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FUZZY ASSESSMENT ON RESERVOIR WATER QUALITY

Ruey-Tyng Lin[1] and Wen-Cheng Huang[2]

Key words: fuzzy set theory, membership function, Carlson's Trophic State Index (CTSI), Feitsui Reservoir.

ABSTRACT

Carlson's Trophic State Index (CTSI) has long been used in the Taiwan region to assess reservoir eutrophication, however this approach can often lead to confusion because the assessment criteria for CTSI (such as Secchi disk Depth) can be degraded by factors such as turbidity, which does not actually reflect the increased eutrophication.

Mountainous subtropical islands suffer from serious storm-driven erosion problems, leaving reservoir water quality subject to seasonal weather conditions, torrential rains, typhoons and turbidity. Thus the CTSI alone may be insufficient or inappropriate at certain times to evaluate water quality.

In pratice, we found that this indicator could produce biased results due to high flooding, seasonality, and high turbidity. In this study we use fuzzy sets to assess water quality rating, to investigate the appropriateness of its use in evaluating water quality, and to improve the evaluation for reservoir eutrophication.

Results indicate that using fuzzy sets as a method of analysis is appropriate for determining water quality levels at Taiwan's Feitsui Reservoir, and that it can be used to represent water quality caused by hydrological phenomena.

I. INTRODUCTION

The Feitsui Reservoir is a Phase IV reservoir development project in the greater Taipei area, serving 5,000,000 residents in all of Taipei City and parts of New Taipei City, while providing support to Keelung, Panchiao and Hsinzhuang. It is northern Taiwan's largest and key reservoir. The greater Taipei area obtains 97% of its water from the Hsintian River, which is the confluence of the Nanshih Creek and the Peishih Creek, which respectively provide 54.3% and 45.7% for the raw water demand downstream. Effective management of the reservoir ensures appropriate water release, and thus full and effective use of water resources. In response to the completion of engineering work to improve the quantity and quality of water available to Panchiao and Hsinzhuang, current supplies are divided between Taipei City and New Taipei City at a ratio of 53/47. With the completion of the second stage of the Pan-Hsin engineering project, the amount of water demand will increase significantly, thus greatly increasing the risk of water scarcity. To ensure water quality and quantity, at the outset of the project a "Taipei Water District Management Committee" (predecessor of the Taipei Water Conservation Office) was established to manage water and soil conservation in the reservoir's watershed area, and to oversea management planning work in the catchment area. The reservoir storage area is managed under the provisions of the "Taipei Reservoir Management, Storage Range and Management Guidelines", and it is the responsibility of the Taipei Feitsui Reservoir Administration to maintain a maximum normal water service at an elevation of 170 m above sea level. Water quality is rigorously monitored, with regular sampling, testing, analysis. The reservoir staff continuously engaged in efforts to educate the public as to the importance of water conservation, and advocacy for good maintenance. Fig. 1 shows the location of the reservoir along with sampling points.

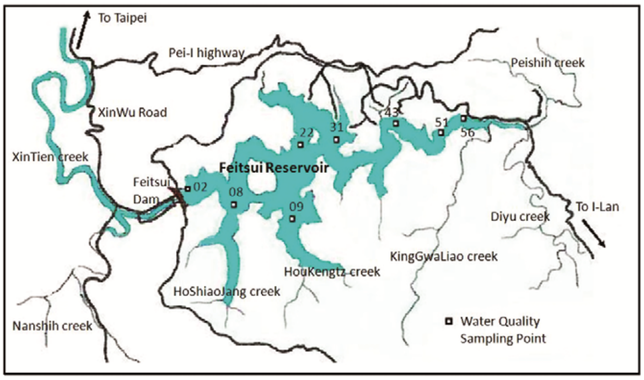

Fig. 1. Water quality sampling stations (Source: Taipei Reservoir Management Administration Annual Report).

Generally speaking, CTSI for reservoir water is impacted

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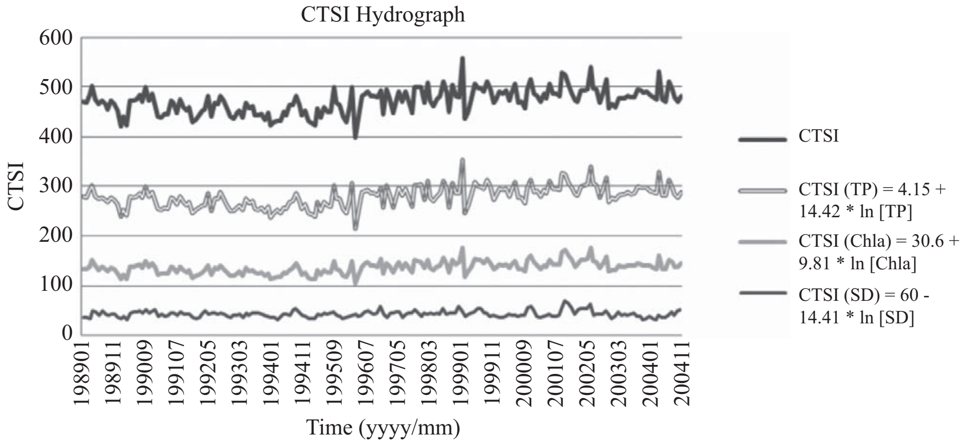


Fig. 2. Feitsui Reservoir CTSI, 1989-2004.

upon pollutants entering the water due to erosion caused by heavy rainstorms and landslides. Landslides and major construction can also increase water turbidity which negatively impacts on water quality. Since 1996, development projects have gradually reduced water quality in the Feitsui Reservoir, and introduced particularly high levels of phosphorus (Taipei Feitsui Reservoir Administration, 1989-2004). For example, since 1996, the construction of the Taipei-Ilan freeway and torrential rains caused topsoil erosion in the catchment area, resulting in large influxes of nutrient sources and extended periods of high turbidity, thus damaging water quality where the eutrophication level is consistent with the water quality indicator. Water quality deteriorates for a period following each downpour, resulting in an increase to the CTSI eutrophication value. Fig. 2 shows reservoir water quality readings from January 1989 to October 2004.

Physical and chemical indicators of reservoir water quality are typically measured using CTSI, which calculates eutrophication level using three water quality parameters including Secchi disk Depth (SD), Chlorophyll a (Chla), and Total Phosphorus (TP) as follows (see Eqs. (1) to (4)):

$$\text{CTSI} = [\text{TSI (SD)} + \text{TSI (Chla)} + \text{TSI (TP)}]/3 \tag{1}$$

where,

$$\text{TSI (SD)} = 60\text{-}14.41 \ln [\text{SD}] \tag{2}$$

$$\text{TSI (Chla)} = 9.81 \ln [\text{Chla}] + 30.6 \tag{3}$$

$$\text{TSI (TP)} = 14.42 \ln [\text{TP}] + 4.15 \tag{4}$$

and

[SD]: Secchi disk Depth, in meters

[Chla]: Concentration of Chlorophyll a, in μg/l

[TP]: Concentration of Total Phosphorus, in μg/l

Eutrophication level is calculated at each testing station based on CTSI indicator definitions. If CTSI < 40, the water is oligotrophic, while readings between 40 to 50 are mesotrophic and those above 50 are eutrophic.

CTSI occasionally cannot be used to appropriately assess water quality in the Taiwan area because the phosphorus and transparency parameters are susceptible to interference from monsoon rains, typhoons and heavy rainstorms which boosts the eutrophication rating. Chla and TP are difficult to measure accurately due to problems with the assessment techniques or QA/QC issues. For example, in 2002, the continual low test values of Chla were due to problems in the analysis process and the interference from turbidity which directly affected the calculated value for this indicator. In addition, CTSI values may rise due to increased amounts of fine inorganic particles, resulting in inconsistent eutrophication ratings. These fine particles are originated from pollution in the catchment area, and introduce increased phosphorus which negatively impacts water quality. Also, transparency can be significantly decreased by turbidity, mixing or the presence of other chemical substances, thus increasing the CTSI rating. At the beginning of the year, monthly average CTSI values tend to be lower than annual averages, which is obviously a consequence of seasonal variations.

Also, the TSI (SD), TSI (Chla) and TSI (TP) are normally given equal weight in CTSI, but this is not necessarily a reasonable approach. Interaction between these three parameters and the external environment can raise authenticity issues, and directly taking averages will smooth out high and low readings, thus failing to highlight the characteristics of each parameter. Thus, CTSI readings for reservoirs generally show values in the middle range.

Although CTSI has been long-term used as an indicator for eutrophication evaluation, it's difficult to ensure that it's an appropriate indicator for the water quality of reservoirs in Taiwan (CTCI and MWH, 1996). However, there is no other commonly accepted means of distinguishing gradations of water quality. The present study discusses the use of fuzzy set theory to establish factor weightings, and to formulate a more appropriate evaluation method or indicator model for assessing water quality rating.

II. PREVIOUS RESEARCH

Fuzzy set theory has been applied in a range of fields (Zadeh, 1965; Jin, 1991; Zimmermann, 1991) including providing comprehensive evaluations of water shortages, providing early warnings for drought, providing reservoir flood warnings, and assessing water quality. Yuan (2004) used water storage (and demand) assessment factors to reflect the assessment indicator, thus formulating a suitable membership function. Lu and Lo (2002) used SOM to compare evaluation results derived from CTSI and the fuzzy comprehensive assessment method. Liou and Lo (2005) used the fuzzy index mode FCM clustering algorithm to evaluate reservoir euthrophication.

Huang and Chou (2005) established the probability of rainfall exceeding the drought index membership function for three consecutive months to determine the rainfall degree of membership and thus determine regional gradations of rainfall and aridity. Chou (2004) used fuzzy logic sets to establish a membership function to evaluate inflows and gauge lines (i.e., storage capacity) of the Zengwen Reservoir. Through fuzzy operations, he determined future water scarcity levels and arid warning indicator levels to help develop drought coping strategies. Hu (1994) used online fuzzy reservoir operations in dry season to establish a fuzzy comprehensive evaluation model to set reservoir release strategy levels and to evaluate non-inferior solutions derived through dynamic planning methods from which to select optimal compromise release strategies. Chow (1994) developed a Fuzzy Linear Programming Model (FLPM) to establish an expert reservoir operation system to increase the effectiveness of obtaining compromise solutions while simultaneously handling probability and ambiguity.

Chen et al. (1996) applied fuzzy logic to the evaluation of reservoir quality, determining that fuzzy cluster analysis is not appropriate for use data sets with large variability. Hsieh (2010) and Huang and Hsieh (2010) use fuzzy theory and the fuzzy comprehensive assessment to establish a fuzzy set membership function based on hysical quantities (flood levels) which cannot be clearly defined. Their studies of flood warning models further evaluated the impact of various flood impact factors. More recently, the fuzzy set theory combined with ANNs (Annual Neural Networks) has been satisfactorily applied to solve various environmental problems (Chung et al., 2012).

Eutrophication in reservoir lakes can be assessed using two different indicators. The first (CTSI) was developed by Carlson's in his article "A Trophic State Index for Lakes" (Carlson, 1977). The second indicator, single parameter eutrophication index has been adopted by the OECD. Although CTSI has been used for many years, it remains to be determined whether this model is well suited for use for evaluating Taiwan's reservoirs, but no other universal model has been developed. Lin et al. (2004) attempted to apply an analysis of multiple water quality indicators to the Feitsui Reservoir. Their assessment of Feitsui Reservoir eutrophication conducted a regression analysis and correlation analysis of relevant parameters for indicators including SI, QI, ATSI, CTSI and NCTSI, comparing assessment results with actual changes in water quality. This allowed them to determine the applicability of the various indicators to this particular reservoir, and to exclude the impact on eutrophication of climate conditions such as season, torrential rainfall, typhoons, and turbidity.

III. RESEARCH METHODOLOGY

This study primarily establishes a set of reservoir water quality evaluation methods which not only provide a representation of water quality rankings, but resolve the complexity of water quality assessment problems and are simple to use. This study uses Secchi disk Depth (SD), Chlorophyll a (Chla) and Total Phosphorus (TP) as evaluation factors, classifying water quality into one of five grades. Fuzzy set theory is then applied for analysis and the results are then compared with actual hydrology changes due to reservoir operations, actual water quality monitoring results, and changing circumstances to discuss the appropriateness of applying this approach to the Feitsui Reservoir. In the study, each water quality factor is weighted to provide a more expedient evaluation.

1. Fuzzy Theory

Fuzy theory was developed from Fuzzy sets introduced by Zadeh (1965) to investigate the fuzzy nature of problems, expiatially converting them from their original "either-or" membership affiliation to "both a and b" relative affiliations for fuzzy operation analysis for policy decisions or program development parameters. Chang and Wang (1995) explored the application of fuzzy mathematics to water resource planning. Huang and Yang (1996) used fuzzy decision analysis to explore issues related to river flow design and water quality, while Liou and Lo (2005) used the FCM clustering algorithm to evaluate reservoir eutrophication.

In this study, due to presence of "both a and b" characteristics between various factors and assessment levels, it is necessary to first determine the assessment levels for each evaluation factor, thus determining water quality. In fact, under fuzzy concepts, this cannot be clearly defined using traditional mathematical methods, so the fuzzy multiple assessment method is used to conduct a comprehensive and objective determination of the assessment target. Generally, in fuzzy set theory relations, an element h in the domain H is a member of the fuzzy set, as illustrated in Eq. (5) where $\mu_{\tilde{A}}$ is the membership function of $\tilde{A}$, and the degree of membership $\mu_{\tilde{A}}(h)$ represents the degree of attribution of $\tilde{A}$ for h.

$$\tilde{A} = \left\{ \left(h,\ \mu_{\tilde{A}}(h) \ \middle|\ h \in H \right) \right\}, \quad 0 \le \mu_{\tilde{A}}(h) \le 1 \tag{5}$$

Table 1. Water quality parameter classification.

Water quality constituent \ Level	Excellent **1**	Good **2**	Average **3**	Fair **4**	Poor **5**	Mean allowable value (C0i)	unit
Secchi disk Depth (SD)*	> 4.5	4.5~3.7	3.7~2.3	2.3~1.7	< 1.7	3.0	m
Chlorophyll a (Chla)*	< 2	2.0~3.0	3.0~7.0	7.0~10.0	> 10.0	5.0	μg/l
Total phosphorus (TP)*	< 8	8~12	12~28	28~40	> 40	20.0	μg/l
CTSI**	< 20	20~40	40~50	50~70	> 70	50	-

Notes: * Trophic state as a function of nutrient levels defined by OECD.
** Adopted from the study "Reservoir eutrophiction prediction and prevention by using remote sensing technique (2/2)" (Hydrotech Research Institute, 2005).

2. Confirmation of Assessment Factors

Generally speaking, factors used in evaluating reservoir water quality are very complex. The key evaluation factors include Secchi disk Depth (SD), chlorophyll a (Chla), total phosphorus (TP), dissolved oxygen (DO) ammonia (NH3) biochemical oxygen demand (BOD) and temperature (TEMP) and so forth. Indices generally can be classified as taking single-factor of multiple factor approaches to evaluation. CTSI, the North Carolina Trophic State Index (NCTSI), the Algae Trophic State Index (ATSI), the Saprobic Index (SI) and the comprehensive averaged diversity index (QI) are multi-factor indices, while the indices used by the OECD and USEPA are single-factor. This study is primarily concerned with assessing the appropriateness of CTSI. In order to provide comparison with CTSI results, this study also selects the same factors as CTSI's and these factors (i.e. SD, Chla and TP) are commonly used in reservoir water quality assessment.

3. Establishing Relevant Parameter Assessment Sets

Assessment sets for each selected assessment factor are determined according to the development of assessment levels to establish fuzzy membership functions for different assessment levels. Through such fuzzy membership functions, the assessment levels can indicate the representation of the indicator for each assessment factor. This study uses the OECD's single indicator water quality differentiations (see Table 1) (Hydrotech Research Institute, 2005) to produce five levels for each of the defined assessment factors as follows: 1 (excellent), 2 (good), 3 (average), 4 (fair) and 5 (poor), and can be represented as follows (see Eq. (6)):

$$V = \{\text{Excellent } (\nu 1), \text{Good } (\nu 2), \text{Average } (\nu 3), \text{Fair } (\nu 4), \text{Poor } (\nu 5)\} \tag{6}$$

As the membership function of the fuzzy set is applied to the actual root of the problem, this study applies triangular or trapezoidal fuzzy functions to represent the fuzzy membership function for each assessment grade, and the corner values show the corner membership values, thus the assessment set established for each evaluation factor is explained as follows:

1) Secchi Disk Depth (SD) Evaluation Set

Following the OECD individual indicator Secchi disk Depth (SD) differentiation for eutrophication, we formulate a fuzzy membership function for the evaluation levels for water quality based on transparency (see Fig. 3).

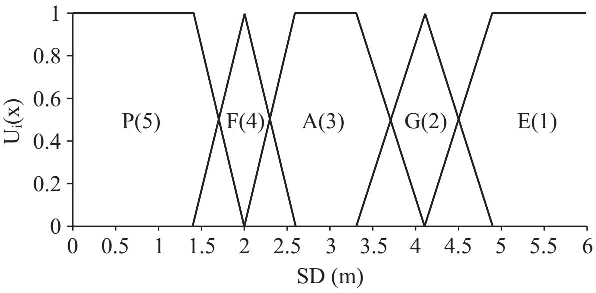


Fig. 3. Membership functions for Secchi disk Depth (SD) assessment levels.

The corner values for the water quality trapezoidal fuzzy number for "excellent", "average" and "poor", along with the water quality triangular fuzzy membership values for "good" and "fair" are expressed as follows (see Eq. (7)):

$$\begin{aligned}
&(1)\ \mu 1(\nu 5) = (0.0, 0.0, 1.4, 2.0)\\
&(2)\ \mu 1(\nu 4) = (1.4, 2.0, 2.6)\\
&(3)\ \mu 1(\nu 3) = (2.0, 2.6, 3.3, 4.1)\\
&(4)\ \mu 1(\nu 2) = (3.3, 4.1, 4.9)\\
&(5)\ \mu 1(\nu 1) = (4.1, 4.9, 16.0, 16.0)
\end{aligned} \tag{7}$$

2) Chlorophyll A (Chla) Evaluation Set

Following the OECD individual indicator chlorophyll a (Chla) differentiation for eutrophication, we formulate a fuzzy membership function for the evaluation levels of water quality based on chlorophyll a (see Fig. 4).

The trapezoidal corner values correspond to "excellent", "average", "poor"and "fair" water quality ratings, while the triangular corner value correspond to "good" as follows (see Eq. (8):

$$\begin{aligned}
&(1)\ \mu 2(\nu 1) = (0.0, 0.0, 1.5, 2.5)\\
&(2)\ \mu 2(\nu 2) = (1.5, 2.5, 3.5)\\
&(3)\ \mu 2(\nu 3) = (2.5, 3.5, 6.0, 8.0)
\end{aligned}$$

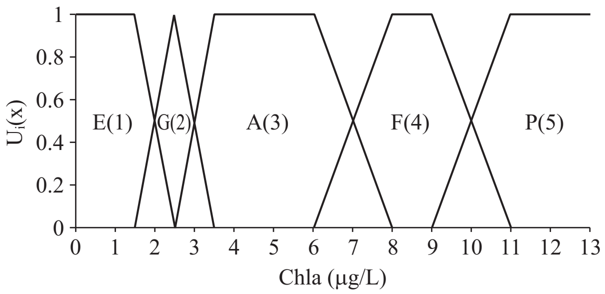
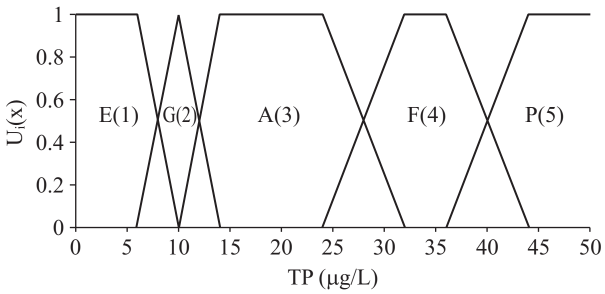


Fig. 4. Membership functions for chlorophyll a (Chla) assessment levels.



Note: E(1)-Excellent, G(2)-Good, A(3)-Average, F(4)-Fair, and P(5)-Poor.

Fig. 5. Membership functions for total phosphorus (TP) assessment levels.

(4) $\mu 2(\nu 4) = (6.0, 8.0, 9.0, 11.0)$

(5) $\mu 2(\nu 5) = (9.0, 11.0, 20.0, 20.0)$ (8)

3) Total Phosphorus Evaluation Set

Following the OECD individual indicator total phosphorus (TP) differentiation for eutrophication, we formulate a fuzzy membership function for the evaluation levels of water quality based on chlorophyll a (see Fig. 5).

The trapezoidal corner values correspond to "excellent", "average", "fair" and "poor" water quality ratings, while the triangular corner values correspond to "good" as follows (see Eq. (9)):

(1) $\mu 3(\nu 1) = (0.0, 0.0, 6.0, 10.0)$

(2) $\mu 3(\nu 2) = (6.0, 10.0, 14.0)$

(3) $\mu 3(\nu 3) = (10.0, 14.0, 24.0, 32.0)$

(4) $\mu 3(\nu 4) = (24.0, 32.0, 36.0, 44.0)$

(5) $\mu 3(\nu 5) = (36.0, 44.0, 100.0, 100.0)$ (9)

4. Fuzzy Evaluation Matrix

Eq. (10) shows a fuzzy assessment matrix ($\tilde{R}$) constructed according to the assessment set of confirmed assessment factors.

$$\tilde{R} = \begin{array}{c} \begin{matrix} v_1 & v_2 & \cdots & v_n \end{matrix} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \end{array} \begin{array}{c} \\ u_1 \\ u_2 \\ \vdots \\ u_m \end{array} \tag{10}$$

where $U = \{u_1, u_2, ..., u_m\}$ is the assessment factor and $V = \{v_1, v_2, ..., v_m\}$ is the assessment level. In the fuzzy assessment matrix ($\tilde{R}$) is the factor determination of the single factor u_i ($i = 1, 2, ..., m$) in the assessment factor U, so according to the membership function, factor u_i is confirmed as the degree of membership r_{ij} for each level v_j (j = 1, 2, ..., n), where $r_{ij} = \mu_{\tilde{A}}(u_i, v_j)$, thus the fuzzy assessment set $r_{ij} = \{r_{i1}, r_{i2}, ..., r_{mn}\}$ for the single assessment factor represents the selection assessment level of factor u_i. Thus, the fuzzy assessment matrix ($\tilde{R}$) can be expressed as in Eq. (11).

$$\tilde{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & r_{14} & r_{15} \\ r_{21} & r_{22} & r_{23} & r_{24} & r_{25} \\ r_{31} & r_{32} & r_{33} & r_{34} & r_{35} \end{bmatrix} \tag{11}$$

5. Determination of Weighting Coefficients

Because each assessment factor has a different degree of impact on the comprehensive indicator, this degree of impact can be viewed as a fuzzy set $\tilde{A}$ as follows (see Eq. (12)):

$$\tilde{A} = \{a_1, a_2, \Lambda, a_m\} \tag{12}$$

where, a_i ($0 \le a_i \le 1$) is the degree of membership of u_i for $\tilde{A}$, and is thus the degree of impact of the property u_i in the decision objective of the comprehensive assessment, and can serve as an adjustment coefficient, limiting coefficient or a weighting coefficient.

6. Transforming the CTSI Degree of Eutrophication to a Fuzzy Water Quality Rating

This study uses fuzzy set membership functions to transform the original three CTSI eutrophication levels into a set of five levels for comparison with the results obtained in Hydrotech Research Institute (2005) by the Water Resources Agency, Ministry of Economic Affairs. We formulate a fuzzy membership function for the evaluation levels on CTSI (see Fig. 6).

The trapezoidal corner values correspond to "excellent", "good", "fair" and "poor" water quality ratings, while the triangular corner value correspond to "average" as follows (see Eq. (13)):

(1) $\mu 4(\nu 1) = (0.0, 0.0, 15.0, 25.0)$

(2) $\mu 4(\nu 2) = (15.0, 25.0, 35.0, 45.0)$

(3) $\mu 4(\nu 3) = (35.0, 45.0, 55.0)$

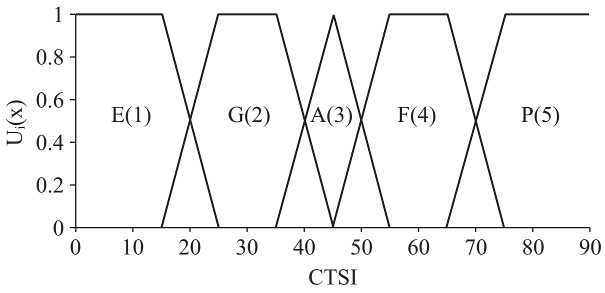


Fig. 6. Membership function for CTSI weighed levels.

(4) $\mu 4(\nu 4) = (45.0, 55.0, 65.0, 75.0)$

(5) $\mu 4(\nu 5) = (65.0, 75.0, 100.0, 100.0)$ (13)

7. Fuzzy Arithmetic

Finally, using the fuzzy assessment matrix $\tilde{R}$ and the assessment factor weighting set $\tilde{A}$, fuzzy arithmetic calculates the fuzzy comprehensive assessment set $\tilde{B}$ as follows (see Eq. (14)):

$$\tilde{B} = \tilde{A} \circ \tilde{R} = \{b_1, b_2, \cdots, b_n\} \tag{14}$$

where, "$\circ$" is a fuzzy arithmetic symbol called the fuzzy transformation. Each element b_j of the abovementioned fuzzy transformation $\tilde{B}$ are calculated using generalized fuzzy arithmetic, abbreviated as the arithmetic model $M(\overset{\bullet}{*}, \overset{+}{*})$, and calculated as follows (see Eq. (15)):

$$b_j = (a_1 \overset{\bullet}{*} r_{1j}) \overset{+}{*} (a_2 \overset{\bullet}{*} r_{2j}) \overset{+}{*} \cdots \overset{+}{*} (a_m \overset{\bullet}{*} r_{mj}) \quad j = 1, 2, \cdots, n \tag{15}$$

In which,

a_m: weighting for each factor among all factors.

b_j: the weighting for each level j after fuzzy arithmetic for each factor, which j is corresponding to "v_j" in III-3.

r_{mj}: weighting for each factor m in level j after fuzzy arithmetic

and where, "$\overset{\bullet}{*}$" is the generalized fuzzy "intersection (and)" operation and "$\overset{+}{*}$" is the generalized fuzzy "union (or)" operation. Generally, there are several methods to achieve fuzzy transformation with no specific applicable standards, and selection is based on the nature of the practical problem and the attitude of the decision-makers. For example, $M(\bullet, +)$ is a conventional matrix arithmetic mode, belonging to the "weighted average-type" fuzzy transformation, while $M(\wedge, \vee)$ is an arithmetic of taking small value ($\wedge$) and taking large value ($\vee$), belonging to the "Key factor determination-type" fuzzy transformation. This study applies the fuzzy transformation operating mode to compare with actual water quality conditions, and uses the operating modes of these two formulae to determine water quality. We first use the $M(\bullet, +)$ calculation mode, primarily considering the ability of this calculation process to appropriately allocate weightings to the assessment factors. We then obtain the fuzzy comprehensive assessment sets using Eq. (16), and then cumulatively calculate the reaction of the comprehensive assessment elements, defining the relative assessment level of comprehensive assessment values greater than 0.5 (Huang and Yuan, 2004), and comparing the assessment results for different levels of water quality using Eq. (17):

$$b_j = \sum_{i=1}^{m} a_i r_{ij}, \quad j = 1, 2, \cdots, n \tag{16}$$

$$\sum\nolimits_{j=1}^{n} b_j > 0.5 > \sum\nolimits_{j=1}^{n-1} b_j \tag{17}$$

IV. RESERVOIR WATER QUALITY SIMULATIONS

1. Case Study

This study reviews monthly data from eight sampling points on the Feitsui Reservoir from 1989-2004. Secchi disk Depth (SD), chlorophyll a (Chla) and total phosphorus (TP) are selected as assessment factors. We also arrange the water quality level for each assessment factor by applying the fuzzy membership function according to the OECD classification. The abovementioned fuzzy transformation analysis and comprehensive fuzzy assessment results are used to determine the quality of reservoir water. Comparisons are made with observations of hydrological conditions and actual testing of water quality to determine the feasibility and applicability of the model.

2. Simulation Results

For the purposes of this study, the original three eutrophication grades produced by CTSI are transformed into five levels to provide a basis of comparison. For this study, fuzzy comprehensive assessment values greater than 0.5 are treated as being highly consistent with historical CTSI results (see Fig. 7 and Table 2). Individual CTSI indicators (e.g., indicators for SD, Chla or TP) are of limited use in assessing Feitsui Reservoir water quality, and in places individual parameters fail to match actual water quality conditions or original definitions. In terms of bio-mass, if the average CTSI value of the three parameters shows signs of being modified or if the characteristics of individual indicators have been weakened, it results in low TP levels and high Chla levels, or high turbidity will result an unreasonable scenario of a high TSI (SD) value but a low TSI (Chla) value. The averaged values fail to properly distinguish the real pros and cons, resulting in modification of the eutrophication conditions and leveled allocation. Water quality assessments are inconsistent because CTSI lacks weightings individual parameters affecting water quality.

V. RESULTS AND DISCUSSION

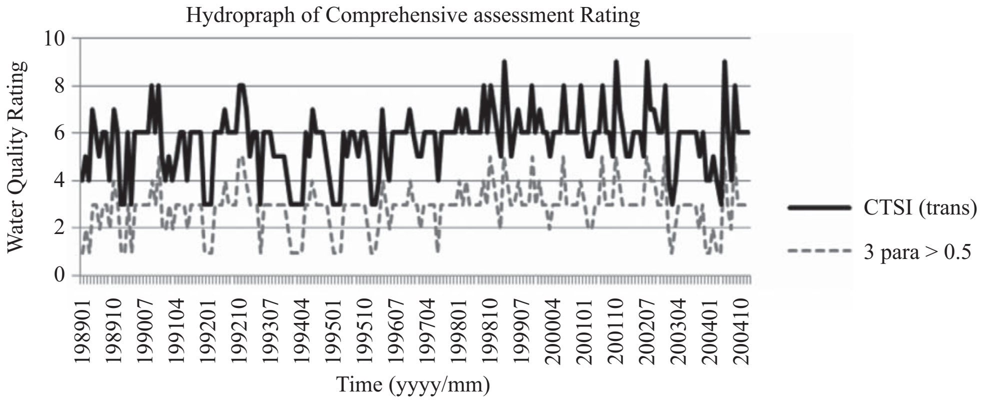
1. Comparison with CTSI

As shown in Fig. 7, comparing the results of this study with

Table 2. Fuzzy level analysis results using SD, Chla and TP (>0.5).

3-par (>0.5)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1989	1	2	1	3	3	3	3	3	2	4	3	1
1990	1	3	1	3	3	3	3	3	4	3	5	2
1991	2	3	2	3	3	3	2	3	3	3	3	1
1992	1	1	3	3	3	4	3	3	3	5	5	4
1993	3	3	3	1	3	3	3	3	3	3	3	2
1994	1	1	1	1	3	3	4	3	3	3	3	2
1995	1	1	1	3	3	3	3	3	3	3	2	1
1996	1	2	4	3	2	3	3	3	3	3	4	3
1997	3	2	3	3	3	3	1	3	3	3	3	3
1998	4	3	4	3	3	3	3	4	3	5	4	3
1999	2	5	4	3	3	4	3	3	3	5	3	4
2000	3	3	2	3	3	3	5	3	3	3	3	4
2001	3	2	2	3	3	5	3	3	3	5	4	3
2002	3	3	3	3	3	3	5	4	4	3	3	5
2003	2	1	2	3	3	3	3	3	3	2	3	1
2004	1	2	1	1	5	3	2	5	3	3	3	3

Notes: a. 3-par: The 3 water quality parameters (SD, Chla and TP) used in this study.
b. In this table, the values show the water quality levels after fuzzy evaluation calculation from Jan. 1989 to Dec. 2004.



Notes: a. 3-par: The 3 water quality parameters (SD, Chla and TP) used in this study.
b. CTSI (trans): Transforming the CTSI value of eutrophication to fuzzy water quality level by fuzzy arithmetic. (See III-6)

Fig. 7. Comparison of each water quality comprehensive fuzzy assessment (>0.5).

CTSI shows that the two approaches show highly similar tendencies, while also matching historic flood and heavy rains. However, the proposed approach for assessing water quality levels can also resolve blind spots arising from the weighting of individual indicators in CTSI.

2. Correspondence with Flooding

Table 3 shows a clear correlation between the reservoir's eutrophication level or water quality level and simulated results for downpours. For both CTSI and this approach, the results shown that the water quality levels are getting worse after the hitting of typhoons or storms. This simulation thus demonstrates the appropriateness of the proposed model to make up for the drawbacks of CTSI.

3. The Proposed Approach Can Solve the Propensity of CTSI to be Inappropruately Impacted by Seasonal Rains, Typhoons, Downpours and Reservoir Overturning, Thus Providing Results Which Better Reflect Actual Water Quality Conditions

The calculated CTSI value includes total phosphorus and transparency which frequently are affected by environmental factors, resulting in increased indictor levels. Historical data shows that seasonal rains, typhoons, downpours and reservoir overturning can raise turbidity, which not only impacts transparency, but can also increase total phosphorus, thus decreasing the accuracy of the CTSI assessment value.

For example, the TSI value in chlorophyll tests tends to rise in September and October 2013, thus resulting in higher CTSI

Table 3. Feitsui Reservoir operational statistics for rainfall exceeding 300 mm (1989-2004).

Typhoon (No.)	Period	Rainfall (mm)	Max. Hourly rainfall (mm)	Inflow (m^3)	CTSI	CTSI (Trans)	3-Parameter
SARAH (8919)	19890908-0914	505.6	24.4	153,987,000	46.39	3	4
OFELIA (9005)	19900621-0625	294.4	17.5	80,270,000	47.07	3	3
YANCY (9012)	19900816-0821	386.5	27.6	103,238,200	51.29	4	4
ABE (9014)	19900829-0901	286.5	33.2	90,667,700	51.29	4	4
DOT (9017)	19900906-0910	390.4	25.3	131,573,000	51.29	4	4
TED (9219)	19920920-0924	304.7	19.7	101,789,000	47.57	3	5
HERB (9608)	19960730-0803	577.3	43.9	190,871,876	48.10	3	3
WINNIE (9714)	19970817-0820	380.9	33.7	86,575,260	43.69	3	3
BABS (9812)	19981023-1029	629.9	24.4	223,422,812	49.01	3	4
XANGSANE (0020)	20001030-1103	651.2	56.0	205,701,724	48.88	3	3
NARI (0116)	20010915-0919	997.5	42.2	296,390,204	51.73	4	5
LEKIMA (0119)	20010923-0929	668.9	21.2	209,593,084	51.73	4	5
AERE (0417)	20040823-0826	538.0	40.1	138,056,112	46.75	3	3
911 monsoon and HAIMA (0420)	20040911-0913	354.2	36.9	100,818,600	46.75	3	3
NANMADOL (0427)	20041203-1204	363.8	39.4	86,086,024	43.54	3	3

Notes: a. Rainfall Exceeding 300 mm means it is for each typhoon or storm during that period.
b. CTSI (trans): Transforming the CTSI value of eutrophication to fuzzy water quality level by fuzzy arithmetic (See III-6).
c. 3-parmeter: The 3 water quality parameters (SD, Chla and TP) used in this study, the values show the water quality level for each typhoon/storm.

values. This is the key reason that chlorophyll a levels in algae seem to rise consistently in certain seasons (Wu, 2013). Desmids, large algae with high chlorophyll a, result in elevated Chla levels, but these are not eutrophic algal species, and thus CTSI assessments may be unable to reflect actual water quality conditions.

VI. RESULTS AND RECOMMENDATIONS

1. The fuzzy analysis on the weighting of CTSI indicator for assessing water quality levels can avoid the difficulties associated with the application of CTSI for assessing water quality in reservoirs. Through comparison analysis, this approach provides a good assessment of the pros and cons of Feitsui Reservoir water quality and is worth promoting.
2. This fuzzy set analysis method provides sufficient and appropriate indication of Feitsui Reservoir water quality conditions, and can reflect most hydrological actual conditions during flooding.
3. Mountainous subtropical island countries suffer from serious erosion due to concentrated rain storms, and reservoir water quality is easily impacted by climate conditions including seasonal rainfall, downpours, typhoons and turbidity. CTSI alone may not serve as an appropriate or sufficient indicator for assessing water quality. The proposed model can eliminate the above mentioned interfering factors and could provide a good basis for assessing reservoir water quality.
4. We recommend using the proposed model combined with appropriate reservoir water quality models to analyze the water quality for each water layer within reservoirs to establish a strategic reference for water release during high water season. For example, release operations should optimize stored water quality, and the analysis process should not impact the quality of downstream drinking water. Turbid water and water with low DO levels should be prioritized for release, thus improving the quality of stored water. In addition, surface water and turbid water should be released during typhoons and flooding, thus reducing potential sources of eutrophication such as algae and sediment, thus maintaining high quality water and reducing impurities sedimentation.

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