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Application of fuzzy evaluation technique and grey clustering method for water quality assessment of the coastal and estuaries of selected rivers in Sarawak

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Abstract

Background: Estuarine and marine water quality has remarkable importance because these water resources are used for multiple reasons for instance: transportation, tourism, recreation, and other human or economic ways to use water. The objective of the study was to assess the water quality of the coastal and estuaries of the Rambahan, Sibul, Salak, and Santubong rivers in Sarawak, Malaysia. Water samples were collected from 10 locations and analyzed by employing standard techniques. A fuzzy comprehensive evaluation, grey clustering evaluation methods, Thailand Marine Water Classification System, and the Malaysian Marine Water Quality Index (MMWQI) and its classification system were applied to compute the index of each water quality parameter.

Results: The results showed that all the analyzed water quality parameters were within the allowable threshold levels. The results obtained by the application of fuzzy comprehensive evaluation and grey clustering evaluation methods proved that the coastal and the estuaries waters were clean with exception of coastal location CZ9 and the estuary of Salak river which showed slight pollution. Based on the Malaysian Marine Water Quality Index, it was observed that all the locations were in the classification group of moderate (i.e. 50–79%). This suggests that the estuaries of selected rivers can be used for natural resource conservation, while the coastal regions are good for fish farming.

Conclusion: It can be deduced that the suggested techniques were workable and logical. The method developed and the information in this study can serve as a reference and decision support for scientists and policymakers of concern.

Keywords: Fuzzy comprehensive evaluation, Grey clustering method, Classification system, Water quality index, Water sources

Background

Water pollution is one of the major environmental issues in the Sarawak State of Malaysia and thus water quality assessment is the foundation of the river, marine,

and coastal water pollution control, which is significant for implementing management practices to rivers, estuaries, and coastal marine zones (Asare et al. 2019a, b; Omorinoye et al. 2019). A large number of boatyards are located along the estuaries and the coastal marine zones of river Rambahan, river Sibul, river Salak, and river Santubong in the Sarawak State of Malaysia are involved with various commercial activities, which include

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transportation of passengers, farm input materials, and products, fishing, and different business products. No matter their size, the impact of boatyards on the environment depends on these commercial activities. The biological productivity and ecological sustainability of the estuaries and the coastal marine environments rely on coastal water quality (Omorinoye et al. 2020). Nevertheless, coastal marine water quality is decreasing because of the elevated concentration of different pollutants. A lot of assessment techniques have been employed to determine the water quality of rivers and coastal marine areas; the majority of the methods appeared not perfect (Zhang 2014). These techniques include artificial neural network (ANN) (Kim and Seo 2015; Csábrági et al. 2017), the Bayesian discrimination (BD) (Fassnacht et al. 2016), the fuzzy comprehensive assessment technique (FCA) (Zou et al. 2013; Jiao et al. 2016; Yang et al. 2017), and the grey correlation analysis (Yeh and Chen 2011; Chen et al. 2016). Out of these techniques, the practicable technique for tackling water environmental safety evaluation, and has been extensively applied in several fields, such as water environmental protection, water resource management, the safety evaluation of drinking water sources, etc. is the fuzzy comprehensive assessment technique (Ding et al. 2017; Zhang and Feng 2018). The application of fuzzy mathematics to examine the influence and the effects of environmental issues has increased considerably in the past 25 years. Silvert (1997) opined that most activities, either anthropogenic or natural, have many consequences and any environmental index should offer a consistent meaning including a coherent quantitative and qualitative appraisal of all these effects. The fuzzy evaluation technique is efficacious for correcting the problems in which the information is too fuzzy to compute and the evaluation purpose is restricted by several factors (Ding et al. 2017). Out of the various advantages of applying fuzzy evaluation techniques to composite situations, the most significant is possibly the essence to combine different indicators. The most important merit of the application of the fuzzy evaluation technique for the development of ecological indicators is that it is feasible when combines with several aspects with much more flexibility as compared to other techniques. Fuzzy mathematics and MATLAB were used to assess the Jinan water supply system (Li et al. 2011). The ecological safety status of Mianyang City from 1998 to 2005 was evaluated using fuzzy comprehensive assessment, demonstrating the eco-safety status of the city, inferring that fuzzy comprehensive assessment could correct the uncertainty in assessing the urban eco-safety standard (Zhao and Zhao 2010). Deng (2000) opined that two or more techniques are combined to assess the environmental water quality in other to achieve comprehensive and accurate results

(Zhang 2014). The Grey clustering evaluation method can quantify and differentiate the water quality under the situation of few samples and inadequate information and has been extensively used (Zhan et al. 2017). Currently, several researchers have used the grey clustering technique to assess the surface water quality and different researchers have improved the techniques in terms of index transformation (Yicheng and Hui 2015) and whitening weight function (He et al. 2011). Nevertheless, the contribution rate of each water quality index is the same when computing the clustering coefficient process, which does not give the difference of contribution of other water quality indicators. When the water quality of location is not certain with a fuzzy mathematics evaluation, which depicts that the technique has lost some information, the feasible technique to overcome such defect is the grey clustering evaluation method (Zhang 2014). For this reason, the physicochemical and microbiological parameters were computed and classified using fuzzy comprehensive evaluation technique combined with the grey clustering evaluation, Thailand marine water classification system, and the Malaysian Marine Water Quality Standard Index (MMWQSI) to determine the environmental water quality of the estuaries and the coastal marine areas of river Rambungan, river Sibul, river Salak, and river Santubong in the Sarawak state of Malaysia.

Methods

Study area and sampling locations

The study area was conducted at the estuaries of river Rambungan, river Sibul, river Salak, river Santubong, and the coastal marine areas connected to the above rivers. Water samples were collected at ten stations. The ten water samples were marked as CZ1 (N01°41' 37.7" E 110°08' 24.5"), CZ2 (N01°44' 46.8" E 110°08' 45.4"), CZ3 (N01°46' 22.6" E 110°08' 37.8"), CZ4 (N01°44' 46.8" E 110°08' 45.4"), CZ5 (N01°45' 50.4" E 110°11' 30.2"), CZ6 (N01°47' 23.5" E 110°10' 39.7"), CZ7 (N01°40' 41.1" E 110°16' 59.2"), CZ8 (N01°42' 45.7" E 110°27' 63.1"), CZ9 (N01°44' 49.6" E 110°29' 72.3"), and CZ10 (N01°42' 32.6" E 110°19' 02.3"). The CZ1 stands for the location of the estuary of river Rambungan, CZ4 represents the estuary of river Sibul, CZ7 represents the estuary of river Salak, and CZ10 is the estuary of river Santubong. The rest of the codes are the locations in the coastal marine zones.

Sampling method and analytical techniques

In-situ water quality analysis was carried from September 2020 to October 2020. Plastic bottles were also used to collect the water samples for ex-situ analysis and were

stored in an ice chest, transported to the laboratory, and processed in 4 h of collection.

In-situ measurement of field parameters using hydro lab

Dissolved oxygen (DO), temperature, pH, oxidation–reduction potential (ORP), and electrical conductivity were measured in-situ as field parameters using the hydro lab 4a (Al-Badaai et al. 2013). Before field measurement, the storage (calibration) cup was removed, thread on the weighted guard, and the bail was attached with an appropriate length of rope and the Data Sonde 4a was placed in the water. An ample time was allowed for the readings to stabilize to ensure accurate readings of various parameters. Dissolved oxygen (DO), temperature, pH, oxidation–reduction potential (ORP), and electrical conductivity (EC) parameters were recorded in a field logbook. After readings, the weighted guard was removed and the storage cup was replaced (half-filled with water). It was ensured that the sensors were not dry out. After the completion of measurements, the probes were rinsed with distilled water followed by the replacement of a storage cup, with about 50 mL of tap water.

Turbidity and total suspended solids (TSS) assessment

The protocol used to measure the clarity of the water samples was adapted by APHA (2003). Turbidity is caused by particles and colored substances in water. The turbidity of the water was measured directly with a turbidimeter. Turbidity meter uses nephelometry (90° scattering) technique for fast and accurate turbidity quantifications on water samples. The unit at which the clarity of water samples was measured is FNU. The primary cause of turbidity is total suspended solids (TSS). The most common and feasible technique of measuring suspended solids is by weight. To quantify TSS, water samples were filtered, dried at 100–107 °C, and weighed (APHA 2003).

Salinity assessment

The water salinity was measured by passing an electric current between two electrodes of a salinity meter in a sample of water (APHA 2003). The electrical conductivity of a water sample is controlled by the composition and concentration of dissolved salts. Salts increase the propensity of a solution to conduct an electrical current; therefore a high electrical conductivity value suggests a high salinity level. The unit at which the salinity of the water samples was measured is ppt.

Nitrate (NO₃) evaluation

About 60 mL water sample was filtered through Whatman filter paper no. 1. 1.5 mL of sulphinamide reagent

was added. N-(1-Naphthyl)ethylenediamine (NEDA) was added to it after 2–6 min. In acid solution, the nitrite yields nitrous acid which diazotizes sulphinamide. The diazonium salt reacts with aromatic NEDA forming a pink azo dye which was spectrophotometrically determined at 543 nm. The nitrite was deduced from a standard curve. A standard curve was prepared taking sodium nitrite of known concentrations (APHA 2003; HACH 2003).

Phosphate (PO₄) determination

Because organic phosphates are recalcitrant compounds that do not like to break down easily. To test for them, it is important not to only digest the water sample first with sulphuric acid and heat, but also requires an addition of strong oxidant for example potassium persulfate to break the orthophosphate free from the organic bonds. After digestion, the molybdenum blue phosphorus technique in co-occurrence with UV–Visible spectrophotometer was used for the assessment of phosphorus at 830 nm. Phosphate in the water samples was ascertained at sub-µg/L concentration at 830 nm. Orthophosphate and molybdate ions condense in solution with pH < 7 to produce phosphomolybdic acid, upon selective reduction for instance with hydrazinium sulfate to produce a blue color. The intensity of the blue color is proportional to the quantity of phosphate initially incorporated into the heteropoly acid. The resulting blue complex shows maximum absorbance at 820–830 nm when the acidity at the time of reduction is 0.5 M in sulphuric acid and hydrazinium sulfate is reluctant. The visible spectrophotometer was used to measure the intensity of the color of the solutions (HACH 2003).

Ammonia (NH₃) determination

Nessler's method was adapted to determine the ammonia content in the water samples (APHA 2003; HACH 2003). In the ammonia test, Nessler reagent (K₂HgI₄) was added to the water samples to react with the ammonia present in the samples to produce a yellow-colored species. The intensity of the color is in direct proportion to the ammonia concentration.

Total chromium determination

Water samples were filtered using Millipore filter paper (0.45 µm pore size) and conserved by reducing the pH to less than 3 by adding 5.0 N ultrapure HNO₃ (Giri and Singh 2015). Total Cr was determined by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES).

Fecal coliform (FC)

Fecal coliform (FC) was evaluated based on the membrane filter procedure (APHA 2003). A measured volume (50 mL) of a water sample is filtered, under vacuum; via a cellulose acetate membrane of uniform pore diameter (i.e. 0.54 μm). Bacteria retained on the surface of the membrane was placed on an appropriate selective medium in a sterile container and incubated at 37 °C for 2 days. Characteristic colonies formation that can be counted directly shows that fecal coliforms are present in the water samples.

Evaluation procedures

Fuzzy mathematics method

Han and Yang 2000; Yang and Gao 2001; Zhang 2014 explained the procedure for the fuzzy evaluation technique as follows.

- a. The level of membership of the individual pollution factor is measured. At this moment,

Q functions as the set for all pollution factors, i.e., $Q = \{\text{nitrate, phosphate, turbidity, total suspended solids, chromium, dissolved oxygen}\}$ and R functions as the set for concentration values in the water standard, i.e., $R = \{I, II, III, IV, V, VI\}$. First of all, the individual factor of Q is evaluated, followed by computing the corresponding level of membership (P) of each factor for I, II, III, IV, V,

VI per its monitoring value. Table 1 was used to compute the degree of membership.

- b. The normalization of Fuzzy weight was carried and is attained through computation

by the degree of individual single factor exceeding individual grade standard value. The Fuzzy weight can be calculated by the formula,

$$FW_{ni} = (Ci/Co_i) \times 1 \left\{ \sum_{i=1}^6 (Ci/Co_i) \right\} \quad (1)$$

where I represent a single factor, n represents sampling location, C_i represents monitoring value, and

$$Co_i = (CI_i + CII_i + CIII_i + CIV_i + CV_i + CVI_i)/6 \quad (2)$$

- c. To achieve a comprehensive assessment, the results obtained from the comprehensive evaluation was achieved by the compound operation of M and N , i.e.

$$E = M \times N \quad (3)$$

where E represents the fuzzy comprehensive evaluation value, M represents the matrices made up of the associating degree of membership (P) of the individual single factor for I, II, III, IV, V, and VI, and N represents the matrices made up of fuzzy weight of individual single factor for I, II, III, IV, V, and VI.

Table 1 Membership functions for six grades

P	Expression of membership function	Scope
	1	($C_i \leq CI$)
PI (Ci)	$(CII - C_i) / (CII - CI)$	($I < C_i < CII$)
	0	($C_i \geq CII$)
PII (Ci)	0	($C_i \leq CII$ or $C_i \geq CIII$)
	$(C_i - CI) / (CII - CI)$	($CI < C_i \leq CII$)
	$(CII - C_i) / (CIII - CII)$	($CII < C_i \leq CIII$)
	0	($C_i \leq CII$ or $C_i \geq CIV$)
PIII (Ci)	$(C_i - CII) / (CIII - CII)$	($CII < C_i \leq CIII$)
	$(CIV - C_i) / (CIV - CIII)$	($CIII < C_i \leq CIV$)
	0	($C_i \leq CIV$ or $C_i \geq CV$)
PIV (Ci)	$(C_i - CIII) / (CIV - CIII)$	($CIII < C_i < CIV$)
	$(CV - C_i) / (CV - CIV)$	($CIV < C_i \leq CV$)
	0	($C_i \leq CV$ or $C_i \geq CVI$)
PV (Ci)	$(C_i - CIV) / (CV - CIV)$	($CIV < C_i \leq CV$)
	$(CVI - C_i) / (CVI - CV)$	($CV < C_i \leq CVI$)
	0	($C_i \leq CV$)
PVI (Ci)	$(C_i - CV) / (CVI - CV)$	($CV - C_i \leq CVI$)
	1	($C_i \geq CVI$)

Grey clustering method

There may be a possibility of a loss of some information in the course of fuzzy comprehensive assessment; in this case, the same degree of membership may emerge for independent grades when evaluating a location of the mouth of the estuaries and the coastal zone. Eventually, the particular water quality grade cannot be achieved. Thus, it is very important to some of the fuzzy comprehensive assessment values by the application of a grey clustering assessment.

The technique for grey clustering evaluation was adopted from Deng (2000), Zhang (2014) and is described as follows.

- 1. The values of the whitened function on individual grades for individual single

factors are achieved by the application of whitened function (f_{ij}). Table 2 shows the list of whitened functions for six grades.

Table 2 Whitened functions for six grades

Whitened function	Expression	Scope
f1 (Ci)	1	(0 ≤ Ci ≤ C1)
	(CII-Ci)/(CII-C1)	(C1 < Ci < CII)
	0	(Ci > CII)
f2 (Ci)	(Ci-C1)/(CII-C1)	(C1 < Ci < CII)
	(CIII-Ci)/(CIII-CII)	(CII < Ci < CIII)
	0	(Ci ≤ C1 or Ci ≥ CIII)
f3 (Ci)	(Ci-CII)/(CIII-CII)	(CII < Ci < CIII)
	(CIV-Ci)/(CIV-CIII)	(CIII < Ci < CIV)
	0	(Ci ≤ CII or Ci ≥ CIV)
f4 (Ci)	(Ci-CIII)/(CIV-CIII)	(CIII < Ci < CIV)
	(CV-Ci)/(CV-CIV)	(CIV < Ci < CV)
	0	(Ci < CIII or Ci ≥ CV)
f5 (Ci)	(Ci-CIV)/(CV-CIV)	(CIV < Ci < CV)
	(CVI-Ci)/(CVI-CV)	(CV < Ci < CVI)
	0	(Ci ≤ CIV or Ci ≥ CVI)
f6 (Ci)	0	(0 < Ci < CV)
	(Ci-CVI)/(CVI-CV)	(CV < Ci < CVI)
	1	(Ci > CVI)

2. Also, clustering and its coefficient are calculated. To achieve this, the clustering weight (*Wij*) for various contamination factors on different grades is calculated, and then the associating clustering coefficient can be achieved, which throws back the similarity and dissimilarity of individual contamination factors to each grade. Below is the list of related formulas.

$$Wij = (Ci/Cij) / \left(\sum_{i=1}^6 Ci/Cij \right) \tag{4}$$

$$Nij = \sum_{i=1}^6 fij(Cki) \times Wij \tag{5}$$

where *i* represents a single factor, *j* represents H₂O quality grade, *k* represents clustering object, *Cij* represents the standard value of *i* factor in *j* grade, *Ci* represents monitoring value for a pollution factor, *Wij* represents the weight of factor in *j* grade, *Nk* represents the clustering coefficient, *Fij (Cki)* represents the value of the whitened function of *i* factor of *k* clustering object in *j* grade.

3. Lastly, based on the principle “the maximum of clustering coefficient” the class to which the huge clustering coefficient belongs is considered as the connected location.

Marine water quality standards

See Tables 3 and 4.

The water quality parameters selected stands for the MMWQI include dissolved oxygen, fecal coliform, ammonia, nitrate, phosphate, and total suspended solids.

The MMWQ is computed as:

$$MMWQI* = q_{iDO}^{0.18} \times q_{iFC}^{0.19} \times q_{iNH3}^{0.15} \times q_{iNO3}^{0.16} \times q_{iPO4}^{0.17} \times q_{iTSS}^{0.15} \tag{6}$$

Here,

$$q_{iDO} = - 85.816 + 55.4768(DO) - 4.142(DO)^2, \\ q_{iFC} = 100^{(-0.005(\text{Faecal coliform}))}, \quad q_{iNH3} = 100^{(-0.0046(\text{Unionised Ammonia}))}, \\ q_{iNO3} = 94.8^{(-0.00035(\text{Nitrate}))}, \quad q_{iPO4} = 95.2^{(-0.002(\text{Phosphate}))}, \\ q_{iTSS} = 95.8^{(-0.0043(\text{Total Suspended Solid}))}.$$

The following conditions apply in MMWQI: when DO is < 3 mg/L, *q*_{iDO} = 10; when DO is > 3 mg/L, *q*_{iDO} = 10; if FC > 500 faecal coliform count/100 mL, *q*_{iFC} = 8; when PO₄ > 900 μg/L, *q*_{iPO4} = 10; when TSS > 100 mg/L, *q*_{iTSS} = 20.

The index of Malaysian marine water quality and their respective classifications are as follows: 90–100 mean the

Table 3 Marine water quality standard (Thailand National Environment Board)

Parameters	I	II	III	IV	V	VI
pH	7.0–8.5					
Dissolved oxygen	< 4		< 6	< 4		
Salinity	Any change shall not > 10% of minimum allowable salinity					
Floatable Solids	Not unpleasant					
Nitrate	< 20		< 60			
Chromium hexavalent	< 50					
Phosphate	< 15		< 45	< 15	< 45	
Turbidity	< 10% of the minimum turbidity					

Table 4 Malaysian marine water quality standard (MMWQS)

Parameter ($\mu\text{g/l}$) unless otherwise stated	Class 1	Class 2	Class 3	Interim class E1	Interim class E2	Interim class E3
				Estuaries		
Dissolved oxygen	> 6.0	> 5.0	> 3.0	> 5.0		
Faecal coliform (Cfu/100 ml)	70					
Ammonia	35.0	50.0	320.0	5.0	10.0	10.0
Nitrate	10.0	60.0	700.0	200.0	570.0	430.0
Phosphate	5.0	75.0	670.0	100.0	180	
Total suspended solids	25.0	50.0	100.0	30.0		

Table 5 Average values of the selected parameters at each location in the coastal and estuaries of river Rambungan, river Sibul, river Salak, and river Santubong in Sarawak, Malaysia

Location	Code	Parameter													
		pH	EC	Tem	Turbidity	Salinity	DO	RedoxP	NO ₃	PO ₄	NH ₃	TSS	FC	FS	Cr
Unit		–	$\mu\text{S/cm}$	$^{\circ}\text{C}$	FNU	ppt	mg/L	mV	$\mu\text{g/L}$	$\mu\text{g/L}$	$\mu\text{g/L}$	mg/L	Cfu/100 mL	–	$\mu\text{g/L}$
Rambungan	CZ1	7.1	119.3	28.8	4.81	0.32	6.59	166	5.7	3.3	26.2	8.1	6.0	^a Pleasant	4.1
Coastal area	CZ2	7.7	5037	29.2	0.85	32.77	9.07	314	88.1	41	2.5	14.7	15.0	Pleasant	8.9
Coastal area	CZ3	7.4	5113	28.3	0.69	33.38	9.11	335.97	80.3	32.9	4.32	12.2	13.5	Pleasant	11
Sibu	CZ4	6.3	122	29.4	4.06	0.28	3.93	121	3.5	2.5	15.4	6.9	8.4	^b Unpleasant	3.4
Coastal area	CZ5	7.3	3385	27.8	0.61	31.63	8.37	456	61.3	15.8	4.2	19.1	19.0	Pleasant	6.1
Coastal area	CZ6	7.7	5179	29.1	0.66	33.35	9.01	487.33	57.9	44.1	3.4	17.1	12.7	Pleasant	9.4
Salak	CZ7	6.5	302.3	29.2	3.70	0.27	5.21	114.67	7.4	1.9	9.7	6.6	4.2	Pleasant	2.2
Coastal area	CZ8	7.6	312.7	28.3	0.50	33.99	8.44	312	33.2	22.3	5.2	10.2	11.3	Pleasant	5.8
Coastal area	CZ9	7.5	4996	28.7	0.70	34.36	9.81	503.27	40.1	31.4	2.5	17.7	9.9	Pleasant	7.1
Santubong	CZ10	7.2	441.7	29.7	4.28	0.35	5.14	194.67	2.4	1.4	11.2	9.4	4.4	Pleasant	0.9

EC stands for Electrical Conductivity, Tem represents Temperature, DO stands for Dissolved Oxygen, TSS stands for Total Suspended Solids, FC represents Faecal Coliform, and FS stands for Float Solids

^a Pleasant: Smell's good

^b Unpleasant: Smell's bad

water quality is excellent; 80–89 is good; 50–79 is moderate; 0–49 is poor.

Results

Monitoring results

The results of the monitoring of water quality parameters for different locations are shown in Table 5.

Fuzzy comprehensive assessment

Table 6 shows the values of a fuzzy comprehensive assessment of marine water quality of the coastal and estuaries of river Rambungan, river Sibul, river Salak, and river Santubong.

Water quality index evaluation

Table 7 shows the calculated individual parameter of the water quality index whiles the results of the total water

quality index of the coastal and the selected estuaries are shown in Fig. 1.

Discussion

To evaluate the water quality of the coastal and selected estuaries in the Kuching Division of Sarawak, fuzzy mathematical method, grey clustering technique, the Thailand Marine Water Classification System, and the Malaysian Marine Water Quality Index (MWQI) were applied to compute the water quality for 10 sampling stations. The average values of physical, chemical, and biological/organic parameters of water from the coastal and selected estuaries and the results of estuarine/marine water quality data analysis are highlighted in Tables 5, 6, and 7, and Fig. 2.

The average temperature values varied from 27.8 to 29.7 $^{\circ}\text{C}$. Location CZ5 in the coastal areas recorded

Table 6 Fuzzy comprehensive and grey clustering assessment results

Code	I*	II*	III*	IV*	V*	VI*	Results
<i>Fuzzy comprehensive assessment</i>							
CZ1	0.41	0.43	0	0	0	0	II
CZ2	0.27	0.31	0.11	0	0	0	II
CZ3	0.37	0.21	0.06	0.15	0.04	0	I
CZ4	0.17	0.24	0.24	0.10	0	0	II III
CZ5	0.32	0.30	0.15	0	0	0	I
CZ6	0.36	0.11	0.45	0.03	0	0	III
CZ7	0.17	0.12	0.09	0.21	0	0	IV
CZ8	0.16	0.16	0.07	0.04	0	0	I II
CZ9	0.18	0.05	0.15	0.19	0.02	0	IV
CZ10	0.11	0.05	0.09	0	0	0	I
<i>Grey clustering assessment</i>							
CZ4	0.09	0.26	0.39	0	0	0	III
CZ8	0.03	0.31	0.09	0	0	0	II

Table 7 Results of marine water quality index (MWQI) for the various locations

Location	Marine Water Quality Sub-index											
	q_{iDO}	q_{iFC}	q_{iNH3}	q_{iNO3}	q_{iPO4}	q_{iTSS}	$q_{iDO}^{0.18}$	$q_{iFC}^{0.19}$	$q_{iNH3}^{0.15}$	$q_{iNO3}^{0.16}$	$q_{iPO4}^{0.17}$	$q_{iTSS}^{0.15}$
CZ1	10	93.3	75.8	94.3	93.8	88.4	1.51	2.37	1.91	2.07	2.16	1.96
CZ2	10	84.1	97.4	88.4	78.8	82.9	1.51	2.32	1.99	2.05	2.10	1.94
CZ3	10	85.6	95.5	88.8	81.8	84.9	1.51	2.33	1.98	2.05	2.11	1.95
CZ4	10	90.8	84.9	94.5	93.9	89.5	1.51	2.36	1.95	2.07	2.16	1.96
CZ5	10	80.4	95.7	90.2	88.5	79.3	1.51	2.30	1.98	2.06	2.14	1.93
CZ6	10	86.4	96.5	90.4	77.7	80.9	1.51	2.33	1.98	2.06	2.10	1.93
CZ7	10	95.3	90.2	94.2	94.3	89.8	1.51	2.38	1.97	2.07	2.17	1.96
CZ8	10	87.8	94.6	92.3	85.9	86.6	1.51	2.34	1.98	2.06	2.13	1.95
CZ9	10	89.2	97.4	91.8	82.3	80.4	1.51	2.35	1.99	2.06	2.12	1.93
CZ10	10	95.1	88.8	94.6	94.6	87.3	1.51	2.38	1.96	2.07	2.17	1.96

the lowest value of 27.8 °C while the highest value was recorded in the estuary of Santubong River (i.e. 29.7 °C). The measured values are within the standard acceptable levels of Malaysian Marine Water Quality Standards (MMWQS). Environmental factors such as weather conditions, sampling time, and location influence the temperature difference and it also has an impact on the rate of biological activities, dissolved oxygen, and other parameters (Al-Badaii et al. 2013). The electrical conductivity of the studied environment varied from 119.3 to 5179 µS/cm, and the highest value was recorded at location CZ6, while the lowest value was observed at location CZ1 (see Table 5). Generally, the recommended coastal and marine water’s electrical conductivity is around 5000 µS/cm while freshwater and estuaries are in the range of 100–2000 µS/cm. Therefore, the conductivity values were found to be within the recommended level by MMWQS. Usually, the electrical conductivity in marine

water is affected by inorganic dissolved solids which include aluminum cations, sulfate, chloride, magnesium, nitrate, iron, calcium, and sodium. Besides, organic compounds such as phenol, alcohol, oil, and sugar can affect the coastal water conductivity including temperature (Al-Badaii 2011; Al-Badaii et al. 2013). The values of the redox potential of the study area ranged from 121 to 503.27 mV. Hence, the recorded values were within the recommended level according to MMWQS. The turbidity values ranged from 0.50 to 4.81 FNU. Coastal stations recorded the highest values of turbidity, whereas estuaries stations gave the lowest values. The turbidity values recorded were within standard permissible limits according to WHO UNESCO/WHO/UNEP (2001) and the increase of turbidity value from the estuary to the coast may be attributed to discharges from farm waste, organic contamination, and road runoff.

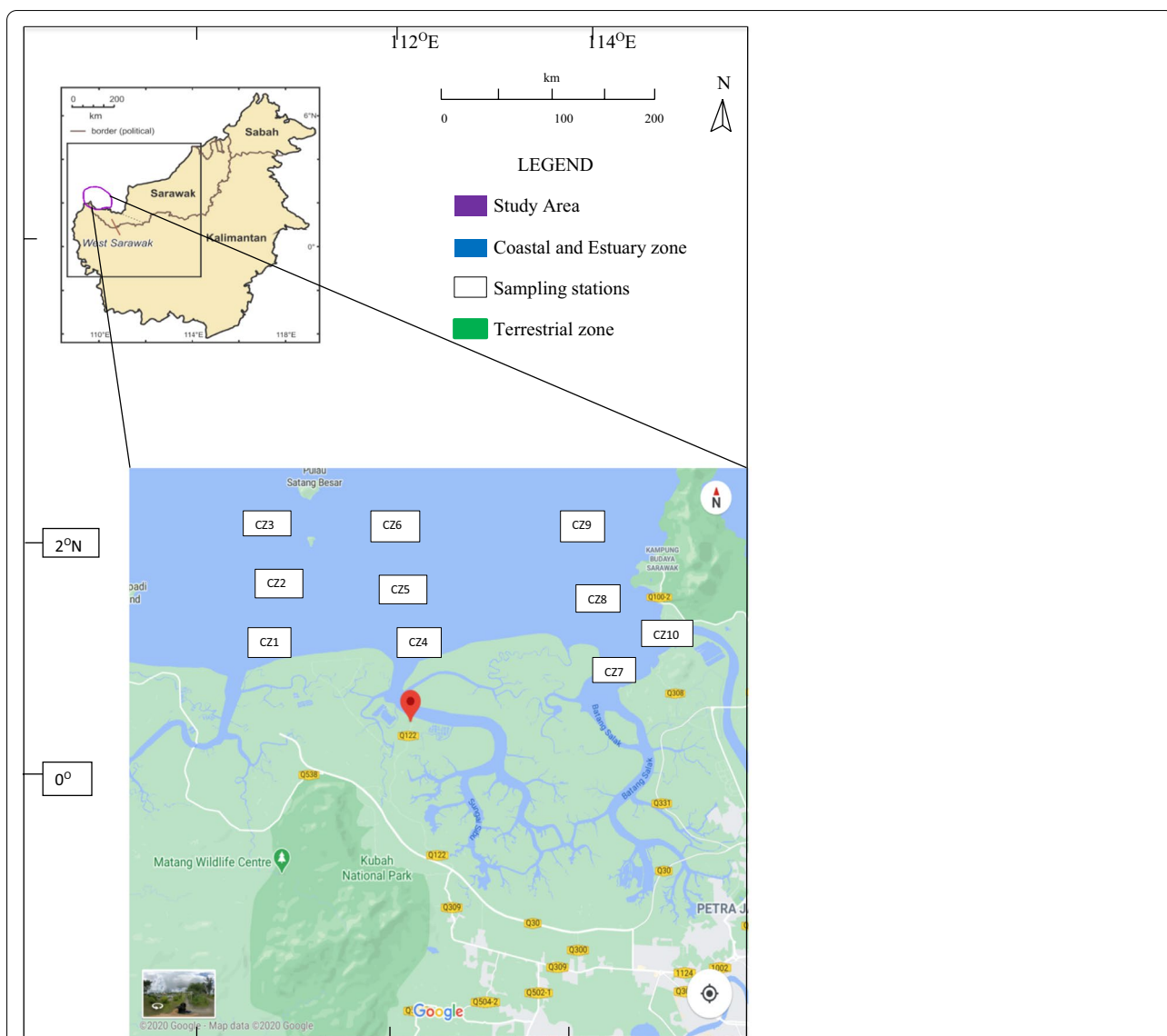
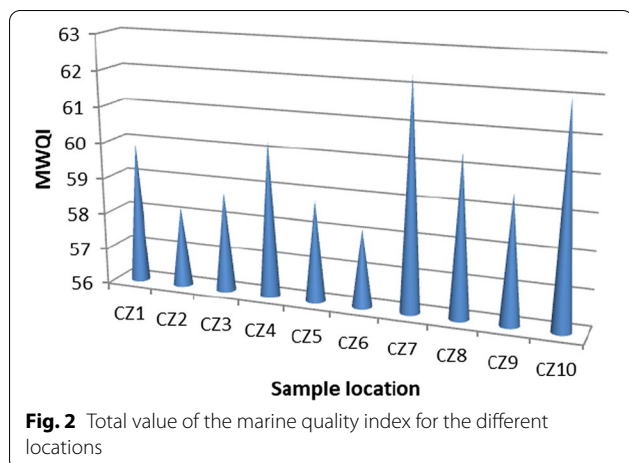


Fig. 1 depicts the study area and sampling stations of the coastal and selected estuaries in Sarawak

The salinity values varied between 0.32 and 34.36 ppt. Estuaries sites reported the lowest salinity values while; coastal sites recorded the highest value. Also, the results obtained in this research were within the acceptable allowable limit by the international water quality standard index (WHO UNESCO//UNEP 2001). The results of dissolved oxygen analyzed from the samples varied between 3.93 and 9.81 mg/L. The maximum value was recorded at coastal station CZ9; while, estuary station CZ4 recorded the minimum value (Table 5). The results obtained are within international acceptable levels of water quality standards (WHO UNESCO//UNEP 2001). The concentration of dissolved oxygen observed in all the stations is sufficient for the

survival of planktons and to do several physiological activities (Rosli et al. 2010; Al-Badaii et al. 2013). Generally, because of diffusion from the atmosphere and aquatic plant photosynthesis, oxygen dissolved in surface waters. Aquatic bodies become unhealthy when there is too much dissolved oxygen too. Extremely high concentrations of dissolved oxygen generally result from photosynthesis by an abundance of plants. Fertilizer runoff is a contributing factor that results in great uncontrolled plant growth, especially algal blooms on the aquatic ecosystem. The total suspended solids values (TSS) ranged from 6.6 to 19.1 mg/L. Coastal station CZ5 recorded the maximum value (i.e. 19.1 mg/L), and a minimum value was observed at the estuary sampling



station CZ7 (Table 5). The total suspended solids values were within the international standard allowable levels. The presence of extreme anthropogenic activities along the course and runoff are the reasons for high TSS concentration (WHO UNESCO//UNEP 2001). The smell of float solids (FS) from all the stations is pleasant except station CZ4 which is unpleasant and this may be attributed to enough surface organic matter decomposition deposited near the estuary banks. The values fecal coliforms bacteria counted varied from 4.2 to 19.0 CfU/100 mL. The highest CF counts were found in samples collected from the coastal sites and this may be attributed to yards carry animal wastes to the coast through storm sewers. Birds can be a significant source of fecal coliform bacteria. Generally, high level of coliform counts normally suggests unsanitary condition.

The concentration of nitrate oscillates between 2.4 and 88.1 $\mu\text{g/L}$ (Table 5). The coastal sites recorded the highest values of nitrates while the estuary stations recorded the lowest content of nitrate. The primary cause of flowing waters with nitrate is due to urban waste discharge and that is the reason why the marine and estuarine water quality is changing from good to moderate status according to the Malaysian marine water quality index. Nitrate and phosphate status are high in coastal stations, unlike ammonia which was found to be high in estuary stations. Contamination of the coastal and estuarine by nitrate, phosphate, and ammonia may be attributed to the introduction of intensive farming practices, with increased application of inorganic fertilizers.

Total chromium concentration analyzed ranged from 0.9 to 9.4 $\mu\text{g/L}$. The chromium levels in estuary water samples detected were lower than the coastal sites water samples. Chromium (IV) occurs naturally in the ecosystem from erosion of natural chromium deposits but it can also be produced by natural processes. Chromium

can be released to the environment by leakage, poor storage, or inadequate industrial waste disposal practices.

About fuzzy comprehensive technique, grey clustering method, and Thailand water classification system, the marine water quality of Rambungan estuary with location code CZ1 and coastal zone with location code CZ2 is non-polluted and can be used for coral reef conservation based on marine water quality standards (Table 6). The water quality of the coastal location with code CZ3, and CZ5, and Santubong estuary with location code CZ10 are very clean and can reserve for natural resource conservation. Besides, the marine water quality of the Sibul estuary with location code CZ4 is between non-polluted and allowable value unlike the marine water quality of location CZ8 which lies between very clean and non-polluted zones. In this case, the location can be used for coral conservation or aquaculture. Furthermore, the marine water quality of the coastal location CZ6 belongs to allowable value but the coastal location CZ9 and the estuary of Salak with location code CZ7 are slightly polluted. Therefore, fuzzy comprehensive evaluation draws attention to the associating membership of individual factors in the marine quality standard. Instead, it throws back the total marine water quality conditions of a location and also discloses the degree of contamination of an individual factor. According to (Han and Yang 2000; Zhang 2014), the degree of membership owns to the various fuzzy data which controls the dissimilarities between marine water index grade standards in various locations and this can be largely used to differentiate marine water quality among kinds of zones, districts, and regional areas. Nevertheless, the marine water quality of locations CZ4 and CZ8 are not certain with a fuzzy comprehensive assessment, which shows that the method has lost some information. For that matter, the applicable method to overcome this defect is the grey clustering technique. The result from the grey clustering technique shows that the marine water quality for location CZ4 is Class III (i.e. allowable pollute value) whereas that of location CZ8 is unpolluted (i.e. Class II). Following the Malaysian Marine Water Quality Index (see Table 7 and Fig. 2), the water quality computed of the sampling stations ranged from 58.16 to 62.0 indicating that the coastal and estuary waters of the studied locations were of moderate quality. This shows that the coastal and the estuaries can be used for tourism, recreation, industrial water supply, ports, and navigation.

Conclusion

The water quality of the coastal and the selected estuaries vary depending on the location of the sampling stations. All the marine water parameters analyzed were in the normal range of Interim Class E1. The combination of fuzzy comprehensive evaluation and grey

clustering method helped to conquer the issue of water index classes' standards that leads to a lack of comparability between various coastal areas owing to different classes' standards. The above evaluation combination also helped to retrieve the useful information which was lost. Based on a fuzzy comprehensive evaluation, grey clustering method, and Thailand water classification system and index, most of the coastal water qualities of the selected locations were clean and within allowable value while the coastal location CZ9 and the estuary of Salak River proved slight pollution. This may be due to anthropogenic activities such as boat activities, fishing, agricultural activities, and domestic sewage going around the area. It is then suggested that advanced agricultural production and measures should be employed to reduce pollution caused by fertilizer and pesticides. According to MMWQI and its classification system, it was observed that the water qualities in all the areas studied were moderate and can be used for many purposes such as recreation, and natural resource conservation.

Abbreviations

DO: Dissolved oxygen; TSS: Total suspended solids; FC: Fecal coliform; FS: Float solids; MMWQSI: Malaysian marine water quality standard index.

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Authors' contributions

EAA, ZBA, and RBW conceived of the study and carried out the design of the experiment. EAA and ZBA carried out the sample preparation and analysis, EAA, RBT, and EKD assessed the data, and EAA, ZBA, and RBW helped to draft and edit the manuscript. All the author(s) read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this paper.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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