SR-39

DEVELOPMENT OF WATER QUALITY INDEX

आपो हि ष्ठा मयोभुवः

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE (UP) - 247 667
1993—1994

PREFACE

A wide variety of demands are made for the use of water resources. Water of specific quality unsatisfactory for one use may be acceptable for another. The level of acceptable quality is often governed by the scarcity of the resource or the availability of water of better quality.

Various authorities and regulating agencies have set standards for deciding the permissible concentrations of quality variables. When some variables exceed the permissible levels, a decision for permitting further use of the water supply has to be made based on the importance of those variables with exceeded concentrations. Therefore, it is considered appropriate that standards for various uses of water should be set through a single number representing the integrated effect of all the variables, keeping due regards to the importance of each water quality variable. Such an integrated water quality index would help as a tool in decision making for water resources management.

The report entitled " *Development of Water Quality Index*" prepared by shri Aditya Tyagi, Scientist B of Environmental Hydrology Division, is a review of works carried out in the field of water quality indices. Several techniques of developing water quality index have also been discussed thoroughly. The report is a part of research work of Environmental Hydrology Division of the Institute. The valuable suggestions provided by Dr K.K.S. Bhatia, Scientist ´F´, shri R.D.Singh, Scientist ´E´, shri N.C.Ghosh, Scientist ´C´ of NIH are mentionable.

(S.M.Seth)
DIRECTOR

CONTENTS

LIST OF TABLES

ABSTRACT

Increasing levels of water pollution, with resulting billion dollar use and control programs, necessitate development of water quality indices that provide a means for quantifying and evaluating the quality of a given body of water. Because data output of current water monitoring stations is enormous, and dimensional reporting units are varied and do not combine in a straight forward algebraic manner, even scientifically trained users are unable to assimilate the data and report true quality of water without some methodology to provide data simplification and summation. Possibly even more serious, users with a limited technical background, such as governmental administrators and the general public, are unable to understand and properly interpret raw water quality data stated in scientific dimensional units such as micromohs per cm. Thus, there is a need for a readily comprehensible water quality index system that will bring the important water polluting elements together within one unifying frame work. The index of water quality would communicate the quality of water to those with limited technical knowledge. The water quality index, to be feasible and useful must reduce the vast quantity of water quality information into the simplest form without losing the relevant information. If the index is well designed, however, the measurements used will be representative and will be quantified in such a way that the pollution level reflected by these various measurements comparable with each other and impart a connotation to the scientifically untrained, as well as to the water quality experts, of the overall quality of the water at a given time.

1.0 INTRODUCTION

In this era of technological development, man has collected vast quantities of data and information about himself, his society, and the physical world around him. This large body of data has grown so rapidly that it challenges man's ability to understand and assimilate it. The same technology which made it possible to create this large data base also has produced the automatic computers which makes the task of storing, analyzing and processing the data more reliable and efficient. The computer, however, is just a tool, a slave to the programmers will, and there still remains the task of extracting from the data the pertinent information required to answer questions of importance. Not only must the data be manipulated and reformulated in a way that is understandable to the user, but exactly the right information must be extracted that is relevant to the questions that are being asked.

In the environmental field, an interested member of the public, a representative of a citizens group, or a governmental official typically may seek to determine whether a particular environmental problem is becoming better or worse. The questioners usually will seek answers in the simplest form. The environmental scientists or professional working in the field may feel, on the other hand, that the answer to the question is complex, requiring the interpretation of hundreds of thousands of measurements of different pollutant concentrations and other variables, some times compounded by missing data, inconsistencies, and quality control problems and often giving vague or uncertain results. Unfortunately, however, the questioner usually will not be satisfied by a 500-page telephone book full of raw data, time series plots, statistical analyses of pollutant concentrations at different locations, and other complex findings. He wants a simpler answer.

The questioner could, of course, hire a consultant already familiar with the data to go through the book of numbers to determine a simple answer to the question. This sometimes happens. Another common but unfortunate is for the questioner to be told that the problem is "too complex", that his question can not be answered unless he is willing to learn more about the technical details of the problem. Usually, the fault does not lie with the person asking the question but with those in the technical and scientific communities who may be unwilling or unable to take the trouble to express the answer in terms that the lay man will understand. One reason, of course, is that technical specialists often do not feel comfortable with simple answers to complex questions, they see many nuances of the questions and possible areas for misunderstanding. They prefer to give no answer rather than an imperfect answer that could lead to misunderstanding. Yet the layman usually prefers an imperfect to no answer at all.

Here is where "indices" can play a potentially important communications role. Ideally, an index or an indicator is a means devised to reduce a large quantity of data down to its simplest form, retaining essential meaning of the questions that are being asked of the data. In short, an index is designed to simplify. In the process of simplification, of course, some information is lost. Hopefully, if the index is designed properly, the lost information will not seriously distort the answer to the question. Unfortunately, however, one may not know in advance which question will be asked. This situation creates the hazards that the index will be used for purposes other than those for which it was designed.

The increasing levels of water pollution, with resulting billion dollar use and control programs, necessitate development of water quality indices that provide a means for quantifying and evaluating the quality of a given body of water. Because data output of current water monitoring stations is enormous, and dimensional reporting units are varied and do not combine in a straight forward algebraic manner, even scientifically trained users are unable to assimilate the data and report true quality of water without some methodology to provide simplification and summation. Possibly even more serious, users with a limited technical background, such as government administrators and the general public, are unable to understand and properly interpret raw water quality data stated in scientific dimensional units such as micromohs per cm. Thus, there is a need for a readily comprehensible water quality index system that will bring the important water polluting elements together within one unifying framework. The Index of water quality would communicate the quality of water to those with limited technical knowledge.

1.1 ROLE OF INDICES

Various authors, governmental officials, and committees have emphasized the desirability of developing and utilizing environmental indices. The role that these indices are to play usually is linked to the basic reasons for which environmental monitoring data are collected. Environmental monitoring data consist of routine measurement of physical, chemical, and biological variables that are intended to give in sight into environmental conditions. These data often provide an important yard stick to judge the effectiveness of regulatory programs in improving environmental quality. From a purely conceptual point of view, environmental monitoring data serve as a feed back loop to evaluate the effectiveness of regulatory activities. Once the environmental monitoring data are collected, there is a further need to translate it into a form that is easily understood. Once the indices are developed and applied, they should serve as a 'tools' to examine trends, to highlight specific environmental conditions, and to help governmental decision-makers in evaluating the effectiveness of regulatory programme.

Environmental indices, of course, are not the only source of information that is brought to bear on environmental decisions. Decision-making will be based on many other considerations besides indices and the monitoring data on which they are based. Ott (1978) identified six basic uses of environmental indices -

i) Resource allocation

Indices may be applied to environmental decisions to assist managers in allocating funds and determining priorities.

ii) Ranking of allocations

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

v) Public information

Indices may be used to inform the public about environmental conditions.

vi) Scientific research

Indices may be applied as a means for reducing a large quantity of data to a form that gives insights to the researchers conducting a study of some environmental phenomenon.

In each of these applications, the index helps in conveying information about the state-of the-environmental phenomeon. Because the questions being asked are different in each application, however the index may differ in terms of the variables included, the basic structure, and the manner in which it is applied. Because different users have different data-reporting needs, identification of the users should be critical part of the development and application of any environmental indices.

2.0 STRUCTURE OF ENVIRONMENTAL INDICES

The environmental indices can be formulated in two general environmental index forms: (1) those in which the index numbers increase with the degree of pollution (increasing scale indices), and (2) those in which the index numbers decrease with the degree of pollution (decreasing scale indices). Some specialists in the field refer to the former as "environmental pollution indices and the later as "environmental quality" indices. This framework is better suited to representing absolute indices than relative indices.

2.1 MATHEMATICAL STRUCTURE

In this general framework, calculation of an index consists of two fundamental steps:

i) calculation of subindices for the pollutant variables used in the index, and

ii) aggregation of the subindices into the overall index.

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

$$I_i = f_i(x_i) \qquad (1)$$

In most environmental index, a different mathematical function is used to compute each pollutant variable, giving the subindex functions $f_1(x_1)$, $f_2(x_2)$...... $f_n(x_n)$. Each subindex function is intended to represent the environmental characteristics of the particular pollutant variable. It may consists 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:

$$I = g(I_1, I_2, \ldots\ldots I_n) \tag{2}$$

The aggregation function, Eq. (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 a maximum operation, in which just the maximum subindex is reported.

The overall process-calculation of subindices and aggregation of subindices to form the index can be illustrated in a flow diagram (Fig.1). In this process, the information contained in the raw data (environmental measurements) flow from left to right and is reduced to a more parsimonious form. Some information may be lost; however, in a properly designed index, the information loss should be of such a nature that it does not cause the results to be distorted or ultimately misinterpreted.

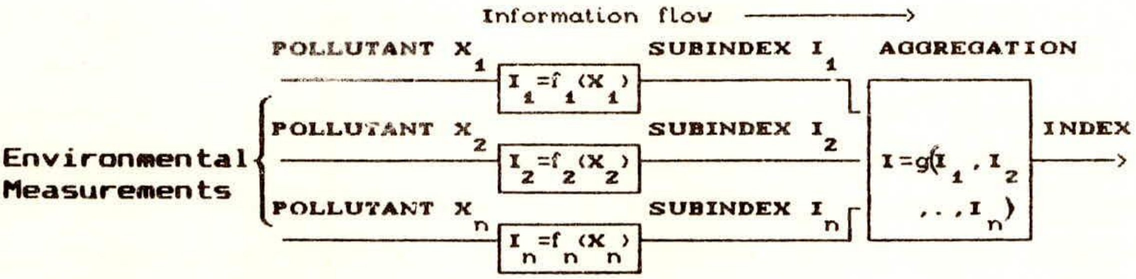

Fig. 1. Information flow process in an Environmental index

2.2 SUBINDICES

Subindices can be classified as one of four general types:

i) Linear

ii) Non linear

iii) Segmented linear

iv) Segmented nonlinear

2.2.1 Linear function

The simplest subindex function is the linear equation:

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

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 have the advantages that they are simple to compute and easy to understand. The disadvantage with linear system is that they provides little flexibility.

2.2.2 Segmented linear function

A segmented linear function consists of two or more straight line segments joined at break points (threshold level). It offers more flexibility. It is especially useful for incorporating administratively recommended limits, such as indian standards limits, WHO limits etc. An important segmented linear function is the step function, which exhibits just two states and therefore is called a dichotomous function. Subindices also may consist of a staircase of steps, giving a multiple-state function. For example, Horton's index (1965) uses subindex functions containing three, four, and five steps. In Horton's dissolved oxygen subindex, I = 0 for x less than 10% saturation, while 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:

Suppose 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, $j = 1, 2, 3, \ldots\ldots\ldots, m$.

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

2.2.3 Non linear function

A non-linear function is any relationship which exhibit curvature when plotted on linear paper. The non-linear functions can be further divided in 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.

In explicit nonlinear functions, curvature is achieved automatically. 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:

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

where $c = 1$

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

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

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

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

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:

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

2.2.4 Segmented Nonlinear Function

Segmented nonlinear functions consist 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, has been used in a number of water quality indices. Prati et.al (1971) used a segmented nonlinear function for the pH subindex in their water quality index. The pH subindex function contains four segments as given in Table 1:

Table 1. Parti's Subindex Functions used for p^H

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

2.3 AGGREGATION OF SUBINDICES

The aggregation process is one of the most important steps in calculating any environmental index. In this step most of the simplification (reduction of information) and distortion takes place. In general, four types of aggregation functions are available as described below:

2.3.1 Additive Forms

The simplest aggregation functions are the additive forms which can be further divided in to following three forms:

2.3.1.1 Linear Sum

Linear sum is the addition of unweighted subindices, in which no subindex is raised to a power other than 1.

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

where I_i = subindex for pollutant variable i

n = number of pollutant variables

In an increasing scale index, the linear sum unfortunately exhibits an ambiguous region; that is, the overall index can report poor environmental quality when no subindex exhibits poor environmental quality as explained below:

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

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

In this simple index, we shall assume that I_1 and I_2 are dichotomous subindices in which $I_1=0$ and $I_2 = 0$ represent zero water pollutant concentrations for pollutant variables x_1 and x_2, and $I_1 \geq 100$ or $I_2 \geq 100$ represent concentration at or above the permissible level. Most users will expect I above 100 to mean unequivocally that permissible level is violated for at least one subindex, and it is unfortunately possible for I to exceed 100 without a permissible limit being violated. For example, if moderate pollution levels occur for both pollutant variables, giving $I = 50$, and $I = 50$ then $I = 100$. Similarly if $I = 60$ and $I = 70$ then $I = 130$. The index conveys the impression that a permissible level has been violated when it has not been, giving an exaggerated and ambiguous reading. This problem is called as ambiguity problem.

2.3.1.2 Weighted Sum

The weighted linear sum has the following general form:

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

where I_i = subindex for i^{th} variable

w_i = weight for i^{th} variable

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

The weighted linear sum avoids the ambiguity problem but introduces a more serious problem called 'eclipsing'. Eclipsing occurs when at least one subindex exhibits poor environmental quality, but the overall index does not exhibit poor environmental quality as explained below:

For the two variable case,

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

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

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

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

from Eq. (15) it is clear that I=0 when both I_1 & I_2 = 0 i.e. (15) report the zero pollution 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.

Now putting $I_1 = 50$ and $I_2 = 110$ with $w_1 = 0.5$, gives I = 80. Because the overall index is less than 100, violation of the permissible level for variable x_2 ($I_2 > 100$) is eclipsed.

2.3.1.3 Root Sum Power

To alleviate the eclipsing problem, a somewhat more complex additive form is available. The root-sum-power is a nonlinear aggregation function of the following form:

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

where p = is a positive real number, greater than 1. As p becomes larger, the ambiguous region becomes increasingly smaller. Thus, for large value of p, the ambiguous region is almost entirely eliminated. For the limiting case in which p approaches infinity, the root-sum-power has desirable properties for aggregating subindices. It possesses neither an eclipsing region nor an ambiguous region. However, because it is a limiting function, it is somewhat unwidely to write and use.

2.3.2 Maximum Operator

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

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

In the maximum operator, I takes on the largest of any of the subindices, and I=0 if and only if 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 environmental 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 report the worst subindex. The suitability of the maximum operator for use in water pollution indices has not been investigated, however, and none of the published water quality indices have employed this aggregation function.

2.3.3 Multiplicative Forms

The multiplicative forms have found use primarily in indices that have decreasing scales. Most of the water quality indices are based on decreasing scale forms. The water quality index proposed by Brown et.al (1970) originally used an additive aggregation function, the weighted linear sum. Later Landwehr (1974) evaluated multiplicative aggregation functions that could be substituted for the additive form, and the multiplicative form has become the most popular version of this index.

Like increasing scale indices, many decreasing scale indices exhibit both the ambiguity and eclipsing problems. In general, the additive forms do not appear well suited for aggregating decreasing scale subindices.

To avoid such problems, the multiplicative forms have been proposed. The most common multiplicative aggregation function is the weighted product, which has the following general form:

$$I = \prod_{i=1}^{n} I_i^{w_i} \tag{18}$$

where $\sum_{i=1}^{n} w_i = 1$ (19)

In this aggregation function, as with all multiplicative forms, the index is zero if any one subindex is zero. This characteristic eliminates the eclipsing problem, because, if any one subindex exhibits poor environmental quality, the overall index will exhibit poor environmental quality. Conversely, I=0 if and only if at least one subindex is zero, and 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:

$$\sum_{i=1}^{n} w_i = n\ w = 1 \qquad (20)$$

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

$$I = \left[\prod_{i=1}^{n} I_i\right]^{w} = \left[\prod_{i=1}^{n} I_i\right]^{1/n} \qquad (21)$$

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:

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

where $$\gamma = \sum_{i=1}^{n} g_i \tag{23}$$

2.3.4 Minimum Operator

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

$$I = \min \left\{ I_1, I_2, \ldots\ldots\ldots\ldots\ldots, I_n \right\} \tag{24}$$

Like the weighted product in the minimum operator functions, eclipsing can not occur, and no ambiguous region exists. 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 apparently remains unexplored.

3.0 WATER POLLUTION INDICES IN THE LITERATURE

In response to the increasing concern with water quality indices, a variety of system have been proposed; comprehensive reviews of these systems have been published by Landwehr (1974) and Ott (1978a, 1978b).

Attempts were made in Germany as early as 1848 to relate the level of water purity and pollution to the occurrence of certain biological organisms. Over the last 150 years, various European countries had developed and applied different systems to classify the quality of the waters within their boundaries. These water classification systems usually were of two types:

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

ii) those concerned with living communities of macro-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.

To present the many physical and chemical indices found in the literature in an orderly fashion, the indices had been classified into five general categories:

i) General water quality indices.

ii) Specific-use indices.

iii) Planning indices.

iv) Statistical approaches.

v) Biological approaches.

3.1 General Water Quality Indices

Water has a variety of different uses, for example, supply of public drinking water, crop irrigation, recreation, and maintenance of fish and wildlife habitats. Water quality requirements vary, depending on the intended use. Some indices, however, are based on the assumption that water quality is a general attribute of surface water, irrespective of the use to which the water is put. There are five indices designed for general water quality use:

i) Horton's quality index

ii) National Sanitation Foundations Water Quality Indices

iii) Parti's Implicit Index for Pollution

iv) McDuffe's River Pollution Index.

v) Dinius Social Accounting Index.

vi) Dinius Index of Water Quality (IWQ)

3.1.1 Horton's Quality Index

Horton (1965) proposed the first formal water quality index for evaluating abatement programs and for giving public information. He argued that water quality and pollution are relative terms, and concluded that there is need for a system whereby water quality could be rated on a comparative basis so that the user may compare different locations and different points in time in terms of gradations in water quality. Horton (1965) imposed the following criteria in selecting the variables for the index.

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

ii) The variables should be of significance in most part of the country.

iii) The variables should reflect the availability of data.

Horton selected 10 widely measured water pollution variables for his index e.g. dissolved oxygen (DO), pH, coliforms, specific conductance, alkalinity and chloride content etc. 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 on 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, and the break points give staircase step function subindices. However, the Horton's index did not include any toxic substances.

In Horton's water quality index a linear sum aggregation function was used. It 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:

$$QI = \frac{\sum_{i=1}^{n} w_i I_i}{\sum_{i=1} w_i} M_1 M_2 \qquad (25)$$

Horton's index has the advantage that is relatively easy to apply, although the coefficients M1 and M2 require some tailoring to fit individual situations. The index structure and its weights and rating seals were considered preliminary and were based on the judgment of the author and his associates.

3.1.2 National Sanitation Foundation's Water Quality Index

Brown et al.(1970) developed a water quality index similar in structure to Horton's index. This effort was supported by the National Sanitation Foundation (NSF), and the resulting index was known as National Sanitation Foundation Water Quality Index (NSF WQI). The NSFWQI was developed using a formal procedure based on the Delphi technique to combine the opinions of a large panel of water experts from throughout the US.

Initially 35 water quality variable were considered and ranked in order of decreasing importance to overall water quality. After that, 9 new variables were introduced e.g. chromium, total organic carbon,cyanides, specific conductance, lead, arsenic, cadmium, selenium, and zink. Out of these 44 variables the investigators identified 9 individual variables and 2 grouped variables of greatest importance. The individual variables were DO, fecal coliforms, pH, 5-day BOD, nitrates, phosphate, temperature, turbidity, and total solids (TS). The grouped variables were toxicants and pesticides. The investigators subsequently averaged the curves from the respondents to produce a set of average curves, one for each pollutant variable.

To calculate the index, one reads the subindex value I_i from the appropriate rating curve for pollutant variable i. In the original structure proposed by Brown et.al (1970), the index, NSF WQIa, is the weighted lienar sum of the subindices:

$$NSFWQI_a = \sum_{i=1}^{n} w_i \; I_i \qquad (26)$$

Although the additive form of the index had been widely used, an alternate multiplicative form, NSFWQIm, was proposed subsequently to overcome the eclipsing which occurs when a single pollutant variable shows extremely poor water quality. The multiplicative form was:

$$NSFWQI_m = \prod_{i=1}^{n} I_i^{w_i} \qquad (27)$$

The NSF WQI had been widely field tested and applied to data from a number of different geographical areas. In 1973, it was applied by Brown et.al to data from california, colorado, Maryland, Michigan, Ohio, Pennsylvania and Tennessee. In 1974, it was applied by McClelland to the Kansas River Basin. Although the index is widely known, some water quality specialists have been reluctant to adopt it, citing various technical reasons.

3.1.3 Prati's Implicit Index of Pollution

Prati et al.(1971) proposed an index for surface waters based on water quality classification systems used in a number of different countries. The investigators advocated that their index may be used as a tool for establishing a comparative inventory of the quality of water resources in a given region or country, but they did not believe it should be used to make waste water treatment decisions.

For the development of this index, the authors first developed their own classification system involving, 13 pollutant variables. The system had five different water quality classes, I to V, and subindex ranged were assigned to each class. the upper limits of the first four ranges were 1,2,4 and 8, which correspond to a geometric progression. Toxic substances were not included. For each subindex, the investigators developed explicit mathematical functions (Table 2).

Table 2. Subindex Function for Parti's Index

S.No	Parameter	Subindex
1	Dissolved Oxygen (%)	$I=0.00168x^2-0.249x+12.25, 0\le x<50$ $I=-0.08x+8, \quad 50\le x<100,$ $I=0.08x-8, \quad 100\le x.$
2	p^H (units)	$I=-0.4x^2+14, \quad 0\le x<5,$ $I=-2x+14, \quad 5\le x<7,$ $I=x^2-14x+49, \quad 7\le x<9,$ $I=-0.4x^2+11.2x+64.4, \quad 9\le x<14$
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)	$I=0.000228x^2+0.0314x, \quad 0\le x<50,$ $I=.000132x^2+.0074x+0.6, 50\le x, 300,$ $I=3.75(0.02x-5.2)^{0.5}, \quad 300\le x$
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)	$I=x$

Prati's index was computed as the arithmetic mean of the 13 subindices:

$$I = \frac{1}{13}\sum_{i=1}^{13} I_i \qquad (28)$$

The index ranges from 0 to 14 (and above). This index was applied by the investigators to data on surface waters in the province of Ferrana, Italy. All the pollutant variables were not available for this pilot application, however, and no papers describing the subsequent fate of this index, or any more extensive applications, could be found in the literature.

3.1.4 McFuffe's River Pollution Index (RPI)

McDuffie and Haney (1973) presented a relatively simple water quality index. According to them the indices could be applied to river water data to facilitate a variety of analysis e.g. a valid index would provide a measurement and picture of water quality at any instant,and a way to compare different rivers as well as trends over the years for a particular river.

A total of eight pollutant variables were included in the index and many of the subindices are of the general linear form:

$$I_i = 10 \left(\frac{x}{x_N} \right)_i \qquad (29)$$

where

I_i = subindex of the ith 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 3). The index did not include pH or toxic substances.

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

Table 3. Subindex Functions for 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)	$I = 10\left(\frac{\log x}{\log 3}\right)$
5	Nonvolatile Suspended Solids	$I = x$,
6	Average Nutrient Excess	$I = \left(\frac{x}{0.2} + \frac{y}{0.1}\right)$, x=Total N, y=Total-Po_4 (ppm)
7	Dissolved Salts	$I = 0.25x$, x=specific conductance
8	Temperature	$I = \frac{x^2}{6} - 65$

$$RPI = \frac{10}{n+1} \sum_{i=1}^{n} I_i \qquad (30)$$

The RPI was applied on a test basis using data from New york State's water quality surveillance network and from other sources. The eventual fate of the RPI was unknown, and no further applications of this index appeared in the literature.

3.1.5 Dinius' Social Accounting System

Dinius'(1972) had proposed a water quality index as a first step toward designing a rudimentary social accounting system which would measure the costs and impact of pollution control efforts. In this water quality index 11 pollutant variables were included. 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 index and McDufie and Haney's index, the subindices 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 (Table 4).

Table 4. Subindex Functions for Dinius' Water Quality Index

S.No	Parameter	Subindex
1	Dissolved Oxygen (%)	$I = x$
2	5-Day BOD (mg/L)	$I = 107x^{-0.642}$
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)	$I = 535x^{-3565}$
6	Chlorides (mg/L)	$I = 125.8x^{-0.207}$
7	Hardness ($CaCo_3$,ppm)	$I = 10^{1.974-0.00132x}$
8	Alkalinity ($CaCo_3$,ppm)	$I = 108x^{-0.178}$
9	p^H	$I = 10^{0.2335+0.44}, x<6.7$ $I = 100, \quad 6.7 \le x \le 7.58$ $I = 10^{4.22-0.293x}, \ x>7,58$
10	Temperature (^{o}C)	$I = -4(x_a - x_s) + 112,$ x_a=actual temp, x_s=std.Temp
11	Color	$I = 128x^{-0.288}$

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

$$I = \frac{1}{21}\sum_{i=1}^{11} w_i I_i \qquad (31)$$

The weights range 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 weights sum was 21, which is the denominator in the index equation.

The index was applied by Dinius an an illustrative basis to data on several streams in Alabama. However, the literature did not contain any subsequent applications of this index.

3.1.6 Dinius Index of Water Quality (IWQ)

A multiplicative water quality index was developed by Dinius (1987) using Delphi technique, originally designed by scientists at the Rand Corporation (Helmer and Rescher 1959 , Dalkey and Helmer 1963). The IWQ included 12 pollutants: dissolved oxygen, 5-day BOD, Coliform count, E-coli, pH, alkalinity, hardness, chloride, specific conductivity, temperature, color, and nitrate for the six water uses of public water supply, recreation, fish shellfish, agriculture, and industry.

The subindex function of each pollutant was expressed in as parsimonious a mathematical function as possible without having the data simplification cause distortion of the index. Table 5 shows the formulation of the Index of Water Quality.

The 12 individual subindex functions were combined into one general function using a multiplicative aggregation function in which the weight of each subindex equation was based on

Delphi-panel member's evaluation of the importance of each pollutant to overall pollution. The final multiplicative aggregation function had the general form:

Table 5. Subindex Functions of 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/100ml	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	$506(SPC)^{-0.3915}$
p^H	$p^H<6.9$	0.077	$10^{0.6803+0.1856(p^H)}$
	p^H-units(6.9–7.1)		1
	$p^H>7.1$		$10^{3.65-0.2216(p^H)}$
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	$127(C)^{-0.2394}$

$$IWQ = \prod_{i=1}^{n} I_i^{v_i} \qquad (56)$$

where

IWQ= the index of water quality, a number between 0 and 100;

I_i= subindex of pollutant variable, a number between 0and 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 can be calculated by subsituting their corrosponding value of subindex function and its weightage. For example, Weighted function for BOD:

$$I_{BOD}^{w_{BOD}} = \left[108\ (BOD)^{-0.3494} \right]^{0.097}$$

The index of Water Quality (IWQ) is the product of the 12 weighted functions so obtained.

3.2 Specific Use Water Quality Index

The most significance problem in the development of water quality indices is that the uses of water are manifold and the quality of water demanded for each purpose varies tremendously. A high value of certain parameter may be desirable in one instance and indifferent or even detrimental in another. For example, a high dissolved oxygen concentration is essential if good fishing is to be found in a body of water, but is only of marginal value in a drinking water supply, while it is highly undesirable in boiler feed water. Even within one use category, such as recreation, different variables have different importance. For example, boating uneffected by dissolved oxygen concentration and coliform count as well, while swimming is drastically affected by the coliform count, and fishing is affected by both.

Some water quality specialists who do not accept the concept of general water quality Indices, believe that each index should be designed for a specific water use. A number of specific-use water quality indices have been proposed:

i) O'Connor's indices (fish and wild life, public water supply)

ii) Deininger and Landwehr's PWS index (public water supply)

iii) Walski and Parker's index (recreation)

iv) Stoner's index (public water supply, irrigation)

v) Nemerow and sumitomo's index (human contact, indirect contact, remote contact)

vi) Bhargave's index (drinking water supply)

3.2.1 O'Connor's Indices

O'Conner developed two water quality indices first for Fish and Wild Life (FAWL) and the second for public water supply (PWS). The FAWL index includes a pollutant variables, and was intended to describe the quality of raw surface water used to sustain a population of fish and wild life. The PWS index includes 13 pollutant variables, and was intended to describe the quality of raw surface water which will be treated as necessary and used for public water supplies. Both indices were developed using an approach similar to the Delphi technique employed by Brown et al. (1970). The parameters and their weights for both the indices are tabulated and compared with the NSFWQI in Table 6.

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

$$I_{FAWL} = \delta \sum_{i=1}^{9} w_i I_i \tag{32}$$

$$I_{PWS} = \delta \sum_{i=1}^{11} w_i I_i \tag{33}$$

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

Table 6: 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
p^H	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

3.2.2 Deininger and Landwehr's PWS index

Deininger and Landwehr (1971) presented a specific use index intended for water used for public water supply (PWS). The overall approach was similar to that used by Brown et al. (1970). To deal the problem in well water situation and free flowing streams, the investigators proposed two public water supply indices, an 11-variable version (without iron and fluorides) and a 13-variable version. The importance ratings were used to develop weights for each of the two versions. The subindex curves were averaged to give mean subindex functions for each of the 13 pollutant variables.

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

Additive

$$PWS_n = \sum_{i=1}^{n} w_i I_i \qquad (34)$$

Geometric mean

$$PWS_n = \left[\prod_{i=1}^{n} I_i^{w_i} \right]^{1/n} \qquad (35)$$

where, n = 11, for 11-variable version

= 13, for 13-variable version.

The variables along with their associated weights for both the versions are tabulated and compared with NSFWQI in Table 7.

Table 7: 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
p^H	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

3.2.3 Walski and Parker's Index:

Walski and Parker (1974) developed a water quality index specifically intended for the recreational use of water, such as swimming and fishing. They 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).

A total of 12 different pollutant variables were used in the index. The subindices consists of nonlinear and segmented nonlinear explicit functions (Table-8). Except for the two unimodel variables, pH and temperature, all subindices are represented by negative exponential equations. The pH and temperature, subindices were represented by parabolic equations. Two subindices were used for temperature; one for actual temperature and another for departure from equilibrium temperature. To aggregate subindices, Walski and Parker choose a geometric mean over an arithmetic mean to avoid the problem of eclipsing. Their aggregation function is as follows:

$$I = \left[\prod_{i=1}^{12} I_i^{w_i} \right]^{1/12} \qquad (36)$$

The published article on this index did not give the value of the weights.

Table 8: Subindex Functions for Index Proposed by Walski and Parker

Pollutant Variable	Equation	Range
Dissolved oxygen (mg/L)	$I=e^{[0.9(x-8)]}$	$0<x\le 8$
	$I=0$	$8<x$
p^H(Std.Units)	$I=0$	$x<2$
	$I=0.04[25-(x-7)^2]$	$2\le x\le 12$
	$I=0$	$12<x$
Total Coliforms(no./100ml)	$I=e^{-0.0002x}$	
Temperature (^oC)	$I=0.0025[1-(x-20)^2$	$0\le x\le 40$
	$I=0$	$\Delta x<-10$
	$I=0.01(100-\Delta x)^2]$	$-10\le\Delta x\le 10$
	$I=0$	$10<\Delta x$
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)	$I=e^{-0.002x}$	
Grease (Concentration(mg/L)	$I=e^{-0.016x}$	
(Thickness, μ)	$I=e^{-0.35x}$	
Odor	$I=e^{-0.1x}$	
Secchi Disk Transparency(m)	$I=\log(x+1)$	$x\le 9$
	$I=1$	$9<x$

3.2.4 Stoner's Index

Stoner (1978) proposed a specific use water quality index designed for two water uses: public water supply and irrigation. This index 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 general types of variables are used in the Stoner's index:

Type I: Variables normally considered toxic (for example, lead, chlordane, radium-226)

Type II: Variables 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.

A total of 26 type I pollutant variables were used in the public water supply version of the index, and 5 type I variables were used in the irrigation version. The type-II pollutant variables in Stoner's index are represented, on the other hand, by explicit mathematical functions. The subindices functions for stoner's public water supply index and for irrigation index as shown in Table 9 and 10.

Table 9: Subindex Functions for Stoner's Public Water Supply Index

Variable	Subindex Function
Group-A(w=0.134)	
Ammonia-Nitrogen(mg/L)	$100-200x$
Nitrate-Nitrogen(mg/L)	$100-100x^2$
Fecal-Coliforms(no./100ml)	$100-0.000025x^2$
Group-B (w=0.089)	
p^H(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)	$100-333x$
Zink (mg/L)	$100-20x$
Color(Pt-Co units)	$100-0.0178x^2$

Table 10: Subindex Functions for Stoner's Irrigation Index

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)	
Aluminum(mg/L)	$100-4x^2$
Beryllium(mg/L)	$100-10^4x^2$
Chromium(mg/L)	$100-10^4x^2$
Cobalt(mg/L)	$100-2000x$
Manganese(mg/L)	$100-500x$
Vanadium(mg/L)	$100-1000x$
Group-D(w=0.028)	
Copper(mg/L)	$100-2500x^2$
Fluorides(mg/L)	$100-100x^2$
Nickel(mg/L)	$100-2500x^2$
Zinc(mg/L)	$100-25x^2$

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

$$I = \sum_{i=1}^{n} I_i + \sum_{j=1}^{m} w_j I_j \tag{37}$$

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.

3.2.5 Nemerow and Sumitomo's Pollution Index

Nemerow and Sumitomo (1970) had proposed an increasing scale water quality index consisting of three specific use indices. The three separate water uses were denoted by j=1,2, and 3.

i) Human contact use (j=1)

ii) Indirect contact use (j=2)

iii) Remote contact use (j=3).

Human contact use includes uses in which humans come into direct contact with the water, such as drinking (including water uses for beverage manufacturing) and swimming. Indirect contact use includes uses in which humans have less direct contact with waters, such as fishing, food processing, and agriculture. Finally, remote contact use 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:

$$I = \alpha x + \beta \tag{38}$$

where $\alpha = \dfrac{1}{x_s - x_o}$;

$\beta = - \dfrac{x_o}{x_s - x_o}$

For unimodel subindex functions, such as pH, two line segments are joined together, one with negative slope and one with a positive slope.

$$I = \frac{x_o - x}{x_o - x_a}, \quad \text{for} \quad 0 \leq x \leq x_o \tag{39}$$

$$I = \frac{x - x_o}{x_s - x_o}, \quad \text{for} \quad x_o \leq x \tag{40}$$

where x = pollutant variable

x_a = lower recommended limit

x_s = upper recommended limit

x_o = desired level.

To reduce eclipsing problems, 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:

$$I_j = \sqrt{\frac{\left[\max_{\text{all } i}\left\{I_{ij}\right\}\right]^2 + \left[\frac{1}{n}\sum_{i=1}^{n} I_{ij}\right]^2}{2}} \tag{41}$$

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 (Table 10).

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

$$I = \sum_{i=1}^{3} w_i I_i \tag{42}$$

3.2.6 Bhargave's Index

Bhargave (1985) presented a water quality index for drinking water supply. For evolving the subindex functions for different variables used in defining the standards for drinking water supply, all the variables were divided into 4 groups. These groups were based on the importance related to the health of the people, and the degree of flexibility in allowing the concentrations to exceed the set standards. The first group includes the concentrations of coliform organisms which represent the bacterial quality of drinking water. The second group of variables include toxicants, heavy metals, etc. Some or all of which have a cumulative toxic effect on the consumer. The third group of variables include the material that cause physical effects, such as odor, color, turbidity, and other aesthetic qualities which are important factors in the public's acceptance and confidence in a public water supply system. The fourth group of variables includes the inorganic and organic nontoxic substances such as chloride, sulfates, foaming agents, iron, manganese, zink, copper total dissolved solids (TDS), etc. The variables with their maximum allowable contaminant level, C_{MCL} as per the US Environmental Protection Agency) and their suggested subindices which includes the effect of concentration and their weights in the use, are given in Table 11.

Table 11. Subindex Functions of Bhargave'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 variables,e.g.,turbidity,color.	$f_1 = \exp[-2(C-1)]$	1TU 15 Color Units
Group IV Organic & Inorganic non toxic substances,e.g., chlorides,sulphates,TDS.	$f_1 = \exp[-2(C-1)]$	250 mg/L each 500 mg/L

The subindices were aggregated according to the following model:

$$WQI = \left[\prod_{i=1}^{n} f_i \right]^{1/n} \tag{43}$$

in which, f_i = subindex for i^{th} variable varied from 0-1.

n = number of variables considered.

Bhargave (1985) applied his model to the raw water quality data at the upstream and down stream side of the Delhi streach of the river Yamuna. He suggested that the public drinking water supplies should have a WQI larger than 90.

3.3 Planning Indices

Planning indices are specifically designed for management decision making. Unlike the general and specific use indices, these indices usually do not depict ambient water quality or related conditions. Rather, they are custom designed to assist the user in making specific decisions or in solving particular problems. Planning indices often incorporate variables other than those routinely measured by water pollution monitoring programs. For example, a planning index designed for allocating water pollution abatement funds might include the cost of waste water treatment facilities.

A great many planing indices had been proposed by different investigators, and some of the example are given below:

i) MITRE's Indices
ii) Dee's Environmental Evaluation System (EES)
iii) Inhaber's Canadian National Index
iv) Zoeteman's Pollution Potential Index
v) Johanson and Johanson's Pollution Index.

3.3.1 MITRE's Indices

MITRE's National Planning Priorities Index (NPPI) is a planning index (Ott 1978) designed to assign priorities to each planning area within the nation in order to ensure that funds are granted and used in a cost effective manner for the planned waste treatment projects. It was computed as the weighted sum of 10 sub indices:

$$NPPI = \sum_{i=1}^{10} w_i I_i \tag{44}$$

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

3.3.2 Dee's Environmental Evaluation System

Dee et al. (1972,1973) proposed a general system for evaluating the environmental impact of large scale water resources projects. The environmental evaluation system was designed to assess environmental impact in four major categories: ecology, environmental pollution, aesthetics, and human interest. These four categories were represented by 18 components and, finally, by 78 individual variables. The 78 variables include factors such as soil erosion, sportfish, waterfowl, housing, land use, ethnic groups and noise. An important part of this system was a water quality index, which was represented by 12 common water quality variables (DO, pH, turbidity, fecal coliforms, etc.) plus pesticides and toxic substances. The sub index functions of various water quality variables were similar to those in the NSFWQI.

In evaluating the overall subindex the index was calculated with out considering the proposed water resources project. Then the calculation was repeated with the proposed project. The difference between the two scores was considered a measure of the environmental impact (EI) of project:

$$EI = \sum_{i=1}^{78} w_i I_i\,(\text{with}) \; - \; \sum_{i=1}^{78} w_i I_i\,(\text{without}) \tag{45}$$

The EES had been criticized by Andrews (1974) because of the relative importance given to the variables by the choice of weights.

3.3.3 Inhaber's Canadian National Index

The Environmental Quality Index (WQI) suggested by Inhaber (1974) as a national index for Canada included an air quality index, a water quality index, and a land quality index.

The water quality index (1974) 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 was, 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 fine sources (municipal wastes and the petroleum-refining, chlor-alkali, fish-processing, and paper industries). The subindices were combined in successive root mean square operations.

3.3.4 Zoeteman's Pollution Potential Index

The Pollution Potential Index (PPI) developed by Zoeteman (1973) was a planning index 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:

$$PPI = \frac{NG}{Q} \times 10^{-6} \qquad (46)$$

in which

N = number of people living in a drainage area

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

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

Zoeteman applied the PPI to 160 river sites through out 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. He, also applied the PPI to the Rhine river (1973) in a detailed fashion. He considered the index as a tool for predicting future water pollution problems.

3.3.5 Johanson and Johanson's Pollution Index

Johanson and Johanson (1976) developed a planning index as a tool or 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:

$$PI = \sum_{i=1}^{n} w_i C_i \qquad (47)$$

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 in place pollutants.

3.4 STATISTICAL APPROACHES

Numerous statistical approaches had been suggested for evaluating and interpreting water quality data. These approaches usually employ some standard statistical procedure already available in the literature. The statistical approaches have the advantage that they incorporate fewer subjective assumptions than the traditional indices; however, they are more complex and often more difficult to apply.

One class of statistical approaches is correlation techniques, examines the associations among variables to determine the importance of each as a determinant of water quality. Shoji, Yamamoto and Nakamuna (1966) applied factor analysis to the Yodo River system in Japan to examine the interrelationships among 70 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: Pollution, Temperature and rainfall. Landwehr (1979) attempted to extend the basis for index assessment by treating indices as random variables. According to him - "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 initially. By manipulating the matrix of correlation coefficients, they were able to identify linear combinations of the variables which best explain the variance but which have low correlations with each other. The approach retains the most important information in the raw data while eliminating redundant variables. They 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 then were applied to the Snake and Colorado River Basins in Nevada. Finally, the Index of Total Nutrients (with the variables DO, BODs, total phosphates, temperature and conductivity) was selected, and its performance was compared with that of the NSFWQI using water quality data from 20 locations in the U.S.

In another correlation study, Coughlin et al. (1972) examined the relationship between the NSFWQI and the uses of a stream made by 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 or fish in it. They reported that increased water pollution was associated with reduced wading, fishing, picnicking, bird watching, walking and other activities.

3.4.1 Harkin's Index

Harkin (1974) presented a statistical approach for analyzing water quality data which was based on the rank order of observations. He felt that absolute indices, such as the NSF WQI by Brown et al. (1970) lack objectivity.

Harkin's index was an application of Kendall's (1975) nonparametric classification procedure. The approach begins by ranking the observations 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 (Ric), divided by the standard deviation of the ranks S:

$$Z_{ij} = \frac{R_{ij} - R_{ic}}{S_i} \qquad (48)$$

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 ranks for the i^{th} variable then the index is computed for each observation by adding the square of the transform for n pollutant variable:

$$I_j = \sum_{i=1}^{n} Z^2_{ij} \qquad (49)$$

the standard deviation S_i:

$$S_i = \sqrt{\frac{m^2_i - 1}{12}} \qquad (50)$$

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

within the observations, the same value often appears more than ones; these repeated values reduce the variance and must be taken into account. When repeated values occur, the standard deviation S_i was calculated as follows:

$$S_i = \left[\frac{1}{12\, m_i} \left\{ m_i^3 - m_i - \sum_{k=1}^{q_i} (t^3 - t)_k \right\} \right]^{1/2} \qquad (51)$$

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 was 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 sets. Landwehr et al. (1974) criticized this property.

3.4.2 Beta Function Index:

Schaeffer and Janardan (1977) exploited the Harkin's (1974) approach in to a statical index which has a fixed range, the Beta Function Index. The Beta Function Index uses the same ranking procedure employed in Harkin's index. Two additional values were computed from the ranks- the sum of the square of the Z-transforms given by Eq. (z_{ij}) and the sum of all the ranks excluding the control values:

$$S = \sum_{i=1}^{n} \sum_{j=1}^{m_i} Z_{ij}^2 \qquad (51)$$

$$T = \sum_{i=1}^{n} \sum_{j=1}^{m_i - 1} R_{ij} \qquad (52)$$

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

n = number of pollutant variables

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

$$I = \frac{1}{b}\left[\frac{S}{S + T}\right]^{1/2} \tag{53}$$

$$b = \left[\frac{2\sum_{i=1}^{n} m_i^{\,2}}{3\sum_{i=1}^{n} m_i^{\,2} + \sum_{i=1}^{n} m_i - 2n}\right]^{1/2} \tag{54}$$

If the number of observations for each variable is the same (i.e., $m_i = m$, for all i), then Eq. (54) can be simplified:

$$b = \left[\frac{2\,m^2}{3\,m^2 + m - 2}\right]^{1/2} \tag{55}$$

Because it was assumed to have a chi-square distribution and T was approximately constant, the investigators conclude that the index follow a beta probability distribution. Thus, the index is non parametric; it distribution is the same regardless of the underlying distribution of the data.

3.5 Biological Indices

Biological water quality indices generally evaluate water quality in terms of its impact on aquatic life in some form. There are three basic approaches.

The first approach focuses on the types and quantities of certain indicator organisms. An example is the saprobic classification systems employed in environments rich in degradable organic matter. The saprobic systems divide a stream into various zones of pollution depending principally on the type of organisms present. The saprobic system were summarized by Orlando and Wrightington (1976). Another example is enteric bacteria, such as fecal coliforms, which are the normal inhabitants of the digestive tract of man and other warm-blooded animals. The presence of these indicator organisms is taken as evidences of contamination with fecal material.

The second approach concentrates on the mathematical properties of populations of organisms. For example, some techniques use information theory to describe the diversity of species within biological communities. Other species-diversity techniques employ various probabilistic models in their formulations. Pielou (1977) discussed some of the statistical population techniques.

The third approach examines the physiological or behavioral responses of certain organisms to pollution. For example, pesticides are known to inhibit acetylcholinesterase activity in the brains of fish; therefore, fish brain cholinestrase activity has been used as a monitor for pesticide pollution. Behavioral changes of certain species, such as increased activity and agitation of fish in response to toxic substances also had been studied as an indicator of environmental pollution.

Biological measures of pollution have the advantage that they have a pollution integrating tendency. Fish and other organism tend to respond to the entire historical record of water quality. Thus, if some toxic substances are present on rare occasions and go undetected in routine water quality monitoring activities, the presence of these pollutants would still be measured in terms of their effects on aquatic organisms. Orlando and Wrightington observe that this integrating feature enables biological organisms to cover more variables and conditions than conventional measurements.

4.0 CONCLUSIONS

4.1 GENERAL DISCUSSION

The physical and chemical indices published in the literature show considerable variation in terms of the number of variables, scales, and ranges as shown in Table 12 and 13.

Indices in the general and specific-use categories (Table 12) share a common characteristic: they are absolute indices designed to depict the quality of free-flowing surface waters. In the 11 indices in these two groups, the number of variables included varies from 8 to 31. Most of these indices have decreasing scales, and the majority (6 to 11) have fixed ranges o to 100. One of these indices can be negative, and the others have ranges of 0 to 1 or above, o to more than 15, or 0 to more than 1,000.

By contrast, most of the planning indices (6 to 7) have increasing scales, and none has a fixed range of 0 to 100 (Table 13). Part of the variation among planning indices probably reflects the fact that they usually are designed for special-purpose applications. More than half of the statistical approaches also have increasing scales. The ranges generally differ from each other and from those of the general and specific use indices. The statistical approaches are relatively flexible, permitting the user to include any number of variables and define the range as he please.

If the variables in the 11 general and specific use water quality indices are compared, it can be seen that there is great variety. Although Dee's water quality index is part of a large planning system called the Environmental Evaluation System, the index shares many characteristics with general water quality indices.

Table 12. Summary of the General and Specific Use Water Quality Indices Published in the Literature

Index Name	Developed By	No.of Variab.	Range
General Water Quality Indices			
Quality Index (QI)	Horton	10	0 to 100
Water Quality Index (NSFxWQI)	Brown et al	9	0 to 100
Implicit Index of Pollution	Parti et al	13	0 to 15
River Pollution Index (RPI)	McDuffie et al	8	0 to 1000
Social Accounting System	Dinius	11	0 to 100
Specific use Water Quality Indices			
Fish and Wildlife (FAWL) Index	O'Connor	9	0 to 100
Public Water Supply (PWS) Index	O'Connor	13	0 to 100
Index for Public Water Supply	Deininger et al	11\13	0 to 100
Index for Recreation	Walski & Parker	12	0 to 1
Index fro Dual Water Uses	Stoner	31	100 to 10
Index for Three Water Uses	Nemerow & et al	14	0 to 1

Table 13: Summary of Planning Indices and Statistical Approaches Published in the Literature

Index Name	No. of Variables	Range
Planning Indices		
Truett et al.Prevalence Duration Intensity (PDI) Index	b	0 to 1
Truett et al.National Planning Priorities Index (NPPI)	b	0 to 1
Truett et al.Priority Action index (PAI)	b	0 to 1
Dee et al.Environmental Evaluation System (EES)	78	0 to 1000
Inhaber Canadian National Index	b	0 to 1
Zoeteman Potential Pollution Index (PPI)	3	0 to 1000
Johanson &Johanson Pollution Index (PI)	b	0 to 100
Statistical Approaches		
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	b	N.A.
Harkin'sHarkins' Index (Kendall ranking)	b	0 to 100
Schaeffer & Janardan Beta Function Index	b	0 to 1

The mathematical structures of the published water pollution indices also are quite varied. However, all of the general and specific-use water quality indices can be analyzed by the mathematical system discussed in chapter 2.

As shown in Table 14, water quality indices frequently use nonlinear (implicit and explicit) subindex functions. Nonlinear subindices are much more common in water indices. Horton's index uses staircase step functions (segmented linear); the NSF WQI uses implicit nonlinear functions based on expert judgment; Dinius' index uses a mixture of linear and power (explicit nonlinear) functions; and Walski and Parker's index uses exponential and parabolic (explicit nonlinear) functions.

Most of the general and specific use water quality indices use the weighted linear sum aggregation function. As discussed in chapter 2, the weighted linear sum has serious eclipsing problems when it is used in decreasing scale indices. If a single sub index exhibits poor water quality ($I_i = 0$ for some i), the weighted linear sum unfortunately does not exhibit poor water quality. The weighted product aggregation function, which was evaluated by Landwehr for use in the multiplicative $NSFWQI_m$, was designed to circumvent this problem. Although it reduces eclipsing, it becomes a nonlinear transform when the weights are small. Nevertheless, indices using the weighted product had given good correlations with independent expert opinion (Landwehr 1976). Nemerow and Sumitomo offer a more complex aggregation function, the root mean square of the maximum index and mean of indices. This aggregation function reduces, but does not eliminate, the eclipsing problem.

Table 14. Mathematical Characteristics of General and Specific Use Water Quality Indices Published in the Literature

Index	Subindices	Aggregation Function	Comments
General WQIs			
Horton	Segmented Linear (Step Functions)	Weighted sum Multiplied by 2 Dichotomous Term	Eclipsing Region
Brown et al. (NSF WQI_a)	Implicit Nonlinear	Weighted Sum	Eclipsing Region
Landwehr (NSF WQI_m)	Implicit Non linear	Weighted Product	Nonlinear
Parti et al.	Segmented Non linear	Weighted Sum (Arithmetic mean)	Eclipsing Region
McDuffie & Haney	Linear	Weighted Sum	Eclipsing Region
Dinius	Nonlinear	Weighted Sum	- -do--
Dee et al.	Implict Nonlinear	--do--	- -do--
Specific Use WQ Indices			
O'Connor (FAWL,PWS)	Implict Nonlinear	Weighted Sum	Eclipsing Region
Deininger & Landwehr(PWS)	--do--	Weighted Sum Weighted Product	Eclipsing Nonlinear
Walski & Parker	Nonlinear	Weighted Product Geometric Mean	--do--
Stoner	--do--	Weighted Sum	-ve Value
Nemerow & Sumitomo	Segmented Linear	Root mean square Of Max.& Arithmetic Mean	

To make detailed comparisons of individual subindex functions, it is first necessary to compensate for differences in scales and ranges. To convert an increasing scale subindex which ranges from 0 to k into a decreasing scale subindex which ranges from 0 to 100; the following transform suggested by Ott (1978) can be used:

$$I = -\frac{100}{K} I' + 100 \tag{57}$$

where, I = transformed decreasing scale index(0

I' = original increasing scale index

K = constant equal to the maximum value of the original index.

4.2 RESEARCH NEEDS

Although the literature reveals that considerable effort has gone into the development of water quality indices, it does not indicate which indices are being used in practice. According to a National survey conducted by Ott (1978) of U.S. Water Pollution control agencies, the most commonly used index is the NSF WQI, followed by Harkin's index. And most of the other indices in the literature are not being used in practice. However, both of these indices have their own limitations. For example, the NSFWQI does not include color or oil and grease, variables that are important for the recreational and aesthetic uses of water. Further, NSFWQI is difficult to apply if the temperature depart from equilibrium. Therefore there is need for an integrated inform water quality index which must include parameter namely for general water use. The advantage of such a uniform index will be manifold:

i) The uniform water quality index will help in the comparison of different water bodies at a given time.

ii) Generally, the water quality trends are shown by various water quality parameters which is a very cumbersome process to conclude a concrete picture by using a number of figures showing water quality variations. The water quality index can be used as a tool to show the water quality trends overtime for a given water body. Further, if the same WQI for all the water bodies is used then the comparison of their trends will be very simple.

iii) The uniform water quality index will be very much helpful in the management of a given water body as it can be used to examine the changes in water quality response to water pollution control efforts consequently, it can be used to evaluate the impact on water quality of a stream by certain industry.

iv) Among the number of water quality indices already developed by various researchers, the index developed by Bhargave (1985) for drinking water supply is notable. Similarly for other uses namely recreation, industrial, agricultural, and wild life maintenance etc., there is need for development of water quality indices.

v) Above all, it will be very much useful if one can develop a uniform water quality index based on the relevant parameters of interest for the intended use which would be applicable to all the beneficial water uses.

5.0 REFERENCES:

1. Horton, R.K. (1965), "An Index Number System for Rating Water Quality", J. Water Pollution Control Administration, 37(3), 300 pp.
2. Nemerow, N.L. and Hisashi Sumitomo (1970), "Benefits of Water Quality Enhancement", Syracuse university, Syracuse, N.Y.,Report No. 16110 DAJ.
3. Brown, R.M. et al.. (1970), "A Water Quality Index - Do We Dare?"., Water Sewage Works, 11, 339-343.
4. Prati, L. et al. (1971), "Assessment of Surface Water Quality by a Single Index of Pollution", Water Research, 5, 741-751.
5. Dinius, S.H. (1972), "Social Accounting System for Evaluating Water", Water Resources Research, 8(5),1159-1177.
6. Zoeteman, B.E.J. (1973), "The Potential Pollution Index as a Tool for River Water Quality Management," Tech. Report No.6, Government Institute for Water Supply, WHO, The Netherlands.
7. Dee, N.I. et al.(1973), "An Environmental Evaluation System for Water Resources Planning", Water Resources Research, 9(3), 523-535.
8. Mc Duffie Bruee, and Jonathan T. Haney (1973), "A Proposed River Pollution Index",American Chemical Society, Div. of Water, Air, and waste Chemistry, New York, NY.
9. Walski, T.M., and Parker, F.L.(1974), "Consumers Water Quality Index", J. Environ. Eng. Div., ASCE, 593-611.

10. Landwehr, J.M. (1974), "Water Quality Indices - Construction and Analysis", Ph.D. dissertation, University of Michigan, Ann Arbor Michigan.

11. Inhaber, H. (1974), "Environmental Quality; Outline for a National Index for Canada", Science (186) 29, 798-805.

12. Harkins, R.D. (1974), "An Objective Water Quality Index," J. Water Poll. Control Fed. 46(3), 588-591.

13. Truett, J.B. et al. (1975). "Development of Water Quality Management indices", Water Resources Bull., 11(3), 436-448.

14. Johanson, E.E. and Johnson, J.C.(1976), "Identifying and Prioritizing Locations for the Removal of In place-Pollutants, "Contract No. 68-01-2920, U.S. Environmental Protection Agency, Washington, D.C.

15. Landwehr, J.M. (1976), "A Statistical View of a Class of Water Quality Indices", Water Resources Research , 15(2), 460-468.

16. Landwehr, J.M., and Deininger, R.A. (1976). "A Comparision of Several Water Quality Indices", J. Water Poll. Control Fed. 48(5), 954-958.

17. Schaeffer, David J., and Konanur, G.J. (1977), "Communicating Environmental Information to the Public: A Water Quality Index," J. Environ. Educ., 8(4), 18-26.

18. Pielou, E.C. (1977), "Mathematical Ecology," John Wilay and Sons, Inc., New York.

19. Stoner, J.D. (1978), "Water Quality Indices for Specific Water Use", U.S. Geological Survey, Reston, Y.A. Circular 140-770.

20. Joung, H.M. et al. (1978), "A Water Quality Index Based on Multivariate Factor Analysis,"Experiment Staticen J.,Series No. 378. University of Nenada, Reno, NV.

21. Ott, W.R. (1978). "Water Quality Indices: A urvey of Indices used in the United States," U.S. Env. Production Agency, Washington, DC, EPA-600\4-78-005).

22. Ott, W.R. (1978a), "Water Quality Indices" : A Survey of Indices Used in the United States, EPA - 600/4-78-005, Environmental Protection Agency, Washington, D.C.

23. Ott., W.R. (1978b), "Environmental Indices, Theory and Practice, Ann Abbor. Science, Ann Arbor, Michigan.

24. Bhargave, D.S. (1985), "Expression For Drinking Water Supply Standards, " ASCE, 111(3), 304-317.

25. Dinius, S.H. (1987), "Design of an index of Water Quality, "Water Resources Bulletin, 23(5),833-843.

DIRECTOR : DR. S.M.SETH
GROUP COORDINATOR : DR. G.C.MISHRA
DIVISIONAL HEAD : DR. K.K.S.BHATIA
STUDY GROUP : ADITYA TYAGI