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Original Article

Development of specific water quality index for water supply in Thailand

Chaiwat Prakirake[1] Pawinee Chaiprasert[2] and Sudarut Tripetchkul[2]*

[1] *Joint Graduate School of Energy and Environmental,*

[2] *School of Bioresource and Technology,*
King Mongkut's University of Technology Thonburi, Thung Khru, Bangkok, 10140 Thailand.

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Abstract

In this study, the specific water quality index for assessing water quality in terms of water supply (WSI) usage has been developed by using Delphi technique and its application in Thai rivers is proposed. The thirteen parameters including turbidity, DO, pH, NO_3-N, TDS, FCB, Fe, color, BOD, Mn, NH_3-N, hardness, and total PO_4-P are employed for the estimation of water quality. The sub-index transformation curves are established for each variable to assess the variation in water quality level. An appropriate function to aggregate overall sub-indices was weighted Solway function that provided reasonable results for reducing ambiguous and eclipsing effects for high and slightly polluted samples. The developed WSI could be applied to measure water quality into 5 levels - very good (85-100); good (80-<85); average (65-<80); poor (40-<65) and very poor (<40). The proposed WSI could be used for evaluating water quality in terms of water supply. In addition, it could be used for analyzing long-term trait analysis and comparing water quality among different reaches of rivers or between different watersheds.

Keywords: water quality evaluation, specific water quality index, water supply, Delphi technique, weighted Solway function

1. Introduction

Water is one of the most important natural resources to sustain life. Ascertaining its quality is crucial for numerous activities such as drinking, agricultural, recreational, and industrial purposes. Since not all available water bodies are suitable for all specific usages, therefore, specific sets of water quality criteria have to be consulted for each specific purpose.

Water used for water supply purposes, i.e., domestic, industry and agriculture, is one of a major beneficial uses of water bodies in Thailand (PCD, 2004). Water demand of the whole country for three water usages including domestic, industrial and agriculture is approximately 3,567, 2,227 and 28,838 MCM, respectively, in 2003 and the demand is predicted to rise 3.36, 16.6 and 212.64% by 2024 (Koontanakulvong, 2006). Actually, water deficit has been a major problem in Thailand, especially in rural areas of the northeast for several decades due to elevated population growth rate and climate changes and global warming causing prolonged periods of drought in the area especially in the dry season (PWA, 2008). Koontanakulvong (2006) reported that the water deficit in each river basin has been increased from 827 MCM in 2003 to 2,728 and 2,821 MCM for dry year and normal year, respectively, in 2024. Since 95% of water supplies for those purposes are derived from surface water sources such as Mae Nam Khong Basin, Chao Pharaya-Thachin Basin etc (Koontanakulvong, 2006), availability and quality of the water from such resources has declined tremendously due to negligence and pollution stemming from industrial and every day life activities as well as from agriculture (Simachaya, 2003). The water supply sources for domestic, industrial and agricultural uses are from natural water available in the neighboring area such as rainfall

*Corresponding author.
Email address: sudarut.tri@kmutt.ac.th

collection, rivers, canals, wells and ponds. Detrimental water quality, therefore, has a great effect on water supply proposes. Further, although the quality of most receiving water still complies with the national quality standards (PCD, 2004), rivers in populated areas became increasingly polluted (Simachaya, 2003). In terms of water management, water supply should be of high priority concerning health hazard and high demand. Furthermore, there are still some questions whether the receiving water qualities are appropriate for each specific water usage. For managing water resource and maintaining the carrying capacity of receiving waters, a specific water quality index approach is, therefore, considered desirable for evaluation and management of water resources at both regional and national levels.

Several attempts have been made to develop general water quality indices for assessing surface water quality. Generally, the Delphi technique was developed by Rand Corporation (Brown, 1970) to integrate the opinions of experts without the disadvantageous effects of group response by using a series of questionnaires. Important features of the technique are anonymity of individual responses, statistical analysis of responses, and increasingly refined feedback (Dinius, 1987). In the process, panel members are provided with response patterns acquired during the previous round, enabling them to view the total judgment of all respondents, and them asked to reconsider their earlier responses if necessary. This process continues until a desirable degree of consensus among respondents is acquired.

Brown and colleagues (1970) using Delphi technique proposed the water index known as the National Sanitation Foundation Water Quality Index (NSF WQI). Liou *et al*. (2004) developed a generalized WQI for assessing water quality in Taiwan while Lumb *et al*. (2006) proposed the Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) for evaluating water quality in the Mackenzie River basin in Canada. The Pollution Control Department (PCD), Ministry of Natural Resource and Environment of Thailand, has adopted the National Sanitation Foundation Water Quality Index (NSF-WQI) developed by Brown and coworkers in 1970 as a tool for the water quality assessment since 1995. Typically, the water indices were designed to evaluate general water quality based on the assumption that water quality is a general attribute of surface water irrespective of the use to which the water body is put. Therefore, it cannot be used for describing water quality in terms of specific usage since each specific use naturally concerns a specific set of water quality criteria.

Since general water quality indices are incapable of assessing water for individual specific usage and different water resources are of diverse chemical and physical characteristics, several authors developed specific water quality indices (SWQI) for the water quality for specific individual usage (O'Connor, 1971; Walski and Parker, 1974; Walski and Parker, 1974; Nemerow and Sumitomo, 1975; Stoner, 1978; Juong *et al.*, 1979; Sinsupan 1980; Gray, 1996). The objective of this study is develop a specific water quality index for water supply purpose (WSI) for Thai water body.

2. Materials and Methods

2.1 Study area and sampling sites

Locations of the rivers and sampling stations are illustrated in Figure 1. Information regarding the river characteristics and land use was provided by PCD (1997) and Simachaya (2000). Six major rivers of central basin of Thailand, which are Chaophraya, Thachin, Maeklong, Bangpakong, Khwae Noi, and Khwae Yai, were chosen for this study with 63 sampling stations arbitrarily distributed along the length of the rivers. They serve over 20 million people in an area of 100,000 square kilometers. According to the water quality data obtained from the PCD between 1997 and 2000, the water qualities of these rivers could be classified as follows: poor (lower part of both Chaophraya and Thachin rivers), average (upper and medium parts of Chaophraya and Thachin as well as Bangpakong and Meklong rivers), good (Khwae Noi and Khwae Yai rivers) (PCD, 2000; Simachaya, 2003).

The period of sampling was eight months starting from April to November of the year 2000. Samples from each river chosen were collected twice for the entire period of study. Parameters included in this study were adopted according to standards recommended by several official bodies such as WHO and EU including PCD. Water samples were subjected to analysis for 37 parameters, among which 16 were routinely analyzed by PCD (PCD, 2000) and 21 analyzed specifically for this study (Table 1). Collection, stabilization, transportation, storage and analysis of water samples were conducted according to the standard methods described in APHA, AWWA and WPCF (1998).

2.2 Development of specific water quality index for water supply purpose (WSI)

In this study, effort was made to develop the specific water quality index for water supply purpose (WSI) using Delphi technique (Sinsupan, 1980), which is provided elsewhere (Singg and Webb, 1979). Procedures involved were determination of selected variables, significance rating and weighting for each variable, and index calculation.

2.2.1 Determination of selected variables, significance rating and weighting scale

Prior to the formulation of WSI, parameter selection, weighting scale and significance rating for each parameter had to be developed. Subsequently, the index form could be established. Data regarding water qualities were solicited from 24 water quality management experts in Thailand using two sets of questionnaires which were modified from those of Brown *et al.* (1970). Parameters included in both question-

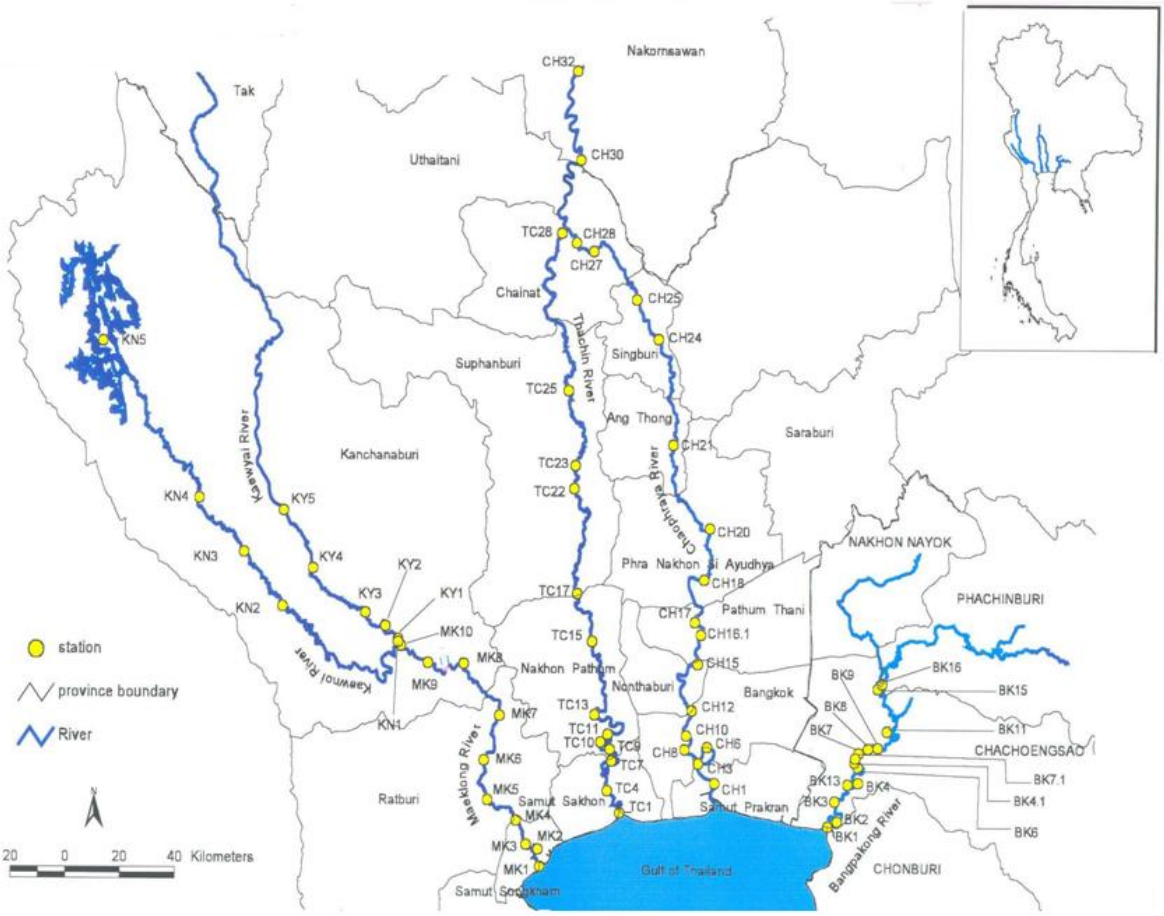


Figure 1. Locations of the river basins and the sampling stations

Table 1. Measured parameters for water quality evaluation

Parameters		
Group I[(1)]	Group II[(2)]	
Temperature	Color	Manganese (Mn)
Turbidity	Sulphate (SO_4^{2-})	Nickel (Ni)
Electrical Conductivity	Free CO_2	Zinc (Zn)
pH	Alkalinity	Copper (Cu)
Total Solids (TS)	Bicarbonate (HCO_3^-)	Lead (Pb)
Suspended Solids (SS)	Sodium Adsorption Ratio (SAR)	
Total Dissolved Solids (TDS)	Chloride (Cl)	
Dissolved Oxygen (DO)	Potassium (K)	
Biochemical Oxygen Demands (BOD)	Fluoride (F)	
Total Coliform Bacteria (TCB)	Calcium (Ca)	
Fecal Coliform Bacteria (FCB)	Magnesium (Mg)	
Ammonia – Nitrogen (NH_3-N)	Sodium (Na)	
Nitrate – Nitrogen (NO_3-N)	Iron (Fe)	
Nitrite – Nitrogen (NO_2-N)	Cadmium (Cd)	
Hardness	Total Chromium (Total Cr)	
Total Phosphate Phosphorus (Total PO_4-P)	Total Mercury (Total Hg)	

Note: [(1)] Parameters were analyzed by the PCD officials.
[(2)] Analyses were specifically for this study.

Table 2. Parameters included in the first questionnaire

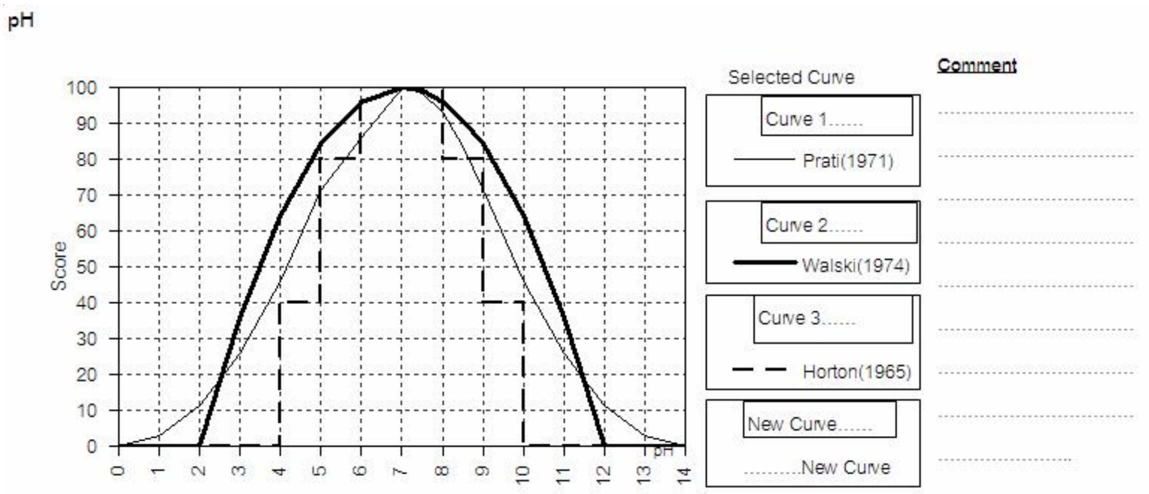
Parameter			
Color	NO_3-N	Aluminium	Total Organochlorine
Odor	TKN	Arsenic	Endrin
Taste	NH_3-N	Barium	Heptachor & Heptachor epoxide
Temperature	Total PO_4-P	Cadmium	Methyl parathion
EC	Hardness	Total chromium	Total Nitrogen (exclusive of NO_3^-)
Turbidity	$AgSO_4$+$NaSO_4$	Chromium Hexavalent	ABS (Alkyl Benzyl Sulfonates)
TS	Sulphate	Copper	Carbon Chloroform Extract
SS	Boron	Iron	
TDS	Calcium	Lead	
TCB	Chloride	Manganese	
FCB	Cyanide	Nickle	
Algae	Fluoride	Silver	
pH	Lithium	Zinc	
DO	Magnesium	DDT	
BOD	Selenium	Alpha-BHC	
COD	Sodium	Dieldrin	
Organics Carbon	Sulfide	Aldrin	

naires were selected based on several water quality standards utilized in several countries such as USA, EU, Australia, Japan, Philippines, Russia and India as well as Thailand (ANZECC, 1992; ESCAP, 1997; Chapman, 1996; PCD, 1994a; PCD, 1997b).

The first questionnaire, containing a total of 58 water qualities (Table 2), was specifically designed to solicit information from experts relevant to the water quality standard evaluation. Each expert was requested to independently select specific water quality parameters necessary for WSI formulation and rated their relative significance using a scale of 1-5 signified highest to lowest importance. However, if parameters the experts believed to be of significant importance for the formulation of the WSI were not included, the panelists were encouraged to recommend freely. The second questionnaire was prepared according to results obtained from the first questionnaire including recommendations made by experts. Experts were once more requested to select parameters to be included in the WSI formulation and provided significance rating of each parameter as mentioned above. Subsequently, the arithmetic means of the significance ratings were calculated based on data obtained from the second questionnaire. Weighting scales for each parameter were defined as the ratio of temporary weight to the sum of temporary weights. Temporary weight was developed by dividing the significance rating of the parameter with the highest significance rating by the average significance rating of individual parameters. Final weight (weighting scale) was obtained by approximating the ratio of temporary weight for each variable to the sum of temporary weights (Brown *et al.*, 1970).

2.2.2 Construction of sub-index transformation curves for individual selected parameter

To assign the sub-index values, the water quality parameters previously obtained were transformed and, subsequently, presented as a two-dimensional (X-Y coordinate) plot where the X and Y axes denoted, respectively, water quality parameter and water quality index (WQI) scale with the WQI (Y axis) ranging on the scale of 0 and 100, where 0 and 100 represented the poorest and the highest water quality, respectively. Each recipient of the second questionnaire was required to select, modify and/or construct the new sub-index transformation curve for the selected parameters in the X-Y coordinate, as shown in Figure 2. Supporting information provided included (1) range of the WQI scale modified from a color spectrum scale as proposed by Brown and coworkers in 1970 - water quality and score ranges were subdivided into 7 classes as follows: Excellent (90-100); Good (80-89); Slightly Good (70-79); Average (50-69); Slightly Bad (40-49); Bad (20-39); and Very Bad (0-19) -, (2) sub-index transformation curves for each selected parameter obtained from the existing rating curves (Horton, 1965; Brown *et al.*, 1970; Parti, 1971; Walski and Parker, 1974; Bolton *et al.*, 1978; Lu, 1979; Sinsupan, 1980; and Smith, 1990), (3) existing surface water quality standards for water supply of several countries such as USA, EU, Australia, Japan, Philippines, Russia and India as well as Thailand (Chapman, 1996; ANZECC, 1992; ESCAP, 1997; PCD, 1994a; PCD, 1997b), and (4) the existing water quality data for six Thai rivers, Chaophraya, Thachin, Meklong, Bangpakong, Khwae Noi, and Khwae Yai, between year 1997 and 1999 (PCD, 2000). The basis for



1. Water Quality Standard

Source	Range (mg/l)	Water Quality Class			
		Good	Medium	Poor	Very poor
1. SWQ	5.0 - 9.0	-	-	-	-
2. EU	5.5 - 9.0	6.5-8.5	5.5-9.0	<5.5 or >9.0	
3. JAN, Phi,AUS	6.5 - 8.5	-	-	-	-
4. USA	6.0-8.5	-	-	-	-

2. River Water Quality Data (1997-1999)

rivers	CH	TC	MK	BK	KY	KN
min	6.0	5.7	6.5	5.9	6.4	6.3
max	8.7	8.0	8.6	8.1	8.2	8.3
p50	7.3	7.1	7.6	7.1	7.5	7.3

Source : Pollution Control Department (PCD)
CH = Chaophraya river, TC = Thachin river, MK = Mekong river
BK = Bangpakong river, KY = Khwae Yai river, KN = Khwae Noi river

Figure 2. Example of sub-index transformation curves and water quality standards for pH provided in the second questionnaire

selecting the concentration levels for each of the parameters under consideration of each class is subject to the expert's discretion.

Criteria utilized for the selecting suitable curve for each selected parameter were as follows:

(1) Any rating curve was considered suitable, if the proposed sub-index transformation curve received greater than 80 % recommendation;

(2) Any rating curve may be subjected to modification, if such sub-index transformation curve received less than 80 % recommendation.

Based on these criteria, the sub-index transformation curves for each selected parameter were assigned. Subsequently, rating equations (sub-index functions) for each parameter were numerically formulated by curve fitting and approximation of functions method using the Microsoft EXCEL 2000. With the aid of the rating equation, scores for each selected parameter were then approximated.

2.3 Aggregation functions

The aggregation process is one of the most important steps in calculating any environmental index. To minimize the ambiguity and eclipsing effect, it is necessary to identify an appropriate function for calculating an aggregated score. In this study, six functions were utilized to calculate an aggregated score (index score) for WSI:

1) The weighted and unweighted Solway functions (WS and UWS) suggested by Lu (1979) and Gray (1996).

$$WS = \frac{1}{100}\left(\sum_{i=1}^{n} w_i q_i\right)^2 \quad \text{and} \quad UWS = \frac{1}{100}\left(\frac{1}{n}\sum_{i=1}^{n} q_i\right)^2$$

2) The weighted geometric and unweighted geometric functions (WG and UWG) suggested by Brown (1973), McClelland (197) and Landwehr (1974).

$$WG = \prod_{i=1}^{n} q_i^{\,w_i} \quad \text{and} \quad UWG = \left(\prod_{i=1}^{n} q_i\right)^{\frac{1}{n}}$$

3) The Root-Mean-Square (RMS) functions suggested by Nemerow and Sumitomo (1975).

$$RMS_{\min} = \sqrt{\frac{1}{2}\left[\left(\underset{all\ i}{Min}(I_i)\right)^2 + \left(\frac{1}{n}\sum_{i=1}^{n} I_i\right)^2\right]}$$

4) The unweighted harmonic square mean formula (UHSM) was proposed by Cude (2001).

$$UHSM = \sqrt{\frac{n}{\sum_{i=1}^{n}\frac{1}{I_i^2}}}$$

where q_i = quality rating of the i^{th} parameter
w_i = relative weight of the i^{th} parameter
n = total number of parameters

Among the six aggregation functions, the aggregation functions capable of minimizing the ambiguous and eclipsing effect were selected by comparing both the eclipsing and ambiguous region of the general common forms of each function by means of a graphical technique involving two sub-indices. This technique allows one to examine the behavior and limitation of each aggregation function, and, at the same time, this technique could be generalized when more than two pollutant variables were involved (Ott, 1978). The best function offering the smallest eclipsing and ambiguous regions in the general forms was adopted for approximating the aggregated score.

2.4 Classification of ranges for WSI descriptor categories

Typically, during the formulation of WSI, "descriptor categories", range scales, and "descriptive language", must be provided. Five types of descriptor categories (very good, good, average, poor, and very poor) for WSI were defined according to the classification levels of surface water quality standard of Thailand (1992), descriptive language for different water uses (Dinius, 1987), and a general water quality index scale (Hose and Eills, 1987). Range scales for each selected parameter were attempted by modifying several water quality standards (ANZECC, 1992; ESCAP, 1997; Chapman, 1996; PCD, 1994a; PCD, 1997b) together with the sub-index transformation curves previously developed, and, subsequently, validating against collected water quality data obtained from selected sampling sites.

2.5 Application of WSI

The developed WSI was applied to determine water qualities of the six Thai rivers and, at the same time, the water quality between each sampling point spatially compared. In addition, with the aids of a minimum operator, the lowest sub-index that denoted the worst water quality problem in each sampling station, attempts was then made to identify the critical pollutant variable for each sampling station (Ott, 1978). The general form of minimum operator is as follows:

$$\textit{Minimum Operator}\ (I_{\min}) = \min\{q_1, q_2, ..., q_n\}$$

where q = quality rating of each selected parameter of WSI

n = total number of selected parameters

Moreover, the WSI was used to evaluate trend of water quality used for water supply from the year 2003-2006 for Chaophraya river at upper Amphur Muang (Samlae Temple), Pathum Thani province and Maeklong river at Amphur Ta Moung, Kanchanaburi province (Metropolitan Waterworks Authority (MWA), 2008).

3. Results and Discussion

3.1 Selected variables, weighting scales and rating curve construction

In the process of a water quality index development, information on water quality parameters to be included in the index formulation and their corresponding significant ratings was solicited from experts by means of questionnaire. In the first questionnaire, 58 parameters were chosen arbitrarily for initial consideration by the respondents. Results from the first questionnaire showed that additional 13 parameters for WSI determination recommended by expert such as Chromium Hexavalent, Endosulfan, Monocrotophose, Methamidophose, $AgSO_4$+$NaSO_4$, Radioactivity, DOC (Disolved Organic Carbon), Microcystin LR and Dioxin etc. were included. Therefore, a total of 71 variables was taken into consideration for WSI formulation. Parameters were selected according to their significance rating and experts' recommendation as well as water quality standard of Thailand. Some variables such as trace organics were eliminated since they are generally considered indicators rather than parameters (Brown *et al.*, 1970). Further, if the total content of any detected pesticides or toxic element exceeded the maximum permissible value reported by water quality standards of Thailand for water supply, fish and wildlife, or irrigation usages it was immediately rejected, regardless of its quality. As a result, only 16 parameters were taken into consideration for WSI formulation, namely pH, chloride, EC, color, NO_3-N, TDS, BOD, TCB, FCB, Turbidity, DO, Fe, Mn, Hardness, NH_3-N, and Total PO_4-P (Table 3).

For the second questionnaire, each member of the same group was requested to independently and freely review their original rating and/or modify their responses if desired. Parameters with greater than 80% response rate and average significance rating lower than 2.5 were selected as significant parameters to be included in the development of the specific index. Although it is generally known that information collected using questionnaire is rather subjective, reliability of this technique was ascertained by comparing changes of significance rating obtained from the panel. It was found that among the 16 parameters selected the changes (%) in significance rating of most parameters were relatively small (data not shown). In addition, it was found that 13 parameters were selected for the development of WSI. Table 3 provides the corresponding significance ratings arranged in decreasing order and weighting scale for all selected parameters obtained from the second questionnaire. It can be seen that, according to the experts' opinion, Turbidity whose weighting scale of 0.09 was considered the most important variable for determining water supply quality while DO, pH, NO_3-N, TDS,

Table 3. Selected parameters with their corresponding weighting scales from the second questionnaire

No	WSI			
	Parameter	SR	TW	WS
1	Turbidity	1.40	1.0	0.09
2	DO	1.60	0.9	0.08
3	pH	1.60	0.9	0.08
4	NO_3-N	1.60	0.9	0.08
5	TDS	1.60	0.9	0.08
6	FCB	1.60	0.9	0.08
7	Fe	1.75	0.8	0.08
8	Color	1.80	0.8	0.07
9	BOD	1.80	0.8	0.07
10	Mn	1.80	0.8	0.07
11	NH_3-N	1.90	0.7	0.07
12	Hardness	2.00	0.7	0.07
13	Total PO_4-P	2.00	0.7	0.07
Total	10.6	1.00		

Note: SR = Significant Rating, TW = Temporary Weighting, WS = Weighting Scales

FCB, Fe with weighting scale of 0.08 were deemed the second most importance.

3.2 Development of sub-index transformation curves for individual parameter

Information regarding the construction of sub-index transformation curve for individual parameter were solicited from experts by means of questionnaire. Transformation curves for each parameter adopted previously were proposed and experts were then requested to select, modify and/or draw appropriate curves according to their discretion. Table 4 shows mathematical expressions obtained for each sub-index transformation curve. Therefore, for any particular concentration, the corresponding index could be obtained directly.

3.3 Aggregation functions

Generally, aggregation functions, either additive or multiplicative forms, suffered from both eclipsing and ambiguous effects (Smith, 1990; Ott, 1978, Bolton *et al.*, 1978; Cude, 2001; Liou *et al.*, 2004). In this study, for the purpose of minimizing eclipsing and ambiguous effects on the formulation of WSI, the six aggregation functions were opted for comparing the eclipsing and ambiguous effects by scrutinizing eclipsing and ambiguous regions of general common forms of each function. For general common forms of each function, I_1 and I_2 were assumed to be sub-indices of decreasing scale, where $0 \leq I_1 \leq 100$ and $0 \leq I_2 \leq 100$. I_{WS}, I_{UWS}, I_{WG}, I_{UWG}, I_{RMS} and I_{UHSM} represented the overall index calculated by WS, UWS, WG, UWG, RMS and UHSM, respectively, with values ranging from 0 to 100, where 0 and 100 designate, respectively, the poorest and the highest water quality. On the other hand, the weight indices may be calculated by assuming that $w_1 = w_2 = 0.5$ (where w_1 and w_2 are weighted score of I_1 and I_2, respectively). As a result, the general common forms of each function are of the forms given in Figure 3. Both eclipsing and ambiguous effects of each function could be compared graphically on the (I_1, I_2) plane for selected values of I_{WS}, I_{UWS}, I_{WG}, I_{UWG}, I_{RMS}, and I_{UHSM} using the general common forms of each function (Figure 3).

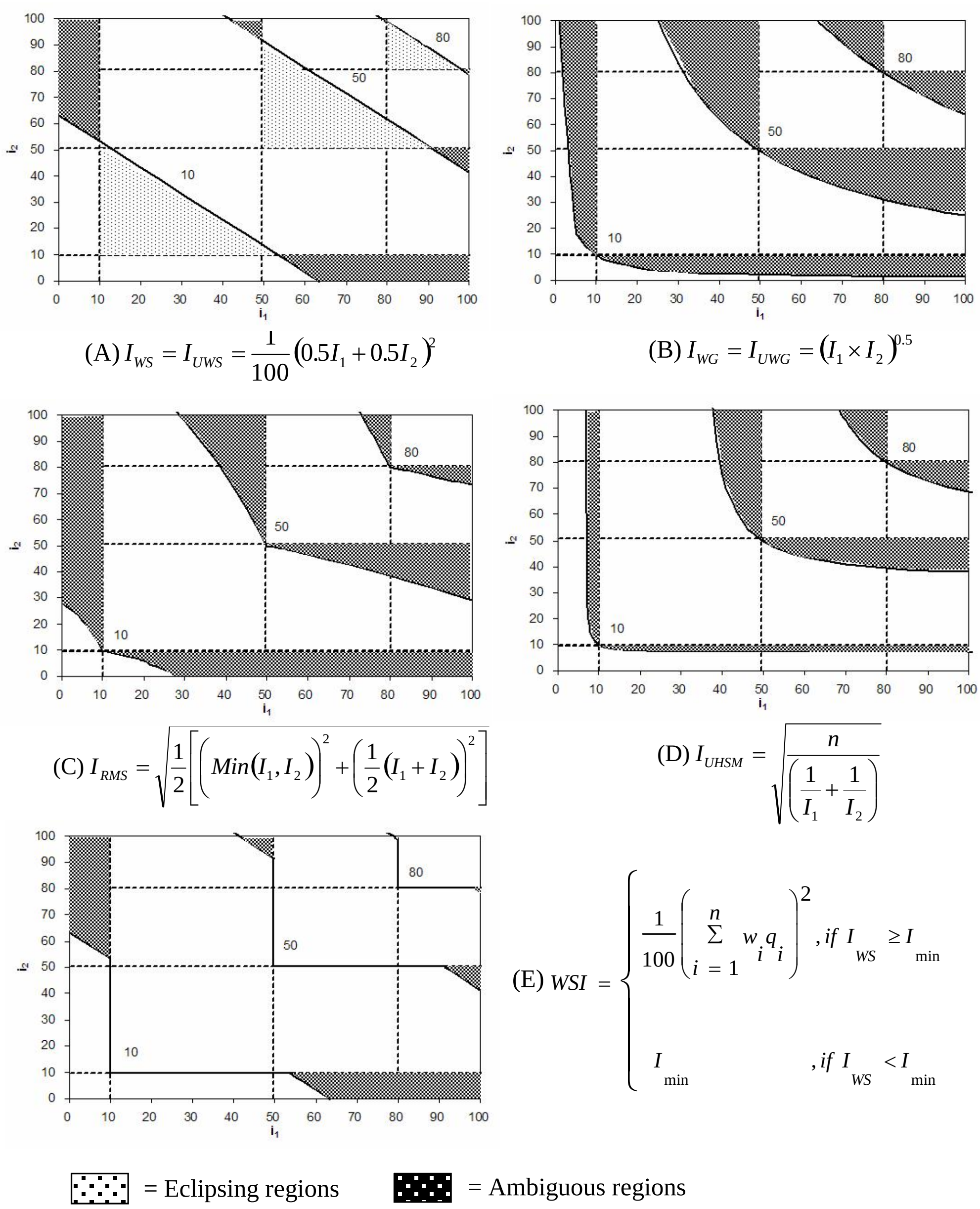
As can be seen in Figure 3, there are no ambiguous regions in weighted geometric and unweighted geometric functions (B), root-mean-square function (C), and unweighted harmonic square mean function (D). High eclipsing region occurs for both weighted and unweighted geometric function (B) and root-mean-square function (C) when I equals 10, 50, and 80. Eclipsing region became evident when I takes on the value greater than 10, 50 and 80 while either I_1 or I_2 is lower than 10, 50, and 80, respectively. The unweighted harmonic square mean function (D) proposed by Cude (2001) shows smaller eclipsing region for low range score of index value (10) and is more sensitive to changes in a single variable, whereas eclipsing regions for average (50) and high (80) range score of index values are large.

As can be seen from Figure 3, the eclipsing regions of weighted or unweighted Solway function (Figure 3A) suggested by Lu (1979) and Gray (1996) are smaller than those of other indices, especially in the regions of average (50) and high (80) range score of index values. However, there are ambiguous regions for weighted Solway (WS) or unweighted Solway function (UWS) tending to underestimate water quality when I_{WS} or I_{UWS} is less than 10, 50 and 80 and either I_1 or I_2 is greater than 10, 50, and 80, respectively. However, this drawback could be minimized by using the minimum operator as aggregation function in cases where I_{WS} or I_{UWS} is less than I_{min}. Therefore, in this study, weighted Solway function (2) was chosen for WSI formulation.

$$WSI = \begin{cases} \dfrac{1}{100}\left(\sum\limits_{i=1}^{n} w_i q_i\right)^2 & , if\ I_{WS} \geq I_{min} \\ I_{min} & , if\ I_{WS} < I_{min} \end{cases}$$

where WSI = Water quality index for water supply, a number between 0 and 100

q_i = quality rating of the i^{th} parameter, a number between 0 and 100



(A) $I_{WS} = I_{UWS} = \frac{1}{100}\left(0.5I_1 + 0.5I_2\right)^2$

(B) $I_{WG} = I_{UWG} = \left(I_1 \times I_2\right)^{0.5}$

(C) $I_{RMS} = \sqrt{\frac{1}{2}\left[\left(Min(I_1, I_2)\right)^2 + \left(\frac{1}{2}(I_1 + I_2)\right)^2\right]}$

(D) $I_{UHSM} = \sqrt{\frac{n}{\left(\frac{1}{I_1} + \frac{1}{I_2}\right)}}$

(E) $$WSI = \begin{cases} \frac{1}{100}\left(\sum_{i=1}^{n} w_i q_i\right)^2 & , if\ I_{WS} \geq I_{min} \\ I_{min} & , if\ I_{WS} < I_{min} \end{cases}$$

Figure 3. Graphical representation of the six functions as products of two pollutants in the (I_1, I_2) plane showing eclipsing regions and ambiguous regions

w_i = relative weight of the i^{th} parameter, a number between 0 and 100
n = number of parameters
I_{WS} = WSI calculated by the weighted Solway function
I_{min} = WSI calculated by the minimum operator

Figure 3E shows relationship of I_1 and I_2 for Solway function subjected to minimum operator. It is evident that there is no ambiguous effect regions in the (I_1, I_2) plane for low (10), average (50) and high (80) index scores. Further, eclipsing effect could also be significantly reduced for average and high range score in comparison with other functions (Figure 3 B, C and D).

3.4 Water quality classification and range scales

In order to develop the WSI, water classification systems practically adopted in many countries were thoroughly reviewed. Based on collected information, selected variables including 13 parameters were categorized into 5 water quality classes - very good, good, average, poor and very poor - whilst score ranges were assigned to each variables according to specific water standards and sub-index transformation curves (Table 4). The descriptor categories of water quality and range scales for the selected water quality

Table 4. Empirical models of sub-index transformation curve for WSI

Equations of sub-index transformation curve for WSI		
Parameters	Values	Equations
Turbidity (NTU)	35	$I = 0.0007X^3 - 0.0403X^2 - 0.9531X + 100$
	100	$I = 0.0039X^2 - 0.85X + 69.761$
	500	$I = 0.00005X^2 - 0.08X + 30$
	>500	$I = 2$
DO (mg/l)	0.71	$I = 2$
	4.94	$I = 1.9384X^2 + 0.9489X - 0.1297$
	7.11	$I = (-1.9341)X^2 + 45.327X - 124.91$
	>7.11	$I = 100$
pH	2.62	$I = 2$
	7.0	$I = (-0.2978)X^4 + 2.7631X^3 - 11.013X^2 + 9.5532X - 3$
	11.38	$I = (-0.3408)X^4 + 14.767X^3 - 232.64X^2 + 1559.8X - 3667.95$
	>11.38	$I = 2$
NO_3-N (mg/l)	5.5	$I = 0.2245X^3 - 1.5988X^2 - 10.418X + 100$
	21.6	$I = (-0.008X^3) + 0.5198X^2 - 10.453X + 74.926$
	>21.6	$I = 2$
TDS (mg/l)	900	$I = (0.000003)X^2 - 0.0798X + 99.164$
	1,514	$I = 0.00005X^2 - 0.1655X + 138$
	> 1,514	$I = 2$
FCB (MPN/100ml)	4,000	$I = (-3\times10^{-10})X^3 - (8\times10^{-8})X^2 - 0.0137X + 99.355$
	6,750	$I = (9\times10^{8})X^{-2.0518}$
	9,360	$I = (3\times10^{-7})X^2 - (9\times10^{-3})X + 59.998$
	>9,360	$I = 2$
Fe (mg/l)	1.0	$I = (-28.867)X^3 + 70.74X^2 - 90.593X + 98.72$
	3.13	$I = 3.6387X^2 - 36.875X + 82.206$
	> 3.13	$I = 2$
Color (Unit Pt- Co)	90	$I = 0.0069X^2 - 1.4715X + 98.469$
	211	$I = 0.0006X^2 - 0.3405X + 47.143$
	> 211	$I = 2$
BOD (mg/l)	9.8	$I = 100-10X$
	>9.8	$I = 2$
Mn (mg/l)	0.001	$I = 100$
	0.2	$I = (-6479.2)X^3 + 2765.4X^2 - 436.08X + 100.48$
	0.8	$I = 361.11X^3 - 532.14X^2 + 147.46X + 60.643$
	1.6	$I = 27.056X^2 - 87.768X + 75.502$
	> 1.6	$I = 2$
NH_3-N (mg/l)	0.019	$I = 100$
	0.4	$I = 58.87X^2 - 186.96X + 103.49$
	0.9	$I = 60.269X^2 - 116.8X + 73.873$
	2.83	$I = (-0.6221)X^2 - 5.6526X + 22.949$
	> 2.83	$I = 2$
Hardness (mg/l as $CaCO_3$)	1,260	$I = 10^{(1.974-(0.00132X))}$
	> 1,260	$I = 2$
Total PO_4-P (mg/l)	1.48	$I = 100e^{-2.5X}$
	> 1.48	$I = 2$

Note: X = water quality concentration, I = sub-index value

parameter for WSI calculation are provided in Table 5.

The developed specific water quality classification for each parameter (Table 5) was applied to water quality data to verify its classification ranges. The 97 data sets of 63 sampling stations from the Chaophraya, Thachin, Meklong, Bangpakong, Khwae Noi, and Khwae Yai rivers obtained from PCD in the year 2000 were selected. A distribution curve of WSI values calculated from the field data could be

Table 5. Range scales of the selected water quality parameter for water supply usage

No.	Parameter	Unit	Water quality classification for water supply				
			Very good	Good	Average	Poor	Very poor
1	Turbidity	NTU	≤ 8[1]	20[1]	75[8]	144[1]	> 144[1]
2	DO	mg/l	≥ 6.6[1]	5.32[3]	3.8[3]	2.28[3]	< 2.28[3]
3	.pH	-	6.5 - 8.5[3]	6.5 - 8.5[3]	5.5 - 9.0[3]	5.0 - 9.0[2]	< 5.0, > 9.0[2]
4	NO_3-N	mg/l	≤ 0.85[1]	2.3[1]	5[2]	10.2[4]	> 10.2[4]
5	TDS	mg/l	≤ 200[5]	500[6]	1,000[6]	1,500[4]	> 1,500[4]
6	FCB	MPN/100 ml	≤ 20[3]	1,000[2]	4,000[2]	20,000[3]	> 20,000[3]
7	Fe	mg/l	≤ 0.1[1]	0.45[1]	1[1]	50[4]	> 50[4]
8	Color	Pt-Co	≤ 10[3]	20[3]	100[3]	200[3]	> 200[3]
9	BOD	mg/l	≤ 1[1]	3[3]	5[3]	7[3]	> 7[3]
10	Mn	mg/l	≤ 0.03[1]	0.25[1]	1[1]	5[1]	> 5[1]
11	NH_3-N	mg/l	≤ 0.04[3]	0.19[1]	0.78[3]	1.56[3]	> 1.56[3]
12	Hardness	mg/l as $CaCO_3$	≤ 20[1]	100[1]	200[1]	500[7]	500[7]
13	Total PO_4-P	mg/l	≤ 0.04[1]	0.14[1]	0.28[1]	0.65[1]	> 0.65[1]

Note: (1) to (8) refer to the following references: (1) = Sub-index transformation curve of WSI, (2) = Surface water quality standard of Thailand (PCD, 1994), (3) = European quality standards for water to be used for direct abstraction to potable supply (PCD, 1997), (4) = Raw Water Source standard for Water Supply of World Health Organization (PCD, 1997), (5) = Water Quality standard for Water Supply in USA (Tuntoolavest, 1999), (6) = Establishment of water quality criteria for usage of water and disposal to receiving water bodies in the Philippines (ESCAP, 1997), (7) =The Australian Water Quality Guidelines for Fresh and Marine Waters (ANZECC, 1992), (8) = Turbidity data of Chaophraya river, Samlae Temple station, at the 50th percentiles (MWA, 2008)

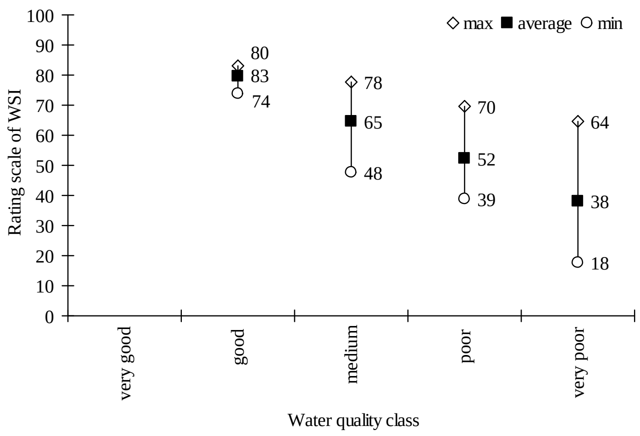


Figure 4. Distribution curves for water quality classification of WSI

generated and classified by the range scales of the selected water quality parameter. Maximum-average-minimum WSI scores for the water collected from different rivers were used as baseline classification (Figure 4).

As shown in Figure 4, the actual water qualities of the six rivers were in the range of very poor to good (PCD, 2000; Simachaya, 2003). Ranges of scale were adjusted using average value of WSI obtained from a family of distribution curve for each water quality classification. Results are presented in Table 6. Scores of the very good class for each SWQI were taken as the maximum data point of the "good" class. From Figure 4, the maximum data point of the "good" class was 83, which may be approximated as baseline of very good class score (score of 85). Therefore, range scales for the good and average for individual class were designated, respectively, as the average scores to upper limit scores and average scores of the "average" to average values of the "good" class. As a consequence, the range of the "poor" class spanned between average scores of the "average" and "very poor" class.

3.5 Application of WSI

The WSI was applied for evaluating water qualities of six Thai rivers (Figure 5). Results showed that the water quality of Khwae Noi river was average to good whlist the quality of the upper Maeklong River was average. Meanwhile, water qualities of the lower Chaophraya river (station numbers CH01 - CH8), lower Thachin (station numbers TC1-TC13), Bangpakong and Khwae Yai rivers were poor. Further, minimum operator indicated that the most frequently occurring critical pollutants of the four rivers mentioned above were turbidity, FCB and DO. Erosion is a major problem that causes of turbidity (Chapman, 1996), while organic waste discharges from domestics and animal farming

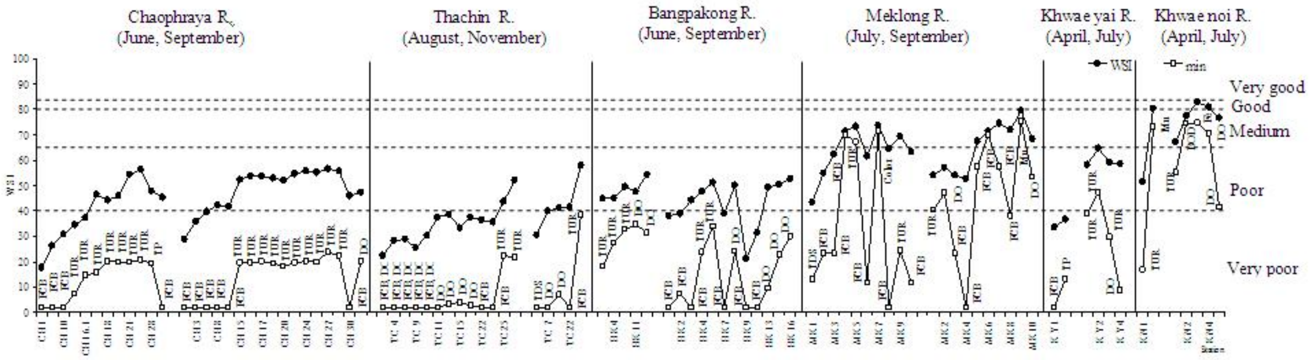


Figure 5. Classification of water qualities of the Chaophraya (CH), Thachin (TC), Maeklong (MK), Bangpakong (BK), Khwae Noi (KN), and Khwae Yai (KY) using the developedWSI and minimum operators (min)

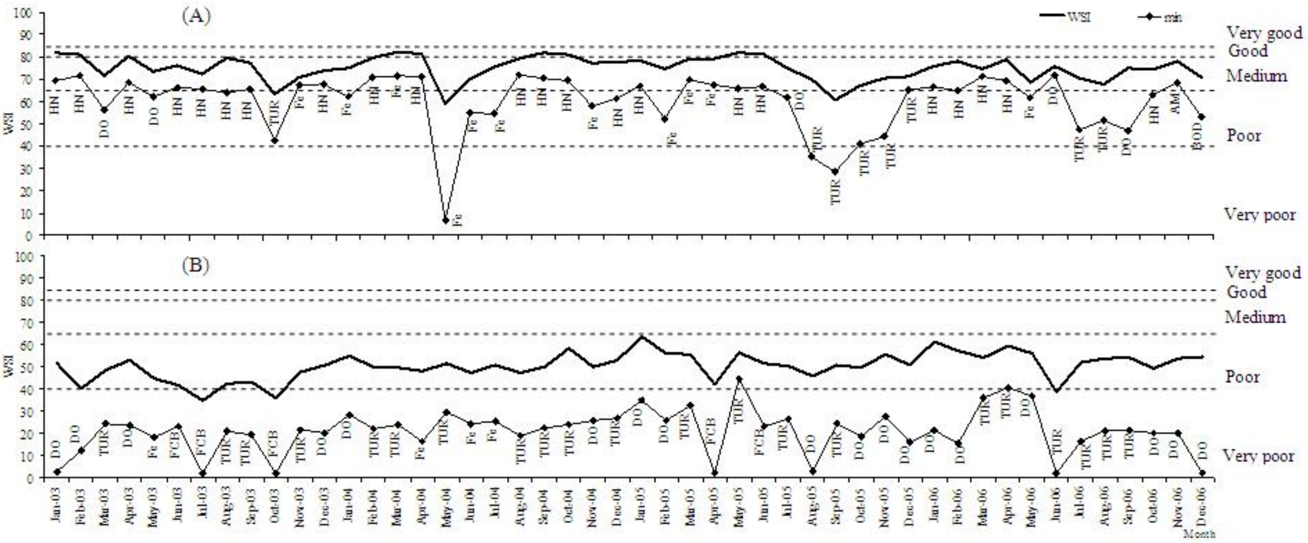


Figure 6. Trend of water quality for Maeklong river (A) and Chaophraya river (B) between the year 2003-2006 assessed by WSI and minimum operator

increase the FCB contamination in water. High organic pollutions influenced the decrease of DO in rivers. PCD (1997) reported that activities leading to water quality degradation in the lower Chaophraya, lower Thachin and Bangpakong rivers included industrial operations, agricultural, and domestic operations whereas the Khwae Noi and upper Maeklong rivers were slightly polluted from those activities. Turbidity is a significant problem of Khwae Yai River during rainy season. Although the minimum operator was rather sensitive to the most impact variable which tended to underestimate water quality at the lower end of the quality scale (House and Ellis, 1987), it was possible to assess water quality when applying it in combination with water supply index formulated previously.

For long-term analysis, surface water quality data during 2003-2006 from the natural water resources intended for water supply, Chaophraya river at upper Amphur Muang (Samlae Temple), Pathum Thani province and Maeklong river at Amphur Ta Moung, Kanchanaburi province, were analyzed and evaluated using the WSI. As shown in Figure 6, water qualities of the Chaophraya River in general were poor and the main constituents affecting water quality were FCB, turbidity and DO. On other hand, water qualities of the Maeklong River were average and the principal water pollutant was turbidity and iron during the rainy season. It was suggested that raw water from the Ta Moung station was more appropriated for water supply than that from the Samlae station. For consumption purpose, it requires conventional water treatment process or advanced water treatment process before use since the water quality was poor (Table 6). It is typical that eclipsing effect encountered when evaluating water qualities yields obscure water quality. However, the index proposed showed that eclipsing effect on water quality prediction was alleviated. For example, for Maeklong River, whereas turbidity, iron and turbidity were identified, respectively, as the critical pollutants (Figure 6) for October (2003), May (2004) and August (2005), water qualities predicted using the proposed index exhibited low quality.

Table 6. The 5 types of descriptor categories of water quality and ranges of the WSI scores

Class	Descriptor Categories	Score	Descriptive language
1	Very Good	85 -100	Extra clean fresh water resources. Consumption requires only ordinary process for pathogenic destruction
2	Good	80 – <85	Very clean fresh water resources. Consumption requires ordinary water treatment process which minor purification required before use
3	Medium	65 –<80	Medium clean fresh water resources. Consumption requires conventional water treatment process before use
4	Poor	40 – <65	Fairly clean fresh water resources. Consumption requires specific or advance water treatment process before use
5	Very poor	< 40	Unacceptable

For routine water quality monitoring, the developed WSI may be used instead of the traditional water quality evaluation since the developed WSI requires only 13 variables rather than 42 parameters generally involved in the traditional water quality assessment. It was illustrated that the WSI provides a convenient means for summarizing information rendering better understanding than a long list of numerical values for a group of parameters. This enables the public and non-scientific communities to share and understand the data monitored. The WSI can assist those in charge to the water resource to make more efficient and informed decisions of the authorities with regard to improving water quality to sustain water supply usage. In addition, the water qualities of Chaophraya river and Maeklong River assessed by the WSI agreed with those reported by the Metropolitan Waterworks Authority (MWA) (MWA, 2008), the potable water supply agency of Bangkok. The results suggested that the WSI are appropriate for water supply.

Overall, it may be inferred that the WSI may serve as a tool for describing water quality in terms of the specific water usage for water supply. The WSI may also be used as a tool for measuring trends of water quality in the water resource. The developed water supply index together with the minimum operators may be used as an indicator reflecting the presence of pollutants in the river or water resource.

4. Conclusion

The effective specific water quality index for assessing water supply usage (WSI) was developed using Solway aggregation function together with minimum operator. The proposed index helps to lessen the eclipsing effect and, simultaneously, reflect the critical pollutants present in water bodies. The WSI provides a convenient way for evaluating the water quality of rivers in terms of the specific water usage for water supply, comparing water quality among different reaches of rivers, and measuring trends of water quality in the water resources. Effort should be made to validate effectiveness of the proposed index against the real situation, particularly, Metropolitan Waterworks Authority and Provincial Waterworks Authority. Since NSF WQI employed by the Thai PCD classified water quality as “general”, the developed index may, in part, facilitate the modification of NSF WQI into a more specific one. Additionally, knowledge gained in developing this index may serve as a basis for formulating specific NSF WQI for Thailand rather than adopting a foreign standard (USA).

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