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A New Water Quality Index for Environmental Contamination Contributed by Mineral Processing: A Case Study of Amang (Tin Tailing) Processing Activity

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Abstract: A Water Quality Index (WQI) is a mean to summarize large amount of water quality data into simple terms (e.g., good or bad, clean or contaminated) for reporting to authorities management and the public in a consistent manner. Few water quality index systems have been developed and none are widespread use. Available indices are either highly specialized (e.g., those applicable only to lakes) or very simple in terms of the numbers of variables considered. None seem to be geared to the protection of multiple water uses or to encompass the variety of measurements of water quality. Current WQIs provide indications of the quality of water influenced by domestic and some general industrial effluents. Unfortunately they were not formulated to quantify the quality of water impacted by mining. This study looked at the suitability of using current WQIs to describe water quality contributed by mining activities and in specific tin mining and amang (tin tailing) processing. An amended and new WQI was introduced integrating parameters relevant to such activities. A vast field measurements including physical, chemical and radionuclides analysis were carried out. A questionnaire survey was also carried out to facilitate the selection and integration of the best and appropriate water quality parameters. In this particular study, Water Quality Index (WQI) was calculated by summing up of nine individual quality parameters i.e., pH, NO_3^-, radionuclides, dissolved oxygen, PO_4^{3-}, heavy metals, electrical conductivity, SO_4^{2-} and suspended solid.

Key words: Water quality index, mining, tin tailing

INTRODUCTION

Water quality index, in common with many other indices systems, relates to a group of water quality parameters to a common scale and combines them into single number in accordance with a chosen method or model of computation. WQI is desired to provide assessment of water quality trends for management purposes even though it is not meant especially as an absolute measure of the degree of pollution or the actual water quality (Anonymous, 1997b).

Water quality indices were first seriously proposed and demonstrated beginning in the 1970s but were not widely utilized or accepted by agencies that monitor water quality (Cude, 2003). According to Nives (1999) WQI is a mathematical instrument used to transform large quantities of water quality data into a single number which represents the water quality level while eliminating the subjective assessments of water quality and biases of individual water quality experts. The common denominator for all water quality indices is the basic principle that a quality index must synthesize data such as analytical results by means of a simple quality vector. This method makes the information more easily and rapidly interpretable than a list of numerical values. Consequently, a water quality index is a communication tool for transmitting information. The users of this information can range anywhere from being closely associated to being distantly connected to the resource (for instance, general public, users, scientists, managers, lawmakers, engineers etc.).

Traditional reports on water quality typically consist of complex variable-by variable and water body-by-water body statistical summaries. This type of information is of value to water quality experts, but may not be meaningful to people who want to know about the state of their local water bodies. Political decision-makers, non-technical water managers and the general public usually have neither the time nor the training to study and understand a traditional, technical review of water quality data. They require concise information about those water bodies. The index also allows water quality data to be compiled and reported in a consistent manner.

A number of indices have been developed to summarize water quality data in an easily expressible and easily understood format (Couillard and Lefebvre, 1985). Horton (1965) proposed the first Water Quality Index (WQI), a great deal of consideration has been given to the development of index methods. The basic differences among these indices are the way their sub-indices were

developed. Walski and Parker (1974) used an exponential function to represents the sub indices of various quality variables. Landwehr (1979) suggested the Pearson type 3-distribution function to represents the sub indices of all the quality variables. Bhargava (1987) modified the exponential formula; Dinius (1987) used power function for the majority of sub indices. Nives (1999), Swamee and Tyagi (2000)) proposed aggregate index for water quality description. In addition Harrison *et al.* (2000), Faisal *et al.* (2003), Ahmed *et al.* (2004) and Shiow-Mey *et al.* (2004), each have recently modified a water quality index.

Some of the sub indices have since been incorporated into water quality indices used by agencies such as the National Sanitation Foundation (NSF) (Ahmad *et al.*, 2004). The most important WQIs belonging to environmental departments or agencies are the National Sanitation Foundation (NSF), British Colombia Water Act Quality Index, Oregon Water quality Index, Stream Watch (Southern Indiana), Malaysian Water Quality Index, France Water Quality Index, French Creek quality index, Florida Stream water Quality index, British Colombia Water Quality Index, Canadian Water Quality index, Taiwan Water Quality index and Washington State Water Quality index.

Comparison among several WQI systems currently in use showed that none of them describes quality of water from mining effluent because most of sub indices in current WQIs are not relevant to indicating changes in water quality brought about by mining activities.

It is important to remember that, prior to this study no significant water quality information (using mining index) was available for mining or tin by product activities. This survey provides the first WQI applicable to describe the quality of water as a consequence of mining and related activities.

MATERIALS AND METHODS

Thirty three water samples were taken from seven amang (tin tailing) processing plants located in the state of Selangor and Perak, Malaysia. The amang plants comprise of three employing the open and close (natural and man made) management systems. In open water management system the water used in the processing of tin tailing is drawn from a river and the effluent from the plant is discharged directly into the same river. In the close water management system the water is recycled. All water samples were collected and analyzed in accordance with procedures outlined (Anonymous, 1997a).

Elemental analyses were carried out using ICP-MS and ICP-OES. Radionuclides activity concentration were determined using multi channel analysis integrated to a Hyper Pure Ge-Li detector. Expert input via questionnaire survey was employed to facilitate selection of parameters to be used in WQI. In this respect, a survey form was prepared and was sent to 95 scientists who are experts in water and wastewater treatment around the world. The survey asked respondent the expert opinion to help formulate possible new sub-indices for measuring WQI specific measuring water quality as a consequent to mining and mineral processing. Respondents are requested to select and ranked water quality parameters listed that they consider critical and should be included in the equation to calculate this WQI.

Proposal of a new WQI: The main objective of this study was to propose a new water quality index applicable to mining effluent. Generally, there are five basic steps involved in the development of most water quality indices. These include:

- Selecting the set of water quality variables (parameters) of concern.
- Aggregation or designing framework of formula.
- Weighting the indicators based on their relative importance to overall water quality.
- Developing rating curves for comparing indicators on a common scale.
- Computing the overall water quality index

RESULTS AND DISCUSSION

Selecting the set of water quality variables: Variables of concern to water quality should be selected from several commonly recognized impairment categories including health aspect, physical and chemical characteristics. In each WQI, these selected parameters could be varying. In this study, a wide measurement of parameters in whole water samples such as physical, chemical and environmental parameters (including heavy metals and radionuclides) were carried out. Table 1 showed that the important parameters in amang processing effluent water samples (based on chemical reactions and physical interactions in amang processing) were pH, PO_4^{3-}, NO_3^-, electrical conductivity, total solid, solid suspended, total dissolved solid, dissolved oxygen, SiO_2, radionuclides (U-238 and Th-232), some elements (Na, Mg, K, Ca, Al) and some heavy metals (Mn, Fe, Ni, Cu, Zn, As, Se, Cd, Pb).

Table 2 ranked the 10 most preferred parameters perceived by respondents to be important in calculating water quality index. Table showed that the most important environmental parameter or indicator is pH (38 points).

Table 1: Comparisons between average water quality parameters of sampled water and INWQS/Canadian and USEPA standards

Parameters	Average±SD	Standards
pH	3.440±1.00	5-9 (Class IV)* 6.5-8.5 (drinking water)**
EC (μs cm^{-1})	736.900±385.0	700 (Drinking water)** 1000 (Agriculture) **
TDS (mg L^{-1})	308.590±187.85	500 (Class I)*
Susp solid (mg L^{-1})	18.400±49.7	25 (Class I)* 50 (Class II)*
PO_4^{3-} (mg L^{-1})	11.510±8.95	0.1 (class III)*-
Turbidity (FTU)	33.310±61.40	>50 (class III)*
Solid total (mg L^{-1})	517.730±430.86	>1000 (class IIB)*-
SiO_2 (mg L^{-1})	7.690±4.57	Class IIA/IIB*
DO (mg L^{-1})	4.980±0.63	3-5 (Class III)*
SO_4^{2-} (mg L^{-1})	309.670±272.98	200 (Classical)* 500 (drinking water)**
Total iron (mg L^{-1})	4.360±4.15	1.0 (Class IV)* 0.3 (Drinking and Agriculture)**
NO_3^- (mg L^{-1})	3.860±1.84	10 (drinking and Agriculture)**
^{238}U (Bq L^{-1})	53.550±3.45	0.37***
^{232}Th (Bq L^{-1})	1.510±0.24	3.4***
Cd (mg L^{-1})	0.003±0.008 ppm	0.005 Drinking water** 0.005 Agriculture **
Pb (mg L^{-1})	0.843±0.250 ppm	0.01 Drinking water ** 0.2 Agriculture **
As (mg L^{-1})	0.076±0.025 ppm	0.025 Drinking water ** 0.1 Agriculture **
Ni (mg L^{-1})	0.047±0.013 ppm	0.2 Drinking water** 0.02 Agriculture **
Mn (mg L^{-1})	5.617±0.805 ppm	0.05 Drinking water ** 0.2 Agriculture**
Total Fe (mg L^{-1})	16.248±4.045 ppm	0.3 Drinking water** 5.0 Agriculture***

*: Interim National Water Quality index (INWQS)-Malaysia, **: Canadian standard; ***: United State Environmental Protection Agency (USEPA)

Table 2: Selected parameters and points scored based on respondents preference

Parameters	Points scored
pH	38
NO_3^-	28
Radionuclides (^{238}U and ^{232}Th)	26
Dissolved oxygen	24
PO_4^{3-}	23
Heavy metals (Cd, Pb, As, Hg, Ni, Mn, Fe)	23
Electrical conductivity	18
SO_4^{2-}	17
Solid suspended	16
TDS	13

The other nine parameters were NO_3^- (28 points), radionuclides ^{238}U and ^{232}Th (26 points), DO (24 points), PO_4^{3-} (23 points), heavy metals (23 points), Electrical Conductivity (18 points), SO_4^{2-} (17 points), Suspended Solid (16 points) and Total Dissolved Solid (13 points).

A WQI should be made up of sub indices of parameters that could explain the quality of water comprehensively. Redundancy should be avoided. The survey showed that both Total Dissolved Solids (TDS) and electrical conductivity were selected in the top 10 preferred parameters. Since there is apparent and direct relationship between total dissolved solid and electrical conductivity which was ranked 6th and 10th, respectively it was decided that electrical conductivity was preferred over TDS to be included in the WQI calculation.

Aggregation or designing skeleton of formula: The new WQI proposed is in accordance to Nives (1999). The WQI was calculated by summing up individual quality rating (q_i) and weighting these parameters in total quality evaluation (w_i) as shown in Eq. 1.

$$WQI = \sum_{i=1}^{i=n} q_i w_i \quad (1)$$

Where:

q_i = Water quality score of parameter i.
w_i = Weighting factor of parameter.
i and n = No. of parameters.

Based on nine selected parameters the new WQI proposed is as shown in Eq. 2.

$$WQI = A\,(SI\ pH) + B\,(SI\ NO_3^-) + C\,(SI\ Radionuclides) + D\,(SI\ DO) + E\,(SI\ PO_4^{3-}) + F\,(SI\ Heavy\ metals) + G\,(SI\ Electrical\ conductivity) + H\,(SI\ SO_4^{2-}) + I\,(SI\ Solid\ Suspended) \quad (2)$$

Where, A, B, C, D, E, F, G, H and I are weighting factors for the respective sub indices. These weighting factors shall indicate the importance of the related sub indices toward the overall WQI.

The Sub Index (SI) of each parameter is obtained from related rating curves or equations. The main advantage of a rating carve is that it rapidly transformed the concentration or quotient of a parameter into a quality score i.e., Sub-Index (SI). Axes in rating curve consist of X and Y axes, representing concentration or quotient of the parameter tested and corresponding SI, respectively.

Sub index for radionuclides: For radionuclides, r(average) is calculated using Eq. 3:

$$r(average) = \frac{\sum_{i=1}^{i=n} r_i}{n} \quad (3)$$

Where, $\Sigma[r_i]$ is the summation of r_i and r_i is the activity concentration quotient of radionuclide i, while n is the number of radionuclides considered in the calculation.

$$r_i = \frac{C_i}{C_s} \quad (4)$$

Where:
C_i = Concentration of radionuclide i in sample
C_s = Maximum Permissible Activity Concentration of radionuclide i.

The Maximum Permissible Activity Concentrations of radionuclides are provided in the National Water Quality Standard.

Due to the toxicity of radionuclides, a limit for r_i is introduced. SI for radionuclides becomes zero if any one radionuclide quotient,

$$r_i = \frac{C_i}{C_s} \geq 1 \cdot$$

In such a case, the SI for radionuclides equal zero. The SI for corresponding r(average) is obtained from Fig. 5.

Sub index for heavy metals: Similar mathematical approach to that in deriving the SI of radionuclide is used for heavy metals. Again for heavy metals h(average) can be calculated according to formula Eq. 5:

$$h(\text{average}) = \frac{\sum_{i=1}^{i=n} h_i}{n} \quad (5)$$

Where:
Σh_i = The summation of h_i.
h_i = The concentration quotient of element i.
n = The number of elements considered.

$$h_i = \frac{C_i}{C_s} \quad (6)$$

Where:
C_i = The concentration of element i (heavy metal) in sample and
C_s = Maximum permissible concentration of element i (According to Water Quality Standard)

The national authority shall determine selection for the number of heavy metals to be considered in the calculation of SI. However, as a result of toxicity of heavy metals, there is a limitation where the SI (heavy metals) shall be forced to become zero. It is zero, if and only if at least one of the quotients of concentrations (h_i) is equal or more than 1. In other word SI for heavy metals, equals to zero when the concentration of at least one heavy metals in the water sample is larger than its maximum permissible concentration, i.e.,

$$\text{If } h_i = \frac{C_i}{C_s} \geq 1, \text{ then SI for heavy metals} = 0$$

The SI for corresponding h(average) is obtained from Fig. 6.

Weighting factors for SI: Weighting factors indicate the importance of each test parameters towards the overall water quality. In the case of the new WQI, the weighting factors for pH, nitrates, radionuclides, dissolved oxygen, phosphates, heavy metals, electrical conductivity, sulphates and suspended solids are A, B, C, D, E, F, G, H and I, respectively (Eq. 2). Weighting factors for A-I were calculated based on the frequency of respondents that selected each test parameters (Table 2) and then weighting factors were normalized. The calculated frequency (in fraction) for each test parameters is integrated into equation 2 to produce a new WQI (Eq. 7).

$$\text{WQI} = 0.18\ (\text{SI pH}) + 0.13(\text{SI } NO_3^-) + 0.12(\text{SI Radionuclides}) + 0.11\ (\text{SI DO}) + 0.11\ (\text{SI } PO_4^{3-}) + 0.11\ (\text{SI Heavy metals}) + 0.08\ (\text{SI Electrical conductivity}) + 0.08\ (\text{SI } SO_4^{2-}) + 0.08\ (\text{SI Solid Suspended}) \quad (7)$$

Developing rating curves for SIS: This step involves the transformation of all test parameters to an equal and dimensionless scale. This is generally accomplished using rating curve, where each test parameter concentrations or quotients are mapped against a dimensionless measure such as relative water quality value or SI.

Rating curves has to be developed for all test parameters. These rating curves have been developed using existing rating curves, or from secondary data and in consultations with experts in the field of water quality. The rating curves for pH, dissolved oxygen, nitrate and phosphate were taken directly from the curves developed by National Sanitation Foundation (NSF). The rating curve for radionuclides, heavy metals and also for sulfate and electrical conductivity were developed and designed through reviewing of literatures on the relationships between water quality and known concentrations of elements. In addition, Maximum Permissible Value (MPV) and Maximum Permissible Standards (MPS) information belonging to United State Environmental Protection Agency (USEPA, 2002), classification of water prescribed by the Department of Environmental of Malaysia (Anonymous, 1998) and Canadian quality standards (Faisal, 2003) were considered in the development of the rating curves. Table 3 shows list of drinking water contaminants according to USEPA, DOE Malaysia and Canadian quality standards. Rating curves developed for use with the proposed WQI are as shown in Fig. 1-9.

Table 3: List of water quality standards

Parameters	MCLG* (USEPA)	MCL** (USEPA)	DOE Malaysia (class IV)-	Canadian Quality
	----------	----------	(mg L^{-1})	----------
Cd	0.005	0.005	0.01	0.005 drinking 0.00002 aquatic 0.005 agriculture
Pb	0	0.015	5.00	0.01 drinking 0.001 aquatic 0.2 agriculture
As	0	0.010	0.10	0.025 drinking 0.005 aquatic 0.1 agriculture
Hg	0.002	0.002	0.002	0.0001 drinking 0.0001 aquatic 0.003 agriculture
Ni	-	0.100 (PMFA)	0.200	0.2 drinking 0.025 aquatic 0.02 agriculture
Mn	-	0.050***	5.000	0.05 drinking 0.1 aquatic 0.2 agriculture
Total Fe	-	0.300***	1.000	0.3 drinking 0.3 aquatic 5.0 agriculture
SO_4^{2-}			250 (IIA/IIB)	500 drinking NA aquatic 1000 agriculture
Solid suspended			300 (class IV), 150 (class III) 50 (class IIA/ IIB) 25 (class I)	
E.C			1000 µs cm^{-1} (class I, IIA) 6000 µs cm^{-1} (class IV)	700 Drinking NA Aquatic NA Agriculture
^{238}U	0	0.37 Bq L^{-1}	-	-
^{232}Th	0	3.40 Bq L^{-1}	-	-

*: MCLG: Maximum contamination level goal- The level of the contaminant in drinking water below which there is no known or expected risk to health. **: MCL: Maximum contamination level- The highest level of a contaminant that is allowed in drinking water. ***: According to US Environmental Protection Agency there is no value (amount) in National Primary Drinking water Regulation and these values are belonging to National Secondary Drinking Water Regulations

As mentioned earlier, case of this study is related to effluent from amang (tin tailing) processing activity. In this case seven heavy metals are recommended and considered in calculating sub index for heavy metals. These heavy metals are Cd, Pb, As, Hg, Ni, Mn and Fe. Selection of these heavy metals is related to high concentration of these elements in amang effluent and their high toxicity.

Similarly uranium-238 and thorium-232 were considered as the most important radionuclides because of their high concentrations in amang and its effluent. In addition amang processing has been shown to enhance these naturally occurring radionuclides (Ismail *et al.*, 2003).

The Canadian water quality standard was used for calculating ratio (r_i). Canadian water quality standards was used because their MPLs were very close to standard values belonging to USEPA (2002) and are lower than the values used by the DOE, Malaysia. It should also be mentioned that based on the Canadian standard, the high quality of water or the best class of water belongs to those use for drinking water followed by aquatic uses and finally agriculture uses. In this study agriculture values (lowest class) belonging to Canadian water quality standards were used as maximum permissible value for heavy metals and calculating concentration ratio (Table 4).

SI for WQI parameters may be determined using related rating curves or using related fit Equation(s).

SI for pH: In accordance with Fig. 1 and reference to WQI of the DOE-Malaysia, The SI for pH is estimated as follows:

$$SI\ pH = 0 \text{ If } pH \leq 2.0 \quad (8)$$

$$SI\ pH = 0 \text{ If } pH \geq 12.0 \quad (9)$$

$$SI\ pH = 17.2 - 17.2\,X + 5.02\,X^2 \text{ If } X \leq 5.5 \quad (10)$$

$$SI\ pH = -248 + 95.5\,X - 6.67\,X^2 \text{ If } 5.5 < X \leq 7 \quad (11)$$

$$SI\ pH = -181 + 82.4\,X - 6.05\,X^2 \text{ If } 7 < X \leq 8.75 \quad (12)$$

Table 4: Maximum permissible levels (MPLs) used in this study for the development of sub index and WQI

Parameters	MPL (mg L^{-1})	Based on
Cd	0.005 (Agriculture use)	Canadian standard
Pb	0.2 (Agriculture use)	Canadian standard
As	0.1 (Agriculture use)	Canadian standard
Hg	0.003 (Agriculture use)	Canadian standard
Ni	0.02 (Agriculture use)	Canadian standard
Mn	0.2 (Agriculture use)	Canadian standard
Total Fe	5.0 (Agriculture use)	Canadian standard
SO_4^{2-}	500 (Drinking use)	1000 (Agriculture use) Canadian standard
Suspended solid	25 (class I) 150 (class III)	DOE-Malaysia
E.C	700 µs cm^{-1} (Drinking use) 6000 µs cm^{-1} (class IV)	Canadian standard DOE-Malaysia
^{238}U	0.37 Bq L^{-1}	USEPA
^{232}Th	3.4 Bq L^{-1}	USEPA

$$SI\ pH = 536 - 77.0X + 2.76\ X^2 \text{ If } X \geq 8.75 \quad (13)$$

If 2 < pH < 12 then above equations may be substituted with a single best fit equation of the rating curves (Fig. 1) as follows:

$$SI\ pH = -0.0185\ X^6 + 0.8068\ X^5 - 13.695\ X^4 + 113.96\ X^3 - 482.71\ X^2 + 987.12\ X - 759.41 \quad (14)$$

Where, X is pH.

SI for NO_3^-: SI for NO_3^- may be determined using rating curve shown in Fig. 2 or using a best fit equation of the rating curve as shown in Eq. 15:

$$SI\ NO_3^- = 3E\text{-}06\ X^4 - 0.0009\ X^3 + 0.0908\ X^2 - 4.2812\ X + 91.769 \text{ If } X \leq 100.0 \quad (15)$$

$$SI\ NO_3^- = 2 \text{ If } X > 100.0 \quad (16)$$

Where, X is concentration of NO_3^- (mg L^{-1})

SI for DO: SI for Dissolve Oxygen (DO) may be calculated using the best fit equation for the estimation of sub-index value for dissolved oxygen as proposed by DOE-Malaysia:

$$SI\ DO = 0 \text{ If } X \leq 8 \quad (17)$$

$$SI\ DO = 100 \text{ If } X \geq 92 \quad (18)$$

$$SI\ DO = -0.395 + 0.030\ X^2 - 0.00020\ X^3 \text{ If } 8 < X < 92 \quad (19)$$

$$SI\ DO = 0 \text{ If } X > 140.0 \quad (20)$$

Where, X is dissolved oxygen. (% saturation)
SI for DO may also be calculated using the best fit equation for the rating curve shown in Fig. 3 (Eq. 21).

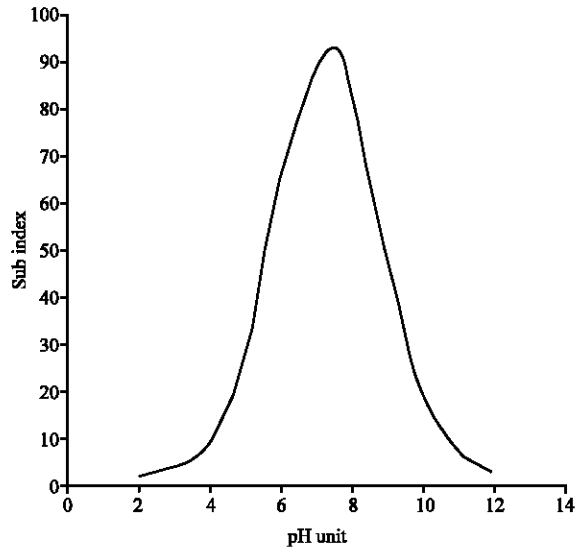

Fig. 1: pH rating curve

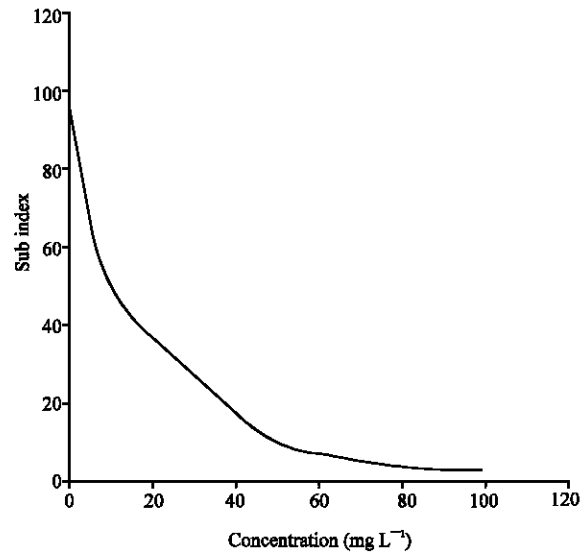

Fig. 2: Nitrate rating curve

$$SI\ DO = 1E\text{-}06\ X^4 - 0.0004\ X^3 + 0.048\ X^2 - 0.6916\ X + 6.8854 \quad (21)$$

Where, X is dissolved oxygen (% saturation)

SI for PO_4^{3-}: The best-fit equations (Eq. 22 and 23) for the estimation of sub index value for phosphate are derived from the curve shown in Fig. 4.

$$SI\ P\text{-}PO_4^{3-} = 0.047\ X^4 - 1.338\ X^3 + 13.276\ X^2 - 55.247\ X + 94.434 \text{ If } X \leq 10 \quad (22)$$

$$SI\ P\text{-}PO_4^{3-} = 2 \text{ If } X > 10 \quad (23)$$

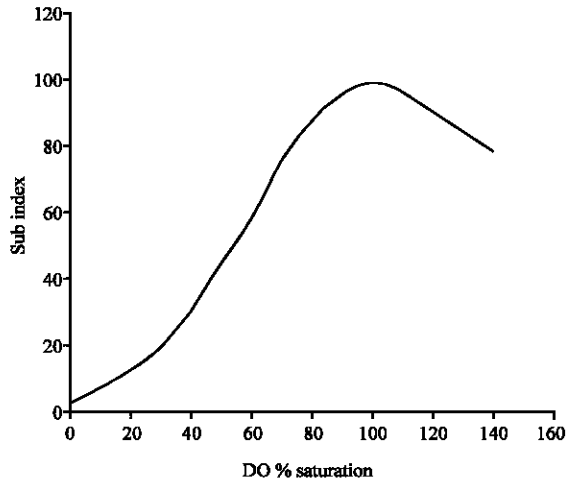

Fig. 3: DO rating curve

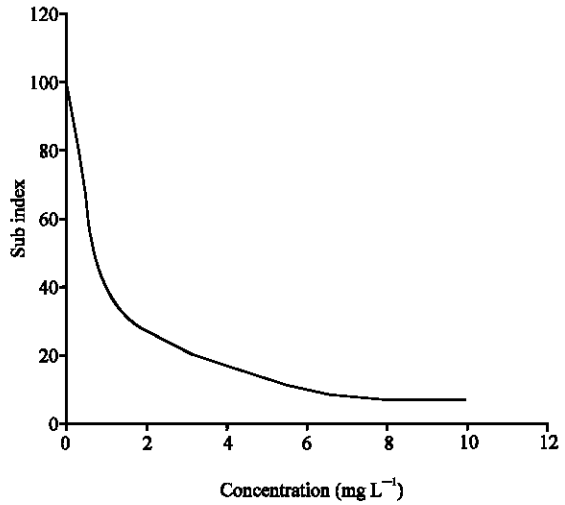

Fig. 4: Total phosphate rating curve

Where, X is concentrations of PO_4^{3-} (mg L^{-1})

Direct estimation of SI for may also be made directly from the rating curve shown in Fig. 4.

SI radionuclides: SI for radionuclides is estimated using Fig. 5, or estimated using the best-fit Eq. 24 and 25. SI for radionuclides is estimated based on activity concentration quotients (r_i). The use of activity concentration quotients (r_i) for radionuclides allow the use of 1 rating curve for all radionuclides. This is made possible because the determination of SI is based on relative concentrations of measured values and those of permissible concentrations as prescribed in the national water quality standards. Examples of some of these maximum permissible values are shown in Table 3. Equation 24 is for estimating SI

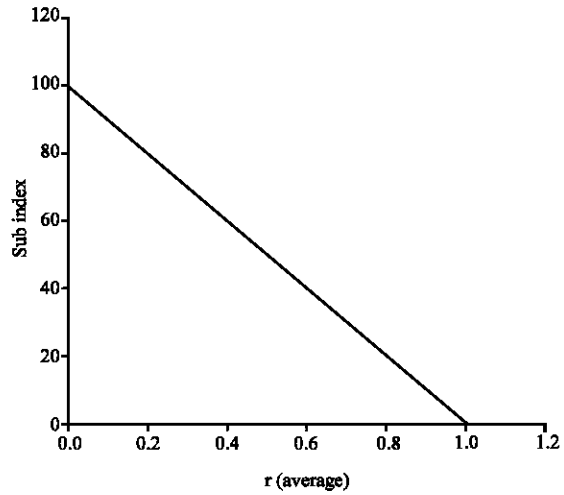

Fig. 5: Radionuclides rating curve

radionuclides when r(average) is less or equal to one, equation 25 is for estimating SI radionuclides when (r_i) is greater than one.

A linear inverse relationship is proposed for SI and r_i. Such relationship is preferred over up or down bending curves, because an up bending curve may not be economical to implement, while down bending curve allows for unnecessary underestimation of risk (Fig. 5).

$$\text{SI Radionuclides} = -100\,X + 100 \text{ If } X < 1 \quad (24)$$

$$\text{SI Radionuclides} = 0 \text{ If } X \geq 1 \quad (25)$$

Where, X is r(average).

SI for heavy metals: Similar to calculating SI for radionuclides, SI for heavy metals is estimated based on concentration quotients h_i. Similar to the rationale used in determining SI for radionuclides, the use of concentration quotients for heavy metals allow the use of one rating curve for all heavy metals. Equation 26 is for estimating SI heavy metals when h(average) is less than one. Equation 27 is used for estimating SI for heavy metals when h(average) is equal or greater than one (Fig. 6).

Similar argument in using an inverse linear relationship between SI and h_i, over up and down bending curve for radionuclides applies for heavy metals (Fig. 6). SI for heavy metal may also be estimated using a best-fit equation derived from Fig. 6 (Eq. 26).

$$\text{SI heavy metals} = -100\,X + 100 \text{ If } X < 1 \quad (26)$$

$$\text{SI heavy metals} = 0 \text{ If } X \geq 1 \quad (27)$$

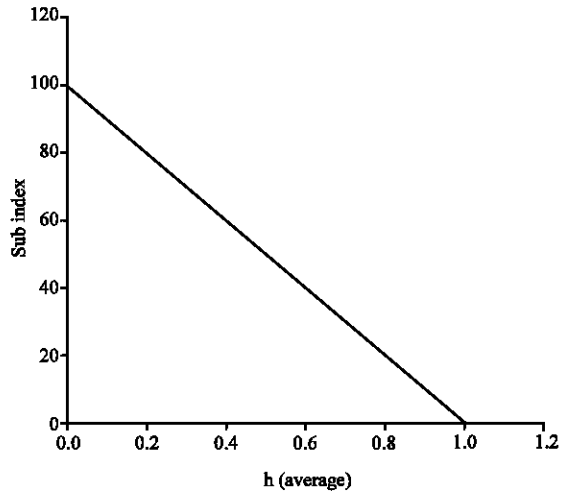

Fig. 6: Heavy metals rating curve

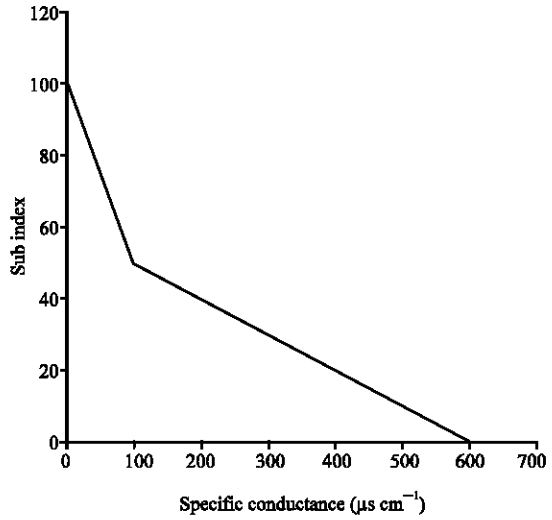

Fig. 7: Electrical conductivity rating curve

Where, X is h(average).

SI for electrical conductivity: This rating curve was developed according to standard values derived from both the Canadian and Malaysian water quality standards since their standards complement each other. According to Canadian water quality index maximum permissible level of electrical conductivity for drinking water is 700 µs cm^{-1} and according to DOE Malaysia, maximum permissible level of electrical conductivity in class IV (lowest quality) is 6000 µs cm^{-1}. The interpretation of Fig. 7 is that, when the electrical conductivity rises to 700 µs cm^{-1} (max permissible level for drinking water), the SI conductivity comes down to 50 and when the electrical conductivity rises to 6000 µs cm^{-1} (max permissible in class IV), the SI conductivity comes down to zero.

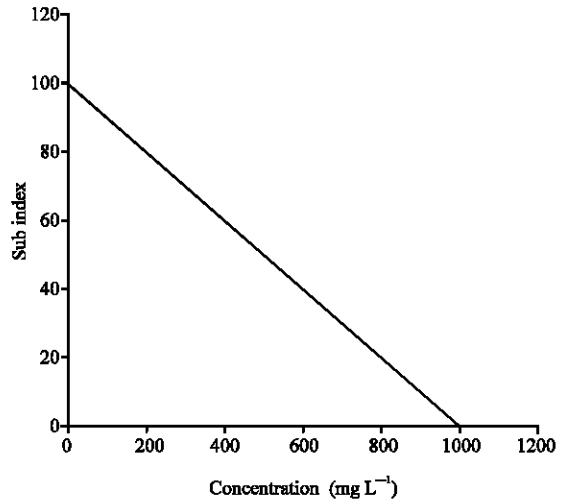

Fig. 8: Sulfate rating curve

The best-fit equations for estimating SI for electrical conductivity are as shown in Eq. 28 and 29.

$$\text{SI conductivity} = -0.0714\,X + 100 \text{ If } X \leq 700 \quad (28)$$

$$\text{SI conductivity} = -0.00943\,X + 56.60 \text{ If } 700 < X \leq 6000 \quad (29)$$

$$\text{SI conductivity} = 0 \text{ If } X > 6000 \quad (30)$$

Where, X is electrical conductivity (µs cm^{-1}).

SI for sulfate: This rating curve was developed based on values drawn from the Canadian and Malaysian water quality standards. Best-fit equation for this rating curve is as shown in Eq. 31. When concentration of sulfate is zero, SI sulfate becomes 100 and when concentration of sulfate rises to 500 mg L^{-1} (maximum permissible value in drinking water according to Canadian standard) SI Sulfate becomes 50 and when concentration of sulfate rises to 1000 mg L^{-1} (maximum permissible value in agriculture uses, according to Canadian standard), SI sulfate becomes zero. An inverse linear relationship between SI and sulfate concentration is proposed to avoid under and over estimation in determining SI for sulfate (Fig. 8).

In accordance with Fig. 8, the best fit Equation for the estimation of sub index value for sulfate is:

$$\text{SI Sulfate} = -0.1\,X + 100 \text{ If } X < 1000 \quad (31)$$

$$\text{SI Sulfate} = 0 \text{ If } X \geq 1000 \quad (32)$$

Where, X is concentration of sulfate (mg L^{-1}).

SI for suspended solid: Rating curve for suspended solid was developed based on the Malaysian Interim National Water Quality Standards. The Standards proposed two levels of suspended solid according to the classification of water, i.e., 20 and 150 mg L^{-1} for Class I and III, respectively. As such three equations are proposed in calculating SI for suspended solids. Equation 33 is for estimating SI for suspended solid concentration <20 mg L^{-1}, Eq. 34 is for estimating SI for suspended solid concentrations between for 20 and 150 mg L^{-1}. SI equals zero if the concentration of suspended solids is greater than 150 mg L^{-1}.

According to Fig. 9, the best-fit equations for the estimation of sub index value for suspended solid are:

$$\text{SI suspended solid} = 100 \text{ If } X < 20 \quad (33)$$

$$\text{SI suspended solid} = -0.77\,X + 115.3 \text{ If } 20 \le X \le 150 \quad (34)$$

$$\text{SI suspended solid} = 0 \text{ If } X > 150 \quad (35)$$

Where, X is concentration of suspended solid (mg L^{-1}).

Application of new WQI to existing data collected: The new WQI was tested using data collected from amang effluent. Result from one station (Table 5) was used to illustrate this. A score of 31.81 classifies the water as very polluted (Table 6).

In this study Malaysian water quality rating scale was employed for classification of water. There are three rating scales (clean, slightly polluted and very polluted) and five water classes (Table 6).

It is important to remember that, prior to this study no specific water quality index to assess the quality of water as a consequence of mining activities. Furthermore, no attempt to study the comparative water quality of large numbers of water samples in amang industries has previously been made. Ahmed *et al.* (2004) proposed a water quality index. However this water quality index cannot be used to indicate contamination from trace metals, organic contaminants, or other toxic substances. Shiow *et al.* (2004) also has proposed a new water quality index but this index mainly focuses on the organic pollution caused by the municipal and agriculture activities. Amang water contains heavy metals and radionuclides which is not only chemically toxic but also posed a radiological risk.

As mentioned earlier, each WQIs has strength and weakness. For example, the current Malaysian Water Quality Index (WQI) is acceptably defined by integrating six sub indices, i.e., dissolved oxygen, pH, BOD, COD, ammoniacal nitrogen and total suspended solid. Unfortunately such definitions of water quality have been loosely used to describe all types of water independent of whether it is domestic or mining effluent. The Malaysian WQI is not appropriate to describes water quality as a consequence of mining, because the sub indices used in manipulating the overall WQI are only applicable to domestic or mostly related to organic wastewater but is not for mining effluent. Parameters such as COD, BOD and Ammoniacal Nitrogen (AN) are neither momentous

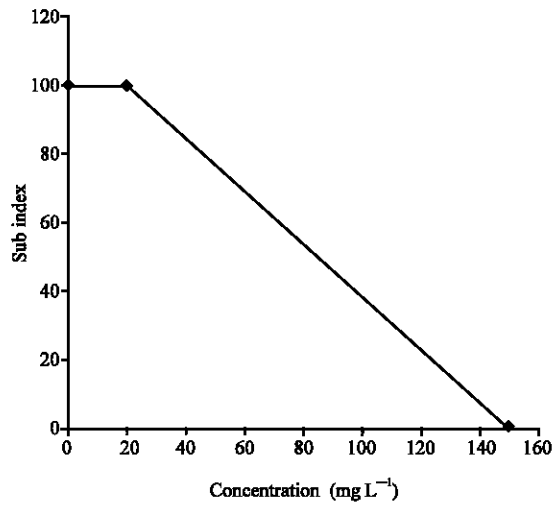

Fig. 9: Suspended solid rating curve

Table 5: Computing the overall water quality index based on the new Equation*

Environmental tests	Result field measurement	Sub index value	Weighting factor	Weighted sub Index
pH	2.98	4.0	0.18	0.72
NO_3^- (mg L^{-1})	3.99	70.0	0.13	9.10
Radionuclides	r(average) = 0	0.0	0.12	0.00
Dissolved oxygen (mg L^{-1})	6.4	87.0	0.11	9.57
PO_4^{3-} (mg L^{-1})	21.8	2.0	0.11	0.22
Heavy metals	h(average) = 0	0.0	0.11	0.00
E conductivity (μs cm^{-1})	960	47.5	0.08	3.80
SO_4^{2-} (mg L^{-1})	950	5.0	0.08	0.40
Solid suspended (mg L^{-1})	17	100.0	0.08	8.00
			Overall WQI	31.81

*: WQI =0.18 (SI pH) +0.13 (SI NO_3^-) +0.12 (SI radionuclides) +0.11 (SI DO) + 0.11 (SI PO_4^{3-}) +0.11 (SI heavy metals) + 0.08 (SI electrical conductivity) + 0.08 (SI SO_4^{2-}) + 0.08 (SI solid suspended); **: Refer to related tables

Table 6: Water quality index classifications

Quality	Range	Class
Clean	80-100	90-100 Class I
		80-90 Class II
Slightly polluted	60-80	50-80 Class III
Very polluted	0-60	40-50 Class IV
		0-40 Class V

Source: Anonymous (1997)

nor relevant in describing changes in the quality of water brought about by mining effluent. The Malaysian water quality index, uses higher constant values of SI not relevant to mining effluent (e.g., BOD, COD and AN) that masked the contribution of changes in SISS and SIpH towards the overall WQI. Current WQIs, also do not take into consideration contribution from inorganic materials and naturally occurring radionuclides present in mining. A review of more than 20 WQIs revealed that not one of these WQIs formulas can illustrate accurate water quality index related to tin mining and amang processing activities.

Some WQIs, for example the Oregon Water Quality (OWQI) comes with limitations in using its index. The OWQI aids in the assessment of water quality for general recreational uses (i.e., fishing and swimming). The OWQI cannot determine the quality of water for specific uses, nor can it be used to provide definitive information about water quality without considering all appropriate chemical, biological and physical data. The OWQI was designed for Oregon's streams and its applications to other geographic regions or water body types should be approached with caution (Cude, 2003).

The introduction of a new water quality index especially for mining provides a fairer assessment of water quality brought about by mining circumstances (i.e., mining and by product processing activities).

CONCLUSIONS

Water quality classes are useful for summarizing information in order to obtain regional and national perspective. Data collected from current study have shown that the current WQIs used to gauge water quality are not appropriate for use to determine the quality of water related to amang processing. This is because the sub indices used in calculating the overall WQI is more applicable for domestic effluent but not for mining effluent. For instance, in current WQIs parameters such as DO, COD, BOD and Ammoniacal Nitrogen (AN) were not significantly affected in amang processing activities. Consequently even though, the water quality was affected in terms of its pH and total suspended solid, the overall quality of water as measured using the current WQI was not affected.

In this study a wide parameters or environmental tests have been tested including physical, chemical, organic and inorganic materials, heavy metals and radionuclides in the process of proposing an appropriate water quality index in mining and especially in amang activities. Finally an amended WQI was introduced integrating parameters relevant to such activities. Nine commonly water quality indicators provide adequate coverage of traditional impairment categories. Water bodies adjacent to amang industries can be effectively summarized using proposed new WQI.

The new proposed WQI has some advantages over other WQIs. The most important advantage of this water quality index is utilizing of relevant and sufficient variables for identifying quality of water from amang processing plants. This index contains nine variables similar in number to those used by NSF quality index. This index gives results very similar to those calculated using NSF. In addition, the newly proposed WQI took greater emphasis on the contributions of heavy metals and radionuclides.

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