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Groundwater Quality Index for Water Supply Production

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Abstract

Groundwater quality index for water supply production, GWQI, was employed as a simple mathematical tool to integrate the complex groundwater quality data into a numerical score. It would guide to select an appropriate water supply treatment process. It was thus necessary to develop such GWQI, which was the main objective of this study. We started searching for significant indicators by requesting 35 Thai experts to consider the importance of 32 water quality parameters through questionnaire based on the Delphi technique. These parameters were aggregated into 10 key parameters, reflecting the appropriate groundwater quality through the process of weighing factors. The most appropriate parameters were estimated from ten such parameters. By reduction of the ten parameters one by one, it was found that the GWQI(6i) was in high agreement with GWQI(10i) (Kappa coefficient = 0.765: 95%CI 0.700 to 0.828). The GWQI (6i) scores were confirmed by Ramesh's tool with a high correlation (*r = 0.768*, 95% CI = 0.529 to 0.894, *p-value = 0.001*). Therefore, the GWQI(6i) could be used as the appropriate tool for groundwater quality assessment. Implementation of GWQI(6i) would save budget and time for analysis, and could provide a rapid water quality determination for the urgent situation.

Keywords: groundwater quality index (GWQI); groundwater quality; water supply; Delphi technique

1. Introduction

Clean water is very important for human health as well as a significant factor for a sustainable socio-economic development. Under the global phenomenon of climate change and a substantially growing population, water is a requirement to enhance food security and rapid urbanization. Groundwater is an alternative water resource for the area where surface water is not available. In Thailand, there is the policy on clean water provision for the rural areas by considering groundwater as a priority source. Groundwater supply is therefore the main source of drinking and domestic water.

Thailand's groundwater quality standard for drinking water consists of 23 parameters, including physical, chemical, toxic and bacterial characteristics. It is difficult to analyze all 23 standard parameters, particularly since the water supply treatment system is carried out by local organizations. It is challenging to develop a simple tool to be employed for drinking water quality management by converting a number of water quality parameters into a simple scale value which can be comprehended by water producers (planner and manager) as well as users.

Recently published articles deal with the development of a groundwater water quality index. The concept of indexing water with a numerical value to express its quality, which is regulated by the permitted standards set by the governments of individual countries (Ho, 2012), based on physical, chemical and biological measurements, was developed in 1965 by the US-based National Sanitation Foundation (NSF). Selection of parameters for NSFWQI is based on the Delphi method on which the GWQI models are formulated in additive and multiplicative forms (Lumb *et al*., 2011). All GWQI employ weighting factors that are standardized into significant parameters. The articles are different in the number of parameters and degree of groundwater quality classification. For example, five parameters and classified scores into five levels (Sharma and Patel, 2010), eight parameters report in an iso-index map by three water quality zones (Saeedi *et al*., 2010), ten parameters report in WQI map by 14 water quality zones (Yidana *et al*., 2010), eleven parameters report in thematic maps with three water quality zones (Rejith *et al*., 2009), eleven parameters report in groundwater composition index (GWCI) map with nine water quality zones (Stigter *et al*., 2006), and the maximum number for 22 parameters are categorized into five groups and classified in scores of six levels (Ramesh *et al*., 2010).

Noticeably, there have been no reports yet on the development of GWQI in the Thai context. The objective of this study was consequently to develop GWQI for community water supply. This would be a potential guideline for producing a database of groundwater quality at time intervals for the regional and national levels.

2. Materials and Methods

The study was carried out in Khon Kaen city, the capital district of Khon Kaen province, Northeastern Thailand. The population of this is 450,000 which currently make it the fourth largest Thai city. Data were obtained from three sources: 1) groundwater quality parameters selected from WHO and Thailand Groundwater Quality Standards implemented by the relevant agencies with a regular analysis in the past 5 years (the whole country: 12,991 groundwater samples and 1,207 villages tap water samples), of which 32 parameters were found in every area; 2) Thai water quality experts, the 35 experts required were assigned from Nowack's study median (Nowack *et al*., 2011); and 3) water quality monitoring of 59 groundwater samples in Khon Kaen city (2007-2011) conducted by the Division of Groundwater Quality Analysis, Department of Groundwater Resources, Ministry of Natural Resources and Environment.

The data analysis was divided into two parts. The first part, selection of key parameters, was based on the Delphi technique through the questionnaires answered by 35 Thai water quality experts. Scoring of such key parameters signified their different values that became a weight in the GWQI equation. The second part, development of a groundwater quality index was made by reducing the parameters and analyzing the significant indicators for equations to represent the GWQI with statistical analysis for validity of the new index.

All statistical procedures were conducted with STATA[tm]10.0. Descriptive statistics, numbers and percentages were used to describe key parameters. Analytical statistics included 3 parts: 1) R^2 was used to analyze prediction power of the goodness of fit of a sub-index rating curves. Values of R^2 outside the range 0 to 1, an R^2 of 1.0 indicates that the regression line perfectly fits the data, while an R^2 closer to 0 indicates a regression line does not fit. 2) The weighted Kappa, Kappa coefficient and 95% confidence intervals were measures of inter-rater agreement, used to analyze the suitable number of parameters; and 3) The Pearson's correlation, P value and 95% confidence intervals were used to explore the validity of the new index. Statistical significance was presented when the P value was less than 0.05.

In addition, this study was approved by the Khon Kaen University Research Ethics Committee (Number: HE 552057).

3. Results and Discussion

3.1 General data of water quality experts:

The 35 experts included 2(5.71%) Director–Generals/Professors, 13(37.14%) Agency Directors/Associate Professors and 20(57.15%) Division Directors/Assistant Professors. They graduated with expertise in Artesian Well Water Systems and/ or Drinking Water Quality with 7(20.00%) bachelor degrees, 15(42.86%) master degrees and 13(37.14%) doctoral degrees.

3.2 Selection of key parameters for development of GWQI:

The number of parameters brought into consideration by ≥80% of the whole number of water quality experts, was 15. However, as there was a limitation of analysis methods for some parameters, only 10 key parameters were selected to represent GWQI. They were later used to calculate mean significant levels, temporary weights and weight factors of each parameter (sub-index weight) in descending order of significance

Table 1. Mean significant level, Temporary weight and Sub-index weight of each key parameter

Key parameters	Mean significant level	Temporary weight	Sub-index weight
pH	2.3226	1.0000	0.10851
Iron (Fe)	2.3235	0.9996	0.10847
Nitrate (NO_3^-)	2.3871	0.9730	0.10558
Manganese (Mn)	2.4848	0.9347	0.10143
Hardness(H)	2.5161	0.9231	0.10017
Chloride (Cl^-)	2.5667	0.9049	0.09819
Total dissolved solids (TDS)	2.5714	0.9032	0.09801
Non carbonate hardness (Non-CO_3^{2}-Hardness)	2.6071	0.8909	0.09667
Fluoride (F^-)	2.6552	0.8747	0.09492
Sulfate (SO_4^{2-})	2.8621	0.8115	0.08806
	Total	9.2156	1.00000

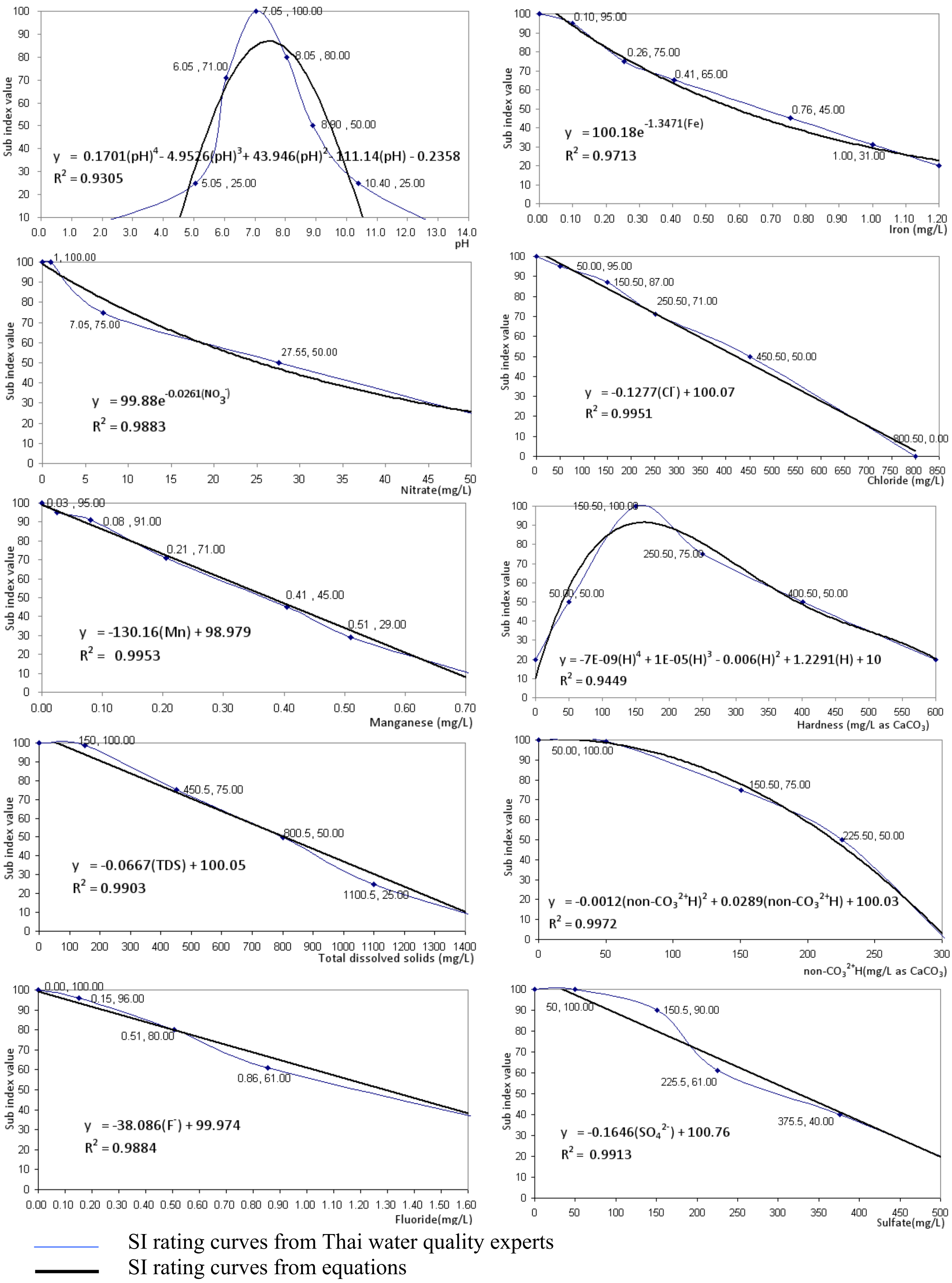

Figure 1. Sub-index rating curve equations and R^2 of each key parameter

(Table 1); indicating that the minimum weight of pH as 2.3226 presented a significant assessment while sulfate with maximum weight of 2.8621 presented less importance than pH.

3.3 Development of sub-index (SI) rating curve:

Sub-indices are value functions to transform the different units and dimensions of groundwater quality parameters to a common scale. For this purpose, each parameter was assigned a ration value between 0 and 100 based on its desirable and acceptable limits of guideline values prescribed by WHO (2008) and Thailand Groundwater Quality Standard (Ministry of Natural Resources and Environment, 2008). The rating of SI value = 100 implied that the sample was within the maximum acceptable limit while the rating of SI value ≤ 30.99 implied that the sample attained the minimum acceptable limit. Other ratings were falling between near 0-100 based on regression statistics. The SI rating curves and mathematical equations for SI development are presented in Fig. 1. The main advantage of a rating curve is that it rapidly transforms the parameter into a quality score to represent the water quality for a given use (Saeedi *et al*., 2010).

3.4 Aggregation of SI:

The SI aggregation of a GWQI mathematically combines sub-indices to an overall index value. The aggregation function of GWQI, given by the following equation, is based on the linear sum aggregation function.

$$\text{GWQI} = \sum_{i=1}^{n} W_i I_i \qquad 1$$

where *Wi* is the *SI* weight of each parameter, *Ii* is the *SI* values, i = 1 to n, and n is the number of parameters.

3.5 Classification of GWQI scores:

The computed GWQI scores are classified into four types, "excellent" to "poor" for community water supply production". Each class in this study was represented by a numerical range, with 0 indicating very poor groundwater quality and 100 indicating excellent groundwater quality. Classification of GWQI scores is given in Table 2.

3.6 Testing the reliability of the GWQI:

This was applied to 59 groundwater samples in Khon Kaen city. Calculated SI weights for different numbers of parameters using GWQI are presented in Table 3. Six indices were developed using five to ten parameters, which were then compared to the most complex index which used all ten parameters (GWQI(10i)). Agreement between GWQI(10i) and itself with indices containing lower numbers of items are shown in Table 4. The GWQI(6i) had a high agreement with that of GWQI(10i), (Kappa coefficient = 0.765, 95%CI 0.700 to 0.828).

3.7 Testing the validity of the GWQI:

According to the comparison with the proposed DWQI with 22 parameters, which was developed by Ramesh *et al*. (2010), the GWQI consisting of 6 parameters was evaluated using Ramesh's study data which was comprised of 24 groundwater samples from the Southern Tamil Nadu region, India. The results revealed that GWQI scores were lower than the proposed DWQI. There was a statistically high correlation between the two indices (Pearson's correlation coefficient = 0.768, 95% CI = 0.529 to 0.894, *p-value < 0.001*). This implied that the GWQI could potentially be substituted for the proposed DWQI for the community groundwater water supply in Thailand.

In addition, the importance of each parameter used in GWQI for community water supply production are as follows.

- pH affects the quality index in regards to both water drinkability and usage. This is due to the fact that pH will have an affect on the ability of heavy metals, minerals and naturally occurring toxin to dissolve. The optimum pH is necessary at all stages of water treatment to ensure satisfactory water clarification, disinfection, and distribution systems. Corrosion of water pipelines will also occur when the pH is chronically low.

- Chloride affects the quality index on drinking and usage. The taste of water is brackish and salty if it contains sodium chloride (NaCl), potassium chloride (KCl) or calcium chloride ($CaCl_2$). It also indicates water contamination from human waste or saline intrusion in the coastal plains, estuary and sea, as well as groundwater basin in the layer of rock salt.

- Nitrate indicates water contamination from human and animal wastes, septic tanks and pit latrines, farming areas with fertilizer use, agricultural activity and garbage dump areas. Clinical epidemiological studies

Table 2. Classification of Groundwater Quality Index scores

Category	Range of index scores	Remarks
Excellent	71.00 to 100	Very clean, suitable for water supply production which requires an ordinary water treatment process before use.
Good	61.00 to 70.99	Clean, suitable for water supply production which requires an ordinary treatment process before use.
Fair	31.00 to 60.99	Fairly clean, suitable for water supply production but requires special water treatment process before use.
Poor	≤ 30.99	The sources which are unsuitable for water supply production.

Table 3. *SI* weight in different number of parameters using GWQI

Key parameters	Mean significant level	GWQI(10i)		GWQI(9i)		GWQI(8i)	
		Temporary weight	*SI* weight	Temporary weight	*SI* weight	Temporary weight	*SI* weight
pH	2.3226	1.0000	0.1085	1.0000	0.1190	1.0000	0.1328
Fe	2.3235	0.9996	0.1085	0.9996	0.1189	0.9996	0.1328
NO_3^-	2.3871	0.9730	0.1056	0.9730	0.1158	0.9730	0.1292
Mn	2.4848	0.9347	0.1014	0.9347	0.1112	0.9347	01241
H	2.5161	0.9231	0.1002	0.9231	0.1098	0.9231	0.1226
Cl^-	2.5667	0.9049	0.0982	0.9049	0.1077	0.9049	0.1202
TDS	2.5714	0.9032	0.0980	0.9032	0.1075	0.9032	0.1200
Non-CO_3^{2-}hardness	2.6071	0.8909	0.0967	0.8909	0.1060	0.8909	0.1183
F^-	2.6552	0.8747	0.0949	0.8747	0.1041		
$SO4^{2-}$	2.8621	0.8115	0.0881				
		9.2156	1.0000	8.4041	1.0000	7.5294	1.0000
Key parameters	Mean significant level	GWQI(7i)		GWQI(6i)		GWQI(5i)	
		Temporary weight	*SI* weight	Temporary weight	Sub-index weight	Temporary weight	*SI* weight
pH	2.3226	1.0000	0.1506	1.0000	0.1744	1.0000	0.2070
Fe	2.3235	0.9996	0.1506	0.9996	0.1743	0.9996	0.2069
NO_3^-	2.3871	0.9730	0.1466	0.9730	0.1696	0.9730	0.2014
Mn	2.4848	0.9347	0.1408	0.9347	0.1630	0.9347	0.1935
H	2.5161	0.9231	0.1391	0.9231	0.1609	0.9231	0.1911
Cl^-	2.5667	0.9049	0.1363	0.9049	0.1578		
TDS	2.5714	0.9032	0.1361				
Non-CO_3^{2-}hardness	2.6071						
F^-	2.6552						
$SO4^{2-}$	2.8621						
		6.6385	1.0000	5.7353	1.0000	4.8304	1.0000

Table 4. Comparison between the GWQI with 5 to 10 parameters analyzed by weighted Kappa

Groundwater quality evaluated by GWQI(xi)		GWQI(10i)				Kappa coefficient	95%CI	Strength of agreement*
		Excellent	Good	Poor	Total			
GWQI(9i)	Excellent	37	0	0	37	0.933	0.869 to 1.000	Very good
	Good	3	15	0	18			
	Poor	0	0	4	4			
	Total	40	15	4	59			
GWQI(8i)	Excellent	31	3	0	34	0.673	0.490 to 0.849	Moderate to very good
	Good	9	8	1	18			
	Poor	0	4	3	7			
	Total	40	15	4	59			
GWQI(7i)	Excellent	30	2	0	32	0.654	0.587 to 0.719	Moderate to good
	Good	10	4	1	15			
	Poor	0	9	3	12			
	Total	40	15	4	59			
GWQI(6i)	Excellent	36	2	0	38	0.765	0.700 to 0.828	Good to very good
	Good	4	10	2	16			
	Poor	0	3	2	5			
	Total	40	15	4	59			
GWQI(5i)	Excellent	32	4	0	36	0.682	0.625 to 0.802	Good
	Good	8	9	1	18			
	Poor	0	2	3	5			
	Total	40	15	4	59			

* The K value can be interpreted as follows: value of K < 0.20 Strength of agreement = poor, 0.21 to 0.40 = fair, 0.41 to 0.60 = moderate, 0.61 - 0.80 = good, 0.81 - 1.00 = very good.

demonstrate that methaemoglobinaemia can occur as a result of extremely high nitrate intake in adults and children.

- Iron is a generally found element, indicating the change in dissolving minerals. With a high amount of iron, water may be of reddish-brown color, high turbidity, and have a metallic taste.

- Manganese indicates a water quality index affecting health, naturally existing heavy metals, contamination of groundwater, industrial waste and harmful garbage burying. Exposing surface with a high amount of manganese in the water may lead to accumulation of deposits in the distribution system.

- Hardness represents water from the groundwater basin in calcium and magnesium rock, which influences the water quality index on drinking and using effects. The degree of hardness in the water may affect its acceptability to the consumer in terms of taste. Hard water forms deposits of calcium carbonate scale and soft water with a hardness of less than 100 mg/L may be corrosive for water pipes.

4. Conclusions

GWQI is a simplified index which includes aggregate values of 6 significant parameters developed from 32 parameters of WHO and Thailand Groundwater Quality Standards. GWQI(6i) is a simple tool for evaluating the general groundwater quality for community water supply production, except in some specific areas where there is toxic substance contamination. The developed index indicates the degree of water quality, which can be used by decision makers to understand the status of groundwater resources. Accordingly, it could be used for an economical and efficient water treatment process. This index could also provide ad hoc explanations of water quality in an acute situation.

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