Assessing the Effectiveness of CCME-WQI, NSF-WQI, OWQI, and Smith Index Water Quality Indices in Karst Areas

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ABSTRAK

Penilaian kualitas air melibatkan berbagai metode, termasuk indeks kualitas air (WQI). Penelitian ini membandingkan beberapa metode WQI untuk mengevaluasi Sungai Sumurup dan Sungai Bawah Tanah Seropan di Kabupaten Gunungkidul. Tujuan penelitian adalah menganalisis keefektifan metode CCME-WQI, NSF-WQI, OWQI, dan Indeks Smith. Seleksi parameter dilakukan menggunakan Analisis Komponen Utama, dan metode NSF-WQI ditemukan sebagai representasi kualitas air yang paling akurat di area penelitian. OWQI menghasilkan hasil yang buruk secara konsisten akibat formula yang terlalu idealis, sementara sensitivitas CCME-WQI terhadap jumlah parameter mengurangi efektivitasnya. Indeks Smith, berdasarkan standar Selandia Baru, memberikan hasil kualitas terendah, tanpa memperhatikan modifikasi parameter. Oleh karena itu, NSF-WQI direkomendasikan untuk menilai kualitas air di daerah karst seperti Sungai Sumurup dan Seropan Bawah Tanah. Penelitian ini menekankan pentingnya memilih metode WQI yang sesuai dengan kondisi lingkungan tertentu untuk mendukung manajemen sumber daya air dan upaya konservasi yang efektif.

Kata kunci: Indeks Kualitas Air, Analisis Komponen Utama, Karst, Kualitas air, Penilaian Lingkungan

ABSTRACT

Water quality assessment employs various methods, including water quality indices (WQI). This study compares several WQI methods to evaluate Sumurup River and Seropan Underground River in Gunungkidul Regency. The study aims to analyze the effectiveness of CCME-WQI, NSF-WQI, OWQI, and Smith Index methods. Parameter selection was conducted using Principal Component Analysis, and the NSF-WQI method was found to best represent water quality in the study area. OWQI produced consistently poor results due to an overly idealized formula, while CCME-WQI's sensitivity to parameter number reduced its effectiveness. The Smith Index, based on New Zealand standards, yielded the lowest quality results, regardless of parameter modifications. Thus, NSF-WQI is recommended for assessing water quality in karst areas like Sumurup and Seropan Underground Rivers. This research underscores the importance of selecting appropriate WQI methods tailored to specific environmental conditions to support effective water resource management and conservation efforts.

Keywords: Water Quality Index; Principal Component Analysis; Karst; Water Quality; Environmental Assessment

1. INTRODUCTION

People around the world mostly use water resources in karst areas as their main source of water (Ford and Williams, 2007). Another uniqueness of karst areas is that the hydrological system of karst areas has a characteristic called "duality of recharge" (Ford and Williams, 2007). This term means that groundwater in karst areas has two types of groundwater recharge, namely allogenic recharge and autogenic recharge. Allogenic recharge is water recharge in karst areas that comes from outside the karst area (Cahyadi et al., 2020), while autogenic recharge is groundwater recharge that comes from rain falling in the karst area itself.

One of the allogenic recharge systems studied in this study is the allogenic river, namely the Sumurup River, while the autogenic recharge system in this area is in the Seropan Underground River. Groundwater in karst areas is an important water resource (Renouf et al., 2017). However, karst groundwater is extremely vulnerable to anthropogenic pollution, and it is challenging to recover contaminated groundwater (Ren et al., 2019). Water resource management is especially important in karst areas, as karst aquifers are highly susceptible to pollution (Widyastuti et al.,

2012). River water quality is at risk in many nations and locations around the world as a result of anthropogenic disruptions that have seriously disrupted natural hydrological and nutrient cycles (Mandaric et al., 2018; Ockenden et al., 2017). These hydrological cycles can result in surface runoff along riverbanks and have a direct impact on the drainage system of water bodies (Lobato et al., 2015). Another water quality assessment method developed in recent centuries is the Water Quality Index. The Water Quality Index (WQI) is a mathematical technique that converts water quality factors to a single integer value that expresses the general condition of a water body (Abbasi and Abbasi., 2012; Tian et al., 2019).

In karst regions, the water quality index has already been applied by Barakat et al. (2018) using the NSF-WQI and Xiong et al. (2022) using the CCME-WQI. The water quality index chosen for this study include CCME-WQI, NSF-WQI, OWQI and Smith Index. Referring to previous research conducted by Marselina et al. 2020 and each method has pros and cons, as shown in a review of water quality indexes by Uddin et al. in 2021. Based on previous research, the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) presents a simple mathematical framework for aggregating final index values that assist users in determining the health status of water bodies (Tirkey et al., 2015); there is no involvement with sub-index development, weight assignment, or conventional index aggregation. To combine all the altered water quality data into a single numerical form, or a single water quality index score (Uddin et al., 2021; Sutadian et al., 2016), the NSF model uses an additive aggregation function and a multiplication function. The Oregon Water Quality Index(OWQI) is used to assess the condition of surface water bodies in Oregon and other regions. The formula, which employs the idea of arithmetic mean, provides the mathematical expression for this approach (Tyagi et al., 2013). The Smith Index, also referred to as the minimum operator approach, and the water quality index developed by Ott (1978) in New Zealand are comparable measures of water quality. Smith (1990) combined the weight and rating curves for each parameter that was selected to develop the MO method.

The selection of water quality parameters plays a crucial role in determining the WQI's effectiveness. In this regard, Principal Component Analysis (PCA) has been employed in our study. PCA's significance in water quality research lies in its ability to pinpoint the most influential parameters by reducing the data's dimensionality without compromising its variance (Jolliffe, 2002). Through PCA, we can discern which parameters exhibit the most considerable variation, thus understanding their relative importance in the context of water quality in karst areas (Singh et al., 2007). This analytical approach assists in refining the parameters that should be prioritized in WQI calculations, ensuring a more accurate representation of water quality (Abdi and Williams, 2010). Given this

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background, this study aims to identify the optimal WQI method for karst landscapes using multivariate statistical techniques, focusing on previously unexplored terrains to determine the best approach for monitoring water quality in these pollution-sensitive regions.

2. RESEARCH METHODOLOGY
2.1. Study Area and Location

The study site is in Gunungkidul, a regency in the Special Region of Yogyakarta Province, which is known for its karst terrain. The unit of analysis of this study is Sumurup River as surface water in karst area and Underground River of Seropan as karst underground water. Sumurup River is located in Wonosari Subdistrict, Gunungkidul Regency and Seropan Cave underground river autogenic recharge system is located in Ngeposari Village, Semanu Subdistrict, Gunungkidul Regency. To assess the total water quality during both the rainy and dry seasons, the collection was done over a nine-month period from the start of the rainy season in March 2022 to the end of the rainy season in December 2022. The Seropan Underground River was selected as the study site because it is one of the clean water supplies that the community relies on, both within the Gunungsewu Karst area and outside of it, in places like the Wonosari Basin. Meanwhile, the Sumurup River was chosen as the study site because it is one of the water supplies used for washing, irrigation, and latrines along the river's banks. Sampling points in the Sumurup River were conducted at 4 sample points based on differences in land use from upstream to downstream. In the Seropan Underground River, sampling points were carried out at one point only due to accessibility and safety factors. Figure 1 displays the map of the sampling locations.
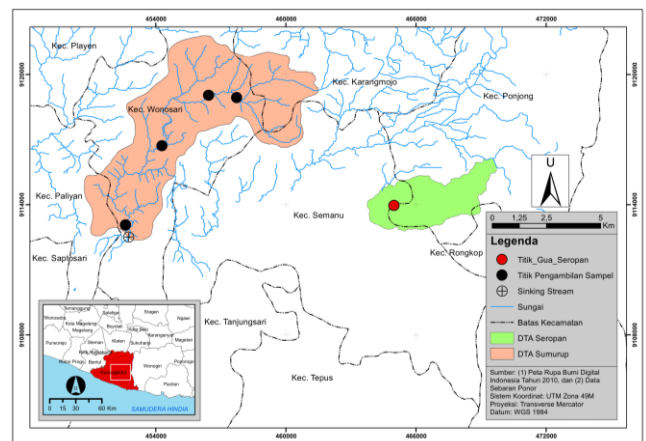

Figure 1. Research Location (Round Dots Indicate Sampling Sites)

2.2. Water Quality Index Formula

The water quality index methods used in this study are CCME-WQI, NSF-WQI, OWQI and Smith Index. The calculation of each index is presented below:

A. CCME-WQI Calculation
CCME-WQI can be calculated by:

$$CCME - WQI = 100 - (\frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732}) \qquad (1)$$

Table 1. Water Quality Value CCME-WQI

CCME-WQI Value	Water Quality Status
95-100	Excellent
80-94	Good
60-79	Fair
45-59	Marginal
0-44	Poor

Source : CCCME (2001)

B. NSF-WQI Calculation
This index is calculated based on the formula:

$$NSF - WQI = \Sigma_{i=1}^{n} WiQi \qquad (2)$$

Tabel 2. Water Quality Value (NSF-WQI)

NSF-WQI Value	Water Quality Status
90-100	Very good
70-90	Good
50-70	Moderate
25-50	Bad
0-25	Very Bad

Source : Darvishi et al (2016)

C. OWQI Calculation

$$OWQI = \sqrt{\frac{n}{\Sigma_{i=1}^{n} \frac{1}{Si^2}}} \qquad (3)$$

Tabel 3. Water Quality Value OWQI

OWQI Value	Water Quality Status
90-100	Excellent
85-89	Good
70-84	Fair
60-70	Poor
59-0	Very Poor

Source : Darvishi et al (2016); Tyagi et al (2013)

D. Smith Index Calculation
An aggregation function that avoids eclipsing is the "minimum operator", a term apparently first coined by Ott (1978):

$$I = min (Isub_1, Isub_1, .., Isub_n) \qquad (4)$$

It uses the lowest sub-index rank to generate the final index score.

Table 4. Descriptors for the Range of Sub-Index Values (/sub)

Smith Index Value	Water Quality Status
100 ≥ Isub ≥80	*Eminently suitable for all uses*
80 > Isub ≥ 60	*Suitable for all uses*
60 > Isub ≥ 40	*Main use and/or some uses may be compromised*
40 > Isub ≥ 20	*Unsuitable for main and/or several uses*
20 > Isub ≥ 0	*Totally unsuitable for main and/or many uses*

Source : Smith, 1990

The parameter simulation approach was used to evaluate the Water Quality Index method's applicability and efficacy for determining the state of water quality. The Water Quality Index methods being compared are CCME-WQI, NSF-WQI, OWQI and Smith

Index. In order to be compared, it is necessary to select representative parameters with the same number and type of parameters for a simulation. Parameter selection for simulation is based on the water quality parameter requirements of each method, especially methods that require weighting and sub-index values from the curve.

The selection of parameters for parameter simulation is based on WQI -INA which involves a weighting system and sub-index curves where the parameter weight value and number of parameters are adjusted to the characteristics of rivers and waters in Indonesia. Therefore, 10 water quality parameters were selected to be simulated by considering the number of parameters and types of parameters selected in the WQI -INA method. Parameter simulation was conducted with 3 scenarios with different number of parameters (10 parameters, 8 parameters and 6 parameters). Scenario I with 10 parameters, Scenario II uses a total of 8 parameters and Scenario III uses 6 most influential parameters that was carried out by multivariate analysis of Principal Component Analysis method using 10 parameters used at the beginning. By using PCA analysis, the number of parameters is reduced to just those that have the most bearing on the water's quality. Using Principal Component Analysis, the weights of each parameter in each scenario were also determined. The number of parameters is simulated and examined then calculations are carried out until the WQI value is obtained. This method was previously applied by (Saraswati et al., 2014) to assess the sensitivity of the WQI formula. Furthermore, the results of the parameter simulation for each method will be presented in graphical form to see the significance of the number of parameters with the WQI value

3. RESULTS AND DISCUSSION
3.1. Parameter Selection and Weighting using Principal Component Analysis (PCA)
The role of Principal Component Analysis (PCA) in this study was twofold: selecting key parameters and determining their respective weights, both pivotal for assessing water quality. For our parameter selection process under scenario I, ten parameters were evaluated. As depicted in Table 5, those with component values exceeding 0.7 were identified as having a significant influence on water quality. Specifically, parameters such as phosphate, DO, temperature, TDS, COD, and BOD emerged as dominant factors and were subsequently adopted for scenario simulations.

The weighting process hinged on PCA's ability to extract eigenvalues, which essentially signify the variance magnitude carried by each principal component. These eigenvalues, coupled with the loading values of parameters, help in understanding the relative importance of each parameter. As proposed by Alver (2019), the weighting of a parameter is determined by multiplying its relative

eigenvalue with its loading value. This approach ensures that each parameter's weight reflects its relevance and contribution to the overall water quality.

Tabel 5. Component Value

Parameter	Component		
	1	2	3
Nitrate	0.327	0.813	0.030
Phosphate	0.765	-0.035	0.357
Dissolved Oxygen	0.769	0.350	-0.059
pH	0.514	0.047	0.170
Temperature	0.770	0.407	0.111
Total Dissolved Solid	0.787	0.040	-0.346
Total Suspended Solid	0.437	-0.430	-0.676
Fecal Coliform	0.196	-0.447	0.687
Chemical Oxygen Demand	0.874	-0.283	-0.005
Biological Oxygen Demand	0.817	-0.434	0.033

Our application of the NSF-WQI methodology was guided by the adjusted weights presented in Table 6. In the computation for the Q-value, we employed a hybrid sub-index curve that amalgamates attributes from both the NSF-WQI and WQI-INA. This decision was informed by Ratnaningsih's 2020 study, which suggested negligible disparities between using the native NSF-WQI curve and the combined curve of NSF-WQI and WQI-INA. Hence, the combined curve was selected, offering an alternative perspective in computing the Water Quality Index value, ensuring a more comprehensive assessment.

3.2. Sensitivity of OWQI Formula

In the OWQI method, the simulation results of scenario I, II and III parameters show results that are not much different as shown in Figure 1. Out of the five sampling stations, the findings reveal that the WQI value is below the part of the graph that indicates that the WQI value is low and the water quality results are poor. The results of scenario I and II WQI values do not show significant differences and even the values tend to be the same at each point in the Sumurup River and the sample points in the Seropan Underground River. In scenario III, the resulting WQI value experienced a slight increase with a better value, this change shows that the selected parameters greatly affect the results of the OWQI value. This also means that the OWQI calculation formula takes into account the equal contribution of each parameter because this method

does not involve parameter weighting. Unfortunately, the OWQI formula is not sensitive enough to provide an evaluation of the water quality in the Sumurup River and is not representative for the quality assessment of the Seropan Underground River. The WQI value is only based on the conversion of parameter concentrations to SubIndex values so that this method is considered less able to show fluctuations in water quality (Marselina et al., 2022) in the Sumurup River. The formula used in this method causes the method to only show the impact of one water quality parameter (Marselina et al., 2022) which causes low WQI results.

Based on the above review, it can be said that the OWQI evaluation method is unsuitable since it does not depict the variability of water quality in the Sumurup River and does not depict typical water quality in the Seropan Underground River. The water quality data is nearly always lower as evidenced in the water quality status in the Very Poor category by Cude (2001), and the sub-index equation utilized in this method is too ideal to be applied to the research location. Additionally, the lowest value is that the sub-indices obtained from different places are nearly always the same. As a result, there was some similarity in the OWQI calculations' outputs.
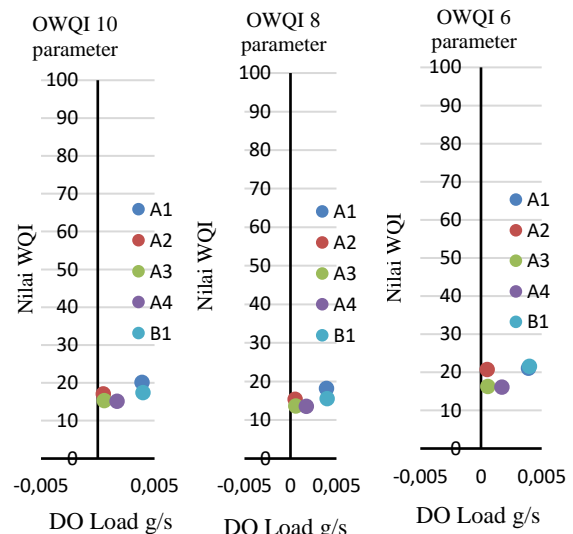

Figure 2. OWQI Parameter Simulation

Tabel 6. Weighting Value of Each Parameter

Scenario I		Scenario II		Scenario III	
Parameter	Weight	Parameter	Weight	Parameter	Weight
Nitrate	0.05	Nitrate	0.09	Phosphate	0.16
Phosphate	0.12	Phosphate	0.15	DO	0.16
DO	0.12	DO	0.16	Temperature	0.16
pH	0.08	pH	0.10	TDS	0.16
Temperature	0.12	TDS	0.15	COD	0.18
TDS	0.13	Temperature	0.17	BOD	0.17
TSS	0.07	Fecal Coliform	0.04		
Fecal Coliform	0.03	BOD	0.14		
COD	0.14				
BOD	0.13				

Note: The weights depicted in this table represent the relative importance of each water quality parameter as derived from the Principal Component Analysis (PCA). A weight signifies the impact a specific parameter has on the overall water quality. The process for determining these weights is elaborated upon in this section, referencing the approach from Alver, 2019.

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3.3. Sensitivity of NSF-WQI Formula

In the NSF-WQI method, the results of scenario I, II and III parameter simulations produce values that are not much different. The distribution of WQI values is at the top of the graph which indicates a high WQI value and good water quality. From 5 sample points, the NSF-WQI method is able to show fluctuations and changes in water quality along the sampling points in the Sumurup River, besides that the WQI results are also considered representative enough to show the water quality of the Seropan Underground River. Based on this review, it can be said that the NSF-WQI method is a method that is suitable or appropriate for the study area because it can show water quality accurately. This is influenced by the NSF-WQI calculation formula which involves a weighting system on water quality parameters, so that it can be reviewed which parameters have the most influence on water quality. The method being used aggregation technique is simple and easy to implement (Marselina et al., 2022). However, the determination of parameter weights is subjective so it is very sensitive to the study area. The NSF-WQI method is able to show fluctuations in water quality in the Sumurup River and also shows the appropriate water quality for the Seropan Underground River. This is possible because the parameter weights used are suitable for the study area so as to produce the right values. WQI values that tend to produce similar values between scenarios indicate that the NSF-WQI formula is effective enough to assess water quality status regardless of the number of parameters used.

The NSF-WQI method is considered suitable for use in surface water in Indonesia where similar research has been conducted by Marselina et al (2022) in the Citarum River with the same result that NSF-WQI is the most suitable method. In this study, NSF-WQI also proved to be an effective technique for assessing the water quality in underground rivers. This is indicated by the calculation results that produce the highest values for the three parameter simulations based on the designation of underground river water as one of the water sources. Similar research indicates that the NSF WQI leads to the highest qualitative classification, whereas the Oregon WQI leads to the lowest (Akkonyulu et al., 2012).
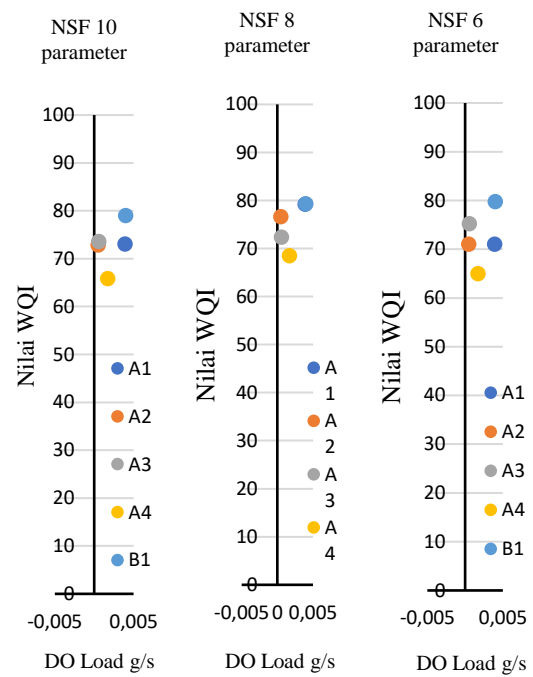

Figure 3. NSF-WQI Parameter Simulation

3.4. Sensitivity of CCME-WQI Formula

In the CCME-WQI method, the WQI results of scenarios I, II and III provide fluctuating values based on variations in the number of parameters when viewed from Figure 3. It can be seen that the IKA results from 5 sample points for scenario I, the data are clustered at the bottom of the graph which indicates the low results of the WQI calculation. The fluctuation of values generated in the CCME-WQI scenario indicates that the number of parameters affects the results of water quality status. The more water quality parameters tested, the more parameters will exceed the quality standard threshold, thus affecting the calculation and final result of the Water Quality Index value. This is because the CCME-WQI calculation involves statistical calculations, causing the WQI value generated from the CCME-WQI method to differ significantly from the NSF-WQI value. The difference in value occurs because the NSF-WQI assessment method involves weighting scores so that the calculated parameters have a significant effect on water quality. However, the calculation of scenario I using the CCME-WQI method resulted in a lower value than scenario II and the value of scenario II was lower when compared to the analysis of scenario III which did not involve bacteriological parameters in the calculation. This indicates that the CCME-WQI method is able to show the impact of water quality parameters on water quality status.
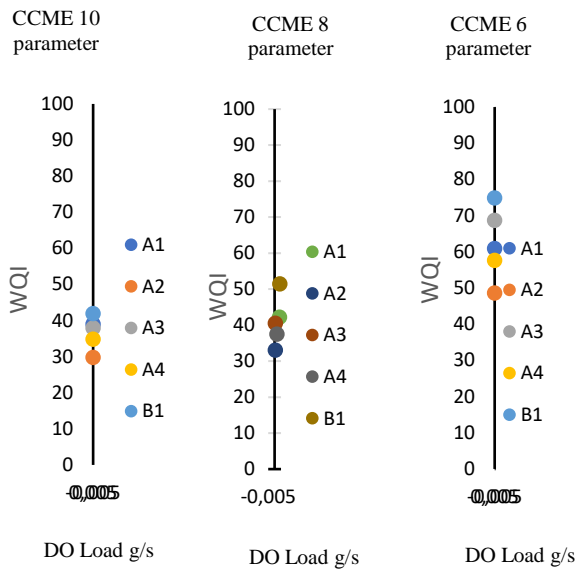
Figure 4. CCME-WQI Parameter Simulation

The aggregation method used by this method is also much more complex because it uses statistical calculations described in the F1, F2 and F3 values (Marselina et al., 2022; Saraswati et al., 2014). The calculation of scenario III resulted in a slightly higher WQI value which demonstrates the ability of the CCME-WQI method to show fluctuations in water quality. Another advantage of the CCME-WQI method is the flexibility in selecting water quality parameters and also the more objective analysis as it is based on the applicable water quality baseline in the study area. However, the CCME-WQI method is not suitable enough to be used in the Sumurup River because the resulting values show very low values. Therefore, it can be concluded that the CCME-WQI method cannot determine water quality in real time and cannot determine daily water quality in the Sumurup River. Similar results were also found in the research of Marselina et al (2022) who conducted a study with a similar IKA method in the Citarum River. The ineffectiveness is likely influenced by the number of parameters analyzed, the greater the number of parameters involved, the more parameters that exceed the quality standard threshold which affects the statistical calculation and causes a low WQI value. The CCME WQI assessment approach was also determined to be ineffective since it would be excessively costly and require at least four different observations during the same monitoring period. The OWQI and CCME were discovered to be substantially "more stringent," according to Zotou et al. (2019), resulting in values that fell between the lowest classes of water quality ratings.

3.5. Sensitivity of Smith Index Formula

In the Smith Index method, the WQI values of scenarios I, II and III show values that tend to be the same based on variations in the multiple parameters. Of the 5 sampling points, the results show the lowest water quality status, besides that there are several

points that have the same WQI value. Slightly different results were shown in scenario III with a total of 6 parameters. The WQI value is better than the previous two scenarios because the Fecal Coliform parameter is not involved so that the resulting WQI value is higher. This is because in the WQI assessment using the Smith Index, the minimum operator method is used to determine the WQI value, where the minimum or lowest value of the conversion results is the overall WQI value of the water body. This method is based on the assumption that the suitability of water for use is mostly determined by its poorest qualities, and is related to the limiting nutrient idea in eutrophication investigations, where one component can determine the quality of the water (Abbasi & Abbasi, 2012). The concentration of the water quality parameter Fecal Coliform is well below the water quality threshold resulting in the lowest water quality value. Therefore, when this parameter is not included in the calculation, the water quality value increases slightly because the minimum value produced is no longer from Fecal Coliform. The Smith Index method in its calculation formula does not use a weighting system, so the resulting value is only based on the conversion of the parameter concentration value to the SubIndex value or SubIndex aggregation.
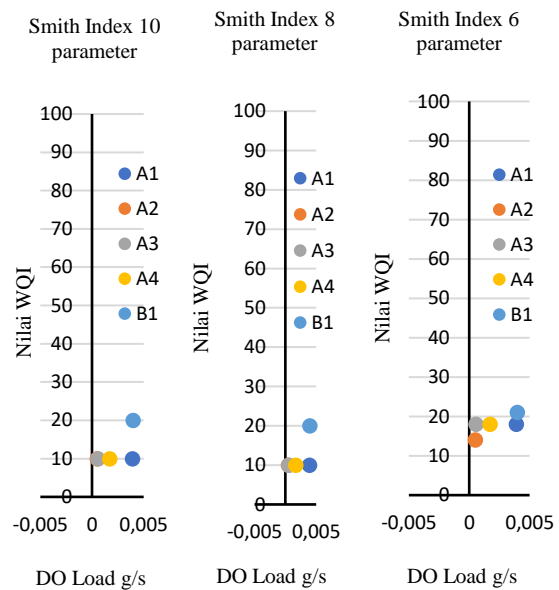

Figure 5. Smith Index Parameter Simulation

The use of the minimum operator method has several advantages as outlined by Abbasi and Abbasi in 2012 including, there is no need to limit the number of parameters or determinants used, new determinants can be introduced (e.g. weighting systems), no weighting is required making it easier to construct the index. Nonetheless, the Smith Index sometimes provides interesting results. Because it is specifically based on environmental conditions in New Zealand, which is a temperate country, it causes the resulting IKA value in Indonesia to be very low. For example, if the bathing water temperature is 26.5°C, it will produce a sub-index value of 44, which is the

lowest sub-index value (Abbasi & Abbasi, 2012). This is because bathing water in New Zealand also has aquatic life such as trout that will experience stress at a temperature of 26.5℃ (Abbasi & Abbasi, 2012). However, the fact is that Indonesia, which is a tropical country, has a water temperature ranging from 26-31.5℃ so that if the temperature of 26℃ produces the lowest SubIndex value even though water with this temperature can still be used for various activities, the Smith Index method assessment is considered inappropriate and not suitable for application in Indonesia.

3.6. Comparison of Water Quality Index Methods

The calculation results of the Water Quality Index for the scenario I parameter simulation with 10 parameters are shown in the graph where the Water Quality Index values are compared between sampling points with 4 different methods. Based on the graph presented, the highest IKA calculation results are produced by the NSF-WQI method regardless of the difference in sample points, while the lowest results are obtained from the Smith Index calculation results. The calculation of IKA with the Smith Index produces the lowest value because it uses the minimum operator method, where the lowest IKA result is used as a value that reflects overall water quality (Smith, 1990). This is based on the assumption that the minimum assessment result is sufficient to represent the overall quality of the water body.
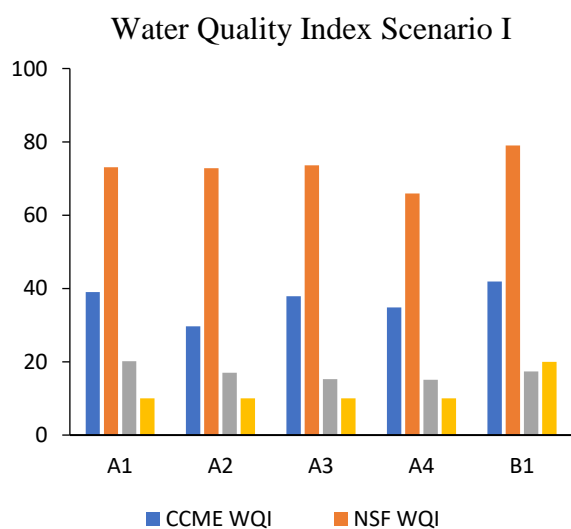

Figure 6. Water Quality Index Results

Based on the graph, it can also be seen that the IKA value of the OWQI calculation results tends to be low because the calculation method is too idealized to be applied in the study area. The WQI value of the CCME-WQI calculation also shows low results since it is based on statistical calculations involving F1, F2 and F3, the more parameters that exceed the threshold of water quality standards cause the WQI value to be low and indicate poor water quality. The application of the

CCME-WQI method does not satisfy the assumption of the WQI method's efficacy, which can reflect water quality regardless of the number of water quality metrics employed. Other influencing factors include the formula used to calculate water quality values and the selection of parameters.

To differentiate between "effectiveness" and "sensitivity" in the context of Water Quality Index (WQI) methods, we should clarify their specific meanings. "Effectiveness" refers to how well a WQI method can represent water quality, regardless of the number of metrics used. On the other hand, "sensitivity" speaks to how quickly and accurately the index reacts to small changes in individual metrics. This means that an index can be very effective, but might not be as sensitive to minor changes, and the other way around.

When we compare these indices, the NSF-WQI appears to be the most well-rounded, being both effective and sensitive in measuring water quality. As shown in our graph, it seems to be the best method for assessing the water quality in our main study areas: the Sumurup River and the Seropan Underground River.

4. CONCLUSIONS

Given how well the water quality index approach works on bodies of water in karst environments, the NSF-WQI method is a pretty effective one to employ. The NSF-WQI calculation can be used to demonstrate that the Seropan Underground River and the Sumurup River water quality, both of which are situated in a karst zone. This shows that the weighting system and index curve are quite effective calculation methods in describing water quality in water bodies, especially in Indonesia. However, NSF-WQI has limitations, namely not being able to show water quality based on water designation, but in general NSF-WQI is able to show water quality in water bodies quite representative. Management and monitoring of water quality in karst areas need to be carried out regularly considering the vulnerability of this area with the utilization of water to meet the needs of the community. Protection of karst areas needs to be done by monitoring water quality in karst hydrology. Assessment using the Water Quality Index can use the NSF-WQI method as an effective WQI method used in the study area.

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