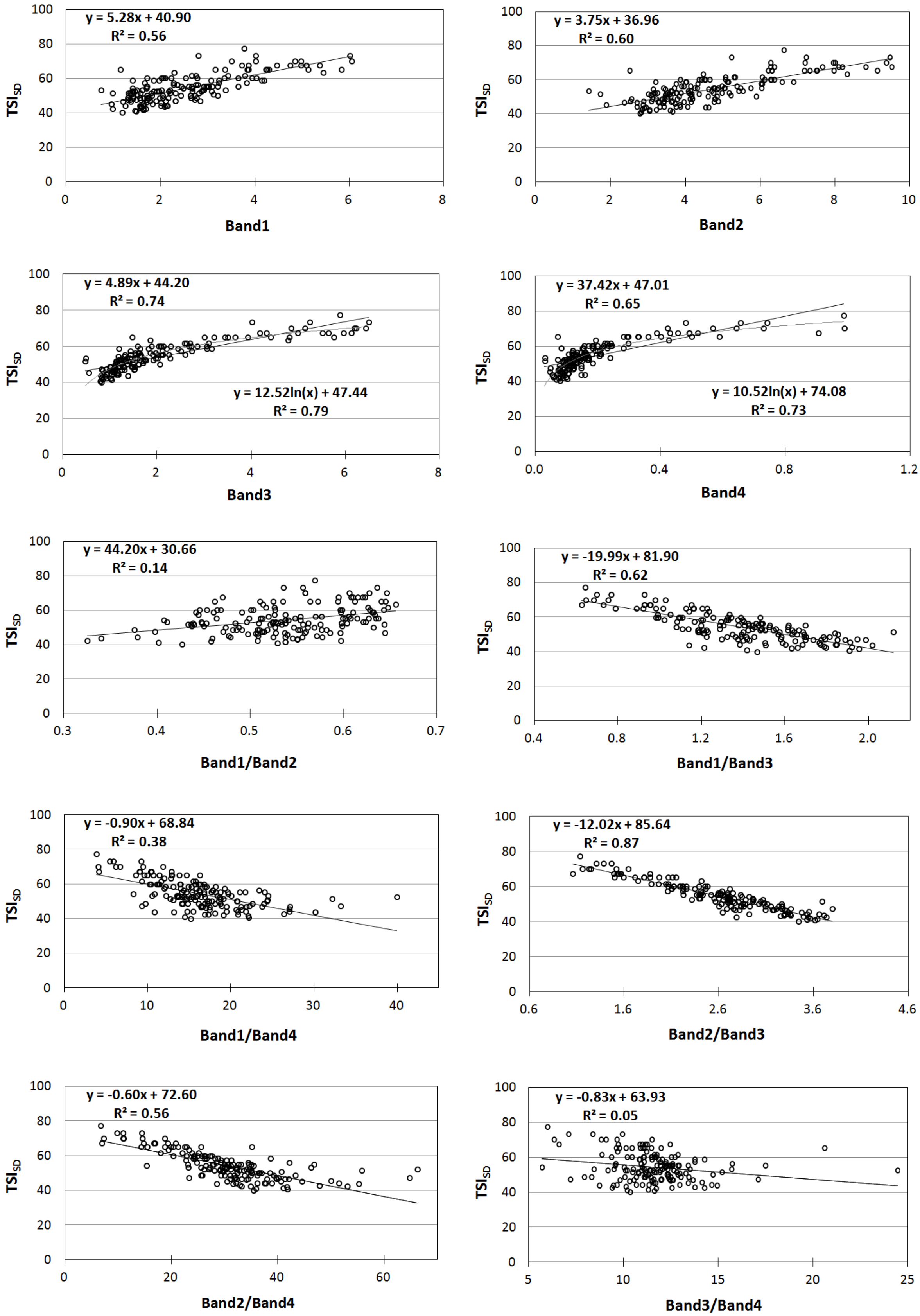

Figure 4. Correlation between TSI_{SD} and several Landsat ETM+ one- and two-band combinations derived using the ground truth measurements acquired during the extended field campaigns at the Asprokremmos Dam, Paphos District.

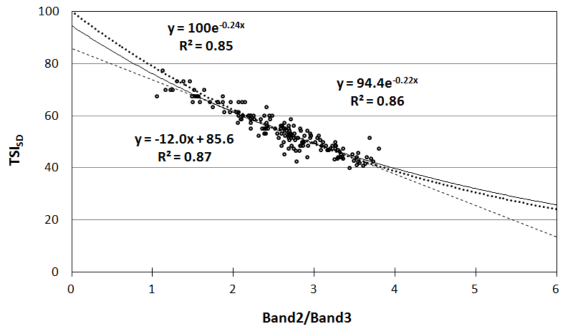

Figure 5. Comparison of a simple linear and two exponential regression models used to describe the relationship between our variables of interest, TSI_{SD} and the ratio Band2/Band3, derived from the ground truth measurements acquired during the extended field campaigns at the Asprokremmos Dam, Paphos District. The linear model is shown as a dashed line, the exponential model is displayed as a continuous line and the exponential model, with an intercept of 100, is displayed as a dotted line.

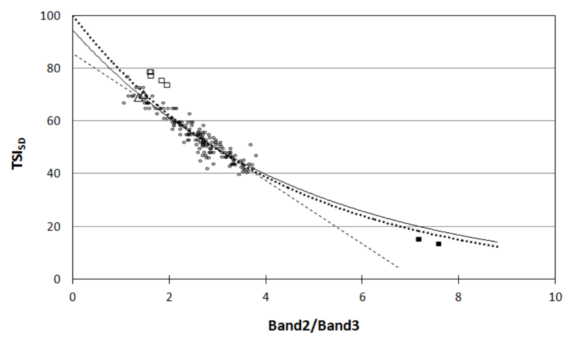

Figure 6. A simple linear and the two exponential regression models used to describe the relationship between our variables of interest, TSI_{SD} and the ratio Band2/Band3, derived from the ground truth measurements acquired during the extended field campaigns at the Asprokremmos Dam, Paphos District. The linear model appears on the diagram as a dashed line, the exponential model is displayed as a continuous line and the exponential model, with an intercept of 100, is displayed as a dotted line. Data are acquired from four different water bodies, Asprokremmos Dam in Paphos District; Larnaca main Salt Lake (Alyki); the coastal area of Limassol and Karla Lake in Volos District, Thessaly, Greece. The empty circles represent measurements taken at the Asprokremmos Dam; the empty triangles represent the measurements taken at the Larnaca main Salt Lake (Alyki); the empty squares referred to the measurements taken at the Karla Lake and the filled squares correspond to data acquired at the coastal area of Limassol.

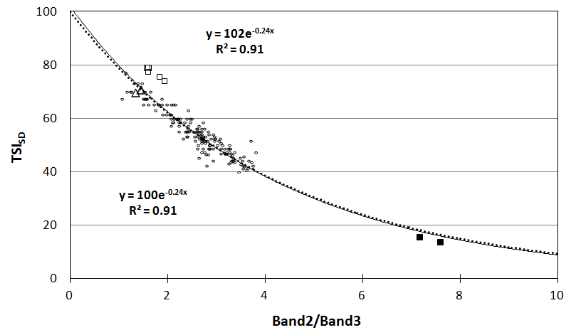

Figure 7. Correlation between TSI_{SD} and ratio Band2/Band3 of the mean in band reflectance of ETM+ derived from the ground truth measurements performed over four different water bodies, Asprokremmos Dam in Paphos District; Larnaca main Salt Lake (Alyki); coastal area of Limassol and Karla Lake in Volos District, Thessaly, Greece. The two exponential regression models used to describe the relationship between our variables of interest are shown. The exponential model is displayed as a continuous line and the exponential model with an intercept of 100 is displayed as a dotted line. The empty circles represent measurements taken at the Asprokremmos Dam; the empty triangles represent the measurements taken at the Larnaca main Salt Lake (Alyki); the empty squares referred to the measurements taken at the Karla Lake and the filled squares correspond to data acquired at the coastal area of Limassol.

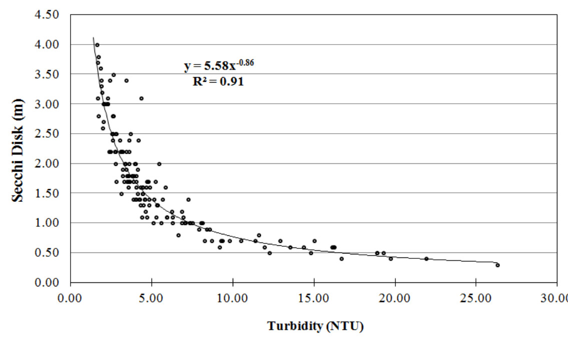

Figure 8. Correlation between SD and turbidity (NTU) acquired during the field campaigns at the Asprokremmos Dam, Paphos District.

the relation to known physical mechanisms that drive this result would be a provoking opportunity. Such possibility is left for future research.

In conclusion, further analysis of the measurements acquired during the sampling campaigns at the Asprokremmos Dam has shown that there is an exponential relation between turbidity (NTU) and SD. As shown in Figure 8, the relation between the two variables can expressed as LnSD = 1.72 - 0.86 LnNTU. This equation can be used in order to convert any available turbidity (NTU) measurement to SD, and to further calculate TSI_{SD} using the extracted equation (3).

4. Conclusions

Trophic state is an important parameter for the water quality studies and there is a great need for its systematic monitoring in different water bodies, such as inland and coastal waters. Above all, TSI_{SD} can be used as an alert tool from the local water management authorities. This study fills the gap of developing a suitable regression model between TSI_{SD} and spectral reflectance values acquired from field spectroscopy with the main aim to assist future satellite observation. The development of a suitable regression model that utilizes reflectance measurements acquired using field spectroscopy assists remote sensing users in retrieving accurate statistical results since atmospheric interventions are eliminated. Data from four different field campaigns were presented and utilized. Specifically, in-situ spectroradiometric measurements and measurements of the SD and turbidity were analyzed and correlated. The TSI values based on SD field measurements were used for the development of a simple algorithm which helps in the direction of estimating TSI_{SD} directly from the Landsat ETM+ spectral bands. We have shown that an optimal correlation between spectral characteristics and TSI_{SD} values may be obtained by using an exponential regression model of the form The formula performs surprisingly well in a wide range of data from very different sources. The acquired empirical equation seems trustful, and could be used as a first guide for the estimation of TSI_{SD} values from spectral characteristics, showing a good overall performance with a smooth behavior between the limiting values of TSI_{SD} (0 - 100) for Case-2 water bodies in the Mediterranean region.

It is important to highlight that the proposed methodology using field spectroradiometric measurements for deriving the TSI_{SD}, can be applied not only on Landsat TM or ETM remotely sensed data but also for any other new satellite sensor (e.g. ESA CHRIS-PROBA) that covers partially the spectral ranges of field spectroradiometers (e.g. for the GER1500 350-1500 nm or the SVC1024 350 -2500 nm). This gives the opportunity to further test the applicability and accuracy of the method deriving also the appropriate trophic index for specific water types. We have focused on the development of an algorithm which can be applied on Landsat TM/ETM satellite image data to obtain the TSI_{SD} values, since it is the most widely used satellite providing a continuous record of earth observations, and a large number of cloud-free archived data are available for the case of Cyprus which is of great importance for monitoring programs. Indeed, we can extent our approach to any new satellite sensor.

5. Acknowledgements

his work was co-funded by the European Regional Development Fund and the Republic of Cyprus through the Research Promotion Foundation (The "SATCOAST" Project ¡PI¿¡EPSILON¿¡NU¿¡EPSILON¿¡KAPPA¿/0609/60).
The authors gratefully acknowledge the Department of fisheries and marine research in Cyprus; the Water Development Department in Cyprus; the Maritime Institute of Eastern Mediterranean, Limassol, Cyprus; the Department of Civil Engineering, University of Thessaly, Volos, Greece and the Management Body of the Eco-Development Area of Karla, Mavrovouni, Kefalovriso and Velestino for their technical support during the in-situ measurements. In addition the authors would like to acknowledge the Cyprus University of Technology / Department of Civil Engineering and Geomatics (Remote Sensing Laboratory), Limassol, Cyprus for supporting this study.

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