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An attempt of modification of Carlson's trophic state index (TSI) for brackish lakes in Japan

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Abstract: At the beginning of this study, as the first stage of trophic state index (TSI) related studies for brackish lakes in Japan, existing studies related to Carlson's TSI were briefly reviewed focusing on brackish lakes in Japan. Carlson's TSI and its modified indices had been applied to some brackish lakes in Japan. However, it had been difficult to find an applicable equation for TSI for these brackish lakes in Japan. Theoretically, the water quality of surface layers should be used for TSI, however, the regression coefficient using surface layer water quality data and all layers water quality data were almost the same to the extent of the preliminary analysis based on the existing study. In this study, TSI was applied to brackish lakes in Japan by following two methods. First, some characteristics of a few Japanese brackish lakes were summarized from lake databases to establish TSI for brackish lakes in Japan. However, it was difficult to find an applicable equation for TSI for brackish lakes in Japan. Second, equations to calculate TSI for brackish lakes in Tottori and Shimane Prefectures were tentatively presented after the regression analysis of publicly monitored water quality data. Preparing database of water quality, water quantity and physiographical parameters for the brackish lakes in Japan, and further consideration on the equations of TSI would be needed for better understanding of these parameters.

Key words: Carlson's trophic state index (TSI), brackish lake, environmental database, water quality, physiographical parameters

1 Introduction

Many kinds of indices to describe the state of lakes have been introduced and applied by for the purpose of lake management (e.g. Asano et al., 1999). These include Carlson's trophic state index (TSI) based on Secchi depth, total phosphorus (TP) and chlorophyll-a (Carlson, 1977) (Table 1) and a lake condition index (LCI) (Uttormark and Wall, 1975). In regards to capability of restoration of lakes, Fulmer and Cooke (1990) investigated some reservoirs in Ohio State and estimated achievable phosphorus concentration in bottom layer of lakes by use of the 25 % values of phosphorus concentration in rivers of most preserved with natural state in the drainage areas. Moreover, they applied hydrologic and demographic data and pollutant load model developed by Canfield and Bachmann (1981), which were based on a database of water quality of 290 natural lakes and 433 artificial lakes in the United States (Asano et al., 1999). Fulmer and Cooke adopted the 25 % values of phosphorus concentration to indicate realistic achievable concentration in the rivers by improving the wastewater treatments. They compared the estimated phosphorus concentration and actual phosphorus concentration, and used Carlson's TSI to indicate the current and predicted states of the reservoirs. They selected four reservoirs with large water quality improvement potential based on largeness of the difference between actual and potential nutrient levels (Fig. 1), in which higher actual nutrition level and lower potential nutrition level were observed.

Uttormark and Hutchins (1978) evaluated the applicability of four input/output models developed by Dillon and Rigler (1974), and Vollenweider (1975, 1976). They discussed on the land based pollutant loads reduction effects for the lakes using the input/output

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Table 1. Carlson's trophic state index (TSI) based on Secchi depth, total phosphorus (TP) and chlorophyll-a. (Carlson, 1977)

TSI	Secchi depth (m)	T-P ($\mu g\ l^{-1}$)	Chlorophyll-a ($\mu g\ l^{-1}$)
0	64	1	0.04
10	32	2	0.12
20	16	4	0.34
30	8	8	0.94
40	4	16	2.6
50	2	32	6.4
60	1	65	20
70	0.5	130	56
80	0.25	260	154
90	0.12	519	427
100	0.06	1032	1183

models e.g. mean depth versus L (1-R) / ρ (where L: specific area phosphorus loading, $ML^{-2}T^{-1}$, R: phosphorus retention coefficient (-) (= (P_{in}-P_{out}) / P_{in}), ρ: flushing rate, (= Q / V, Q: annual water flow rate, L^3T^{-1}, V: lake volume, L^3), zρ (where z: mean depth, L) versus L, residence time versus averaged inflow phosphorus concentration, and flushing rate versus biomass expressed as phosphorus. They evaluated the effectiveness of Carlson's TSI calculated from Secchi depth and LCI (Uttormark and Wall, 1975). They evaluated the effectiveness of these models and indices and pointed out the necessity of their further developments.

Recent studies related to TSI for brackish or lagoon environments, simulation models and their results were discussed to state the trophic conditions of water bodies. Marques et al. (2003) introduced exergy-based indices, the exergy index and specific exergy as ecological indicators (orientors) to exhibit the state of the ecosystem in the Mondego estuarine ecosystem, Portugal, and they found that a more conservative river management would be effective for the restoration of the affected areas. Canu et al. (2003) analyzed the relationships of water quality and quantity parameters including the velocity fields of water, water temperature fields, the dynamics of phytoplankton, zooplankton, nutrients (ammonia, nitrate and phosphate), organic detritus (organic nitrogen, organic phosphorous and carbonaceous biological oxygen demand (CBOD)) and dissolved oxygen using a Finite Element Ecological Model for the Lagoon of Venice (VELFEEM) for the Lagoon of Venice ecosystems, Italy. They used an aggregate index of Water Quality Trophic Index (TRIX) to describe the state of water quality.

In Japan, National Institute of Environmental Studies has conducted accumulative research works on lake

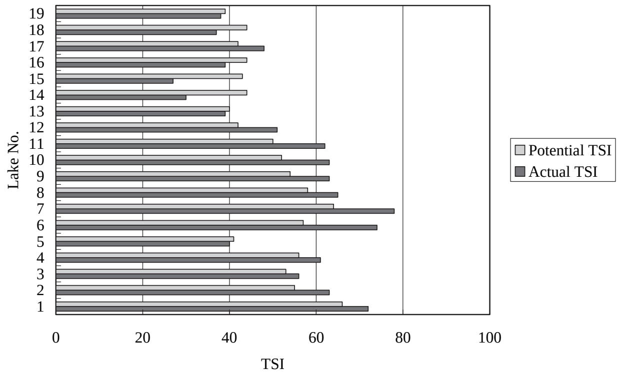

Fig. 1. Current and achievable nutrient conditions in 19 lakes in Ohio State with Carlson's trophic state index (TSI). (TSI < 40: oligotrophic, TSI > 50: eutrophic) (after Fulmer, and Cooke , 1990)

management from late 1970s. Otsuki et al. (1981) applied the Carlson's TSI to 24 Japanese lakes and Aizaki et al. (1981a) modified Carlson's TSI to use for the Japanese freshwater lakes. Amano et al. (1991) investigated water quality characteristics of lakes in Japan using modified TSI developed by Aizaki et al. (1981a).

There were over 260 papers cited in Scopus (http://www.scoups.com) search with the words "trophic state index", however, there was no result by adding "brackish", but a dozen of results was found by adding "salt", of which one-fifth papers were related to medical field, and twenty results were found by adding "salinity" at the end of March, 2006. Therefore, the author concluded that TSI-related research in the fields of brackish or salt water is not so advanced yet.

The aims of this study are to briefly summarize the studies related to TSI especially studies in Japan and to apply the concepts of TSI to some Japanese lakes, especially brackish lakes including Lakes Shinji and Nakaumi to improve the understanding of the water quality indices especially for the brackish lakes.

2 Studies related to the TSI (trophic state index) in Japan

Otsuki et al. (1981) found applicability of Carlson's TSI to 24 lakes in Japan based on the publicly monitored water quality data. Aizaki et al. (1981a) also applied the Carlson's TSI to the Japanese lakes and made modification of the parameters for fresh water lakes. Table 2 shows the modified TSI and its associated parameters. Because of less correlation between the associate parameters for six brackish lakes (Supplement Table 1), they concluded that further investigation would be necessary to establish a TSI for brackish lakes. Better correlations of total nitrogen (TN) with other parameters than total phosphorus (TP) suggested that nitrogen was a

Table 2. Trophic state index (TSI) and its associated parameters for freshwater lakes in Japan. (Aizaki et al., 1981a)

TSI	Chl.-a[a] μg l^{-1}	Secchi[b] m	T-P μg l^{-1}	SS mg l^{-1}	POC mg l^{-1}	PON μg l^{-1}	T-N mg l^{-1}	COD mg l^{-1}	Total bac.[c] No. ml^{-1}
0	0.10	48	0.4	0.04	0.02	3	0.010	0.06	4.2×10^{4}
10	0.26	27	0.9	0.09	0.05	6	0.020	0.12	8.3×10^{4}
20	0.66	15	2.0	0.23	0.10	13	0.040	0.24	1.6×10^{5}
30	1.6	8.0	4.6	0.55	0.21	29	0.079	0.48	3.2×10^{5}
40	4.1	4.4	10	1.3	0.44	62	0.16	0.94	6.4×10^{5}
50	10	2.4	23	2.1	0.92	130	0.31	1.8	1.3×10^{6}
60	26	1.3	50	7.7	1.9	290	0.65	3.6	2.5×10^{6}
70	64	0.73	110	19	4.1	620	1.2	7.1	4.9×10^{6}
80	160	0.40	250	45	8.6	1340	2.3	14	9.6×10^{6}
90	400	0.22	555	108	18	2900	4.6	27	1.9×10^{7}
100	1000	0.12	1230	260	38	6500	9.1	54	3.8×10^{7}

a: Chlorophyll-a; b: Secchi disk transparency; c: Total bacteria.

limiting nutrient in these brackish lakes. Goda (1981) examined the correlation of some physiographical indices to chemical oxygen demand (COD) as an eutrophication index for 26 lakes in Japan. The examined indices were W/V, river basin area per water volume of lakes, P/V, contributing population per water volume of lakes, and PW/V by plotting these indices versus averaged COD. He found the number of highly eutrophicated lakes were more restricted and their plots on the graphs of PW/V versus averaged COD were isolated further from other mesotrophic or oligotrophic lakes than in the graphs of P/V and W/V versus averaged COD. Tai et al. (1981) investigated species and generic entropy to describe the state of algal community in the Japanese lakes and found that the relative entropy, the ratio of entropy for aquatic samples to the maximum entropy, held promise for the studies of eutrophication of lakes. Aizaki et al. (1981b) made a comparative study of outdoor experimental ponds and a part of an actual lake in Japan in regards to phosphorus loading and TP concentration versus chlorophyll-a, POC and PON. They found the similarity of experimental ponds and the actual lake in regards to the relationships between these parameters. They also pointed out the importance of retention time in the lakes for the relationship between the concentration of phosphorus and chlorophyll-a. Kawai et al. (1981) investigated in vivo fluorescence measurement of chlorophyll-a and ascertained the photoinhibition, and they also found that the photoenhancement and longer period pH fluctuation attributed to the algal succession.

Amano et al. (1991) investigated water quality data of 197 monitoring points in 113 lakes in Japan from 1978 to 1988 focusing on COD and categorized the lakes in Japan into four categories: (I) environmental quality standards (EQS) achieved, (II) easy to achieve EQS, only one or two years of excess COD EQS, (III) hard to accomplish EQS, more than three years of excess COD EQS and the averaged COD was under twice of the COD EQS, and (IV) hard to achieve EQS for a long time, all year excess of COD EQS and the averaged COD was more than twice of the COD EQS. They divided land based COD and internally produced COD, and compared to TSI calculated from TP, TSI (TP), and average of internally produced COD from 1985 to 1988 (Supplement Fig. 1). The correlations were reported as relatively high especially for the lakes with phosphorus as a limiting nutrient source and the relationships were almost the same as those reported by Aizaki et al. (1981 a). Based on the results of frequency distribution of TSI calculated from chlorophyll-a, TSI (Chl), based on the three groups of environmental standard zoning, AA, A and "B and C" (B and C were categorized into one group in their study), and four categories from (I) to (IV) described above, respectively, the following conclusions had been obtained. The numbers of the monitoring points with TSI (Chl) of more than or equal to 50 were relatively large for the lakes of the environmental standard zoning of A and "B and C", and category (III) and (IV). (Supplement Fig. 2 and 3).

Amano et al. (1981) further analyzed maximum permissive pollutant loads to accomplish EQS using Vollenweider model with phosphorus as a limiting nutrient (Fukushima et al. 1986). In this model, the following assumptions were hypothesized: 1) lakes were completely mixed, 2) calculation conditions were steady state and annually averaged conditions, and 3) input loading to lake was equal to the differences of pollutant

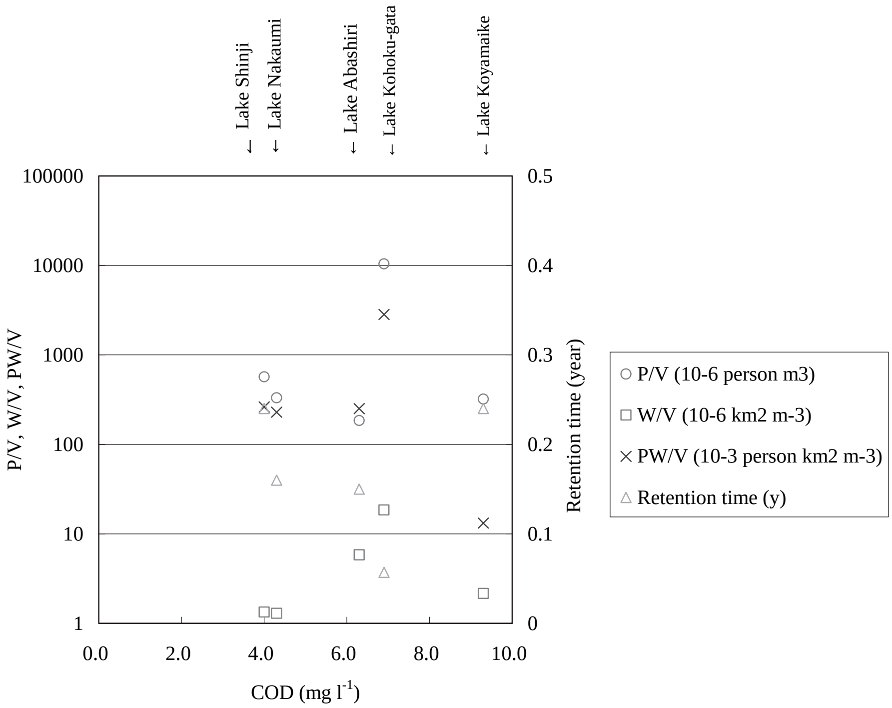

Fig. 2. Annual average COD (1980 or 1978) versus physiographical parameters of five Japanese brackish lakes. (prepared by the author based on Otsuki et al., 1981)

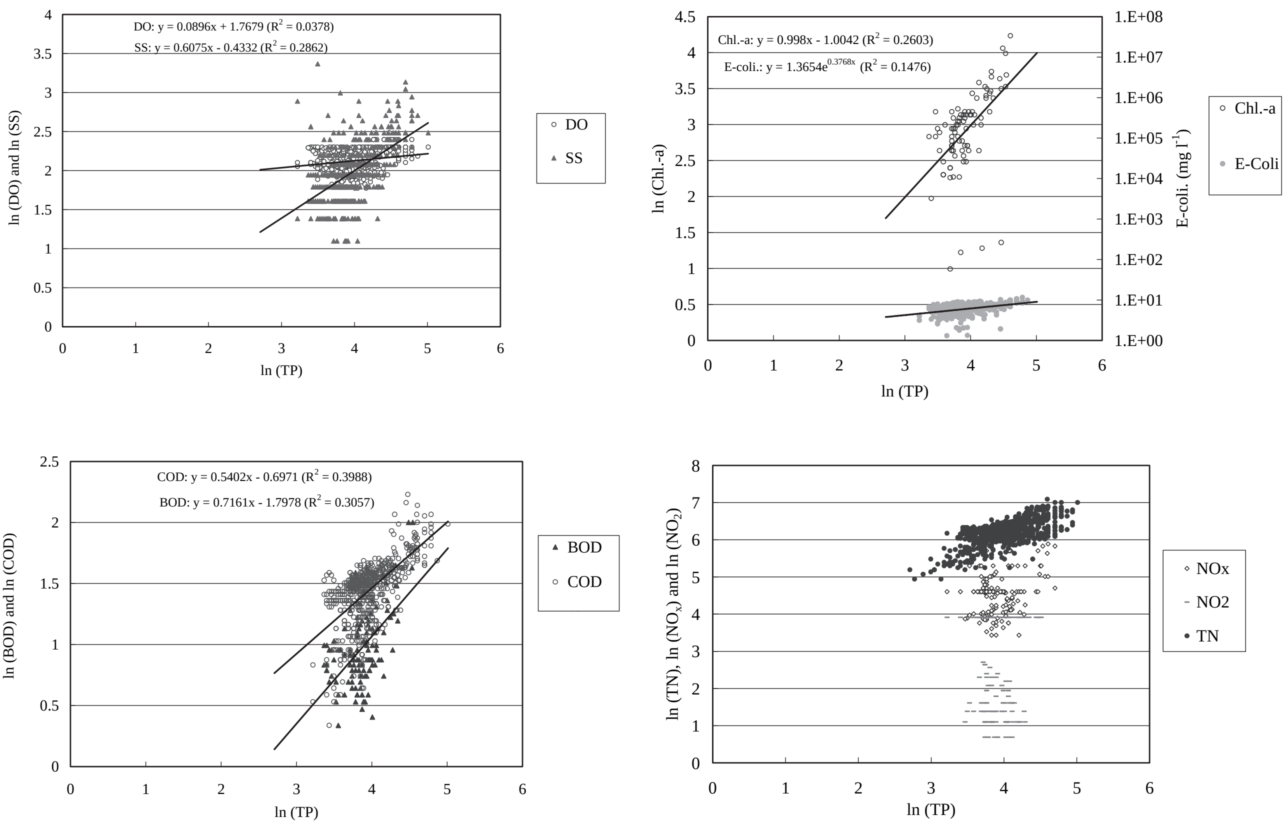

Fig. 3. Correlation relationships between TP and other water quality parameters, DO, SS, Chl.-a, BOD, COD, NO_x, NO_2 and TN for brackish lakes in Shimane and Tottori Prefectures (log scale).

Table 3. Physiographical parameters and indices of five brackish lakes in Japan. (modified by the author after Goda, 1981)

Brackish lake	Catchment area W (km^2)	Water volume V (10^6 m^3)	Mean depth H (m)	Surface area A (km^2)	Population P (10^3 preson)	W/V (10^{-6} km^2 m^{-3})	P/V (10^{-6} person m^3)	COD (1980)[a] (mg l^{-1})	Retention time (y)	PW/V (10^{-3} person km^2 m^{-3})
Lake Abashiri	1357	233	7.2	32.5	43.1	5.824	185	6.3	0.150	251
Lake Kahoku-gata	272	14.7	1.8	8.2	152.8	18.503	10395	6.9	0.057	2827
Lake Koyamaike	41	19	2.8	6.8	6.1	2.158	321	9.3	0.240	13
Lake Nakaumi	690	533	5.5	96.9	176.7	1.295	332	4.3	0.160	229
Lake Shinji	460	344	4.2	81.8	195.7	1.337	569	4.0	0.240	262

a: Observed value of 1978, average of 75 % value for Lakes Kohoku-gata, Nakaumi and Shinji.

load inflow and outflow. Basic functions of the model are:

$$P_j = \frac{L \cdot (1-R)}{q_s} = P_i \cdot (1-R) \quad (1)$$

$$R = \frac{v}{v+q_s} \quad (2)$$

where P_j: average concentration in the lake (g m^{-3}), L: pollutant loads per lake areas (g m^{-2} y^{-1}), q_s: water inflow (m y^{-1}), P_i: average concentration of inflow (g m^{-3}), R: accumulation rate (-), v: apparent settling velocity (m y^{-1}).

Eq. (2) is similar to have been presented by Chapra (1975). To estimate maximum permissive TP loads, P_i was calculated by eq. (1). P_j was determined by environmental standards zoning and TSI (COD) (Supplement Table 2). Pollutant loads and water inflow were derived from the Environmental Agency (1983). Apparent settling velocity was supposed to 20 m y^{-1}. Actual pollutant loads and maximum permissive pollutant loads for TP and COD were calculated for 83 lakes in Japan (Fig. 3). In regards to lakes in category (III) and (IV), they concluded that internally produced COD were relatively larger because land based nutrients highly exceeded the acceptable levels. Lakes Shinji and Nakaumi were classified into category (III).

3 Application of the TSI to some brackish lakes in Japan including Lakes Shinji and Nakaumi

3.1 Current TSI of some brackish lakes in Japan

In this section, firstly the results of the studies by National Institute of Environmental Science in 1981 including physiographical parameter (Goda, 1981) and Carlson's index modified by Aizaki et al. (1981a) were summarized and adopted to some brackish lakes in Japan. Aizaki et al. (1981a) concluded that the modified Carlson's TSI were applicable to fresh water lakes in Japan, but for the brackish lakes in Japan. In this study, the same kinds of modification were applied using available brackish lakes data in Japan. Secondly, TSI and pollutant loads were summarized based on the methods used by Amano et al. (1991).

(1) Physiographical parameters

Goda (1981) investigated 26 Japanese lakes including five brackish lakes on physiographical parameters and COD in the lakes. Table 3 and Fig. 2 show the relationships for five brackish lakes, Lakes Abashiri, Kohoku-gata, Koyamaike, Nakaumi and Shinji. He investigated 26 freshwater and brackish lakes and distinguished between hypertrophic lakes and special eutrophic lakes from other oligotrophic and mesotrophic lakes. Lake Kohoku-gata was considered as hypertrophic lake and Lakes Koyamaike and Abashiri were classified as specially eutrophic lakes based on the index, PW/V. COD was used as a parameter for eutrophication, because of the lack of parameters to indicate directly the conditions of eutrophication (Goda 1981). He stated the importance of mean depth of the lakes and showed that almost all W/V of the lakes with mean depth less than 10 m were larger than 1.0, and W/V of all the lakes with mean depth more than 10 m were less than 1.0. Moreover, COD of the latter were less than 3.0 mg l^{-1}. Considering the brackish lakes in Fig. 2, W/V and PW/V can be reasonable parameters to some extent to explain COD in the Lakes Shinji, Nakaumi, Abashiri and Kohoku-gata, however, it is a little difficult to find good parameters to explain COD for Lake Koyamaike which was known as a lake with large organic carbon pollutant loads.

(2) Carlson's TSI modification

Carlson (1977) used Secchi disk transparency as a major parameter for TSI, however, Aizaki et al. (1981a) pointed out that light diminishment coefficient of phytoplankton was not so large as those of dissolved materials or suspended materials and transparency did not depend so much on phytoplankton concentration. The authors concluded that chlorophyll-a, which indicated phytoplankton mass more directly than transparency, would be a better parameter for TSI. Walker (1979) proposed chlorophyll-a as a parameter for TSI and defined chlorophyll-a 0.25 mg m^{-3} as TSI 0, TSI increases 10 when chlorophyll-a increases twice. Aizaki et al. (1981a) considered on light diminishment in the water and reasonable maximum concentration of chlorophyll-a in lake water, defined chlorophyll-a concentration of 1000 mg m^{-3} as TSI 100, and chlorophyll-a concentration of 0.1 mg m^{-3} as TSI 0.

$$TSI(100) = 10 \times \left(a + \frac{\ln 1000}{\ln b} \right) \quad (1)$$

$$TSI(0) = 10 \times \left(a + \frac{\ln 0.1}{\ln b} \right) \quad (2)$$

From the above equations, they calculated a is 2.46 and b is 2.5, therefore, TSI (Chl) was defined for freshwater lakes in Japan:

$$TSI(Chl) = 10 \times \left(2.46 + \frac{\ln(Chl)}{\ln 2.5} \right) \quad (3)$$

They investigated water quality of 24 freshwater lakes and six brackish water lakes in Japan from 1977 to 1980, and found the following relationship for only freshwater lakes in Japan:

$$\ln(Chl) = 3.69 - 1.53\ln(SD) \quad (r^2 = 0.96) \quad (4)$$

where SD: Secchi disk transparency (m).

$$\ln(Chl) = 6.71 + 1.15\ln(TP) \quad (r^2 = 0.90) \quad (5)$$

where TP: total phosphorus (mg l^{-1}).

By use of equations (3) and (4), and (3) and (5), they proposed the equations to calculate TSI from SD and TP:

$$TSI(SD) = 10 \times \left(2.46 + \frac{3.69 - 1.53\ln(SD)}{\ln 2.5} \right) \quad (6)$$

$$TSI(TP) = 10 \times \left(2.46 + \frac{6.71 + 1.15\ln(SD)}{\ln 2.5} \right) \quad (7)$$

Moreover, they found good correlations between other water quality parameters and TSI (Chl). When TSI (Chl) increased 10, SD increased 1.8 times, TP 2.2 times, SS (suspended solid) 2.4 times, POC (particulate organic carbon) 2.1 times, PON (particulate organic nitrogen) 2.2 times, TN (total nitrogen) 2.0 times, COD 2.0 times and total bacteria 2.0 times. They also found 2.5 times of transparency that was equal to euphotic zone depth (Table 2). On the contrary, in the brackish lakes, a good correlation was observed only between chlorophyll-a and transparency ($r > 0.800$), however, correlations between TP and other parameters were considered as weak ($r < 0.800$) (Table 3). They concluded that the application of TSI for brackish lakes was more difficult.

The water quality data of some brackish lake were added to the data of Aizaki et al. (1981a) and the same kind of analysis was conducted in this study. These brackish lakes were selected from the major lakes list of Geographical Survey Institute, Japan (2006) and their water quality data were obtained from the International Lake Environment Committee. The number of brackish lakes in the former list was 24, and water quality data were available only for four brackish lakes in the latter database, Lakes Shinji, Hamana, Ogawara and Saroma. Regression coefficient of water quality data were calculated (Table 5) based on the collected data (Table 4). Water quality data for surface layer were used for four brackish lakes from the International Lake Environment Committee. In this study, weak correlations were also observed between water quality data of the brackish lakes. Further study would be necessary for applicability of Carlson's TSI like indices to brackish lakes in Japan. Calculation was conducted with all layers average data for four lakes from the International Lake Environment Committee (Table 6). The results showed that the tendency of the regression coefficient was almost the same as those shown in Table 5. Phytoplankton grow in the surface layers with light intensity, therefore, water quality parameters in the surface layers should be used.

3.2 Water quality data analysis for brackish lakes in Tottori and Shimane Prefectures

Correlation relationships were analyzed using publicly monitored water quality data (Ministry of the Environment, 2006; Shimane Prefecture, 2006; Tottori Prefecture, 2006) using SPSS® statistic analysis software. Annual average data from 1980 to 2003 were base of the dataset for the analysis. Some chlorophyll-a data were added from Shimane Prefecture (2006) and Tottori Prefecture (2006). Table 7 shows the regression coefficients, significance probability and number of data used for each calculation of regression coefficient of water quality parameters expressed as natural log scale. Correlation coefficient of TP and chlorophyll-a was the largest, 0.766. Besides this combination, combinations with absolute valued of correlation coefficient larger than 0.500 were observed for seven combinations, TP and BOD, TP and COD, TP and chlorophyll-a (Chl), NO_x and SS, NO_2 and SS, DO and *E.coli*, and DO and TN. There were more combinations with significant relationships as indicated in Table 7.

Fig. 3 shows the correlation relationships between TP and other water quality parameters. The numbers of combinations with correlation coefficients larger than 0.600 in regards to a parameter with the other parameters were, three for COD, and two for TP, SS and TN. TP was selected as a key parameter of Fig. 3.

The relationship between TSI and TP in Table 8 was expressed as the following equation:

$$TSI_{BL}(TP) = 12.458 \cdot \ln(TP) + 11.264 \quad (8)$$

where TSI_{BL} is trophic state index for brackish lakes.

By use of eq. (8) and relationships between TP and other water quality parameters, Chl.a, BOD, COD and TN, relationships between TSI_{BL} and these water quality parameters were expressed as the following equations.

$$TSI_{BL}(Chl.a) = 12.458 \cdot \frac{\ln(Chl.a) + 1.0042}{0.998} + 11.264 \quad (9)$$

Table 4. Water quality parameters of surface layers for some brackish lakes in Japan.

Brackish lakes	Chl.a[a] µg l^{-1}	Secchi[b] m	T-P mg l^{-1}	SS mg l^{-1}	POC mg l^{-1}	PON µg l^{-1}	T-N mg l^{-1}	COD mg l^{-1}	Total bac.[c] No. ml^{-1}
L. Hamana[d]	25.0	1.6	0.044	36.2	2.1	370	0.457	13.3	5.7×10^{6}
L. Inohana[d]	23.0	2.1	0.056	39.5	2.2	350	0.775	9.6	4.5×10^{6}
L. Suigetsu[d]	8.3	2.5	0.580	7.8	1.7	210	0.215	1.8	3.0×10^{6}
L. Suga[d]	6.7	2.4	0.350	4.3	0.94	120	0.129	1.9	2.4×10^{6}
L. Kuguchi[d]	9.5	1.7	0.027	8.8	1.5	195	0.200	2.1	3.0×10^{6}
L. Hyuga[d]	3.7	4.0	0.026	18.0	0.65	67	0.117	7.5	n.a.
L. Shinji[e]	19.2	1.2	0.042	6.2	n.a.	n.a.	0.49	4.0	n.a.
L. Hamana[f]	18.4	3.1	0.034	n.a.	n.a.	n.a.	0.43	1.7	n.a.
L. Ogawara[g]	7.4	3.6	0.021	2.0	n.a.	n.a.	0.68	2.8	n.a.
L. Saroma[h]	n.a.	5.8	0.018	2.3	n.a.	n.a.	0.13	1.7	n.a.

a: Chlorophyll-a; b: Secchi disk transparency; c: Total bacteria; d: Aizaki et al. (1981a); e: 1985; f: 1984; g: 1985-86;
h: 1978-79; e-h: International Lake Environment Committee, n.a.: not available.

Table 5. Square of regression coefficient of water quality parameters of surface layer for some brackish lakes in Japan exhibited in Table 4.

	Chl.a[a]	Secchi[b]	T-P	SS	POC	PON	T-N	COD
Secchi[b]	-0.453							
T-P	-0.389	-0.166						
SS	0.684	-0.359	-0.226					
POC	0.887 *	-0.751	-0.073	0.666				
PON	0.970 *	-0.734	-0.214	0.783	0.971 *			
T-N	0.643	-0.344	-0.344	0.492	0.829 *	0.861 *		
COD	0.421	-0.316	-0.308	0.927 *	0.469	0.639	0.408	
Total bac.[c]	0.967 *	-0.635	-0.579	0.921 *	0.850 *	0.959 *	0.725	0.981 *

a: Chlorophyll-a; b: Secci disk transparency; c: Total bacteria.
The regression coefficient more than or equal to 0.800 are indicated by astersisk.

Table 6. Square of regression coefficient of water quality parameters for brackish lakes in Japan. Water quality of some lakes are the averages of all layers instead of the average of surface layer in Table 5.

	Chl.a[a]	Secchi[b]	T-P	SS	POC	PON	T-N	COD
Secchi[b]	-0.605							
T-P	-0.351	-0.165						
SS	0.725	-0.360	-0.231					
POC	0.887 *	-0.751	-0.073	0.666				
PON	0.970 *	-0.734	-0.214	0.783	0.971 *			
T-N	0.630	-0.338	-0.342	0.465	0.829 *	0.861 *		
COD	0.584	-0.312	-0.308	0.928 *	0.469	0.639	0.391	
Total bac.[c]	0.967 *	-0.635	-0.579	0.921 *	0.850 *	0.959 *	0.725	0.981 *

a: Chlorophyll-a; b: Secci disk transparency; c: Total bacteria.
The regression coefficient more than or equal to 0.800 are indicated by astersisk.

Table 7. Regression coefficients, significance probability and number of data used for each calculation of regression coefficient for the brackish lakes in Shimane and Tottori Prefectures

	ln(TP)	ln(NO_x)	ln(NO_2)	ln(TN)	ln(BOD)	ln(COD)	ln(Chl.a)	ln(SS)	ln(E-coli.)
ln(NO_x)	0.039								
ln(NO_2)	-0.013	0.469 **							
ln(TN)	0.005	-0.114	-0.345 **						
ln(BOD)	-0.501 **	-0.131 *	-0.082	-0.464 **					
ln(COD)	-0.535 **	-0.472 **	-0.415 **	-0.308 **	0.331 **				
ln(Chl.a)	0.766 **	0.216 **	-0.076	0.013	-0.386 **	-0.468 **			
ln(SS)	-0.494 **	-0.526 **	-0.508 **	-0.023	-0.027	0.499 **	-0.381 **		
ln(E-coli.)	-0.199 **	-0.291 **	-0.477 **	0.515 **	-0.458 **	-0.124 **	-0.236 **	0.250 **	
ln(DO)	-0.171 **	-0.073	0.261 **	-0.620 **	0.412 **	-0.140 **	-0.134 *	-0.333 **	-0.585 **

** The correlation is significant with 1% significant level (both sides).
* The correlation is significant with 5% significant level (both sides).

Table 8. TSI (trophic state index) tentatively calculated based on TP for brackish lakes in Shimane and Tottori Prefectures

TSI	TP μg l^{-1}	DO mg l^{-1}	SS mg l^{-1}	Chl.a[a] μg l^{-1}	E-coli. No. ml^{-1}	BOD mg l^{-1}	COD mg l^{-1}	TN μg l^{-1}	NO_x μg l^{-1}	NO_2 μg l^{-1}
0	0.4	5.4	0.4	0.1	4.4E-03	0.1	0.3	35	4.5	4.6
10	0.9	5.8	0.6	0.3	3.2E-02	0.2	0.5	54	7.4	5.4
20	2.0	6.2	1.0	0.7	2.3E-01	0.3	0.7	83	12	6.2
30	4.6	6.7	1.6	1.6	1.7E+00	0.5	1.1	128	20	7.2
40	10	7.2	2.6	3.7	1.2E+01	0.9	1.7	197	34	8.4
50	23	7.7	4.3	8.2	8.6E+01	1.5	2.7	303	57	9.7
60	50	8.3	7.0	18.2	6.2E+02	2.7	4.1	467	94	11.2
70	110	8.9	11.4	40.5	4.5E+03	4.8	6.4	720	157	13.0
80	250	9.6	18.5	90.2	3.3E+04	8.6	9.8	1111	260	15.1
90	555	10.3	30.2	201.0	2.3E+05	15.3	15.1	1712	433	17.5
100	1230	11.1	49.1	447.8	1.7E+06	27.2	23.4	2639	719	20.2

$$TSI_{BL}(BOD) = 12.458 \cdot \frac{\ln(BOD) + 1.7978}{0.5402} + 11.264 \qquad (10)$$

$$TSI_{BL}(COD) = 12.458 \cdot \frac{\ln(COD) + 0.9671}{0.5402} + 11.264 \qquad (11)$$

$$TSI_{BL}(TN) = 12.458 \cdot \frac{\ln(TN) - 4.0382}{0.5391} + 11.264 \qquad (12)$$

TSI for brackish lakes in Shimane and Tottori Prefectures were tentatively calculated using the relationship between TSI and TP for freshwater lakes in Japan (Aizaki et al., 1981a), and the correlation relationships of TP and other water quality parameters (Table 8).

3.3 Fulmer and Cooke's application of TSI to the brackish lakes in Japan

At the planning stage of this study, capabilities of restoration of Japanese brackish lakes were planned to be analyzed using the analytical methods by Fulmer and Cooke (1990) in this section. The author intended to prepare TSI for the brackish lakes in Japan and to make comparison with natural state. However, it was not able to complete analyses for the equations to indicate TSI for the brackish lakes in Japan. Therefore, Fulmer and Cooke's application to brackish lakes in Japan is to be studied further.

4 Conclusion

Studies related to Carlson's trophic state index (TSI) were briefly reviewed focusing on brackish lakes in Japan. Carlson's TSI and its modified indices were applied to some brackish lakes in Japan by two different methods. Firstly, it was difficult to find an applicable equation for TSI for brackish lakes in Japan in accordance with the existing studies. Theoretically, water quality of surface layer should be used for TSI, however, the regression coefficient using surface layer water quality and all layers water quality were almost the same to the extent of the analysis in this study. Secondly, equations to calculate TSI for brackish lakes in Tottori and Shimane Prefectures were tentatively presented after the regression analysis of publicly monitored water quality data.

Preparing database of water quality, water quantity and physiographical parameters for the brackish lakes in Japan, and further consideration on the equations of TSI would be needed for better understanding of these parameters and water quality improvement in the lakes.

Supplement Tables and Figures will be available at ReCCLE homepage.

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