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Reservoir Trophic State Evaluation Using Landsat TM Images

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Abstract

Reservoir water quality is traditionally monitored and evaluated based on field data. Collecting and analyzing field water quality data are cost and time consuming, and whether a limited number of field data truly characterize the spatial variation of trophic state within a vast water body is often disputed. In this study we utilize Landsat TM data to estimate the water quality and trophic state of the Te-Chi reservoir in Central Taiwan. A modified multi-parameter model of Carlson's trophic state index (*TSI*) was developed for the Te-chi reservoir. Water quality parameters (concentration of chlorophyll-a, total phosphorous measurement, and secchi disk depth) required by the model are found to have high correlations with combinations of TM bands. Therefore, TM data are used to map the trophic state of the reservoir. TM-derived *TSI* maps of the reservoir reveal that, in summer, trophic state in the reservoir generally improves from upstream to downstream, and zones of distinct trophic state exist. Trophic state index based on secchi disk depth may give erroneous values in upstream section of the reservoir pool due to high sediment concentration in the reservoir inflow. We conclude that the Te-Chi

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reservoir is eutrophic or worse in summer and meso-eutrophic in winter. Implementation of best management practices to reduce nonpoint source pollution in the upstream watershed is highly recommended. This study demonstrates the capability of mapping trophic state in impounded water bodies using the Landsat TM data.

Keywords: Landsat TM, remote sensing, reservoir, trophic state.

Introduction

Traditionally the quality and trophic state of water in impoundments have been assessed using limnological methods and laboratory analyses of field-sampled data. In the early 1970s, trophic state of lakes was determined by several diverse criteria such as shape of the oxygen curve, species composition of the bottom fauna or of the phytoplankton, concentrations of nutrients, and various measures of biomass or production (Carlson, 1977). Single- and multi-parameter indices were developed for trophic classification of lakes (Brezonik and Shannon, 1971; Beeton and Edmonson, 1972). A multi-parameter index is often limited in its usefulness because of the number of parameters that must be measured, whereas arguments arise over which parameter should be considered for the single parameter index. Carlson (1977) proposed a trophic state index (*TSI*), that retains the expression of the diverse aspects of the trophic state found in 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 depth* (*SDD*), *chlorophyll-a concentration* (*Chla*), 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.

Determination of trophic state using field-collected water quality data is time and cost consuming, and whether a limited number of field data can adequately represent the overall quality of a vast water body is often disputed. To circumvent the disadvantages of traditional data collection method, utilization of remote sensing data for water quality assessment has been investigated. Previous work has shown that remote sensing data can not only be used to estimate certain individual water quality parameters, these data can also be related to trophic state indices developed from single or multiple water quality parameters.

Lillesand *et al.* (1983) utilized Landsat MSS data to classify trophic states of many lakes in Minnesota, United States. A series of regression models was developed to relate digital numbers (DN) of Landsat bands to *TSI* values. Regression relations between

Landsat DN and raw water quality measurements were found to be less successful in comparison to their *TSI* counterparts, indicating that transformation into *TSI* values improves the model performance. Ekstrand (1992) and Tassan (1993) also proposed models for estimation of chlorophyll and sediment concentration in coastal waters using Landsat TM data. Lavery *et al.* (1993) developed regression models for prediction of surface water quality parameters (pigment concentration, *SDD*, and salinity) from TM data, and demonstrated that Landsat TM data has the resolution and accuracy to be a potentially very useful tool for water quality monitoring in estuarine waters. Han (1997) found that the same amount of suspended sediment generated higher reflectance in clear water than in algae-laden water between 400 and 700 nm. Han and Rundquist (1997) tested the use of ratio of near infrared (NIR; 705nm) to red (670nm) based on field spectrometer measurements and found that the NIR/red ratio was not an effective predictor of algae-chlorophyll concentration in relatively turbid reservoirs. Thiemann and Kaufmann (2000) found that a linear spectral unmixing method using IRS –1C satellite data yielded good estimation of chlorophyll-a content in lakes. Avard *et al.* (2000) demonstrated that an exponential model based on the physics of light scattering from particles suspended in water could effectively describe the relationship between chlorophyll concentration in reservoirs and corresponding airborne video data.

Although empirical models have been developed for water quality monitoring using remote sensing data, most of these studies were conducted in coastal or estuarine waters, or used field-spectrometer measurements in inland lakes. Also chlorophyll and sediment concentrations in several Taiwan's reservoirs are found to be much higher than that reported in the above studies. Therefore, objectives of this study include estimation of the water quality and development of a *TSI* model for a reservoir in Central Taiwan, using Landsat TM images.

Carlson Trophic State Index

Carlson's *TSI* model converts raw data of *SDD*, *Chla*, and *TP* to a standard numerical scale ranging from 0 to 100 based on the following empirical relationships between water quality parameters

$$\ln SDD = 2.04 - 0.68 \ln Chla \,, \qquad (1)$$

$$\ln Chla = 1.449 \ln TP - 2.442 \,. \qquad (2)$$

The units are meters for *SDD* and $\mu g/\ell$ for *Chla* and *TP*.

Two important premises of Carlson's *TSI* model are: (1) the zero point on the *TSI* scale is located at an *SDD* value of 64 m, the next integer on the $\log_2$ scale larger than the greatest *SDD* value (41.6 m in Lake Masyuko, Japan) that has been reported (Carlson, 1977), and (2) an increase of 10 *TSI* units corresponds to a halving of *SDD*. For convenience of explanation, we refer to these premises as *the range factor of 64 m* and *the scale factor of 2*. Based on these premises, *TSI* can be calculated from *SDD* measurements using the following equation:

$$TSI(SDD) = 10(6 - \frac{\ln SDD}{\ln 2}) . \quad \text{(3a)}$$

Substituting equations (1) and (2) into Eq. (3a) yields

$$TSI(Chla) = 10(6 - \frac{2.04 - 0.68 \ln Chla}{\ln 2}) , \quad \text{(3b)}$$

$$TSI(TP) = 10(6 - \frac{\ln(48/TP)}{\ln 2}) . \quad \text{(3c)}$$

Hereafter, equations (3a, 3b, 3c) shall be referred to as the Carlson's *TSI* model.

Ranges of *TSI* values are often grouped into trophic state classes. A commonly applied criterion (Novotny and Olem, 1994; Carlson and Simpson, 1996; KDHE, 2001) for trophic state classification of lakes is

oligotrophic $TSI \le 40$;
mesotrophic $40 < TSI \le 50$;
eutrophic $50 < TSI$.

However, a different criterion is also adopted for Florida's lakes (FCPM, 2000)

oligotrophic $TSI \le 60$;
mesotrophic $60 < TSI \le 70$;
eutrophic $70 < TSI$.

Carlson's *TSI* model is a multi-parameter model that, due to empirical relationships between *interrelated* water quality parameters, generally yields similar *TSI* values from

SDD, *Chla*, and *TP* measurements. However, Carlson also emphasized that any significant discrepancy among the three individual *TSI* indices demands a careful investigation. Carlson's model establishes a *TSI* scale that corresponds to reasonable ranges of *Chla* and *TP* measurements, and therefore has been widely applied to many lakes in North America.

An important and often overlooked feature of Carlson's *TSI* model is that the three water quality parameters used in the model are *interrelated*, and *TSI* indices are derived based on empirical relationships (Eqs. (1) and (2)) among these parameters. These empirical relationships are local properties, and therefore, when applied to environments differ from Carlson's study, equations for *TSI*(*Chla*) and *TSI*(*TP*) calculation (Eqs. (3b) and (3c)) should be modified to reflect local water quality characteristics.

Carlson (1977) pointed out that secchi disk transparency might be expected to give erroneous values in lakes containing high amounts of nonalgal particulate matter, and *TSI* index derived from *Chla* is best for estimating algal biomass in most lakes. It is recommended (Carlson and Simpson, 1996) that if data for chlorophyll and phosphorus are available, chlorophyll should be used as the primary index for trophic state classification. Also *deviations* of *TSI*(*SDD*) and *TSI* (*TP*) from *TSI*(*Chla*) should be used to infer additional information about the functioning of the lake. Although many practical applications (Osgood, 1982) used average value of the three indices, Carlson (1983) provided arguments for not to use the average index.

Study Area and Data

The Te-Chi reservoir, located in Central Taiwan, with a drainage basin of 592 km^2, has multiple functions including domestic water supply, irrigation, flood control, and hydropower generation. The reservoir pool is approximately 14 km long and covers an area of 454 hectares (Figure 1). Water depth in the reservoir pool generally ranges from 1.5 m at an upstream sampling location R4 to 13.5 m at a near-dam location S6. Natural forest is the dominant land cover in the watershed, however, agricultural activities, primarily vegetable crops and orchard plantations, dominate land use near streams. Application of fertilizers and pesticides has created heavy pollutant loading to the reservoir.

Water Quality Data The Te-Chi Reservoir Management Committee (TCRMC) and Water Resources Bureau (WRB) of the government jointly established a cooperative project to monitor water quality of the reservoir. Water samples taken at five sampling locations (Figure 1) were analyzed for twenty-five water quality parameters including *Chla*, and *TP*. Six years (1991 – 1997) of *Chla*, *SDD*, and *TP* measurements were used in this study. Statistical properties of the water quality data are shown in Table 1.

Remote Sensing Data Four sets of the Landsat Thematic Mapper (TM) data (23/08/1993, 17/10/1994, 10/01/1995, and 22/07/1996) covering the study area were collected. The TM sensor system records spectral radiances of the earth surface at seven different spectral bands. Each *picture element* or *pixel* of a TM image corresponds to the average radiance of a specific spectral range, measured electronically over the ground area corresponding to each pixel. Characteristics of the TM data is given in Table 2.

Modified Trophic State Index Model for the Te-Chi Reservoir

An important feature of Carlson's *TSI* modeling approach is that, in general, the three individual *TSI* indices are fairly close, and a careful investigation is necessitated when significantly different values result. The reason for having close *TSI* values is that Carlson (1977) initially determined *TSI*(*SDD*) based on *SDD* measurements (Eq. (3a)), and then established equations for calculation of *TSI*(*Chla*) and *TSI*(*TP*) using regression equations of *SDD vs Chla* and *SDD vs TP* (Eqs. (1) and (2)). Therefore, a water sample with *SDD*, *Chla*, and *TP* measurements fitting perfectly to these regression equations has exactly the same value of *TSI*(*SDD*), *TSI*(*Chla*), and *TSI*(*TP*). For convenience of explanation, we shall refer to this kind of water samples as *ideal samples*. For example, an *ideal sample* of (*SDD* = 1 m, *Chla* = 20 $\mu g/\ell$, *TP* = 48 $\mu g/\ell$) gives *TSI*(*SDD*) = *TSI*(*Chla*) = *TSI*(*TP*) = 60, based on Carlson's *TSI* model. However, most of (*SDD*, *Chla*, *TP*) samples are not ideal, and therefore yield close but different *TSI* values.

Water quality data of the Te-Chi reservoir generally yield significantly different *TSI* indices when substituted into Carlson's *TSI* model. For example, a sample of (*SDD* = 1.30 m, *Chla* = 132 $\mu g/\ell$, *TP* = 92 $\mu g/\ell$), which is an ideal sample of the Te-Chi reservoir, corresponds to *TSI*(*SDD*) = 56.15, *TSI*(*Chla*) = 78.47, and *TSI*(*TP*) = 69.39. Divergence in these *TSI* values is due to the differences between empirical water quality relationships of the Te-Chi reservoir and Carlson's study. In general, an ideal sample of the Te-Chi reservoir is not ideal in Carlson's study, and vice verse. Therefore, the original Carlson's *TSI* model is not effective for trophic state evaluation of the Te-Chi reservoir.

In order to develop a model that generally yields close individual *TSI* indices for the Te-Chi reservoir, the original Carlson's model was calibrated based on local regression relationships between water quality parameters.

<u>Model A</u> Measurements of *Chla*, *TP*, and *SDD* of the Te-Chi reservoir were found to have the following empirical relationships (also see figures 2 and 3)

$$\ln SDD = 1.8751 - 0.3264 \ \ln Chla, \quad (r = 0.75,\ n = 114) \tag{4}$$

$$\ln Chla = -0.9816 + 1.2961 \ \ln TP, \quad (r = 0.85,\ n = 115) \tag{5}$$

where n is the number of measurements, *SDD* is in meters and *Chla* and *TP* are in $\mu g/\ell$. Substituting the above equations into Eq. (3a) yields the following *TSI* model, which is simply a *locally calibrated* version of the original Carlson's model, for the Te-Chi reservoir:

$$TSI(SDD) = 10(6 - \frac{\ln SDD}{\ln 2}), \tag{6a}$$

$$TSI(Chla) = 10(6 - \frac{1.8751 - 0.3264 \ln Chla}{\ln 2}), \tag{6b}$$

$$TSI(TP) = 10(6 - \frac{2.1775 - 0.4230 \ln TP}{\ln 2}). \tag{6c}$$

TSI values of Model A and their corresponding *SDD*, *Chla* and *TP* measurements are listed in Table 3. Using Model A, an ideal sample of the Te-Chi reservoir has the same *TSI* value for all of the three *TSI* indices. For example, an ideal sample of (*SDD* = 1.30 m, *Chla* = 132 $\mu g/\ell$, *TP* = 92 $\mu g/\ell$) corresponds to *TSI*(*SDD*) = *TSI*(*Chla*) = *TSI*(*TP*) = 56, in contrast to three different values using Carlson's original model.

However, Model A also yields unreasonably high values of *Chla* and *TP* for *TSI* > 70. For instance, a *TSI* value of 80 corresponds to 21,851 $\mu g/\ell$ and 4,560 $\mu g/\ell$ of *Chla* and *TP* measurements. It is impractical to evaluate a reservoir's trophic state based on such *TSI* scale. This phenomenon is due to differences in regression models of local water quality parameters in Carlson's study and Te-Chi reservoir (Eqs. (1) and (4); Eqs. (2) and (5)), and the two premises adopted by Carlson's *TSI* model. The following section gives a detailed explanation of this argument.

In Carlson's model, *SDD* ranges from 0.0625 m (*TSI* = 100) to 64 m (*TSI* = 0), and an increase of 10 *TSI* units corresponds to a halving of *SDD*. Since the range of *SDD* is fixed, a regression model of ln*SDD vs.* ln*Chla* with smaller slope corresponds to larger range of *Chla*. Figure 4 illustrates that, corresponding to the common *SDD* range of [0.0625, 64], ranges of *Chla* are [0.001, 1527652] and [0.04, 1183] for the Te-Chi reservoir and Carlson's study, respectively. If model A, i.e. Equation (6), were adopted for the Te-Chi reservoir, it is unlikely to have *TSI*(*Chla*) > 70, even though chlorophyll concentrations higher than 1500 $\mu g/\ell$, for which the original Carlson's model yields *TSI*(*Chla*) = 102, have been observed.

<u>Model B</u> In order to develop a feasible *TSI* model for the Te-Chi reservoir, we chose to modify the *SDD* range factor and scale factor, while still maintain a numerical *TSI* scale of 0 to 100. Our major consideration is to modify Model A such that the *TSI* scale will correspond to reasonable ranges of *Chla* and *TP* observed in Te-Chi reservoir.

A generalized expression of Carlson's trophic state index model in terms of the scale and range factors is:

$$b^a = SDD_{\max}, \tag{7}$$

$$TSI(SDD) = 10\left(a - \frac{\ln SDD}{\ln b}\right). \tag{8}$$

In the above equations, b is the scale factor and b^a is the range factor, i.e. the specified maximum value for *SDD*.

Combining equations (4), (5), and (8) yields

$$TSI(Chla) = 10(a - \frac{1.8751 - 0.3264\ln Chla}{\ln b}), \quad (9)$$

$$TSI(TP) = 10(a - \frac{2.1775 - 0.4230\ln TP}{\ln b}). \quad (10)$$

Almost all the chlorophyll concentrations observed in Te-Chi reservoir are lower than 2000 $\mu g/\ell$, therefore we set

$$TSI(Chla \approx 2000) = 100. \quad (11)$$

We also set the range factor $SDD_{\max}$ equal to 42 m, with reference to 41.6 m observed in Lake Masyuko, Japan. Substituting Eq. (11) into Eq. (9) and setting $SDD_{\max}$ equal to 42m yields

$$\begin{cases} a = 8.605 \\ b = 1.544 \end{cases} \quad (12)$$

Finally, the modified Carlson *TSI* indices for the Te-Chi reservoir are

$$TSI(SDD) = 10(8.605 - \frac{\ln SDD}{\ln 1.544}), \quad (13a)$$

$$TSI(Chla) = 10(8.605 - \frac{1.8751 - 0.3264\ln Chla}{\ln 1.544}) \quad (13b)$$

$$TSI(TP) = 10(8.605 - \frac{2.1775 - 0.4230\ln TP}{\ln 1.544}). \quad (13c)$$

Trophic state index of Model B and its corresponding water quality parameters are given in Table 4. Compared to statistical properties of the water quality data (Table 1), modified

TSI of Model B corresponds to reasonable ranges of *Chla* and *TP* measurements observed in Te-Chi reservoir.

A significant difference between Model B and the other two models is that *TSI* values of Model B are defined based on *Chla* measurements whereas *TSI* values of the original Carlson's model and Model A are defined based on *SDD* measurements. This comment is explained below.

Both Model A and the original Carlson's model initially set *TSI*(*SDD*) equal to 0 for *SDD* measurement of 64 m, and apply the criterion of 10 *TSI* increment per *SDD* halving. The other two *TSI* indices, *TSI*(*Chla*) and *TSI*(*TP*), are then derived using *TSI*(*SDD*) and empirical relationships of *SDD* vs *Chla* and *Chla* vs *TP*. In contrast, Model B initially sets *TSI*(*Chla*) equal to 100 for *Chla* measurement of 2000, and then derives *TSI*(*SDD*) and *TSI*(*TP*) based on the pre-specified SDD_{max} and the empirical relationships of *SDD* vs *Chla* and *Chla* vs *TP*. Our choice of using *Chla* concentration to define the *TSI* scale in Model B follows Carlson's recommendation that *Chla* is best for estimating algal biomass in most lakes, and *Chla* is preferable over *TP* if measurements of both parameters are available. We adopt the trophic state indices of Model B in subsequent analyses of this study.

Preprocessing of Landsat TM Images

In the context of digital analysis of remote sensing images, *preprocessing* refers to those operations that are preliminary to the main analysis. Typical preprocessing operations could include (1) radiometric preprocessing to adjust image's digital values for the effect of a hazy atmosphere and (2) geometric processing to bring an image into registration with a map or another image (Campbell, 1996). TM images used in this study were purchased from the Center for Space and Remote Sensing Research (CSRSR). Images were geometrically referenced to the Transverse Mercator geographic reference system by CSRSR. TM images used in this study were acquired at different dates and had different atmospheric scattering effects. Therefore, the *histogram minimum method* (HMM) (Chavez, 1975) was implemented to adjust digital values for atmospheric degradation.

The basic concept of HMM is to identify very dark features within the scene. Based on the principles of remote sensing, large and clear water bodies and shadows cast by clouds or by large topographic features have brightness values at or very near zero because clear water absorbs strongly in the near infrared spectrum and very little infrared energy is scattered to the sensor from shadowed pixels. However, due to significant atmospheric scattering, analysts often find that the lowest brightness values are not at or near zero, but some larger values. For example, values of the lowest brightness for the TM data used in this study (Table 5) are significantly larger than zero in visible bands (TM1, TM2, and TM3). Higher values of the lowest brightness are mainly contributed by the atmospheric scattering effect. One also observes that the lowest brightness values differ from one band to another, with a trend of decreasing with the increasing spectral wavelength λ. This phenomenon is explained by the law of *Rayleigh scattering*, the dominant scattering process in the atmosphere. Rayleigh's law states that the scattering intensity is inversely proportional to the fourth power of the wavelength λ. Therefore, the lowest brightness of the blue band (TM1) is higher than that of the red band (TM3) and the near-infrared band (TM4).

In this study the lowest brightness values were assumed to represent the values contributed by atmospheric scattering and subtracted from the original digital values of the TM images. Subsequent analyses were then based on these preprocessed TM images.

Reservoir *TSI* Estimation Using Landsat TM Images

In order to map the spatial variation of water quality in the reservoir pool using remotely sensed images, we establish the following empirical relationships between digital numbers of the preprocessed TM bands and water quality parameters.

$$\ln Chla = -1.432 + 1.239 \ln(TM\,2) + 1.195 \ln(TM\,4) \qquad r = 0.89 \tag{14}$$

$$\ln TP = 0.675 + 0.01387\ln(TM2) + 1.4116\ln(TM4) \qquad r = 0.89 \tag{15}$$

$$\ln SDD = 2.925 - 0.515\ln(TM2) - 0.629\ln(TM4) \qquad r = 0.88 \tag{16}$$

Figure 5 demonstrates the comparison between water quality measurements and their estimates using equations (14), (15), and (16), along with the root-mean-squared errors (RMSE). We use only bands TM2 and TM4 to estimate *Chla*, *TP*, and *SDD* since data of these two bands are also available for the popular SPOT satellite.

For each of the four sets of TM images, combining equations (14) - (16) and equation (13) yields *pixel-average-TSI* images of the three trophic state indices, *TSI*(*Chla*), *TSI*(*TP*), and *TSI*(*SDD*). Figure 6 shows examples of the TM-derived *pixel-average-TSI* images.

Since Model B is a multi-parameter model, any discrepancy among the three *TSI* indices necessitates a careful investigation, as strongly recommended by Carlson (1977). Figure 7 reveals that values of the three indices are fairly close in the area downstream from S28; whereas, in summer, *TSI*(*SDD*) is significantly larger than *TSI*(*Chla*) and *TSI*(*TP*) in the upstream area of S28. Table 6 shows measurements of concentration of total suspended solid (TSS) corresponding to Landsat TM images used in this study. Evidently, TSS concentration in the upstream portion of the reservoir pool (S39 to R4) is significantly higher than that in the downstream portion in summer, and TSS concentrations are very low within the whole reservoir pool in winter. We believe that departure of *TSI*(*SDD*) from the other two *TSI* indices in upstream area can be attributed to high sediment concentrations flowing into the reservoir pool from the upstream vegetable and orchard plantations. Intensive farming activities and high rainfall intensities in summer contribute to high sediment concentrations in the stream flow.

Trophic State Classification

Trophic state classification of water bodies must consider nutrients loading of the water bodies under investigation. Three major classes – oligotrophic, mesotrophic, and eutrophic, are used in many applications; however, other applications, usually with high nutrient loadings, also exploit more trophic state classes such as slightly eutrophic, fully eutrophic, very eutrophic, and hypereutrophic (OPP, 2000), dystrophic (EPAOW, 2000), and polyeutrophic (Zakova, *et al.*, 1993), for higher TSI values. Using more classes in the higher end of the *TSI* scale is necessary in order to signify the effort and effect of watershed management practices. In this study, based on the *Chla* concentration, six trophic state classes are established for the Te-Chi reservoir (Table 7). These classes are delineated by considering the range of *Chla* concentrations observed in the Te-Chi reservoir, and with reference to *Chla* ranges adopted by other applications in the literature

(Gakstatter *et al.*, 1975; OECD, 1982; Zakova *et al.*, 1993). Figure 8 demonstrates that trophic states derived from *Chla* measurements and from the TM data are generally consistent. Figure 9 manifests variation of the trophic state from upstream to outlet of the reservoir. Trophic state in the reservoir generally improves from upstream to downstream, and zones of distinct trophic state exist. Areas upstream of S39 are polyeutrophic or hypereutrophic in summer, and mostly eutrophic in winter. Areas between of S18 and S39 are eutrophic in summer and mesoeutrophic in winter. Trophic state at S6, near the outlet of the reservoir, is more likely to be mesoeutrophic. Kimmel and Groeger (1984) refer to distinct zones within a reservoir, from upstream to downstream, as riverine (in our case, upstream area of S39), transitional (S18 to S39), and lacustrine (downstream area of S18). For the Te-Chi reservoir, the effect of water quality degradation caused by high sediment concentration in reservoir inflow is most significant in the riverine zone upstream from S39. Trophic state also improves in winter, probably due to low temperature suppression of algal growth and less agricultural activities in the upstream watershed. In conclusion, even though better trophic state exists in the downstream area near the dam, trophic state within the reservoir pool is mostly eutrophic or worse in summer, and meso-eutrophic in winter. Implementation of best management practices (BMPs) to control the nonpoint source pollution from the upstream agricultural activities is highly recommended.

Conclusions

1. We modified Carlson's trophic state model by adjusting its scale and range factors and adopting the local relationships among three water quality parameters, *Chla*, *TP*, and *SDD*. Scale of the trophic state index of the modified model corresponds to reasonable ranges of *Chla* and *TP* measurements observed in the Te-Chi reservoir.
2. We demonstrate that, after preprocessing for atmospheric scattering effect, Landsat TM2 and TM4 data can be used to estimate concentrations of *Chla* and *TP* and secchi disk depth in impounded water bodies. Based on TM estimates of water quality parameters and the modified *TSI* model, a *TSI* map that characterizes the spatial variation of trophic state within the reservoir pool can be developed.
3. Trophic state index based on measurements of secchi disk depth is not effective in environments of high sediment concentration.
4. Within a reservoir, trophic state generally improves from upstream to downstream, and zones of distinct trophic state may exist. For the Te-Chi reservoir, the effect of water quality degradation by high sediment concentration in reservoir inflow is most significant in the riverine zone upstream from S39.
5. We conclude that the Te-Chi reservoir is eutrophic or worse in summer and

meso-eutrophic in winter. Implementation of best management practices to reduce the nonpoint source pollution in the upstream watershed is highly recommended.

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Table 1. Statistical properties of water quality data (Jan. 1991 – Jan. 1997) of the Te-Chi Reservoir.

Parameter	minimum	maximum	mean	standard deviation
SDD (m)	0.3	7.2	2.82	1.50
Chla ($\mu g/\ell$)	1.14	1560	67.68	172.71
TP ($\mu g/\ell$)	3	444	35.35	51.01

Table 2. Characteristics of the Landsat TM data.

Band	Spectral Wavelength λ (micrometers)		Spatial Resolution (meters)
TM1	0.45-0.52	(blue)	30
TM2	0.52-0.60	(green)	30
TM3	0.63-0.69	(red)	30
TM4	0.76-0.90	(near infrared)	30
TM5	1.55-1.75	(mid infrared)	30
TM6	10.40-12.50	(far infrared)	120
TM7	2.08-2.35	(mid infrared)	30

Table 3. Carlson trophic state index and associated parameters for the Te-Chi Reservoir and Carlson's study.

TSI	*SDD* (m)	*Chla** ($\mu g/\ell$)	*TP** ($\mu g/\ell$)	*Chla*** ($\mu g/\ell$)	*TP*** ($\mu g/\ell$)
0	64	0.001	0.01	0.04	0.75
10	32	0.008	0.05	0.12	1.5
20	16	0.064	0.24	0.34	3
30	8	0.53	1.26	0.94	6
40	4	4.47	6.49	2.6	12
50	2	37	33	6.4	24
60	1	313	172	20	48
70	0.5	2,613	886	56	96
80	0.25	21,851	4,560	154	192
90	0.125	182,705	23,475	427	384
100	0.0625	1,527,652	120,853	1,183	768

* Parameter values (calculated using Eqs. (8b) and (8c)) for Te-Chi Reservoir.

**Parameter values (calculated using Eqs. (4) and (5)) for Minnesota's lakes (Carlson, 1977).

Table 4. Modified Carlson trophic state index and associated parameters for Te-Chi Reservoir.

TSI	*SDD* (m)	*Chla*($\mu g/\ell$)	*TP* ($\mu g/\ell$)
0	42	0.003	0.03
10	27	0.012	0.07
20	18	0.045	0.20
30	11	0.170	0.54
40	7.39	0.645	1.52
50	4.79	2.44	4.25
60	3.10	9.23	12
70	2.01	35	33
80	1.30	132	92
90	0.84	500	258
100	0.55	1,893	721

Table 5. Minimum brightness values for the TM images used in this study.

Image Date	Minimum Brightness Values			
	TM1	TM2	TM3	TM4
31/08/1993	54	16	13	4
05/10/1994	51	14	10	4
09/01/1995	42	12	10	2
22/07/1996	48	13	11	2

Table 6. Measurements of concentration of total suspended solid (unit: NTU).

Location Image Date	S6	S18	S28	S39	R4
31/08/1993	5	8	23	NA*	74
05/10/1994	5	11	13	30	37
09/01/1995	0	1	5	4	8
22/07/1996	4	9	4	31	66

*Data not available.

Table 7. Trophic state classes for the Te-Chi reservoir

Trophic State Classes	*TSI*[*] Range	*Chla* Range ($\mu g/\ell$)
Oligotrophic	*TSI* < 53	*Chla* < 3.7
Mesotrophic	53 ≤ *TSI* < 61	3.7 ≤ *Chla* < 10.8
Meso-eutrophic	61 ≤ *TSI* < 66	10.8 ≤ *Chla* < 21.1
Eutrophic	66 ≤ *TSI* < 78	21.1 ≤ *Chla* < 105
Polyeutrophic	78 ≤ *TSI* < 94	105 ≤ *Chla* < 885
Hypereutrophic	94 ≤ *TSI*	885 ≤ *Chla*

[*] *TSI* values are calculated using Model B.

Figure 1. Map of the study area and water sampling locations.

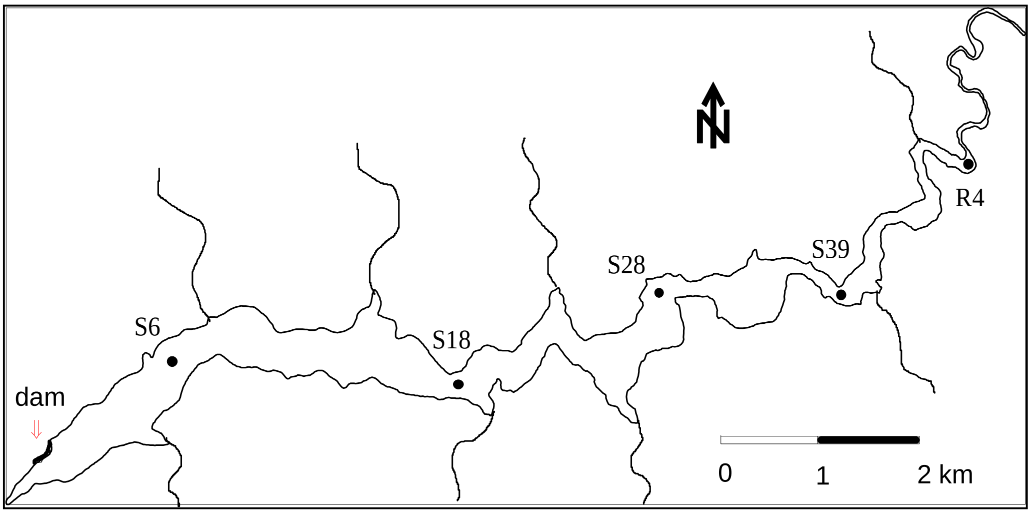
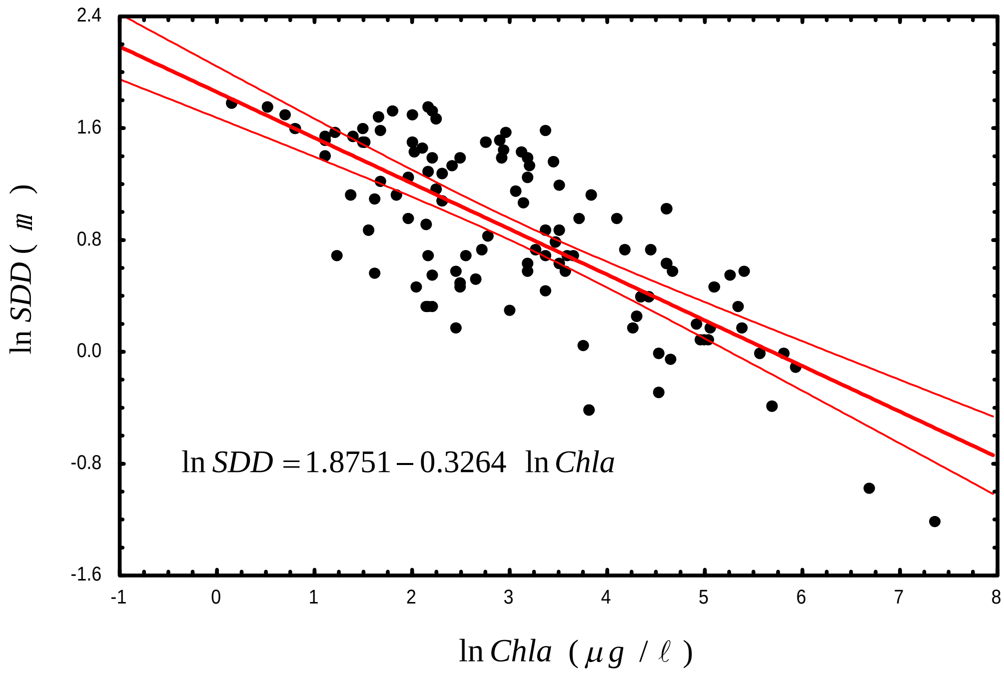
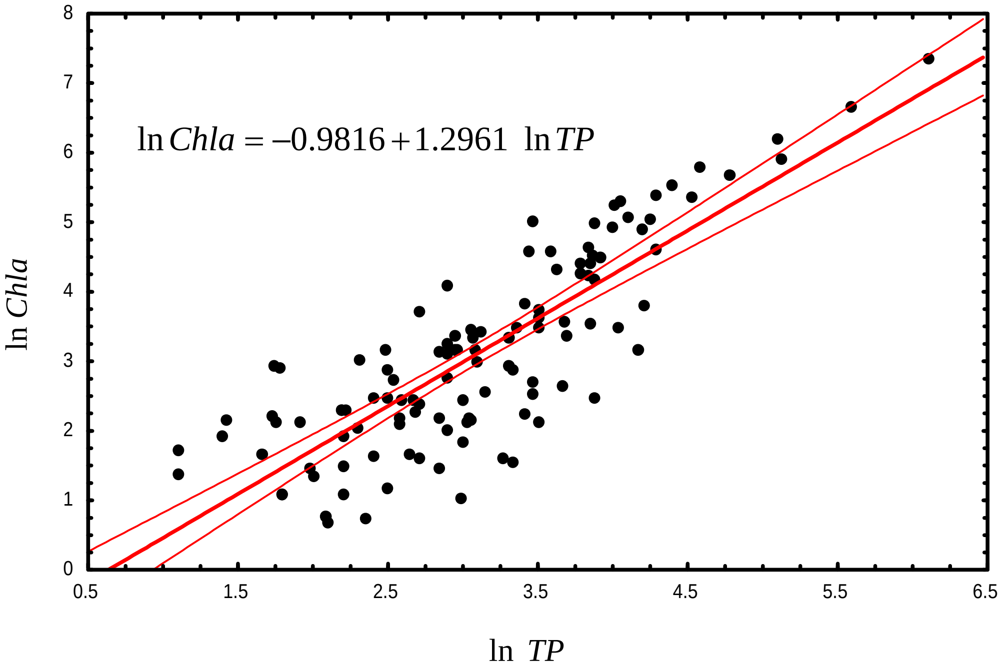

N
R4
S39
S28
S18
S6
dam
0
1
2 km

Figure 2. Regression relationship of *SDD* versus *Chla* for the Te-Chi Reservoir.



2.4
1.6
0.8
0.0
-0.8
-1.6
ln SDD (m)
-1
0
1
2
3
4
5
6
7
8
ln Chla (μg / ℓ)
ln SDD = 1.8751 − 0.3264 ln Chla

Figure 3. Regression relationship of *Chla* ($\mu g/\ell$) versus *TP* ($\mu g/\ell$) for the Te-Chi Reservoir.



$\ln Chla = -0.9816 + 1.2961\ \ln TP$
ln Chla
ln TP
0
1
2
3
4
5
6
7
8
0.5
1.5
2.5
3.5
4.5
5.5
6.5

Figure 4. Comparison of regression models of ln*SDD* vs ln*Chla* for The Te-Chi Reservoir and Carlson's study.

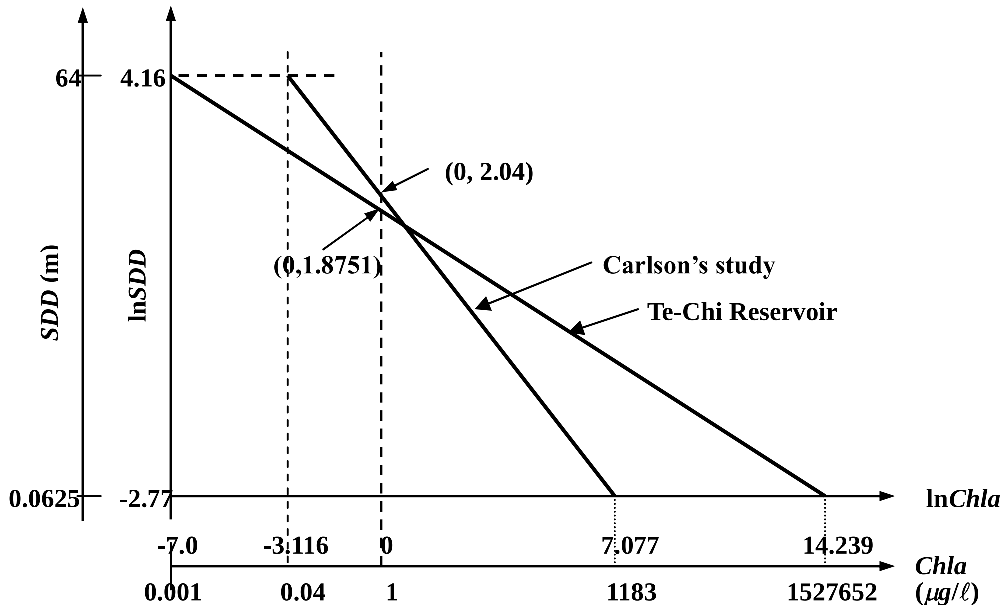
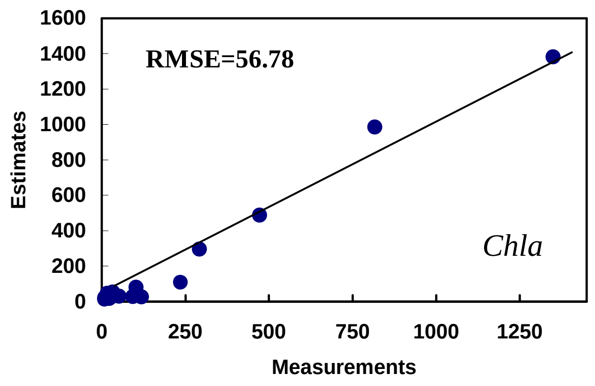
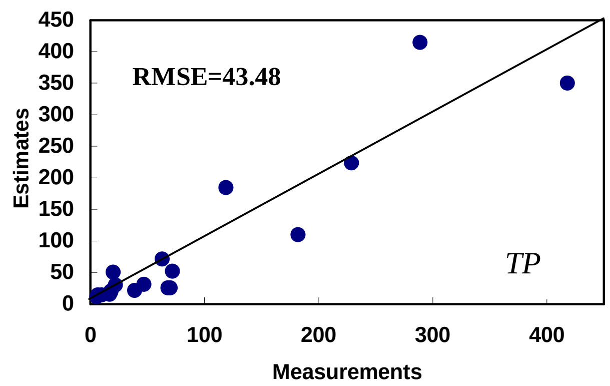

64
4.16
0.0625
-2.77
SDD (m)
lnSDD
(0, 2.04)
(0,1.8751)
Carlson's study
Te-Chi Reservoir
lnChla
-7.0
-3.116
0
7.077
14.239
Chla
(μg/ℓ)
0.001
0.04
1
1183
1527652

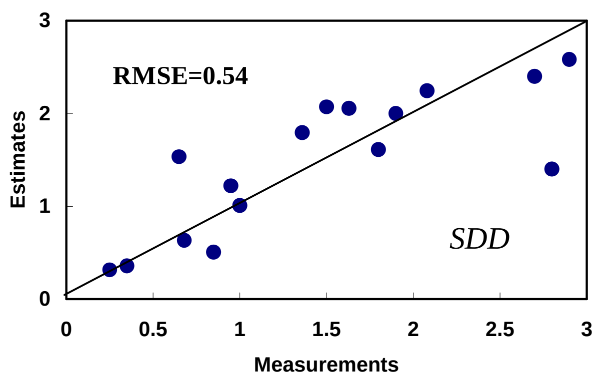
Figure 5. Comparison of water quality measurements and their TM-derived estimates. (Units are $\mu g / \ell$ for *Chla* and *TP* and m for *SDD*.)



RMSE=56.78
Chla
Estimates
Measurements
0
200
400
600
800
1000
1200
1400
1600
0
250
500
750
1000
1250



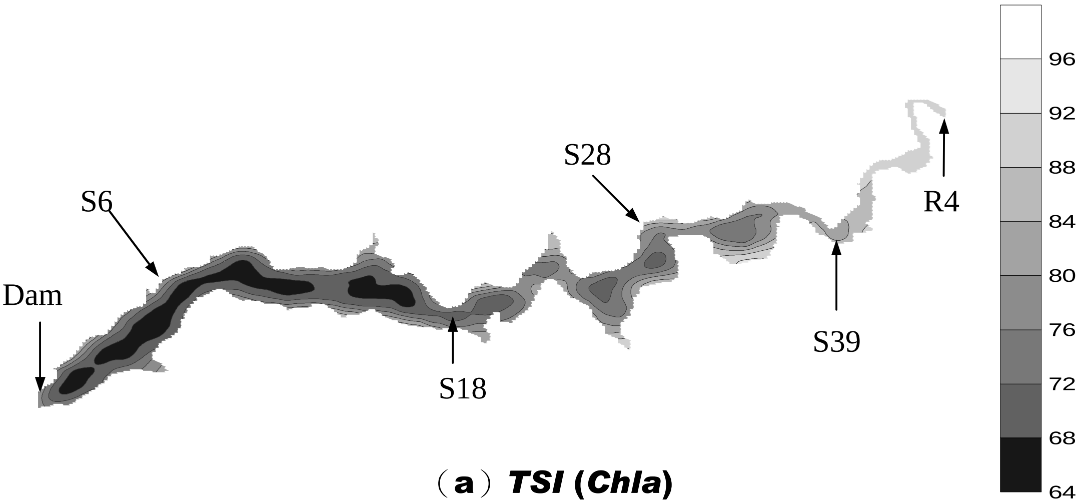
RMSE=43.48
TP
Estimates
Measurements
0
50
100
150
200
250
300
350
400
450
0
100
200
300
400



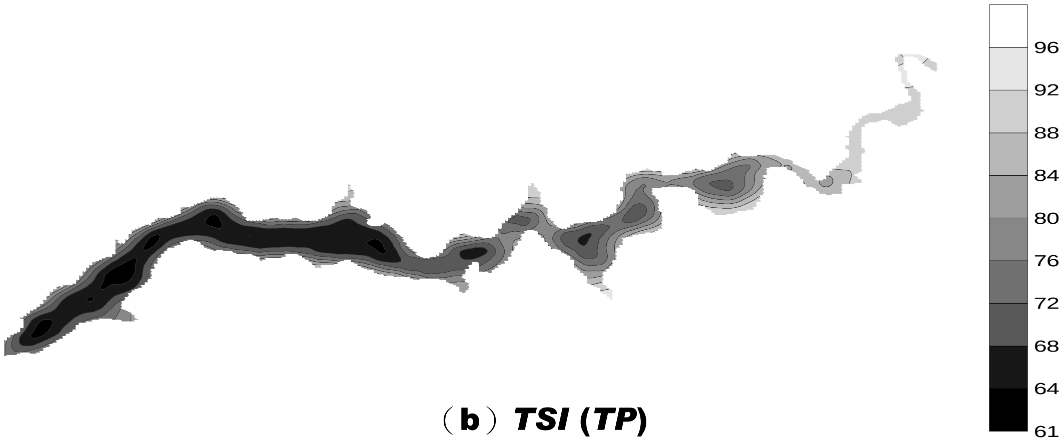
RMSE=0.54
SDD
Estimates
Measurements
0
1
2
3
0
0.5
1
1.5
2
2.5
3

Figure 6. Examples of TM-derived *TSI* images.

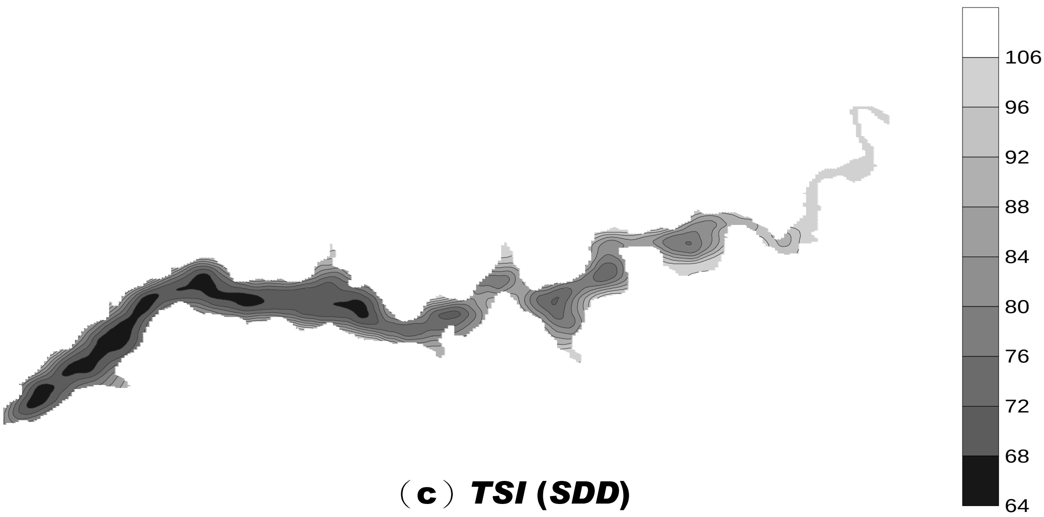
Image Date: 22/07/1996



(**a**) ***TSI*** **(*Chla*)**



(**b**) ***TSI*** **(*TP*)**



(**c**) ***TSI*** **(*SDD*)**

Figure 7. Comparison of the three *pixel-average-TSI* indices.

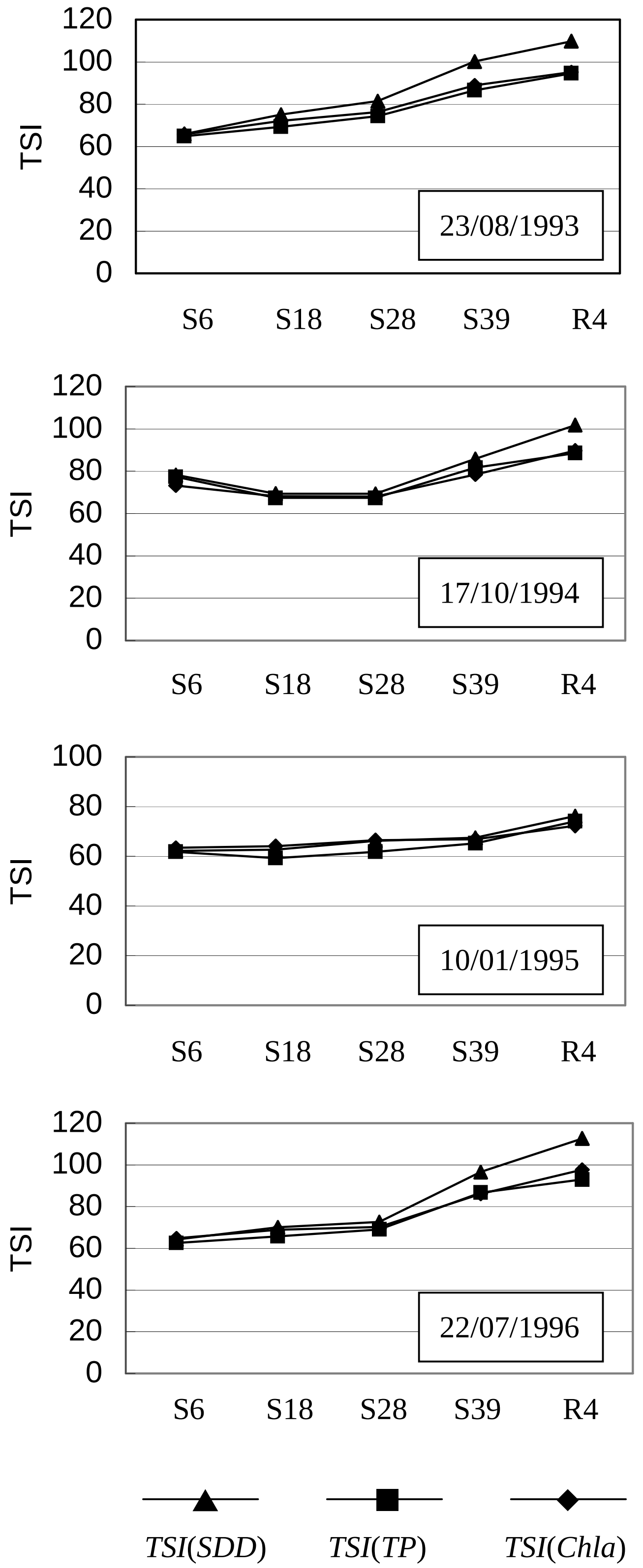

TSI
120
100
80
60
40
20
0
23/08/1993
S6
S18
S28
S39
R4
17/10/1994
10/01/1995
22/07/1996
TSI(SDD)
TSI(TP)
TSI(Chla)

Figure 8. Comparison of trophic state classes derived from *Chla* measurements and from TM data.

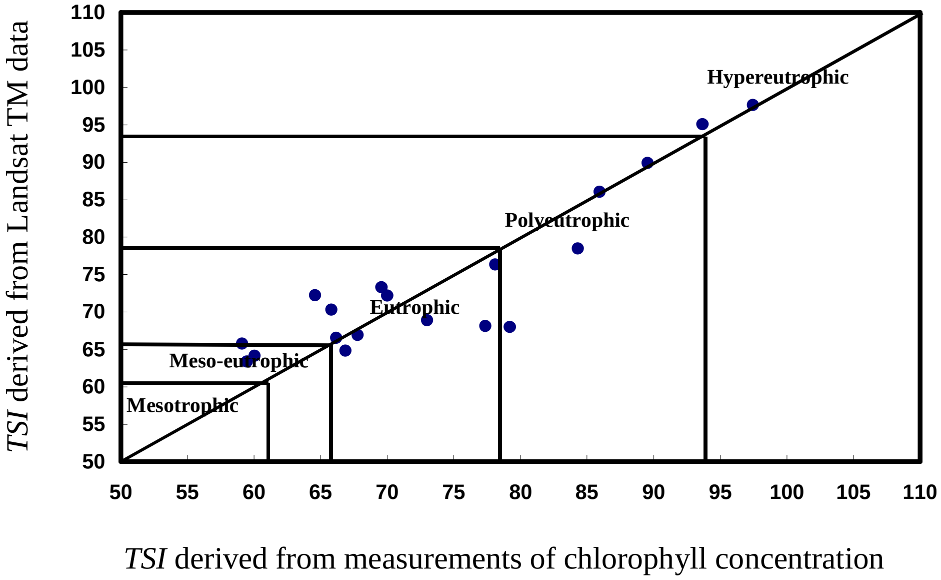
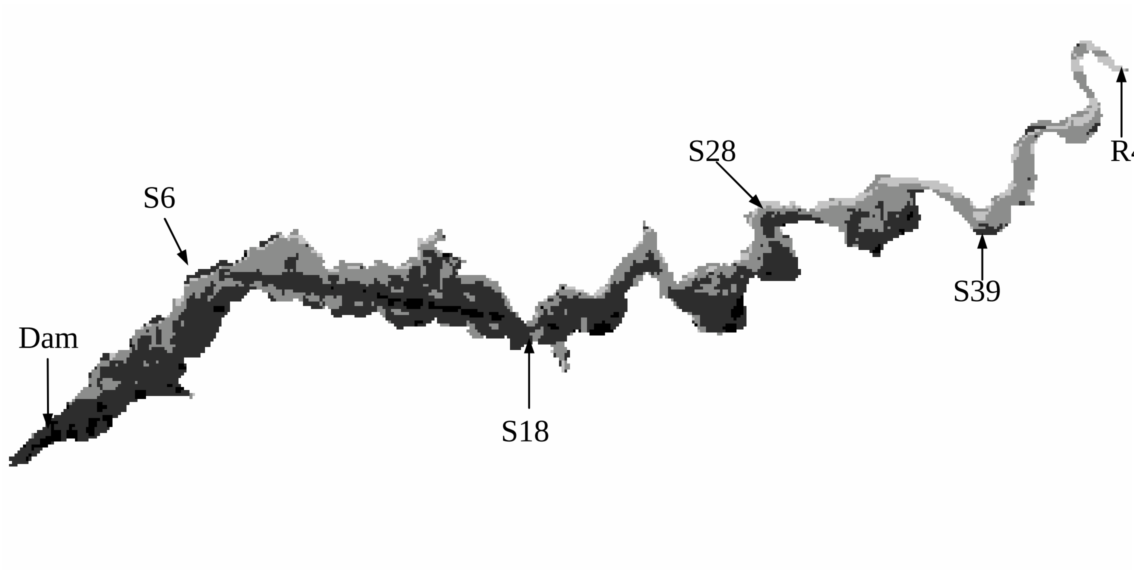

TSI derived from Landsat TM data
110
105
100
95
90
85
80
75
70
65
60
55
50
Hypereutrophic
Polyeutrophic
Eutrophic
Meso-eutrophic
Mesotrophic
50
55
60
65
70
75
80
85
90
95
100
105
110
TSI derived from measurements of chlorophyll concentration

Figure 9. Ttrophic state classes from upstream to outlet of the reservoir.



（a）10/01/1995

（b）22/07/1996

Mesotrohpic **Meso-eutrophic**

Eutrophic **Polyeutrophic** **Hypereutrophic**