PHYSICO-CHEMICAL WATER QUALITY INDICES - A COMPARATIVE REVIEW -

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ABSTRACT
Water quality assessment can be defined as the evaluation of the physical, chemical and biological nature of water in relation to natural quality, human effects and intended uses. Water Quality Indices (WQIs) and Water Pollution Indices (WPIs) reduce a great amount of parameters to a simpler expression, to enable easier interpretation of the monitoring data. Main Difference between WQIs and WPIs included the form how they evaluate the processes of pollution and the number of variables taken in account in each formulation.

In this context, this paper displays a comparative study of 36 (thirty-six) WQIs and WPIs, on the basis of mathematical structure, similarity parameters and behavior given the same set of data. The results indicate that appreciable differences exist between classifications given by different indices on the same water sample. Differing parameter numbers, calculations and aggregation formulas can explain this. Thus, it was possible to establish that the WPIs developed in Colombia by Ramirez et. al. (1997) and the AMOEBA strategy, developed by de Zwart (1995) in The Netherlands, displays great advantages over traditional formulations, because the different kinds the pollution are segregated better.

KEYWORDS
Water Quality Indices, Pollution Indices, Water Pollution, and Water Quality Assessment.

INTRODUCTION
A water quality index basically consists of a simpler expression of more or less complex parameters, which serve as water quality measurements. A number, a range, a verbal description, a symbol or a color could be used to represent the index.

Historically, different organizations of several nationalities involved in water resources control have used a regular form of Physico-Chemical indices for water quality assessment. This has been more evident in the last decade of the 20th Century. In that decade the

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application of water quality indices was given important acceptance, which is made evident at the present time by an appreciable number of formulated indices in different countries around the world, from general to specific purposes. These indices have been the product of efforts and research development from governmental agencies in different strata, as well as from masters' and doctorate research.

According to Cude (2001), the revisions of water quality indices have constituted a continuing interest, as the different studies demonstrate; these studies have shown new approaches, at the same time providing new tools for the development of other indices (Dinius, 1978; Kung et al., 1992; Dojlido et al., 1994). Among the first prominent comparisons of water quality indices were Landwehr & Deininger (1976), followed by Ott (1978), who revised water quality indices used in the USA, besides publishing a detailed discussion about the practices and theories of environmental indices. In Europe contributions have come from van Helmond and Breukel (1997), who demonstrated that at least 30 (thirty) water quality indices are of common use around the world. They have from 3 to 72 variables, with the frequent inclusion of at least 3 (three) of the following parameters DO, BOD and/or COD, NH4-N, PO4-P, NO3-N, pH and Total Solids. In the same way in Croatia, Stambuk-Giljanovc (1999) observed that through the years, several water quality indices have been formulated, each one with its own purpose. Other studies, such as Cooper et al (1994) and Richardson (1997), in South Africa and Australia respectively, have been occupied in for generating indices for estuaries. In Central America the developments of Montoya (1997) and León (1998) are evident.

In Colombia according to The National Water Study (IDEAM, 2000), the measurements of physical and chemical parameters are an ordinary activity. However, the calculation of water quality indices is not, in spite of recommendations through legislation and of Ramirez et al (1997) formulations' development, being applied regularly in the oil industry. In other industries and environmental organizations, only some autonomous regional corporations in Santafé de Bogotá, Barranquilla, Bucaramanga, Cali and Manizales are applying North American formulas, especially the NSF index, in their monitoring programs.

Therefore, the current research is generated to contribute in a direct way to improving the knowledge on this subject, especially in Colombia, where these kinds of contributions could fill a avoid. Thus, this paper carries out a review of the more important indices used in water quality assessment, which are available in articles, agencies and web sites, and has the objective of displaying updated information about indices composition and structure, and realizing a comparative and evaluative analysis among these indices.

METHODOLOGY

The basic methodology consisted of an extensive review of different kinds of formulations of water quality indices that have been used in several countries. Once they had been compiled, the indices were evaluated by composition of parameters and mathematical structure; this was a multivariate classification analysis carried out with the Sorensen-Dice Similarity Index (Dice, 1945;Sorensen, 1948).

With the purpose of facilitating the simpler calculation of indices and their comparisons, the ICATEST v1.0 software was developed (Fernández, et al, 2003). In this software the indices were introduced, on original curves values, regression equations and final aggregation formulas. From curves and values algorithmic solutions were adapted. In this way ICATEST v1.0 could compare the 22 (twenty-two) indices using the same set of data, with the objective of observing the performance of each one in water quality assessment.

RESULTS AND DISCUSION

General Procedure to Calculate Elements of Water Quality Indices

The common factor of the analyzed indices is in its calculated structure, based principally on the following 3 steps:

(I) Parameter Selection. This is carried out by professional judgment of experts, agencies or governmental institutions that are determined in the legislative area. With this in mind, Dunnette (1979) recommends selecting the variables from the 5 categories most ordinarily recognized as: (1) oxygen level, (2) eutrophication, (3) health aspects, (4) physical characteristics and (5) dissolved substances.

(II) Determination of Quality Function (curve) for Each Parameter, understood as The Sub-index. Subindices transform to non-dimensional scaled values from the variables of its different units (ppm, saturation percentage, counts/volume, etc).

(III) Sub-indices Aggregation with Mathematical Expression. This is frequently utilized through arithmetic or geometric averages.

Water Quality Indices and Pollution Indices Composition

From the analyses of 36 indices, it appears that they have 35 common parameters of which, the most common and frequent in half of the cases is the dissolved oxygen (15 indices). DO is combined regularly with total solids (in 12), pH (in 11), fecal coliforms (in 11) BOD (in 11), total phosphorous and phosphates (in 11), nitrates (in 10). Previous variables are common to one-third part of the indices. Turbidity (in 9), temperature (in 8) and ammonia (in 8) are of similar importance.

As it can be seen, one index could have variables from different ecological processes such as: reduction-oxidization or mineralization. On the other hand pH is the most important expression of the carbon - carbonate system, because measurements of alkalinity and hardness are not frequent although important.

The selection of parameters for early water quality indices was more focused on the effect of the organic pollution than the effect on the water quality of other processes with the same or more importance. This focus could be supported on the basis of the kind of point-source pollution existing in the 60s and 70s in developed countries, and the subsequent evolution of pollution control. Currently, it is possible to observe how index development has been considered because of other pollutants, such as detergents and agrochemical pollution, and the effects of these and other factors on biological diversity and species composition; plus the effect they have on bio-ecological processes like organism production and respiration.

In addition, between indices taken in account in this study, an interesting case is the British Columbia Water Quality Index (BCWQI) that considerer a large amount of variables, because this index work on a combination of three factors: (1) the number of variables whose objectives are not met (Scope); (2) the frequency with which the objectives are not met (Frequency) and (3) the amount by which the objectives are not met (Amplitude). In this way, BCWQI is using to assess water quality relative to its desirable state (as defined by British Columbia Surface Water Quality Objectives) and to provide an insight into the degree to which water quality is affected by human use (BCWQI, 1996).

Similarity Analysis Between Indices' Composition

Figure 1 shows the classification dendrogram for part of the indices taken into account this study.

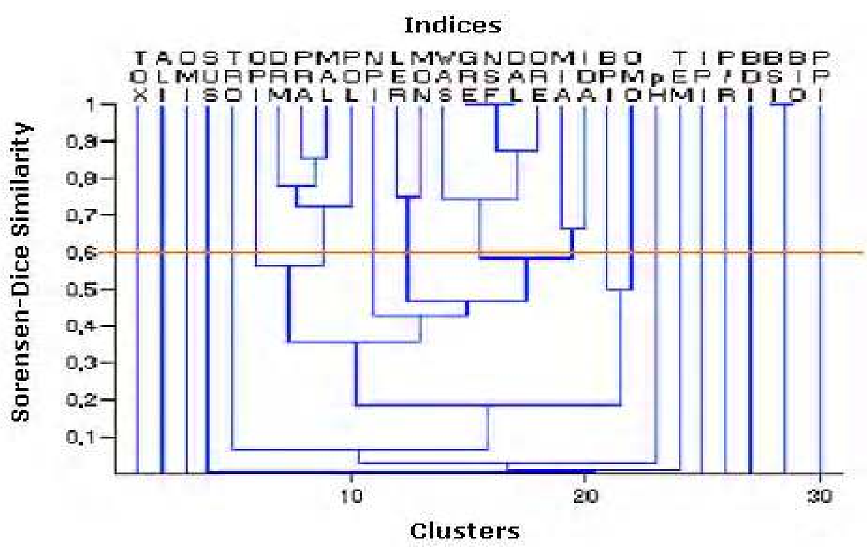

Figure 1. WQIs Dendrogram Clusters by Sorensen-Dice Index

According to this it is possible to observe that there is an association group, conformed by the following sub groups, which are listed from high to low similarity.

Group A: Greensboro (Brown, et al. 1970;Landwehr, 1974), NSF (Brown, et al. 1970) and Dalmatia (Stambuk-Giljanovc, 1999) (100% identical), with Oregon-OWQI (Cude, 1999) (87%), linked with Washington-WQI (Hallock, 1990) (75%). This group is linked with Miami Valley Index (WEP, 1996) and Idaho-WQI (Said, et al. 2002) around 58% of similarity; variables prominent are representative of organic matter decomposition.

Group B: León (León, 1998) Index and Montoya (Montoya, 1997) Index with 75% of similarity. Both Mexican indices have between 15 and 18 variables and classify the water with the same use.

Group C: Prati (Prati, 1971) and Malaysia (85%), with DRM (Kahler-Royer, 1999) (78%), linked to index used in Poland (Raczynska, et al. 2000) on 72% of similarity. The next subgroup linked the Organic Pollution Index (OPI) from AMOEBA (de Zwart, 1995) strategy around 58%; its association is due to BOD, COD and Ammonia. DO, pH and Solids link this last group with the groups A and B.

Other groups don't have significant similarities. This demonstrates that they are composed of very different parameters. There is BPI (D. de Zwart, op. cit) with ICOMO (Ramirez and Viña, 1999) (49%), which are linked by 18% similarity with afore-mentioned groups.

As for dissimilar indices from left to right there are: ICOTOX, ICOALIs (Pollution Indices that included Aliphatic and Aromatic Hydrocarbons), ICOMI, ICOSUS and ICOTRO, ICOPH, ICOTEMP all proposed by Ramirez (1997, 1999), IPI, P/R, BDI, BSI, ICOBIO and PPI, as well as those proposed by de Zwart in the AMOEBA strategy (de Zwart, op. cit). This demonstrates that in both proposals the indices are complementary, because they segregate similar kinds of pollution; while it was observed as a whole in general water quality evaluation strategies. These indices allow the study of particular problems and avoid that problem that certain environmental pollution variables remain hidden by other variables.

Table 1. Number of Parameters, Structure and Aggregation Formula in the Indices

Table 1 lists the 36 indices taken into account and they are presented in a comparative form with the number of variables, its structure and its aggregation formula.

As it can be seen in this table, there are several methods for calculating a WQI (Quality) or a WPI (Pollution), as well as the evidence of the preference for calculating a central tendency measure (average). In this aspect, highlighting the House (1989) study, which carried out a revision of different formulations for sub-indices aggregation, it concluded that the weighted arithmetic average (Stojda & Dojlido, 1983) and the

Table 1. Number of Parameters, Structure and Aggregation Formula in the Indices

Comparative Structure of Each Index

Index	Parameters Number	Structure	Aggregation Formula	Index	Parameters Number	Structure	Aggregation Formula
Water Quality Indices (WQIs)				Organic Pollution Index (OPI)	5	Diagrams	Weighted average modified
Bacterial Pollution Index (BPI)	1	Diagram	Direct Reading	Oregon (OWQI)	8	Equations	Unweighted Harmonic Square Mean
Benthic Saprobity Index (BSI)	At least 30	Table	Percentage average	Pesticide Pollution Index (PPI)	2 to 7	Diagrams	Weighted average modified
Biological Diversity Index (BDI)	Indeterminate	Table	Proportion	Poland	6	Formula	Square of harmonic average
British Columbia	Up to 47	Formulas	Harmonic Square sum	Prati	8 to 13	Formula	Unweighted average
Dalmatia	9	Formulas	Proportion of Weighted Sum	Production Respiration Index	2 to 3	Diagram	Direct Reading
Dinius (1987)	12	Equations	Weighted geometrical average	Washington	8	Equation	Quadratic Equation
DRM	7	Diagrams	Weighted average	**Water Pollution Indices (WPI)**			
Greensboro	9	Diagrams	Unweighted Multiplicative	ICOMI (Mineralization)	3	Equations	Arithmetic average
Idaho	5	Equation	Logarithmic proportion	ICOMO (Organic Matter)	3	Equations	Arithmetic average
Leó n (1998)	15	Formulas	Weighted geometrical average	ICOSUS (Suspended Solids)	1	Diagram and Equation	Direct Reading
Industrial Pollution Index (IPI)	5 a 14	Diagrams	Weighted average modified	ICOTRO (Trophic State)	1		Direct Reading
Malaysia	6	Equations	Weighted average	ICOTEMP (Temperature)	1	Diagram and Equation	Direct Reading
Montoya (1997)	17	Equations	Weighted average	ICO-pH (pH)	1	Diagram and Equation	Direct Reading
Miami River Index	7	Table	Sum	ICOTOX (Toxicity)	1 Toxic per time	Equations	Equation
Nutrient Pollution Index (NPI)	9	Diagrams	Weighted average modified	ICOBIO (Biological)	Indeterminates	Equations	Equation
NSF	9	Diagrams	Weighted geometrical average	ICOs for Hydrocarbons (5 Indices**)	1 for each index	Equation	Equation

modified weighted sum (Couillard & Lefebvre, 1985) provided the best results for the indexation of the general water quality. In the same way, the weighted geometrical average has been widely used, especially where there is a great variability among samples. Also, when the samples have great variability or when it is important to considerer low values, it is better to use the harmonic mean or its square (Cude, 2001). The latter is the most sensible method in a data set with low values, because these take more weight than those with high values.

Currently, with the advent of the personal computer more powerful algorithms (or formulations) are available to the individual researcher. This lead to improved characterization of water quality by index (Cude; pers. com, 2003). These utilities can be incorporated for the analyses to more recent formulations (e.g. OWQI in Cude 2001; Ramirez et al., 1997,1999) that show work on the basis of equations for fit curves, from regression of each of the variables.

Comparison From The Same Set of Data

For comparative effects Table 2 was generated showing the maximum permissible values for drinking water (Colombian Health Ministry, Decret 475 of 1985) and wastewater that could be treated for the water supply (Colombian Health Ministry, Decret 1594 of 1984) in Colombia, lacking data to be obtained from international legislation for the same uses.

Table 2. Parameters Based on The Indices Comparison
*Lethal Concentration for 50% of the organism at toxicity test in 96 hours

Parameter	Drinking Water	Wastewater	Parameter	Drinking Water	Wastewater
Alkalinity (mg/L)	95	500	HCH dissolved (ug/L)	0,01	3500
Ammonia's (mg/L)	0,04	1	HCH in Sediments (ug/L)	0,0095	3000
Bacteria's Thermo-Tolerant (MPN/100ml)	1	2000	Nitrates (mg/L)	9,5	18
Chlorophyll a (mg/L)	10	120	Nitrites + Nitrates (mg/L)	9,51	24
Chloride (mg/L)	245	250	Nitrates +Ammonia (mg/L)	9,54	19
Fecal Coliforms (MPN/100ml)	0	2000	Nitrogen Total (mg/L)	9,55	25
Total Coliforms (MPN/100ml)	1	20000	Oxygen Dissolved (mg/L)	7	2
Color (Units Pt-Co)	14	75	pH (Units)	6,8	9
Conductivity (micromhos/cm)	125	400	Oxygen Production (mg/L)	2	1
Chrome dissolved (mg/L)	0,0095	0,05	Mean Temperature (ºC)	20	30
Chrome in Sediments (mg/L)	0,0097	0,052	Oxygen Respiration (mg/L)	3	5
BOD (mg/L)	0,2	30	Saturation DO %	80	28
Temperature Difference (ºC)	2	11	Solids Suspended (mg/L)	120	650
COD (mg/L)	1	30	Solids Totals (mg/L)	280	730
Hardness (mg/L)	155	250	Air Temperature (ºC)	26	37
Phenols (mg/L)	0,001	0,002	Water Temperature (ºC)	25	35
Phosphates (mg/L)	0,095	0,2	Turbidity (NTU)	4,5	10
Total Phosphorous (mg/L)	0,17	0,5	Hg LC50* (ug/L)	49	25

Table 3. Results From NSF index and Similars
* Scale Color assigned for comparative effects

	Drinking Water			Wastewater		
INDEX	**Value**	**Classification**	**Color Scale**	**Value**	**Classification**	**Color Scale**
INSF	85.17	Good		33.16	Bad	
DRM	60.17	Average		21.39	Very Bad	
OWQI	24.98	Very Poor		10.67	Very Poor	
DINIUS	76.78	Polluted	*	41.30	Strongly Polluted	*
LEON	82.29	Acceptable		44.42	Strongly Polluted	
IDAHO (0-3)	1.768	Average	*	0.627	Poor	*

As it can be seen in Table 3, in spite of similarities among their parameters the classification from each index differs, especially in the evaluation for drinking water that have low quality. This contrasts with the evaluation of wastewaters, where values of indices and their classifications are closer. Here again it is important to remember the final aggregation formula, because it has a great influence on the final value and it could obtain a different evaluation. Also, the difference can be due to the specificity that these indices have in accordance with the geographic region where was generated, as well as for their ranges of classification of water quality.

The Ramirez et al (1997, 2000) group shows how the level of phosphorous is the cause of eutrophication (ICOTRO). Also, average toxicity is due to Hg LC50 level (ICOTOX). The values of drinking water in an individual way are in a good state with respect to Mineralization (ICOMI), Organic Matter (ICOMO), Suspended Solids (ICOSUS), Temperature (ICOTEMP), pH (ICOPH), and Diversity of Species (ICOBIO). But, wastewater has a high Pollution level in the majority of processes. In this way, it is well to know how the nature of these indices are more objective and consistent; furthermore, their scale represents the information from water quality variables better. This confirms the advantages that these indices have: by segregating the kinds of pollution by this process, it allows a good visualization of the different problems in a water system.

Table 4. Results from RAMÍREZ et al. (1997, 1999) Scale 0 (Excelent) – 1(Very High Pollution)

	Drinking Water			Wastewater		
Index	**Value**	**Pollution**	**Color Scale**	**Value**	**Pollution**	**Color Scale**
ICOMI	0.330	Low		1	Very High	
ICOMO	0.067	Nothing		0.704	High	
ICOSUS	0.340	Low		1	Very High	
ICOTEMP	0.00	Nothing		0.833	Very High	
ICOPH	0.030	Nothing		1	Very High	
ICOBIO	0.040	Nothing		0.57	Average	
ICOTOX	0.549	Average		0.837	Very Toxic	
ICOTRO	N.A.	Eutrophic		N.A	Hypereutrophic	

Table 5. Results from AMOEBA Strategy

Index	Drinking Water	Action Recommended	Objective Value	Wastewater	Action Recommended
BPI	99.80	Nothing	90	0	Industrial Processes Revision
NPI	42.43	Effluents Treatment	70	20.39	Tertiary Treatment
OPI	57.84	Effluents Treatment	70	3.81	Industrial Processes Revision
IPI	17.41	Industrial Processes Revision	70	7.11	Industrial Processes Revision
BSI	66.70	Nothing	60-80	3.80	Wastewater Treatment
BDI	0.847	N.A.	N.A.	3.106	N.A
PRI	70.50	Nothing	70	10.00	Effluents Treatment

AMOEBA methodology (de Zwart, 1995) applied to the Ramírez (1997, 1999) indices system, allows a desegregated evaluation of water quality. However, its application shows that for Drinking Water there is a medium to low pollution level, with relation to the objective value in nutrients (NPI), organic pollution (OPI) and industrial pollution due to chrome (IPI). The exceptions are in Bacteria (BPI), biological diversity (BSI) and Oxygen Production/Respiration (PRI). In the wastewater sample the evaluation displays very low levels. This situation is coincident with the other indices and with the general trends. It is important to emphasize that the final aggregation formula has 1/n weight factor and uses natural logarithms that make low values sensible. In the majority of cases this situation is a real advantage for the analysis of pollution.

Summary and Conclusions

It is well known that the main limitation of the several indices studied is that they have been designed as a tool for general water quality evaluation. This means while they summarize the original data, assessment of all physical-chemical and biological parameters should be considered. In this way, these indices give little information. On the other hand these indices can show the spatial and temporal variations and its trends by means of an easy interpretation of wide environmental categories. Then, these could be and should be filtered and validated with more details by means of direct observation of the original data and parameters. Used in this form, assessment of water resource management programs and attempts by interested parties to establish priorities for management purposes are possible.

The Pollution Indices of Ramirez and de Zwart (AMOEBA) are a more current concept which have evolved from the general water quality indices with a focus on segregating categories of pollutants. They show those advantages in comparison to traditional indices.

Also, the British Columbia Index (BCI) is an interesting case to be considered, because of the integration of three factors, these factors are taken in account on the data and their relation to the objectives. With this concept focusing on the objectives, the agents must worry more in improving the environmental conditions. This fact has been show in similar way by the AMOEBA strategy that advises about the possible actions for control of the different kinds of pollution for each index.

Finally, it is recognized that it is difficult to define a unique water quality index with a definitive solution. It is admissible that both biological and physical-chemical evaluations are necessary. However each institution, agency or researcher should to try to develop a unique method. At this point it is convenient to take notice of Cude's observation: "In spite of the scores of water quality indices developed in the United States, there is no recognized "US National Water Quality Index". This may be a reflection of the variety of purposes and monitoring programs for with water quality indices have been developed" (Cude, 2002).

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