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WATER QUALITY INDICES

S.A. Abbasi

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Ministry of Water Resources, Govt. of India)

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA

December, 2002

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PREAMBLE

The Indian National Committee on Hydrology is the apex body on hydrology constituted by the Government of India with the responsibility of co-ordinating the various activities concerning hydrology in the country. The Committee is also effectively participating in the activities of UNESCO and is the National Committee for International Hydrological Programme (IHP) of UNESCO. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the committee invites exerts in the country to prepare these reports on important areas of hydrology.

Of all natural resources, water is unarguably the most essential and precious Life began in water, and life is nurtured with water. There are organisms, such as anaerobes, which can survive without oxygen. But no organism can survive for any length of time without water. The crucial role of water as the trigger and sustainer of civilizations has been witnessed throughout the human history. But, until as late as 1960s, the overriding interest in water has been vis-a- vis its quantity. Except in manifestly undesirable situations, the available water was automatically deemed utilizable water. Only during the last three decades of the twentieth century the concern for water quality has been exceedingly felt so that, by now, water quality has aquired as much importance as water quantity.

What is water quality? This question is immensely more complex than the question : What is water quantity ? Water quality indices aim at giving a single value to the water quality of a source on the basis of one or the other system which translates the list of constituents and their concentrations present in a sample into a single value. One can then compare different samples for quality on the basis of the index value of each sample.

Water quality indices may have gained currency during the last 3 decades but the concept in its rudimentary form was first introduced more than 150 years ago-in-1848-in Germany where presence or absence of certain organisms in water was used as indicator of the fitness or otherwise of a water source.

Rather than assigning a numerical value to represent water quality, these classification systems categorized water bodies into one of several pollution classes or levels. By contrast, indices that use a numerical scale to represent gradations in water quality levels are a recent phenomenon, beginning with in 1965.

The Indian National Committee Hydrology with the assistance of its erstwhile Panel on Water Quality, Erosion and Sedimentation, realising the important role of water quality in the overall planning of water resources decided to invite an expert for preparing a report on the status of water quality Indices. The report has been prepared by Dr. S.A. Abbasi, Senior Professor & Director, Centre for Pollution Control and Energy Technology, Pondicherry University, Pondicherry. The guidance, assistance and review provided by the Panel are worth mentioning. The report has been compiled and finalised by Dr. K.K.S. Bhatia, Sc. F & Member Secretary, Indian National Committee on Hydrology.

It is hoped that this state-of-art report would serve as a useful reference material to practising engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilization of the water resources of the country.

(K.S. Ramasastri)
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CHAPTER - I

Introduction : why WQI

1.0 Water quantity and water quality

Of all natural resources, water is unarguably the most essential and precious. Life began in water, and life is nurtured with water. There are organisms, such as anaerobes, which can survive without oxygen. But no organism can survive for any length of time without water.

The crucial role of water as the trigger and sustainer of civilizations has been witnessed throughout the human history. But, uptill as late as 1960s, the overriding interest in water has been vis a vis its quantity. Except in manifestly undersirable situations, the available water was automatically deemed utilizable water. Only during the last three decades of the twentieth century the concern for water *quality* has been exceedingly felt so that, by now, water quality has aquired as much importance as water quantity.

What is water quality? This question is immensely more complex than the question: *What is water quantity?*

We can say: this reservoir contains 2 million m^3 of water or the present flow in this river is 15 $m^3 sec^{-1}$. Expressing water *quantity* is as simple as this.

But how do we express water quality of the same stream? The quality may be good enough for drinking but not suitable for use as a coolant in an industry. It may be good for irrigating some crops but not good for irrigating some other crops. It may be suitable for livestock but not for fish culture. Wheras water *quantity* is determined by a single parameter – the water mass, the quality is a function of anything and everything the water might have picked up during its journey from the clouds to the earth to the water body: in dissolved, colloidal, or suspended form. And, given the fact that water is a 'universal solvent', it can pick up a hell of a lot!

One way to describe the quality of a given water sample is to list out the concentrations of everything that the sample contained. Such a list would be as long as the number of constituents analyzed; and that may be anything from the 20 – odd common constituents to hundreds!

And how to compare the quality of different water sources? It can't be done easily by comparing the list of constituents each sample contained. For example a water sample containing six components in 5% higher-than-permissible (hence objectionable) levels: pH, hardness, chloride, sulphate, iron and sodium may not be as bad for drinking as another sample with just one constituent – mercury – at 5% higher than permissible.

2.0 Water quality indices (WQI)

Water quality indices aim at giving a single value to the water quality of a source on the basis of one or the other system which translates the list of constituents and their concentrations present in a sample into a single value. One can then compare different samples for quality on the basis of the index value of each sample.

2.1 A novel idea?

The concept of using an indices to represent in a single value the status of several variables is not a novel idea; it has been well–entrenched in economics and commerce. We have the well-known 'consumer price index' in which, on the basis of an 'integration' of the prices of certain commodities, a single value is obtained to determine whether the market is, overall, cheaper or costlier at any given instant compared to any other past instant.

The commodities are selected on the basis of their 'driver power'; in other words the 'power' or the 'reach' of the commodity vis a vis influencing the prices of several other commodities. If a shampoo becomes costlier or cheaper it won't significantly effect the prices of other commodities whereas any change in the price of diesel would.

Then we have the Sensex – the share price index of Mumbai's stock exchange. It is also composed of the prices of certain shares of high driver power (such as cement). In time the Sensex has become an index of not merely the stock traded at Dalal Street but almost the index of the Indian economy!

Indices have also been used in ecology to represent species richness, evenness, diversity etc. Accordingly we have the Shannon Index, the Simpson's Index, and so on.

3.0 Back to water quality indices (WQI)

WQI may have gained currency during the last 3 decades but the concept in its rudimentry form was first introduced more than 150 years ago – in 1848 – in Germany where presence or absence of certain organisms in water was used as indicator of the fitness or otherwise of a water source.

Since then various European countries have developed and applied different systems to classify the quality of the waters within their regions. These water classification systems usually of two types:

i) those concerned with the amount of pollution present, and

ii) those concerned with living communities of macroscopic or microscopic organisms.

Rather than assigning a numerical value to represent water quality, these classification systems categorized water bodies into one of several pollution classes or levels. By contrast, indices that use a numerical scale to represent gradations in water quality levels are a recent phenomenon, beginning with Horton's index in 1965, detailed bellow.

4.0 The first modern WQI : Horton's Index

Horton (1965) set for himself the following criteria when developing the first–ever modern WQI:

i) The number of variables to be handled by the index should be limited to avoid making the index unwidely.

ii) The variables should be of significance in most areas.

iii) Only such variables of which reliable data is available, or obtainable, should be included.

Horton selected 10 most commonly measured water quality variables for his index including dissolved orygen (DO), pH, coliforms, specific conductance, alkalinity, and chloride. Specific conductance was intended to serve as an approximate measure of total dissolved solids (TDS), and carbon chloroform extract (CCE) was included to reflect the influence of organic matter. One of the variables, sewage treatment (percentage of population served), was designed to reflect the effectiveness of abatement activities on the premise that chemical and biological measures of quality are of little significance until substantial progress has been made in eliminating discharges of raw sewage. The index weight range from 1 to 4. Notably Horton's index did not include any toxic chemicals.

The index score is obtained with a linear sum aggregation function. The function consists of the weighted sum of the subindices divided by the sum of the weights and multiplied by two coefficients M_1 and M_2, which reflect temperature and obvious pollution, respectively:

$$QI = \frac{\sum_{i=1}^{n} w_i I_i}{\sum_{i=1} w_i} M_1 M_2$$

Horton's index is easy to compute, eventhough the coefficients M_1 and M_2 require some tailoring to fit individual situations. The index structure, its weights, and rating scale are highly subjective as they are based on the judgement of the author and a few of his associates.

Horton's pioneering effort has been followed up by several workers who have striven to develop less and less subjective but more and more sensitive and useful Water quality indices.

5.0 More on the benefits of WQI

The formulation and use of indices has been strongly advocated by agencies responsible for water supply and control of water pollution. Once the water quality data has been collected through sampling and analysis, a need arises to translate it into a form that is easily understood. Once the WQI are developed and applied, they serve as a convenient tools to examine trends, to highlight specific environmental conditions, and to help governmental decision-makers in evaluating the effectiveness of regulatory programme.

WQI, of course, are not the only source of information that is brought to bear on water-related decisions. Many other factors are considered besides indices and the monitoring data on which the indices are based.

Indeed nearly all the purposes for which one monitors water quality – assessment, utilization, treatment, resource allocation, public information, R&D and environmental planning – are all served by indices as well. In addition, indices make the transfer and utilization of water quality data enormously easier and lucid. To wit, water quality indices help in:-

i) Resource allocation

Indices may be applied in water-related decisions to assist managers in allocating funds and determining priorities.

ii) Ranking of allocations

Indices may be applied to assist in comparing water quality at different locations or geographical areas.

iii) Enforcement of standards

Indices may be applied to specific locations to determine the extent to which legislative standards and existing criteria are being met or exceeded.

iv) Trend analysis

Indices may be applied to water quality data at different points in time to determine the changes in the quality (degradation or improvement) which have occurred over the period.

v) Public information

Index score being an easy to understand measure of water quality level, indices can be used to keep the public informed of the overall water quality of any source, or of different alternative sources, on a day-to-day basis just as Sensex score tells in one word whether the stocks, by and large, went up or down.

vi) Scientific research

The inherent quality of an index – which translates a large quantity of data to a single score, is immensely valuable in scientific research For example in determining the efficacy of any ecorestoration or water treatment Strategy on a water body, the impact of developmental activities on water quality, etc.

CHAPTER - II

Approaches to WQI formulation

1.0 Indices for 'water quality' and 'water pollution'

Water quality indices can be formulated in two ways: one in which the index numbers increase with the degree of pollution (increasing scale indices), and the other in which the index numbers decrease with the degree of pollution (decreasing scale indices). One may classify the former as 'water pollution indices' and the latter as water quality indices. But this difference is essentially cosmetic; 'water quality' is a general term of which 'water pollution – which indicates undesirable water quality' – is a special case.

2.0 The common steps

The following four steps are most often associated with the development of any WQI; depending on the sophistication being aimed at, additional steps may also be taken:

1. Parameter selection
2. Transformation of the parameters of different units and dimensions to a common scale
3. Assignment of weightages to all the parameters
4. Aggregation of sub-indices to produce a final index score

Of these, steps 1, 2, and 4 are essential for <u>all</u> indices. Step 3 is <u>also</u> commonly taken through some indices may be formed without this step as well.

As we may see from the following discussion, and from the numerous examples given in the following chapters on of how different WQI have been developed for different needs, it would be clear that a great deal of subjective opinion and judgement is associated with each step, particularly steps 1 and 3. There is no technique or device by which 100% objectivity or accuracy can be achieved in these steps. Even parameter selection through statistical analysis of past data (detailed in Chapter 4), though apparently objective, is fraught with inherent uncertainties and incompleteness.

One can only try to *reduce* subjectivity and inaccuracy by involving large number of experts in collecting opinion, and doing it by well-developed opinion–gathering techniques such as Delphi (Abbasi 1995, Abbasi and Arya 2000).

3.0 Parameter selection

As we have elaborated in Chapter 1, a water sample may have hundreds of constituents including elements in neutral or ionic form (metals, non-metals, metalloids); organics (pesticides, detergents, other organics of industrial or natural origin); anions such as carbonate, bicarbonate, sulphate, nitrate, nitrite etc. It may also have suspended solids which, in turn, consitute a bewildering range of chemicals. It may also have radioactivity, and may have colour and odour. Then it may have pathogenic bacteria, fungi, helminthic cysts etc.

A WQI would become unwieldly if each and every possible constituent is included in the index. Instead, one needs to chose a set of parameters which, together, *reflect* the overall water quality for the given end use. It is here that subjectivity creeps in. Different experts and end users may have different perceptions of the importance of a parameter vis a vis a given end use. For example a medical expert may perceive water carrying a faint odour but otherwise free from harmful constituents as good. In his/her opinion odour may be a parameter of very little significance. But to others even the faintest odour in their drinking water may be totally unacceptable. They will advocate that odour must be included as a key parameter in any WQI dealing with drinking water.

Even the water quality standards, on which much of our decisions on fitness or otherwise of a water source depend, are not common to all countries. Further, as new research brings to light new facts on the beneficial or harmful effects of a constituent, or gives new information on the concentration beyond which a constituent becomes harmful or the concentration below which a constituent *ceases to be helpful*, the standards are continuously revised.

The criteria of 'acceptability' also veries from region to region. In Kerala drinking water containing more than 500 mg / l of total dissolved solids (which is the BIS limit for ideal drinking water) may be considered unfit for drinking because the State – being well-endowed in terms of water resources – may find ample drinking water in an alternative source meeting with the BIS standard. On the other hand people in Rajasthan, rural Tamil Nadu and elsewhere routinely drink water with TDS well above 500 mg / l.

Therefore parameter selection is as fraught with uncertainty and subjectivity as it is crucial to the usefulness of any index. Enormous care, attention, experience, and consensus-gathering skills are required to ensure the most representative parameters for inclusion in a WQI.

In an attempt to reduce the subjectivity in parameter selection, statistical approaches have been attempted, as described in Chapter 4. While in theory such approaches are objective – because they select parameters on the basis of considerations such as frequency of occurrence of different parameters, the number of other parameters to which they seem to correlate etc – they can lead to erroneous results because correlations can occur by sheer chance and need not have a cause-effect link. For example data on chloride may strongly correlate with data on abundance of a fish species but the two may, in reality, have no link whatsoever.

4.0 Transformation of the parameters of different units and dimensions to a common scale: making sub-indices

Different water quality parameters are expressed in different units. For example temperature is expressed in degrees celsius or forenhiet, coliforms in numbers, electrical conductivity in micro-mhos, and most chemicals in milligram per litre (or microgram per ml). Further, the ranges of levels to which different parameters can occur veries greatly from parameter to parameter. For example dissolved oxygen would rarely be beyond the range 0-12 mg/l but sodium can be in the range 0-1000 mg/l or beyond. Toxic elements such as mercury rarely occur above 1 mg/l level whereas acidity/alkalinity, hardness chloride, and sulphate nearly always occurs at levels above 1 mg/l. Yet again, water containing 10 mg/l of chloride is as fit for drinking as water containing fifteen times higher chloride. But a water sample containing 0.001 mg/l of mercury is acceptable while a water with even twice this concentration of mercury isn't.

In other words, different parameters occur in different ranges, are expressed in different units, and have different *behaviour* in terms of concentration–impact relationship. Before an index can be formulated all this has to be transformed into a single scale – usually beginning with zero and ending at 1. Some index scales have the range 0-100. But this, again, makes only a cosmetic difference.

4.1 Developing Sub-indices

Sub-indices, one for each parameter selected for the index, are developed so that different parameters, their units, and the range of concentrations (from highly acceptable to highly unacceptable) are all transformed onto a single scale.

If we consider a set of n pollutant variables denoted as (x_1, x_2, x_3 ------- x_i, x_n), then for each pollutant variable x_i, a subindex Ii is computed using subindex function f_i, (x_i):

$$I_i = F_i(x_i) \qquad \ldots \qquad (1)$$

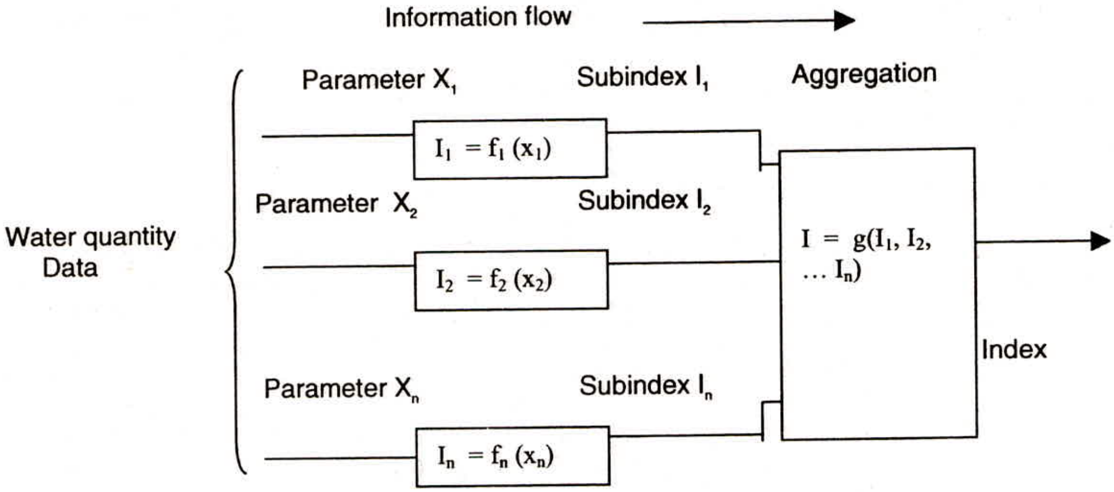
In most indices, different mathematical functions are used to compute different pollutant variables, yielding the subindex functions f_1 (x_1), f_2 (x_2) ------ f_n (x_n). Such functions may consist of simple multiplier, or the pollutant variable raised to a power, or some other functional relationship.

Once the subindices are calculated, they usually are aggregated together in a second mathematical step to form the final index:

$$I = g(I_1, I_2, \text{-----}\ I_n) \qquad \dots \qquad (2)$$

The aggregation function, (2), usually consists either of a summation operation, in which individual subindices are added together, or a multiplication operation, in which a product is formed of some or all the subindices, or some other operation; some of the common aggregation methods are given in Section 6 of this chapter.

The overall process: calculation of subindices and aggregation of subindices to form the index can be illustrated as follows:



4.2 Different types of sub-indices

Subindices can be classified as one of four general types:

i) Linear

ii) Non linear

iii) Segmented linear

iv) Segmented nonlinear

4.2.1 Linear function sub-indices

The simplest subindex function is the linear equation:

$$I = \alpha x + \beta \qquad \ldots \quad (3)$$

Where I = subindex

x = pollutant variable

α, β = constants.

With this function, a direct proportion exists between the subindex and the pollutant variable. The linear indices are simple to compute and easy to understand but have limited flexibility.

4.2.2 Segmented linear function sub-indices

A segmented linear function consists of two or more straight line segments joined at break points (threshold level). It offers more flexibility than linear function and is especially useful for incorporating administratively recommended limits, such as Burean of Indian Standards (BIS) limits, WHO limits etc. One of the important types of segmented linear functions is the step function, which exhibits just two states and therefore is called a dichotomous function. The segmented linear function subindices may also consist of a staircase of steps, giving a multiple-state function. For example, Horton (1965) has used subindex functions containing three, four, and five steps. In Horton's dissolved oxygen subindex, I = 0 for x less than 10% saturation, I = 30 for x between 10% and 30% saturation, and I = 100 for x above 70% saturation.

Mathematically, the general form of segmented linear function can be formulated as follows.

Given that x and I coordinates of the break points are represented by (a_1, b_2), (a_2, b_2), ... (a_j, b_j), any segmented linear function with m segments can be presented by the following general equation:

$$I = \frac{b_{j+1} - b_j}{a_{j+1} - a_j} (x - a_j) + b_j, \ a_j \leq x \leq a_{j+1} \qquad (4)$$

Where, J = 1, 2, 3, ..., m.

Although segmented linear functions are flexible, they are not ideally suited to some situations, particularly those to which the slope changes very gradually with increasing levels of pollution. In these instances, a non linear function is usually more appropriate.

4.2.3 Non linear function

When a cause – effect relationship does not very linearly, it leads to a curvature when plotted on a graph sheet. Such non-linear functions are of two basic types:

i) an implicit function, which can be plotted on a graph but for which no equation is given:

ii) an explicit function, for which a mathematical equation is given.

Implicit functions usually arise when some empirical curve has been obtained from a process under study. For example, Brown et al (1970) proposed an implicit nonlinear subindex function for pH.

Explicit nonlinear functions automatically lead to non-linear curves. An important general non –linear function is one in which the pollutant variable is raised to a power other than one, the power subindex function:

$$I = x^c \qquad \ldots \quad (5)$$

Where $c \neq 1$

Walski and Parker (1974) used the following general parabolic form in evolving the subindices for temperature and pH.

$$I = -\frac{b}{a^2} (x - a)^2 + b, \ 0 \leq x \leq 2a \qquad \ldots \quad (6)$$

Another common nonlinear function is the exponential function, in which pollutant variable x is the exponent of a constant:

$$I = c^x \qquad \ldots \quad (7)$$

The constant usually selected is either 10 or e, the base of the natural logarithm. If a and b are constants, the general form of an exponential function is written as follows:

$$I = a\,e^{bx} \qquad \ldots \qquad (8)$$

4.2.4 Segmented nonlinear function

Segmented nonlinear function consists of line segments similar to the segmented linear function; however, at least one segment is nonlinear. Usually, each segment is represented by a different equation which applies over a specific range of the pollutant variable. Segmented nonlinear function being more flexible than the segmented linear function, has been used for a number of water quality sub-indices. For example Prati et.al (1971) used a segmented nonlinear function for the pH subindex in their water quality index. The pH subindex function contained four segments:

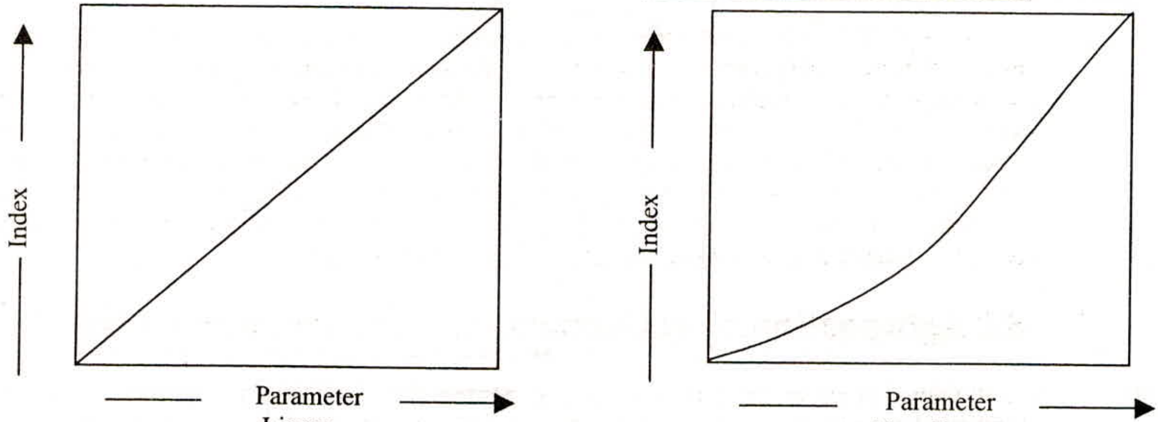
Segment	Range	Function
1	$0 \le x \le 5$	$I = -\ 0.4x^2 + 14$
2	$5 \le x \le 7$	$I = -2\,0x + 14$
3	$7 \le x \le 9$	$I = x^2 - 14x + 49$
4	$9 \le x \le 14$	$I = -0.4x^2 + 11.2x - 64.4$

Typical sub-index functions are presented in Figure 2.1

5.0 Assignment of weightages

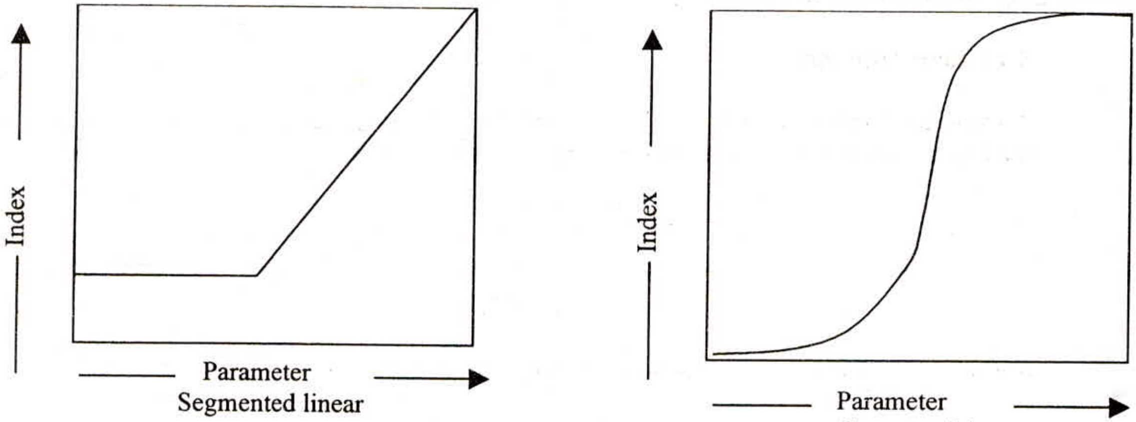
We have explained at some length in Chapter 1 and in section 3.0 of this chapter that it is a necessary as well as a very challenging task to short-list a few from among hundreds of water quality parameters so that a balance is achieved between size of an index, genuineness of the water quality data, and effectiveness of the index.

But even after a short-list of 10-20 parameters has been made, it still remains a major task to assign weightage to each parameter. Because even as all short listed parameters are deemed to be important as water quality indicators, they would still not be equally important. Within the selected parameters some would be of greater importance than some others.



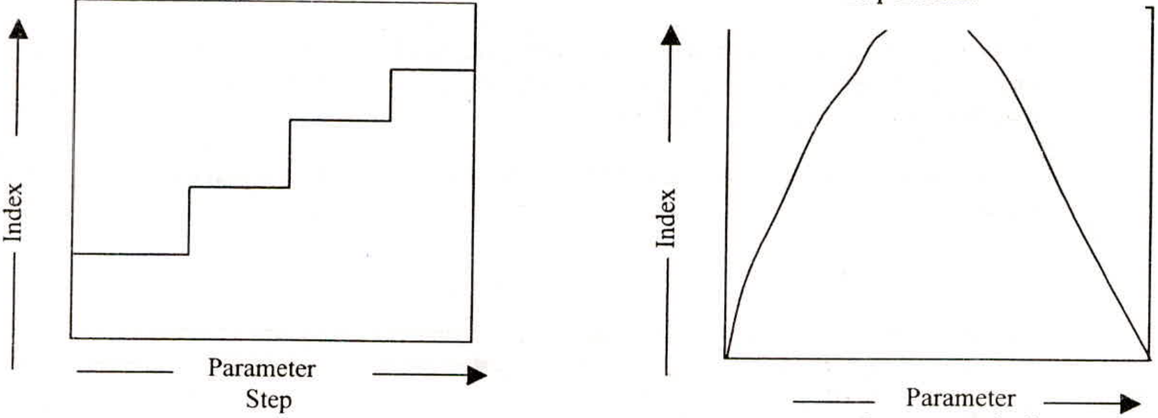
Linear

Non–linear



Segmented linear

Exponential



Step

Inverse parabolic

Figure 2.1 Typical sub-index functions

Some of the indices assume equal weightage of all the parameters. But in great many, different weightage is given to the different parameters. The assignment of weightage is, like selection of parameters, a matter of opinion, hence subjective. For this, too, well-formulated techniques of opinion-gathering such as Delphi (Abbasi 1995, Abbasi & Arya 2000) are utilized to minimise subjectivity and enhance credibility. It must be brought to the attention of the readers that Delphi is a rather cumbursome and time-consuming exercise. Perhaps this is one reason why we don't find as many new indices based on Delphi being proposed as we otherwise might have.

6.0 Aggregation of sub-indices to produce a final index

In the final step, the sub-indices are aggregated to obtain the final index. Several methods of aggregation are possible; the more common of the index forms based on different methods of aggregation are described below.

6.1 Linear sum index

A linear sum index is computed by the addition of unweighted subindices, in which no subindex is raised to a power other than 1.

$$I = \sum_{i=1}^{n} I_i \qquad \dots (9)$$

where I_i = subindex for pollutant variable i

n = number of pollutant variables

The simplicity of linear summation is outweighed by the disadvantage that the resulting index can project poor water quality even when no individual parameter is below acceptable level as explained bellow:

Given that a linear sum water pollution index is formed consisting of just two subindices, I_1 and I_2

$$I = I_1 + I_2 \qquad \dots \quad (10)$$

Assuming that $I_1 = 0$ and $I_2 = 0$ represent zero concentration and $I_1 \geq 100$ or $I_2 \geq 100$ represent concentration at the cut-off or below the permissible level. If the summation leads to $I > 100$, the users would infer that permissible level is violated by at least one subindex, whereas, in reality, one can get $I > 100$ even when both the individual parameters constituting I are within permissible limits. This phenomena is called 'ambiguity problem'.

6.2 Weighted sum index

A weighted sum index is given by:

$$I = \sum_{i=1}^{n} w_i I_i \qquad \ldots \qquad (11)$$

where I_i = subindex for i^{th} variable

w_i = weight for i^{th} variable

$$\sum_{i=1}^{n} w_i = 1 \qquad \ldots \qquad (12)$$

This index steers clear of the kind of ambiguity which dogs the linear sum index but suffers an equally serious problem called 'eclipsing'. Eclipsing occurs when at least one subindex reflects poor water quality as explained below:

For the two variable case,

$$I = w_1 I_1 + w_2 I_2 \qquad \ldots \qquad (13)$$

$$w_1 + w_2 = 1 \qquad \ldots \qquad (14)$$

Equation 13 and 14 can be written in a single equation as:

$$I = w_1 I_1 + (1 - w_1) I_2 \qquad \ldots \qquad (15)$$

From Equation (15) it is clear that $I = 0$ when both I_1 & $I_2 = 0$ i.e. the zero pollution is indicated properly. Further, I will not be 100 until and unless one of the subindex is more or equal to 100. Hence the problem of ambiguity is also removed.

But in situations such as the ones arising when $I_1 = 50$ and $I_2 = 110$ with w_1 and both $w_2 = 0.5$, gives $I = 80$. In other words the overall score indicates acceptable water quality eventhough one of the constituents as reflected in I_2 was above the permissible limit of 100. This type of situation when the index score 'hides' the unacceptable level of one or more constituent parameters is called 'eclipsing'.

6.3 Root sum power index

The root sum power index is formed by a nonlinear aggregation function:

$$I = \left[\sum_{i=1}^{N} I_i^{p} \right]^{1/p} \qquad \dots \qquad (16)$$

where p is a positive real number, greater than 1. As p becomes larger, the ambiguous region becomes smaller. For large values of p, the ambiguous region is almost entirely eliminated. The root-sum-power function is a good means for aggregating subindices, because it neither yields an eclipsing region nor an ambiguous region. However, because it is a limiting function, it is somewhat unwidely.

6.4 Maximum operator index

The maximum operator index can be viewed as the limiting case of the root sum power index as p approaches infinity. The general form of the maximum operator is as follows:

$$I = \max \left\{ I_1 + I_2 + \dots\dots\dots\dots\dots\dots, I_n \right\} \qquad \dots \qquad (17)$$

In the maximum operator, I takes on the largest of any of the subindices, and I=0 if and only if $I_i = 0$ for all i. It is ideally suited to determine if a permissible value is violated and by how much.

The limitation of the maximum operator becomes apparent when fine gradations of water quality, rather than discrete events, are to be reported and a number of subindices are to be aggregated.

The maximum operator is ideally suited to applications in which an index must report if at least one recommended limit is violated and by how much. Of course, if several subindices violate a recommended limit, the maximum operator will according yield increasingly desirable subindex. The suitability of the maximum operator for use in water pollution indices has not been explored as it ought to have been, however, and none of the published water quality indices have employed this aggregation function.

6.5 Multiplicative form indices

The most common multiplicative aggregation function in such indices is the weighted product, which has the following general form:

$$I = \prod_{i=1}^{n} I_i^{w_i} \quad \ldots \quad (18)$$

where

$$\sum_{i=1}^{n} w_i = I \quad \ldots \quad (19)$$

In this aggregation function, as with all multiplicative forms, an index is zero if any one subindex is zero. This characteristic eliminates the eclipsing problem, because, if any one subindex exhibits poor water quality, the overall index will exhibit poor water quality. Conversely, $I \doteqdot 0$ if and only if at least one subindex is zero; this characteristic eliminates the ambiguity problem.

If the weights in equation (19) are set equal, $w_i = w$ for all I, then Eq. (19) can be written as follows:

$$\sum_{i=1}^{n} w_i = nw = 1 \quad \ldots \quad (20)$$

For this situation, w = 1/n, Eq. (18) becomes the geometric mean of subindices:

$$I = \left(\prod_{i=1}^{n} I_i\right)^{w} = \left(\prod_{i=1}^{n} I_i\right)^{1/n} \quad \ldots \quad (21)$$

Thus, the geometric mean is a special case of the weighted product aggregation function. A common version of the weighted product is the geometric aggregation function:

$$I = \left(\prod_{i=1}^{n} I_i^{g_i}\right)^{1/\gamma} \qquad (22)$$

$$\text{where } \gamma = \sum_{i=1}^{n} g_i \qquad \ldots \qquad (23)$$

6.6 Minimum operator index

The minimum operator index, when summing decreasing scale subindices, performs in a fashion similar to the increasing scale maximum operator index. The general form of the minimum operator is:

$$I = \min \left\{ I_1, I_2, \ldots\ldots\ldots\ldots\ldots\ldots\ldots, I_n \right\} \qquad \ldots \qquad (24)$$

As is with in the miximum operator functions, eclipsing does not occur with this aggregation method, nor does an, ambiguous region exist. Consequently, the minimum operator appears to be a good candidate for aggregating decreasing scale subindices. However, none of the published environmental indices employ the minimum operator, and its potential, too, remains unexplored.

CHAPTER – III

Indices for determining fitness of waters for different uses

1.0 General

In Chapter 1, section 4 we have described Horton's (Horton, 1965) water quality index which can be considered as the forerunner of modern WQIs.

In this chapter we present a wide cross-section of indices which followed Horton's. These indices are a) based on parameter selection by methods other than statistical analysis (which has been detailed in Chapter 4), and b) are aimed at determining characteristic of water bodies vis a vis general or specific (such as for drinking / irrigation / bathing) use of their water.

2.0 Brown's or the National Sanitation Foundation's water quality index (NSFWQI)

Brown et al. (1970) developed a water quality index similar in structure to Horton's index but with much greater rigour in selecting parameters, developing a common scale, and assigning weights for which elaborate Delphic exercises were performed. This effort was supported by the National Sanitation Foundation (NSF). For this reason Brown's index is also referred as NSFWQI.

A panel of 142 persons with expertise in water quality management was formed for the study. The panelists were asked to consider 35 parameters for possible inclusion in the index. The panelists were free to add to the list any parameter of their choice. Each parameter was to be assigned one of the following choices: 'do not include', 'undecided', or 'include'. They panelists were asked to rank the parameters marked as 'include' according to their significance as contributor to the overall quality. The rating was done on a scale of 1 (highest) to 5 (lowest). The responses of the panel were brought to the knowledge of every member of the panel and the members were allowed to review their individual judgement in the light of the full panel's response.

Finally the panelists were asked to select not more than 15 parameters which they considered to be the most important. The complete list of parameters arranged in decreasing order of significance as determined by average rating of the panel was presented to each member. Continuing in this fashion, a list of eleven parameters was finalized (Table 1).

Table 1. List of parameters chosen as most significant by a Delphi conducted by Brown (1970) for the NSFWQI

Parameter	*Rank of importance*
Dissolved oxygen	1
Biochemical oxygen demand	2
Turbidity	3
Total solids	4
Nitrate	5
Phosphate	6
pH	7
Temperature	8
Faecal coliforms	9
Pesticides	10
Toxic elements	11

The panelists were asked to assign values for the variation in the level of water quality produced by different concentrations of the parameters selected as above. The concentration-value relationship of each parameter was obtained in the form of graph. These graphs were produced by the panelists to denote curves which, in their judgement, best represented the variation in level of water quality produced by possible measurements of each respective parameter. The judgement of all the respondents was averaged to produce a set of curves, one for each parameter. Figure 3.1 shows the rating curve for DO. For pesticides and toxic elements it was proposed that, if the total contents of detected pesticides or toxic elements (of all types) exceeds 0.1 mg/1, the water quality index be automatically registered zero.

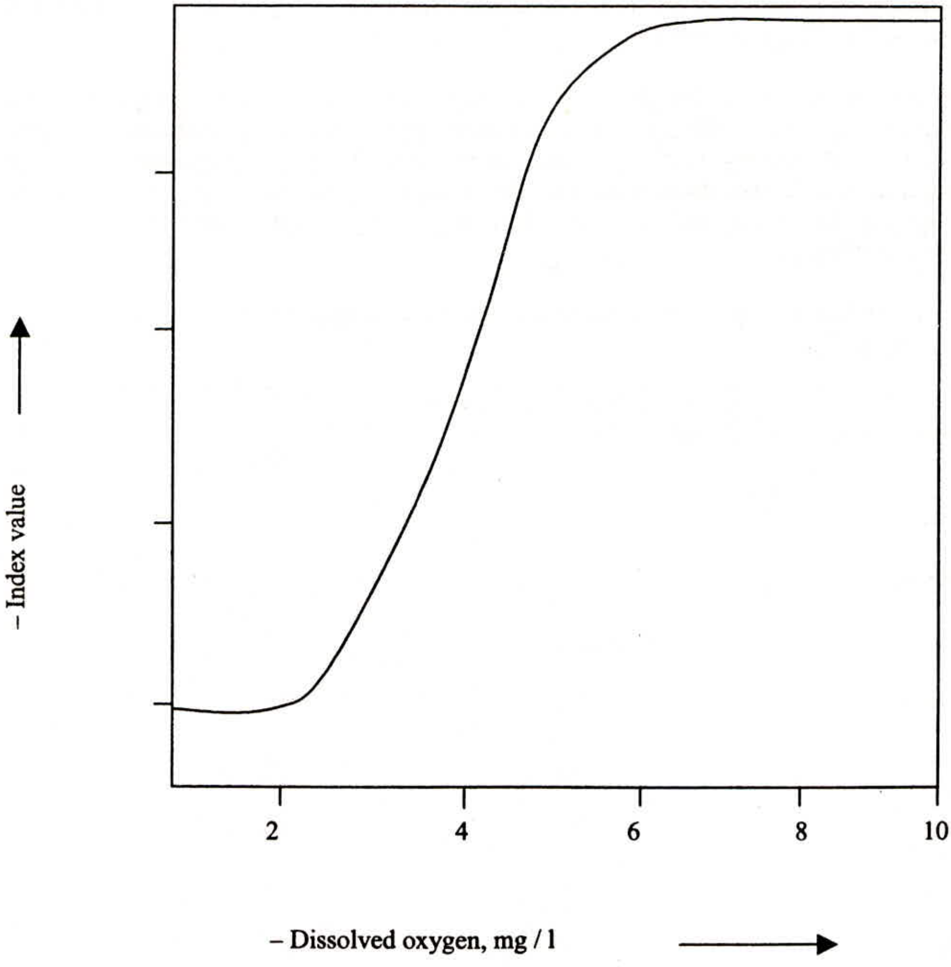


Figure 3.1 Sub-index for DO. For blower values of DO the sub-index score is close to the lower end of rating and at DO levels of 7 mg / l and above the index score is close to the highest

The panelists were asked to compare relative overall water quality using a scale of 1 (highest) to 5 (lowest) for the finally selected parameters. Arithmamatic mean was calculated for the ratings of experts.

To convert the rating into weights, a temporary weight of 1.0 was assigned to the parameter which received the highest significance rating. All other temporary weights were obtained by dividing each individual mean rating by the highest rating. Each temporary weight was then divided by the sum of all the temporary weights to arrive at the final weight. Table 2 gives the mean rating, temporary weights and final weights of the selected parameters.

Table 2. Significance ratings and weights for parameters included in Brown's (NSF) WQI

Parameters	*Mean of all significance ratings returned by respondents*	*Temporary weights*	*Final weights*
Dissolved oxygen	1.4	1.0	0.17
Fecal coliform density	1.5	0.9	0.15
Ph	2.1	0.7	0.12
BOD (5-day)	2.3	0.6	0.10
Nitrates	2.4	0.6	0.10
Phosphates	2.4	0.6	0.10
Temperature	2.4	0.6	0.10
Turbidity	2.9	0.5	0.08
Total solids	3.2	0.4	0.08
		Total	1.00

The index is give by

$$\text{NSFWQI} = \sum_{i=1}^{n} w_i\, q_i \qquad \ldots \qquad (1)$$

where q_i = the quality of the i^{th} parameter (a number between 0 and 100 read from the appropriate subindex graph)

w_i = the weight of the i^{th} parameter

The calculation of the index value is illustrated in Table 3.

Brown's index represents general water quality. It does not recognize and incorporate specific water functions like drinking water supply, agriculture, industry, etc. Related to this difficulty was an apparent tendency for some respondents to be heavily influenced in their judgement of parameter suitability for inclusion in a WQI by factors such as data availability and existing analytical methodologies for measuring the various parameters.

3.0 Prati's implicit index of pollution

This index was developed by Prati et al (1971) on the basis of water quality standards. The concentration values of all the pollutants were transformed into levels of pollution expressed in new units through mathematical expressions. These mathematical expressions were constructed in such a way that the new units were proportional to the polluting effect relative to other factors. In this way even if a pollutant is to be present in smaller concentrations than other pollutants, it still will exert a large impact on the index score if its polluting effect is greater.

In the fist step, water quality was classified vis a vis all the parameters based on water quality standards (Table 4).

In the second step, one pollutant was taken as reference and its actual value was considered directly as reference index.

In the third step, mathematical expressions were formed to transform each of the values of the other pollutants into indices. This transformation took into account the polluting capacity of the parameters related to selected reference parameter. In the construction of these functions, the analytical properties of various curves were used to ensure that the resulting transformation would be applicable not only to small values of pollutant concentrations but also to those exceeding class V.

Table 3. Illustrative example of a calculation of Brown's (NSF) WQI

Parameters	*Measured values*	*Individual quality rating (q_i)*	*Weights (w)*	*Overall quality rating ($q_i \times w_i$)*
DO, Percent sat	100	98	0.17	16.7
Faecal coliform density. 1b/100 ml	0	100	0.15	15.0
pH	7	92	0.11	10.1
BOD_5 mg/l	0	100	0.11	11.0
Nithate, mg/l	0	98	0.10	9.8
Phosphate, mg/l	0	98	0.10	9.8
Temperature C departure from equal	0	94	0.10	9.4
Turbidity, units	0	98	0.08	7.8
Total solids, mg/l	25	84	0.08	6.7
WQI = $w_i q_i$ = 96.3				

Table 4. Classification of water quality for the development of Prati's index

Parameter	*Excellent*	*Acceptable*	*Slightly Polluted*	*Polluted*	*Heavily Polluted*
PH	6.5–8.0	6.0–8.4	5.0–9.0	3.9–10.1	<3.9–>10.1
DO (% Sat)	88–112	75–125	50–150	20–200	<20–>200
BOD_5 (ppm)	1.5	3.0	6.0	12.0	>12.0
COD (ppm)	10	20	40	80	>80
Suspended solids (ppm)	20	40	100	278	>278
NH_3 (ppm)	0.1	0.3	0.9	2.7	>2.7
NO_3 (ppm)	4	12	36	108	>108
CI (ppm)	50	150	300	620	>620
Iron (ppm)	0.1	0.3	0.9	2.7	>2.7
Manganese (ppm)	0.05	0.17	0.5	1	>1
ABS (ppm)	0.09	1	3.5	8.5	>8.5
CCE (ppm)	1	2	4	8	>8

The resulting functions (subindices) are given in Table 5

The index was computed as the arithmetic mean of the 13 subindices:

$$I = 1/13 \sum_{i=1}^{13} I_i \qquad (2)$$

The index ranges form 0 to 14 (and above) and was applied by Prati *et al* to data on surface waters in Ferrana, Italy.

4.0 McDuffie's river pollution index (RPI)

It is a relatively simple water quality index in which eight pollutant variables are included. Most subindices are of the general linear form:

$$I_i = 10 \frac{x}{x_{N \quad i}} \qquad \dots \qquad (3)$$

Table 5. : Subindex functions of Parti's index

S.No	*Parameter*	*Subindex*
1	Dissolved Oxygen (%)	$I = 0.00168x^2 - 0.249x + 12.25,$ $0 \leq x < 50$ $I = -0.08x + 8,$ $50 \leq x < 100,$ $I = 0.08x - 8,$ $100 \leq x.$
2	pH (units)	$I = -0.4x^2 + 14$ $0 \leq x < 5,$ $I = -2x + 14,$ $5 \leq x < 7,$ $I = x^2 - 14x + 49,$ $7 \leq x < 9,$ $I = -0.4x^2 + 11.2x + 64.4,$ $9 \leq x < 14$
3	5-Day BOD (mg/L)	$I = 0.66666x$
4	COD (mg/L)	$I = 0.10x$
5	Permanganate (mg/l)	$I = 0.04x$
6	Suspended Solids (mg/L)	$I = 2^{[2.1 \log (0.1x-1)]}$
7	Ammonia (mg/L)	$I = 2^{[2.1 \log (10x)]}$
8	Nitrates (mg/L)	$I = 2^{[2.1 \log (0.25)]}$

9	Chlorides (mg/L)	$I=0.000228x^2 + 0.0314x,\quad 0 \le x < 50,$ $I=.000132x^2+.0074x+0.6,\quad 50 \le x, 300,$ $I=3.75\ (0.02x - 5.2)0.5,\quad 300 \le x$
10	Iron	$I=2^{[2.1\log(10x)]}$
11	Manganese (mg/L)	$I=2.5x + 3.9\sqrt{x},\quad 0 \le x < 0.5,$ $I=5.25x^2 + 2.75,\quad 0.5 \le x$
12	Alkyl Benzene sulfonates (mg/L)	$I=-1.2x + 3.2\sqrt{x},\quad 0 \le x < 1,$ $I=0.8x + 1.2,\quad 1 \le x$
13	Carbon choloroform Extract (mg/L)	$I=x$

where

I_i = subindex of the 1th pollutant variable

x = observed value of the pollutant variable (100 for highly polluted,

x_N = natural level of the pollutant variable (usually 10)

Six of the eight subindices described by McDuffie and Haney were explicit linear functions, and two (coliform count and temperature) were explicit non-linear functions (Table 6). The index did not include pH or toxic substances.

The overall index is computed as the sum of n subindices times a scaling factor 10 / (n+1) :

Table 6. Subindex functions of McDuffie's index

S. No	*Parameter*	*Subindex*
1	Percent Oxygen Deficit	$I = 100-x$, $x = DO$ %
2	Biodegradable Organic Matter	$I = 10x$, $x = BOD_5$ (ppm)
3	Refractory Organic Matter	$I = 5(x-y)$, $x = COD$, $y = BOD_5$
4	Coliform Count (no./100 ml)	$I = 10 \frac{\log x}{\log 3}$
5	Nonvolatile Suspended Solids	$I = x$,
6	Average Nautrient Excess	$I = \frac{x}{0.2} + \frac{y}{0.1}$, x = Total N y = Total – Po_4 (ppm)
7	Dissolved Salts	$I = 0.25x$, x = Specific conductance
8	Temperature	$I = \frac{x^2}{6} - 65$

$$RPI = \frac{10}{n+1} \sum_{i=1}^{n} I_i \qquad \ldots \qquad (4)$$

The RPI was applied on a test basis using data from New York State's water quality surveillance network and from other sources.

5.0 Dinius' water quality index (1972)

This index broke new ground in the sense that through it an attempt was made to design a rudimentary social accounting system which whould measure the costs and impact of pollution control efforts. In this sense, Dinius' WQI is a forerunner of the 'planning' or 'decision-making' indices described in Chapter 5. Eleven parameters were selected. Like Horton's index and the NSF WQI, it had decreasing scale, with values expressed as a percentage of perfect water quality which corresponds to 100%.

Like Prati's, and McDuffie Haney's, indices, the subindices in Dinius' index were developed from a review of the published scientific literature. Dinius examined the water quality described by various authorities to different levels of pollutant variables, and from this information she generated 11 subindex equations (Tabie 7).

Table 7. Subindex functions of Dinius' index

S.No	*Parameter*	*Subindex*
1	Dissolved Oxygen (%)	$I = x$
2	5 – Day BOD (mg/L)	$I = 107\, x^{-0.642}$
3	Total Coliforms (MPN/100ml)	$I = 100\, (x)^{-0.3}$
4	Fecal Coliforms (MPN/100ml)	$I = 100\, (5x)^{-0.3}$
5	Specific Conductance (μmho/cm)	$I = 535x^{-9565}$
6	Chlorides (mg/L)	$I = 125.8x^{-0.207}$
7	Hardness ($CaCo_3$, ppm)	$I = 10^{1.574-0.00132x}$
8	Alkalinity ($CaCo_3$, ppm)	$I = 108x^{-0.178}$
9	pH	$I = 10^{0.2335+0.44}, x < 6.7$ $I = 100, 6.7 \leq x \leq 7.58$ $I = 10^{4.22-0.293x}, x > 7, 58$
10	Temperature (°C)	$I = -4\,(x_a - x_3) + 112,$ x_a = actual temp, x_a = std. Temp
11	Color	$I = 128\, x^{-0.288}$

The index was calculated as the weighted sum of the subindices, like Horton's index and the additive version of the NSF WQI :

$$I = 1/21 \sum_{i=1}^{11} w_i \quad I_i \qquad \dots \qquad (5)$$

The weights ranged from 0.5 to 5 on a basic scale of importance. On this scale, 1,2,3,4 and 5 denote, respectively, very little, little average, great, and very great importance. The sum of the weights was 21, which is the denominator in the index equation.

The index was applied by Dininus on an illustrative basis to data on several streams in Alabama, USA.

6.0 Dininus' second index

A multiplicative water quality index was developed by Dinius (1987) / with liberal use of Delphi in decision making (Helmer & Rescher 1959, Dalkey & Helmer 1963, Abbasi & Arya 2000). The index included 12 pollutants: dissolved oxygen, 5–day BOD, cliform count, E – coli, pH, alkalinity, hardness, chloride, specific conductivity, temperature, color, and nitrate, for six water uses : public water supply, recreation, fish shellfish, agriculture, and industry. The subindexs functions were worked out as summarized in Table 8.

Table 8. Subindex functions of the second Dinius' index of water quality

Parameter	*Dimension*	*Weight*	*Function*
DO	% saturation	0.109	$0.82DO + 10.56$
5 – Day BOD	mg/l, at 20 °C	0.097	$108(BOD)^{-0.3494}$
Coli	MPN–Coli/100 ml	0.090	$136(COLI)^{-0.1311}$
E.Coli	Fecal–Coli/100 ml	0.116	$106\ (E\text{–}COLI)^{-0.1286}$
Alkalinity	ppm $CaCo_3$	0.063	$110(ALK)^{-0.1342}$
Hardness	ppm $CaCo_3$	0.065	$552\ (HA)^{-0.4488}$
Chloride	mg/l, fresh water	0.074	$391(CL)^{-0.3480}$
Sp.Conductance	micromhos/cm 25 °C	0.079	$306(SPC)^{-0.3315}$
pH	$pH < 6.9$	0.077	$10^{0.6803 + 0.1856\ (pH)}$
	pH – units (6.9 – 7.1)		1
	$pH > 7.1$		$10^{3.65 - 0.2216\ (pH)}$

Nitrate	as No_3, mg/l	0.090	$125\ (N)^{-0.2718}$
Temperature	°C	0.077	$10^{2.004-0.0382\,(T_a - T_s)}$
Color	Color units – Pt std	0.063	$127\ (C)^{-0.2394}$

The individual subindex functions were combined using a multiplicative aggregation function in which the weight of each subindex equation was based on evaluation of the importance by the Delphi panel members of each parameter to overal quality. The final multiplicative aggregation function had the general form:

$$IWQ = \prod_{i=1}^{n} I_i^{w_i} \qquad \dots (6)$$

where

IWQ = the index of water quality, a number between 0 and 100;
I_i = subindex of pollutant variable, a number between 0 and 100;
W_i = unit weight of pollutant variable, a number between 0 and 1;
n = number of pollutant variables.

The weighted function $(I_i)^{w_i}$ for each pollutant was calculated by subsituting the corresponding value of subindex function and its weightage. For example, Weighted function for BOD:

$$I_{Bod}^{\ BOD} \overset{w}{=} [108\ (BOD)^{-0.3494}]^{0.097}$$

7.0 O'Connor's indices

O'Conner developed two water quality indices: for fish and wild life (FAWL), and for public water supply (PWS). Both indices were developed using Delphi technique for reducing subjectivity of the judgements on parameter selection etc. The parameters and their weights for the two indices are compared with the Brown's or the National Science Foundation's Water Quality Index (NSFWQI) (Brown et al 1970) in Table 9.

The FAWL and PWS indices were computed as the weighted sum of the subindices times a factor which takes into account pesticides and toxic substances:

$$I_{FAWL} = \delta \sum_{i=1}^{9} w_i \; I_i \qquad \ldots \quad (7)$$

$$I_{PWS} = \delta \sum_{i=1}^{9} w_i \; I_i \qquad \ldots \quad (8)$$

where, $\delta = 0$, if pesticides or toxic substances exceed recommended limits $= 1$, otherwise.

8.0 Deininger and Landwehr's PWS index

Deininger and Landwehr (1971) presented an index pertaining to water used for public water supply (PWS). It employed 11 parameters for surface water sources and 13 for ground water sources.

Two aggregation functions were considered: an additive form and a geometric mean. The 11 variable and the 13 variable versions of the indices were computed for each aggregation function:

Additive

$$PWS_b = \sum_{i=1}^{n} w_i \, I_i \qquad \ldots \quad (9)$$

Table 9. Comparison of weights used in three water quality indices

Pollutant Variable	*NSF WQI*	*O' Connor's Indices*	
		FAWL	**PWS**
Dissolved Oxygen	0.17	0.206	0.056
Fecal Coliforms	0.15		0.171
pH	0.12	0.142	0.079
5 – Day BOD	0.10		
Nitrates	0.10	0.074	0.070
Phosphates	0.10	0.064	
Temperature	0.10	0.169	
Turbidity	0.08	0.088	0.058
Total Solids	0.08		
Dissolved Solids		0.074	0.084
Phenols		0.099	0.104
Ammonia		0.084	
Fluorides			0.079
Hardness			0.077
Chlorides			0.060
Alkalinity			0.058
Color			0.054
Sulphares			0.050
Total	1.00	1.00	1.00

Geometric mean

$$PWS_n = [\prod_{i=1}^{n} I_i^{W_i}]^{1/n} \qquad \ldots \qquad (10)$$

where, n = 11, for 11 – variable version

= 13, for 13 – variable version.

The variables along with their associated weights for the two versions are compared with NSFWQI in Table 10.

Table 10. Comparison of weights in the NSF WQI and the two (additive) water supply indices

Pollutant Variable	*NSF WQI*	**Deininger and Landwehr**	
		PWS_{11}	**PWS_{13}**
Dissolved Solids	0.17	0.06	0.05
Fecal Coliforms	0.15	0.14	0.12
pH	0.12	0.08	0.07
5 – Day BOD	0.10	0.09	0.08
Nitrates	0.10	010	0.09
Phosphates	0.10		
Temperature	0.10	0.07	0.06
Turbidity	0.08	0.09	0.08
Total Solids	0.08		
Dissolved Solids		0.10	0.08
Phenols		0.10	0.08
Color		0.10	0.08

Hardness		0.08	0.07
Fluorides			0.07
Iron			0.07
Total	1.00	1.01	1.00

9.0 Walski and Parker's index

This index (Walski and Parker, 1974) is based on empirical information on the suitability of water for a particular use, and was developed specifically for the recreational water (such as used for swimming and fishing). The authors introduced four general categories of variables:

i) those which affect aquatic life (e.g., DO, pH, and temperature),

ii) those which affect health (e.g., coliforms),

iii) those which affect taste and odor (e.g., threshold odor number); and

iv) those which affect the appearance of the water (e.g., turbidity, grease and color).

In the second step, the sensitivity functions were determined to assign each parameter a value between one and zero, representing ideal conditions and completely unacceptable conditions respectively. The nature of the sensitivity function was determined by the impact of a change in the value of the parameter on water quality. For substances that are inversely related to water quality a negative exponential curve was thought to best represent the sensitivity function.

The authors determined values for the parameters which would be considered perfect, good, poor and intolerable; and assigned to each of these values the numbers 1, 0.9, 0.1 and 0.01 respectively. With these sets of values, the sensitivity functions could be found easily.

For example, to determine a sensitivity function for temperature, a listing of lethal temperatures was consulted. As the maintenance of aquatic life is difficult at low as well as high temperatures, it was felt that the sensitivity function for temperature should consist of an inverted parabola (Figure 3.2) described as follows:

$$F(T) = \frac{a^2 - (T-a)^2}{a^2}$$

In which a = ideal temperature f(a) = 1

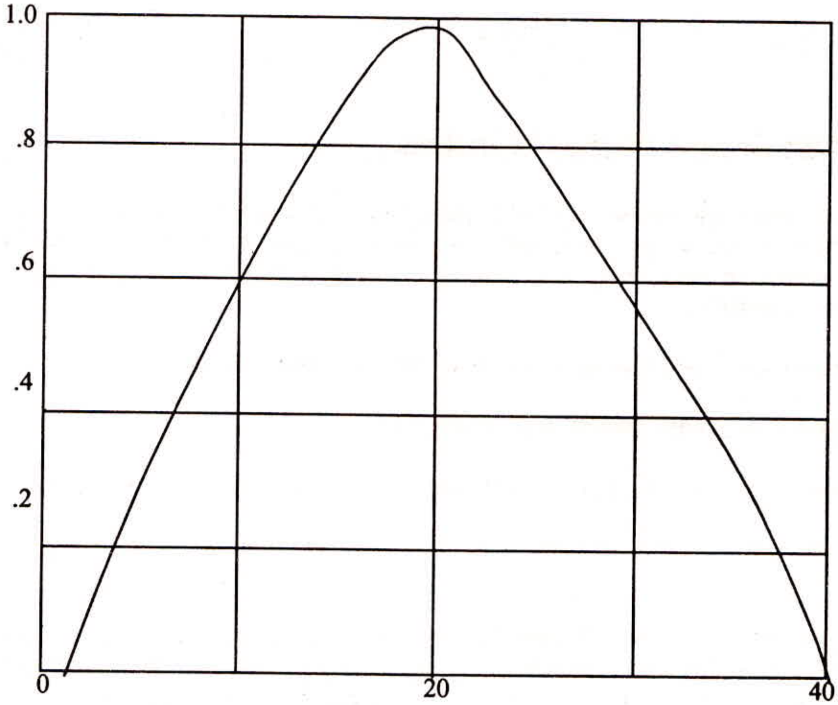


Figure 3.2. Inverted parabola as the sub-index function for temperature used in Welski – Parker index.

A total of 12 different pollutant variables were used in the index. The subindices consist of nonlinear and segmented nonlinear explicit functions (Table 11). Except for the two unimodel variables, pH and temperature, all subindices are represented by negative exponential equations. The pH was represented by parabolic equation as was temperature (noted above). Two subindices were used for temperature; one for actual temperature and another for departure from equilibrium temperature. To aggregate the subindices, a geometric mean was employed over an arithmetic mean to avoid the problem of eclipsing. Their aggregation function is as follows:

Table 11. Subindex functions of Walski – Parker index

Pollutant Variable	*Equation*	*Range*
Dissolved oxygen (mg/L)	$I = e^{[0.3\,(x-8)]}$	$0<x\leq 8$
	$I = 0$	$8<x$
PH (Std. Units)	$I = 0$	$x<2$
	$I = 0.04\,[25-(x-7)^2]$	$2\leq x\leq 12$
	$I = 0$	$12<x$
Total Coliforms (no./100 ml)	$I = e^{-0.0002x}$	
Temperature (°C)	$I = 0.0025\,[\,1-(x-20)^2$	$0\leq x\leq 40$
	$I = 0$	$\Delta x<-10$
	$I = 0.01\,(100-\Delta x)^2]$	$-10\leq\Delta x\leq 10$
	$I = 0$	$10<\Delta x$
Phosphates (mg/L)	$I = e^{-2.5x}$	
Nitrates (mg/L)	$I = e^{-0.16x}$	
Suspended Solids (mg / L)	$I = e^{-0.02x}$	
Turbidity (JTU)	$I = e^{-0.001x}$	
Color (c units)	$I = e^{-0.002x}$	
(Concentration (mg/ L))	$I = e^{-0.016x}$	
Grease (Thickness, μ)	$I = e^{-0.35x}$	
Odor	$I = e^{-0.1x}$	
Secchi Disk Transparency (m)	$I = \log(x+1)$	$X\leq 9$
	$I = 1$	$9<x$

$$I = \left[\prod_{i=1}^{12} I_i^{w_i}\right]^{1/12} \qquad \dots \qquad (11)$$

10.0 Stoner's Index

This index, aimed for use in public water supply and irrigation, employed a single aggregation function which selects from two sets of recommended limits and subindex equations. Although Stoner applied the index to just two water uses, it could be adapted to additional water uses as well.

Two types of water quality parameters are used in the Stoner's index:

Type I: Parameters normally considered toxic (for example, lead, chlordane, radium–226)

Type II: Parameters which affect health or aesthetic characteristics (for example, chlorides, sulphur, color, taste and odor).

The type I pollutant variables were treated in a dichotomous manner, giving subindex step functions. Each type I subindex is assigned the value of zero if the concentration is less than or equal to the recommended limit and the value 100 if the recommended limit is exceeded. The *type II* pollutant variables are represented, by explicit mathematical functions.

A total of 26 *type I* pollutant variables were used in the public water supply version of the index, and 5 type I variables in the irrigation version (Tables 12 & 13).

The overall index was computed by combining the unweighted type I subindices with the weighted type II subindices :

$$I = \sum_{i=1}^{n} I_i + \sum_{j=1}^{m} w_j I_j \qquad \dots \qquad (12)$$

where

I_i = subindex for the i^{th} *type I* pollutant variable
W_j = weight for the j^{th} *type II* pollutant variable
I_j = subindex for the j^{th} *type II* pollutant variable.

11.0 Nemerow and Sumitomo's pollution index

This increasing scale water supply index has been proposed by Nemerow and Sumitomo (1970). It consists of three individual use indices:

i) human contact use (j = 1)

ii) indirect contact use (j = 2)

iii) remote contact use (j = 3)

Table 12. Subindex functions of Stoner's index for public water supply

Variable	*Subindex Function*
Group – A (w=0.134)	
Ammonia – Nitrogen (mg/L)	$100 - 200x$
Nitrate – Nitrogen (mg/L)	$100 - 100x^2$
Fecal – Coliforms (no./100 ml)	$100 - 0.000025x^2$
Group – B (w=0.089)	
pH (Standard Units)	$-1125+350x-25x^2$
Fluorides	$98.8+24.7x - 123x^2$
Group – C (w=0.067)	
Chlorides (mg/L)	$100 - 0.4x$
Sulphates (mg/L)	$100 - 0.4x$
Group – D (w=0.053)	
Phenols (µg/L)	$100 - 100x$
Methylene Blue Active Sub.	$100 - 200x$

Group – E (w=0.045)	
Copper (mg/L)	$100-100x^2$
Iron (mg/L)	$100-333x$
Zinc (mg/L)	$100-20x$
Color (Pt–Co units)	$100-0.0178x^2$

The first category includes drinking (including water uses for beverage manufacturing) and swimming. The second category includes fishing, food processing, and agriculture. The last category includes uses in which human contact is very indirect, such as in navigation, industrial cooling, and some recreational activities (aesthetics, picnicking, hiking, and visits to the area).

Each specific use index includes pollutant variables represented by linear or segmented linear subindex functions:

Table 13. Subindex functions for Stoner's index for irrigation water

Variable	*Subindex Function*
Group – A (w=0.111)	
Sodium Absorption Ratio	$100-x^2$
Specific Conductance (μmho)	$100-0.0002x^2$
Fecal Coliforms (no./100ml)	$100-0.0001x^2$
Group – B (w=0.074)	
Arsenic (mg / L)	$100-1000x$
Boron (mg/L)	$100-100x^2$
Cadmium (mg/L)	$100-10^6x^2$
Group – C (w=0.0555)	

To reduce eclipsing problem, the subindices were aggregated in a unique manner. For each specific use j, the maximum subindex was combined with the arithmetic mean of n subindices in a root mean square operation :

$$I_j \quad = \quad [\max \mathrm{all}_i \{ I_{ij} \}]^2 + [\,1/n \sum_{i=1}^{n} I_{ij}]^2 \; / \; 2 \qquad \ldots \qquad (16)$$

Using this approach, each specific use index reflects both the highest subindex (a measure of the extreme) and the average of all subindices (a measure of central tendency). The investigators recommended the use of 14 pollutant variables in the index.

The general water quality index is computed as the weighted sum of the three specific use indices:

$$I \quad = \quad \sum_{i=1}^{3} w_i \, I_i \qquad \ldots \qquad (17)$$

12.0 Smith's index (1987)

The index has been designed by the author for four water uses – contact as well as non-contact.

It is a hybrid of the two common index types and is based on expert opinion as well as water quality standards.

The index addresses four types of water use:

1. General
2. Regular public bathing
3. Water supply
4. Fish spawning

The selection of parameters for each water class, developing sub indices, and assigning weightages were all done using Delphi. Besides the usual Delphic steps, additional rounds of questionnaire were employed to arrive at greater convergence of opinion. The panel members were allowed to phone the co-ordinator to seek clarifications. This was a departure from the Standard Delphic procedure wherein direct contact and discussions among panel members is discouraged with the view that such discussions may lead to some members unduly influencing some others. However in the procedure adopted by Smith, it was considered prudent to let the experts interact and thrash out points of doubt.

To obtain the sub index values the panel members were provided with the following :

1. Expected values of parameters likely to be encountered
2. Mutually agreed set of descriptors for the range of sub index values as follows :

   0 – 20 totally unsuitable

   20 – 40 inadequate for use

   40 – 60 marginally suitable

   60 – 80 suitable for use

   80 – 100 eminently suitable for use

3. Numerical standards for all the parameters for all the classes and the sub index value for the standard. Mostly, 60 was taken as the fixed sub index value which corresponds to the lowest value in the 'suitable for use' category.
4. Blank graph formats with X axis representing the expected range of parameter value, and Y axis representing the sub index values ranging from 0 to 100.

The panel members were asked to indicate graphically what the likely sub index value would be at different values of the parameter. It was stipulated that the graph should pass through the fixed reference point corresponding to the standard value of the parameter.

For example, for bathing water the pH must not fall below 6.5 or rise above 9. Therefore two fixed points would occur in the graph: (6.5, 60) and (9.60) – as illustrated in Figure 3.3.

The curves drawn by the panel members were then averaged to produce the final graphs. New curves were returned to panel members for comment and approval.

From the water quality data sub index values were obtained for all the parameters for all the water classes from graphs.

The minimum operator technique was used to obtain the final index score:

$$I_{min} = \sum \min (I_{sub1}, I_{sub2}, \ldots\ldots I_{subn})$$

Where I_{min} equals the lowest sub index value

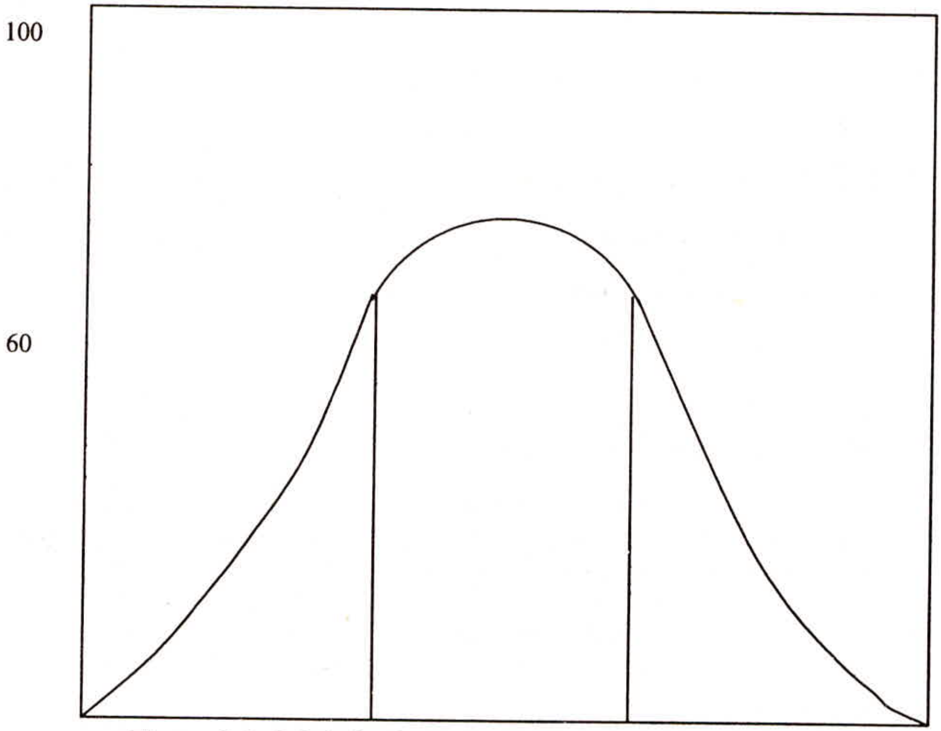


Figure 3.3 Sub-index function for pH in Smith's index

13.0 Viet and Bhargava's Index (1989)

This index was developed for the evaluation of the water quality status of the Saigon river for it's various desired uses. It is based on the Welski – Parker index with slight modifications.

$$WQI = \pi_{i=1}^{n} (f_i (P_i))^{1/n} \; 100$$

in which n is the number of variables considered more relevant to the use than the rest of the variable; and fi (Pi) is the sensitivity function of the i th variable.

Typical sub-index function values are shown in figure 3.4.

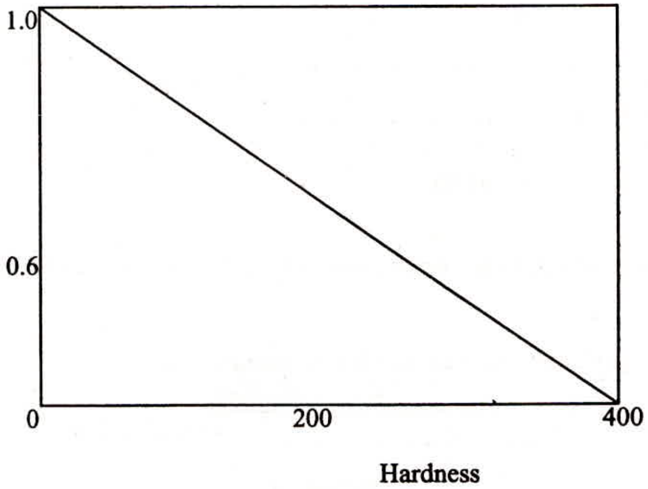
For example for fish culture and wild life the following parameters are considered relevant

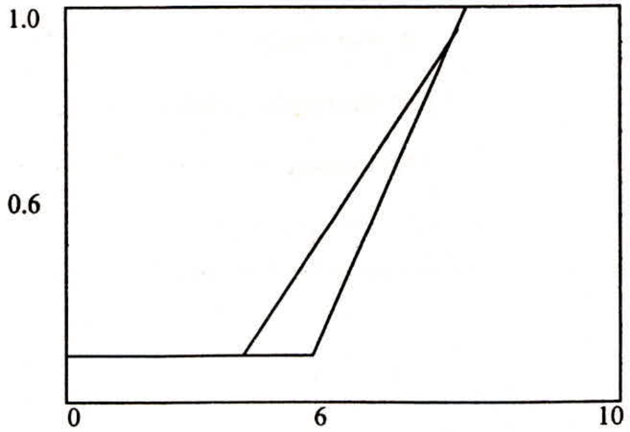
1. Temperature : value of the sensitivity function – 0.58
2. Chloride : value of the sensitivity function – 1.0
3. DO : value of the sensitivity function – 0.70
4. BOD : value of the sensitivity function – 0.73

The overall index is calculated as follows:

$$WQI = (0.58 \times 1.0 \times 0.70 \times 0.73)^{1/4} \times 100$$

The classification of water resources is given in Table 14.





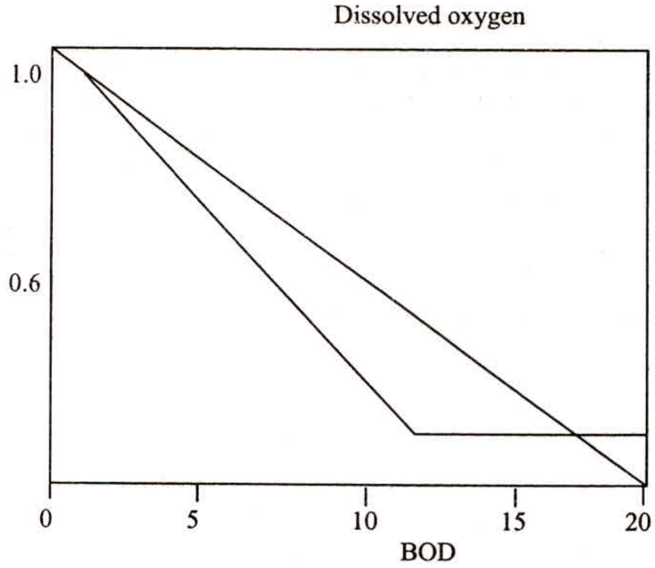


Figure 3.4 Representative sub-index employed by Viet & Bhargava 1989

Table 14. Water resource classification as per Viet & Bhargava's index

WQI Value	*Classification*
90>	I Excellent
65–89	II Permissible
39–64	III Marginally suitable
11–34	IV Inadequate for use
10<	V Totally unsuitable

14.0 Use of an adaptive model of water-quality index for improving the efficiency of in-line monitoring (Gekov et al 1991)

The use of an adaptive model of water quality index in online monitoring of water quality was explored by Gekov et al (1991). The authors find that this enables considerable saving of the amount of time necessary for data processing in real-time surface water pollution assessment efforts.

15.0 Chesapeake Bay water quality indices (Haire et al 1991)

The Maryland Department of Environment has developed a nutrient loading index and a eutrophication index for Chesapeake Bay and its major tributaries to provide easily understandable summary information concerning nutrient reduction and water quality trends in the bay to legislators, administrators, and the public. The nutrient loading index documents the average daily load of N and P to the system.

Some features of the eutrophication index include comparison of observed conditions to model projections of desired water quality, segmentation of each system into salinity zones, and analysis of data collected through the comprehensive Chesapeake Bay monitoring program.

For the Patuxent Estuary, the Potomac Estuary, and the Chesapeake Bay mainstream, the results of the nutrient loading index show that significant progress has been made in the reduction of phosphorous point source loads. The eutorphication index for each of these estuaries indicates that the water quality is variable, largely because of flow conditions, but has generally improved over the last decade.

16.0 Li's regional water resource quality assessment index (1993)

A comprehensive quality index including function damage rate of water bodies combined with water quality, which has reasonable structure and strong synthetic ability, was proposed by Li (1993). It assesses the water quality for not only sections of rivers but also systems of regional water resources.

Application of the index, as illustrated by the author, can play an important role in water resource development as well as in water pollution control.

17.0 Coastal water quality index for Taiwan (Shyue et al 1996)

A Coastal Water Quality Index (CWQI) was established to better understand the coastal water quality for the general public. Six coastal water quality experts in Taiwan were surveyed by using Delphi to select several parameters from Marien Water Quality Standard.

The fourth order polynomial regression was performed to process the surveyed data for each parameter as the scoring function. The minimum scoring method gave more diverse results for different water quality monitored sites than the geometric weighted method. Therefore, the minimum scoring method was favored in order to distinguish the degree of the pollution.

The parameters identified for the CWQI are: pH, DO, BOD, cyanide, coliform, Cu, Zn, Pb, Cd, and Cr.

18.0 A comparison

A comparison of various indices is presented in Table 15.

Table 15. An overview of types of subindices, aggregation functions, and flaws

Index	*Subindices*	*Aggregation function*	*Flaws*
Horton's	Segmented linear (step functions)	Weighted sum multiplied by 2 Dischotomous Term	Eclipsing region
Brown *et al.* (NSF WQI_a)	Implicit nonlinear	Weighted sum	Eclipsing region
Landwehr (NSF WQI_m)	Implicit nonlinear	Weighted product	Non linear
Parti *et al.*	Segmented non linear	Weighted sum (arithmetic mean)	Eclipsing region
McDuffie & Haney	Linear	Weighted Sum	Eclipsing region
Dinius	Non linear	Weighted sum	-----do-----
Dee *et al.*	Implicit nonlinear	-----do-----	-----do-----
O'Connor's (FAWL, PWS)	Implicit nonlinear	Weighted sum	Eclipsing region
Deininger &	-----do-----	Weighted sum	-----do-----
Landwehr (PWS)		Weighted product	Non linear
Walski & Parker	Non linear	Weighted product	-----do-----
		Geometric mean	– ve value
Stoner	-----do-----	Weighted sum	–
Nemerow & Sumitomo	Segmented linear	Root mean square of max. & arithmetic mean	–
Smith	Multiple types	Minimum operator	
Viet & Bhargava	-----do-----	Weighted product	

CHAPTER - IV

Indices based on statistical analysis of water quality data

1.0 An Overview

We have seen in the preceding chapters that simple statistical methods such as averaging and summation have been used in all indices from Horton's onwards. But the indices were always based on parameters, concentration – acceptability relationships of the parameters, weightages etc selected or defined by the index developer with or without the help of other experts. In contrast, for the type of indices described in this chapter, the parameters of importance and the extent of their importance are determined on the basis of analysis of water quality and related data by statistical techniques such as factor analysis and principal component analysis.

This approach has the advantage that there are fewer subjective assumptions than in the traditional indices; however, the indices based on statistical analysis are more complex and more difficult to apply.

Of the statistical techniques on which some of these indices are based, the ones focussing on correlation explore associations among variables to determine the importance of each as a determinant of water quality. Shoji *et al* (1966) applied factor analysis to the Yodo river system in Japan for interrelationships among 20 pollutant variables. By comparing the correlation of each variable with every other variable and selecting combinations with the highest correlations, they identified three major factors that effect the river water quality: pollution, temperature and rainfall.

In an attempt to examine the very basis of the concept of indices, Landwehr (1979) observed, "regardless of its construct, an index is a random variable in as much as the water quality constituents upon which it depends are themselves random variables". He derived and compared the statistical properties of the most widely used functional structures of indices.

Joung et al. (1978) used factor analysis to develop water quality indices by examining water quality data from Carson Valley, Nevada. Ten pollutant variables were considered. By manipulating the matrix of correlation coefficients, the authors were able to identify linear combinations of the variables which best explain the variance but which have low corrleations with each other. The approach retains the most important information in the raw data while eliminating redundant variables. The authors used the approach to identify the most significant variables and index weights for two water quality indices containing five variables each: the Index of Partial Nutrients and the Index of Total Nutrients. These indices were then applied to the Snake and the Colorado river basins in Nevada, USA. Of the two, the Index of Total Nutrients (with the variables DO, BOD_5, total phosphates, temperature and conductivity) was selected, and its performance was compared with that of the Brown's NSFWQI .(Brown et al 1970) using water quality data from 20 locations in the U.S

In another effort at correlation, Coughlin et al. (1972) studied the relationship between the Brown's NSFWQI and the uses of a stream made by the nearby residents. They used principal component analysis to examine the relationships among individual NSFWQI variables and such factors as distance of residence from the stream, land values, and tendency for residents to walk along the stream or to wade in it or fish in it. They reported that water pollution was correlated with wading, fishing, picnicking, bird watching, walking and other activities.

2. 0 Harkin's Index

Based on the premise elaborated in the preceding section, that conventional indices, such as the NSFWQI developed by Brown *et al* (1970), and others described in Chapter 3, lack objectivity, Harkin (1974) presented a statistical approach for analyzing water quality data based on the rank order of observations.

Harkin's index was an application of Kendall's (1975) nonparametric classification procedure. It begins with ranking the observatins for each pollutant variable, including a control value, which is usually a water quality standard or recommended limit. For each observation j of pollutant variable i, the transform Zij was computed as the difference between the rank order of the observation and the rank order of the control value (R_{ic}), divided by the standard deviation of the ranks S:

$$Z_{ij} = R_{ij} - R_{ic} \ / \ S_i \quad \dots \quad (1)$$

where R_{ij} = rank of the j^{th} observation of the i^{th} variable

R_{ic} = rank of the control value for the i^{th} variable

S_i = standard deviation of the ranks for the i^{th} variable

The index was computed for each observation by adding the square of the transform for n pollutant variable:

$$I = \sum_{i=1}^{n} Z^2_{ij} \qquad \ldots \quad (2)$$

the standard deviation S_i:

$$S_i = m^2_i - 1 / 12 \qquad \ldots \quad (3)$$

where m_i = number of values (observation + control value) for pollutant variable i.

In Harkin's treatment, the same value often appears more than once; these repeated values reduce the variance and must be taken into account. When repeated values occur, the standard deviation S_i is calculated as follows:

$$S_i = [1 / 12\, m_i \{m_i^3 - m_i - \sum_{k=1}^{q_i} (t^3 - t)_k\}]^{1/2} \qquad \ldots \quad (4)$$

where m = number of values for each variable I

t = number of repeated values (ties)

q = number of separate occurrences of ties

Harkin's index is a relative rather than an absolute index; values generated with one data set can not be compared directly with those generated with a different data set.

3.0 Beta Function Index:

The approach of Harkin (1974) was extrapolated by Schaeffer and Janardan (1977) in to a statical index which has a fixed range: the Beta Function Index. It uses the same ranking procedure as employed in Harkin's index. Two additional values were computed from the ranks: the sum of the square of the z-transforms given by Eq1 and the sum of all the ranks excluding the control values:

$$S = \sum_{i=1}^{n} \sum_{j=1}^{m_i} Z^2_{ij} \qquad \ldots \quad (5)$$

$$T = \sum_{i=1}^{n} \sum_{j=1}^{m_i - 1} R_{ij} \qquad \ldots (6)$$

where, m_i = number of values for pollutant variable i.

n = number of pollutant variables

The Beta Function Index was calculated using the transform of S and T:

$$I = 1/b \left(\frac{S}{S+T} \right)^{1/2} \qquad \ldots (7)$$

$$b = \left[2\sum_{i=1}^{n} m_i^2 \,/\, 3\sum_{i=1}^{n} m_i^2 + \sum_{i=1}^{n} m_i - 2n_{ij} \right] \qquad \ldots (8)$$

If the number of observations for each variable is the same (i.e., m_i = m, for all I), then Eq. (8) can be simplified as:

$$b = [\,2\,m^2 / 3m^2 + m - 2\,]^{1/2} \qquad \ldots (9)$$

Since it was assumed to have a chi-square distribution and T was approximately constant, the investigator concluded that the index follows a beta probability distribution. The index is thus non parametric; it's distribution is the same regardless of the underlying distribution of the data.

4.0 Index based on fuzzy clustering analysis (Kung et al 1992)

A general methodology for fuzzy clustering analysis was developed and illustrated with a case study of water quality evaluation for Dianshan Lake, Shanghai, China. According to Kung et al (1992), fuzzy clustering analysis may be used when a composite classification of water quality incorporates multiple parameters. In such cases, according to the authors, the technique may be used as a complement or an alternative to comprehensive assessment. In fuzzy clustering analysis, the classification is detailed by a fuzzy relation. After a fuzzy similarity matrix is established and the fuzzy relation stabilized, a dynamic clustering chart can be developed. Given a suitable threshold, the appropriate classification is worked out.

5.0 A comparison

The number of variables and the scales used in various indices based on statistical techniques are summarized in Table 1.

Table 1. Number of variables and scales used in indices based on statistical techniques

Index	*No. of variables*	*Scale*
Shoji *et al.* Comfposite Pollution Index (CPI)	18	−2 to 2
Joung *et al.* Index of Partial Nutrients	5	0 to 100
Joung *et al.* Index of Total Nutrients	5	0 to 100
Coughlin *et al.* Principal Component Index	*	N.A.
Harkin's Index (Kendall ranking)	*	0 to 100
Schaeffer & Janardans Beta Function Index	*	0 to 1
Kung *et al*, Fuzzy clustering	*	@

* *Variables not fixed; worked out by the index*

@ *Matches the results with the standards*

CHAPTER - V

'Planning' or 'decision – making' indices

1.0 The 'planning or 'decision-making' indices

As we have detailed in Chapter, especially its concluding section, each and every WQI can be used as a tool in a) assessing water quality of different sources, b) comparing the water quality of different sources and linking the findings with the impacting factors, c) evolving measures to improve water quality based on the previous step d) undertaking resource allocation and ecomanagement exercises accordingly, etc. In other words each and every WQI can be a tool for planning and decision–making.

Nevertheless, some indices have been specifically reported as 'planning tools'. This chapter describes the significant ones among them.

2.0 Ott's NPPI

Ott (1978) formulated the National Planning Priorities Index (NPPI) as a tool for assigning priorities to different demand sectors in order to ensure that funds are granted and used in a cost-effective manner for the planned water treatment projects. It was computed as the weighted sum of 10 sub indices:

$$\mathrm{NPPI} = \sum_{i=1}^{10} w_i \quad I_i \qquad \dots (1)$$

in which, each subindex I_i was computed using a segmented linear function.

WQI in Dee's Environmental Evaluation System

Dee et al. (1972, 1973) proposed a system for evaluating the environmental impact of large scale water resources projects. The system included a water quality index, which was represented by 12 common water quality variables (such as DO pH, turbidity, and fecal coliforms), besides pesticides and toxic substances. The subindices of various water quality variables were similar to those in the Brown's NSFWQI (Brown et al 1970).

The index was calculated with and without considering the proposed water resources project. The difference between the two scores provided a measure of the environmental impact (EI) of project :

$$EI = \sum_{i=1}^{78} w_i \; I_i \text{ (with)} - \sum_{j=1}^{78} w_j \; I_j \text{ (without)} \qquad \text{... (2)}$$

3.0 Inhaber's Canadian National Index (1974)

This national index for Canada included an air quality index, a water quality index, and a land quality index.

The water quality index combined two subindices in a root mean square operation: an ambient water quality subindex and a pollutant source subindex based on effluents from point sources. The ambient water quality subindex, in turn, comprised of three subindices: (1) a trace metals subindex based on cadmium, lithium, copper, zinc and the hardness of water; (2) a turbidity subindex; and (3) a commercial fish catch subindex based on weight and mercury content of fish landed by canadian ships. The pollutant source subindex was based on pollutant variables measured in effluents from five sources (municipal wastes and the petroleum-refining, chlor-alkali, fish-procesing, and paper industries). The subindices were combined in successive root mean square operations.

4.0 Zoeteman's Pollution Potential Index (PPI)

This index was developed by Zoeteman (1973) as a planning tool based not on observed water quality variables but on indirect factors assumed to be responsible for pollution. It was based on the size of the population within a given drainage area, the degree of economic activity, and the average flow rate of the river:

$$PPI = NG / Q \times 10^{-6} \qquad \text{... (3)}$$

in which

N = number of people living in a drainage are

G = average per capita (gross National Product (GNP)

Q = yearly average flow rate (m^3 / sec)

Zoeteman applied the PPI to 160 river sites throughout the world, comparing PPI values with the pollutant variables for which more than 40 observations were available. The PPI ranged from 0.01 to 1,000 for these rivers. The PPI was also applied to the Rhine river (1973).

5.0 Johanson and Johanson's Pollution Index

Johanson and Johanson (1976) developed a planning index as a tool to assist in the process of identifying candidate polluted locations. He used the index to screen 652 data sets from water–ways across the nation. For each location Pollution Index (PI) was computed as follows:

$$PI = \sum_{i=1}^{n} w_i \quad C_i \qquad \ldots (4)$$

where:

w_i = weight for pollutant variable i,

C_i = highest concentration of pollution variable i reported in a location of interest.

For each pollutant i, the weight was based on the reciprocal of the median of observed national concentrations. Using the index, it was possible to scan the data by computer and identify the locations receiving the highest priority for removal of pollutants.

6.0 A comparison

A comparison of various 'planning' indices is presented in Table 1.

Table 1. Number of variables and scales used in planning indices

Index Name	*No. of Variables*	*Range*
Truett et al. Prevalence Duration Intensity (PDI) Index	Not fixed	0 to 1
	"	0 to 1
Truett et al. Priority Action index (PAI)		
	"	0 to 1
Dee et al. Environmental Evaluation System (EES)		
	78	0 to 1000
Inhaber Canadian National Index		
Zoeteman Potential Pollution Index (PPI)	Not fixed	0 to 1
Johanson & Johanson Pollution Index (PI)	3	0 to 1000
	Not fixed	0 to 100

CHAPTER - VI

Indian WQIs

1.0 Use of WQI in India

Water quality indices have been used in India but not as extensively as the tool deserves. Except for the first reported Indian WQI (Bhargava 1985), other indices have been mostly weighted sum indices (section 6.2, chapter 2), apparently inspired by Brown's WQI (section 2.0, chapters 3).

2.0 Bhargava's Index (1985)

This is one of the first reported indices by an Indian author, and addresses the issue of drinking water supply.

To develop the index, Bhargava (1985) identified 4 groups of parameters. Each group contained sets of one type of parameters. The first group included the concentrations of coliform organisms to represent the bacterial quality of drinking water. The second group included toxicants, heavy metals, etc, some or all of which have a cumulative toxic effect on the consumer. The third group included parameters that cause physical effects, such as odor, color, and turbidity. The fourth group included the inorganic and organic nontoxic substances such as chloride, sulfate, foaming agents, iron, manganese, zinc, copper, total dissolved solids (TDS) etc. The variables, with their maximum allowable contaminant level, C_{MCL} (as per the US Environmental Protection Agency), and the subindices worked out by Bhargava, which include the effects of concentrations of different parameters and their weightage, are given in Table 1.

Table 1. Subindex functions of Bhargava's drinking water supply index

Variables	*Subindex Function*	C_{MCL}
Group I Coliform organisms, e.g., coliform bacteria	$f_1 = \exp[-16(C-1)]$	Coliform bacteria / 100 ml
Group II Heavy metals, other toxicants, etc., e.g., Cr, Pb Ag etc.	$f_1 = \exp[-4(C-1)]$	0.05 mg / l each
Group III Physical vriables, e.g., turbidity, color.	$f_1 = \exp[-2(C-1)]$	1 TU 15 Color units
Group IV Organic & Inorganic non toxic substances, e.g., chlorides, suplhates, TDS.	$f_1 = \exp[-2(C-1)]$	250 mg/L each 500 mg/L

The subindices were aggregated as follows :

$$\underset{i=1}{\overset{n}{WQI}} \overset{1/12}{=} [\Box f_i] \qquad \ldots \qquad (1)$$

in which, f_i = subindex for i^{th} variable varied from 0 – 2.
n = number of variables considered

The index was applied to the raw water quality data at the upstream and downstream of river Yamuna at Delhi. The author suggested that the public drinking water supplies should have a WQI larger than 90.

3.0 The River Ganga Index of Ved Prakash *et al* (1990)

The index was developed to evaluate the water quality profile of river Ganga in its entire stetch and to identify the reaches where the gap between the desired and the existing water quality is significant enough to warrant urgent pollution control measures.

The index had the weighted multiplication form:

$$W.Q.I = \sum_{i=1}^{p} w_i I_i$$

Where I_i = sub index for i th water quality parameter

W_i = weight associated with i th water quality parameter and

P = number of water quality parameters

This index was based on the index of Brown *et al* or National Sanitation Foundation WQI (described in section 2.0, chapter 3), with slight modifications in terms of weightages to confirm to the water quality criteria for different categories of uses as set by Central Water Pollution Board, India.

A list of parameters were selected through Delphi. Sub-Index values were obtained by using sub index equations as shown in Table 2.

Table 2. Sub-index equations of the index reported by Ved Prakash et al (1990)

Parameter	*Range applicable*	*Equation*	*Correlation*
DO	0–40% saturation	IDO = 0.18+0.66 (% sat)	0.99
	40–100% saturation	IDO = -13.5+1.17 (% sat)	0.99
	100–140% saturation	IDO = 263.34-0.62 (% sat)	–0.99
BOD (mg/l)	0–10	IDO = 96.67–7.00 x (BO)	–0.99
	10–30	IBOD = 38.9–1.23 x (BOD)	–0.95
	2–5	IpH = 16.1+7.35 x (pH)	0.925

PH	5–7.3	IpH = 142.67+33.5 x (pH)	0.99
	7.3–10	IpH = 316.96–29.85 x (pH)	–0.98
	10–12	IpH = 96.17–8.00 x (pH)	–0.93
Fecal coliform	$1–10^3$	Icoli = 97.2–26.80 x (Icoli)	–0.99
	$10^3–10^5$	Icoli = 42.33–7.75 x (Icoli)	–0.98
	10^5	Icoli = 2	

To assign weightages, significance ratings were given to all the selected parameters. A temporary weight of 1 was assigned to the parameter which received highest significance rating. All other temporary weights were obtained by dividing each individual mean rating with the highest. Each temporary weight was then divided by the sum of all weights to arrive at the final weights. These weights were modified to suit the water quality criteria for different categories of uses.

The method of obtaining weights and modified weights is illustrated in Table 3. The classification of water *vis a vis* the final index values is given in Table 4.

Table 3. Method of obtaining weights and modified weights, *cf* Table 2

Parameters	*Mean of all significance ratings*	*Temporary weights*	*Final weights*	*Modified weights*
DO	1.4	1.0	0.17	0.31
Fecal coliforms	1.5	0.9	0.15	0.28
PH	2.1	0.7	0.12	0.22
BOD	2.3	0.6	0.1	0.19
		Total	0.54	1.00

Table 4. Water class as per index score; *cf* Table 2

S. N	*WQI*	*Description*	*Class*
1	63 – 100	Good to excellent	A
2	50 – 63	Medium to good	B
3	38 – 50	Bad	C
4	38	Bad to very bad	D,E

4.0 Use of WQI to assess pond water quality (Sinha 1995)

The portability of the water of two ponds used by the villagers of Muzaffarpur district, Bihar, was assessed by Sinha (1995). He also used an index similar to Brown's (NSFWQI, 1973; described in section 2.0, chapter 3). Ten parameters – pH, hardness, DO, chloride, Na, K, Zn, Fe, turbidity and coliform – contributed to the sub-indices forming the WQI. The manner of computation of the index is illustrated in Table 5. The water quality characteristics of the two ponds and the monthly variation in the index scores are presented in Tables 6 and 7. The author concluded that the pond waters, though used for drinking, were actually not potable and needed proper treatment.

Table 5. Calculation of water quality index of Susta pond for the month of January, 1986

Water quality parameter	*I.C.M.R. standard*	*Unit weight (Wi)*	*Value of water sample*	*Quality Rating (di)*	*Parameter sub-index (diwi)*
PH	7.0–8.5	0.229	7.8	53.33	1.2213
Hardness	300 mg/L	0.0006	52.0	17.33	0.0104
Dissolved oxygen	5 mg/L •	0.0352	6.2	87.5	3.08
Chloride	250 mg/L	0.0007	48.5	19.4	0.0136
Sodium	20 mg/L	0.0088	5.2	26.0	0.2288
	10 mg/L*	0.0176	5.8	58.0	1.0208

Potassium					
Zinc	5 mg/L	0.0352	0.05	1.0	0.0352
Iron	0.3 mg/L	0.5859	0.18	60.0	35.154
Turbidity	1.5 mg/L*	0.1172	10.0	666.66	78.1325
S.P.C. of coliform	1/100 ml.	0.1758	1000	400.0	70.00

$$W.Q.I = \sum_{i=1}^{10} q_i w_i = 188.89$$

@ – *European Economic Community (E.E.C.) standard.*

* – *Soviat State Standard (TOCT) No.2874–73.*

5.0 Use of WQI to study Hanumantal (Hanuman lake), Jabalpur (Dhamija and Jain 1995)

Hanumantal was studied on the basis of a WQI formed with 9 parameters which were assigned weights as summarized in Table 8. The unit weight (w_i) for each parameter was calculated as :

$$W_i = \frac{w_i/9}{\sum_{i=1} w_i}$$

Table 6. Physico-chemical characteristics of the water

Sl. N 0	*Pararmeters*	*Susta pond range*		*Madhaul pond range*	
		1st year	*2nd year*	*1st year*	*2nd year*
1.	Turbidity (mg/L)	17.5 ± 7.5	20 ± 10	20 ± 9	20 ± 10
2.	Conductivity (ml mhos / cm)	0.34 ± 0.11	0.36 ± 0.12	0.435 ± 0.095	0.43 ± 0.08
3.	Dissolved Oxygen (mg/L)	5.8 ± 1.4	6.5 ± 1.1	6.2 ± 1.4	6.1 ± 1.3
4.	pH	7.85 ± 0.35	7.9 ± 0.5	7.85 ± 0.65	7.95 ± 0.45
5.	Sodium (mg/L)	5.2 ± 0.6	5.8 ± 0.9	5.35 ± 0.95	5.6 ± 0.8
6.	Potassium (mg/L)	6.25 ± 0.45	6.4 ± 1	5.75 ± 0.65	5.9 ± 1.4
7.	Zinc (mg/L)	0.095 ± 0.085	0.095 ± 0.065	2.6 ± 1	2.5 ± 1.1
8.	Iron (mg/L)			0.2 ± 0.08	0.14 ± 0.14
9.	Chloride (mg/L)	0.235 ± 0.075	0.155 ± 0.155	45.35 ± 6.85	52.11 ± 13.12
10	Hardness (mg/L)	60.37 ± 11.88	54.75 ± 10.25	65.6 ± 14.4	64 ± 12.8
		60 ± 12	63.5 ± 17.5		

Each subindex was given by

$$(SI)_i = q_i \ w_i$$

where q_i is the quality rating of the i^{th} parametere

Then,

$$W.Q.I = \sum_{i=1}^{i=9} q_i w_i$$

The rating scale was set up in 0 – 100 range (Table 9). A typical calculation of WQI is illustrated in Table 10. The seasonal fluctuation in WQI as a function of the fluctuations in the values of the various parameters, is reflected in Table 11.

Table 7. Water quality index of two ponds (January 1986 to September 1987)

Month	*Susta pond*	*Madhaul pond*
January (1986)	188.89	290.51
March	233.99	227.81
May	253.70	248.39
July	321.54	276.47
September	300.61	296.89
November	252.78	226.68
January (1987)	203.42	238.59
March	307.77	248.67
May	285.54	268.98
July	342.71	303.91
September	239.59	313.69

6.0 Towards a national WQI

Considering the ever increasing demand for water – especially safe drinking water – in India and considering that lay people can make little sense out of a water analysis report, WQI can immensely help the public in getting an idea of how safe the water they drink is. Once a layperson has been informed that, say, a water of a WQI value 5 and above is drinkable, and that higher the WQI value better is the water, it can become enormously easy for everyone to judge the fitness of any water source. Therefore, it may be worthwhile if Bureau of Indian Standards, Ministry of Environment & Forests, or Central Pollution Control Board encourage various Indian states to formulate regional indices, and a national index is also formulated by aggregating state indices or by adopting the index common to the most number of states. Such a national WQI, on the lines of the national consumer price index, or national stock-market index, would be very useful in the public comprehension and broad assessment of water quality everywhere in India.

Table 8. Assignment of weightage to water quality parameters

Parameters	*Standards*	*Weights*	*Unit weights*
PH	7.0-8.5	4	0.16
Total Hardness (as $CaCo_3$) mg/l	100-500	2	0.08
Calcium mg/l	75-200	2	0.08
Magnesium mg/l	30-150	2	0.08
Total Alkalinity mg/l	<120	3	0.12
Dissolved oxygen mg/l	>6	4	0.16
Total solids (mg/l)	500-1500	4	0.16
Total suspended solids (mg/l)	<100	2	0.08
Chloride (mg/l)	200-500	2	0.08

Table 9. Rating scale for water quality parameters

Degree of Pollution Rating (qi)	*Permissible*	*Slight*	*Moderate*	*Severe*
	100	*80*	*50*	*0*
PH	7–8.5	8.6–8.8 6.8–7.0	8.9–9.2 6.5–6.7	>9.2 <6.5
Total Hardness (mg/l)	<100	101–300	310–500	>500
Calcium Hardness (mg/l)	<75	76–137	138–200	>200
Magnesium Hardness (mg/l)	<30	31–90	91–150	150
Total Alkalinity (mg/l)	50	51–85	86–120	>120
Dissolved Oxygen (mg/l)	6	4.4–4.9	3–4.5	<3
Total Solids (mg/l)	500	500–1000	1000–1500	>1500
Total Suspended Solids (mg/l)	<30	30–65	65–100	>100
Chloride (mg/l)	<200	201–400	401–600	>600

Table 10. Calculation of WQI of Hanumantal Lake for site I in summer

Parameters	*Value in summer*		
	qi	*Wi*	qiWi
pH	100	0.16	16.0
Total Hardness (mg/l)	100	0.08	8.0
Calcium Hardness (mg/l)	100	0.08	8.0
Magnesium Hardness (mg/l)	100	0.08	8.0
Total Alkalinity (mg/l)	0	0.12	0.0
Dissolved Oxygen (mg/l)	100	0.16	16.0
Total Solids (mg/l)	100	0.16	16.0
Total Suspended Solids (mg/l)	80	0.08	6.4
Chloride (mg/l)	100	0.08	80.0
WQI			86.4

Table 11. Seasonal fluctuations in different parameters and WQI at Hanumanutal, Jabalpur

Parameters	*Summer*		*Monsoon*		*Winter*	
	Site I	*Site II*	*Site I*	*Site II*	*Site I*	*Site II*
pH	7.51 (100)	7.41 (100)	7.45 (100)	7.37 (100)	7.68 (100)	7.61 (100)
Total hardness (mg/l)	94.0 (100)	92.5 (100)	153.0 (80)	167.5 (80)	130.0 (80)	111.87 (80)
Calcium hardness (mg/l)	73.7 (100)	73.7 (100)	118.0 (80)	127.5 (80)	83.73 (100)	73.75 (100)
Magnesium hardness (mg/l)	20.25 (100)	18.75 (100)	35.0 (80)	27.5 (100)	38.75 (80)	45.62 (80)
Total alkalinity (mg/l)	123.5 (0)	128.0 (0)	191.25 (0)	201.25 (0)	107.5 (50)	95.62 (50)
Dissolved oxygen (mg/l)	6.97 (100)	7.25 (100)	7.87 (100)	6.625 (100)	7.0 (100)	6.65 (100)
Total solids (mg/l)	300.25 (100)	305.25 (100)	340.0 (100)	357.75 (100)	370.5 (100)	372.25 (100)
Total suspended solids (mg/l)	63.25 (80)	64.75 (80)	75.5 (50)	84.25 (50)	71.0 (50)	81.0 (50)
Chloride (mg/l)	103.96 (100)	106.46 (100)	58.73 (100)	58.72 (100)	69.97 (100)	64.93 (100)
WQI	86.4	86.4	79.2	80.8	86.8	86.8

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