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WATER QUALITY INDICES

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Middlesex Polytechnic, Queensway, Enfield.

Dissertation submitted for the Degree
of
DOCTOR OF PHILOSOPHY

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ABSTRACT

Given the present constraints on capital expenditure for water quality improvements, it is essential that best management practices be adopted whenever possible. This research provides an evaluation of existing practices in use within the water industry for surface water quality classification and assesses water quality indices as an alternative method for monitoring trends in water quality. To this end, a new family of indices have been developed and evaluated and the management flexibility provided by their application has been examined.

It is shown that water quality indices allow the reduction of vast amounts of data on a range of determinand concentrations, to a single number in an objective and reproducible manner. This provides an accurate assessment of surface water quality which will be beneficial to the operational management of surface water quality.

Previously developed water quality indices and classifications are reviewed and evaluated. Two main types of index are identified: biotic indices and chemical indices. The former are based exclusively upon biological determinands/indicators and are used extensively within the United Kingdom in the monitoring of surface water quality. The latter includes a consideration of both physico-chemical and biological determinands, but with an emphasis on the former variables. Their use is still the subject of much controversy and discussion.

Four main approaches to the development of chemical indices can be identified in accordance with the aims and objectives of their design. Those developed for general application are known as General Water Quality Indices (WQIs) or Indices of Pollution, with the latter based predominantly upon determinands associated

with man-made pollution. Those which reflect water quality in terms of its suitability for a specific use are termed use-related; whilst planning indices are those which attempt to highlight areas of high priority for remedial action on the basis of more wide-ranging determinands. The derivation and structure of previously developed indices have been evaluated and the merits and strengths of each index assessed. In this way, nine essential index characteristics were identified, including the need to develop an index in relation to legal standards or guidelines. In addition it was recognised that one requirement of an index should be to reflect potential water use and toxic water quality in addition to general quality as reflected by routinely monitored determinands.

The development of river quality classifications within the United Kingdom is reviewed and the additional management flexibility afforded by the use of an index evaluated by comparing the results produced by the SDD (1976) Index with those of the National Water Council (NWC, 1977) Classification. The latter classification is that presently used to monitor water quality in Britain. The SDD Index was found to be biased towards waters of high quality and provided no indication of potential water use or toxic water quality. Nevertheless, it displayed a number of advantages over the NWC Classification in terms of the operational management of surface water quality. It was therefore decided to develop a new family of water quality indices, each based upon legally established water quality standards and guidelines for both routinely monitored and toxic determinands and each relating water quality to a range of potential water uses, thereby indicating economic gains or losses resulting from changes in quality.

Four stages in the development of a water quality index are discussed: determinand selection; the development of determinand transformations and weightings; and the selection of appropriate aggregation functions.

Four separate indices have been developed as a result of this research. These may be used either independently or in combination with one another where a complete assessment of water quality is required. The first of these is a General Water Quality Index (WQI) which reflects water quality in terms of a range of potential water uses.

This index is based upon nine physico-chemical and biological determinands which are routinely monitored by the water authorities and river purification boards of England, Wales and Scotland. The second, the Potable Water Supply Index (PWSI) is based upon thirteen routinely monitored determinands, but reflects water quality exclusively in terms of its suitability for use in potable water supply (PWS). The two remaining indices, the Aquatic Toxicity (ATI) and Potable Sapidity (PSI) Indices are based upon toxic determinands such as heavy metals, pesticides and hydrocarbons which are potentially harmful to both human and aquatic life. Both indices are use-related, the former reflecting the suitability of water for the protection of fish and wildlife populations; the latter, the suitability of water for use in PWS. Each index is based upon nine and twelve toxic determinands respectively.

These indices were developed in as objective and rigorous a manner as possible, utilising an intensive interview and questionnaire programme with members of both the water authorities and river purification boards. Rating curves were selected as the best way in which individual determinand concentrations could be transformed to the same scale. The scales selected for the

WQI and PWSI are 10 - 100 and 0 - 100 respectively, whilst those of the ATI and PSI are 0 - 10. Each has been sub-divided in such a way as to indicate not only water quality, but also possible water use. Thus, the indices reflect both current and projected changes in the economic value of a water body which would occur as a result of the implementation of alternative management strategies. The curves were developed using published water quality standards and guidelines relating to specific water uses. Therefore, they contain information on standards which must be adhered to within the United Kingdom and this adds a further dimension to their management flexibility.

Determinand weightings indicating the emphasis placed by water quality experts upon individual determinands were assigned to the determinands of the WQI and PWSI. However, weightings were omitted from the ATI and PSI due to the sporadic nature of pollution events associated with these determinands. These vary spatially and temporally, both in concentration and in terms of which determinand is found to be in violation of consent conditions. Therefore, on a national scale, no one determinand could be isolated as being more important than any other.

Three aggregation formulae were evaluated for use within the developed indices: the weighted and unweighted versions of an arithmetic, modified arithmetic and multiplicative formulation.

Each index was applied to data collected from a series of water quality monitoring bodies covering a range of water quality conditions. In each instance, the modified arithmetic formulation was found to produce index scores which agreed most closely with a predetermined standard, normally the classifications assigned using the NWC classification. In addition, this formulation produced scores which best covered the ascribed index range. However, the multiplicative unweighted formulation was retained for use within the ATI and PSI for the detection of zero index scores, i.e. when concentrations in excess of legal limits were recorded for these toxic determinands.

The results from these studies validate the ability of each index to detect fluctuations in surface water quality. Therefore, the utility of the developed indices for the operational management of surface water quality was effectively demonstrated and the flexibility and advantages of an index approach in providing additional information upon which to base management decisions was highlighted. Amongst these advantages was the ability of an index to provide information upon which potential cost-benefit assessments could be made in relation to either spatial or temporal changes to surface water quality.

Finally, the need for both general and use-related indices was investigated and found to be an advantage, although not strictly necessary, because the WQI efficiently recorded the range in quality conditions associated with the use of water in potable water supply.

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PART ONE

THE BACKGROUND & DEVELOPMENT OF INDICES

CHAPTER 1

INTRODUCTION

1.1. BACKGROUND INFORMATION

Water as it flows over the earth's surface is neither chemically pure, nor biologically sterile (Hawkes, 1974). Thus, natural rivers have considerably different chemical and biological compositions. In most cases, the biological quality of water is assessed objectively using any one of a range of biological indices which have been devised since their original conception by Kolkwitz and Marsson in 1908. However, even today subjective decisions regarding the chemical quality of a river or stream are often made as "value judgements" by water experts based upon ranges in the concentration of specific determinands. While these decisions reflect a process of weighting and integration of multiple determinand values, the end result does not readily lend itself to precise and effective communication (Brown et al, 1972). Nor are these decisions upon the quality of water necessarily reproducible by another expert. In addition, the range of chemical determinands which pollute receiving waters have increased in number and complexity in recent years. In many urban rivers toxic determinands such as zinc and cadmium are becoming a cause for concern. Consequently, the classification of water quality based on a limited number of determinands is unsatisfactory particularly as subjective methods of assessment are employed.

In order to be of maximum value to water quality managers, a classification system should not only categorise water according to quality, but also provide an indication of possible economic and beneficial uses. In addition, the economic gains and losses which result from water quality improvements or deteriorations ideally need to be tied to a water quality classification scheme (Newsome, 1972).

Water quality management within the United Kingdom has greatly improved since the late 1950's when 13% of the rivers of England and Wales were so polluted that they were unable to support fish populations. By 1975 this figure had been reduced to 7% (Young, 1979). However, if this improvement in receiving water quality is to be sustained, it is essential that the best management practices (BMP) be adopted whenever possible. Given the present constraints on expenditure for water quality improvements, it is imperative that management decisions be based on accurate and precise information. In addition, with the recent implementation of Part II of the Control of Pollution Act (1974), there is an urgent need for those involved in decision making to be knowledgeably aware of the quality status, and the temporal and spatial changes in that status, of a given surface water. To this end, Water Quality Indices (WQIs) have been used in the United States of America since the early 1970s as a means of assistance in water quality management and BMP.

Most people involved in the monitoring of water quality are familiar with the concept of WQIs. However relatively few in Britain have actually given this method of water quality monitoring much consideration. Only two of the ten water authorities of England and Wales - the Anglian and Yorkshire Water Authorities, - have undertaken evaluation studies involving indices (Anglian and Yorkshire Water Authority, Internal Reports, 1978).

Water quality indices were first developed in the United States by Horton in 1965 as a theoretical replacement to purely subjective methods of water quality classification. Since that time the ideas of Horton have been developed and applied primarily in the United States (Brown et al, 1970 to 1976; O'Connor, 1971; Deininger et al, 1971; Dinius, 1972; Harkins, 1974; Landwehr et al, 1976, and Dunette, 1979) and in a limited way more recently in Europe and the United Kingdom (Liebmann, 1966; Prati et al, 1971; Scottish Development Department, 1976; Ross, 1977; Bolton et al, 1978). At issue is the alleged longstanding need for a uniform method of measuring water quality; a 'yardstick' with simple, stable and reproducible units.

The Scottish Development Department (SDD 1976), has defined a water quality index as follows:-

"The index number is a form of average derived by relating a group of variables to a common scale and combining them into a single number. The group should contain the most significant parameters of the data set, so that the index can describe the overall position and reflect change in a representative manner".

Although a refined form of classification might not be necessary for all management purposes a water quality index, based upon those determinands considered to be most indicative of water quality change, can be used to summarise vast quantities of data to a single number more objectively than is at present possible using the classifications available. Therefore, if a universally acceptable water quality index were to be produced, it would allow direct comparison of the overall quality of different water bodies and assist in the formulation of effective management objectives.

It can be demonstrated that an index allows the quantification of 'good' and 'bad' water quality, as well as summing individual determinand effects, and so allows the user to examine waters in terms of ranked order. Hence the value of a water quality index may be summarised as follows:

a) It can be used as a "yardstick" with units which are stable, consistent and reproducible, thus allowing the comparison of surface water quality both temporally and spatially.

b) It enables the reduction of vast amounts of data to a single index value in a more objective and reproducible manner than present classification systems permit.

c) It performs a function as a 'bridging-tool' between water expert and layman.

d) It assists in pin-pointing river stretches which have altered significantly in quality and which, if necessary, can be investigated in greater detail (Ross, 1977).

e) It can be used either in combination with an existing classification or sub-divided into a number of water quality classes. In this way a water-course can be accurately located within a class, thus allowing a comparison to be made of water-courses within the same class.

f) The index scale can be sub-divided to reflect possible use. In this way it can also indicate gains and losses in economic value resulting from management strategies (House, 1985).

g) Indices can be used to show the importance of the sampling frequency used in monitoring river quality (McClelland et al, 1973).

However, despite the attributes of WQIs their acceptance is limited. Dunnette (1979) believes that the lack of progress in the acceptance of WQIs by those bodies responsible for water quality management is due to:

i) a lack of concensus on index design;

ii) an apprehension amongst water quality experts that indices may be misused, and technical information lost or hidden in aggregated data;

iii) that expert knowledge may become superfluous or at least eroded and devalued;

iv) the index gives no information on economic benefits obtained from any improvements in water quality.

It is the purpose of this research to evaluate water quality indices in terms of the advantages and disadvantages outlined above and assess the potential of this form of classification to water quality monitoring in the United Kingdom.

1.2. AIMS AND OBJECTIVES OF RESEARCH

The aim of this research can be subdivided into two main objectives on the basis of priority. These have been termed primary and secondary.

1.2.1. Primary Objectives

i) To review the development of WQIs and examine both water quality classification systems and WQIs at present in use within the UK, and assess their relative merits and strengths as water quality management tools.

ii) To develop a WQI which includes toxic determinands directly within its structure. In so doing the index will be suitable for application to both clean and polluted rivers alike.

iii) To develop an index which indicates the potential use to which water of a given quality may be put.

iv) To assess the need for use-related as opposed to general indices, and develop one or more of these as deemed necessary.

1.2.2. Secondary Objectives

i) To compare the performance of general and use-related indices and assess the need/desirability of both forms of index.

ii) To evaluate the potential of WQIs for use in cost-benefit analysis.

1.3. GENERAL METHODOLOGY

To achieve the above objectives the research programme was divided into a number of discrete stages. The first of these was to assess the diverse nature of water quality in terms of sources of pollution. In this way the scale of water quality monitoring and classification, in terms of the number of determinands which had to be considered, could be appreciated.

Secondly, a historical review of the development of WQIs, both biological and chemical, use-related and general, was undertaken.

Thus the ideology and structure of various indices could be evaluated.

By stage three it became possible to define a list of essential characteristics an index must possess if it is to be accepted by water quality managers in the UK as an alternative form of classification system.

This was followed by a review of water quality classifications developed in the United Kingdom since the publication of the Eighth Report of the Royal Commission on Sewage Disposal in 1912. As part of this review the information provided by the National Water Council classification (NWC, 1978), the most recent classification to be developed in Britain, was compared with that provided by a selection of WQIs. From this study it was evident that WQIs could provide information, over and above that of the NWC classification, which could be of value to the operational management of water quality.

On the basis of information gained via the stages outlined above it was decided to develop a new WQI. In so doing it became evident that officers of the Water Authorities of England and Wales perceived the use of water in potable water supply (PWS) as a use which merited special attention. Consequently, a use-related index, the Potable Water Supply Index (PWSI), was developed. Toxic determinands were included within both indices in the form of optional sub-indices of toxicity.

Finally, the managerial advantages of using either or both of these indices have been evaluated using data from the Thames and Severn Trent Water Authorities.

CHAPTER 2

SOURCES OF POLLUTION

2.1. INTRODUCTION

There are three principal sources of pollution within urban and rural catchment areas: domestic sewage; commercial/industrial waste; and non-point runoff and spillage. In addition, the discharge of treated effluents into rivers and stream can still cause serious occurrences of both organic and inorganic pollution. Pollutants can be found in three forms:-

(i) organics and floating debris;
(ii) suspended solids, toxics and dissolved material;
(iii) bacteria, viruses and other disease carrying organisms.

2.2. DOMESTIC SEWAGE

Domestic sewage varies in concentration from one site to another depending upon the assimilative capacity of the stream. Many standard tests have been developed to ascertain the quality of effluents and receiving waters including dissolved oxygen (DO percentage saturation), biochemical oxygen demand (BOD), total and faecal coliforms and the determination of ammonia, phosphate and chloride concentrations. All of the above are taken to be indicative of sewage contamination.

2.3. COMMERCIAL AND INDUSTRIAL WASTES

The polluting effect of commercial and industrial wastes will depend upon the type of industry involved, the size and organisation of the establishment, the specific processes employed, the quality of supervision and control of emissions. In recent years the tightening of legislative control on emission standards has greatly reduced the occurrence of industrial pollution. In fact many industrialists would argue that in many instances, the emission standards imposed upon industries are too stringent (Chalmers, 1983).

The following types of pollution can be caused by discharges of commercial and industrial wastes:-

(a) Chemical Pollution:- Chemicals are produced as by-products from industrial processes. If they are not bio-oxidisable they usually require special treatment processes to ensure neutralisation or adsorption. These can vary from detergents, acids and alkalis to phenols and heavy metals such as cyanide, copper, arsenic and cadmium.

(b) Pollution by Oil and Grease:- These can greatly reduce the biochemical operation of a treatment plant, or prevent the re-aeration of waters by coating the surface layers. In either instance toxic conditions may prevail.

(c) Acute Toxicity:- A variety of toxic substances such as heavy metals can be discharged by industry into rivers and streams without the consent of the water authorities. These can cause high mortalities of both flora and fauna, even at low concentrations.

(d) Thermal Pollution:- Heat from cooling or production processes can dramatically change the ambient temperature of the water resulting in fish kills, algal blooms, as well as reducing the biochemical purification capacity of the water body due to the reduction in dissolved oxygen.

2.4. AGRICULTURAL RUN-OFF AND SPILLAGE

Inorganic fertilizers are high in both nitrates and phosphates. This promotes algal blooms which cause oxygen depletion during the night, choke or poison other biota, release odours, discolour waters and result in drifting and decaying masses of vegetation which interfere with nearly all uses of the water body. Excess nutrient accumulation can also occur in urban catchments. During the drought in 1976 severe eutrophication occurred in many small urban catchments in the UK (Ellis 1980).

In addition, runoff from silage during periods of high precipitation can lead to high concentrations of organic acids and alcohol which can have adverse effects on aquatic life. (Jones, 1985).

Finally, the washing of pesticides from the surface of vegetation and accidental spillage can have lethal effects on fish and wildlife populations (Holdgate, 1979).

2.5. OTHER SOURCES OF POLLUTION

Other sources of urban and rural pollution include stormwater runoff which in the first flush after a long dry spell can be more offensive than sewage pollution. Impermeable surfaces collect debris from the urban atmosphere; abrasion from streets, pavements, tyres and vehicles; oil and petrol spillage; dog and bird droppings and litter of all descriptions. Cumulatively this can be of raw sewage quality (Ellis 1985).

Increases in the discharge of inorganic phosphates and nitrates can be related to agricultural runoff or biological treatment processes. Detergents and poorly treated sewage discharges which have resulted from increased urban population densities are also responsible for nutrient increases as has been shown in the Norfolk Broads.

2.6. SUMMARY

The sources of pollution are therefore diverse and lead to a variety of pollutant types. These can lead to dramatic changes in water quality and hence affect potential use. Alternatively, the capacity of a river or stream may be such that discharges of these pollutants have little or no effect on surface water quality. In either instance an index, if it is to be of value in water quality management, must consider all such sources of pollution within its determinand selection process.

CHAPTER 3

HISTORICAL REVIEW OF BIOLOGICAL AND CHEMICAL INDICES

3.1. THE BIOLOGICAL EVALUATION OF WATER QUALITY

Biological methods of water quality assessment have been developed independently throughout the world. In Europe, the most widely used methods for the biological assessment of water quality are based upon the presence of 'indicator species'. These methods can be sub-divided into two main groups; Saprobic Indices and Biotic Indices. Saprobic indices, based on the work of Kolkwitz and Marsson (1908), are most commonly used in central and eastern Europe. However, the versions developed by Pantle and Buck (1955) and Liebmann (1966) are more usually employed at the present time. Biotic indices are mainly used in the United Kingdom and France (Woodiwiss, 1960, 1964; Graham, 1965; Chandler, 1970).

In the United States diversity indices are normally used for the biological assessment of water quality (Shannon-Weaver, 1963; Wilhm and Dorris, 1968).

3.1.1. Saprobic Indices

Kolkwitz and Marsson (1908, 1909) based their index on the presence or absence of organisms belonging to four saprobic groups, each group being related to the different stages of oxidation which occur in organically enriched water. The saprobic zones identified by Kolkwitz and Marsson (1908) were:

- polysaprobic; a zone of gross pollution;

- alpha and beta mesosaprobic; a transitional zone;

- oligo-saprobic; a zone of recovery, dominant in pure water.

Pantle and Buck (1955) modified the saprobic index of Kolwitz and Marsson (1908) to include information on the abundance of organisms rather than merely their presence or absence. Pantle and Buck (1955) ascribed an 'h' value, a number between 1 (occurring incidentally) and 5 (occurring abundantly), to each sample to express the relative abundance of each organism within the different groups. In addition, each sample was ascribed an 's' value, to express the saprobic grouping of the organisms (s = 1, oligosaprobic group to s = 4, polysaprobic group). Finally, the mean saprobic index is calculated as follows:-

$$S = \frac{\Sigma sh}{\Sigma h}$$

The adaptation of the saprobic index undertaken by Liebmann (1966) abandoned the four grades of the saprobic system in favour of grades of water quality based on chemical, biological and physiological criteria.

Saprobic indices have been criticised on several counts, including the idea that if an index is to be based on indicator organisms, community composition - rather than simply the presence or absence of specific organisms - should be considered (Sladecek, 1965).

Despite these criticisms, with some modifications the saprobic index system could become the most efficient system of assessing biological water quality (Balloch et al, 1976).

3.1.2. Biotic Indices: The Trent Biotic Index

Woodwiss (1960) based the Trent Biotic Index on the number of groups of benthic macro-invertebrates inhabiting riffle reaches of Midland rivers. He related the index to the presence of six key organisms or groups of organisms. Depending on the number of groups present and the key organisms found in the fauna, the biotic index values ranged from 10 (clean water associated fauna) to zero (polluted water associated species). The index is generally based on the order in which benthic macro-invertebrates disappear with decreasing water quality. The index is based on the relationship between fauna and organic pollution and Woodiwiss drew attention to the fact that in cases of toxicity the relationships may become more complicated.

3.1.3. Graham's Biotic Index

Graham's Biotic Index (1965) was an adaptation of the Trent Biotic Index and was used in the Lothians River Purification Board up until 1972. This index has a six point scale where a value of 1 is indicative of a clear stream, increasing to a value of 6 indicating that no benthic macro-invertebrates are present. The index is again based on the number of 'key' groups of benthic macro-invertebrates present. However, the smaller number of fixed-index levels rendered the index less flexible than the Trent Biotic Index, which led to its replacement by the latter in the Lothians River Purification Board area.

3.1.4. Chandler's Score System

Chandler's Score System (1970) is also based on the order in which benthic macro-invertebrates disappear with decreasing water quality. However, this system incorporates a more detailed list of species, and includes information on abundance. An index score is obtained by identifying and enumerating each species group present. Sensitive species have a high score and tolerant species a low one. All species' scores increase with abundance. The index has no definite range, but possesses a graduation of values between 0 (no macro-invertebrates present) to 45 - 300 (moderate pollution levels) and 300 to over 3000 (mildly polluted to unpolluted conditions). Chandler thought that the score system would be inappropriate when applied to lowland rivers although recent work on the River Tamar (Nuttal and Purves, 1974) would question this conclusion.

3.1.5. Community Diversity Index

Shannon and Weaver (1963), using the Shannon-Weaver functions, introduced the following expression to evaluate community diversity.

$$d = \sum_{i}^{t} = 1 \quad (n_i/N) \log_e (n_i/N)$$

where d = diversity index
t = number of species
n = number of individuals in each species
N = total number of individuals
e = 2.78.

This index is useful in pollution studies as it provides an unbiased numerical value for community diversity, and is largely independent of sample size. Clean waters have a value greater than 3, moderate pollution from 1 - 3 and heavy pollution a 'd' value less than 1.

3.1.6. Discussion of Biotic Indices

Balloch et al (1976) have evaluated all the above biotic indices. Index scores were calculated for them using data from three British rivers, the River Taf, the North Esk and the Ivel.

Chandler's score system (1970) was found to be the most responsive to changes in water quality. The Trent Biotic Index (Woodiwiss 1960), although simple to use and interpret, was found to be inflexible to moderate change in water quality. The computation time necessary to calculate the Community Diversity Index (Shannon and Weaver, 1963) was lengthy, and the determination of the number of individuals and species necessitated a more vigorous quantitative sampling method. Graham's Biotic Index (1965) was found to be less sensitive to deteriorations in water quality than other indices and, in general, was considered to be a simplified version of the Trent Biotic Index.

Although Chandler's score system was considered by Balloch et al (1976) to be the most sensitive to changes in water quality, they still considered that the system should be modified as more information is gathered on the tolerance of different species to deteriorations in water quality.

Thus despite the fact that biotic indices are still in need of additional modifications, they are being used by Water Authorities and River Purification Boards. However, chemical indices have only been adopted by a small selection of River Purification Boards.

3.2. CHEMICAL WATER QUALITY INDICES

A number of water quality indices (WQIs) have been developed since Horton's in 1965. These may be classified into four distinct groups:

a) General water quality indices

b) Indices of Pollution

c) Use-related water quality indices

d) Planning Indices

The following discussion is not meant as a critique of existing indices as this will be undertaken in subsequent chapters. Here the ideology and methodology of these indices will be reviewed within the context of their historical development.

3.3. GENERAL WATER QUALITY INDICES

General WQIs have been developed by Horton (1965), Brown et al (1970-1976), Dinius (1972), Harkins (1974), Inhaber (1975), Janardan and Schaeffer (1975), Scottish Development Department (1976), Bolton et al (1978) and Dunnette (1979). Each index relates water quality to a numerical scale of varied degree.

3.3.1. Horton 1965)

Horton (1965) proposed water quality indices for the monitoring of surface water quality as a theoretical alternative to existing methods of classification. Horton defined a WQI as:

> "...... a rating reflecting the composite influence as overall quality of a number of individual quality characteristics"

The construction of this theoretical index was subjective, with Horton selecting the eight physico-chemical determinands which he considered to be the most indicative of water quality deterioration. Horton then introduced the idea of 'rating scales'. These transformed the concentration of each determinand onto a scale of 0-100, depending upon the effect on water quality. A zero score equated the concentration of a determinand to water of very low quality, whereas a score of 100 signified that the water was pristine in quality.

Next Horton designed a series of determinand weightings to account for the relative importance of each determinand to overall water quality. Both the rating scales and the weightings devised by Horton (1965) were arbitrary, and were used only to show the possible form a water quality index might take.

The final index number was obtained using a simple cumulative formulation of the form:-

$$WQ = \left[\sum_{i=1}^{n} C_i W_i \Big/ \sum_{i=1}^{n} W_i \right] M_1 M_2$$

where C_i = the determinand rating
W_i = the determinand weighting
$M_1 M_2$ = the coefficients for additional determinands.

Horton made no attempt to pursue the further development and use of WQIs following the construction of the basic index. Foremost in the continuation of Horton's work however has been the National Sanitation Foundation (NSF, 1970 to 1976).

3.3.2. National Sanitation Foundation (NSF, 1970 to 1976)

The main authors of the work undertaken by the NSF are Brown et al (1970 to 1973), Landwehr et al (1973 to 1976) and McClelland et al (1973 to 1976). The main aim of their studies was to produce a more objective WQI on the basis of the original theoretical work of Horton (1965).

The final index developed has subsequently become known as the National Sanitation Foundation Index (NSFI). It is based on nine determinands and uses rating curves as a means of determinand transforms.

Brown et al (1970-1976) adopted a modified DELPHI opinion research technique to obtain information on these particulars from a wide and diverse panel of 'water experts'. Seventy-seven of 142 'experts' initially approached completed a series of four questionnaires with accompanying feedback information. The questionnaires dealt firstly with determinand selection. In addition to the nine determinands finally selected for inclusion within the index, toxic substances and pesticides were considered where applicable. Secondly the respondents were requested to draw rating curves for each determinand, which entailed graphically expressing determinand concentrations on a scale of 0-100. A zero score equates the concentration of individual determinands to that of crude sewage. A score of 100 reflects conditions close to pristine water. Where the concentration of toxic substances or pesticides exceed recognised standards a water body is automatically zero rated. This inclusion of toxic substances within an index added a new dimension to the potential use of indices in water quality management, even though their consideration was only indirect and in need of further investigation. Finally, weightings indicating the relative importance of individual determinands to overall water quality were obtained.

The final index number was produced using either a weighted arithmetic mean formulation (Brown et al (NSF) 1970), or a multiplicative weighted formulation (McClelland et al, (NSF) 1973), which were of the form:

$$WQI = \sum_{i=1}^{n} q_i w_i \qquad \text{Arithmetic Weighted}$$

$$WQI = \prod_{i=1}^{n} q_i^{w_i} \qquad \text{Multiplicative Weighted*}$$

where w_i = the unit weight of the ith determinand a number between 0 and 1

q_i = the quality of the ith determinand, a number between 0 and 100

n = the number of determinands

Footnote

*The multiplicative weighted index formulation of NSFI has been adopted by the SDD (1976) and named the geometric weighted formulation. However, Brown et al (1972) also developed a geometric weighted formulation which they later abandoned.

The NSF have continued their work on indices which included the assessment and development of use-related indices (see Section 3.5.1. to 3.5.3.)

3.3.3. Dinius (1972)

This index was designed as part of a "social accounting system" for the state of Alabama. It was designed to extend the use of indices beyond that of simply water quality classification to their use as a basis of cost-benefit analysis. This was facilitated by dividing the 0 to 100 index range in terms of potential use. A score of 100, (Q = 100%), equated water quality to that of distilled water and indicated its suitability for all uses. Water quality at any point in time could be expressed as a percentage from that ideal. Thus, a quality score approaching 0% would indicate highly polluted water unacceptable for most economic uses.

The index was based on eleven physical, chemical and biological determinands. Toxic determinands were not considered for inclusion within the index. Mathematical functions were used to transform determinand concentrations to the same units, and weightings ranging between 0.5 to 5.0 were ascribed to each determinand. The sum of the weightings represents the denominator in the index calculation which has been simplified by Ott (1978) to:

$$I = \frac{1}{21} \sum_{i=1}^{11} w_i I_i$$

where w_i = the weighting of the ith determinand;

I_i = the sub-index function (rating) of the ith determinand

Determinand selection, transforms and weightings were in essence subjectively determined by the author with reference to the lierature and expert opinion.

Dinius presented the results obtained from using this index in a manner similar to that of an accountant's balance sheet. Water of pristine purity (Q = 100%) was considered as the 'original asset'. The percentage pollution present at any point in time represents the 'liabilities'. These liabilities are subtracted from the original asset to represent the value of a water body at that time. This in accounting terms indicates the 'available capital'. Hence the change in this 'available capital' over time, associated with management strategies applied over that period, can be evaluated and expressed as economic benefits. Hence, this index of Dinius, although developed subjectively, adds a new dimension to the use of WQIs in water quality management.

3.3.4. Harkins (1974)

The index developed by Harkins uses a statistical approach to water quality assessment. Harkins did not agree that the development of the NSFI was truly objective. To obtain greater objectivity, Harkins employed a non-parametric classification procedure developed by Kendall (1963). Using this technique the nature of the underlying data probability distribution does not affect any probability statement which might be derived from the results. Harkins' index requires computing the standardised distance from the observation to a well chosen control observation.

Four steps are involved in the development of Harkins' index:

a) Control vectors, which should essentially represent some optimum condition or standard, are selected for each water quality determinand used.

b) Each column of water quality determinands are ranked, including the control vectors.

c) The rank variance is computed for each determinand using:

$$\mathrm{Var}\ (R_i) = 1/12n \times \left[(n^3 - n) - \sum_{i=1}^{k} (t_k{}^3 - t_k) \right]$$

where p = the number of determinands
n = the number of observations, plus the number of control points
k = the number of ties encountered

d) The standardised distance for each member of observation vector is computed using:

$$Sn = \sum_{i=1}^{p} \quad (R_i - R_c)^2 \quad \mathrm{Var}\ (R_i)$$

where R_c = the rank of the control value.

Harkins used a standard transform, based on the square of the difference between the control value and the rank order number. Thus the square root of the transform is normally distributed, and the transform is the square of a normally distributed random number and poses a Chi squared distribution.

3.3.5. Janardan and Schaeffer (1975)

The index developed by Janardan and Schaeffer (1975) is an extension of Harkins' index. Again a standard, such as a legal limit, was selected for each determinand and used as a control value. Data are ranked and a normalised deviate, Z_{ij}, is calculated for the jth value of the ith determinand.

Hence, $Z_{ij} = (R_{ij} - R_{ic})\ S_{Ri}$

where R_{ij} = the rank of the jth observation for the ith determinand

R_{ic} = the rank of the control value for the ith determinand

S_{Ri} = the standard deviation of R_{ij} for the ith determinand

The index p_1 is given by:

$$p_1 = \left[S/(T + S)\right]^{\frac{1}{2}} \quad \text{and } p_1 = p_1/b$$

where

$$S = \sum_{i=1}^{p} \sum_{j=1}^{n_i} Z_{ij}{}^2 \qquad \text{and } T = \sum_{i=1}^{p} \sum_{j=1}^{n_i} R_{ij}$$

Thus in the index of Janardan and Schaeffer (1975), the ranked variable Z_{ij} follows a standard normal distribution and the variate, S, is distributed as Chi-square.

Harkins' index (1974) increases with the degree of pollution, ie as the standardised distance from the control value increases, but unlike NSFI, it has no end point. The index of Janardan and Schaeffer (1975) ranges from 0-1, with a score of zero indicating 'good' water quality, increasing to 1 for polluted water.

3.3.6. Inhaber (1975)

Inhaber (1975) produced a WQI as a constituent part of an Environmental Quality Index (EQI). It was hoped that this could be used to monitor changes in the environmental quality of Canada, however there is no evidence that it has ever been used. The index ranges from zero, indicating the best possible environmental conditions, to higher numbers for progressively worse environmental quality and like that of Harkins (1974) it has no endpoint.

The use of national data, was suggested, or data which appeared to be reasonably uniform to be considered within national scope, for the production of this WQI. Exactly how Inhaber would define 'national data' was left unclear and consequently leaves the user of this index to make assumptions about the data before he can apply the index.

Inhaber's index is based on two sub-indices which are then combined mathematically using the root mean square method. The first sub-index-Industrial and Municipal Effluent - was designed to reflect the magnitude of polluted effluent discharge. The second sub-index - Ambient Water Quality Index - deals with the prevailing water environment, as well as secondary effects of water quality, such as the contamination of water supplies and commercial fisheries. Seven and eight determinands are considered in the production of the two sub-indices respectively.

3.3.7. Scottish Development Department (1976)

The index developed by the Scottish Development Department (SDD, 1976) was produced as part of an investigation into the improvement of existing river quality classification systems employed in Scotland. The co-operation of members from the Tweed and Solway River Purification Boards (RPBs) was elicited, and the index was based upon the original work of Brown et al (NSFI, 1970-1976).

Determinand selection, rating curves and weightings were first considered separately by members of the two co-operating RPBs, and later discussed and finalised at a joint meeting of these members, and representatives of the SDD. Ten determinands, largely similar to those selected by Brown et al (NSFI 1970-1976), were finally chosen for inclusion with the index, with toxic substances and pesticides considered where applicable.

Six water quality index formulations were tested by the Tweed and Solway RPBs. These were the weighted and unweighted arithmetic and multiplicative formulae of the NSFI (1970); 1973; 1974) and a modified weighted and unweighted arithmetic formulation devised by the Solway RPB (SDD, 1976) which was of the form:

$$WQI = \frac{1}{100}\left[\frac{1}{n}\sum_{i=1}^{n} q_i\right]^2$$

Modified Arithmetic
Unweighted.
(Solway Unweighted)

$$WQI = \frac{1}{100}\left[\sum_{i=1}^{n} q_i w_i\right]^2$$

Modified Arithmetic
Weighted.
(Solway Weighted).

The SDD (1976) report concluded that the modified arithmetic weighted formulation was the most economic in terms of calculation time, and it was considered sufficiently sensitive for the range of water quality conditions sampled in Scotland.

3.3.8. Dunnette (1979)

The WQI of Dunnette (1979) was produced for application in Oregon. Unlike those of Brown et al (1970-1976), Harkins (1974), and the SDD (1976), it was not an attempt at the development of a universal WQI.

The selection of determinands for inclusion within Dunnette's index (1979) consisted of four stages. The criteria used included determinands previously included within a water quality index; a rigorous rejection rationale process; a modified DELPHI opinion assessment technique; and finally a consideration of major water quality impairment categories. The index was finally based on six determinands.

Determinand weightings were based on the significance of each determinand relative to Dissolved Oxygen which was originally given a temporary weighting of 1. Weightings were obtained using the modified DELPHI opinion research technique.

Dunnette's determinand transforms produced sub-index quality functions for each of the determinands. These are in essence similar to the rating curves produced by Brown et al (1970-1976) and the SDD (1976). However the logarithmic transform used in the index assumes that a change in magnitude at lower concentrations has a greater impact than an equal change at higher concentrations. Dunnette's transforms were based on a scale of 10-100, unlike that of Brown et al (1970-1976), the SDD

(1976) and Janardan and Schaeffer (1975). The summation formulation for Dunnette's index takes the form:

$$WQI = PT_oW_o + PT_fW_f + PT_nW_n + PT_tW_t + PT_bW_b + PT_p + W_p$$

where W = a determinand's importance weighting factor

PT = determinand transforms

Sub-notations refer to the determinands, e.g.

o = oxygen, f = faecal coliforms, etc.

3.4. INDICES OF POLLUTION

Indices of pollution are often developed in preference to a general WQI in areas where the occurrence of river pollution is the norm. All indices of pollution developed to date deal with the occurrence of pervasive pollution associated with urbanisation and man's impact upon the environment. No index of pollution has been developed to quantify specific pollution effects such as the impact of abandoned mine drainage upon the state of a river. Nor has such an index been developed for other similar cases of river pollution which occur in isolated areas.

Therefore indices of pollution, as developed to date, are in essence general WQIs. However, only determinands indicative of man-made or artificial pollution have been considered for inclusion within such indices. Indices of pollution have been developed by Shoji et al (1966), Prati et al (1971), McDuffie and Haney (1973), Ross (1977) and Joung et al (1978).

3.4.1. Shoji et al (1966)

Shoji et al (1966) developed a Composite Pollution Index in an attempt to evaluate the degree of gross stream pollution of the Yodo River Systems in the Kanasi district of Japan. Factor analysis was carried out using monthly analytical data for the year 1960-61. Twenty determinands were selected as testing items for the factor analysis. From the factor analysis programme, three definite factors were identified, i.e. pollution, temperature and rainfall factors. This reduced the list of determinands to eighteen. Beta weights were then computed for the eighteen determinands and the Composite Pollution Index (CPI) which ranged between -2 and +2 was calculated using:

$$\text{C.P.I.} = \sum_{i=1}^{n} B_i Z_i$$

where B_i = the Beta weights for each determinand
Z_i = the concentration of each determinand
n = the number of determinands

3.4.2. Prati et al (1971)

Prati et al (1971) developed a classification of surface water quality on the basis of water quality classifications adopted in England (Wisdom, 1966), the Federal Republic of Germany, USSR, Czechoslovakia, New Zealand (WHO, 1967), Poland (Koziorowski, 1963), and the United States. The classification developed was in the form of an index of pollution based on thirteen determinands of equal weighting. Mathematical transforms were constructed for each determinand to express the relative 'polluting effect' of individual determinands as index numbers. These determinand transforms replaced the rating curves or tables, and the weightings used in the production of other indices (Brown et al, NSFI 1970-1976, SDD, 1976; Ross, 1977; Dunnette, 1979).

The 'total index of pollution' was calculated as the arithmetic mean of the thirteen determinand index scores. The index increases with the degree of pollution from zero to a gross pollution value of 14. A score greater than eight is considered to denote pollution.

3.4.3. McDuffie and Haney (1973)

A River Pollution Index (RPI) was developed by McDuffie and Haney (1973) to monitor the effect of the Binghamton metropolitan area on the water quality of the Susquehanna River. The index was based on seven water quality determinands and an exponential temperature factor. The index is a linear sum of terms normalised for the number of terms included. Each determinand used in the index is expressed as a ratio of the observed concentration level to the 'natural' or unpolluted level. However this would be difficult to assess as the unpolluted level would vary according to the use of the water body and is, therefore, not constant. Additional determinands to those recommended for inclusion within the index, may also be used to make the RPI a more complete characterisation. The index is computed as the sum of a sub-indices times a scaling factor 10/n+1:

$$RPI = \frac{10}{n+1} \sum_{i=1}^{n} I_i$$

where n = the number of determinands used
I_i = sub-index for the ith pollutant determinand

The purpose of the scaling factor is to make the index, which has an increasing scale, vary from approximately 100 ('natural' levels) to 1000 ('highly polluted' levels). However, the range can be extended to zero.

3.4.4. Ross (1977)

Ross (1977) developed an index of pollution for the Clyde RPB in an attempt to detect long term trends in water quality from a vast amount of data which had been collected by the Board between

1966 and 1974. An index of pollution was selected in preference to a general WQI because many of the rivers in the Clyde catchment would inevitably record scores within the lower reaches of the index range.

From a list of twelve determinands sampled monthly for the Clyde catchment, Ross selected five determinands which he considered to be the most indicative of pollution. Rating tables and weightings were devised for the determinands selected, and a pollution index score between zero (quality akin to septic crude sewage) and ten (pristine purity) was obtained by dividing the sum of the ratings for all determinands, by the sum of the weightings. All index values were rounded to the nearest whole number. This index of pollution is purely subjective as all decisions relating to the index development were made by the author.

Ross (1977) also investigated the possibility of including flow as a variable within an index of pollution. However, it was evident that the relationships between flow and water quality were too complex for it to be considered as a determinand within such an index.

Ross advocated the use of this index in combination with the Trent Biotic Index (Woodiwiss, 1960).

3.4.5. Joung et al (1978)

The index proposed by Joung et al although called a WQI is recognised by the the authors as being an index of pollution due to restrictions being made on the determinands considered for inclusion within it. Whilst realising the inherent limitations to such an approach, factor analysis was used as the basis for the development of this index, as in this way it was thought that 'subjective bias' would be excluded from determinand selection.

Of ten determinands initially considered for inclusion within the index six, were finally selected and two indices, each consisting of five determinands, were developed. However, it was recognised that in each instance the determinands included within these indices could only explain 69.55 per cent of variations in water quality.

Polynomial regression analysis was used to develop rating equations for each determinand and a scale ranging from 0 to 100, (low to high pollution) was adopted. Coefficients of correlations were used to develop weightings.

Both indices were produced using additive formulae as follows:

$$\underset{(PN)}{WQI(TN)} = \sum_{i=1}^{n} X_i Y_i$$

where X_i = the weighting of the ith determinand

Y_i = the rating equation of the ith determinand

n = the number of determinands

3.5. USE RELATED WATER QUALITY INDICES

Use related indices have been designed, as their collective name suggests, to define water quality in terms of its suitability for specific uses. These have been developed for the use of water in potable water supply (Deininger and Maciunas, 1971; O'Connor, 1971 and Stoner, 1973); for the protection of fish and wildlife populations (O'Connor, 1971); for waters used in irrigation (Stoner, 1978); for recreational purposes (Walski and Parker, 1974); and for a diverse range of uses by man, including industry and agriculture (Nemerow and Sumitomo, 1970).

There is much controversy over the need for use-related indices and many of the advantages and disadvantages of use-related indices have been discussed in a paper by Brown et al (1972). Before reviewing their conclusions the indices mentioned above will be outlined.

3.5.1. Deininger and Maciunas (1971)

Following the development of the NSFI by Brown et al (1970), it became evident that many 'water quality experts' were of the belief that water use was a significant factor in the development of WQIs. Subsequently, Deininger and Maciunas (1971) produced a water quality index for surface water bodies which was to be used for public water supply. The co-operation of twelve of the 'water experts' who participated in the development of the NSFI (Brown et al, 1970) was elicited. The 'experts' consulted were those with a knowledge of the requirements necessary for a surface water body to be used for public water supply. The index was developed using the DELPHI opinion research technique.

Originally two versions of this public water supply index were produced, one with eleven determinands, the other with thirteen.

This was because iron and fluoride were selected by the 'water quality experts' for inclusion within the index, although Deininger and Maciunas considered that these determinands were irrelevant to the situation specified in the questionnaire. The questionnaire had specified the situation where a free flowing stream would be used for potable water supply, whereas iron and fluoride are more often a problem in a 'well-water' situation. The weighted arithmetic formulation of NSFI (Brown et al, 1970 see 3.3.2.) was used to produce the final index numbers for the two data sets, together with a specially devised geometric formulation of the form:

$$WQI = \sqrt[n]{\prod_{i=1}^{n} q_i^{g_i}} \qquad \text{geometric weighted.}$$

where g_i = the geometric weight of the ith parameter. Just as the sum of the arithmetic weights for any one index equals 1, the product of the geometric weights equals 1 for any one index.

The geometric formulation has since been abandoned in favour of a multiplicative weighted formulation as the latter has been shown statistically to be more accurate at assessing water quality.

3.5.2. O'Connor (1971)

O'Connor developed two additional indices to that of the NSFI. The first of these - FAWL - was for surface water bodies intended to sustain fish and wildlife. The second - PWS - for a water source to be treated and used for public water supply. O'Connor interviewed a selection of the experts approached by Brown et al (1970, - NSFI) to obtain the determinands, ratings and weightings to be used in the development of these two use-related indices. Nine and thirteen determinands were respectively selected for inclusion within the FAWL and PWS indices. The final index scores are computed as the weighted sum of the sub-indices multiplied by a factor which takes into account pesticides and toxic substances:

$$\text{FAWL} = \sigma \sum_{i=1}^{9} q_i w_i \qquad \text{PWS} = \sigma \sum_{i=1}^{11} q_i w_i$$

where $\sigma = 0$ if pesticides or toxic substances exceed recommended limits

$\sigma = 1$ otherwise.

Not surprisingly, four of the determinands included within FAWL and PWS are common to the NSFI, as too are seven of the determinands in the public water supply index of Deininger and Maciunas (1971).

Deininger and Maciunas (1971) compared the scores obtained for the two versions of their public water supply index, with those of the NSFI for a series of data sets. The weightings of the original NSFI of Brown et al (1970) were recalculated for the purpose of applying the geometric formulation. The values for the use-related and general indices were found to be fairly close, thus Deininger and Maciunas concluded that this use-related index ".... did not seem to rate water quality levels in a manner markedly different from the rating made by a general, non-specific use-orientated index".

O'Connor (1971) compared the values obtained by FAWL and PWS with those for NSFI by means of correlation analysis on four sample sets of data. From the results it was apparent that NSFI correlated better with FAWL and PWS than the two use-related indices did with each other. Thus O'Connor concluded that a general water quality is a kind of mean approximation to the PWS and FAWL indices, ie FAWL and PWS are reporting only a subset of the information contained within the NSFI. This finding should strengthen the case for both use-related indices and general water quality indices, since they serve different objectives. Thus, O'Connor believed that both types of indices were of value depending upon the aims of the user.

3.5.3. Brown et al (1972)

Brown et al (1972) listed a number of disadvantages in developing use-related indices. These included the fact that determinands, weights and scales will vary for each of the large number of water uses available; more data will be required to support the additional determinands measured; greater expense will be incurred; and communication processes with the public will become more complex. Obviously these disadvantages would have to be weighed up against the economic goals of individual studies. However in view of these drawbacks, and the results from the comparative studies of O'Connor (1971) and Deininger and Maciunas (1971), Brown et al (1972) concluded that it would be more profitable if time was spent perfecting a sensitive general water quality index rather than producing numerous use-related indices.

3.5.4. Walski and Parker (1974)

Walski and Parker (1974) developed a WQI where the use of water for recreation was treated as the principal consideration. Even when recreation is taken as the water use to be considered by an index, it is difficult to decide which recreational activities should be included under this heading. Recreational activities are diverse, and have many different requirements in terms of determinand concentrations. Determinands for inclusion within this index are selected from a list of 65 regularly employed chemical analyses listed in 'Standard Methods' (1971). Twelve determinands, grouped under four different headings - Appearance, Odour and Taste, Affect on Aquatic Life and Effect on Health - were finally selected for inclusion within this index.

Sensitivity functions which assigned a value of between zero and 1 to each determinand were developed by the authors. A score of 1 represents ideal conditions and zero conditions which are totally unacceptable. These sensitivity functions produce curves which can be equated to the rating curves developed by Deininger and Maciunas (1971). The published article on this index does not give the values of the weightings.

Walski and Parker (1974) selected a geometric mean formulation to combine the determinand scores. This was of the form:

$$WQI = \left[\prod_{i=1}^{n} f_i^{a_i}(P_i) \right]^{1/\sum_{i=1}^{n} a_i}$$

where: P_1 = the value of the ith determinand

$F_i\,(P_i)$ = the sensitivity function for the ith determinand

a_i = the weight attached to the ith determinand

n = the total number of determinands

3.5.5. Stoner (1978)

Stoner (1978) proposed a use-related index designed for two water uses: public water supply and irrigation. This index can accommodate two water uses by substituting the sub-index functions (rating curves) and weightings into the index aggregation formula. Stoner believes that this approach can be used to accommodate any water use.

Two types of determinands are used to produce Stoner's index:

Type I : Toxic determinands

Type II : Determinands which affect health or aesthetic characteristics

Each Type I determinand is assigned a score of zero if the concentration is less than or equal to the recommended limit, and a value of -100 if this limited is exceeded. The recommended limits are based on water quality criteria such as those published by the National Academy of Sciences (1972). Totals of 26 and 5 Type 1 pollution determinands were included within the public water supply and irrigation versions of this index respectively.

Type II determinands were represented by simple explicit mathematical functions as opposed to the step functions employed in producing Type I sub-indices. Thirteen and sixteen Type II determinands were included within the public water supply and irrigation versions of this index respectively. In Stoner's index the constants in each sub-index equation for the Type II determinands are such that I = 0 when a recommended limit is reached, and I = 100 when the ideal value of that pollutant is attained. In order to weight these determinands, all Type II determinands are classified into groups, and weightings are specified for each group of determinands. Type I determinands are unweighted.

The overall index is computed by combining the sum of the unweighted Type I sub-indices, with the sum of the Weighted Type II sub-indices.

$$I = \sum_{i=1}^{n} T_i + \sum_{j=1}^{m} W_j I_j$$

where T_i = sub-index for the ith Type I pollution determinand
W_j = weights for the jth Type II pollution determinand
I_j = sub-index for the jth Type II pollution determinand
n and m = the number of Type I and Type II determinands respectively

The right hand term of this equation can never exceed 100. However when one Type I determinand exceeds its recommended limit the left hand term becomes -100, making the overall index zero or less. Therefore this index can become negative if only one Type I determinand exceeds the recommended limit. Therefore, Stoner's index ranges from I = 100 (best possible water quality) to a large negative number (worst water quality).

The public water supply version of Stoner's index has been applied to several water bodies in Texas, where the index was found to range from I = -8,560 to I = +87.5.

Stoner's index highlights that the complexity of an index is greatly increased when used to reflect different water uses. If water uses such as recreation and the maintenance of fisheries and wildlife habitats were included within this index additional determinands, weights and sub-index functions would be required.

3.5.6. Nemerow and Sumitomo (1970)

This index consists of three independent use-related indices which, when combined, produce an overall index of pollution which is a weighted average of the three specific indices. The uses considered by this index have been defined according to the degree of human contact involved. These uses are denoted by j = 1, 2 and 3 and are as follows:

- j = 1, Human Contact Uses - including drinking and swimming;
- j = 2, Indirect Contact Uses - including fishing, boating, agriculture and food processing;
- j = 3, Remote Contact Uses - including navigation, industrial cooling and recreational activities.

The users recommend the inclusion of fourteen subjectively selected determinands for the calculation of each index. Determinand transforms are expressed as linear or segmented linear mathematical functions which are based on recognised water quality standards or criteria. The index scale ranges between 0 to 1; the latter being the critical value. Values greater than 1 signify a critical condition under which treatment is essential for that use to be maintained. The final index score for each specific use is expressed as a mathematical average value of all determinands.

Finally, the Pollution Index is computed as the weighted sum of the three specific-use indices.

$$PI = \sum_{i=1}^{3} w_i PI_i$$

where: w_i = the weighting of the ith sub-index
PI_i = the index score of the ith sub-index.

It is unclear how these weightings are determined, although, they appear to reflect the importance of each use in relation to one another, and will vary from one area to another.

3.6. THE USE OF WQIs IN THE USA

As most of the indices described above have been developed in the USA it is not surprising that they have been most readily adopted in that country. However, even in the USA only 14 US agencies have been regularly using indices as part of their water quality monitoring programmes (Ott, 1978). Almost half of the country's state agencies were either unfamiliar with indices or had evaluated their use and rejected them as a management tool. The former category of agencies includes the state of Alabama for which Dinius (1972) had developed her 'social accounting' system. Six of the ten states using indices had selected the NSFI index developed by Brown et al (1970 to 1976); Oklahoma State adopted that of Harkins (1974); and three states developed their own index (Ott, 1978). Included in this last group was Oregon, for whom Dunnette (1979) had developed his index. Four of the six states using the NSFI have modified it slightly, mainly by deleting determinands which are not regularly monitored. This simply requires the recalculation of weightings (see Sect. 4.8.). Ott (1978) discovered that the uses to which indices were put varied from one agency to another. However, the three most common uses of indices were: for the analysis of trends in water quality; for the presentation of data in annual water quality reports; and for informing the public of water quality status. In association with the use of indices for data presentation, the state of Michigan uses the data collected from their river surveys to map water quality. In addition, the New England Interstate Water Pollution Control Commission used the NSFI to assess the improvements in water quality resulting from the expenditure of $30 million on new wastewater treatment facilities (Ott, 1978).

Thus only a small proportion of water quality agencies had adopted WQIs as part of their routine monitoring programme by 1978. However, the use of WQIs was still a recent phenomenon at that time; hence it is likely that since 1978 more state and interstate agencies have opted to use WQIs. Certainly those that were using WQIs were of the opinion that water quality indices had much to offer water quality managers over and above existing systems of water quality classification.

3.7. PLANNING INDICES

3.7.1. Background Information

Planning indices have been developed by the MITRE Corporation (Greeley et al, 1972 and Truett et al, 1975), Dee et al (1973), Zoeteman (1973), and Johanson and Johnson (1976). These indices have been designed with a very different objectives in mind to those described in the previous sections. With the exception of the index devised by Johanson and Johnson (1976), these indices go beyond the assessment of water quality in terms of physical, chemical and biological determinands alone, to a situation in which the pollution of an area is assessed in terms of wider ranging indirect measures. These include: the calculation of the total stream length within an area that is polluted; an assessment of the population within the area affected by this pollution; the extent of pollution control present; the degree of economic activity within an area; the average flow rate of a river and the investment priority attached to a particular area. Hence, these indices are designed to assist in the decision-making and planning processes for the expenditure of capital investment in pollution abatement within a country.

The index of Dee et al (1973) goes even further than this. Indices are viewed by them as a means of evaluating the quality of the environment as a whole. Thus water pollution is only one of eighteen categories of environmental quality to be considered. Given the diverse nature of these quality categories, the end product from this type of index would be extremely difficult to interpret, despite the application of weightings.

Therefore these indices go beyond the realms of this research. However, they do indicate the way in which any index developed from the present research study may be further developed and applied within water quality management programmes. Hence, to exemplify the basis of these types of indices, those developed by the MITRE Corporation will be outlined briefly.

3.7.2. The MITRE Corporation (1972; 1975)

This work was undertaken jointly by personnel from the Environmental Protection Agency (EPA) of the USA and the MITRE Corporation (Greeley et al, 1972 ; Truett et al, 1975).

Three indices were developed by these authors; each with a different set of objectives. The first of these could be described as an index of pollution. It is known as the Prevalence, Duration and Intensity index (PDI). Before applying this index, water quality is subjectively assessed in relation to legally established water quality criteria for individual determinands. The determinands or standards to be considered were not stipulated. Once a condition of water pollution has been established and "pollution zones" recognised, the index can be applied. The first stage is to establish the Prevalence (P) factor. This entails the calculation of the total length of polluted water which exists within a "pollution zone". Secondly, the Duration (D) factor is determined. In this case a weighting is applied to the polluted watercourses indicating the length of time, over a twelve month period, that pollution exists. These vary between 0.4, indicating a pollution period of three months only; to 1.0 which indicates that pollution exists throughout the year. Finally, the Intensity factor (I), which indicates the severity of the pollution is calculated. This is evaluated in terms of the degree of impairment to three categories of water use: ecological, utilitarian and aesthetic. Each degree of impairment is weighted and the Intensity factor is equal to the sum of the weightings from the three use categories.

The final PDI score is calculated as:

$$\mathrm{PDI} = \frac{P \times D \times I}{m}$$

where m = the total stream length within the area.

The second index, the Priority Planning Index (PPI), was designed to assist in the "decision-making" processes of water quality management. It helps to ensure the most cost-effective water pollution control measures are selected; that the maximum percentage of the nations population benefits from the application of pollution control techniques and to ensure that the maximum percentage of the country's water meets the required water quality standards.

Ten determinands were considered within this index including; the current population of a specified planning area; the extent of available pollution control; the PDI score for the planning area and the estimated per capita planning costs. Rating curves were drawn for each determinand relating changes in each to a scale of 0.1. Weightings were then assigned to each determinand and the final PPI score calculated using:

$$PPI_i = \sum_j a_j f_j(x_{ij})$$

where i = a particular planning area;
j = a particular determinand;
a_j = the weighting for that determinand;
x_{ij} = the value of the jth determinand for the ith planning area;
f_j = the rating for the jth determinand

The final index score, which lies between 0-1, indicates those areas where priority for pollution control should be applied.

Finally, the Priority Action Index (PAI) was designed to inform the EPA of areas of absolute priority for pollution abatement schemes. It is based on four of the ten determinands included within the PPI with the weightings accordingly adjusted.

The final calculation of the PAI was as follows:

$$PAI = \sum_{i=1}^{4} (weight_i)\ (determinand_i)$$

Hence, these three indices, although no longer used as part of the water quality monitoring programme of the EPA, show how WQIs may be used to assist in cost-benefit or cost-effective water quality analysis and management.

3.8. OTHERS: QUALITY STATES

Quality States are a type of index where economic factors are equated to chemical factors. Newsome (1972) defined a Quality State as ".... an ordered set of 'significant ranges' of concentration of constituents describing the quality of a water resource with which a particular benefit or cost function is associated".

Eight steps are involved in the development of quality states. Steps (a)-(d), involve the selection of determinands to be used in the development of quality states. Step (e) requires the establishment of significant concentration levels for all determinands, or groups of determinands, for all possible uses of the river under consideration. The cost of removal function is next calculated for each determinand or group of determinands (f), and the concentration at which this function increases significantly is stipulated. In (g) the significant levels in (e) and (f) are superimposed. If there are n significant levels, there will be n + 1 significant ranges. Finally (h), merges the combinations of significant ranges, which although different in quality, have the same economic implications. The combinations of significant ranges remaining are the mutually exclusive quality states for that particular river system.

3.9. SUMMARY

A number of water quality indices have been developed since the theoretical index of Horton in 1965. Many of these differ fundamentally in both structure and development. The number of determinands included within a WQI ranges from five (Ross, 1977) to twenty six (Stoner, 1978), and the type of determinand selected varies depending upon the objectives of each index. For example, toxic determinands are not included directly within any general WQI or index of pollution; indeed their presence is only evaluated within the indices of the NSF (1970-1976) and SDD (1976). However, they are considered directly within the use-related indices of Stoner (1978).

Most of the general and pollution indices described above are only designed to reflect water quality and give no direct indication of potential use. If an index is to provide information on the economic gains or losses due to management strategies, an indication of potential use is essential.

The arguments for and against use-related indices remain at present unresolved, with both appearing to have a place in water quality management.

Most of the water quality indices reviewed have been constructed independently, without any consideration of indices developed previously, with the exception of NSF (Brown et al, 1970-1976), Harkins (1974), SDD (1976) and Dunnette (1979).

What is now required is a thorough investigation to test and develop a standard, universal index, possibly based on an existing mode, which will be acceptable for most conditions, rather than developing additional independent indices.

The major problem associated with this objective is the different emphasis placed upon different determinands by water quality monitoring authorities in different countries. However, if an agreed approach can be reached, determinands, ratings and weightings can be readily altered.

CHAPTER 4

ESSENTIAL CHARACTERISTICS OF AN INDEX

4.1. INTRODUCTION

If water quality managers are to accept WQIs as an alternative to existing water quality classifications, an index must not only classify water bodies but also provide additional information in as concise and comprehensible a fashion as possible, (see page 51). Each index must be capable of resolving criticisms posed by water experts and which have been highlighted by Dunnette (1979), (see Chapter I).

In order to be acceptable, an index should possess certain well defined characteristics. Water quality indices must be objective; their raison d'etre is due to the need to replace the more subjective classifications of surface water quality. In all cases, objective standardisation is possible when using a water quality index because mathematical formulae are used to replace the subjective opinion of one or two water 'experts' who classify a surface water body on the basis of a list of determinand concentrations.

One of the criticisms of indices recognised by Dunnette (1979), concerned the lack of concensus on index design. The varied methodology adopted in index development can be explained by the fact that those responsible for their development come from a variety of academic backgrounds including planning; statistics; environmental pollution etc. Although it is desirable for index design to be standardised, it is more important that they be developed as objectively as possible so that any element of bias is removed from their formulation.

The results produced by an index must also reflect expert opinion, thereby answering the criticism that technical information is lost or hidden as a result of aggregation. Obviously it is impossible to produce an index based on a restricted number of determinands which will satisfy all expert opinion. Therefore, the criteria or methods used in developing an index must be diverse or, alternatively, include opinion from a wide range of water quality experts.

Hence, indices must possess the following basic and essential characteristics if they are to attain universal acceptance. These include:

i) an objective development;

ii) ease of interpretation;

iii) the results produced must be comparable in space and time;

iv) they must be sensitive to changes in water quality;

v) they must be in agreement with expert opinion;

vi) they must conform with, and be based on, legal standards or accepted criteria and guidelines;

vii) they must be capable of adjustment to suit the data available which will vary with sampling frequency;

viii) they must include information on toxic determinands;

ix) they must include some information on the potential use associated with each category of water quality. In this way some assessment of the economic benefits that may accrue from upgrading water quality can be made.

4.2. THE OBJECTIVE DEVELOPMENT OF AN INDEX

For an index to be considered objective, determinand selection, transforms and weightings must all be developed objectively. O'Connor (1971), Brown et al (1972) and SDD (1976) considered that the critical factor in the development of a water quality index was determinand selection. For an index to be truly objective, every possible determinand would have to be included within the index. While this might be ideal, it is clearly impractical, therefore the procedures adopted in the determinand selection stage of the development of an index must be as rigorous and as objective as possible.

The approach of Dunnette (1979) in selecting the determinands to be included within an index appears to be the most rigorous and objective. Dunnette (1979) employed four steps for determinand selection, including a DELPHI opinion research programme and various sets of rejection rationale. Weightings for this index were based on the results from a DELPHI programme. However, the determinand transforms used by Dunnette to produce sub-index quality functions were developed subjectively by the author and, after examining these curves, it is unclear why certain reference points were used in their production.

The DELPHI opinion research technique was first used in the development of water quality indices by Brown et al (NSF, 1970-1976), and later modified and used by SDD (1976) and Dunnette (1979). Brown et al (NSF, 1970-1976) and SDD (1976) used the

DELPHI technique for all stages in the development of their indices. Harkins (1974) argues that the DELPHI technique is not truly objective as the opinion of one panel of experts may vary with that of another. Landwehr (1976) maintains that the DELPHI panel consisted of a random subset of 'experts' drawn from a variety of backgrounds. It was shown statistically that the panel may be considered to be a good estimator of what the concensus of a full set of all experts would be. A criticism of the modified DELPHI approach of SDD (1976) could be that those involved all worked in areas of good water quality, consequently the index is more accurate when applied to areas of high water quality (Anglian Water Authority, Internal Report, 1978; Yorkshire Water Authority Internal Report, 1978). In addition to the DELPHI technique, the SDD also used the work of Brown et al (NSF 1970-1976) as a guide when producing the SDD index (1976).

Despite Harkins' (1974) criticism of the DELPHI technique, he failed to suggest alternative methods for determinand selection or for deciding which standards to use to compute the standardised distances necessary when using Harkins' index. Therefore when employing this index the user must ultimately make a decision and thus objectivity is lost. Determinand weightings are replaced by a ranking system in Harkins' index. The indices of Horton (1965), Nemerow + Sumitomo (1970), Prati et al, (1971), Dinius (1972), Walski and Parker (1974), Inhaber (1975) and Ross (1977) were developed subjectively in that all decisions were made by the individual authors. However certain criteria were considered in their development. All authors selected determinands from lists of those regularly monitored in their individual areas. Prati et al (1971) referred to surface water quality classifications from several countries, and used these as a guideline for producing sub-index scores, but left all determinands with equal weights. Inhaber (1975) considered criteria laid down in the Department of Environment, Ottawa - 'Guidelines for Water Quality Objectives and Standards' - when interpreting effluent and ambient water quality, but produced his own system of weightings. The reconstruction of rating tables and weightings for Ross' index (1977) was totally subjective.

Arguably the most objective methods of index development are those based on statistical techniques such as factor analysis (Shoji et al, 1966). However, the disadvantages of such methods are that they are totally dependent upon the information provided by the user which, ultimately, relies upon subjective user decisions. In addition, when using these statistical techniques, the user must decide upon the threshold score above which a determinand will be selected. Finally, in using statistical techniques to define determinand transforms and weightings, the procedure becomes so complex that the validity and interpretation of the end results become questionable (Joung, et al, 1978).

4.3. THE INTERPRETATION OF AN INDEX

To be of value, an index must be simple to use and interpret and have a definite range. It is important to remember that not all bodies responsible for water quality monitoring have access to computer facilities. Therefore an index must be simple to produce manually and within a minimum amount of time. This necessarily depends upon the aims and objectives of the index. Some management problems require a more complex solution and therefore a more complex index may be appropriate.

Index formulations range from arithmetic means - (Horton, 1965; Brown et al (NSF) 1970; Prati et al 1971; Dinius, 1972; Ross, 1977; Joung et al, 1978; Dunnette, 1979), modified arithmetic mean (McDuffie and Haney 1973, Solway Formulation, SDD, 1976), geometric formulations (Deininger and Maciunas, 1971; Brown et al 1972; 1973; Walski et al 1974), multiplicative formulations

(Brown et al 1973; McClelland et al 1973, 1976, SDD, 1976), the use of factor analysis (Shoji et al 1966), non-parametric classifications (Harkins, 1974; Janardan et al 1975) and other mathematical formulae (Inhaber, 1975). In terms of calculation time, the arithmetic formulations are the most efficient. However, the multiplicative formulations cover a wider range of the water quality index scales and, although requiring a longer calculation time, can be used without access to a computer. All of the indices within these two categories, with the exception of that of Prati et al (1971), are easy to use. The determinand transforms for the index of Prati et al (1971) and Dinius (1972) are complex, both for the purpose of calculation and interpretation. The indices of Harkins (1974) and Janardan et al (1975) are easy to use and understand. But, beyond a certain number of determinands and observations, it would be impossible to calculate the index manually, which is also true of the indices of Inhaber (1975), Shoji et al (1966) and Joung et al (1978).

All indices, apart from those of Shoji et al (1966), Harkins (1974), and Inhaber (1975), have a definite water quality scale. Without such a scale, interpretation of results produced by the index, and comparison in space and time, is impossible. Index scales range from 0-100 (Horton, 1965, Brown et al (NSF) 1970-1976; Dinius, 1972; SDD, 1976), 10-100 (Dunnette, 1979), 100-1000 (McDuffie and Harvey (1973), 0-15 (Prati et al 1971), 0-10 (Ross, 1977), 0-1 (Janardan et al 1975) and -1000 to +100 (Stoner, 1978). With practice most of these index scales can be interpreted with relative ease. It has been argued that a scale of 0-100 is too large and unnecessary for describing water quality (Ross, 1977). However Ross (1977) advocates a scale of 0-10, with index scores being rounded to the nearest whole number. This can cause a significant decrease in accuracy. Likewise the scale of 0-1 of Janardan et al (1975) is extremely limiting. Bolton et al (1978) have shown that a change in an index score of five units, on a 0-100 scale, can be significant. Therefore information would be lost by a reduced scale. The scale of 10-100 advocated by Dunnette (1979) solves the problem of zero scores which can occur from a 0-100 scale using the multiplicative and geometric formulations, yet still covers a wide enough range to retain the maximum amount of information and accuracy. Those larger scales of 100-1000 (McDuffie and Haney, 1973) and -1000 to +100 (Stoner, 1978) are so large as to make interpretation extremely difficult, and in many respects the indices become meaningless.

Interpreting water quality from these index scales obviously requires practice. Tervet (personal communication 1979), interprets the 0-100 scale of the SDD water quality index (Bolon et al, 1978), as shown in Table 1.

Table 1. Interpretation of the SDD Index Scale

90 - 100	Clean water
80 - 90	Good quality water
70 - 80	Good quality with some treatment
40 - 70	Tolerable quality, requires improvement
30 - 40	Polluted
20 - 30	Severely Polluted
0 - 20	Water akin to Piggery Waste

This index covers a range of good quality water, a transitional zone where normal treatment would be sufficient to increase the quality of a surface water body to an acceptable state, and a zone of severe pollution where additional remedial action would be required. However, one criticism of this index scale is that it is biased towards water at the high quality end of the scale.

Table 2. Interpretation of Ross Index Scale (Ross 1977)

10	Pristine purity
8	Slight pollution
6	Pollution
3	Gross pollution
0	Quality akin to septic crude sewage

Table 2 gives the interpretation provided Ross' index (1977). Here the problem of using an index of pollution as opposed to a general water quality index is highlighted, as the upper end of the quality range on this scale is limited.

Both these indices use water quality description as a means of interpretation. Index interpretation would be more meaningful if the index scale were sub-divided into the possible uses of the water as is the case with the NWC classification (1978) the index of Dinius (1972) and the Quality States of Newsome (1972). In this way the index would be a more useful management tool and could also relate quality to economic gains or losses. In instances where an index is sub-divided in terms of use it is also important to include information on water quality standards or criteria (Joung et al, 1978) to allow variations in quality to be meaningful (see also 4.7).

4.4. THE USE OF WQIs FOR TEMPORAL AND SPATIAL COMPARISONS

To be a useful management tool, the resultant water quality index scores produced by each individual index should be comparable in space and time. This is possible for all indices, apart from those of Harkins (1974), and Joung et al (1978). These indices require the ranking of the water samples for each determinand as well as the control values. These rankings are a function of the specific values of the water samples in a particular data set.

Therefore a given sample will have a different index score when considered within the context of a different data set. Thus Harkins' (1974) and Janardan et al (1975) indices must be recalculated every time a new comparison is to be made.

4.5. THE SENSITIVITY OF AN INDEX TO CHANGES IN WATER QUALITY

If an index is to be used to monitor trends in water quality, it must be sensitive to changes in water quality.

A validation project was carried out by Brown et al (1973) using data from numerous federal, interstate, state, regional and local agencies in Tennessee, Maryland, Pensylvania, Ohio, Michigan, Colorado and California, to show that the weighted arithmetic version of the NSFI developed in 1970 was responsive to actual changes in water quality. Analysis of over 80 sample sites for periods up to 15 months showed that NSFI was responsive to changes in water quality conditions. McClelland et al (1973) produced a more intensive validation project for the Kansas River Basin, using 26 sample sites. In this study the use of a water quality index for establishing optimum frequencies of sampling, computing and recording was also investigated. Least squares regression was used to test the feasibility of substituting alternative determinands into NSFI to replace the nine determinands previously selected. This was found to be inadvisable. Four determinands were found to explain 90% of the variance in NSFI over the study period. In this study of the Kansas River Basin the multiplicative weighted index formulation was also adopted as the arithmetic formulation was found insensitive to the effect of a single poor determinand. Both formulations were found to be sensitive to changes in water quality.

The river pollution index of McDuffie and Haney (1973) has been tested using data for the Susquehanna River, upstream and downstream from the Binghamton area. The index successfully showed the impact of the metropolitan area on water quality. Also using data from the New York State Water Quality Surveillance Network for the Upper Susquehanna, Upper Delaware, Mohawk, and Lower Hudson Basins, the index was found successful in showing the relative water quality of these rivers.

Harkins (1974) applied his index to two stations, one upstream and one downstream from an area of heavy municipal and industrial effluent discharges. The index scores obtained for the downstream station were significantly higher than those of the upstream station, thus indicating that the index is sensitive to changes in water quality. But Landwehr et al (1974) explain that the data sets used by Harkins in this example are extremely different and feel that if a more homogeneous data set, more akin to that normally obtained in a water survey, were used, the index may not have produced such distinctive index scores for the two data sets.

Ross' Index (1977) was used to calculate index scores for selected points on the River Clyde, River Kelvin, White Cart Water, Leven Water, North Calder and South Calder Waters in the Clyde catchment, using annual average data collected between 1966 and 1974. The results of this work by Ross (1977) indicated that the index was indeed useful in showing trends in water quality. The use of the index also assisted in pinpointing factors causing an increase or decrease in pollution, and in locating river stretches which required greater investigation due to significant changes in quality. Ross (1977) felt that this index could be successfully used to monitor long-term and short-term changes in water quality.

Monthly data for two stations on the Williamette River for the years 1971-1976 was used to test the sensitivity of Dunnette's Index (1979). Annual improvements recorded for the two sites were found to coincide with efforts by the Department of Environmental Quality, industry and municipalities to control wastewater discharge into the Williamette River.

The Yorkshire and Anglian Water Authorities (1978) individually conducted pilot studies within their regions testing the application of the SDD index. The Yorkshire Water Authority used annual average data for April 1976 - March 1977 for the River Aire. The modified arithmetic weighted and geometric weighted index formulations were used.

Annual mean data for 48 river points covering a broad section of river types between Lincolnshire and Essex were used by the Anglian Water Authority to investigate the use of the SDD index. The modified arithmetic weighted and geometric weighted formulations were also tested. However, where the concentration of determinands caused a zero score on the rating curves, they were recorded as 1 to avoid a resultant zero index score which would have occurred using the weighted geometric formulation. In all instances the index was found to be sensitive to actual changes in water quality. However, it was felt that modifications to the index were necessary in applying the index to English rivers.

Joung et al (1978) evaluated both forms of their index using data from Carson Valley, Nevada and other locations within the USA. From this study, the WQITN version of the index was found to be the most "geographically acceptable" in displaying changes in water quality.

Prati et al (1971) applied their index to a number of rivers in the Ferrara province in Italy. However, the results of this study do not appear to have been published, which would tend to suggest that the results may not have been favourable.

Both the PWS index of Deininger and Maciunas (1971) and the use-related indices of O'Connor (1971) have been applied to a wide range of water quality conditions. In each case the indices were found to be sensitive to changes in water quality.

The index of Janardan and Schaeffer (1975) has been applied extensively to data from gauging stations in the State of Illinois, USA. Not only did the index satisfactorily reflect water quality trends, but the results produced showed close agreement with those of biological indices applied to the same data (Schaeffer and Janardan 1977).

Finally, Stoner (1978) applied his index to data from surface waters in Texas. Although the results show that the index is sensitive to variations in water quality, the results produced indicate that perhaps it is either oversensitive, or that the index scale is too large (see 3.5.5.).

4.6. THE AGREEMENT OF AN INDEX WITH EXPERT OPINION

The aim of a water quality index is to produce objectively standardised index scores which will agree with the variable subjective opinion of a group of water quality experts. Work by McClelland et al (NSF 1973, 1974), Landwehr (1976), Schaeffer and Janardan (1977), Bolton et al (1978), Joung et al (1978) and Aston et al (1979) has shown that index scores subjectively ascribed to water quality data by water quality experts can agree with those produced by WQI calculations over a wide range of water quality conditions. A study undertaken by Deininger and

Newsome (1984) compared the index scores produced using the NSFI with those subjectively assessed by water quality experts from the UK, USA and Brazil. Each set of results showed reasonable agreement between the two methods. The study was extended to include a comparison between the index scores produced by the water experts from these three countries. It was generally the case that water quality experts from both Britain and Brazil rated water quality below that of experts from the USA.

4.7. THE INCLUSION OF LEGAL STANDARDS OR ACCEPTED WATER QUALITY CRITERIA

Indices must include information on legal water quality standards or recognised criteria where standards are not available. Without this reference to standards, the interpretation of the index scale in terms of quality becomes meaningless or, at least, very much more difficult. The use of water quality standards facilitates the sub-division of an index scale into possible uses which in turn provide more information to the user.

4.8. THE FLEXIBILITY OF AN INDEX TO THE DATA AVAILABLE

It must be possible to use an index when the full range of determinand values is not available. This regularly occurs in the UK as the sampling frequency varies from one determinand to another. Most indices only require the re-calculation of weightings when the full range of recommended determinands is unavailable (Brown et al, (NSF) 1970-1976; SDD, 1976; Ross, 1977; and Dunnette, 1979). However, in some instances the accuracy of the index score may be impaired when a reduction in the number of determinands is used, (Anglian and Yorkshire Water Authority Internal Reports, 1978). When using the indices of Harkins (1974), Janardan and Schaeffer (1975) and Joung et al (1978) any number of combinations of determinands may be used but the results obtained would not necessarily be comparable.

4.9. THE INCLUSION OF TOXIC DETERMINANDS

Pollution due to toxic determinands such as heavy metals (copper, lead, zinc, cadmium and mercury) pesticides, hydrocarbons and polyaromatic hydrocarbons (PAHs) is becoming increasingly common as urban/industrial regions continue to expand. Consequently any index which does not consider such determinands, at least indirectly within its formulation, may in some instances be meaningless.

4.10. A CONSIDERATION OF POTENTIAL USE

A consideration of the potential use to which water of a particular quality may be put will make an index that much more complete. It allows an index range to be sub-divided in a more meaningful manner than a description of water quality alone and enables a number of water quality standards to be built into the

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Footnote to 4.8. SDD index correction equations:

Corrected modified arithmetic weighted index =
Corrected geometric weighted index

$$= \text{weightings of uncorrected WQI} \quad x \quad \frac{1}{1-y}$$

where x = sum of the weightings for which data are available

y = sum of weightings of data for which data are unavailable index structure. In this way information on the economic gains and losses that can accrue from pollution abatement measures may be evaluated. Only Dinius (1972) has sub-divided a WQI index range in this way.

4.11. SUMMARY

A number of water quality indices exist, each with their strengths and weaknesses. However, many of these indices are being used successfully to monitor trends in water quality (Chapter 5). They agree with 'expert' opinion and are undoubtedly more objective than the water qualify classification systems at present used in the United Kingdom, (see Chapters 6 and 7). Because of this increased objectivity, comparisons in space and time are more accurate.

Table 3 outlines the characteristics of various water quality indices, and compares each index to the total range of indices considered in this report.

Table 3. Essential Characteristics of a General Water Quality Index

Characteristics	Horton (1965)	Brown et al NSFI (1970-1976)	Prati et al (1971)	Dinius (1972)	McDuffie and Haney (1973)	Harkins (1974)	Nemerow and Sumitomo (1970)	Inhaber (1975)	Janardan and Schaeffer (1975)	SDD (1976)	Ross (1977)	Joung et al (1978)	Dunnette (1979)
The Objective Development of an Index													
a) Determinand Selection	No	Yes	No	No	No	No	No	No	No	Yes	No	Yes/No	Yes
b) Determinand Transforms	No	Yes	No	No	No	Yes	Yes	No	Yes	Yes	No	Yes	No
c) Determinand Weightings	No	Yes	None	No	No	Yes	No	No	Yes	Yes	No	Yes	Yes
The Interpretation of an Index													
a) Simple to Use	Yes	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes
b) Easy Interpretation	Yes	Yes	No	Yes	No	No	Yes	No	Yes	Yes	Yes	No	No
c) Definite Scale	0-100	0-100	0-15	0-100	0-1000	No	0-1	No	0-1	0-100	0-10	0-100	10-100
Sensitive to Changes in Water Quality	?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Agree with 'Expert' Opinion	?	Yes	?	?	?	?	?	?	Yes	Yes	Yes	Yes	Yes
Include Information on Standards or Accepted criteria	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Insensitive to the Number of Determinands Used	?	Yes	Yes	?	Yes	Yes	?	No	Yes	Yes	Yes	Yes	Yes
Index Scores should be Comparable in Space and Time	?	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes
Include Information on Toxic Determinands	No	Yes	No	No	No	No	No	No	Yes	Yes	No	No	No
Include Information on Potential Use	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No

CHAPTER 5

THE DEVELOPMENT OF WATER QUALITY CLASSIFICATION SYSTEMS IN THE UNITED KINGDOM

5.1. EARLY APPROACHES TO WATER QUALITY CLASSIFICATIONS

The Eighth Report of the Royal Commission on Sewage Disposal (1912) suggested a water quality classification based on the general visible state of a watercourse. Characteristics such as smell, turbidity, the presence or absence of fish, the presence of suspended matter, and the nature of algal growths were recommended for consideration within such a classification.

By examining average analytical data from the physical and biological condition of rivers above and below sewage outfalls, it was found that BOD was the best chemical indicator of the condition of a river. This determinand can be used as a measure of the polluting capacity of an effluent as it is indicative of the amount of dissolved oxygen used by micro-organisms to decompose the organic matter present in the sewage. Thus, the higher the BOD concentration, the greater the amount of sewage likely to be present. The classes of water quality suggested by the Commission were: very clean, clean, fairly clean, doubtful, and bad, with each related to a range in BOD concentration. These standards were adopted by many of the old river boards and were often modified to take into account the influence of other determinands. For example, the Trent River Authority (1966) used ammoniacal nitrogen concentration, as opposed to BOD, to classify water quality. In addition to this classification the Commission recommended the 20/30 standard for all sewage effluents. This meant that after treatment all discharges into rivers from sewage works should have a maximum BOD concentration of 20 mgl^{-1} and a suspended sediment concentration of 30 mgl^{-1}. In this way it was hoped that pollution due to sewage effluent might be avoided.

In essence the BOD classification suggested by the Commission was a water quality index based on a single determinand (Bolton et al, 1978). From this, many river authorities developed classifications based on various combinations of a number of determinands including dissolved oxygen (DO), ammoniacal nitrogen, the ability of a water to support fish, suspended solids and the presence of toxic compounds.

Today a simple BOD classification is still used by the Solway and Tweed RPBs, (Table 4).

Table 4. A BOD Classification

Classification	BOD (mgl^{-1})
Very Clean	1
Clean	1-2
Fairly Clean	2-4
Unsatisfactory	4-6
Bad	6

(Taken from the Solway River Purification Board Annual Report, 1977).

It would, perhaps, seem somewhat illogical that these two Boards, who were responsible for the production of the SDD (1976) index, should only use that index officially for internal purposes.

5.2. THE DoE AND SDD RIVER SURVEY CLASSIFICATIONS

In an attempt to overcome the predominantly descriptive classification of water quality proposed by the Royal Commission (1912), the DoE and SDD developed a four-banded classification system for the production of the original River Pollution Surveys of England, Wales, and Scotland in 1972. The classification was designed to reflect the physical, chemical and biological nature of a surface water body which would be based on a small number of determinands (Table 5). The criteria laid down for each class are imprecise. This often results in rivers of greatly differing quality being placed within the same class. The classification is subjective, and the final classes produced by one expert may not agree with those of another examining the same data. Thus, using this classification, it could well be meaningless to try to compare the quality of two rivers which have been similarly classified.

The disadvantages of this classification were highlighted in the internal reports of the Anglian (1978) and Yorkshire Water Authorities (1978), when comparing its performance to the SDD (1976) index (see Section 5.6).

This classification was modified by many of the water authorities to include additional determinands, and the Yorkshire Water Authority introduced an additional class, Class 0, for waters intended for potable water supply. This represented the first indication of use within a water quality classification in the UK.

5.3. THE COMBINED USE OF BIOLOGICAL AND CHEMICAL CLASSIFICATION

In an attempt to overcome the shortcomings of the simple River Pollution Survey Classification, the SDD, in their 1975 survey used separate chemical and biological classifications, and compared the results. The chemical classification was similar to that above, with the biological references deleted. It was mainly

Table 5. The DOE and SDD River Pollution Survey Classification (1972)

Class	Description	Characteristics
1	Rivers Unpolluted and Recovered from Pollution	Rivers which are known to have received no significant discharges of pollution. The BOD concentration is less than 3 mgl^{-1}, and they are well oxygenated.
2	Rivers of Doubtful Quality and Needing Improvement	Rivers not classified as Class 1 on the basis of their BOD concentration, and possessing substantially reduced DO levels. Or rivers which regardless of their BOD concentration are known to have received significant toxic discharges which cannot be proved to have had harmful effects.

Table 5. (continued)

Class	Description	Characteristics
3	Rivers of Poor Quality Requiring improvement as a Matter of Urgency	Includes rivers not in Class 4 on the basis of their BOD concentration, but possessing a DO concentration below 50 per cent saturation for lengthy periods. They may contain substances which are known to be actively toxic at times, and may also be effected by suspended solid discharges.
4	Grossly Polluted Rivers	Rivers with a BOD concentration of 12 mgl^{-1} or above and known to be incapable of supporting fish life. Rivers which are known to be completely disoxygenated at any time and which have an offensive appearance.

based on dissolved oxygen and BOD concentrations. The Trent Biotic Index (Woodiwiss, 1966) was used as the basis for the biological classification, but modified to a four-point scale to allow comparison with the chemical classification. This classification, although better than the original River Pollution Survey Classification (1972), is still subjective, and has similar disadvantages. Consequently, the SDD developed their own water quality index (1976).

5.4. THE NATIONAL WATER COUNCIL CLASSIFICATION

The most recent water quality classification to be developed was that of the National Water Council (NWC 1978). This classification is based on a quality classification scheme originally developed by Thames Water Authority (1976). The classification consists of five classes which are related to both potential use and environmental considerations (Table 6). Each class is defined by 'class limiting criteria' for each determinand, which must be achieved by 95% of the samples taken as part of the normal monitoring process. This classification incorporates chemical and biological considerations, as well as EEC (1975) and EIFAC (European Inland Fisheries Advisory Commission, 1964-1983) directives. In addition, the Thames Water Authority Classification uses sub-notations to indicate a river, which although belonging to a specific class, will be upgraded when possible.

These two classifications are undoubtedly a vast improvement upon the DoE River Pollution Survey classifications, but inherit many similar problems. In discussions with members of the water authorities of England and Wales who use the NWC classification system, many felt that it was still very subjective. The EIFAC data are rarely available for consideration, therefore the subjective assessment of the toxicity of a surface water body to fish is necessary. Although the use of five classes makes this classification more refined, much information is still hidden. Class 2 of the NWC classification covers a wide range of water quality, yet the quality of individual rivers belonging to this class is still not distinguished. At a time when the water authorities are striving to achieve River Quality Objectives (RQOs), it is surely desirable to know if a river is a 'good' or 'bad' Class 2 river. Although the inclusion of EEC (1975) and EIFAC (1964-1983) Directives within these classifications improves the assessment of water quality, it means that a

Table 6. The National Water Council Classification (1978)

River Class	Quality criteria	Remarks	Current potential uses
1A	Class limiting criteria (95 percentile) (i) Dissolved oxygen saturation greater than 80%. (ii) Biochemical oxygen demand not greater than 3 mg/l. (iii) Ammonia not greater than 0.4 mg/l. (iv) Where the water is abstracted for drinking water it complies with requirements for A2** water. (v) Non-toxic to fish in EIFAC terms (or best estimates if EIFAC figures not available).	(i) Average BOD probably not greater than 1.5 mg/l. (ii) Visible evidence of pollution should be absent.	(i) Water of high quality suitable for potable supply abstractions and for all other abstractions. (ii) Game or other high class fisheries (iii) High amenity value.
1B	(i) DO greater than 60% saturation (ii) BOD not greater than 5 mg/l. (iii) Ammonia not greater than 0.9 mg/l. (iv) Where water is abstracted for drinking water, it complies with the requirements for A2** water. (v) Non-toxic to fish in EIFAC terms (or best estimates if EIFAC figures not available).	(i) Average BOD probably not greater than 2 mg/l. (ii) Average ammonia probably not greater than 0.5 mg/l. (iii) Visible evidence of pollution should be absent. (iv) Waters of high quality which cannot be placed in Class 1A because of high proportion of high quality effluent present or because of the effect of physical factors such as canalisation, low gradient or eutrophication. (v) Class 1A and Class 1B together are essentially the Class 1 of the River Pollution Survey.	Water of less high quality than Class 1A but usable for substantially the same purposes.
2	(i) DO greater than 40% saturation (ii) BOD not greater than 9 mg/l (iii) Where water is abstracted for drinking water it complies with the requirements for A3** water (iv) Non-toxic to fish in EIFAC figures not available).	(i) Average BOD probably not greater than 5 mg/l. (ii) Similar to Class 2 of RPS. (iii) Water not showing physical signs of pollution other than humic colouration and a little foaming below weirs.	(i) Waters suitable for potable supply after advanced treatment. (ii) Supporting reasonably good coarse fisheries. (iii) Moderate amenity value.
3	(i) DO greater than 10% saturation. (ii) Not likely to be anaerobic. (iii) BOD not greater than 17 mg/l*.	Similar to Class 3 of RPS.	Waters which are polluted to an extent that fish are absent or only sporadically present. May be used for low grade industrial abstraction purposes. Considerable potential for further use if cleaned up
4	Waters which are inferior to Class 3 in terms of dissolved oxygen and likely to be anaerobic at times.	Similar to Class 4 of RPS.	Waters which are grossly polluted and are likely to cause nuisance.
X	DO greater than 10% saturation		Insignificant watercourses and ditches not usable where objective is simply to prevent nuisance developing.

(a) Under extreme weather conditions (e.g. flood drought freeze up) or when dominated by plant growth or by aquatic plant decay, rivers usually in Classes 1, 2 and 3 may have BODs and dissolved oxygen levels or ammonia content outside the stated levels for those Classes. When this occurs the cause should be stated along with analytical results.

(b) The BOD determinations refer to 5 day carbonaceous BOD (ATU) ammonia figures are expressed as NH_3.

(c) In most instances the chemical classification given above will be suitable. However, the basis of the classification is restricted to a finite number of chemical determinands and there may be a few cases where the presence of a chemical substance other than those used in the classification markedly reduces the quality of the water. In such cases, the quality quality classification of the water should be downgraded on the basis of the biota actually present and the reasons stated.

(d) EIFAC (European Inland Fisheries Advisory Commission) limits should be expressed as 95% percentile limits.

* This may not apply if there is a high degree of re-aeration.

** EEC category A2 and A3 requirements are those specified in the EEC Council Directive of 16 June 1975 concerning the Quality of Surface Water Intended for Abstraction of Drinking Water in the Member States.

subjective assessment of water quality must be made from a list of over 46 determinands. This obviously promotes inaccuracies. Despite the improvements provided by these classifications, many users still base their final assessment of water quality on the concentration of three or four determinands: dissolved oxygen, biochemical oxygen demand, ammonia and suspended solids.

The fact that so many classifications of water quality have been developed in recent years suggests that a more objective method of classifying water quality is desirable. Could water quality indices be the solution to this problem?

5.5. WATER QUALITY INDICES

Following the combined use of chemical and biological indices, the SDD (1976) investigated the use of WQIs in the management of water quality in the USA. In their efforts to develop a more objective classification they decided to develop and evaluate a WQI of their own (see Section 3.3.7.). This index has been extensively tested on data gathered by the Tweed, Tay and Solway RPBs and has been judged accurate in the assessment of water quality within these areas. In fact this index is used for all internal water quality monitoring purposes. However, because of the mandatory need for national comparability of data, the NWC classification is used for all official documentation of surface water quality.

The pollution index of Ross (1977) was developed in the following year for application to rivers of the Clyde RPB (see Section 3.4.4.). Many of these rivers are polluted and it was thought that the SDD (1976) index, developed within areas of high quality water, would not adequately highlight the more subtle changes in quality which occur in these areas. Again, this index is only used for internal purposes within the Clyde RPB.

WQIs have not been developed within any of the ten water authorities of England and Wales. However, two of these authorities, the Anglian and Yorkshire Water Authorities, have independently assessed the performance of the SDD (1976) index in the evaluation of water quality within their catchments (Anglian and Yorkshire Water Authority Internal Reports, 1978).

5.6. THE APPLICATION OF THE SDD (1976) INDEX TO RIVERS OF THE ANGLIAN AND YORKSHIRE WATER AUTHORITIES

5.6.1. Details and Results of the Yorkshire Water Authority Study

In applying the SDD (1976) index to the River Aire, in the Yorkshire Water Authority region, E. Coli and conductivity measurements were omitted. E. Coli was not included as it was not considered important to the water quality of the river Aire because it is not used for public water supply. Neither E. Coli nor conductivity are regularly measured in the water quality monitoring programme of the River Aire. Tervet and Welsh (Internal Report to Solway RPB) and Currie (personal communication 1979) agree with the exclusion of E. Coli as fluctuations in the concentration of this determinand are difficult to interpret. E. Coli was originally included within the SDD (1976) index because of the importance the NSFI (1970-1976) placed on this determinand. Because of the exclusion of E. Coli and conductivity, the remaining determinand weightings were recalculated using the SDD correction equations (see footnote to Section 4.8.).

Rating curves were used unchanged, but some difficulty was encountered in using the rating curve for ortho-phosphates. This is because analyses for the River Aire showed values in excess of 0.5 mgl^{-1} ortho-phosphate. These values were included in the analysis, but received a rating of 0.1 to avoid zero scores which were considered unjustified. The modified arithmetic and geometric weighted index formulations were used to calculate the final index scores (see Section 3.3.7.).

The SDD (1976) index was evaluated as being efficient in assessing water quality. It was therefore decided to compare the information provided by this index with that of the DoE River Pollution Survey Classification. For this comparative study the index range was initially sub-divided into four equal classes (Table 7).

Table 7. Four Class Banding of the SDD Index

DoE Class	Values of WQI	DoE Description
1	100 - 75	Good
2	74 - 50	Doubtful
3	49 - 25	Poor
4	24 - 0	Bad

A five-banded classification was also adopted to illustrate more subtle changes in river water quality identified by the respective SDD WQI scores (Table 8).

Table 8. Five Class Banding of the SDD Index

DOE Class	Value of WQI	DOE Class	Value of WQI
1	100 - 80	4	39 - 20
2	79 - 60	5	19 - zero
3	59 - 40		

Both these classifications of the WQI scales were used to produce water quality maps for the River Aire. (Figures 1-5).

It was found that the four-banded classification system for the SDD Index successfully indicated the deterioration in quality of the River Aire as it reaches Skipton, which the DoE River Pollution Survey classification failed to indicate (Figures 1, 2 and 5). When the index scores produced by the modified arithmetic weighted formulation were used for the four-banded classification, a minor improvement in quality was recorded due to self purification and extra dilution by Harden Beck (Figure 1). The geometric weighted formulation failed to classify the river downstream of Esholt as being in class 4, although the next sewage discharge downstream places the river in class 4.

The five banded classification system of the SDD index scores was found to be more refined, and it was difficult to assess which index formulation was most accurate (Figures 3 and 4).

In conclusion, it was felt that the use of water quality indices allows a much more detailed picture of river water quality to be presented than that afforded by the DoE classification. The report concludes that the SDD index has undoubted merits over the DoE classification in that all the information necessary for an index calculation is stored in the present data archive, and additional information is not required. However it must be remembered that the DoE classification was developed for use at a different level of management to that of WQI. An index also allowed a finer distinction of changes in water quality to be made. It was felt that an index could be a useful tool if the determinands included were relevant to particular water quality targets or objectives. Thus, use-related indices were advocated, or a general water quality index based on only Biochemical Oxygen Demand (BOD), Ammonia and Dissolved Oxygen.

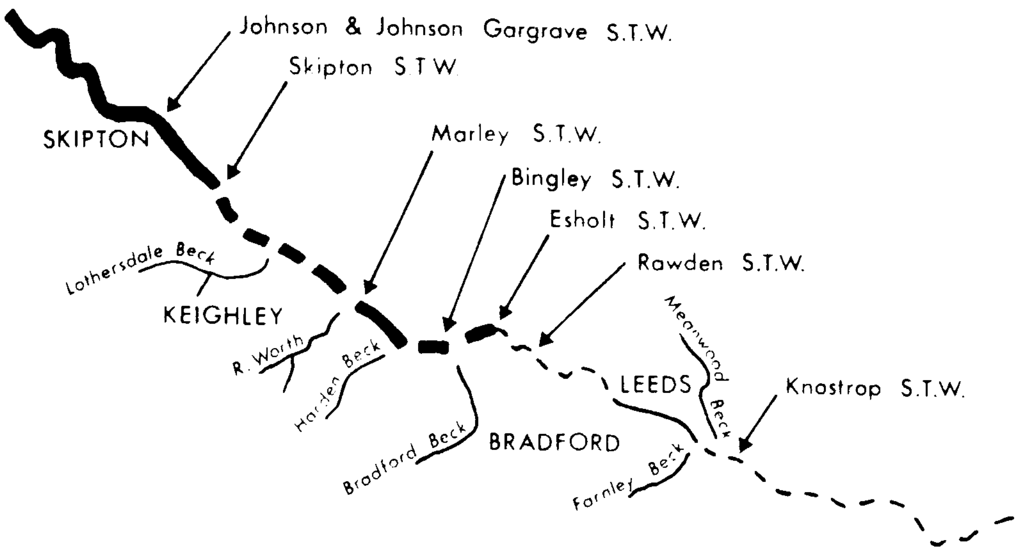


Fig 1 Classification Based on the SW Formulation of the SDD WQI 1976-77 Data for the River Aire

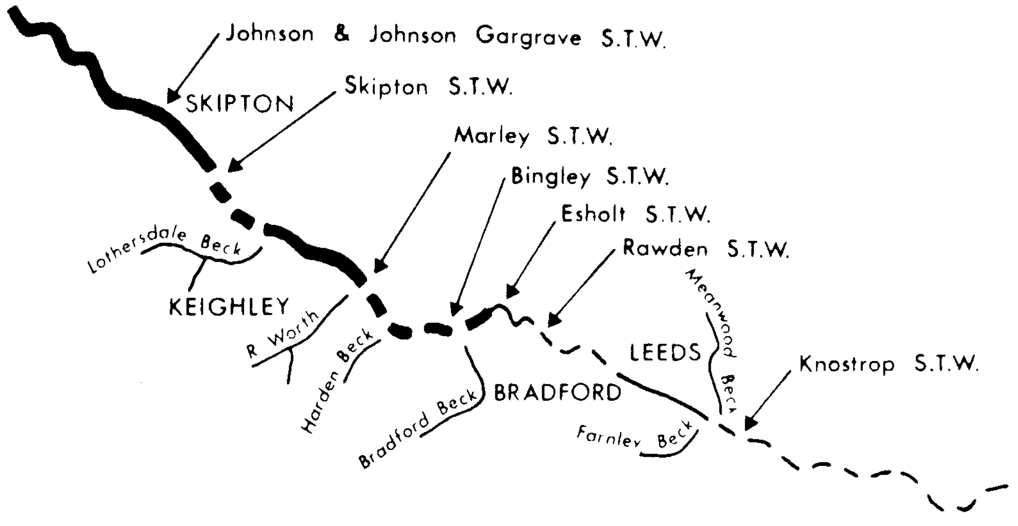


Fig 2 Classification Based on the GW Formulation of the SDD WQI. 1976-77 Data for the River Aire

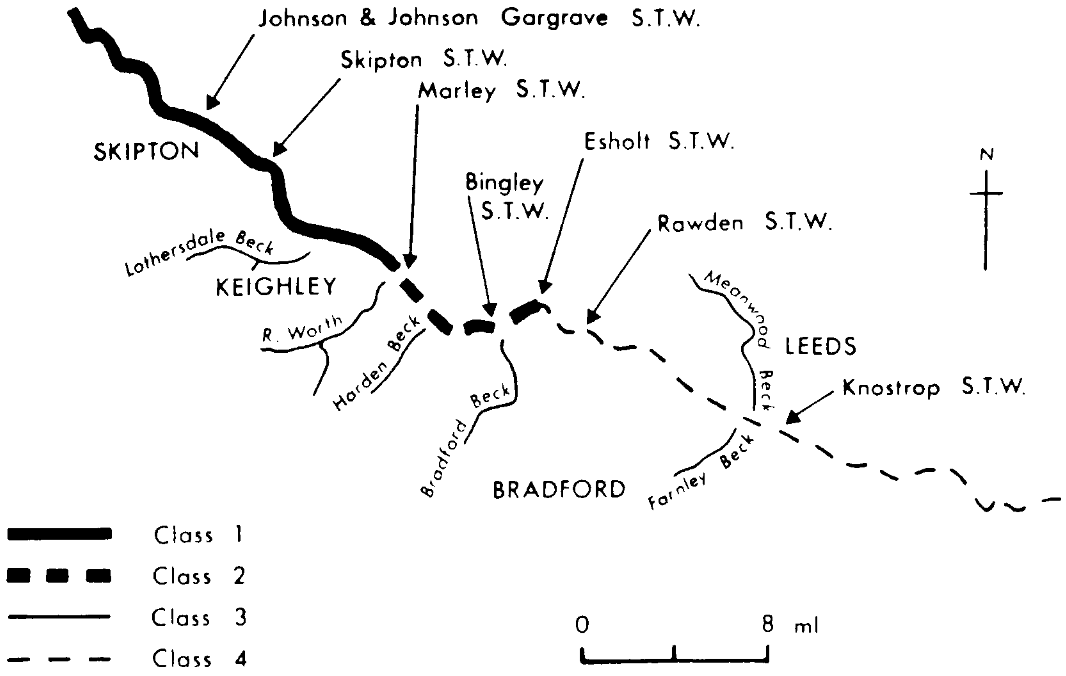


Fig 5 Classification of the River Aire Based on the DOE River Pollution Survey Classification

Fig 3 Five Banded Classification Based on SW Formulation of the SDD WQI. 1976-77 Data for the River Aire

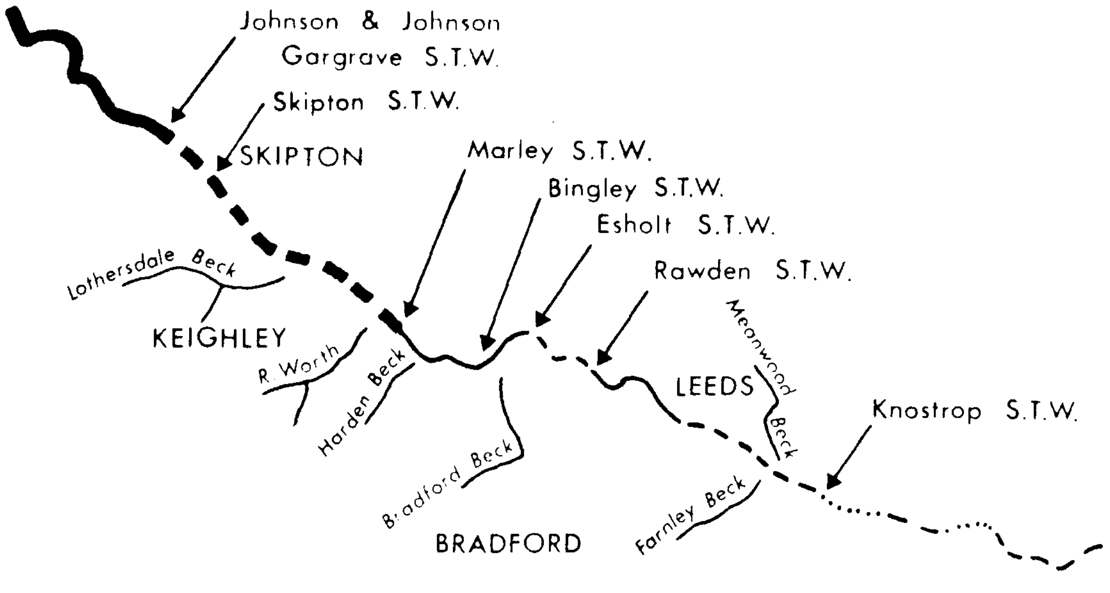
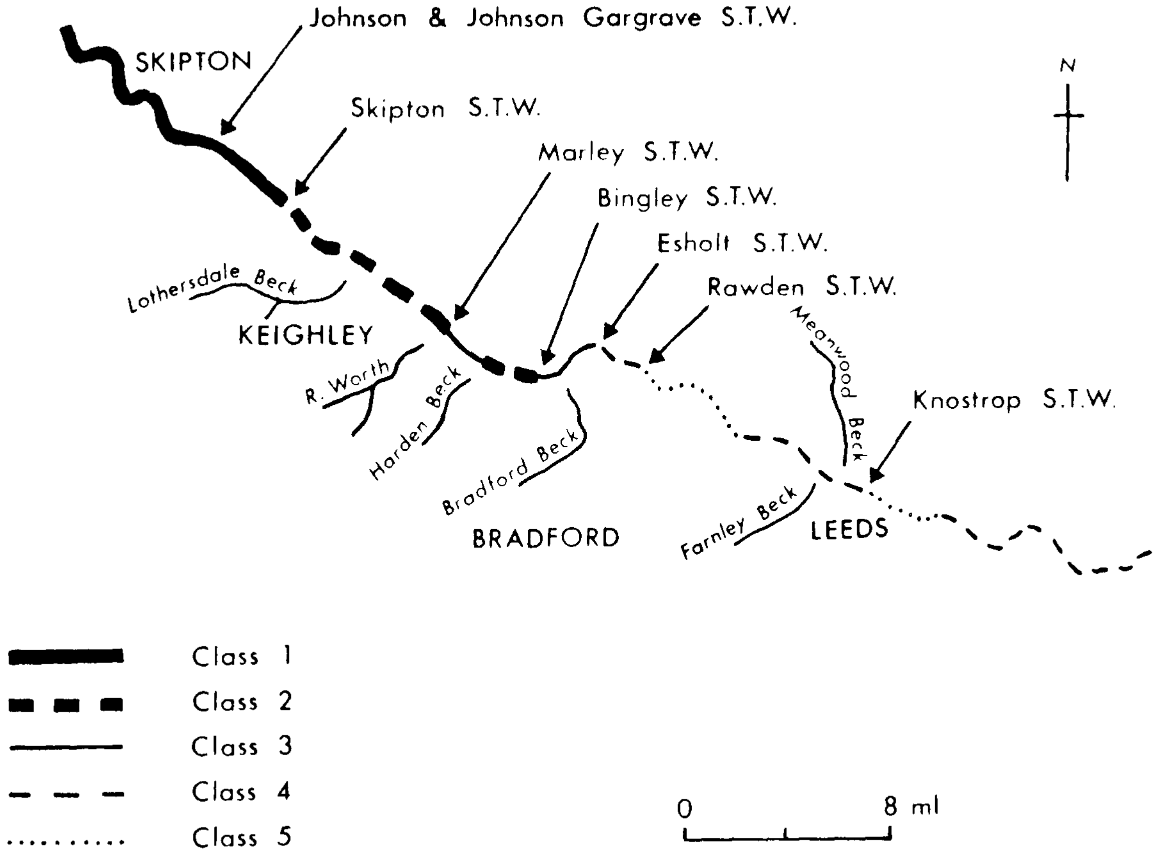


Fig 4 Five Banded Classification Based on GW Formulation of the SDD WQI. 1976-77 Data for the River Aire



5.6.2. Details and Result of the Anglian Water Authority Study

When the SDD index was applied to a variety of rivers in the Anglian Water Authority region, E. Coli was again omitted. Phosphates, conductivity and suspended solids were also excluded at some sites as these are not regularly measured in all areas of the Anglian Water Authority region. Therefore the correction equations were used to re-calculate determinand weightings (see Footnote to Section 4.8.). The SDD index was again banded into four classes for comparison with the DOE classification (Table 7). The mean index scores showed the expected ranks, but the spread about the mean was wide and resulted in overlapping of classes. The results produced by the two index formulations were very similar. However, the geometric weighted formulation was considered better when data on all determinands was not available, and the correction equation was used. (Table 9). The report also questioned the value of temperature measurements when monitoring the water quality of English rivers, as they considered thermal pollution to be a rare occurrence. The results from this study indicated that the index is more accurate when all determinands are used and the correction equation is not employed (Table 9).

Table 9. The Effect of E.Coli Data Upon WQI and Scores

Sampling points	RPS Class	Mod.Arith.Weighted WQI		Geometric Weighted WQI	
		with E. Coli	Without* E. Coli	With E. Coli	Without* E. Coli
R. Rhee, Ashwell	1	74	62	74	71
Bourn Brook	1	50	42	41	38
R.Cam. Dimmocks Cote	2	35	27	35	30
R. Cam. Bottisham Lock	3	24	18	31	27

*Corrected as in Footnote to 4.8.

The rating curves for total organic nitrogen, phosphates and conductivity within the SDD index were considered inappropriate for rivers within the Anglian Water Authority region. Values obtained for these determinands were frequently at, or close to zero, thus distorting the index. pH values often tended to be higher than those considered as the optima for Scotland. Similarly, it was considered that weightings would possibly need to be modified for the index to be more accurately applied to the rivers within the Anglian Water Authority.

In conclusion, the report stressed the value the increased objectivity allowed by the use of the SDD index over the DoE classification. Two analysts could now produce the same water quality index score for a particular data set. The method is well suited to a computer-based data processing system, and the staff involved in the calculations preferred the approach to the DoE classification system.

With modifications, it was thought that the SDD (1976) index could be successfully applied in the Anglian Water Authority region and probably used more widely. It would provide a valuable 'yardstick' to monitor temporal increases or decreases in water quality. However, the index gives no indication of the suitability of water for a given use, which the Anglian Water Authority considered to be one disadvantage of the technique.

5.6.3. General Conclusions of Case Studies

These two studies have shown that water quality indices can be applied to British water courses. Those using the SDD (1976) index thought that it provided more information than the DoE River Pollution Survey classification, which contradicts the reasoning offered by many 'water quality experts' for not using water quality indices to monitor trends in surface water quality. The major criticism levelled by these two reports was that the SDD (1976) index gave no indication of the suitability of the water for a specific use. However, with modifications, this can be built into a water quality index system.

CHAPTER 6

A COMPARATIVE STUDY OF WQIs AND THE CLASSIFICATIONS OF THE NATIONAL WATER COUNCIL (NWC) AND THAMES WATER AUTHORITY (TWA)

6.1. A COMPARISON BETWEEN THE NWC CLASSIFICATION AND WQIs

Following the results of the Anglian and Yorkshire Water Authorities' investigations into the use of the SDD (1976) index in the management of surface water quality, it was decided to extend this type of study to include the NWC (1978) classification. The results of this study have been published previously (House, 1980; House and Ellis, 1980) but are developed more fully in this Chapter.

To compare the NWC classification system and water quality indices, data which had previously been classified using the NWC classification system were utilised. The data selected for this comparison were those used by Aston et al (1979) in a study of the change in the quality of London's Metropolitan watercourses during the seventies. In this study Aston et al (1979) produced NWC classifications and index scores using Ross' (1977) index for selected points on eight Metropolitan watercourses. In addition to Ross' index, the SDD (1976) index was selected for this comparison with the NWC classification system, due to the fact that these are the only two chemical indices to have been developed within the United Kingdom. As such they are most likely to reflect the way in which water quality is assessed in the United Kingdom. In addition, members of both the water authorities and river purification boards were likely to be more familiar with their formulation and application.

Only four determinands were considered in the data sets used by Aston et al (1979). Therefore, in order to calculate the SDD index scores, it was necessary to re-calculate the weightings for the four determinands, (Table 10), using the SDD index correction equations (see Section 4.8.). The four determinands were supended solids, ammoniacal nitrogen, BOD, and the percentage saturation of dissolved oxygen.

Table 10. Re-calculated Weightings for the SDD INDEX
(From House and Ellis, 1980)

Determinand	Weighting
Suspended Solids	0.14
Ammoniacal Nitrogen	0.23
Biochemical Oxygen Demand	0.29
Dissolved Oxygen (% sat'n)	0.34
	1.00

The arithmetic weighted, geometric weighted and modified arithmetic weighted (Solway weighted), index formulations were used for the calculations of the SDD index scores. The rating curves developed by SDD were used unchanged. However, where a determinand concentration equated to a zero rating, it was recorded as 1 to avoid the occurrence of zero index scores when using the geometric weighted index formulation.

SDD index scores were calculated for 27 sample points on seven Metropolitan watercourses in 1970, and 30 sample points for eight rivers in 1977. These were then compared with the NWC classifications and Ross index scores calculated by Aston et al (1979).

To allow a direct comparison between the NWC classifications and the SDD index scores, the 0 -100 index range has been subdivided into five classes (Table 11).

Table 11. Five Class Banding of the SDD Index Scale (From House and Ellis, 1980)

NWC Classes	SDD Index Range
1A	91 - 100
1B	71 - 90
2	41 - 70
3	21 - 40
4	0 - 20

In the previous studies undertaken by the Yorkshire (Internal Report 1978) and Anglian Water Authorities (Internal Report, 1978), the SDD index range was divided into four or five equal classes (Tables 7 and 8). This banding into equal classes resulted in many of the water quality index scores producing class overlaps. Therefore, subdivision of the water quality index range into equal classes is not the most appropriate method of categorisation. The class divisions suggested in Table 11 are intended to reduce the occurrences of overlapping classes. For example, Class 2 of the NWC classification covers a wide range of water quality conditions and possible uses. Consequently a water quality index range of between 41-70 would be more appropriate in recording this diversity. Rivers classified into Class 2 could be considered as being in a transitional phase between 'good' and 'bad' water quality. The class divisions used in this study are largely based upon the interpretation of the 0-100 SDD water quality index scale given by Tervet, (Personal communication, 1979; see Section 4.3.).

6.2. THE RESULTS OBTAINED FOR THE COMPARISON BETWEEN THE NWC CLASSIFICATION AND THE SDD INDEX

Tables 12 to 15 show the results obtained from this comparative study. When the 57 data sets were re-classified using the Solway modified arithmetic weighted formulation (SW), the geometric weighted formulation (GW) and the arithmetic weighted formulation (AW), 42 (73.6%), 36 (63%) and 23 (40%), of the SDD water quality index scores respectively, classified the rivers into the same classes as the NWC classification.

Inspection of the tabled data shows the SW formulation to underestimate water quality at the lower range of the water quality scale, ie below a water quality index score of 50. This characteristic caused the mis-classification of 14 rivers belonging to NWC classes 2 and 3. The SW formulation, which is based on the AW formulation, was developed by the Solway RPB to compensate for the over-estimations produced by the latter method. As shown by the results in Table 12, this has been successfully achieved for rivers of good water quality.

The fact that the SW formulation underestimates water quality at the lower range of the water quality scale was also reported by the Yorkshire Water Authority (Internal Report 1978), where the SW formulation indicated an incident of gross pollution which was considered doubtful.

The classifications produced using the GW formulation indicated that this formulation suffers from overestimating water quality at the upper end of the water quality scale. The GW formulation was developed by NSF in 1973 because the AW formulation, as well as overestimating water quality at the upper end of the quality scale, was also found to be insensitive to a single 'bad' determinand score, and therefore overestimated water of low

Table 12. Results obtained from the Comparative Study between the NWC Classification System and the SDD Index (From House and Ellis, 1980).

Location and Date	NWC Classes	Ross Index Scores	SDD Index Scores		
			AW	GW	SW
River Wandle 1970					
Croydon Arm - Upper Reaches	3	6	52	47	27
Croydon Arm - Lower Reaches	3	6	51	47	26
Carshalton Branch	3	6	46	37	21
Goat Bridge - US of Beddington STW	3	7	56	49	31
Watermeads - DS of Beddington STW	4	3	18	6	3
DD of Wandle Valley and US of Wimbledon STW	4	2	14	5	2
US of the Tideway	4	3	15	6	2
Beverley Brook 1970					
Beverley Brook - DS Worcester Park STW	4	3	18	6	3
Pyl Brook - DS of Sutton STW	3	6	43	38	18
Beverley Brook - US of Tideway	3	5	39	29	15
River Ravensbourne 1970					
River Ravensbourne - US of Pool	2	7	72	65	52
River Pool	2	7	64	55	41
River Quaggy	2	7	75	63	56
River Ravensbourne - US of Tideway	2	7	67	61	45
River Crane and Duke of Northumberland's River 1970					
River Crane - Upper Reaches	3	7	56	51	31
River Crane - US of the Duke's River	2	8	74	67	54
River Crane - US of Tideway	2	8	74	68	55
Duke's River - US of the Tideway	2	9	74	68	55

Table 12. (continued)

River Brent 1970					
Silk Stream	3	6	49	44	24
Dollis Brook	2	6	55	50	30
River Brent - DS of the Welsh Harp	2	8	68	63	46
River Brent - US of Grand Union Canal	2	7	57	52	32
River Brent - US of the Tideway	2	7	54	50	29
Grand Union Canal 1970					
Grand Union Canal - on entry to MPC Area	2	7	72	69	51
Grade Union Canal - US of the confluence with River Brent	2	6	49	46	23
Paddington Arm	2	7	52	44	27
Regent's Canal - US of the Tideway	2	8	75	69	57
River Wandle 1977					
Croydon Arm - Upper Reaches	1B	10	95	95	90
Carshalton Branch	1B	10	94	94	89
Goat Bridge - US of Beddington STW	1B	10	91	90	82
Watermeads - DS of Beddington STW	3	6	43	35	18
DD of Wandle Valley and US of Wimbledon STW	2	6	53	44	28
US of Tideway	2	6	57	47	32
River Darent and Cray					
River Darent - Upper Reaches	1B	10	90	90	81
River Darent - US of the Tideway	1B	10	93	92	86
River Shuttle	1B	9	83	83	69
River Cray - US of the Tideway	1B	10	88	87	77

Table 12. (continued)

Beverley Brook 1977					
Beverley Brook - DS Worcester Park STW	3	5	35	26	12
Pyl Brook - DS of Sutton STW	3	5	38	30	14
Beverley Brook - US of the Tideway	2	7	62	58	38
River Ravensbourne 1977					
River Ravensbourne - US of the Pool	2	9	80	79	65
River Pool	2	9	79	78	62
River Quaggy	2	9	78	76	61
River Ravensbourne - US of the Tideway	2	9	81	79	66
River Crane and Duke of Northumberland's River 1977					
River Crane - US of the Duke's River	2	8	71	69	50
Duke's River - US of the River	2	9	77	76	60
River Crane - US of the Tideway	2	8	73	72	54
Duke's River - US of the Tideway	2	9	74	71	54
River Brent 1977					
Silk Stream	2	9	74	72	55
Dollis Brook	2	9	79	77	62
River Brent - DS of Welsh Harp	2	9	80	79	64
River Brent - US of Grand Union Canal	3	8	57	56	33
River Brent - US of Tideway	2	9	71	68	50

Table 12. (continued)

Grand Union Canal 1977					
Grand Union Canal - on entry to MPC Area	2	6	61	51	37
Grand Union Canal - US of the confluence with the River Brent	3	6	55	51	31
Paddington Arm	3	7	58	53	33
Regent's Canal - US of the Tideway	1B	9	88	88	77

NOTE: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification system.

Table 13. Results of SW v NWC Classification
(From House and Ellis, 1980)

NWC Classes	NWC Classifications	SW. Classifications	SW Range
1B	8	7	69 - 90
2	31	22	23 - 66
3	14	9	12 - 33
4	4	4	2 - 3
	57	42 (73.6%)	

Table 14. Results of GW v NWC Classification
(From House and Ellis, 1980)

NWC Classes	NWC Classifications	GW. Classifications	GW Range
1B	8	5	83 - 95
2	31	21	44 - 79
3	14	6 (+8)	25 - 56
4	4	4	5 - 6
	57	36 (44, 76%)	

Table 15. Results of AW v NWC Classification
(From House and Ellis, 1980)

NWC Classes	NWC Classifications	AW Classifications	AW Range
1B	8	4	83 - 95
2	31	12	49 - 80
3	14	3	35 - 57
4	4	4	14 - 18
	57	23 (40%)	

quality. The GW formulation is generally accepted as being very accurate in recording the quality of rivers of 'poor' quality. However, of the 57 data sets analysed in this study, 14 were classified as being Class 3 by the NWC classification, and only 6 were classified similarly using the GW formulation. For the 8 rivers which were not similarly classified, the index scores ranged between 44 and 57 and, in some instances, the scores were considerably higher than expected. However, from the data available on the few determinands used to obtain these classifications, it is not obvious why these rivers were classified as Class 3 on the NWC scale.

It must, therefore, be assumed that these rivers were classified on the basis of other data which were not available for inclusion within the water quality index calculations. In some instances the BOD and ammoniacal nitrogen scores for these rivers were high, but they still fell within the guidelines laid down by NWC for a Class 2 river. The water quality index scores produced using the GW formulation would agree with a Class 2 classification. If the results of these 8 rivers were to be ignored on the basis of the above reasoning, this would increase the agreement with the NWC classification when the GW formulation is used to 44 out of 57 cases (75%).

Therefore, both the Solway modified arithmetic weighted index formulation and the geometric weighted formulation produce SDD water quality index scores which compare favourably with the NWC classification system.

The results obtained using the arithmetic weighted index formulation are dubious. This formulation appears to over-estimate water quality at both extremes of the scale. It was only in the middle range of water quality that the arithmetic weighted formulation could be considered accurate.

6.3. THE RESULTS OBTAINED FOR THE COMPARISON BETWEEN THE NWC CLASSIFICATION AND ROSS INDEX

For this comparison with the NWC classification, Ross' Index was banded into five classes (Table 16), based on the interpretation of the 0-10 index scale given by Ross (1977) (see Section 4.3.).

The results obtained from this study (Tables 12 and 17) show that only 29 (50%) of the Ross index classifications agreed with those of the NWC. Ross' index consistently over-estimated water quality throughout the range of the index scale.

Table 16. Five Class Banding of the Ross Index Scale (From House, 1980)

NWC Classes	Ross Index Range
1A	10
1B	9
2	6-8
3	4 and 5
4	0-3

Table 17. Results of Ross Index v NWC Classifications (From House, 1980)

NWC Classes	NWC Classifications	Ross Index Classifications	Ross Index Range
1B	8	2	9-10
2	31	20	6-9
3	14	3	5-8
4	4	4	2-3
	57	29 (50%)	

Thus, it would appear that arithmetic mean formulations are inaccurate in producing water quality index scores.

6.4. A COMPARISON BETWEEN THE TWA CLASSIFICATION AND THE SDD INDEX

For this study, data from 'Thames Water Statistics 1976, Volume 2' on eight rivers with urban catchment areas, was utilised. TWA classifications for the years 1973-1976 were compared with SDD index scores calculated using the AW, GW and SW index formulations. The SDD index was banded into five classes as for the previous study (Table 11). Of the data used by the Thames Water Authority to produce their classifications, only six determinands agreed with those suggested for inclusion within the SDD index. Thus, only the data on those six determinands: suspended solids, temperature, BOD, dissolved oxygen percentage saturation, ammoniacal nitrogen and total organic nitrogen were used for the calculations of the SDD index scores. The re-calculated index weightings are given in Table 18.

Table 18. Recalculated Weighting for SDD Index
(From House and Ellis, 1980)

Determinand	Weighting
Temperature	0.08
Suspended Solids	0.11
BOD	0.23
Dissolved Oxygen (% sat'n)	0.28
Ammoniacal Nitrogen	0.18
TON	0.12

6.5. THE RESULTS OBTAINED FOR THE COMPARISON BETWEEN THE TWA CLASSIFICATION AND THE SDD INDEX

Tables 19-22 show the results obtained in this comparative study. When the 32 data sets were classified using the SDD index formulations, 16 (50%), 26 (81%) and 23 (72%) of the index scores produced using the SW, GW and AW formulations respectively, agreed with the TWA classifications (Tables 20-22).

In this instance the SW formulation underestimated water quality throughout the 0-100 index range. The GW formulation underestimated the quality of three Class 3 Rivers, and two Class 1B rivers. However, again the overall agreement between the GW formulation and the TWA classification was high. The performance of the AW formulation has also improved, and this may have been related to the increase in the number of determinands considered in these calculations. It did however, still over-estimate water quality at the lower end of the index scale.

Table 19. SDD WQI Scores and TWA Classifications for Selected Rivers Within the Metropolitan Area
(From House and Ellis, 1980)

Location/Year	TWA Classification	SDD Index Scores		
		AW	GW	SW
Grand Union Canal (Solebay Street)				
1973-74	1B	89	89	80
1974-75		76	67	58
1975-76		86	81	74

Table 19. (continued)

River Crane				
1973-74	2/UIB	79	69	62
1974-75		66	59	43
1975-76		69	64	48
Silk Stream				
1973-74	2/UIB	61	59	37
1974-75		59	56	34
1975-76		58	57	33
Dollis Brook				
1973-74	2/UIB	64	62	41
1974-75		66	63	44
1975-76		70	63	49
River Brent				
1973-74	3/2/UIB	49	55	34
1974-75		40	36	16
1975-76		43	40	18
Beverley Brook (Priest's Bridge)				
1973-74	3/U2	44	24	19
1974-75		43	25	19
1975-76		47	29	22
River Wandle (Goat Bridge)				
1973-74	1B	75	71	56
1974-75		88	82	78
1975-76		73	65	54

Table 19. (continued)

River Wandle (Watermeads)				
1973-74	3/U2	ND	ND	ND
1974-75		45	27	20
1975-76		31	12	10
River Wandle (Causeway)				
1973-74	3/U2	41	19	17
1974-75		46	27	21
1975-76		37	18	14
River Darent (Otford Gauging Station)				
1973-74	IB	78	78	60
1974-75		85	83	73
1975-76		84	81	70
River Darent (Mill Pond Road, Dartford)				
1973-74	IB	78	74	60
1974-75		83	75	69
1975-76		88	85	78

NOTE: Water quality index scores that are underlined are those which place the rivers into the same class as the TWA classifications system.

Table 20. Results of SW v TWA Classification
(From House and Ellis, 1980)

TWA Classes	TWA Classifications	SW Classifications	SW Range
1B	12	6	54 - 80
2	9	6	33 - 62
3	11	4	10 - 34
	32	16 (50%)	

Table 21. Results of GW v TWA Classification
(From House and Ellis, 1980)

TWA Classes	TWA Classifications	GW Classifications	GW Range
1B	12	10	65 - 89
2	9	9	56 - 69
3	11	7	12 - 55
	32	26 (81%)	

Table 22. Results of AW v TWA Classification
(From House and Ellis, 1980)

TWA Classes	TWA Classifications	AW Classifications	AW Range
1B	12	12	73 - 89
2	9	8	58 - 79
3	11	3	31 - 59
	32	23 (72%)	

6.6. DISCUSSION OF THE RESULTS FROM THE COMPARATIVE STUDIES BETWEEN THE SDD INDEX AND THE NWC/TWA CLASSIFICATION SYSTEMS

The results obtained from these two comparative studies are encouraging. The GW formulation of the SDD index shows consistently high agreement in both analyses, although the pattern of disagreement between the SDD index and the two classifications is slightly different. It must be remembered that the results from these two comparative studies are based on the assumption that the NWC/TWA classification is accurate. It may be that this investigation in fact highlights the variable results which must emerge when using such subjective classifications. However, bearing in mind the limitations of the data - the reduced number of determinands in each data set from the ideal recommended by the SDD, and the relatively small sample sets used - the results would indicate that the SDD WQI can be successfully used to monitor changes in water quality. The Anglian Water Authority (1978) concluded that the index is most accurate when data on all the determinands are considered. This could account for some of the disagreement which occurred in this study.

The good agreement between the GW formulation of the SDD index and the NWC/TWA classification systems would suggest that a general WQI is as efficient as a multitude of use-related indices in monitoring water quality. Both the NWC and TWA classifications consider potential water uses, and if the SDD index can similarly classify water quality then use-related indices become superfluous.

The adoption of a water quality index would have many advantages over the existing classifications. Although a WQI is not absolutely objective it is a more efficient method of monitoring trends in water quality. It enables the reduction of large amounts of data to a single index value in a more reproducible manner than present classifications permit. It is not always possible for two 'water experts' to agree on the classification of a water sample on the basis of a subjective assessment of a list of determinand concentrations. With a WQI the use of rating curves and mathematical formulae enables such reproducibility. It has been argued that in reducing large amounts of data to a single index number, information is lost. However, this is also the case with any classification system, and, as with classifications, the raw data are still available if additional information is required. The use of a WQI actually provides more information on the quality of a water body than either the NWC or TWA classifications. In addition to classifying a water body into a specific class, the use of index numbers can indicate the position of that river within the class. For example, two sampling stations on the Beverley Brook, the Pyl Brook, and the Beverley Brook upstream of the Tideway, are classified as NWC Class 3, whilst the SDD GW formulation allocates them index scores of 38 and 29 respectively (Table 12). Consequently, greater detail of the water quality at these two stations on the Beverley Brook is given by the SDD index. With reference to the same example, an index reports on the specific quality of a river reach rather than the quantitative approximation provided by the NWC/TWA classifications, and the use of an index is less ambiguous. Finally a WQI can be used to pin-point river reaches which have altered in quality more efficiently than either the NWC or TWA classifications. The Grand Union Canal, on entry to the Metropolitan Pollution Control Area, is classified by NWC as Class 2 for both 1970 and 1977 returns (Table 12). However application of the SDD index (GW formulation) shows that the quality had in fact decreased from a value of 65 to 51 over this period.

Such detail of trends in water quality provided by the use of a WQI, whether the trends be spatial as in the Beverley Brook, or temporal, as on the Grand Union Canal, provides distinct managerial and operational advantages. All potential water uses have threshold values, and for the survival of fish for example, this threshold is attained at an SDD WQI score of around 40. Therefore, while it is theoretically possible for fish to survive in the Pyl Brook (WQI 38), it would be virtually impossible in the case of the Beverley Brook upstream of the Tideway (WQI 29). Thus, the use of a WQI to determine the position of a water body within a specific NWC/TWA class, as in the two examples above, would provide greater management flexibility and consequently more effective and better management practice. Bearing in mind the recently emphasised accountability of future pollution control investment and improvements, WQIs provide 'harder' information for public appreciation of trends in environmental quality. Interested pressure groups would undoubtedly be better informed of subtle or persistent secular changes in the quality of the waters they use, and this could promote a better understanding between layman and operational management.

Modifications to the SDD index are undoubtedly necessary. Both the Yorkshire and Anglian Water Authorities in their 1978 internal reports have shown that many of the rating curves of the SDD index are only suitable for areas of 'good' water quality. This has been confirmed by the present study. The accuracy of the SDD index is undoubtedly reduced when applied to water of 'low' quality regardless of the formulation used, but the SW formulation appears to be the most severely affected. The 0-100 scale of the SDD index is biased towards high quality water, with scores of between 41 and 100 denoting water of tolerable to excellent quality. More detail at the lower end of the quality scale is required. However, despite the modifications which are necessary to the SDD index, it did show favourable agreement with the NWC and TWA classifications. Thus WQIs can be an effective management tool for monitoring trends in water quality.

6.7. SUMMARY TO PART I

Water quality indices have been shown to possess a number of advantages over water quality classification systems presently used in the United Kingdom. The specific advantages can be summarised as follows:

a) an index can be used as a 'yardstick' with units which are stable, consistent, and reproducible thus allowing the comparison of both surface and groundwater quality in time and space;

b) it enables the reduction of large amounts of data to a single index value in an objective and reproducible manner (SDD, 1976);

c) it is an unambiguous way of communicating information about trends in water quality (Ross, 1977), and it performs a function as a 'bridging-tool' between water expert and layman;

d) it assists in pin-pointing river reaches which have altered significantly in quality and which, if necessary, can be investigated in greater detail.

A number of WQIs have been developed since the theoretical index of Horton (1965), yet no index has been devised in such a way as to conform to all nine of the essential characteristics of an index as outlined in Chapter IV.

The SDD (1976) index has been applied successfully to rivers in the United Kingdom, with the geometric weighted formulation showing the best agreement with the classification systems used. However, it was obvious from the results of these investigations that some modifications were required if this index were to be universally applied to surface watercourses. In addition, the index could be greatly improved to include information on toxic determinands directly within its structure, as well as provide information on potential water use and, therefore, economic gains/losses resulting from management strategies.

With these latter points in mind it was decided to develop a new WQI which would resolve many of the problems associated with the SDD index, and other indices outlined herein.

PART TWO

THE DEVELOPMENT OF A NEW FAMILY OF INDICES

CHAPTER 7

DETERMINAND SELECTION

7.1. INTRODUCTION

As stated in Chapter 1, Section 1.2.1., the main aim of this research project is to develop a general water quality index for application to clean and polluted rivers alike. The index is intended not only to relate water quality to a numeric scale but also to indicate the range of potential economic uses suited to specific quality conditions. Thus the index should be of value in the operational management of surface water quality and provide the more general information on water quality trends required at the directorate level.

The index has been developed in such a way as to comply with the nine essential characteristics of an index outlined in Chapter 4. In addition, problems associated with previously developed indices, such as those highlighted in Chapter 6 in relation to the use of the SDD (1976) index, or those reported by Dunnette (1979) as more general criticisms, have been considered and acted upon where appropriate.

It is envisaged that the index will consist of two sub-indices. The first sub-index, (the WQI), will be based on a range of determinands which are frequently monitored by the water authorities and RPBs of England, Wales and Scotland and are indicative of water quality change. The second, an optional sub-index of toxicity, will include determinands such as heavy metals, pesticides and oils which are potentially harmful or lethal to human or aquatic life, but are only monitored at sites where one or more is known to be a potential pollutant. Hence, where pollutant concentrations are low, their measurement by WAs is relatively restricted. For this reason these sub-indices will be developed independently, leaving the sub-index of toxicity available for use as considered appropriate by the user. In this way, greater management flexibility can be afforded, and the effect of missing determinands upon the final index score produced when using the WQI, can be avoided. Thus, in essence two separate indices will be developed.

Determinands such as heavy metals, pesticides and oils have not previously been directly included within a general water quality index. However their inclusion is considered to be essential if the index produced is to be applicable in all surface water situations.

Thus, when using the WQI, the sub-index of toxicity need only be applied where one or more of the determinands considered within it are known to affect water quality. The scores produced by this sub-index would nullify the score produced by the general WQI because, if the water were found to be toxic, it would inevitably imply less or diminished management potential. In this way the index can be applied to water bodies of vastly different character and quality, but still rate water quality according to the same scale.

The first stage in the development of the proposed index is determinand selection. This is arguably the most important stage of development because the determinands selected must not only cover the diverse sources of pollution which occur within a catchment, (see Chapter 2), but also contain those determinands which are of most significance to the principal uses of water, potential water use being the major consideration in water quality management.

A number of criteria were employed to assist in the selection of determinands for inclusion within the index:

a) determinands previously selected for inclusion within an index;

b) determinands regularly monitored by the water authorities of England and Wales, and known to be significant indicators of water quality standard;

c) determinands selected by officials from each of the water authorities of England and Wales;

d) selection based on EEC and EIFAC criteria;

e) the use of water quality impairment categories;

f) the use of rejection rationale.

A consideration of the determinands upon which previously developed indices have been based was included as a selection criterion, as this provided an initial objectively derived list of determinands to which other criteria could be applied. Determinands could then be added or subtracted from this list as deemed advisable by the application of other criteria. In addition, it was assumed that these determinands had been included within a previous index because of their significance to water quality management.

The monitoring frequency of different determinands was established in order to determine the feasibility of including certain determinands within the index. This is not to say that those determinands which are most frequently monitored should be included within the index to the exclusion of those which are only infrequently monitored. However, it was considered to be a valid additional method of objectively reducing the list of potential determinands.

Brown et al (1970) introduced the use of opinion research techniques to ascertain the determinands a panel of experts would select for inclusion within an index. This technique has since been adapted and used by other workers such as Deininger and Maciunas (1971), O'Connor (1971), the SDD (1976) and Dunnette (1979). Thus an interview and questionnaire programme was included as one of the criteria in obtaining an objective selection of determinands for the proposed index.

The determinands included within EEC and EIFAC Directives and Guidelines were considered for inclusion within the index because the monitoring of these determinands is legally required as part of the management strategy of European surface water quality.

Investigations into the effect of various determinands on water quality impairment categories such as public health, eutrophication, oxygen depletion and the protection of aquatic life have been used by Walski and Parker (1974) and Dunnette (1979). These criteria have also been included within this study to ensure that the most significant determinands are finally selected for inclusion within the proposed index.

Finally a series of rejection rationale were applied to the list of potential determinands which were obtained from the steps (a) to (f) described above in order to avoid overlap and repetition. For example, where two or more determinands are indicative of the same type of pollution, or duplicate the same water quality test, one or more will be considered redundant and excluded from the index.

The use of multivariate factor analysis as a means of determinand selection was rejected for the purposes of this study. This method has been employed by Shoji et al (1966) and Joung et al (1979) within the development of their respective indices. Although the use of statistical analysis might be the most objective method of selecting determinands, it is ultimately dependent upon the data provided for analysis. Hence, the resultant list of determinands may vary from one data set to another. Thus the use of this objective method becomes subjective as the data set(s) must be selected by the user.

The independent use of any one of these selection criteria would not produce total objectivity but, by using such a rigorous and flexible approach to the selection of determinands, it is hoped that those factors which predominantly influence the diverse quality and uses of surface waters within the United Kingdom will be discerned, whilst at the same time preserving maximum objectivity.

7.2. A REVIEW OF DETERMINANDS INCLUDED WITHIN PREVIOUSLY DEVELOPED GENERAL AND USE RELATED INDICES AND WATER QUALITY MONITORING PROGRAMMES

In this review of determinand selection based on previously developed indices and water quality monitoring programmes, both general and use-related versions have been considered. Use-related versions were included because water use is a major consideration in water quality management, and any general index must contain the most significant determinands for a range of potential water uses.

Twenty WQIs have been used to assist in determinand selection. Of these, twelve were general WQIs (Horton 1965; Shoji et al 1966; Brown et al 1970; Nemerow et al 1970; Prati et al 1971; Dee et al 1972; McDuffie et al, 1973; Inhaber 1974; SDD 1976;

Ross 1977 and Dunnette 1979), and eight were use-related. Within this latter group, four were for water intended for use in potable water supply (PWS), (Deininger et al 1971; O'Connor 1971; Sayers and Ott 1976 and Stoner 1978); two were developed for waters supporting fish and wildlife populations (FAWL), (O'Connor 1971 and Sayers and Ott 1976); and two further indices for irrigational (Stoner 1978) and recreational uses (Walski and Parker 1974) respectively. Seventeen water quality monitoring programmes covering a range of potential water uses were selected. Included within these monitoring programmes was the use of Quality States as developed by Newsome (1972); various use-related monitoring programmes developed by Price and Pearson (1979) and Sayers and Ott (1976); the determinands recommended by EIFAC (European Inland Fisheries Advisory Commission) for the protection of fisheries (1964-1983); and those for which the EEC (1975) has proposed mandatory quality criteria for surface waters to be used for potable water supply.

The results from these studies are shown in Tables 23 and 24. In addition to listing the determinands included within the various forms of water quality indices and monitoring programmes, the frequency of inclusion within each form was calculated for each determinand and expressed as a percentage of the total. In this way, the importance attached to each determinand could be evaluated.

From Tables 23 and 24, it can be seen that, in total, sixty five and fifty three determinands have been included within previously developed indices or water quality monitoring programmes respectively.

TABLE 23. Determinands Previously Included within General and Use-Related Water Quality Indices

DETERMINANDS	GENERAL USE	PWS	FAWL	IRRIGATION	RECREATION
D.O.	92%	50%	100%	----	x
B.O.D.	83%	25%	----	----	----
C.O.D.	17%	----	----	----	----
Alkalinity	25%	25%	50%	----	----
Hardness	33%	50%	----	----	----
Iron	25%	50%	----	----	----
Manganese	17%	----	----	x	----
Ammonia	50%	25%	50%	----	----
Nitrate	25%	75%	50%	----	x
Nitrite	8%	25%	----	----	----
Other Nitrogen	25%	----	----	----	----
Phosphates	42%	----	100%	----	x
Other Phosphates	8%	----	----	----	----
Nutrients (N+P)	----	----	50%	----	x
Chlorides	42%	75%	----	----	----
Fluorides	----	100%	----	x	----
Sulphates	17%	75%	----	----	----
Lithium	8%	----	----	----	----
P.V.	17%	----	----	----	----
CO_2	----	----	50%	----	----
Phenols	8%	75%	50%	----	----
A.B.S.	8%	----	----	----	----
C.C.E.	17%	----	----	----	----
Trace Organics	----	25%	----	----	----
Trace Metals	----	25%	----	----	----

Table 23. (continued)

Toxic Substances	----	25%	50%	x	----
Oil and Grease:					
a) Thickness	----	----	----	----	x
b) Concentration	----	----	----	----	x
Methylene Blue Reactive Substances	----	25%	----	----	----
Mercury	8%	25%	----	----	----
Copper	8%	25%	----	x	----
Cyanide	8%	50%	----	----	----
Zinc	8%	25%	----	x	----
Sodium Absorption Ratio	----	----	----	x	----
Arsenic	----	25%	----	x	----
Boron	----	----	----	x	----
Cadmium	8%	25%	----	x	----
Beryllium	----	----	----	x	----
Chromium	8%	25%	----	x	----
Cobalt	----	----	----	x	----
Vanadium	----	----	----	x	----
Nickel	----	----	----	x	----
Aluminium	----	----	----	x	----
Lead	----	25%	----	----	----
Selenium	----	25%	----	x	----
Barium	----	25%	----	----	----
Radioactivity	----	25%	----	----	----
pH	75%	75%	100%	----	x
Temperature	67%	25%	100%	----	x
Conductivity	33%	----	----	x	----
Turbidity	33%	75%	100%	----	x

Table 23. (continued)

Dissolved Solids	17%	75%	100%	----	----
Suspended Solids	50%	----	----	----	x
Total Solids	17%	----	----	----	----
Colour	25%	100%	50%	----	x
Change in Temp.	----	----	----	----	x
Odour/Taste	----	25%	----	----	x
Transparence	----	----	50%	----	x
Salinity	----	----	50%	----	----
Settleable Material	----	----	50%	----	----
Floating Material	----	----	50%	----	----
Faecal Coliforms	50%	75%	----	x	----
Total Coliforms	25%	25%	----	----	x
E. Coli	8%	----	----	----	----
Bacteria	8%	----	----	----	----
TOTAL	38	35	18	18	14
GRAND TOTAL	65				

x = those instances in which only one index was considered, therefore it was not possible to produce percentages for inclusion.

Table 24. Determinands Previously Included Within Water Quality Monitoring Programmes

DETERMINANDS	GENERAL USE	PWS	FAWL	IRRIGATION	LIVESTOCK WATERING	INDUSTRIAL USES	RECREATION /AMENITY
D.O.	x	50%	100%	----	33%	25%	33%
B.O.D.	x	50%	50%	----	----	25%	33%
T.O.C.	x	----	----	----	----	----	----
Alkalinity	----	50%	50%	----	----	50%	----
Hardness	----	50%	50%	----	----	75%	33%
Iron	----	100%	50%	50%	----	50%	33%
Manganese	----	50%	50%	50%	33%	25%	33%
Ammonia	x	100%	100%	----	----	25%	33%
Nitrate	----	100%	50%	----	100%	25%	33%
Other Nitrogen	x	----	----	----	----	----	----
Phosphates	----	50%	----	----	----	25%	33%
Chlorides	x	50%	100%	100%	100%	50%	33%
Fluorides	----	100%	50%	50%	100%	75%	----
Sulphates	----	100%	----	----	100%	25%	----
Silica	----	----	----	----	----	50%	----
Sodium	----	50%	----	50%	----	----	----
Calcium	----	50%	50%	100%	33%	----	33%
Magnesium	----	50%	50%	100%	33%	----	33%
Potassium	----	----	----	50%	----	----	----
Phenols	x	100%	100%	----	----	----	33%
Trace Organics	----	----	----	----	66%	50%	----
Trace Metals	----	----	----	50%	66%	50%	----
Mercury	----	100%	50%	50%	33%	----	33%
Copper	x	100%	100%	50%	33%	----	33%
Cyanide	----	100%	50%	----	100%	25%	33%
Zinc	x	100%	100%	50%	33%	----	33%

Table 24. (continued)

Sodium Absorption Ratio	----	----	----	50%	----	----	----
Arsenic	----	100%	50%	50%	33%	----	----
Boron	----	50%	----	100%	33%	----	----
Cadmium	x	100%	100%	50%	33%	----	----
Chromium	x	100%	50%	50%	33%	----	----
Nickel	x	----	50%	50%	----	----	----
Aluminium	----	----	----	----	----	25%	25%
Barium	----	50%	----	----	----	----	----
Lead	x	100%	50%	----	33%	----	33%
Selenium	----	100%	----	50%	33%	----	----
Radioactivity	----	----	----	----	66%	25%	----
pH	----	50%	100%	50%	33%	75%	66%
Temperature	x	100%	100%	----	----	50%	100%
Conductivity	----	50%	50%	100%	33%	25%	33%
Turbidity	----	----	----	----	66%	50%	100%
Dissolved Solids	x	60%	50%	100%	100%	100%	33%
Suspended Solids	x	50%	100%	----	----	75%	33%
Colour	----	100%	----	----	66%	50%	100%
Odour/Taste	----	50%	----	----	66%	25%	100%
Total Coliforms	----	----	----	----	66%	25%	33%
Floating Material	----	----	----	----	----	----	66%
Settleable Material	----	----	----	----	----	----	66%
Nutrients	----	----	----	----	----	----	66%

Table 24. (continued)

Anionic Synthetic Detergents	----	----	----	----	----	----	33%
P.A.H.	----	50%	----	----	----	----	----
Hydrocarbons	----	50%	----	----	----	----	----
Pesticides	----	50%	----	----	----	----	----
TOTAL	16	37	27	22	28	27	34
GRAND TOTAL	53						

x = those instances in which only one water quality monitoring programme was considered, therefore it was not possible to produce percentages for inclusion.

There are many reasons for the diversity and variety of determinands selected by previous workers:

(i) Many WQIs and water quality monitoring programmes have been developed in different countries where different water quality conditions are experienced. In the USA for example, strong emphasis is placed on nitrates and bacteriology, whereas little concern is paid to ammonia.

(ii) Water quality monitoring programmes have been developed over more than 20 years and many of the determinands included within early WQIs have now been replaced by alternative, and often more precise, methods of assessment.

(iii) WQIs and monitoring programmes have usually been developed independently and thus many different tests have been employed to monitor similar conditions.

Therefore, many of the determinands are duplicates eg suspended solids (SS) and turbidity, total dissolved solids and conductivity, total solids and SS/TDS/TVS (total volatile solids). The lumped determinands such as trace organics, trace metals and toxics also contain many individual determinands.

When the results from Tables 23 and 24 are combined it can seen that seventy five determinands have been included within previously developed water quality indices or monitoring programmes (Table 25). These seventy five determinands can be subdivided according to the use to which the particular index or monitoring programme relates (Tables 23 to 25).

Table 25. The Combined Selection Frequencies for Determinands previously used in Water Quality Indices and Water Quality Monitoring Programmes

DETERMINANDS	GENERAL USE	PWS	FAWL	IRRIGATION	LIVESTOCK WATERING	INDUSTRIAL USES	RECREATION
D.O. ***	92%	50%	100%	----	33%	25%	50%
B.O.D.	85%	33%	25%	----	----	25%	25%
C.O.D.	15%	----	----	----	----	----	----
T.O.C.	8%	----	----	----	----	----	----
Alkalinity	23%	33%	50%	----	----	50%	----
Hardness	31%	50%	25%	----	----	75%	25%
Iron *	23%	66%	25%	33%	----	50%	25%
Manganese	15%	17%	25%	66%	33%	25%	25%
Ammonia * ***	54%	50%	75%	----	----	25%	25%
Nitrate *	23%	82%	50%	----	100%	25%	50%
Nitrite	8%	17%	----	----	----	----	----
Other Nitrogen	23%	----	----	----	----	----	----
Phosphates	38%	17%	50%	----	----	25%	50%
Other Phosphates	8%	----	----	----	----	----	----
Nutrients (P+N)	----	----	25%	----	----	----	75%
Chlorides ***	46%	66%	50%	66%	100%	50%	25%
Fluorides *	----	100%	25%	66%	100%	25%	----
Sulphates *	15%	82%	----	----	100%	75%	----
Silica	----	----	----	----	----	50%	----
Sodium	----	17%	----	33%	----	----	----
Calcium	----	17%	25%	66%	33%	----	25%
Magnesium	----	17%	25%	66%	33%	----	25%
Potassium	----	----	----	33%	----	----	----
Lithium	8%	----	----	----	----	----	----
P.V.	15%	----	----	----	----	----	----
CO_2	----	----	25%	----	----	----	----
Phenols * ** ***	15%	82%	75%	----	----	----	25%
A.B.S.	8%	----	----	----	----	----	----
C.C.E.	15%	----	----	----	----	----	----

Table 25. (continued)

Trace Organics	----	17%	----	----	66%	50%	----
Trace Metals	----	17%	----	33%	66%	50%	----
Toxic Subst.	----	17%	25%	33%	----	----	----
Anionic Synthetic Detergents	----	----	----	----	----	----	25%
Oil and Grease							
a) Thickness	----	----	----	----	----	----	25%
b) Concentration	----	----	----	----	----	----	25%
Methyl. Blue ** React. Subst.	----	17%	----	----	----	----	----
Mercury *	8%	50%	25%	33%	33%	----	25%
Copper * ***	15%	50%	50%	66%	33%	----	25%
Cyanide	8%	66%	25%	----	100%	25%	25%
Zinc * ***	15%	50%	50%	66%	33%	----	25%
Sodium Absorption Ratio	----	----	----	66%	----	----	----
Arsenic *	----	50%	25%	66%	33%	----	25%
Boron	----	17%	----	100%	33%	----	----
Cadmium * ***	15%	50%	50%	66%	33%	----	25%
Beryllium	----	----	----	33%	----	----	----
Chromium * ***	15%	50%	25%	66%	33%	----	25%
Cobalt	----	----	----	33%	----	----	----
Vanadium	----	----	----	33%	----	----	----
Nickel	8%	----	25%	66%	----	25%	25%
Aluminium	----	----	----	33%	----	----	----
Lead *	8%	50%	25%	----	33%	----	25%
Selenium *	----	50%	----	66%	33%	----	----
Barium *	----	33%	----	----	----	----	----
Radioactivity	----	17%	----	----	33%	25%	----
pH ** ***	69%	66%	100%	33%	33%	75%	75%
Temperature * ***	69%	50%	100%	----	----	50%	100%
Conductivity	31%	17%	25%	100%	33%	25%	25%
Turbidity	31%	50%	50%	----	66%	50%	100%
Dissolved Solids	23%	66%	75%	66%	100%	100%	25%
Suspended Solids ***	54%	17%	50%	----	----	75%	50%
Total Solids	15%	----	----	----	----	----	----
Colour * **	23%	100%	25%	----	66%	50%	100%
Change in Temp.	----	----	----	----	----	----	25%
Odour/Taste	----	33%	----	----	66%	25%	100%
Transparency **	----	----	25%	----	----	----	25%

Table 25. (continued)

Salinity	----	----	25%	----	----	----	----
Settleable Mats.	----	----	25%	----	----	----	75%
Floating Mats.	----	----	25%	----	----	----	75%
Faecal Coliform **	46%	50%	----	33%	----	----	----
Total Coliforms **	23%	17%	----	----	66%	25%	50%
E. Coli	8%	----	----	----	----	----	----
Bacteria	8%	----	----	----	----	----	----
Pesticides *	----	17%	----	----	----	----	----
Hydrocarbons **	----	17%	----	----	----	----	----
P.A.H. *	----	17%	----	----	----	----	----
TOTAL	41	46	37	28	28	27	38
GRAND TOTAL	75						

x = those instances in which only one index or water quality monitoring programme was considered, therefore it was not possible to produce percentages for inclusion.

* = those determinands with mandatory EEC (1975) criteria for water used for PWS

** = those determinands with mandatory EEC (1975) criteria for bathing waters.

*** = those determinands recommended by EIFAC (1964 to 1983) for the protection of freshwater fisheries.

An index based on seventy five determinands would, patently, be too cumbersome to operate and further consideration of determinand selection was necessary to derive a viable listing. Assuming that the most acceptable determinands for inclusion within an index would be those most frequently selected for inclusion within previously developed indices and water quality monitoring programmes, it is possible to exclude many of the seventy five determinands by analysing the percentage results shown in Table 25. To this end a 66% criteria was adopted. This meant that unless a determinand had been previously selected for inclusion within a specific form of index or water quality monitoring programme at least 66% of the time, it would no longer be considered for inclusion within the proposed index. This two-thirds criterion was adopted because any more stringent criterion would have been unrealistic considering the diverse nature of previously developed indices and monitoring programmes. However, a lesser criterion would have been too lax. This approach reduced the list of seventy five determinands to thirty seven (Table 26). Although these thirty seven determinands had the highest selection frequencies for previously developed indices or water quality monitoring programmes, they are not necessarily the most informative determinands in terms of water quality or potential water use. It could be argued that some are included because of the ease with which they can be monitored, or on the basis that they have been historically included within indices or monitoring programmes. It can be seen that many of the selected determinands duplicate the same test, and that some determinands cover a wider range of significance than others in terms of water use. For example, phenols, pH and dissolved solids are frequently included for both public water supply and fish and wildlife indices. Determinands such as chlorides, fluorides and sulphates are frequently included within indices for water used for irrigational and livestock water purposes in addition to public water supply.

Table 26. Determinands with 66% selection frequency for previously developed WQIs and water quality monitoring programmes

DETERMINAND	GENERAL	PWS	FAWL	IRRIGATION	LIVESTOCK	INDUSTRIAL	RECREATION/ AMENITY
D.O.	+	-	+	-	-	-	-
B.O.D.	+	-	-	-	-	-	-
Hardness	-	-	-	-	-	-	+
Iron	-	+	-	-	-	-	-
Manganese	-	-	-	+	-	-	-
Ammonia	-	-	+	-	-	-	-
Nitrate	-	+	-	-	+	-	-
Chloride	-	+	-	+	+	-	-
Fluoride	-	+	-	+	+	-	-
Sulphate	-	+	-	-	+	+	+
Calcium	-	-	-	+	-	-	-
Magnesium	-	-	-	+	-	-	-
Phenols	-	+	+	-	-	-	-
Trace Organics	-	-	-	-	+	+	-
Trace Metals	-	-	-	-	+	+	-
Copper	-	-	-	+	-	-	-
Cyanide	-	+	-	-	+	-	-
Zinc	-	-	-	+	-	-	
Sodium Abs. Rat	-	-	-	+	-	-	-
Arsenic	-	-	-	+	-	-	-
Boron	-	-	-	+	-	-	-
Cadmium	-	-	-	+	-	-	-
Chromium	-	-	-	+	-	-	-
Nickel	-	-	-	+	-	-	-
Selenium	-	-	-	+	-	-	-
pH	+	+	+	-	-	+	+
Temperature	+	-	+	-	-	-	+
Conductivity	-	-	-	+	-	-	-
Turbidity	-	-	-	-	+	-	+
Dissolved Solids	-	+	+	+	+	+	-
Suspended Solids	-	-	-	-	-	+	-
Colour	-	+	-	-	+	-	+
Odour/Taste	-	-	-	-	+	-	+
Nutrients	-	-	-	-	-	-	+
Total Coliforms	-	-	-	-	+	-	-
Settleable Materials	-	-	-	-	-	-	-
Floating Materials	-	-	-	-	-	-	+

+ = those determinands with a 66% or greater selection frequency.

If, as was suggested by Robinson (1980), it is agreed that PWS, FAWL and the protection of the Environment are the major water uses to be considered, and that their protection would satisfy all other uses, it would only be necessary to consider the determinands in the first three columns of Table 26. Then, for all practical purposes, the list of potential determinands would be further reduced to fourteen (Table 27).

Table 27. Determinands with a 66% selection frequency which cover the most significant usages of water (General, PWS and Fawl)

Dissolved Oxygen	Phenols
Biochemical Oxygen Demand	Cyanide
Sulphates*	pH*
Iron	Temperature
Ammonia	Fluorides*
Nitrate	Dissolved Solids
Chlorides*	Colour

* = those determinands which have a 66% selection frequency for the widest range of potential water uses.

Therefore, by listing and analysing determinands previously used within indices and water quality monitoring programmes, it is possible to begin to form a picture of which determinands merit further consideration for inclusion within the proposed index to cover all possible water quality conditions and potential water uses. In essence, the fourteen determinands listed in Table 27 can be considered to be the primary determinands for further investigation on the basis of this particular selection criterion.

7.3. DETERMINANDS WHICH ARE REGULARLY MONITORED BY THE WATER AUTHORITIES

For an index to be acceptable to water quality managers it must, for the most part, include determinands which are regularly monitored by the water authorities. To discover which are regularly monitored, interviews were arranged with members from each of the ten water authorities. It was difficult to produce a single list containing all the determinands, because each authority has a variety of water quality monitoring programmes. Also, the number and type of determinands monitored may vary regionally within individual authorities. Water quality monitoring programmes in use by the water authorities include the following:

- Routine sampling	Most commonly monthly/quarterly
- Key point sampling	Every two weeks
- Special site sampling	Weekly
- Sampling of minor sites	Quarterly
- Harmonised monitoring	Varies within authorities
- Continuous monitoring	Varies within authorities

The majority of sampling sites within the ten authorities fall into the routine sampling category. In this sampling programme the determinands which are consistently monitored by all ten authorities are outlined in Table 28.

Table 28. Determinands regularly monitored as part of the routine water quality monitoring programme of the ten water authorities of England and Wales

Dissolved Oxygen
Biochemical Oxygen Demand
Alkalinity
Hardness
Ammonia
Nitrates (Total Oxidised Nitrogen)
Chlorides
pH
Temperature
Conductivity
Suspended Solids

Additional determinands are monitored at sites where they are considered to be of importance to water quality. Table 29 lists those determinands monitored as part of one or more of the WAs' water quality monitoring programmes.

Of the thirty seven determinands listed in Table 26 (those previously included within a WQI or water quality monitoring programme), only three, - Trace Organics, Trace Metals and Sodium Absorption Ratio - are not included within any of the water quality monitoring programmes of the ten water authorities. However, trace organics and trace metals are monitored as individual determinands, eg pesticides and hydrocarbons, or zinc, copper, lead etc. Therefore, if a water quality index based on any of the remaining thirty four determinands were developed, it would be possible for all ten water authorities to use the index, although not necessarily at every sampling site. Obviously the index would be of greatest application if based on the determinands routinely monitored by all the authorities (Table 28).

However, should a determinand which is not monitored be proven to be desirable for inclusion within an index on the basis of alternative rationale, it should be recognised as such and a place reserved into which the determinand may be placed. Thus, this criteria was not considered as being definitive.

Of the fourteen determinands listed in Table 27, seven form part of the routine water quality monitoring programme of the ten water authorities. However, the relative importance of each determinand to the overall water quality of British watercourses must also be considered.

Table 29. Determinands included within the water quality monitoring programmes of the water authorities

D.O.
B.O.D.
C.O.D.
T.O.C.
Alkalinity
Hardness
Iron
Manganese
Ammonia
Nitrate
Nitrite
T.O.N.
Kjeldahl N.
Total Phosphate
Ortho Phosphate
Chlorides
Fluorides
Sulphates
Vanadium
Nickel
Aluminium
Lead
Selenium
Barium
Silver
Antimony
Radioactivity
Chlorophyll A
pH
Temperature
Conductivity
Turbidity
Dissolved Solids
Colour Hazen Units
Odour/Taste
Transparency

Table 29. (continued)

Silica
Sodium
Calcium
Magnesium
Potassium
N/80 P.V.
O_2 absorbed in 24 hrs

Pesticides
P.A.H.
Copper
Zinc
Boron
Beryllium
Cobalt

Salinity
Total Coliforms
E. Coli
Faecal Streptococci
Lithium
Free CO_2
Syn. Det. Anionic & Non-ionic
Hydrocarbons
Mercury
Cyanide
Arsenic
Cadmium
Chromium

To gain a knowledge of the relative importance of the numerous determinands monitored (Table 29), as part of the interview process, officials from each water authority were asked to list those determinands which have the greatest influence upon the water quality of their area (Table 30). Of the twenty two determinands listed in Table 30, many were selected by only one or two authorities. However in developing an index, the purpose of which is to reflect general water quality, it is important to be aware of those determinands which are known to cause a reduction in water quality standard.

Table 30. Determinands which one or more of the ten Water Authorities consider to significantly influence the water quality of their area

- Dissolved Oxygen
- Biochemical Oxygen Demand
- Iron
- Manganese
- Ammonia
- Organic Nitrogen
- Nitrate
- Nitrite
- Ortho Phosphate
- Chloride
- Sulphates
- Phenols
- Syn. Detergents
- Organo-chlorine pesticides
- Hydrocarbons
- Polyaromatic Hydrocarbons
- Zinc
- Mercury
- Cyanide
- Lead
- Suspended Solids
- Colour

7.4. DETERMINANDS SELECTED BY MEMBERS OF THE WATER AUTHORITIES OF ENGLAND AND WALES

An additional objective of the interview programme with members of the ten water authorities, was to obtain from each interviewee a list of the determinands they would include within a WQI if it were to be applied to their catchment areas. These lists were collated and tabulated (Table 31). Over 50% of the determinands listed in Table 31 were selected by only one or two authorities.

Table 31. Determinands selected by members of the ten water authorities of England and Wales for inclusion within a water quality index prior to the questionnaire survey

Dissolved Oxygen
Biochemical Oxygen Demand
C.O.D.
T.O.C.
Alkalinity
Iron
Manganese
Ammonia
Nitrate
Nitrite
Total Oxidised Nitrogen
Ortho Phosphate
Chloride
pH
Conductivity
Suspended Solids
Transparency
Phenols
Hydrocarbons
Pesticides
Mercury
Copper
Zinc
Arsenic
Boron
Cadmium
Nickel
Lead
Cyanide
Total Annual Toxicity Fraction (Brown & Alabaster)
Sulphate
Temperature
Turbidity
Colour
Chlorophyll A
Synthetic Detergents
Polyaromatic Hydrocarbons

Following the interview programme a questionnaire was sent to each interviewee (see Appendix I). This was based on the thirty seven determinands listed in Table 31. These determinands were sub-divided into two groups. Group I contained those determinands which are most regularly monitored by the water authorities; whereas Group II contained 'special' determinands ie: determinands of toxicity or those which are monitored at specific sites or monitored infrequently. It was envisaged that these determinands would from the basis of the sub-index of toxicity.

The type of index for which determinands were being selected was restricted. For example, although the index is to be one of general water quality, it should contain not only those determinands which best reflect overall water quality, but also those of most importance to the major potential uses of a water body.

The questionnaire was divided into two operations (see Appendix 1). Each respondent was first asked to reconsider their individual determinand selections for inclusion within the proposed index in the light of the response given by others at the interview stage. In addition, a brief explanation of their reasons for selecting those determinands was to be given. Secondly, the respondents were asked to rank each determinand selected in terms of their relative importance to one another. These rankings were then used to assist in the development of weightings to be used in the final index.

The results obtained from the questionnaire study are outlined in Table 32. Unfortunately, only eight of the ten water authorities completed the questionnaire.

Table 32. Results From The Questionnaire Study On Determinand Selection

Routine Sub-index Determinands	Include			Sub-index of Toxicity Determinands	Include		
	Yes	No	Poss		Yes	No	Poss
Dissolved Oxygen	100%			Phenols	72%		28%
B.O.D.	100%			Syn. Det.	43%	43%	14%
C.O.D.		50%	50%	Hydrocarbons	72%		28%
T.O.C.		25%	75%	P.A.H.	29%	14%	57%
Alkalinity	12.5%	62.5%	25%	Pesticides	57%		43%
Iron	37.5%	50%	12.5%	Hg.	57%		43%
Manganese	37.5%	50%	12.5%	Cu.	43%	14%	43%
Ammonia	100%			Zn.	43%	14%	43%
Nitrate	75%	12.5%	12.5%	As.	43%	43%	14%
Nitrite	25%	50%	25%	B.	29%	42%	29%
T.O.N.	37.5%	25%	37.5%	Cd.	86%		14%
Ortho Phosphate	25	12.5%	62.5%	Ni.	42%	29%	29%
Chloride	50%	12.5%	37.5%	Pb.	86%		14%

Table 32. (continued)

Sulphate	37.5%	50%	12.5%	CN	71%		29%
pH	50%		50%	Total Annual Toxicity Fraction	25%	62.5%	12.5%
Temperature	37.5%	12.5%	50%				
Conductivity	50%	25%	25%	<u>Additional Determinands</u>			
Turbidity	50%	12.5%	37.5%	Hardness	25%	75%	
Suspended Solids	50%	25%	25%	Cr.	12.5%	87.5%	
Colour	12.5%	50%	37.5%	Bacteriological Determinands	12.5%	87.5%	
Transparency	12.5%	75%	12.5%				
Chlorophyll A		43%	57%	Total Heavy Metals Equivalent	12.5%	87.5%	

The results of the questionnaire revealed a considerable change in attitude by the water authority members. Many determinands which were previously selected by only one or two respondents were now quite highly recommended for inclusion within the proposed index. To analyse the results of the questionnaire more fully, it was decided to adopt a 66% acceptance criteria as previously used in Section 7.2. In this way the proposed list of twenty-two determinands for the WQI sub-index was reduced to four. Chlorophyll A has been placed into this sub-index as it was originally incorrectly classified (see Appendix I). These four determinands can be considered as the primary determinands. An additional list of secondary determinands consists of those determinands which, although not receiving a clear 66% acceptance by the respondents, would comply with the acceptance criteria if responses under the "possible inclusion" column were considered. Therefore these determinands should still be considered for inclusion within the proposed WQI (Table 33).

Of the 15 determinands initially suggested for inclusion within the sub-index of toxicity, five were selected as primary and six as secondary determinands as a result of the questionnaire survey (Table 33).

Table 33. Determinands to be further considered for inclusion within the proposed index as a result of the questionnaire analysis

(i) WQI Sub-index

Primary Determinands	Secondary Determinands
D.O.	Chloride
B.O.D.	Turbidity
Ammonia	Suspended Solids
Nitrate	Ortho Phosphate
	pH
	Temperature
	Conductivity

(ii) Sub-index Toxicity

Phenols	Poly aromatic Hydrocarbons
Hydrocarbons	Pesticides
Cadmium	Mercury
Lead	Copper
Cyanide	Zinc
	Nickel

As a final part of the questionnaire survey, respondents were asked to list any additional determinands they considered, in retrospect, to be of value to an index. Only four extra determinands were listed - total hardness, chromium, total heavy metal equivalent and bacteriological determinands. These determinands had to be given further consideration for inclusion within the proposed index.

Therefore, having completed an intensive interview and questionnaire programme with officials from the water authorities of England and Wales, various lists of determinands were obtained, all of which were important to the final decision on the inclusion of determinands within the proposed index. However, in interpreting the results from the questionnaire study, one must consider the possibility that the percentage in favour may be representing a familiarity with selected determinands, rather than their desirability for inclusion within an index.

7.5. SELECTION BASED ON EEC AND EIFAC CRITERIA

Many of the standards from which water quality is judged, are contained within the Directives and Criteria respectively produced by the EEC and EIFAC. Thus, the determinands included within these documents must be considered for inclusion within the proposed index.

Two Directives relating to the quality of water intended for use in potable water supply have been produced by the EEC (1975; 1980). The former relates to the quality of surface waters intended for the abstraction of potable water supplies; the latter to the quality of water supplied at the consumer's tap. Thus, the 1975 Directive relates to the quality of raw water prior to water treatment, whilst the 1980 Directive relates to that at the consumer's tap i.e. after treatment and passage through the distribution system. Both these Directives have recently become legislative, thus the determinand concentrations recommended by these documents are now legal standards and of prime importance to the operational management of surface water quality, and therefore to the proposed index. As the aim of the proposed index is to reflect surface water quality in addition to possible water use, the standards contained within the 1975 Directive are of the greater significance to the present research, as these relate to both raw water quality and potential water use. Two further EEC Directives of importance are those relating to the quality of water required for bathing purposes (1975) and the protection of fish species (1978).

The determinands of greatest importance in the EEC Directive (1975) on drinking water abstractions are those with mandatory criteria. These 21 determinands have been included within Table 24 and are asterisked on Table 25. Many of these determinands are considered 'black list' determinands which require careful observation because of their potential toxic effects.

In the Council's Directive on the quality of bathing water (1975), the main emphasis is placed on microbiological determinands. This is due to the potential health hazards which may arise from swimming in bacterially polluted waters. The determinands with mandatory criteria for the use of waters for bathing purposes are also indicated in Table 25.

The inclusion of these determinands within the index is of less importance than those for drinking water because, for operational management purposes, swimming is not considered to be one of the major water uses. However, where human health is at risk, the relevant determinands must be considered for inclusion within the index.

EIFAC (European Inland Fisheries Advisory Commission; 1964 to 1983) have produced a series of reports relating to the protection of freshwater fisheries based on eleven determinands:

- finely divided solids (1964)
- pH values (1968)
- temperature (1968, 1969)
- ammonia (1970)
- monohydric phenols (1972)
- dissolved oxygen (1973)
- chlorine (1973)
- zinc (1973)
- copper (1976)
- cadmium (1977) and
- chromium (1983)

Although many of these guidelines are tentative, often based only on laboratory experiments, they indicate the varied effect of these determinands on the growth, behaviour, distribution, migration and reproduction of fish. As the maintenance of healthy fisheries is one of the most important management objectives, these determinands must be considered for inclusion within the proposed index.

7.6. THE EFFECT OF VARIOUS DETERMINANDS ON WATER QUALITY IMPAIRMENT CATEGORIES

A selection of the determinands included within previously developed indices and water quality monitoring programmes has been reviewed to examine the degree of impairment to different categories of water use such as those for public health purposes, fisheries, other wildlife and eutrophication. In this way their importance to overall water quality and as indicators of pollution might be satisfactorily evaluated.

7.6.1. Dissolved Oxygen

The concentration of dissolved oxygen is one of the most significant indicators of stream purity. Among the most important controls affecting the dissolved oxygen concentration are the amount and nature of organic matter present, the temperature, bacterial activity, dilution available for pollutants, photosynthesis and atmospheric aeration.

One of the first indications of the presence of organic pollution is a fall in the dissolved oxygen content of a stream below the effluent source.

At least sufficient dissolved oxygen must be present in the receiving water to prevent the onset of septic conditions. Insufficient dissolved oxygen promotes the anaerobic decomposition of any organic materials present. This decomposition causes the formation of noxious gases such as hydrogen sulphide and the production of carbon dioxide and methane in the sediments which bubble to the surface. During hydraulic surges, this decomposed substrate can be disturbed or overturned causing a substantial demand on the receiving stream oxygen regime.

A high dissolved oxygen concentration is highly desirable in water used for public water supply because this acts as an indicator of the satisfactory water quality in terms of low residuals of biologically available organic materials. However, sewage pollution may also lead to waters being supersaturated with oxygen. Therefore caution is necessary in the interpretation of dissolved oxygen loadings.

Dissolved oxygen prevents the chemical reduction and subsequent leaching of iron and manganese from the sediments (Environmental Protection Agency, 1973). These metals can cause taste problems, and lead to the staining of plumbing fixtures (National Academy of Sciences (NAS) 1974).

Dissolved oxygen is necessary for the biochemical oxidation of ammonia to nitrate. In water to be put into potable water supply, this reduces the chlorine demand of the water, and ultimately increases the efficiency of the disinfection ability of chlorination.

Considerable evidence exists to suggest that when the dissolved oxygen concentration of a fishing stream falls below 5 mgl^{-1} fish, especially game fish, are likely to be adversely affected (Ellis 1937; Brinley 1944; Klein 1959; Duodoroff and Shumway 1970). The effect upon a fish population of a dissolved oxygen concentration below 5 mgl^{-1} will vary according to species, age, activity, temperature, nutritional state and the life processes involved. Laboratory data have been collected which indicate that certain levels of dissolved oxygen can cause impairment and alteration of fish survival, growth, reproduction, swimming ability and behaviour.

The dissolved oxygen concentration is especially important to fish when poisonous substances are also present in the water. Normally harmless levels of toxic substances can become lethal to fish at low dissolved oxygen concentrations because water is pumped over the gills at a greater rate, thus increasing the amount of poison in contact with the gill surface where it is absorbed. Here the concept of delayed oxygen demand is important as BOD is essentially an 'instantaneous' determinand (see Section 7.6.2). Sediment Oxygen Demand (SOD) can be substantially delayed and can cause dissolved oxygen depression over prolonged periods long after the effluent event has ceased. Thus, this is one explanation for the scarcity of urban stream biota (Hvitved-Jacobsen and Harremoes, 1982).

The effect of dissolved oxygen concentration is dependent on many other factors including temperature which affects the solubility of oxygen in water and also the metabolic rate of poikilotherms. Generally, the minimum dissolved oxygen concentration that fish are able to tolerate increases with a rise in temperature, especially near upper lethal thermal limits (European Inland Fisheries Advisory Council (EIFAC) 1973).

7.6.2. Biochemical Oxygen Demand

Oxygen depletion occurs when large amounts of organic material, which require oxygen for their decomposition, are introduced into a river or stream. Sewage pollution can cause such conditions. In addition, oxygen is required by nitrifying bacteria to oxidise inorganic compounds produced in the decomposition of nitrogenous organic materials. The amount of oxygen necessary for the anaerobic decomposition of materials by micro-organisms is known as the Biochemical Oxygen Demand (BOD) of the material. Although the measurement of BOD is a 'blanket' test running for five days, years of experience have made it meaningful. Thus, along with dissolved oxygen concentration, BOD is an important indicator of pollution, and therefore of the general water quality of a river or stream. However, many would argue that in heavily polluted situations the BOD test is less meaningful because of delayed dissolved oxygen demand and the fact that metal toxicity may inhibit bacterial activity and therefore cause inaccurate BOD measurements.

7.6.3. Additional Tests for Organic Nitrogen

Three common chemical tests for organic nitrogen are the Permanganate Value (P.V.), the Chemical Oxygen Demand (C.O.D.) and the Total Organic Carbon (T.O.C.). These tests are quicker to perform than B.O.D. The C.O.D. test is a more effective method of assessing organic pollution than the P.V. test because it ensures a more complete oxidation of the organic matter present. The T.O.C. test can be carried out instrumentally in minutes and is therefore more reproducible than either the B.O.D. or C.O.D. tests. However, it does not account for organic matter that is biodegradable, therefore it is sometimes used in conjunction with the BOD test, as is also the case for both the PV and COD tests.

7.6.4. Alkalinity

The alkalinity of water used in public water supply affects the quantity of chemicals necessary for coagulation, softening and control of corrosion in distribution systems. If water is intrinsically alkaline, this assists in the neutralisation of excess acid produced when materials such as aluminium sulphate are added during chemical coagulation. High alkalinity is not considered to be a health hazard, per se, in potable water supplies. In fact the reverse is true, and there are cases where low alkalinity has shown a positive correlation with the occurence of cardio-vascular diseases e.g. in South Wales.

Alkalinity is important to fish and wildlife because it acts as a pH buffer to changes which occur naturally within the water due to photosynthesis. High alkalinity reduces the toxicity of ammonia. Components of alkalinity, such as carbonates and bicarbonates, will complex some toxic heavy metals, and therefore markedly reduce their toxicity to fish.

Excessive alkalinity can cause eye irritations to swimmers due to alterations in lacrimal fluid. However this problem is considered by many involved in water quality management to be relatively unimportant.

High alkalinity can be damaging to food producing industries, but in other industries water with a high alkalinity is preferred because it is much less corrosive.

If waters with an alkalinity in excess of 600 mgl^{-1} are used in spray irrigation, chlorosis may occur in the plants.

7.6.5. Hardness

Hardness determinations are a useful method of estimating the total dissolved solids present in raw water when calculating chemical dosages for lime-soda softening. The ions causing hardness can reduce the toxicity of various metal ions to fish and wildlife. This is due either to the formation of metallic hydroxides and carbonates caused by the associated increase in alkalinity, or because of the sequestering effect of calcium, or a combination of both.

7.6.6. Iron

Iron in public water supply is objectionable because it causes discolouration, turbidity, deposits, taste and induces staining in pipes and fixtures. In addition, washing may be stained, and iron stains can rot cloth. Iron can be toxic to fish and aquatic wildlife at concentrations of less than 1 mgl^{-1} (Brandt 1948; EIFAC 1964). The toxicity of iron is controlled by alkalinity, pH and temperature because these factors affect the valence state and solubility of the metal and hence its availability for assimilation. Suspended iron is also aesthetically objectionable. Iron at exceedingly high concentrations has been shown to be toxic to livestock (NAS 1974). Whilst iron can be a desirable constituent of waters used in some industrial processes, eg certain types of paper production, bleaching and dyeing of textiles, and some chemical industries, it must be completely absent in water used in most other industrial processes.

7.6.7. Manganese

Manganese in public water supplies can cause staining and taste problems. It is probable that the presence of low concentrations of iron may compound the problems produced by manganese (Train 1979). Manganese is not considered to be a problem to aquatic fauna as it is rarely found in sufficient concentrations in freshwater. However, it is usually precipitated out in streams and can cause problems to flora. Manganese is not known to cause problems when in waters used for livestock watering, but it can be toxic to plants when used for the irrigation of soils of pH lower than 6.0 (Train 1979).

7.6.8. Ammonia

The toxicity of aqueous solutions of ammonia is attributed to the un-ionized ammonia molecule. The toxicity of ammonia is dependent upon pH, as well as the concentration of total ammonia. Temperature and ionic strength are also important as the concentration of un-ionized ammonia (NH_3) increases with an increase in temperature, and decreases with increasing ionic strength.

Ammonia is toxic to fish and this toxicity varies with pH and hardness. In most natural waters, the pH range is such, that ionized ammonia (NH_4) predominates. However, in slightly alkaline waters, the NH_3 fraction can reach toxic levels. Even in concentrations which are not directly lethal to fish, adverse physiological or histopathological effects are experienced.

Ammonia is also a fundamental indicator of either domestic or industrial pollution. Due to the introduction of intensive stock rearing, the presence of ammonia may also be an indication of agricultural pollution. As ammonia is oxidised to nitrites and nitrates, oxygen depletion may occur depending upon re-aeration rates.

7.6.9. Nitrates and Nitrites

An intake of nitrates can cause a hazard to warm-blooded animals under conditions which could cause its reduction to nitrite. Nitrates can be reduced to nitrites in the gastro-intestinal tract which then reaches the bloodstream and reacts with haemoglobin to produce methaemoglobin which impairs the transport of oxygen in the blood. This can be especially hazardous for babies under 6 months of age that are bottle fed. Fatal poisoning has occurred when untreated well waters with concentrations over 10 mgl^{-1} nitrate nitrogen have been ingested. Water with nitrite nitrogen concentrations of over 1 mgl^{-1} should not be used for infant feeding. Water with a high nitrite nitrogen concentration would usually be heavily polluted and bacteriologically unacceptable.

Adequate protection is afforded to most warm water fish at nitrate and nitrite nitrogen concentrations of 90 mgl^{-1} (Knapp and Arkin, 1973) and 5 mgl^{-1} (McCoy, 1972) respectively. However, for the protection of salmonid species, a nitrite nitrogen concentration of 0.6 mgl^{-1} has been proposed by Russo et al (1974) . It is unlikely that the higher levels for either nitrate or nitrite nitrogen will be exceeded in natural surface waters, therefore they are not considered to be of major importance to fish and aquatic fauna. However, they are antagonistic to flora, and can cause eutrophication problems especially in association with phosphates.

7.6.10. Phosphorus and Phosphates

Elemental phosphorus is particularly toxic and is subject to bio-accumulation. Phosphate phosphorus is one of the major nutrients required by plants and is essential for life.

Phosphates in water have various sources including such natural sources as rocks and sands e.g. Greensand, as well as being derived from chemical fertilizers and sewage. Phosphates from human excreta and detergents account for much of the phosphate in polluted urban rivers. Phosphates are not monitored as an index of sewage pollution because it would only confirm any indications already given by the nitrate and chloride content. However, evidence indicates that phosphorus concentrations are associated with the acceleration of eutrophication in waters where all other growth promoting factors are present.

Algal growths promoted by excess phosphates can impart undesirable tastes and odours to water, be aesthetically unpleasant, interfere with water treatment and alter the chemistry of the water supply. In the UK, the greatest problems of eutrophication are usually associated with lakes and reservoirs, rather than streams. The concentration of phosphates necessary to promote nuisance growths of algae varies from one geographical region to another and with the other nutrients present. In addition, many lakes and reservoirs may act as phosphate sinks. Elemental phosphorus at low concentrations can cause high mortalities in fish. The predominant features of phosphorus poisoning in salmon are external redness and haemolysis.

7.6.11. Chloride

The measurement of chloride ion concentration can be indicative of sewage pollution as it is abundant in urine. Industrial discharges may contain high quantities of chloride ions, and chlorides, especially potassium chloride, may also be derived from artificial fertilizers.

The chloride concentration also affects the corrosive character of the water. Chloride ions contribute greatly to the conductivity of a water and, the higher the conductivity, the more easily corrosion occurs. Hence a high chloride concentration in public water supply could lead to corrosion of pipes and fittings and can cause a saline taste in drinking water. However, chloride concentration is not the controlling factor for all metals, because aluminium and copper for example, suffer severe pitting in waters with a low chloride content.

An increase in chloride concentration can also be indicative of sea water intrusions, mine water discharges and salt bearing strata.

Chlorides in excessive concentrations can be harmful to freshwater fish and aquatic wildlife. This is undoubtedly an osmotic phenomenon.

7.6.12. Sulphates and Sulphides

Sulphates of magnesium, sodium and calcium are often found in London clay, and clays belonging to the Oxford, Kimmeridge and Keuper Marl formations. The solution of large amounts of magnesium and sodium sulphates gives rise to highly mineralized waters which, while they are effective for medicinal purposes due to the laxative effects of these salts, are not so desirable in drinking water.

The facility with which sulphates may be biologically reduced to sulphide can also cause problems in water supply. By oxidation in the free atmosphere, corrosive sulphuric acid may be produced which acts directly on pipes, pumps and any other structures made of metal. Sulphides can act directly on concrete and cause rapid deterioration. Sulphides can also cause gastro-intestinal irritations and odour problems when found in drinking water. In winter, when the pH values are at or below neutral and the dissolved oxygen concentration is low, the hazard of sulphides to fish is exacerbated. Fish have a strong inherent dislike of sulphide and often are repelled by it before they are harmed.

7.6.13. pH

pH is an important variable in the chemical and biological systems of natural waters because it affects the degree of dissociation of weak acids and bases. This is important because the toxicity of many compounds is affected by the degree of dissociation. For example the toxicity of cyanide to fish is increased as the pH is lowered. Conversely, increases in pH can cause an increase in NH_3 concentration which may then be toxic to fish. Ammonia has been shown by EIFAC (1969) to be 10 times more toxic to fish at pH 8.0 than at pH 7.0.

A knowledge of the pH of raw and treated water used in public water supply is important because, without adjustment to a suitable level, such waters may cause corrosion of pipes and fittings and adversely affect treatment processes, including coagulation and chlorination. Butterfield (1948) has shown that chlorine disinfection is more effective at pH values of less than 8.0. Corrosion of plant equipment can lead to the introduction of metal ions such as copper, lead, zinc and cadmium.

EIFAC (1969) have reported that as the pH value of water is further removed from a pH below 6.5 and above 8.3, a deterioration in fish populations occurs. A pH range between 5 and 9 is not directly toxic to fish but changes within this range may increase the toxicity of many pollutants to fish and therefore result in fish mortalities. Also acid discharges may produce sufficient CO_2 to be directly toxic to fish, or to cause the pH range of 5-6 to become lethal.

pH values close to neutral are preferred for waters used in industrial processes to avoid corrosion and other deleterious chemical reactions.

7.6.14. Temperature

Undesirable aesthetic and sanitary conditions can be caused in a water body due to the effect of temperature upon the process of self-purification. A rise in temperature will increase the rate of biodegradation of organic material, and thus increase the demand on the dissolved oxygen resources of an individual system. This situation is exacerbated by the fact that oxygen becomes less soluble as water temperature increases. Therefore, under such conditions, oxygen depletion and obnoxious septic conditions may result.

Enteric bacteria and pathogens are also affected by temperature. Ballentine et al (1968) have shown that both total and faecal coliforms die away more rapidly in an environment with elevated temperatures.

Temperature can affect treatment processes such as coagulation and chlorination. For example, a decrease in temperature decreases the effectiveness of chlorination.

Temperature changes in water bodies can alter the existing aquatic community. Upper and lower limits for temperature have been established for many aquatic organisms. Many factors such as diet, activity, age, general health, osmotic stress and even weather, contribute to the lethal effect of temperature. The ability of a species to acclimatise to temperature changes and the exposure time are critical factors (Parker and Krenkel 1969).

Changes in temperature can affect fish metabolism, respiration, behaviour, distribution, migration, feeding rate, growth and reproduction. De Sylva (1969) has summarised the effects of temperature on the toxicity of certain metals to fish. Toxicity generally increases with temperature, and organisms subjected to stress from toxic materials are less tolerant of temperature extremes. They also require an increase in the D.O. concentration to survive.

7.6.15. Total Dissolved Solids

Excessive dissolved solids are objectionable in drinking water because of possible physiological effects, unpalatable mineral tastes and high costs arising from corrosion or the necessity for additional treatment. Physiological effects of dissolved solids include laxative effects, principally from sodium sulphate and magnesium sulphate. Specific constituents in the dissolved solids may cause mineral tastes at lower concentrations than other constituents eg chloride ions. Corrosion and incrustation of metallic surfaces by water containing dissolved solids is well known. Damage in household systems occurs in water piping, wastewater piping, water heaters, taps, toilet flushing systems etc. This corrosion can cause substantial costs in replacement.

Variations in the dissolved solid concentration in streams can affect the osmotic stress on fish and aquatic wildlife. Fish must be able to tolerate a range of dissolved solid concentrations in order to survive under natural conditions.

Agricultural uses of water are also limited by the concentration of dissolved solids. The use of water for irrigation is not only dependent upon the osmotic effect of dissolved solids, but also on the ratio of various cations present (Train 1979).

Industrial requirements regarding dissolved solids in raw water are quite variable due to the different needs of industrial processes and the problems of corrosion in pipes etc.

7.6.16. Suspended Solids and Turbidity

The turbidity limit for drinking water is based on health considerations because the efficiency of the disinfection process is a function of the turbidity. Suspended matter provides sheltering sites where micro-organisms do not come into contact with the chlorine disinfectant (NAS 1974).

Waters with high suspended solid concentrations are detrimental to recreational and aesthetic enjoyment of water and turbid waters can be highly undesirable for swimming. The less turbid the water the more desirable it is for contact recreation.

EIFAC (1965) identified four ways in which suspended solids adversely affect fish and aquatic wildlife. High suspended sediment concentrations can act directly upon swimming fish and either choke them or reduce their growth rate and resistance to disease by coating the surface of the gill membranes. It can affect the successful development of fish eggs and larvae, and modify the natural movements and migrations of fish. Finally, it can reduce the abundance of food available to them.

In addition, settleable materials blanket the bottom of water bodies and damage or alter the benthic invertebrate population and block gravel spawning beds. They also reduce the growth of flora. If organic, they can remove dissolved oxygen from the overlying water.

Plankton and inorganic suspended solids reduce light penetration into a water body. This reduces primary production and decreases the quantity of available fish foods (NAS 1974).

7.6.17. Colour

Surface waters may appear coloured due to suspended solids. This is known as apparent colour as opposed to true colour which is due to colloidal humic materials (Sawyer 1960). Water colour is usually detrimental to aesthetic pleasure. Dyes and non-natural colours should not be perceptible to the human eye.

The effect of colour in water used in public water supply is also mainly aesthetic. Aquatic life is affected primarily by a reduction in light penetration.

7.6.18. Phenols

Phenols can cause problems in waters used in drinking water supplies because they are not removed efficiently by conventional water treatment and, when chlorinated, taste and odour problems arise.

Phenolic compounds can adversely affect freshwater fish by their toxicity to both the fish and their food organisms. This is due to the high oxygen demand of phenolic compounds and by the tainting of fish flesh. Phenol is toxic in low concentrations to both adult and immature organisms (EIFAC 1973).

Various environmental conditions will increase the toxicity of phenol - lower dissolved oxygen concentration; increased salinity and increased temperature all enhance the toxicity of phenols to fish.

A major aesthetic problem associated with phenols are their organoleptic properties in water and fish flesh; these cause undesirable odour problems.

7.6.19. Mercury

Mercury, even at low concentrations, is very toxic to humans and dramatic incidences of toxicosis in man and animals have occurred in countries such as Japan, Iraq and Pakistan. Mercury toxication may be acute or chronic and the toxic effects can vary according to the form of the mercury and its mode of entry into the organism.

Several forms of mercury occur in the environment. The discovery that certain micro-organisms have the ability to convert inorganic and organic forms to the highly toxic methyl or dimethyl mercury has made any form of mercury highly hazardous in the environment (Jensen and Jermelow 1969). Therefore, the total mercury level of water is important.

Algae and aquatic plants accumulate mercury by surface absorption and thus fish take in mercury both directly from the water and from food (Hannerz 1968).

The amount of mercury in both drinking water and that used for livestock watering must be monitored because of the health risks.

Chronic toxicity tests have shown that organomercurials adversely affect the survival, growth and reproduction of many fish species.

7.6.20. Copper

Prolonged intake of copper may cause liver damage, although water supplies seldom have sufficient copper to cause any health problems. However, copper in excess of 1 mgl^{-1} may impart an objectionable taste to water.

The toxicity of copper to aquatic life increases with a decrease in alkalinity.

Other factors affecting toxicity include pH and organic compounds. Relatively high concentrations of copper may be tolerated by adult fish for short periods, but the greater effects of copper toxicity are experienced by juvenile fish. In general, it would appear that salmonids are very sensitive to copper while coarse fish are less sensitive (Train 1979).

7.6.21 Zinc

Drinking water supplies can contain up to 27 mgl^{-1} of zinc without adversely affecting human health. However, at a threshold around 5 mgl^{-1}, water acquires a bitter and objectionable taste (Cohen et al 1960). Zinc also produces undesirable aesthetic effects.

The toxicity of zinc to fish and aquatic wildlife is influenced by the hardness, dissolved oxygen content and temperature of the water. An increase in temperature and a reduction in dissolved oxygen can both enhance the toxicity of zinc to fish and aquatic wildlife. Toxic concentrations of zinc compounds cause morphological and physiological changes in fish. In general, it has been found that fish are most sensitive to zinc in soft water, while other aquatic life are more sensitive to zinc in hard water (Water Research Centre (WRC), 1984).

Zinc has also been shown to be toxic to a number of plants (Hewitt 1948). Water with a high zinc concentration used in irrigation has produced iron deficiencies in plants such as sugar beet.

7.6.22. Arsenic

Arsenic in waters used in public water supply constitutes a direct health hazard. Since the early 19th Century arsenicals have been suspected of being carcinogenic (Heuper and Payne 1963). Frost (1967) has shown that the most toxic arsenicals can be tolerated at concentrations of 10 to 20 ppm arsenic in the diet.

In man, the symptoms of mild chronic poisoning are fatigue and loss of energy. In more severe toxication, gastro-intestinal catarrh, kidney degeneration, bone marrow injury, exfoliate dermatitis and altered skin pigmentation may occur (Goodman and Gilman 1965).

Although arsenic is concentrated in aquatic organisms, it is evidently not progressively concentrated along a food chain. Concentrations of sodium arsenite in excess of 4 mgl^{-1} have been found to reduce the survival and growth rate of fish, and to reduce bottom fauna and plankton populations (Gilderhus 1966).

Arsenic in water used in spray irrigation has been found to produce toxic symptoms in seedlings of pineapple and orange plants. Clements et al (1939) reported an 80% reduction in the yield of tomatoes when water containing a 0.5 mgl^{-1} concentration of arsenic as arsenite was used for spray irrigation.

7.6.23. Boron

Extremely high concentrations of boron (19,000 mgl^{-1}) as boric acid would be necessary to cause mortalities to minnows, (Le Clerc and Devlaminck 1955).

Bradford (1966) has shown that when the boron concentration in irrigation waters is greater than 0.75 mgl^{-1}, some sensitive plants began to show injury. Therefore, a criteria of 0.75 mgl^{-1} is thought by Train (1979) to protect crops during long-term irrigation.

7.6.24. Cadmium

Cadmium has been shown to be toxic to man when ingested or inhaled. The ingestion of cadmium causes symptoms similar to those of food poisoning.

Presently, there are no known physiological needs for cadmium in the body, and no mechanism by which it can be maintained at a constant safe level. Once absorbed, it is stored in the kidneys and liver and is excreted at an extremely slow rate. Once the accumulation of cadmium in the kidneys of an individual reaches a critical concentration, chronic kidney disease occurs. This concentration can vary between individuals. Therefore a recommended limit of 10 μgl^{-1} of cadmium in drinking water has been suggested by Train (1979). Assuming a daily consumption of two litres of water per day, the maximum daily intake of cadmium would be 20 µg from this source, and while this is considered to be tolerable, even this low level is not considered desirable.

Fish and certain invertebrates have been found to be sensitive to low levels of cadmium in water (30 μgl^{-1}). Salmonids and cladocerans appear to be the most sensitive (Eaton 1974a).

Increased hardness and/or alkalinity have been demonstrated to decrease the toxicity of cadmium (Pickering and Gast 1972; Eaton 1974a; Benoit et al 1980).

Page et al (1980) have shown that yields of beans, beet and turnips were reduced by 25% due to 0.10 mgl^{-1} cadmium in nutrient solution. Cabbage and barley yields decrease by 20%-50% at 1.0 mgl^{-1}.

Yamagata and Shigematsu (1970) have shown that crops grown in cadmium polluted soils, and irrigated with cadmium polluted water can accumulate sufficient quantities of the metal to be a health hazard to man if consumed.

7.6.25. Nickel

Nickel is considered to be relatively non-toxic to man. McKee and Wolf (1963) have shown that the toxicity of nickel to aquatic life varies with species, pH, synergistic effects and other factors. Nickel adversely affects the reproduction of freshwater crustaceans at concentrations as low as 95 μgl^{-1} (Biesinger and Christensen 1972). Reproduction of the fathead minnow is detrimentally affected by nickel at concentrations as low as 730 μgl^{-1} (Pickering 1974).

Vanselaw (1966) demonstrated that nickel in concentrations between 0.5 mgl^{-1} and 1.0 mgl^{-1} is toxic to a number of plants.

7.6.26. Lead

The toxicity of lead in water is influenced by pH, hardness, organic materials and the presence of other metals. The aqueous solubility of lead ranges from 500 μgl^{-1} in soft water to 3 μgl^{-1} in hard water (Train 1979).

Lead is a toxic metal and accumulates in the tissues of man and other animals; irreversible brain damage can result from lead ingestion by children. The major toxic effects of lead include anaemia, neurological malfunctions, and renal impairment. Therefore in drinking water, lead should be kept to a minimum. The US Public Health Service recommend a limit of 50 μgl^{-1}.

A concentration of 100 μgl^{-1} of lead in soft water was shown to have detrimental effects on rainbow and brook trout (NAS 1974). Davies and Everhart (1973) found the highest mean continuous flow concentration of lead which did not adversely affect the survival, growth and reproduction of rainbow trout was 360 μgl^{-1} in hard water. For soft water this figure was 11.9 μgl^{-1}. In general salmonids are most sensitive to lead in soft water.

Concentrations of lead between 10 mgl^{-1} and 50 mgl^{-1} as lead nitrate in nutrient solution would be necessary to cause toxic effects to plants.

7.6.27. Cyanide

Lethal toxic effects from the ingestion of water containing cyanide occur only when cyanide concentrations are high and overwhelm the detoxifying mechanisms of the human body.

Free cyanide concentrations in the range of 50 to 100 μgl^{-1} as cyanide have proved eventually fatal to sensitive fish species (Karsten 1934; Herbert and Merkens 1952; Doudoroff et al 1966).

Downing (1954) has shown that the toxicity of cyanide increases with a reduction in the dissolved oxygen concentration below 100% saturation. The tolerance of fish to toxic concentrations of cyanide is reduced with an increase in temperature.

Sub-lethal effects of cyanide include reduced growth rate and a reduction in swimming ability of fish and occur at concentrations as low as 10 μgl^{-1}.

Cyanide does not appear to affect agricultural or industrial use of water.

7.6.28. Chromium

A knowledge of the toxicity of hexavalent chromium to human health has been obtained from occupational health effects. Lung cancer and a number of respiratory complaints have been linked to chromium toxication. The toxic effects of chromium in drinking water are not fully understood. However, a limit of 50 μgl^{-1} of chromium has been suggested for drinking water as this concentration is considered to be reasonably safe and should avoid health hazards to humans.

Fish appear to be relatively tolerant of chromium, but some aquatic invertebrates are quite sensitive. Toxicity varies with species, pH and chromium oxidation state.

Pickering (NAS 1974a) found 96-hour LC_{50} and safety hexavalent chromium concentrations of 33 mgl^{-1} and 1 mgl^{-1} respectively for fathead minnows in hard water. Benoit (1980) found these values to be 59 mgl^{-1} and 0.2 mgl^{-1} respectively for brook trout in soft water. Therefore, a criteria of 0.10 mgl^{-1} should provide adequate protection for freshwater fish (Train, 1979).

7.6.29. Faecal Coliforms

Information on the relationship between faecally-associated microbes and potential disease was developed by Escherich when he described Bacillus Coli (Escherichia Coli) as an indicator of pollution (Wolf 1972).

Microbiological indicators have been used to indicate the safety of water for drinking, livestock watering, swimming and spray irrigation. Faecal coliforms, especially E. Coli, are considered primary indicators of recent faecal contamination due to sewage discharges.

Pollution of aquatic systems by excreta of warm-blooded animals creates public health problems for man and animals, and potential disease problems for aquatic life. It is known that pathogens may inhabit the gut of warm-blooded animals and these are shed in the faeces. Therefore, the number of faecal coliforms present in a water sample is indicative of the degree of health risk associated with using the water for drinking or swimming.

Outbreaks of typhoid fever have been associated with swimmers in heavily polluted coastal resorts in Australia (Kovacs 1959). Evidence has also been produced to suggest a sharp increase in the frequency of detection of the presence of salmonella when faecal coliform densities are above 200 organisms per 100 mls of freshwater (Train 1979).

It is often difficult to interpret the results obtained from microbiological studies since the number of organisms required to cause disease varies depending upon the organism, the host and the manner in which the bacteria and host interact. Under some circumstances a single cell of salmonella may be all that is required to cause disease or clinically recognisable symptoms of it. However, in other instances, the number of bacteria necessary to cause an illness may be as high as 10^6 to 10^7. The use to which water is put, the type of water, and the geographical location are all important factors to be weighed in determining safe microbiological criteria.

7.6.30. Conclusions

It is obvious from the 32 determinands reviewed that some have a greater effect on water use than others. Determinands such as alkalinity and hardness affect the toxicity of ammonia and metals to fish and aquatic life, but are, in themselves, harmless. Conversely, determinands such as ammonia and cadmium have a direct influence upon the potential use of a water body. In deciding which determinands should be included within an index, obviously those with the most significant influence on water quality and potential use should be selected.

7.7. THE SELECTION OF DETERMINANDS FOR INCLUSION WITHIN THE PROPOSED WATER QUALITY INDEX

In deciding which determinands to include within the proposed index, the results obtained from the application of the selection criteria outlined in Sections 7.2 to 7.6 were collated and various rejection rationale introduced (Table 34).

7.7.1. The Selection of Determinands for Inclusion within the WQI Sub-Index

It is apparent from Table 34 that certain determinands are obvious candidates for inclusion within this sub-index. Dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia and nitrates are of prime importance because they have been highly rated for inclusion within previously developed indices and water quality monitoring programmes (Tables 23 to 26); and the combined use of these four determinands indicates the suitability of a water body for use in potable water supply (PWS) or the maintenance of healthy fish populations. In addition, they reflect the degree of environmental protection afforded to a water body. These four determinands are also measured regularly as part of the routine water quality monitoring programmes of the ten water authorities of England and Wales (Table 28). It is evident from Table 30 that members of some of the water authorities consider these determinands to indicate significant changes in the quality of the water within their individual catchment areas. They were all selected as primary determinands by water authority members after the completion of the questionnaire study (Table 32 and 33). In addition, ammonia and nitrates have mandatory EEC (1975) criteria for waters intended for use in potable water supply (Table 25 and Section 7.5); and guidelines on the effect of variations in D.O. and ammonia concentrations have been produced by EIFAC (1973, 1970) for the protection of fish and wildlife populations. All four of these determinands are indicative of sewage pollution and are of importance to the major uses of a water body (section 7.6.) Therefore, D.O, B.O.D, ammonia and nitrate were selected as primary determinands for the WQI sub-index.

Table 34. Collated Results from Selection Criteria

I. WQI Sub-Index Determinands

Selection Criteria Determinand	Previously Developed Indices and Monitoring Programmes (66% Criteria)	Monitoring Frequency	Known to be Indicative of Water Quality Change	Question-naire Selection	EEC Mandatory Criteria	EIFAC	Range of Impairment (see Footnote for abbreviations used)	Rejection Rationale
Dissolved Oxygen	Yes	Routine	Yes	P		Yes	I of Quality. All uses	
B.O.D.	Yes	Routine					Indicator of Pollution	
Iron	Yes	Special Sites	Yes		PWS		PWS. Fish. Ind. Livestock	
Ammonia	Yes	Routine	Yes	P	PWS	Yes	I. of Poll'n. Fish	
Nitrate	Yes	Routine	Yes	P	PWS		I. of Poll'n. Eutrophication	1
Chloride	Yes	Routine	Yes	S		Yes	I. of Poll'n. PWS Fish	2
Fluoride		Special Sites			PWS		PWS	
Sulphate	Yes	Special Sites	Yes		PWS		PWS	2
pH	Yes	Special Sites		S	Swimming	Yes	PWS. Fish. Industry	3
Temperature	Yes	Routine		S	PWS	Yes	I. of Quality. PWS. Fish	
Total Dissolved Solids	Yes	Varies					PWS. Irrigation. Industry	2
Colour	Yes	Special Sites	Yes		PWS		Aesthetic Quality. PWS	
Alkalinity		Routine					PWS.	3
Hardness		Routine					Fish	2
Suspended Solids		Routine	Yes	S		Yes	Aesthetic Quality. Fish. PWS	4
Turbidity		Varies		S			Aesthetic Quality. PWS	4
Manganese		Special Sites	Yes				PWS	
Nitrite		Varies	Yes				Indicator of Poll'n Eurtroph'n	
Ortho Phosphate		Varies	Yes	S			Eutrophication. I. of Poll'n.	1
Conductivity		Routine		S			PWS	2
Synthetic Detergents		Varies	Yes				Indicator of Pollution	
Total Coliforms		Varies			Swimming		Health Hazard. All contact.	
II. Sub-Index of Toxicity Determinands								
Phenols	Yes	Varied	Yes	P	PWS	Yes	PWS. Fish	
Cyanide	Yes	Varied	Yes	P	PWS		PWS. Fish	
Pesticides		Varied	Yes	S	PWS		PWS. Fish	
Hydrocarbons		Varied	Yes	P	PWS		PWS. Fish	
PAH		Varied	Yes	S	PWS		PWS. Fish	
Zinc		Varied	Yes	S	PWS	Yes	PWS. Fish. Irrigation	
Mercury		Varied	Yes	S	PWS		PWS. Fish	
Lead		Varied	Yes	P	PWS		PWS. Fish	
Copper		Varied		S	PWS	Yes	PWS. Fish	
Nickel		Varied		S			Irrigation. Fish	
Cadmium		Varied		P	PWS	Yes	PWS. Fish. Irrigation	
Chromium		Varied			PWS	Yes	Fish. Possibly man.	
Arsenic		Varied			PWS		PWS. Fish. Irrigation	
Boron		Varied					Irrigation	
Selenium		Rarely			PWS			
Barium		Rarely			PWS			

Footnotes

P	= Primary Determinand	PWS	= Important to water used in potable water supply
S	= Secondary Determinand	Fish	= Affects fish and wildlife populations
I	= Indicator of Pollution	Irrig'n	= Of importance in waters used in spray irrigation
Ind	= Industry	1 to 4	= Determinands which are either similar or duplicate the same test

Chlorides have been previously included within numerous indices and water quality monitoring programmes covering a wide range of water use (Tables 23 to 27). They are monitored as part of the routine monitoring programme of all the water authorities (Table 28), and several authorities consider chlorides to be significant indicators of pollution within their catchment area (Table 30).

Chlorides were initially selected by only three authorities for inclusion within the WQI (Table 31), however on completion of the questionnaire, 50% of respondents agreed to its selection with 37.5% of responses inconclusive (Table 32). Chlorides do not have a mandatory EEC criterion for waters intended for use in potable water supply (Section 7.5), but they are of importance to many potential water uses (Section 7.6.11). An increase in chloride ion concentration may be indicative of both sewage pollution and industrial discharges (Section 7.6.11).

Thus, due to the overall importance of chloride concentration to both general water quality and for waters intended for a specific use, chlorides have been included as a primary determinand within the proposed index.

pH and temperature have both been highly rated for inclusion within previously developed indices and water quality monitoring programmes (Tables 25 and 26), and both are of importance to the major potential uses of a water body (Table 27). Both determinands are regularly monitored by the ten water authorities (Table 28), but neither is known to indicate significant changes in the water quality of any individual catchments.

The results from the questionnaire study on the inclusion of these two determinands are inconclusive, but are sufficient to merit their selection as secondary determinands.

	Agreed	Disagreed	Inconclusive
pH	50%	-	50%
Temperature	37.5%	12.5%	50%

(Abstraction from Table 32)

The direct influence of pH on fish, aquatic life and potable water supply is outlined in Section 7.6.13. pH is also indirectly important due to its synergistic influence on metal toxicity and its control of ammonia levels, which are of particular importance to fish.

Temperature is a mandatory EEC criterion for waters to be used for potable water supply and guidelines on the protection of fisheries from variations in pH and temperature have been produced by EIFAC (1968, 1969).

Temperature variations influence the solubility of oxygen in water, can reduce self-purification and directly affect fish and aquatic life (Section 7.6.14).

Although thermal pollution is not a widespread occurrence within most of the water authority regions, the influence of temperature, as with pH, can affect potential water use. Therefore, both these determinands have been included within the index as primary determinands.

Suspended solids and turbidity have both been previously selected for inclusion within water quality indices and monitoring programmes (Tables 23 to 26) although neither conformed to the final criteria employed in their analysis. Suspended solids form part of the routine water quality monitoring programme of the ten water authorities of England and Wales (Table 28), and are known to indicate changes in the standard of water quality within some catchment areas (Table 30). Both were selected as secondary determinands for inclusion within the WQI sub-index by water authority officials (Table 32).

Neither of these determinands have mandatory EEC criteria for waters intended for use in potable water supply (Section 7.5), but guidelines on the acceptable levels of suspended solids for freshwater fisheries have been produced by EIFAC (1964). Both these determinands are of importance for environmental protection, especially in terms of the aesthetic value of a water body (Section 7.6.16). Therefore, these determinands should be included within the proposed index.

However, as turbidity and suspended solids are in essence both tests to ascertain the concentration of organic and inorganic particulate matter in water, it is not strictly necessary to have both of them within a general index. Therefore, suspended solids was selected in preference to turbidity as it is regularly monitored by the ten water authorities. This is an example of the way in which the rejection rationale was employed to assist in the final selection of determinands. However, it is important to note that the significance of these two determinands varies slightly in that the suspended solid concentration is of greater interest to those responsible for the management of sewage treatment, while turbidity is of more importance to those in charge of water treatment. But, as other determinands closely associated with turbidity eg colour, have been selected for inclusion within this sub-index (see below), the exclusion of turbidity can be justified. As 75% of respondents to the questionnaire study selected either turbidity or suspended solids for inclusion within the proposed sub-index, suspended solids was selected as a primary determinand.

Although iron and manganese are not indicative of sewage pollution, high concentrations of these metals in water can occur from mining wastes, industrial discharges or natural sources (Section 7.6.6. and 7.6.7). Both these determinands are important for potable water supply, but neither is an important indicator of general water quality. Iron has been previously included within indices and water quality monitoring programmes designed for potable water supply by over 66% of authors (Tables 26 and 27). But neither iron nor manganese is monitored regularly by all the water authorities, although they are monitored where water supply is the major water use (Table 29). Only one water authority considered iron and manganese to indicate significant water quality deteriorations within their catchment area (Table 30).

The response of the water authority members to the suggested inclusion of iron and manganese within a general water quality index was mixed. Of the replies, 37.5% agreed, 50% disagreed and 12.5% were inconclusive (Table 32).

However, iron is a mandatory criterion for waters intended for use in potable water supply by the EEC (1975) (Section 7.5). Therefore, because of the importance of iron to potable water supply and the fact that it is only monitored in areas where this is the major water use, iron was included within the index as a 'special' determinand and manganese omitted.

Colour has been most highly rated for inclusion within those previously developed indices and water quality monitoring programmes designed for the management of potable water supply (Tables 23 to 26). This determinand is not routinely monitored as part of surface water quality management, but it is monitored at water treatment plants where surface water is used in potable water supply. In addition, colour is known to cause significant changes in the standard of water quality within one authority's catchment area (Table 30).

The results from the questionnaire analysis showed that 12.5% of respondents agreed with the inclusion of colour within the proposed index; however, 50% disagreed and 37.5% were inconclusive.

Thus, colour is of importance to water used in potable water supply and it also affects the aesthetic value of a water body (Section 7.6.17). Determinands such as suspended solids and iron are often of importance in producing discolouration of water. As these determinands are already included within the index, it is possible that the inclusion of colour is unnecessary. However, there is a mandatory EEC (1975) criterion for colour for waters used in potable water supply. Therefore colour has been included within the index as a 'special' determinand.

Sulphate has been included as a determinand within over 66% of previously developed indices and water quality monitoring programmes covering a range of potential water usage (Tables 23 to 27). However, sulphate determinations do not form part of the routine water quality monitoring programme of all the water authorities (Table 28), although they are known to cause significant water quality changes in some authority catchment areas (Table 30). The concentration of sulphates can be at or near unacceptable levels for some waters currently in use within potable water supply.

The results from the questionnaire study on the inclusion of sulphate within the proposed sub-index were the same as those for iron; 37.5% agreed, 50% disagreed and 12.5% were inconclusive.

Sulphates in high concentrations are known to cause problems in water used in potable water supply, consequently, the EEC have proposed a mandatory criterion for sulphate concentrations in waters intended for this use. Therefore, because of the importance of sulphates to potable water supplies, sulphate, like iron and colour, has been included within this sub-index as a 'special' determinand.

Microbiological determinands such as faecal coliforms, E. Coli and total coliforms have been selected for inclusion within previously developed indices and water quality monitoring programmes (Tables 23-26). However, these determinands are neither routinely monitored by the water authorities, nor known to cause significant changes in water quality.

Microbiological determinands are of importance to waters used for potable water supply, swimming and spray irrigation because they are indicative of potential health risks (Section 7.6.29).

These determinands were not originally suggested as possible candidates for inclusion within the proposed WQI by the water authority members interviewed, because the results from bacterial analysis are considered difficult to interpret; and because effective chlorination should remove any potential health risk. However, a member from one of the water authorities did suggest the addition of microbiological determinands to those listed within the questionnaire (Table 32).

Although microbiological determinands are not mandatory EEC criteria for waters in use as drinking water abstractions, both faecal and total coliforms are, in the case of waters used for bathing purposes (Section 7.5).

Therefore, as these determinands present a health risk to almost all possible water uses (Section 7.6.29), total coliforms have been included within the index as a primary determinand. The inclusion of such a determinand within an index may assist in alleviating the difficulties in their interpretation.

Fluorides have been selected for inclusion within previously developed WQIs and water quality monitoring programmes covering a wide range of water use by over 66% of authors (Tables 23 to 27). However, fluorides do not form part of the routine monitoring programmes of the ten water authorities and are generally only monitored at special sites. Fluorides have not been shown to be indicative of water quality change within any of the individual water authorities' catchment areas.

Fluorides were not suggested as a possible determinand for inclusion within the proposed WQI, however, the EEC (1975) have applied a mandatory criterion to the fluoride concentration of waters used in potable water supply (Section 7.5). Because of the importance of the fluoride concentration in drinking waters, fluoride has been included within the WQI sub-index as a 'special' determinand.

A decision on the inclusion of alkalinity and hardness into an index is not so straightforward. Neither has a significant direct effect on any potential water use, however the indirect effects of both these determinands in reducing the toxicity of certain metals to either man or fish and wildlife is of importance (Sections 7.6.4 and 7.6.5). Neither determinand has been regularly selected for inclusion within previously developed indices or water quality monitoring programmes (Tables 23 to 26), but both are regularly monitored by the ten water authorities of England and Wales (Table 28). However, only one authority considered hardness to be indicative of significant water quality changes within their catchment area (Table 30). Although alkalinity was initially suggested by water authority members as a determinand worth considering for inclusion within the WQI sub-index (Table 31), it received only a 12.5% inclusion rating after the completion of the questionnaire (Table 32). Hardness was selected by only 25% of the respondents.

As the proposed index is to include a sub-index of toxicity, whereby the influence of these two determinands would be considered within each individual determinand's rating curve, it was considered that these determinands may be omitted from this sub-index.

The question of the inclusion of ortho-phosphate posed similar problems to those of alkalinity and hardness. Phosphates have not been used extensively in previously developed WQIs and water quality monitoring programmes (Tables 23 to 26), and they do not form part of the routine water quality monitoring programmes of all the water authorities (Table 28). However, ortho-phosphates have been found to indicate significant changes in the water quality of one authority's catchment area (Table 30).

The overall result from the questionnaire on the inclusion of ortho-phosphate within the index were ambivalent (Table 32); 25% of respondents agreed with its inclusion, 12.5% disagreed and 62.5% were inconclusive. Ortho-phosphates are indicative of sewage pollution and are known to be one of the major causes of eutrophication (Section 7.6.10). However, other determinands indicative of sewage pollution have already been selected for inclusion within the WQI sub-index. Therefore the additional inclusion of phosphates would be duplicative. Despite the importance of this determinand to eutrophication, the additional information which would be afforded by its inclusion within a general WQI does not appear to have been considered sufficiently important in the past, (Section 7.2) or, indeed, at present (Section 7.4). Therefore, ortho-phosphate was omitted from the index.

Conductivity has only been regularly selected for inclusion within indices and water quality monitoring programmes designed for waters intended for use in spray irrigation (Tables 23 to 26); whilst total dissolved solids have been regularly included in almost all forms of use-related indices and water quality monitoring programmes. However, conductivity can be considered to be, in essence, a measure of the total dissolved solids loading of a water body.

Conductivity is measured regularly as part of the routine monitoring programmes of the ten water authorities (Table 28). However, it has not been known to indicate serious deteriorations in water quality within individual catchments.

The results from the questionnaire study on the inclusion of conductivity within the index were as follows; 50% agreed, 25% disagreed and 25% were inconclusive.

Conductivity can indicate that changes from the norm are occurring within a water body. In its capacity as an indicator of the total dissolved solids loading of a water body, it is of possible importance to potable water supply. However, chlorides and sulphates, which have very significant effects on potable water supply, have already been selected for inclusion within the index. The inclusion of conductivity in addition to these determinands was considered duplication. Therefore, conductivity has not been selected for inclusion within the index.

Other determinands such as total organic carbon (T.O.C.) and chemical oxygen demand (C.O.D.) should, ideally, be included within the index as they provide a more efficient and reproducible method of detecting sewage pollution than B.O.D. measurements. However, neither of these determinands has been regularly accepted for inclusion within previously developed indices or water quality monitoring programmes (Tables 23 to 26). T.O.C. is more regularly monitored by the water authorities than C.O.D. However, neither determinand forms part of the routine water quality monitoring programmes of all the authorities. In some authorities these determinands may only be monitored as part of the harmonized monitoring programmes. Therefore, although the inclusion of one or other of these determinands within the index would be of value, it is not really practical at this time.

Nitrites have not been frequently selected for inclusion within previously developed indices or water quality monitoring programmes (Tables 23 to 25). They do not form part of the regular water quality monitoring programmes of all the water authorities. However, one authority found nitrite concentrations to be sufficiently high to indicate significant water quality deteriorations within parts of their catchment area (Table 30).

The results obtained from the questionnaire study showed that 25% of respondents agreed with the inclusion of nitrites within the index, with 50% disagreeing and 25% inconclusive.

Nitrites act as an indicator of sewage pollution and can cause eutrophication (Section 7.6.9). However, ammonia concentrations indicate that sewage pollution is present, and nitrates that longer term sewage pollution has become established. As these determinands have already been selected for inclusion within the index, the inclusion of nitrite would not add to the potential of the index. In addition, nitrites are rarely found at concentrations high enough to cause fish mortalities. Thus nitrites were omitted from the proposed WQI sub-index.

7.7.2. Summary of Determinands Selected For Inclusion Within the WQI Sub-Index

The thirteen determinands selected for inclusion within the WQI sub-index of the proposed index have been summarised in Table 35. They are all known, directly or indirectly, to influence surface water quality and/or potential water use. The primary determinands are, with the exception of total coliforms, monitored as part of the routine water quality monitoring programmes of the water authorities of England and Wales. An index based on these nine determinands alone would be capable of monitoring the quality of both clean and polluted rivers alike.

Table 35. Determinands selected for inclusion within the WQI Sub-Index

Primary Determinands	Special Determinands
Dissolved Oxygen	Iron
Biochemical Oxygen Demand	Sulphates
Ammonia	Colour
Nitrate	Fluorides
Suspended Solids	
Chloride	
pH	
Temperature	
Total Coliforms	

The 'special' determinands selected are those which are of particular importance to water bodies used in potable water supply. As these determinands are, in general, only monitored at such sites, it is suggested that they be included within the index calculation when the suitability of a river as a source for potable water supply is under investigation.

7.7.3. The Selection of Determinands For Inclusion Within the Sub-Index of Toxicity

Phenols, hydrocarbons, cadmium, lead and cyanide were all clearly rated as primary determinands for inclusion within a water quality index by the water authority members who completed the questionnaire survey (Table 32). All of these determinands, with the exception of cadmium, have been known to cause a change in the water quality of one or more of the water authority's catchment areas (Table 39) and phenols and cyanide have been regularly selected for inclusion within previously developed indices and water quality monitoring programmes.

Both cadmium and lead are cumulative poisons and, once ingested by humans, fish or other aquatic life they are retained within the body (Section 7.6.24 and 7.6.26). These determinands are highly undesirable in waters used for potable water supply or fisheries purposes (Section 7.6). They have all been ascribed mandatory water quality criteria by the EEC (1975) in their Directive on Drinking Water. Also EIFAC (1972; 1977) has produced reports on the toxicity of phenols and cadmium to fish.

Because of the influence of these determinands on potential water use, it was imperative that they be included within the proposed index.

Pesticides and mercury were selected for inclusion within the sub-index of toxicity by 57% of respondents to the questionnaire with the remaining 43% inconclusive (Table 32). These determinands have been indicative of water quality deterioration in some water authority catchments (Table 30), and both are mandatory EEC criteria for waters used in potable water supply (Section 7.5).

Both determinands have a significant influence on the potential use of a water body (Section 7.6), and were therefore included within the index.

Polyaromatic hydrocarbons (PAHs) have a significant influence upon potential water use and are known to indicate water quality change within one authority's catchment area (Table 30). The results from the questionnaire study indicate that 29% of respondents agreed to the inclusion of this determinand within the index, 14% disagreed and 57% of respondents were inconclusive. Thus PAH, which is a mandatory EEC (1975) criterion for waters used in potable water supply, was selected as a determinand for inclusion within the sub-index of toxicity.

Neither copper nor zinc constitute a health hazard to humans even when found in high concentrations in waters used in potable water supply. However, both impart an objectionable taste to drinking water (7.6.20 and 7.6.26). For this reason both have been ascribed mandatory criteria by the EEC (1975) for waters used for the abstraction of drinking water (Table 26).

Both these determinands are toxic to fish and guidelines on the permissible concentrations of these determinands have been produced by EIFAC (1973b and 1976).

The results from the questionnaire on the inclusion of copper and zinc within the index were identical - 43% of respondents agreed with their inclusion, 14% disagreed, and 43% were inconclusive.

In view of the importance of these determinands to fish and wildlife populations both determinands were included within the proposed sub-index of toxicity.

Nickel is relatively non-toxic to man, but can be detrimental to the survival of fish and wildlife. However, nickel has most commonly been included within indices and water quality monitoring programmes designed to assist in the management of surface waters used for spray irrigation (Tables 23 to 26).

On completion of the questionnaire, nickel was selected as a secondary determinand by the water authority members. The results were as follows: 42% agreed to its inclusion, 29% disagreed and 29% were inconclusive (Table 32). However, unlike other secondary determinands selected in this way, nickel has neither EEC nor EIFAC mandatory or guideline criteria for waters intended for either potable water supply or fisheries purposes. In addition, nickel is not considered as a problem by any of the water authority officials questioned. Consequently, nickel was excluded from the proposed sub-index of toxicity.

Arsenic is undesirable in potable water supplies and is toxic to fish (Section 7.6.22). However, it is not considered to be a widespread pollutant in this country, its effects being limited to only one water authority. Arsenic was not selected as either a primary or secondary determinand by water authority members on completion of the questionnaire study (Tables 32 and 33). However, it does have a mandatory EEC criterion for waters used in potable water supply and recommended limits have been proposed by the Water Research Centre (WRC, 1984) for the protection of fish and wildlife populations. These recommendations have been adopted by the DoE in the monitoring of surface water quality in Britain. Therefore, arsenic was included within the index, mainly on the basis of these criteria.

Boron is not generally considered to be either toxic to human or aquatic life in the concentrations found in this country. Boron was not selected as either a primary or secondary determinand by the water authority members who completed the questionnaire study. The results of the questionnaire were as follows: 29% agreed, 42% disagreed and 29% of respondents were inconclusive (Table 32). In addition, boron has neither mandatory EEC (1975) criteria for waters intended for drinking water abstraction, nor EIFAC guidelines for the protection of commercial fisheries. Thus, although boron is of importance to waters used in spray irrigation, it was not included within the proposed sub-index of toxicity.

Chromium was regularly included within water quality indices and monitoring programmes designed for application to waters used for spray irrigation (Tables 23 to 26). However, chromium is not known to cause significant changes to the quality of water within any of the water authority catchment areas. It was not initially suggested for inclusion within the proposed index by water authority officials. However, one respondent to the questionnaire did consider chromium worth adding to the list of potential determinands.

Chromium is potentially toxic to both human and aquatic life (Section 7.6.28), thus mandatory and guideline criteria have been proposed by the EEC and EIFAC (1983) to safeguard the use of water in potable water supply and for the protection of fisheries. Thus chromium was selected for inclusion within the sub-index of toxicity.

Finally, two determinands - barium and selenium - qualified for inclusion within the proposed sub-index of toxicity on the basis of the EEC Directive on the Quality of Waters used for Drinking

Water Abstractions (1975). However, neither of these determinands is considered to be important to the management of surface water quality in Britain. So much so, that neither is monitored by all ten water authorities and those that do monitor these determinands, do so on a very restricted basis. Hence, these determinands were excluded from the proposed sub-index of toxicity.

7.7.4. Summary of the Determinands Selected for Inclusion Within the Sub Index of Toxicity

Although the concentration of many of the determinands selected for inclusion within the sub-index of toxicity, and listed in Table 36, seldom reach a level at which they become toxic to human or aquatic life, they must be included within this sub-index because of their dramatic effect on water use when these levels are attained.

Table 36. Determinands selected for inclusion within the Sub Index of Toxicity

Phenols	Pesticides
Hydrocarbons	Mercury
Cadmium	P.A.Hs
Lead	Copper
Cyanide	Zinc
Chromium	Arsenic

Toxics have not previously been directly integrated within a general water quality index, even though the effect of toxics may eradicate a good water quality rating produced from the consideration of only routine water quality determinands.

7.8. SUMMARY

Six selection criteria were employed to assist in the selection of determinands for inclusion within the proposed index. The index was divided into two sub-indices: the WQI sub-index designed for general application; and a sub-index of toxicity to be used as deemed necessary. Nine primary and four special determinands were selected for inclusion within the former sub-index, and twelve determinands were selected for inclusion within the latter.

Although a total of twenty-five determinands has been selected for inclusion within the index, the majority of sites will only require the index calculation to be based on the nine primary determinands of the WQI sub-index.

By examining water quality data from a variety of geographical and industrially developed areas and from sites with a range of water use, it is possible that these lists of determinands may be either reduced or increased further at a later date.

As both sub-indices have now acquired independent and definable characteristics, each can now be re-defined as an index in its own right. Thus, in effect, the basis of two separate indices has been established. They have, therefore, been named the General Water Quality Index (WQI) and General Toxicity Index (GTI). Each index will be further developed independently. However, it must again be emphasised that a complete assessment of water quality can only be achieved by applying both indices at every site, although this would be dependent upon the data available.

Having defined the determinands to be included within the proposed indices, it is possible to proceed with the development of determinand transformations.

CHAPTER 8

DETERMINAND TRANSFORMATIONS

8.1. INTRODUCTION

Determinand transformations are essential to the development of a water quality index because they are a means of relating each determinand concentration to the same scale. Thus, data collected in a variety of units can be meaningfully aggregated to produce a final index score. In developing these transforms, it is important to provide the maximum amount of information possible to the user.

Thus, a number of important points must be considered in the development of determinand transformations. These can be summarised as follows:

i) the transforms must be developed as objectively as possible;

ii) they must be easy to interpret;

iii) they must be sensitive to changes in water quality;

iv) they must include information on legal standards or mandatory criteria;

v) they should agree with expert opinion; and

vi) they must include information on possible water use.

Consequently there are four main stages involved in the development of determinand transforms:

a) a decision must be made upon the form the transformations are to take;

b) the scales over which water quality can be displayed must be selected;

c) these scales must be defined in terms of both water quality and potential use; and

d) easy interpretation must be facilitated.

The WQI determinands for which transforms are to be developed have been divided into two main groups:

- the nine primary determinands which were selected because they are indicative of water quality change and influence a variety of possible water uses;

- and the 'special' determinands which were selected because of their importance to potable water supply (PWS).

The latter determinands are only to be included within the index calculation where this use, or other uses requiring similarly high quality water, is under investigation. This poses a problem in the development of determinand transforms for the thirteen WQI determinands. The index scale selected for the nine primary determinands will be sub-divided so as to reflect general water quality covering a variety of potential uses. However, the subdivisions of the index scale for the four 'special' determinands has to be biassed towards the use of water in PWS.

It is probable, therefore, that the two sets of curves will be incompatible. Thus, it is necessary to construct an additional set of determinand transforms for the nine primary determinands with the single management objective of PWS in mind.

Hence, it is necessary to move away from the concept of developing one general water quality index, to a situation in which an additional index - the Potable Water Supply Index (PWSI) - will be developed for application to watercourses for which PWS is the singular management objective.

Similar problems arose in the development of determinand transforms for the General Toxicity Index (GTI) determinands. These determinands are potentially lethal to human or aquatic life, or both. However, they are not equally toxic and their toxicity is different when considered from the point of view of their effect on human as opposed to aquatic life. For example, copper and zinc are toxic in low concentrations to aquatic life whereas those same concentrations would have no discernible effect on humans. Because of these differences in toxicity, it would be impractical to include all the determinands in a single GTI which was classified according to potential water use.

Thus, it was decided to create two parallel indices using the same determinands. The first of these, the Aquatic Toxicity Index (ATI), will reflect the suitability of a water body to support fish and wildlife populations and provide a general indication of amenity value. This index will not contain information on the suitability of a water body for use in PWS, but will be capable of reflecting general toxic quality in terms of most other water uses. The second will be known as the Potable Sapidity Index (PSI), and will reflect the suitability of a water body for use in PWS. This cannot strictly be called an index of toxicity, because not all of the determinands selected for inclusion within the GTI are toxic to man. However, those determinands which are not toxic, eg copper and zinc, impart an objectionable taste to drinking waters, as do many of the other more toxic determinands (Section 7.6.). Thus, the index has been named the Potable Sapidity Index, sapidity being defined for the purpose of this research as pertaining to taste, colour and wholesomeness, with the last being reflected in terms of toxicity. Each of these indices may be used independently or in combination with either the WQI or PWSI as deemed necessary by the user.

Although the initial aim of this research was to develop a single, general water quality index for use in the operational management of surface water quality, an additional index for waters used in PWS will be developed, (PWSI). Each index will have its own index of toxicity, the ATI and PSI respectively, to be applied where it is considered appropriate.

8.2. THE DEVELOPMENT OF DETERMINAND TRANSFORMS

8.2.1. The Selection of Determinand Transforms

Within the construction of previously developed water quality indices, the methods of transforming individual determinand concentrations to the same scale have been of two main types: the production of rating curves/tables, or the statistical calculation of the deviation of each determinand concentration from a previously selected standard. The statistical approach to the production of transforms was adopted by Shoji et al (1966), Harkins (1974), Schaeffer and Janardan (1977) and Joung et al (1979). Although more objective than methods used for the development of either rating curves or tables, they are difficult to use and interpret (see Section 4.2.). Consequently, this approach to the further development of the proposed indices was rejected.

Various methods of rating curve construction have been previously developed (see Section 4.2.). These include a DELPHI technique where the rating curves produced by a number of experts were averaged to generate mean curves for each determinand (NSF, 1970; 1972). An alternative approach was the extrapolation of a curve based on two or three selected points derived by reference to published standards or criteria (Dunnette, 1979). A combination of these two techniques was used by the Scottish Development Department (SDD, 1976) in the development of their index. Other workers (Horton, 1965; Prati et al, 1971; McDuffie and Haney, 1973; Dinius, 1972; Dee et al, 1973; Walski and Parker, 1974; Stoner, 1978; and Nemerow and Sumitomo, 1970) applied appropriate mathematical functions to individual determinands to produce their rating curves. These were of four main types:

i) segmented linear functions (Horton, 1965; Nemerow and Sumitomo, 1970);

ii) segmented non-linear functions (Prati et al, 1971);

iii) linear functions (McDuffie and Haney, 1973); and

iv) non-linear functions (Dinius, 1972; Walski and Parker 1974; and Stoner, 1978).

Although the use of mathematical functions is, arguably, a more objective approach than many of the statistical or DELPHI approaches in applying an index score to individual determinand concentrations, the shape of the curve is determined by the type of function selected. This is essentially a subjective decision made by the author(s). In addition, no information on guidelines, legal water quality standards or criteria can be included within the rating curves produced. Such curves would also be difficult to interpret in terms of potential water use (see Section 4.3.).

The development of mean curves from those produced by a number of water quality experts (NSF 1970; SDD 1976) would, in the final analysis, be more objective than the use of mathematical functions. However, information on water quality standards and criteria would again be omitted. This often resulted in criticism, particularly in respect of the lower end of the quality scale, which is often considered as being too severe (Anglian and Yorkshire Water Authority Internal Reports, 1978 and Section 5.6.). Therefore, it is essential to include such information within an index and also relate sub-divisions of the index scale to potential water use. This would clarify water quality conditions at any particular point on the rating curve, as well as yield the maximum amount of information to the user.

It was therefore decided to construct the rating curves for the proposed indices in a manner similar to that of Dunnette (1979). By using use-related water quality standards and criteria as the basis for the development of the proposed curve, the index scores produced will reflect not only water quality, but potential water use. An index score derived from such curves can be used to indicate the economic value of a watercourse, or the potential gain/loss in value resulting from a change in water quality. 'Value' can therefore be assessed in terms of potential use and the cost of maintaining that use, defined as the cost of treatment. Both of these may increase or decrease with a change in water quality.

Therefore, the selected index scales have been sub-divided so as to reflect the possible water uses associated with different levels of water quality, and the recommended standards found within the literature for these different water uses will be applied to the index sub-divisions.

Directives, guidelines and criteria produced by the EEC (1975; 1978; 1980), EIFAC (1964 to 1983), World Health Organization (WHO 1963; 1970; 1971), the US Environmental Protection Agency (USEPA, 1972; 1979) the Ontario Water Resources Commission (Ontario WRC, 1970) and the Water Research Centre (1984) have been considered in the development of these rating curves. Additional recommendations, resulting from intensive studies of British watercourses, have also been considered where appropriate (eg The Bedford Ouse Study, 1979; the work of Price and Pearson, 1979) (Appendices II and III).

Using the above recommendations, as many points as possible equating determinand concentrations to index ratings have been plotted. The final curves were then drawn using a line plotter computer program. Although not completely objective, the final index scores produced for a water body conform to what have now become legal standards for various water uses, rather than being a subjective assessment of water quality based on curves developed by a group water quality experts.

8.2.2. The Selection of Appropriate Index Scales

The first stage in the actual development of the rating curves was the selection of appropriate index scales.

The range of index scales which have been used previously within water quality indices vary between -100+ to 100+ (Stoner, 1978), and zero to 1000+ (McDuffie and Haney, 1973). The adoption of either of these extremes, or many of the intermediate scales, makes any final index score produced difficult to interpret (see Section 4.3.).

The index range selected for the proposed WQI is the same as that proposed by Dunnette (1979) i.e. 10-100. A score of 10 equates water to crude sewage with navigation, coke quenching and effluent transport as the only potential water uses, whereas a score of 100 indicates water of pristine purity suitable for all potential uses. A score of 10 was selected as the base for the WQI in preference to zero because this index considers all potential water uses and economic objectives. Thus, although a water body may be very severely polluted, it still possesses an intrinsic economic value as a form of transportation and therefore should not be zero rated. It was also considered that no additional managerial information could be provided by extending the WQI scale from 10 to zero. Apart from potential use, which would remain the same, the only other information provided would be an assessment of the cost of upgrading such waters. In most instances, water attaining a score of 10 will already require advanced treatment. Thus, the additional upgrading costs resulting from any further deterioration in quality would be marginal and, therefore, do not merit the index range being extended to zero. This, then, is the practical limit for this index. The only other reason for extending the index range to zero would be for the mathematical completeness of a 0 to 100 range, and as explained above, in this instance it is not considered necessary.

However, a scale of zero to 100 has been selected for the PWSI. Here, a zero score equates water to crude sewage and indicates that such waters are totally unsuitable for use in PWS, even though they may have an inherent economic value for an alternative or navigational use. A score of 100 indicates water of excellent quality which can be used in PWS without treatment apart from mandatory disinfection. It was considered necessary to extend the PWSI to zero because of the potentially toxic effects of certain determinands occurring in concentrations in excess of recommended limits. Thus, such waters would be totally unacceptable for their management purpose and, therefore, of no economic value, except at high cost.

Index scales which ranged to 100 were selected in both instances because they are broad enough to allow an adequate description of all water quality conditions and potential uses, but still allow the detection of subtle changes which may occur in the quality of a water body. Much valuable information or emphasis may be lost with an index scale either smaller or greater than this (see Section 4.3.). For example, where an index scale extends to several hundreds (McDuffie and Haney, 1973), interpretation of the index becomes very complex. However, where the index scale is reduced to 0-10 (Ross, 1977), it is difficult to emphasise the importance of changes within the index and small, but significant changes, may be overlooked. This has been shown by Bolton et al (1978) who demonstrated that a change of five points on the 0-100 SDD (1976) index scale can indicate a significant change in water quality. Similarly, House and Ellis (1980), illustrated the managerial advantages of such a scale when applying the SDD index to a selection of London's watercourses (see Chapter 6).

However, in selecting an appropriate scale for the Potable Sapidity and Aquatic Toxicity Indices, it was decided that information on 'limited' or 'subtle' changes in the level of toxicity or impairment was unnecessary. It is contended that only an indication of the degree of toxicity is required. Thus a scale of zero to 10 was adopted for both indices of toxicity. It was thought essential to lower the base of these indices to zero because of the potentially lethal effects that toxic determinands may have. Thus, a zero score indicates waters which are toxic and therefore a potential danger to either human or aquatic life. A score of 10 indicates water which is free of toxic substances and ideally suited to its management purpose.

8.2.3. The Definition of Index Scales

With the index scales defined it was next necessary to produce interpretations and threshold sub-divisions for these scales relating specific water quality conditions to potential water use, thus facilitating the development of the rating curves using legislative criteria (see Section 8.2.).

In setting the threshold values, it was decided to review existing indices and classifications. A major criticism of the SDD index is that it is too biased towards clean rivers; 60% of the index scale relating to waters of reasonably good quality. Many of the individual determinand curves were considered by the Anglian and Yorkshire Water Authorities (Internal Reports, 1978), as being too severe for application to many of the more polluted rivers within their catchments. For example, the concentrations of nitrates, phosphates and ammonia found in many of the rivers within the two water authority areas were often rated at, or close to zero, according to the SDD curves. Although these rivers undoubtedly suffer from pollution, they are not considered by the authorities to be of such poor quality as to be zero-rated (see Section 5.6.). Thus, these waters still have a substantial economic value as a resource. This tendency of the SDD index to underestimate the value of water at the lower end of the quality scale was confirmed by House and Ellis (1980). In the same study it was also found that the pollution index of Ross (1977) had a tendency to over-estimate water quality throughout the index range (Chapter 6). An additional criticism of both these indices has been that neither gives any indication of potential water use (Anglian and Yorkshire Water Authorities, Internal Reports, 1978).

The NWC classification (1978) is the most recent classification of surface waters to be developed within the UK. This approach considers both water quality and potential water use and incorporates EEC and EIFAC directives within its format. Most water authority members were satisfied with the content and aims of the classification, but admitted to finding it difficult to use. This was because a subjective decision had to be made on the quality of a water body from an extensive list of determinand concentrations.

Therefore, all the above factors needed to be considered and evaluated in developing a methodology for rating curves for use in the proposed indices.

With these factors in mind, the index scales were sub-divided as outlined in Tables 37 to 40. Each sub-division of the index scales consists of both a description of the water quality equated to that range and, secondly, relates that range to a list of potential water uses. In this way, the index sub-divisions can also allow the assessment of the economic value of a particular water body, or the loss/gain in value resulting from its degradation or improvement. In addition, some idea of the costs involved in exploiting a water body for a specific use can be applied to each sub-division.

8.2.4. The Classification of the Index Scales

From Figure 6 which displays all potential uses to which the WQI relates, (an approach first used by Dinius (1972)), it is evident that the WQI scale can be reduced to four main sub-divisions, or classes, of water quality as follows:

i) Class I (71-100) indicates water of high quality suitable for all high value uses at low cost;

ii) Class II (51-70) indicates waters of reasonable quality suitable for high value uses at moderate costs;

iii) Class III (31-50) indicates polluted waters with generally moderate value uses and high treatment costs;

iv) Class IV (10-30) indicates badly polluted waters of low economic value requiring a large investment in treatment facilities if they are to be upgraded.

By reducing the index scale in his way, the user can not only assess the economic value of a watercourse and its potential use, but also monitor any fluctuations in quality which occur either within the same class or between classes.

Similarly, from Figure 7 it can be seen that it is possible to reduce the PWSI scale to the same four classes of water quality. In this instance Classes I, II and III indicate water suitable for use in PWS after varying degrees of treatment. Thus, the cost of using water in PWS will increase as the index score decreases, but the economic value of the water will decrease with a decrease in the index score.

Class IV of the PWSI ranges from zero to 30 and indicates waters which are unsuitable for use within PWS without very high capital investment. However, where a score towards the upper end of this class range is achieved, such waters, although undesirable for use in PWS, are likely to be of some economic value. Waters

Table 37. Interpretation of the 10 - 100 Index Scale for the General Water Quality Index (WQI)

Index Score	Quality	Potential Water Use
91-100	Excellent	Water can be used in PWS and selected industrial or agricultural uses without treatment except for mandatory disinfection. Water suitable for all species of fish and all recreational activities. Restricted navigation.
71-90	Very good	Minor purification *necessary for waters used in PWS and for industries requiring high quality water. Water suitable for all fish species, agricultural uses and recreational purposes. Restricted navigation.
61-70	Good	Conventional treatment** required for waters used in PWS. No treatment necessary for some industrial uses, although treatment required for waters used in industrial processes. Quality becoming marginal for trout and other high class game fish. Acceptable for all recreational uses.
51-60	Slightly Polluted	Conventional treatment** required for waters used in PWS. No, or little treatment required for some industrial uses. Water capable of supporting good coarse fish populations, but of very doubtful quality for the survival of sensitive fish species. Aesthetically becoming polluted but still suitable for most recreational purposes, but of doubtful quality for direct contact sports (a).
41-50	Slight - Moderate Pollution	Advanced treatment*** required for water used in PWS, most industrial and agricultural uses. Only suitable for indirect contact recreation (b). Reasonably good coarse fish populations would be expected.
31-40	Moderate - Heavy Pollution	Not suitable for PWS. Advanced treatment required for most industrial and agricultural uses. Indirect contact recreation only. Unsuitable for most species of fish with only the sporadic occurrence of tolerant fish species. Acceptable for navigation.
21-30	Heavy Pollution	Low value uses only. Industrial uses requiring only very poor quality water, non-contact recreation (c) and navigation.
10-20	Gross Pollution	Aesthetically unpleasant, for use in navigation only.

Footnote:

*	Minor purification	- simple physical treatment and disinfection (EEC A1, 1975).
**	Conventional treatment	- normal physical treatment, chemical treatment and disinfection (EEC A2, 1975).
***	Advanced treatment	- intensive physical and chemical treatment (EEC A3, 1975).
(a)	Direct contact sports	- swimming and water skiing
(b)	Indirect contact uses	- fishing, sailing
(c)	Non contact uses	- aesthetic, picnicking and visits to the area.

Table 38. Interpretation of the 0 - 100 Index Scale for the Potable Water Supply Index (PWSI)

Index Score	Quality	Suitability for Use
91-100	Excellent	Water can be used in PWS without treatment apart from mandatory disinfection
71-90	Very Good	Water can be used in PWS after minor purification*
51-70	Reasonable	These waters require conventional treatment** before use in PWS
31-50	Polluted	Advanced treatment*** is required before such waters can be used in PWS
11-30	Heavily Polluted	It is very doubtful whether such waters would be suitable for use in PWS. However, these waters may still be acceptable for alternate uses, eg coarse fisheries some industrial and recreational uses and possibly for blending with high quality waters during stress periods eg drought
0-10	Grossly Polluted	Water must not be used in PWS, and are unlikely to be of any economic value apart from navigation

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Footnote. * ** *** See Footnote Table 37.

Table 39. Interpretation of the 0 - 10 Index Scale for the Aquatic Toxicity Index (ATI)

Index Score	Water Quality	Potential Water Use
6.1 to 10	Excellent to Reasonable	Water of high amenity value including direct contact sports (a). Protection afforded to all fish species including game fish (salmon, trout, grayling and white fish).
2.1 to 6.0	Reasonable to obviously polluted	Water of moderate to low amenity value (indirect contact uses (b)). Doubtful for game fish populations except in cases of short-term migratory passage. Good protection afforded to coarse fish species (carp, pike, perch and eel).
0 to 2.0	Severe to Grossly Polluted	Water of very low amenity value (non-contact uses (c)). Of doubtful quality for the protection of fish and wild life. However, such water may offer an alternative economic value

(a) Direct contact sports - swimming and water skiing

(b) Indirect contact uses - fishing and sailing

(c) Non contact uses - aesthetic, picnicking and visits to the area

Table 40. Interpretation of the 0-10 Index Scale for The Potable Sapidity Index (PSI)

Index Score	Water Quality	Potential Water Use
7.1 to 10	Very Good	Water which can be used in potable water supply after only minor purification.*
4.1 to 7.0	Good to Slightly Polluted	Water which requires at least conventional treatment** before use in potable water supply.
1.1 to 4.0	Polluted to Obviously Polluted	Water which requires advanced treatment*** before use in potable water supply.
0 to 1.0	Grossly Polluted	Water which is of doubtful quality for use in potable water supply. However, this water _may_ be suitable for some alternative uses.

Footnote:

* Minor Purification - simple physical treatment and disinfection (EEC, A1, 1975).

** Conventional Treatment - normal physical and chemical treatment, plus disinfection (EEC, A2, 1975).

*** Advanced Treatment - intensive physical and chemical treatment plus disinfection (EEC, A3, 1975).

within the last ten points on the scale are likely to be too toxic for their intended management objective and will only be of use for navigation and effluent transport. Thus, for the purpose of this index they will have no economic value. It was decided to include this information within the index range because many of the standards and criteria available for the individual determinands are guidelines and not mandatory. Thus, although unlikely, it may be possible that waters with a low index score (10-30) can be used for PWS, depending upon the type of treatment locally available. On the other hand, if the management objective for a particular river is that it should be used for PWS, the effect of restorative management strategies may be monitored.

Figure 8 shows that both the ATI and PSI can be reduced respectively to three and four main classes of water quality named A1 to A3 and P1 - P4. In each case the lowest class indicates waters which are of doubtful to unacceptable quality for their intended management purpose. When either index is used independently or in combination with one of the routine indices, the results may be presented in either a numerical fashion where precision is required, or by class notations only. For example a water said to be Class IA3 would be one which is rated as excellent and suitable for all possible uses according to the WQI, but would be unsuitable for fisheries purposes due to high toxic concentrations particularly in the longer term. Under such circumstances the rating for the toxicity index would nullify that provided by the general WQI.

By classifying the index scales in this way information of a general type can be made available for management at the Directorate level, yet the detailed information remains available for use in operational management.

Figure 6. Sub-Divisions of the 10 - 100 General Water Quality Index Scale

Use Score	PWS	FAWL	INDUSTRY	RECREATION	SEWAGE TRANSPORT AND NAVIGATION
100	No treatment required		Selected uses without treatment		
90		Suitable for all species of fish and wildlife			
80	Minor Purification only		Minor purification if high quality water required	Suitable for all recreational activities	Possible Restrictions
70					
		Doubtful for game fish. Supports good populations of coarse fish			
60	Conventional treatment		No treatment for most uses		Completely Acceptable
				Doubtful for direct contact sports	
50					
	Advanced treatment	Reasonable-coarse fisheries	Advanced treatment required for most uses	Indirect and non contact activities only	
40					
	Doubtful use	Tolerant species only			
30			Only industries needing poor quality water	Non-contact uses only	
20					
	Unacceptable	Unacceptable	Unacceptable	Unacceptable	
10					

N.B. * Fish and Wildlife

Figure 7. Sub-Divisions of the 0-100 Potable Water Supply Index Scale

100	
	Disinfection Only
90	
80	Minor Purification*
70	
60	Conventional Treatment**
50	
40	Advanced Treatment***
30	
20	Not Acceptable
10	
0	

Footnote: * ** *** see footnotes to Table 37.

Figure 8. Classification of the 0 - 10 Index Scales of the PSI and ATI

Class	Potable Sapidity Index	Index	Aquatic Toxicity Index	Class
P1		10	High Amenity Value	A1
	Minor	9	High Class Game	
	Purification *	8	Fisheries	
		7		
P2	Conventional	6	Doubtful for more sensitive species	
	Treatment **	5	Good/Moderate Amenity Value	A2
		4	Good Coarse Fisheries	
P3	Advanced	3		
	Treatment ***	2	Doubtful for more sensitive species	
		1	Very doubtful for fish Low amenity value	A3
P4	Very Doubtful			
	Unacceptable except for navigation and cooling	0	Unacceptable except for migration, navigation + cooling	

Footnote: * ** *** see footnotes to Table 37.

Therefore, having decided upon the form and method of construction as well as the scale the determinand transforms were to take and, having defined the index scales selected, it was possible to proceed with the development of the individual determinand curves.

8.3. THE DEVELOPMENT OF RATING CURVES FOR THE GENERAL WATER QUALITY INDEX (WQI)

8.3.1. Introduction

It must be emphasised that the main aim of this index is to reflect general water quality. The potential use indicated by the threshold scores should not be considered as definitive, but merely as an indication of possible use. The interpretation of the index in this way will be of value in terms of management flexibility.

The WQI range outlined in Table 37 and Figure 6 is intended to provide more information than previously developed indices or classifications on the use and potential value of both polluted and clean watercourses alike.

The general approach adopted in the development of the rating curves was to apply the lower threshold values for a particular use (as outlined in Table 37 and Figure 6), to mandatory or maximum permissible (MP) concentrations as defined by the EEC and WHO respectively. Where directives are given in the form of guidelines or maximum desirable concentrations (MD), a median value between the upper and lower threshold limits for that use was given. In this way the rating curves could:

i) reflect waters which are ideally suited to a particular use;

ii) indicate those which are of reasonable quality for the same use; and

iii) show those which are of dubious quality for that use and which require careful monitoring.

Thus, waters which are well within the guidelines for use in PWS with only conventional treatment would receive a water quality rating (WQR) of 70; those which display guideline concentrations would have a WQR of 60; and those with mandatory or MP concentrations would be given a WQR of 50 (see Table 37 and Fig.6).

In applying the above criteria to waters used for fisheries purposes, it was recognised that fish often survive where determinand concentrations exceed mandatory and MP directives. For this reason, the threshold values for both game and coarse fisheries were lowered by ten points to WQRs of 60 and 30 respectively. However, these values relate to sporadic populations only. Thus, mandatory and MP criteria were applied to the higher threshold values of 70 and 40 respectively, because these reflect the existence of permanent, healthy fish populations.

Finally, in developing the rating curves for ammoniacal nitrogen (Amm. nitrogen), nitrates and chlorides, large variations were found between the recommended criteria for the protection of fish and the use of water in PWS. For example, an Amm. nitrogen concentration of 1 mgl^{-1} is a mandatory EEC criterion for the protection of fisheries. Concentrations beyond this level are known to be toxic to fish, but would be suitable for use in PWS after only conventional treatment. A WQR of 40 was given to this Amm. nitrogen concentration, thus applying the mandatory criteria to the threshold value for healthy fisheries, but making the curve biased towards the use of water for fisheries purposes. Similarly, the curves for nitrates and chlorides became biassed towards the use of water in PWS. This can be justified in a number of ways:

i) the index curves are primarily reflecting water quality and not potential water use. The determinand concentrations under review indicate a deterioration in water quality and therefore a loss in economic value;

ii) similarly a water body which can only be put to a limited number of potential uses will be of less economic value than one which offers the full range of potential uses; and

iii) bias only affects a small section of each determinand curve and it is unlikely that a WQR from one curve would reduce the overall index score substantially if all other determinands indicate an ideal quality for a particular use.

Figures 9 to 17 show the rating curves developed for the nine WQI determinands on the basis of the sub-divisions of the WQI range (Figure 6) and the use of published criteria (Appendix II). The rationale for the development of the individual curves is outlined below. All curves are based on 95 percentile concentrations.

8.3.2. Dissolved Oxygen (D.O. % saturation). (cf Figure 9)

Concentration (% saturation)	WQR
96-103	100
80	85
70	75
> 140	60
50	55
30	40
10	20

Rationale:

Waters with a dissolved oxygen percentage saturation of between 96% and 103% could be used for all abstractions without treatment apart from disinfection - effluent discharges temporarily supersaturated with dissolved oxygen always excepted, of course. They would support all types of fisheries and would be suitable for all contact and non-contact recreational activities. Thus, a WQR of 100 was given to this DO % saturation range.

A DO saturation of 80% is proposed as a minimum concentration for high value waters by the NWC (1978). This is also the guideline concentration proposed by the EEC (1975) for waters used for bathing. However, it is in excess of the EEC (1975) guideline for PWSs requiring minor purification and, within the guideline proposed by Price and Pearson (1979) for industries requiring high quality waters. The threshold value that each of these uses would score are WQRs of 85, 80, 90 and 85 respectively. Thus the median of these four, a WQR of 85, was allocated to this DO % saturation.

The EEC guideline concentration for waters used in PWS after minor purification is 70% DO saturation. This is also the minimum permissible concentration for industries requiring high quality abstractions (Price and Pearson 1979). These two potential uses would be given WQRs of 80 and 70 respectively, hence the median WQR of 75 was given to this DO % saturation.

Waters which are supersaturated with DO can cause problems if used in PWS and may indicate sewage pollution (see Section 7.6.1.). In addition, Price and Pearson (1979) have indicated that such waters are only suited to a limited range of industrial abstractions. Thus a WQR of 60, a median industrial use value, was ascribed to waters with a DO % saturation of 140% and above.

The EEC (1975) guideline concentration for waters used in PWS after conventional treatment is 50% DO saturation. However, Price and Pearson (1979) have suggested this as their minimum permissible value for such use. Thus, a WQR of 55, which is the median for these two criteria, was given to this DO % saturation.

Waters with a DO % saturation of 30% would be suitable for use in PWS after advanced treatment (EEC A3 guideline), and would only be of use to industries requiring low quality waters. The median threshold values for these uses are 45 and 35 respectively; thus a WQR of 40 was ascribed to this DO % saturation.

Finally, waters with a DO % saturation of 10% would be showing obvious signs of pollution. They would be of doubtful quality for industrial abstractions and suitable only for non-contact recreation. Thus a WQR of 20 was given to this DO % saturation which indicates a median Class IV watercourse.

8.3.3. Biochemical Oxygen Demand (BOD mgl^{-1}). (cf Figure 10)

Concentration (mgl^{-1})	WQR
0	100
3	80
5	60
7	40
12	20
17	10

Rationale

Waters with a zero BOD concentration would be of excellent quality and suitable for all potential uses. Thus a WQR of 100

Figure 9. Dissolved Oxygen

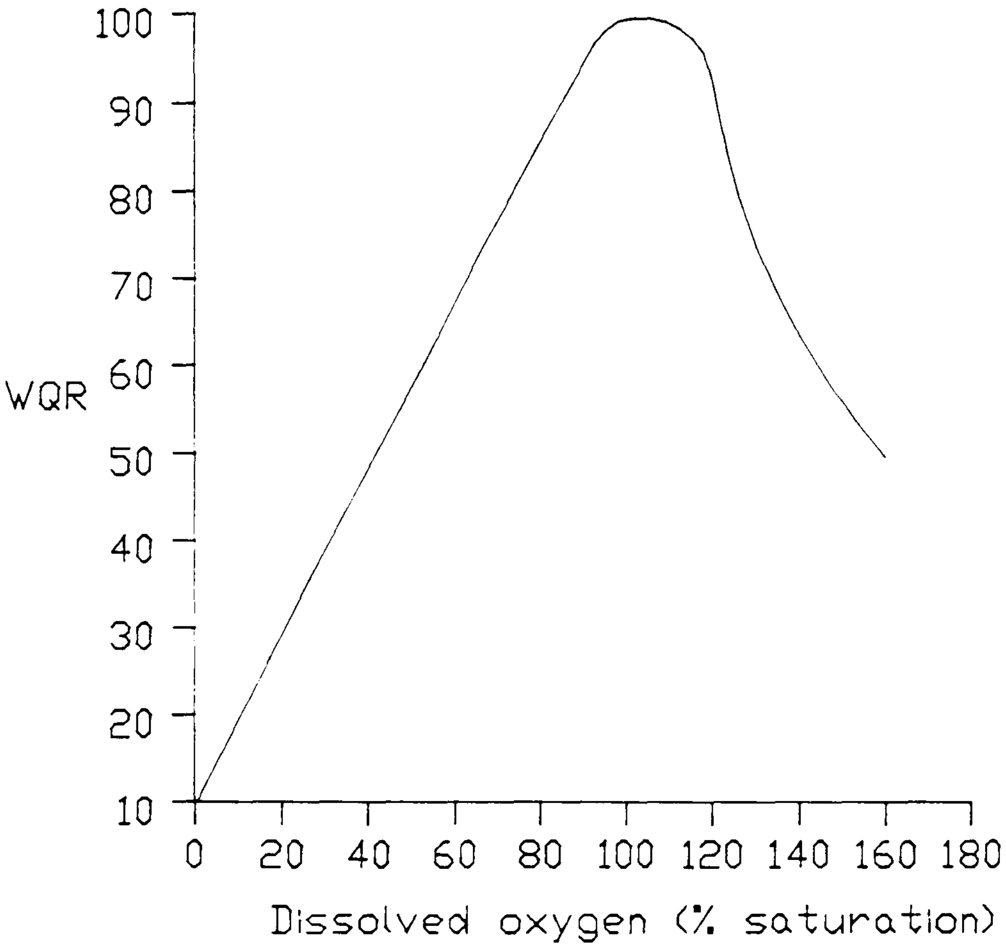
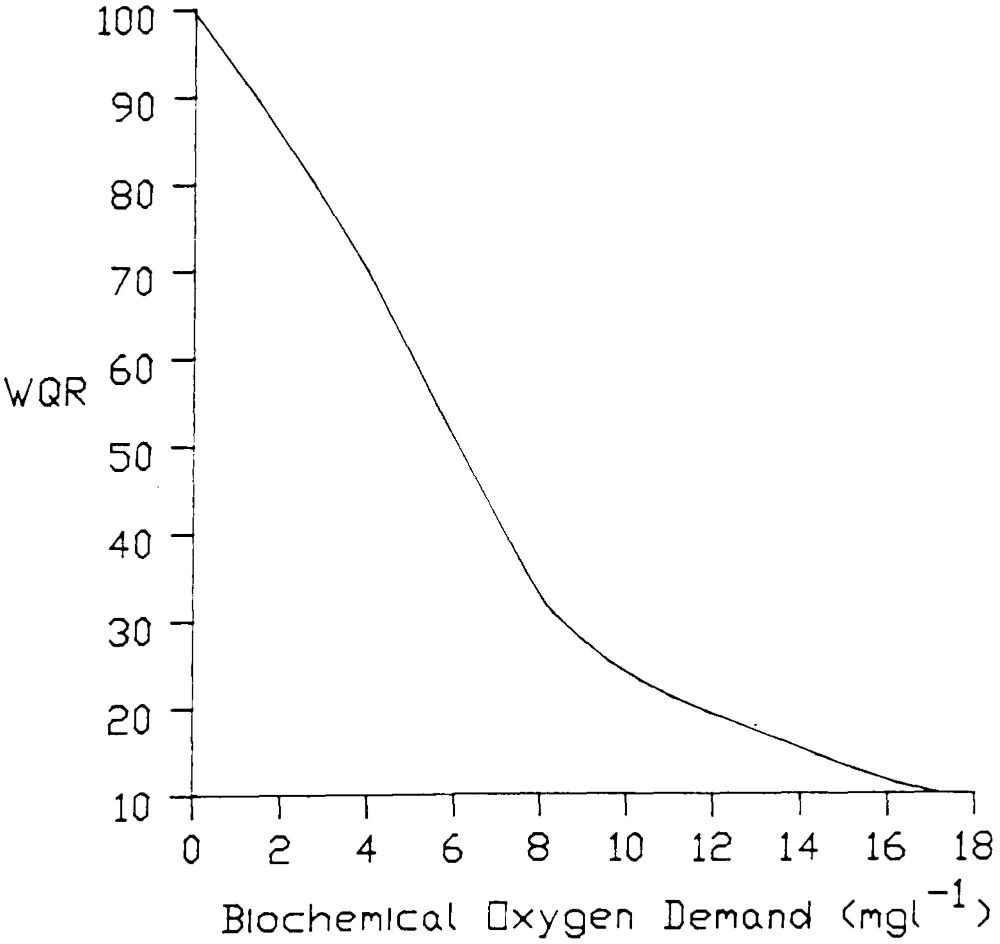


Figure 10. Biochemical Oxygen Demand



was ascribed to this concentration.

The EEC (1975) guideline concentration for water used in PWS after minor purification is 3 mgl^{-1} BOD. The same criteria were proposed for the protection of high class game fisheries. This is also the MD concentration suggested by Price and Pearson (1979) for high amenity (direct contact) water uses. The WQR for each of these water uses would be 80, 85 and 80 respectively. Thus a median WQR of 80 was given to this BOD concentration.

A MP concentration of 5 mgl^{-1} BOD was proposed by Price and Pearson for the protection of game fish. This is also the guideline concentration given by the EEC (1975) for waters used in PWS after conventional treatment. The WQR for both these uses is 60, which was therefore ascribed to this BOD concentration.

Waters with a BOD concentration of 7 mgl^{-1} could be used in PWS after advanced treatment (EEC, A3 guideline), and would be suitable for general amenity (indirect contact) purposes (MD concentration Price and Pearson, 1979). The WQR for both these uses is 45. This WQR was therefore applied to this BOD concentration.

A WQR of 20 was given to a BOD concentration of 12 mgl^{-1} as this is the MP concentration for water used for general amenity purposes (Price and Pearson, 1979).

Finally, a WQR of 10 was ascribed to BOD concentrations of 17 mgl^{-1} and above because such waters would be grossly polluted and likely to cause nuisance.

8.3.4. Ammoniacal Nitrogen (NH_4-N mgl^{-1}) (cf Figure 11).

Concentration (mgl^{-1})	WQR
0	100
0.05	85
0.23	70
1.00	40
2.00	30
5.00	20
8.00	10

Rationale

The ammonia curve presented here is based on ammoniacal nitrogen (Amm. nitrogen) concentrations as this is the form in which most water quality directives and criteria have been presented. Amm. nitrogen concentration is extremely important as an indicator of water quality because un-ionised ammonia is toxic to fish (see Section 7.6.8.). Consequently, a WQR of 100 was ascribed to zero concentrations.

An amm. nitrogen concentration of 0.05 mgl^{-1} was given a WQR of 85 as this is the guideline concentration proposed by the EEC (1975) for high quality potable water supplies. Waters with this NH_4-N concentration would be ideally suited to all other high value uses.

An amm. nitrogen concentration of 0.23 mgl^{-1} has been proposed by EIFAC (1970) as the MP for the protection of high class game fisheries. Thus a use limiting WQR of 70 was given.

Waters with an amm. nitrogen concentration of 1 mgl^{-1} would be ideally suited for use in PWS after only conventional treatment and of value for most industrial abstractions. However, this is the mandatory criterion proposed by the EEC for the protection of healthy populations of all fish species. Thus the threshold WQR for this use, 40, was applied to this NH_4-N concentration.

An amm. nitrogen concentration of 2 mgl^{-1} is indicative of waters which would be totally unsuited to the protection of fish and wildlife populations. However, such waters would be of value in PWS after advanced treatment and as an industrial abstraction where poor quality waters would suffice. The WQR for both these uses is 30. This WQR was therefore given to this NH_4-N concentration.

Waters with an amm. nitrogen concentration of 5 mgl^{-1} would only be suitable for low amenity purposes and navigation as this concentration is the MP suggested by Price and Pearson (1979) for the former. Thus, a WQR of 20 was given to this Amm. nitrogen concentration.

Finally, the curve was extrapolated to a WQR of 10 for an amm. nitrogen concentration of 8 mgl^{-1} and above. Such waters would be severely polluted and thus of very low economic value.

8.3.5. Nitrates (as N, mgl^{-1}). (cf Figure 12).

Concentration (mgl^{-1})	WQR
0	100
5.6	80
11.3	60
22.6	40
100.0	40
140.0	10

Rationale

Nitrate concentrations are of particular importance to waters used in PWS due to the occurrence of infantile methaemoglobinaemia (see Section 7.6.9.). Thus, ideally, nitrates should be absent in all watercourses and a WQR of 100 was ascribed to zero nitrate concentrations.

A nitrate concentration of 5.6 mgl^{-1} is the EEC (1975) guideline for waters used in PWS after minor purification. Thus, the median value for this use, a WQR of 80, was given to this nitrate concentration.

The EEC have proposed a nitrate as N concentration of 11.3 mgl^{-1} as the maximum permissible for waters used in PWS, regardless of the prior method of treatment. This concentration was suggested by WHO E (European Section, 1970) and Price and Pearson (1979) as the MD concentrations for waters receiving conventional treatment before use in PWS. The latter two authors suggest a MP concentration of 22.6 mgl^{-1} nitrates as N. Therefore, although waters with these nitrate concentrations would be ideally suited to practically all other potential uses, the median and threshold

Figure 11. Ammoniacal Nitrogen

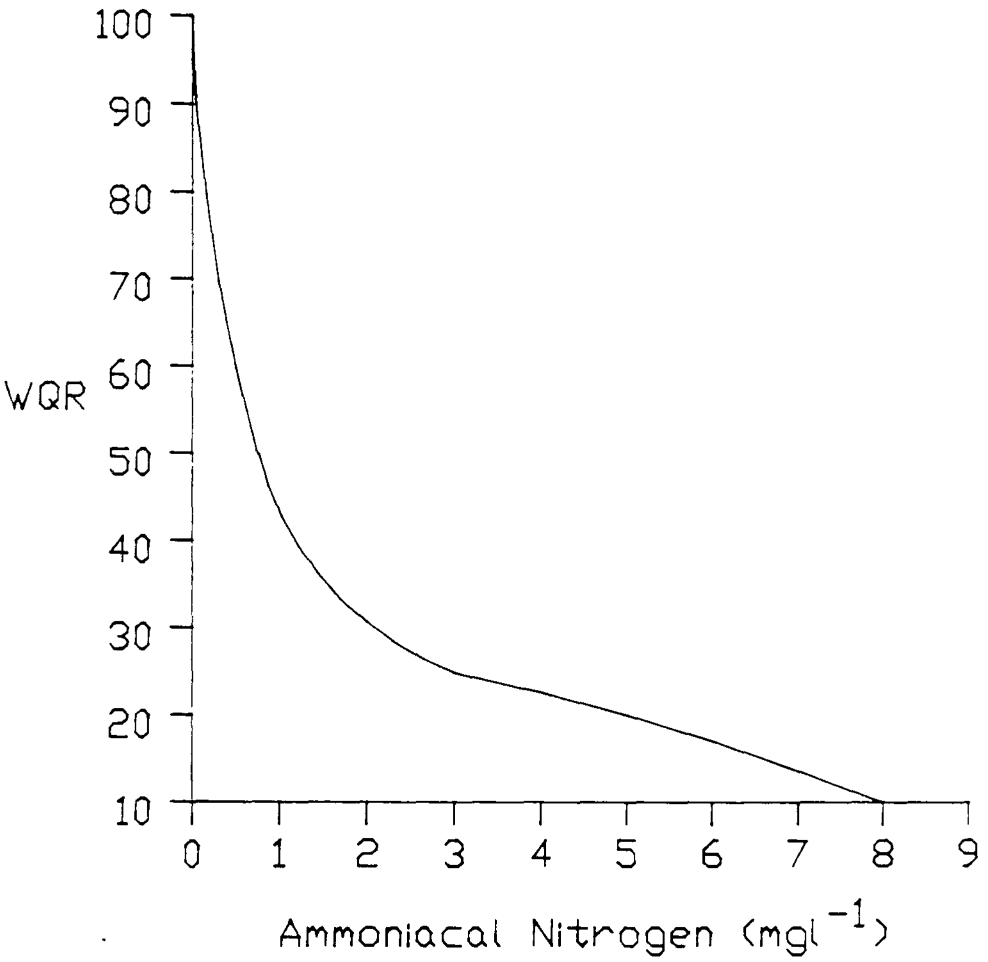
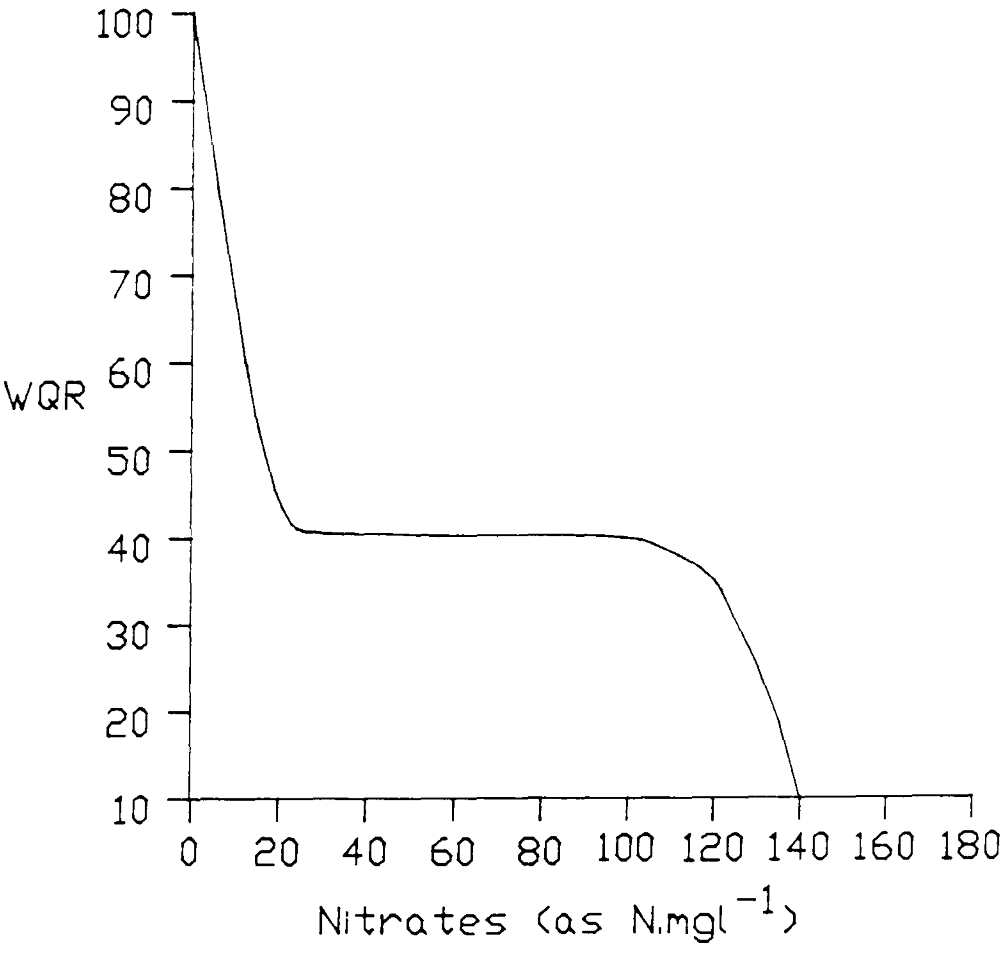


Figure 12. Nitrates



WQRs, 60 and 40, for waters to be used in PWS were ascribed to these nitrate concentrations respectively.

As nitrate concentrations of between 22.6 mgl^{-1} and 100 mgl^{-1} afford adequate protection to most other potential water uses, a WQR of 40 was given to this concentration range. The end point is defined as 100 mgl^{-1} nitrates as N as this is the MP concentration for complete protection of all fish populations (Price and Pearson, 1979).

Finally, a nitrate as N concentration of 140 mgl^{-1} and above was equated to a WQR of 10 as such levels would be indicative of obvious and severe pollution.

8.3.6. Suspended Solids (SS, mgl^{-1}). (cf Figure 13).

Concentration (mgl^{-1})	WQR
0	100
25	80
40	70
80	40
100	30
400	10

Rationale

A zero concentration of suspended solids (SS) was given a WQR of 100 as this is indicative of waters ideally suited to all potential uses.

Waters with an SS concentration of 25 mgl^{-1} would be ideally suited for use in PWS after only minor purification (EEC, 1975, A1 guideline). They would be of high amenity value suitable for direct contact uses (MD concentration, Price and Pearson, 1979), and high level protection would be afforded to high class game fisheries (EEC 1978, and EIFAC 1964, guideline concentration for game fisheries). The respective WQR's for these potential uses are 80, 80 and 85. Thus the median WQR, 80, was ascribed to this SS concentration.

A SS concentration of 40 mgl^{-1} is the MP suggested by Price and Pearson (1979) for the protection of game fisheries. Thus, a WQR of 70, the threshold value for this use, was given to this SS concentration.

EIFAC (1964) have suggested that the protection given to coarse fish populations would be reduced at a SS concentration of 80 mgl^{-1}. This agrees with Price and Pearson (1979), who suggest this concentration to be the MP for such use. Thus a WQR of 40 was given to this SS concentration.

The lower threshold value for coarse fisheries, a WQR of 30, was given to a SS concentration of 100 mgl^{-1}. This concentration is recognised by EIFAC (1964) to have various degrees of effect on fish populations. In addition, such concentrations would limit potential use to industries requiring low quality waters, in-direct contact recreation and navigation.

Finally, waters containing 400 mgl^{-1} SS and above were given a WQR of 10 because such waters would show obvious signs of pollution and be suitable for only low value uses.

8.3.7. pH. (cf Figure 14).

Units	WQR
7.2 to 7.4	100
6.5 to 8.5	80
6.0 to 9.0	60
9.5	40
5.0	35
4.0 to 10.5	10

Rationale

The water quality criteria proposed by the various authorities on the ideal pH value for different water uses vary quite considerably (see Appendix II). Consequently the curve produced is a median curve based on all the proposed standards. However, it was agreed that the ideal pH for all possible uses lies between 7.2 and 7.4 pH units. Therefore, a WQR of 100 was given to this pH range.

Waters with a pH value of 6.5 would be suitable for use in PWS (EEC 1975, A1 guideline). They would support high value game fisheries (EIFAC 1968; EPA 1972; 1976; guidelines) and would be of high amenity value (Price and Pearson (1979) guideline value). The median WQR for these three uses is 80. Thus, this WQR was given to this pH value.

Where pH values of 8.5 are recorded, water would be suitable for similar high value uses to those above (EEC, A1 guideline; EPA, guideline for game fisheries; Price and Pearson, guidelines for high amenity and industry requiring high quality water). Thus, the median WQR for these uses, 80, was given to this pH value.

Water with a pH value of 6.0 would require conventional treatment for use in PWS (Ontario Water Resources Commission, 1970). It would be marginal for use in bathing (EEC 1975 mandatory criterion) and other direct contact recreational uses (Price and Pearson, minimum permissible for high amenity). However, it would only be suitable for industry requiring moderate quality abstractions (Price and Pearson). Thus the median WQR for these uses, 60 was ascribed to this pH value.

A pH value of 9.0 is the upper value given by the above authorities for the same possible uses (EEC bathing 1975, Price and Pearson 1979, high amenity and average industrial use). In addition, this is the guideline value proposed by the EEC (1975) for PWSs requiring conventional or advanced treatment. Again the median WQR for these uses is 60, which was therefore ascribed to this pH value.

The pH values proposed by the various authorities for the protection of fisheries are very diverse and therefore difficult to use in the development of this curve. Those proposed by the EEC (1978), Train (1979) and the Ontario Water Resources Commission (1970), consider pH values of 6.0 and less, 9.0 and greater, to be harmful to all fish species. However, the US EPA (1972, 1976) and EIFAC (1968) consider these pH values as guidelines only (see appendix II). Thus, the WQRs proposed above should provide reasonable information on the possible use of water for fisheries purposes.

EIFAC, Price and Pearson, and the EPA all recommend a pH value of 9.5 as the maximum permissible for the protection of fisheries. Thus, a use limiting WQR of 40 was given to this pH value.

Figure 13. Suspended Solids

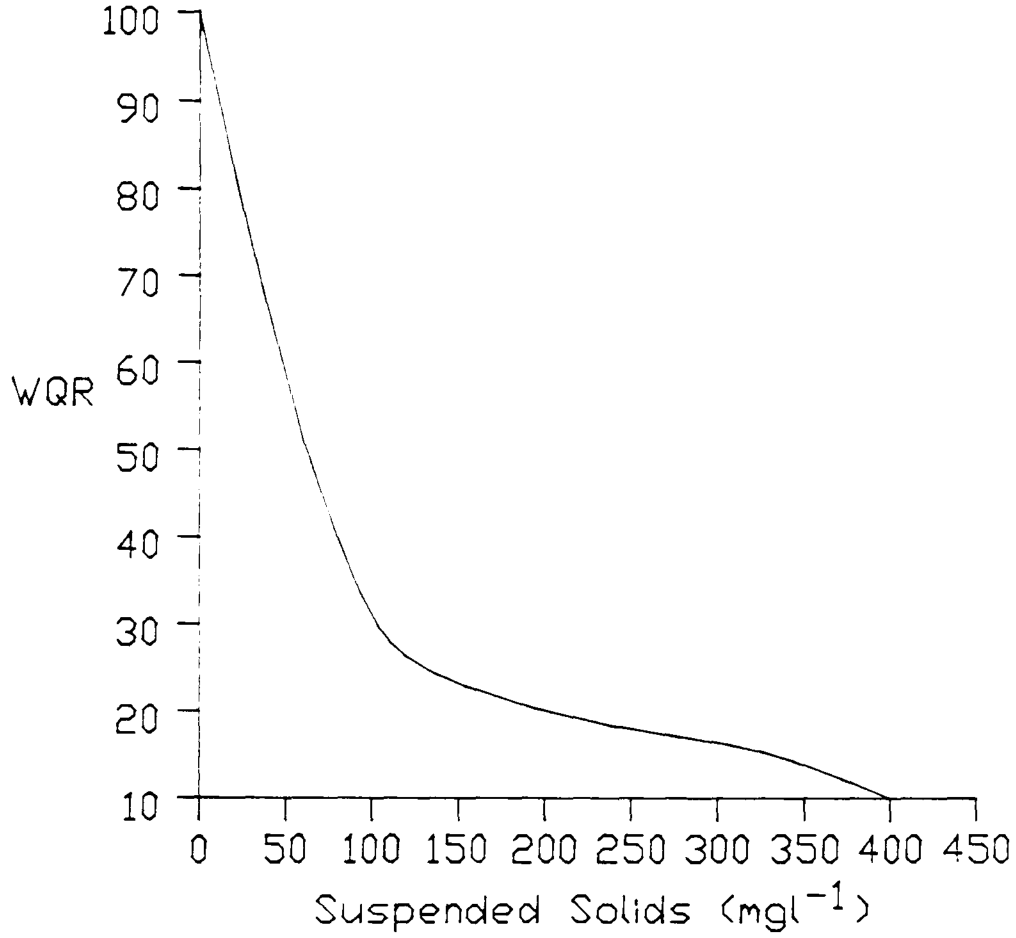
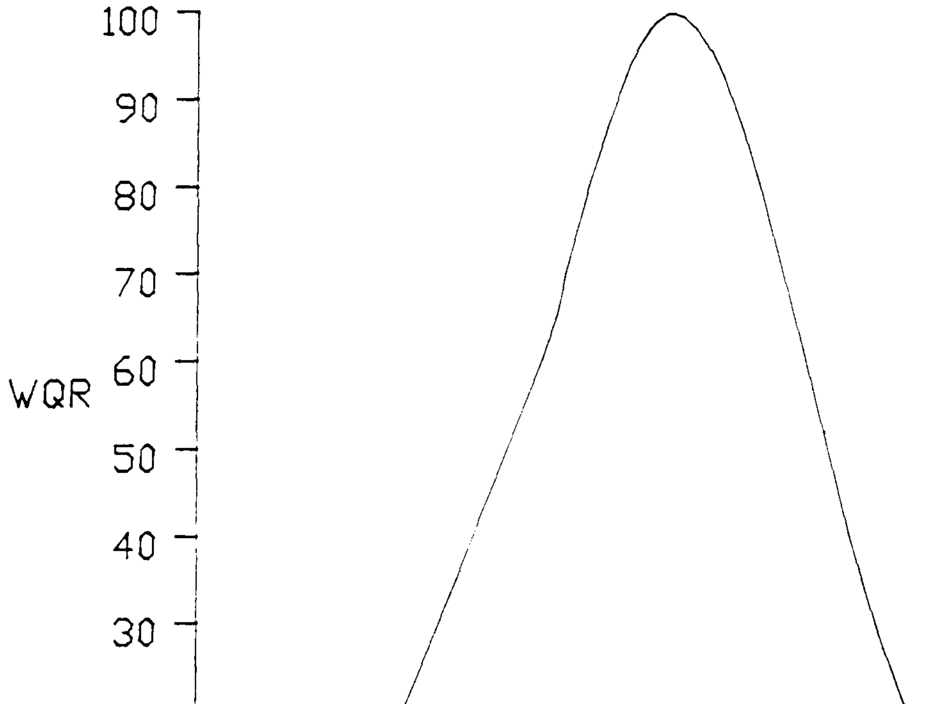


Figure 14. pH



A pH value of 5.0 is considered by EIFAC to provide reasonable protection to coarse fish populations. However, this is well below the other authorities' criteria. Thus, a WQR of 35, which is the median value for the lower threshold for this use, was assigned.

A WQR of 10 was given to pH values of 4 and 10.5 as these would indicate waters of low economic value.

8.3.8. Temperature (^{o}C) (cf Figure 15)

Units (^{o}C)	WQR
0-15	100
20	85
22	65
25	40
30	25
32	10

Rationale

Waters with a temperature of between 0^{o}C and 15^{o}C are considered to be of excellent quality and suitable for all potential uses. Thus a WQR of 100 was given to this temperature range.

Waters with a temperature of 20^{o}C have been given a WQR of 85 as this is the MD summer temperature for the protection of high class game fisheries (EIFAC, 1969 and Price and Pearson, 1979). Thus the median WQR for this use was applied.

The EEC (1975) have proposed a temperature of 22^{o}C as the guideline for waters used in PWS requiring treatment of any kind.

Thus a WQR of 65, which is the median for this potential use, was given.

The mandatory criterion proposed by the EEC for the same water use is 25^{o}C. This is endorsed by Price and Pearson (1979). Thus the threshold WQR of 40 was given to this water temperature.

A water temperature of 30^{o}C is the MP proposed by EIFAC (1969) for the protection of coarse fisheries, however this is in excess of that proposed by Price and Pearson. The latter suggest this value as the MP for general amenity uses. The WQRs for these uses are 30 (lower threshold) and 20 respectively. Thus a median WQR of 25 was ascribed to this water temperature.

Water with a temperature of 32^{o}C and above was given a WQR of 10 as such water would be of little economic value and show signs of severe pollution.

8.3.9. Chlorides (Cl, mgl^{-1}) (cf Figure 16)

Concentration (mgl^{-1})	WQR
0	100
50	90
200	65
300	50
600	40
2000	40
2500	30
3000	20
3500	10

Rationale

Chloride concentrations are of particular importance to PWSs, industrial abstractions and water bodies used for irrigation (see Section 7.6.11). The former two are due to the corrosive effects chlorides may have on pipes and fittings. The latter is due to foliar damage. Fish and wildlife, on the other hand, can tolerate comparatively high chloride concentrations. Thus, due to the detrimental effects of chlorides, an ideal situation is one in which chlorides are absent. Thus a WQR of 100 was given to zero chloride concentrations.

A background concentration of 50 mgl^{-1} of chloride is considered acceptable for all potential water uses (USEPA, 1972). Thus a WQR of 90 was ascribed to this concentration.

A chloride concentration of 200 mgl^{-1} is the guideline concentration suggested by the EEC (1975), WHO I (International Section, 1971) and Price and Pearson (1979) for all waters used in PWS, regardless of the prior methods of treatment. Thus the median WQR for these uses of 65 was given to this chloride concentration.

Price and Pearson suggested that waters with a chloride concentration of 300 mgl^{-1} would adversely affect even moderately sensitive crops if used in spray irrigation. They proposed the same criterion as the MP for PWSs receiving only conventional treatment. Thus a WQR of 50, which is the use limiting value for this form of treatment, was given to this chloride concentration.

The WHO I (1971) have proposed an MP chloride concentration of 600 mgl^{-1} for all PWSs. Thus, a use-limiting WQR of 40 was given to this concentration. However, between 600 mgl^{-1} and 2000 mgl^{-1} the potential water use does not vary, as such waters would be

Figure 15. Temperature

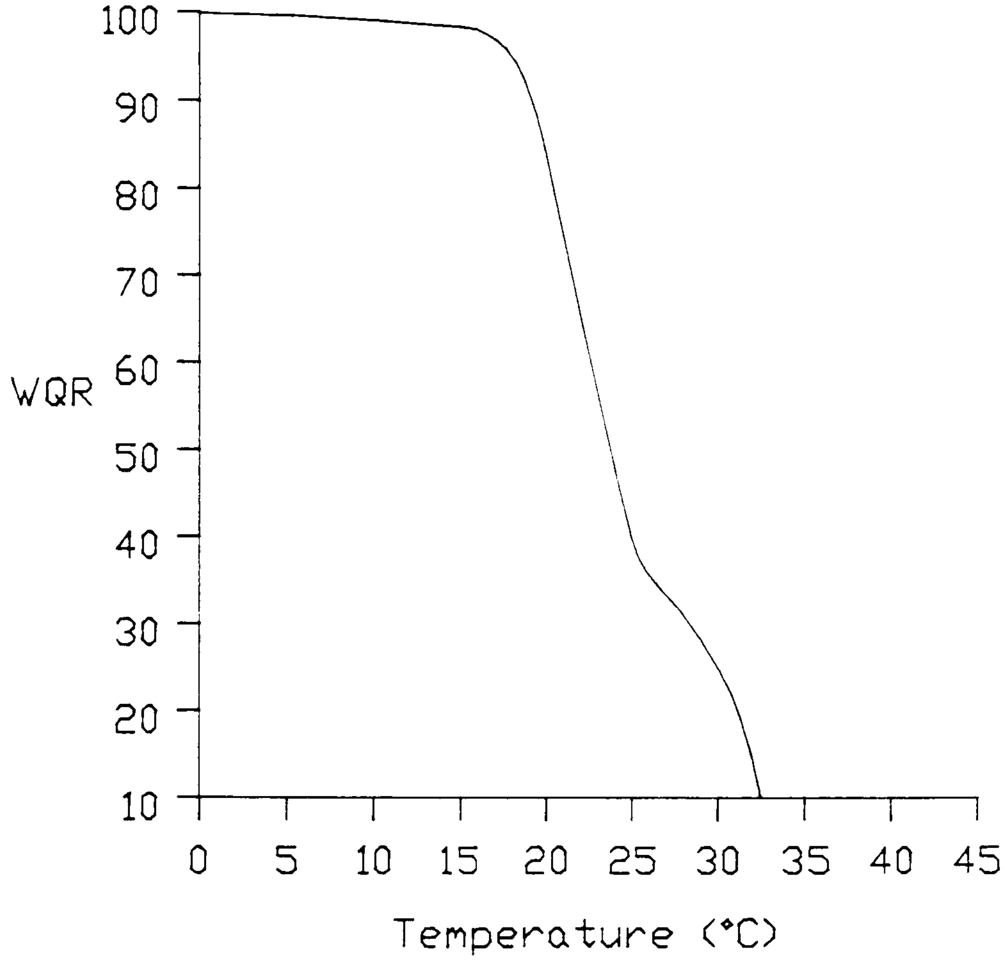
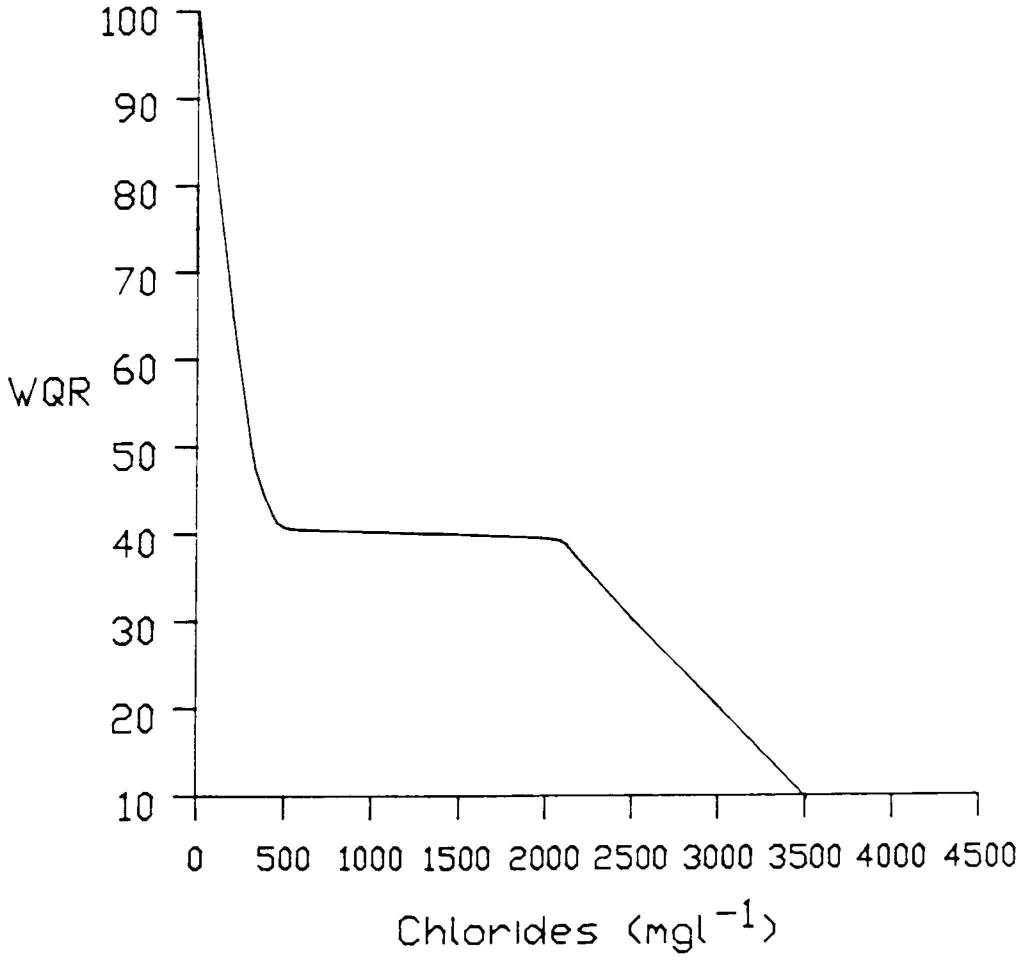


Figure 16. Chlorides



capable of supporting healthy fish populations. An end-point of 2000 mgl^{-1} chloride was selected for this WQR as this is the MP concentration suggested by Price and Pearson (1979) for the protection of most species.

A chloride concentration of 2500 mgl^{-1} was proposed by Price and Pearson for the protection of tolerant fish species. Thus, the lower threshold WQR of 30 was given to this concentration.

Waters with a chloride concentration of 3000 mgl^{-1} would only be of low amenity value (Price and Pearson, MP concentration). Where levels rise to 3500 mgl^{-1} and above severe pollution would exist. In fact such concentrations are akin to sea water. Thus, WQRs of 20 and 10 were given to these chloride concentrations respectively.

8.3.10. Total Coliforms (MPN/100 mls at 37°C) (cf Figure 17)

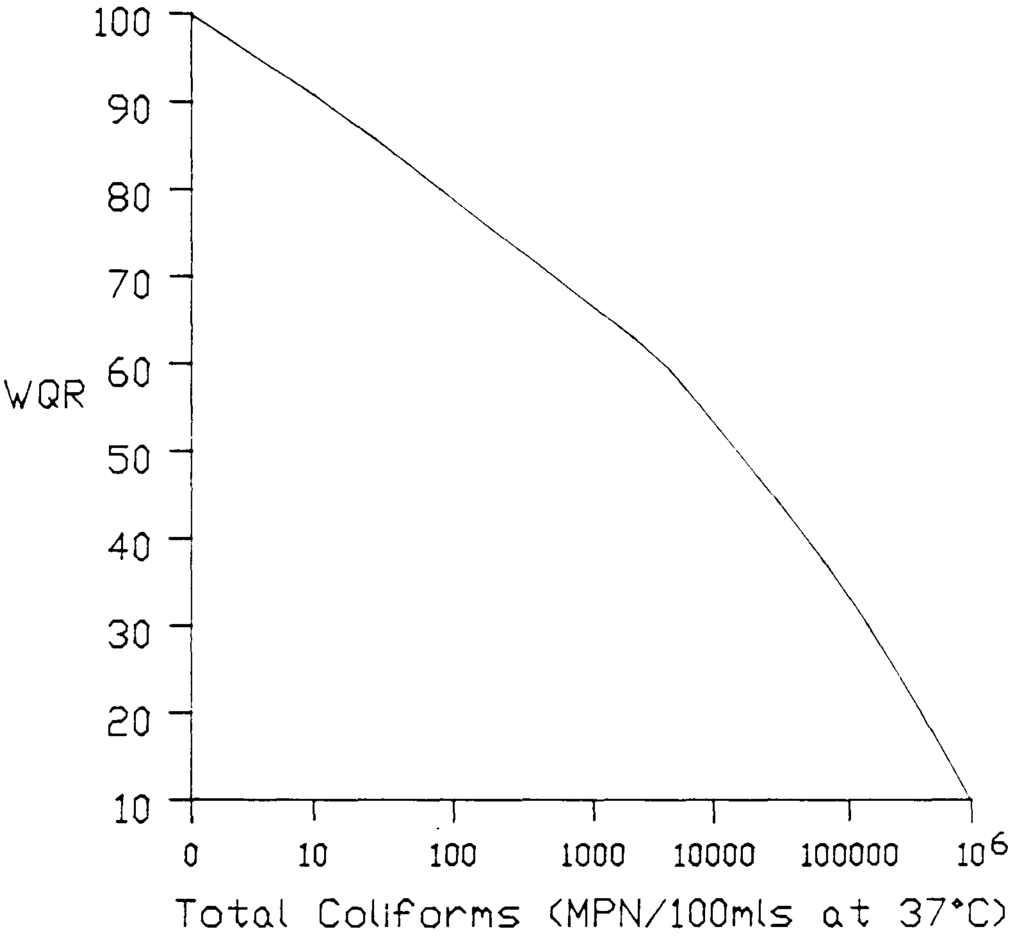
Concentration	WQR
0	100
50	85
5000	60
50000	45
10^6	10

Rationale

Waters completely free of coliforms would be ideally suited to all potential water uses. Thus a WQR of 100 was given to this concentration.

The EEC (1975) guidelines for total coliforms for waters used in PWS after minor, conventional and advanced treatment respectively

Figure 17. Total Coliforms



are 50, 5000 and 50000 organisms per 100 mls of sample. Thus, the median WQRs for each of these uses, 85, 60 and 45 respectively, were applied to these total coliform concentrations.

Total coliform counts above this level are indicative of severe pollution. Thus a WQR of 10 was assigned to total coliform counts of 10^6/100 mls and above.

8.3.11. Summary

Thus the curves developed for the general index and outlined above are capable of reflecting both general quality and potential water use.

8.4. THE DEVELOPMENT OF RATING CURVES FOR POTABLE WATER SUPPLY INDEX (PWSI)

8.4.1. Introduction

The rating curves for the thirteen PWS determinands were derived in the same way as those of the general index. The index range has been extended to zero to indicate waters which are totally unacceptable for their management purpose. However, it must be stressed that such waters may be suitable as a coarse fishery, or an industrial abstraction and they may have a reasonable amenity value.

The derivations of the individual rating curves are outlined below and the final curves produced are shown in Figures 18 to 30. All curves are based on 95 percentile concentrations and the Directives and Criteria used are listed in Appendix II.

8.4.2. Dissolved Oxygen (DO % saturation) (cf Figure 18)

Concentration (% Saturation)	WQR
96-103	100
70	80
50 and 140	55
30	35
0	0

Rationale

Waters with a DO saturation of between 96% and 103% would be ideally suited for use in PWS. This range in DO concentration was ascribed a WQR of 100.

A WQR of 80 was given to a DO saturation of 70% as this is the EEC (1975) guideline for PWSs receiving minor purification. Thus the median WQR for this form of treatment was ascribed.

The EEC guideline for PWSs receiving conventional treatment is a DO saturation greater than 50%. However, this is the minimum permissible level proposed by Price and Pearson (1979) for waters receiving the same form of treatment. The WQRs for both these directives would be 60 and 50 respectively. Thus a median WQR of 55 was ascribed to this DO concentration.

Waters which are supersaturated with DO can cause taste and staining problems if used in PWS (see Section 7.6.1.). Thus, the same WQR was given to DO saturations of 140% and above.

The EEC guideline for PWSs receiving advanced treatment is a DO saturation greater than 30%. This concentration is below the

Figure 18. Dissolved Oxygen

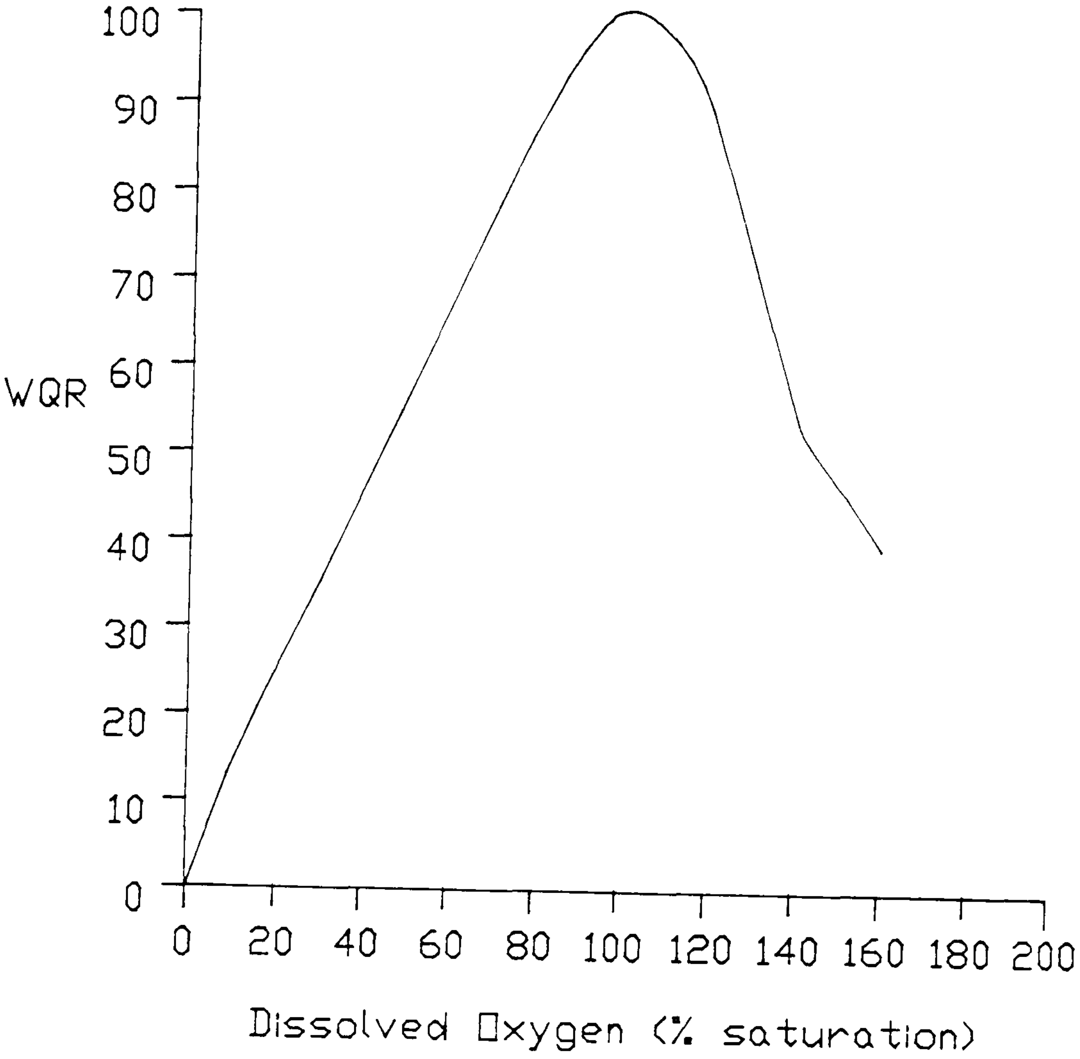
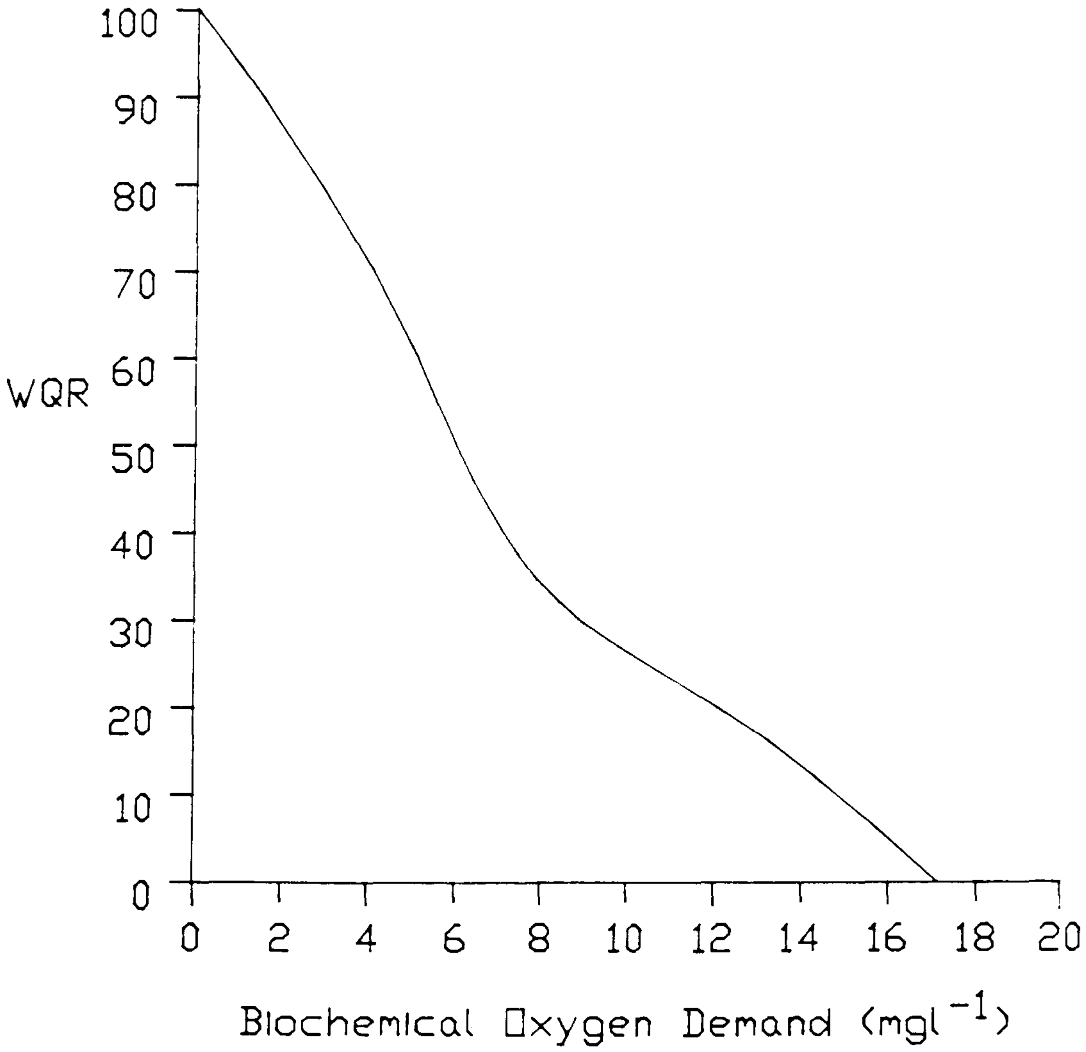


Figure 19. Biochemical Oxygen Demand



minimum permissible proposed by the NWC (1978) for good quality PWSs. The WQRs for these criteria would be of 40 and 30 respectively. Thus a median WQR of 35 was given to this DO saturation.

DO percentage saturations below this level may still afford adequate protection to the use of water as a PWS, but in situations where the DO concentration is low, other determinands are likely to cause additional problems. Thus the rating curve was extrapolated to zero, equating this score to a 0% DO saturation.

8.4.3. Biochemical Oxygen Demand (BOD mgl^{-1}) (cf Figure 19)

Concentration (mgl^{-1})	WQR
0	100
3.0	80
5.0	60
6.0	50
7.0	40
12.0	20
17.0	0

Rationale

Waters with a zero BOD concentration would be ideally suited for use in PWS and were therefore given a WQR of 100.

BOD concentrations of 3 mgl^{-1} and 5 mgl^{-1} are the EEC (1975) guidelines for PWSs receiving minor and conventional treatment respectively. Therefore WQRs of 80 and 60, which are the median WQRs for these forms of treatment, were given to those BOD concentrations respectively.

BOD concentrations of 6 mgl^{-1} and 7.0 mgl^{-1} are the MP suggested by Price and Pearson (1979) and WHO International Committee (1971) for PWSs receiving conventional treatment and the EEC guideline for advanced treatment respectively. Thus, the use limiting and median median WQRs for these uses of 50 and 40 were given to these BOD concentrations.

Waters with a BOD concentration of 12 mgl^{-1} would be polluted and unsuitable for use in PWSs (Environmental Health Division of WHO), but would still be of use for spray irrigation and general amenity. Thus a WQR of 20 was given to this BOD concentration.

Finally, BOD concentrations of 17 mgl^{-1} and above would be indicative of severe pollution and of very low economic value. This concentration was therefore equated to a WQR of zero.

8.4.4. Ammoniacal Nitrogen (NH_4-N, mgl^{-1}) (cf Figure 20)

Concentration (mgl^{-1})	WQR
0	100
0.05	80
0.50	60
1.00	50
2.00	30
4.00	15
6.00	0

Rationale

The development of this curve was complicated by the great divergence in the acceptable levels of Amm. nitrogen proposed by the various water quality commissions. Thus, a compromise had to be made between these recommended limits. Priority was given to the EEC directive (1975) and those produced by Price and Pearson (1979) because the former are legal standards and the latter are based on a study of British watercourses used in PWS (Bedford Ouse Study, 1979).

Ideally Amm. nitrogen should be absent in PWSs. Thus a WQR of 100 was equated to a concentration of zero mgl^{-1}.

The EEC (1975) guideline for PWSs receiving minor purification is 0.05 mgl^{-1} NH_4-N. Thus the median WQR for this use, 80, was given to this concentration.

An Amm. nitrogen concentration of 0.5 mgl^{-1} is the MP proposed by both the International WHO (1963) and the Ontario Water Resources Commission (1970) for PWSs receiving conventional treatment. The same criterion has been suggested as the MD by Price and Pearson (1979) and is well within the directive proposed by the EEC for this use. The WQRs relating to these different levels of acceptability are 50, 60 and 70 respectively. Thus, the median WQR of 60 was ascribed to this Amm. nitrogen concentration.

The EEC guideline concentration for waters used in PWS after conventional treatment is 1 mgl^{-1} NH_4-N. This has been proposed by Price and Pearson (1979) as the MP for that use and is double the MP suggested by WHO I (1963). The respective WQRs for these different degrees of acceptability are 60, 50 and 40. Thus the median WQR of 50 was given to this concentration.

Although the EEC guideline for PWSs receiving advanced treatment is 2.00 mgl^{-1} NH_4-N, it is double the other maximum permissible concentrations suggested by other authors. Nevertheless, a use limiting WQR of 30 was therefore ascribed to this NH_4-N concentration.

An Amm. nitrogen concentration of 4 mgl^{-1} is the mandatory EEC (1975) directive for all PWSs. Waters with this level of Amm. nitrogen would be of doubtful quality for use in PWS. Thus a median Class IV WQR of 15 was given to this concentration.

Finally, waters with an NH_4-N concentration of 6 mgl^{-1} and above would be totally unacceptable for use in PWS and of little other economic value. Thus a WQR of zero was equated to this Amm. nitrogen concentration.

8.4.5. Nitrates (as N, mgl^{-1}) (cf Figure 21)

Concentration (mgl^{-1})	WQR
0	100
5.6	80
11.3	60
22.6	30
45.0	15
120.0	0

Rationale

Ideally nitrates should be absent in waters used in PWS. Therefore, a WQR of 100 was ascribed to this concentration of nitrates expressed as N.

The EEC (1975) proposed a guideline concentration of 5.6 mgl^{-1} for PWSs receiving minor purification. Thus the median WQR for this use, a WQR of 80, was given to this concentration.

A concentration of 11.3 mgl^{-1} nitrates as N has been suggested by the EEC as the maximum level for all PWSs. The same criterion

Figure 20. Ammoniacal Nitrogen

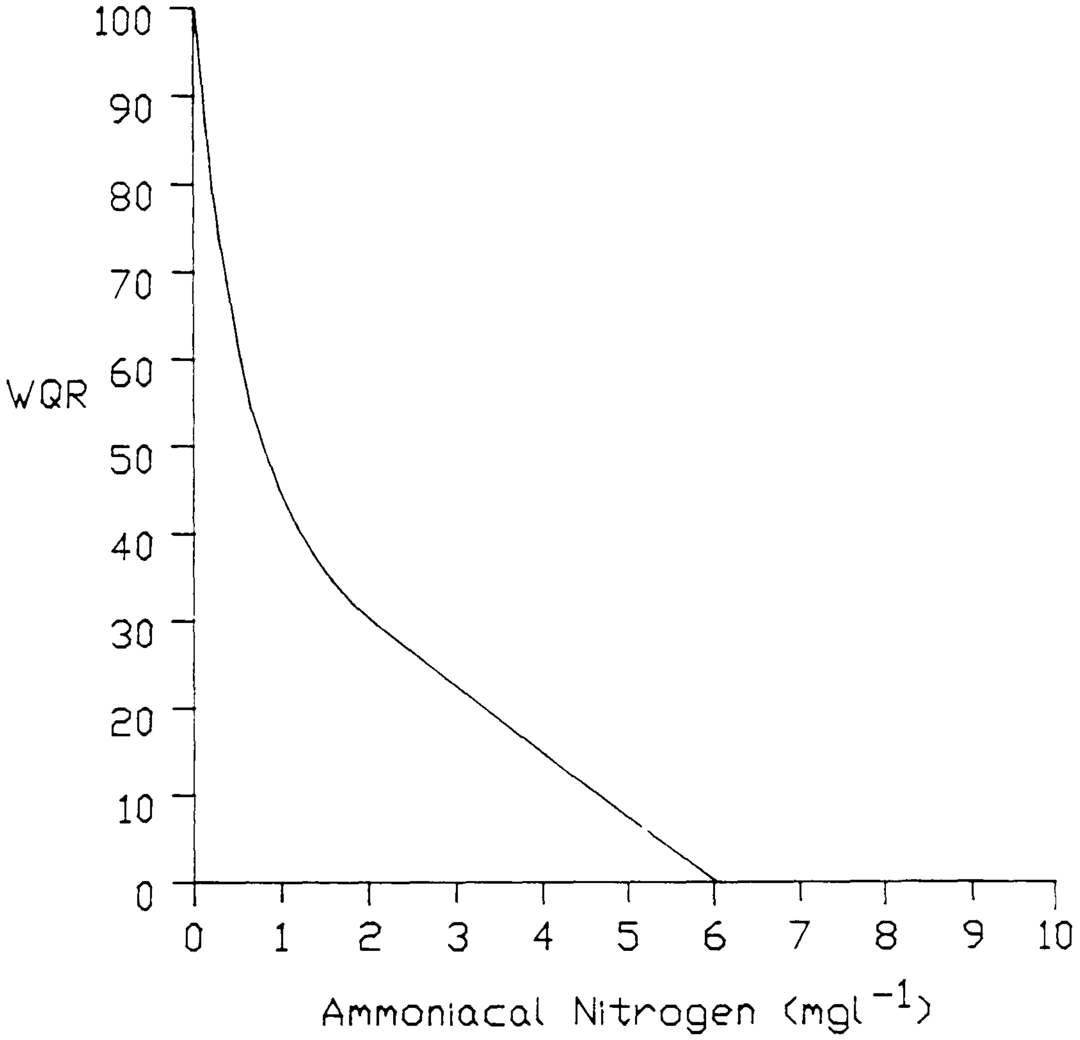
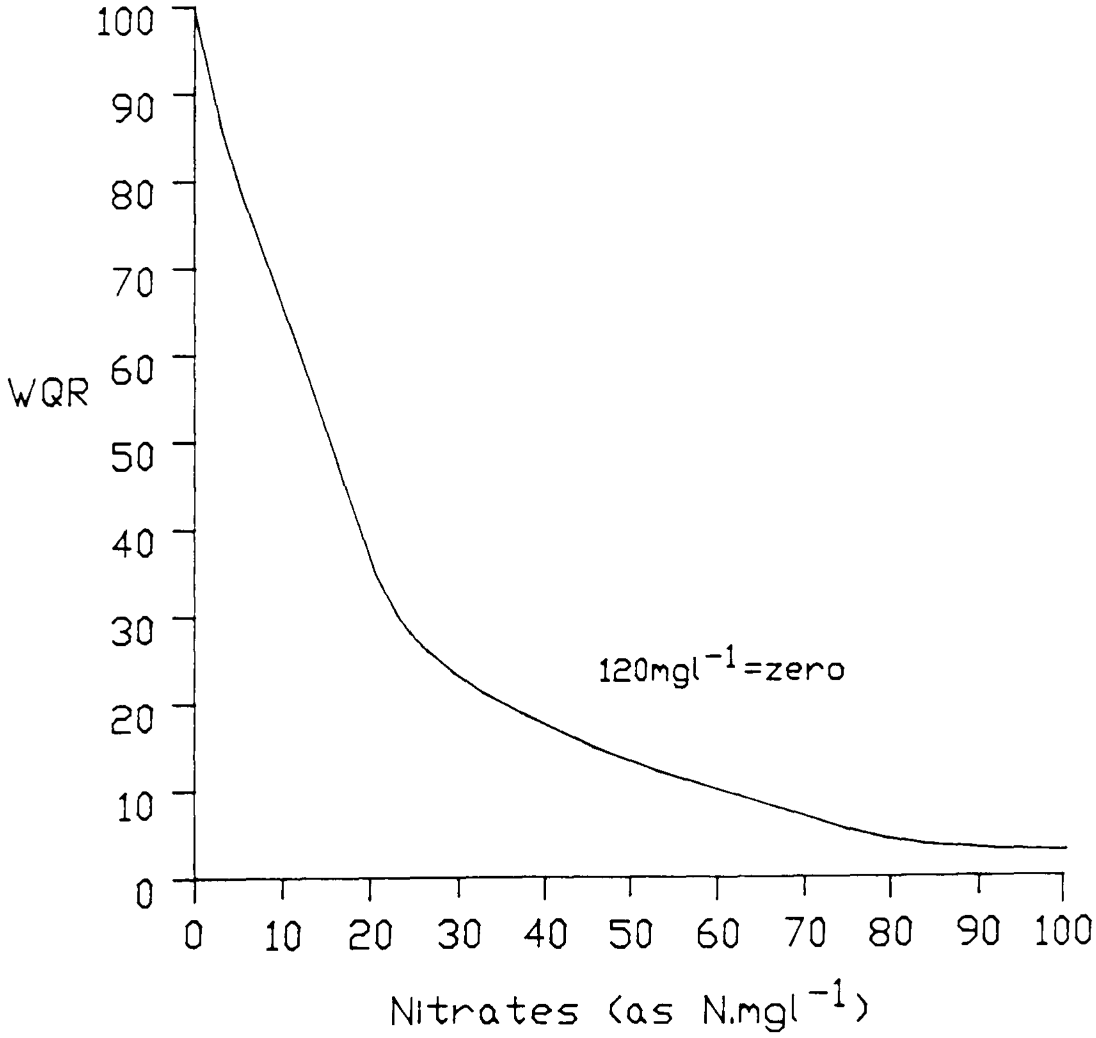


Figure 21. Nitrates



was proposed by Price and Pearson (1979) and the WHO European Commission (1970) as the MD for the same purpose. The latter two authors proposed a MP concentration of 22.6 mgl^{-1}. Nitrate concentrations cause concern in waters used in PWS due to the occurrence of infantile methaemoglobinaemia. The Bedford Ouse Study produced by the Anglian Water Authority (1979) suggests that these problems are unlikely to occur in the UK at concentrations below 22.6 mgl^{-1} nitrates as N due to both climatic factors and the amount of water consumed per person. Thus, the median WQR for all types of treatment, a WQR of 60, was assigned to a nitrates as N concentration of 11.3 mgl^{-1} and a use-limiting WQR of 30 was given to a concentration of 22.6 mgl^{-1}.

A WQR of 15 was given to a nitrate as N concentration of 45 mgl^{-1} indicating median Class IV water of doubtful use in PWS. Although this concentration is double that permitted in a PWS it would still be suitable for use as a fishery or for general amenity purposes.

Finally, a WQR of zero was equated to a Nitrates as N concentration of 120 mgl^{-1} as above. Such levels would be indicative of severe pollution and waters of low economic value.

8.4.6. Suspended Solids (SS, mgl^{-1}) (cf Figure 22)

Concentration (mgl^{-1})	WQR
0	100
25	80
40	70
80	40
100	30
400	0

Rationale

The only published directive on suspended solid concentrations in PWSs is that of the EEC (1975). Within this, a guideline concentration of 25 mgl^{-1} was proposed for PWSs receiving minor purification. Hence the median WQR was ascribed. As no other directives have been proposed, the remainder of the curve is that of the WQI.

8.4.7. pH (cf Figure 23)

Units	WQR
7.2 to 7.4	100
6.5 and 8.5	80
5.5 and 9.0	50
5.0 and 9.2	30
3.5 and 10.0	0

Rationale

A pH range of between 7.2 and 7.4 would be the ideal for all surface water used in PWS. Thus a WQR of 100 was given to this pH range.

The EEC (1975) minimum and maximum guideline values for PWSs requiring minor purification are 6.5 and 8.5. Thus, the median WQR for this form of treatment, a WQR of 80, was given to these pH values.

The minimum and maximum guideline values proposed by the EEC for PWSs receiving either conventional or advanced treatment are 5.5 and 9.0. The WQRs for these forms of treatment range between 70 and 30. Thus a median WQR of 50 was ascribed to these pH values.

Figure 22. Suspended Solids

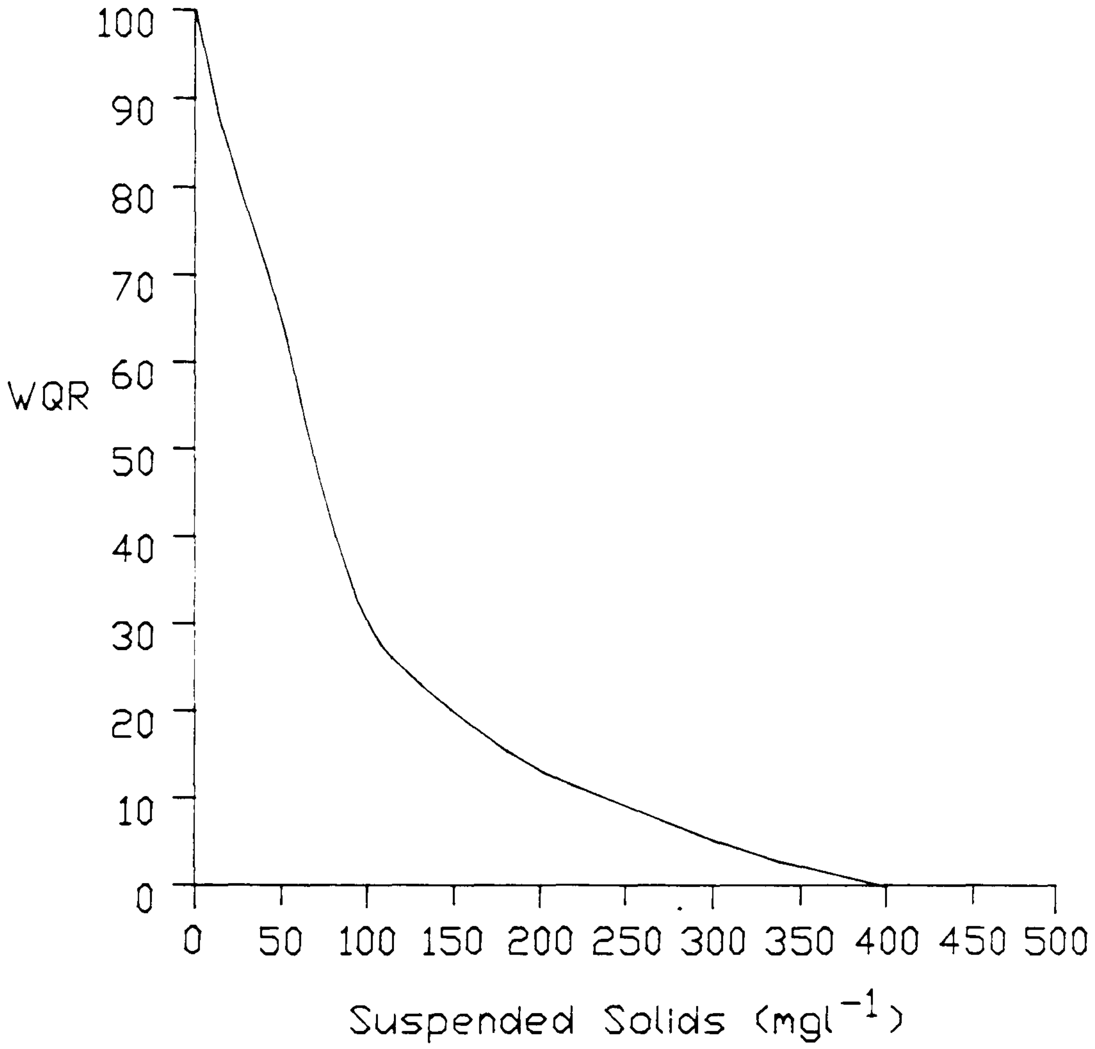
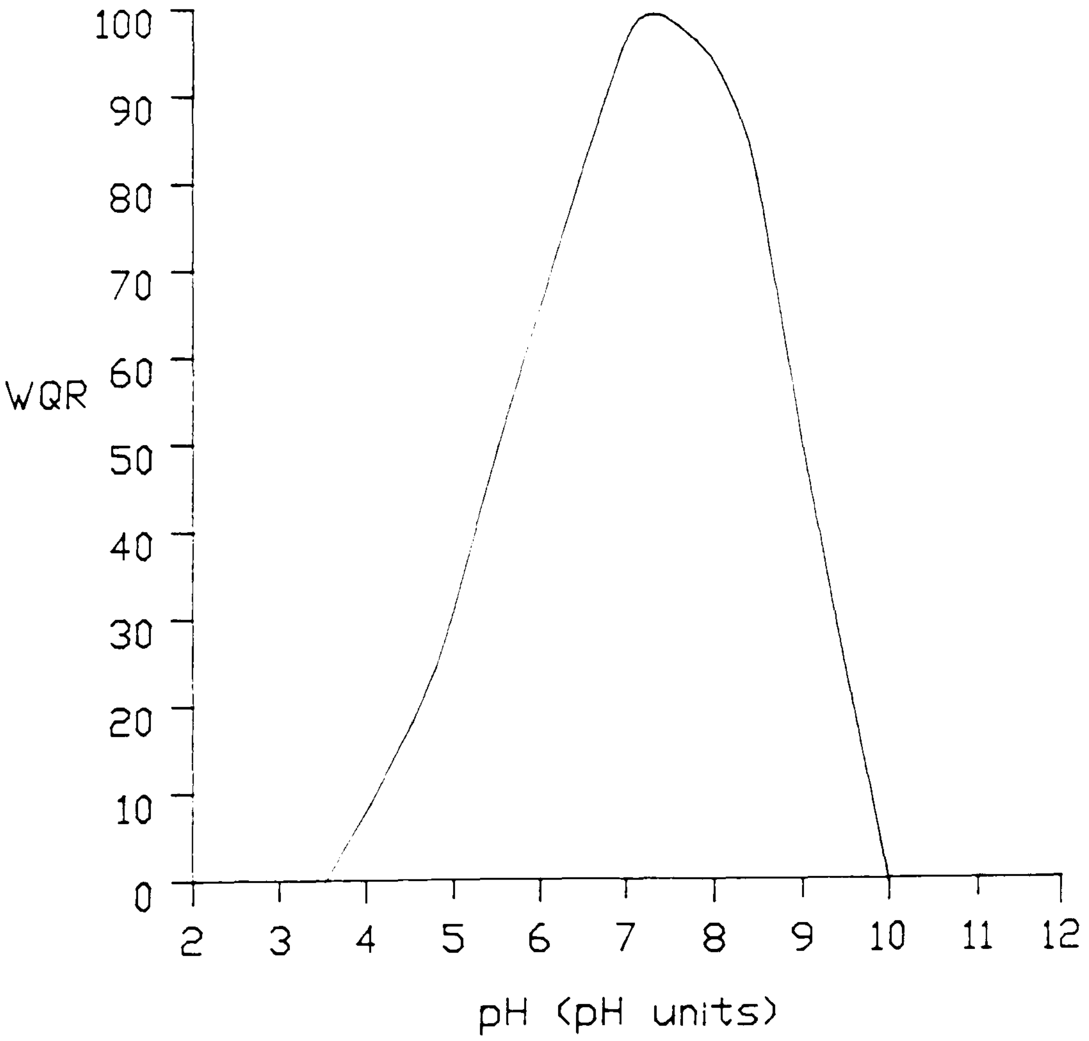


Figure 23. pH



Train (1979) has suggested a minimum acceptable pH value of 5.0 for all potential PWSs, and the WHO I (1971) proposed a maximum permissible value of 9.2 for the same use. Thus, a use limiting WQR of 30 was given to these pH values.

pH values of below 3.5 and above 10.0 were given a WQR of zero as waters with these pH values would be unsuitable for use in PWS and of only low economic value.

8.4.8. Temperature (^{o}C) (cf Figure 24)

Units (^{o}C)	WQR
5 to 10	100
0 and 15	80
22	60
25	30
30	0

Rationale

Waters with a temperature range of between 5^{o} and 10^{o}C would be of excellent quality for use in PWS and were, therefore, given a WQR of 100.

Temperature is of importance to the processes of self-purification and chlorination. These processes may be impaired between the temperature ranges of 0^{o} to 5^{o}C and 10^{o}C to 15^{o}C (see Section 7.6.14). Minor purification would be required for such waters to be used in PWS. Thus, the median WQR for this form of

Figure 24. Temperature

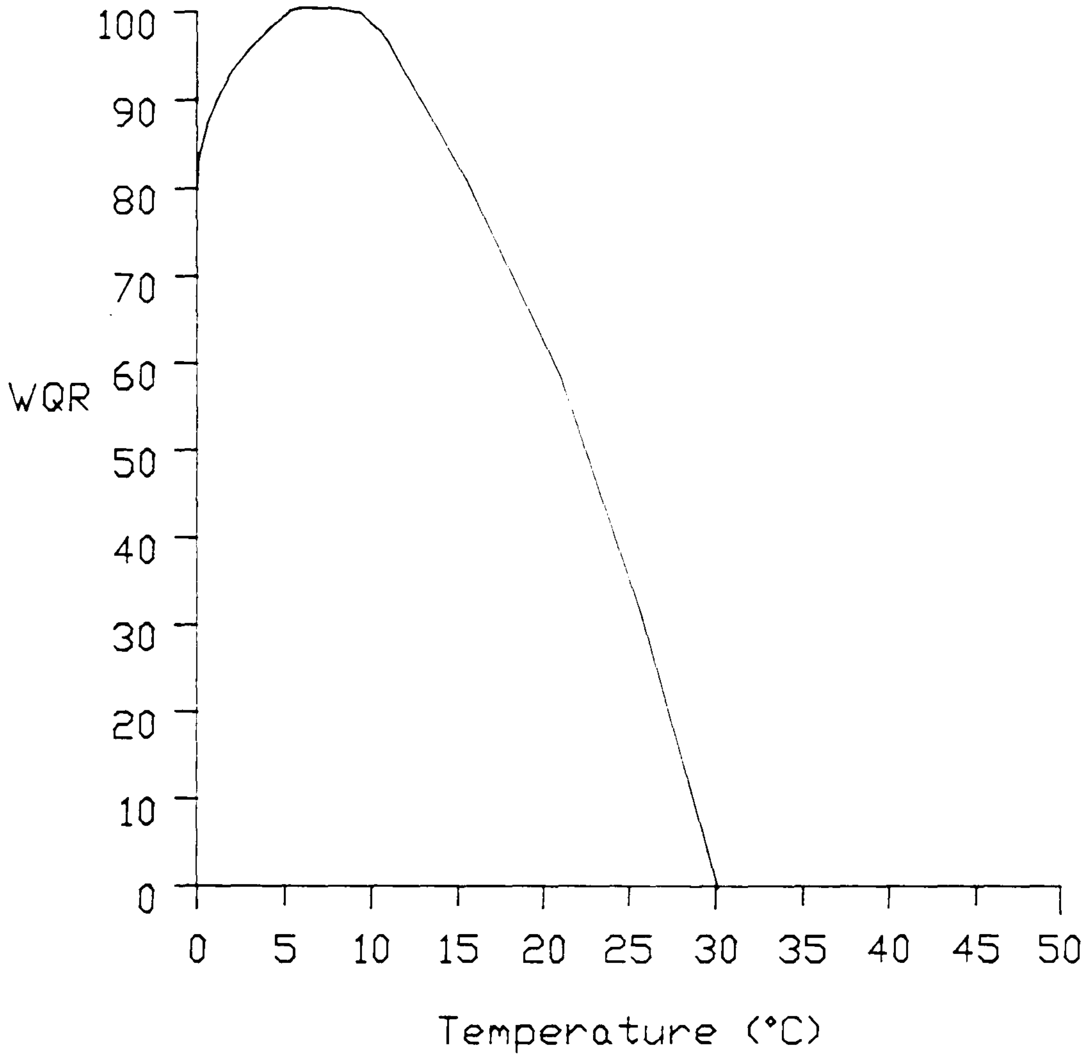
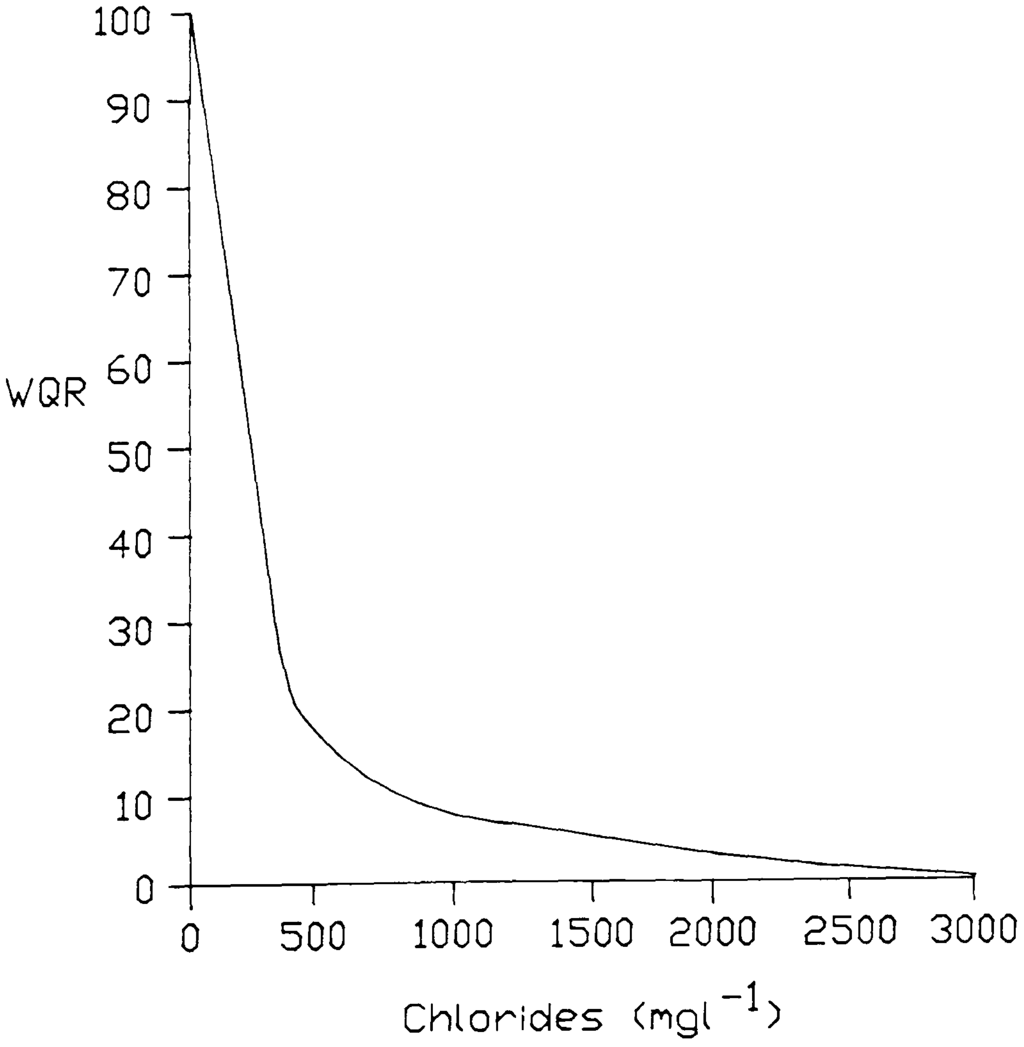


Figure 25. Chlorides



treatment, a WQR of 80, was given to temperatures of $0^{o}C$ and $15^{o}C$.

The EEC (1975) have proposed a guideline temperature of $22^{o}C$ for all potable water abstractions. Thus a WQR of 60, which is the median score for all forms of treatment, was given to this temperature value.

The mandatory EEC directive for the above is a temperature of $25^{o}C$. Thus, a use limiting WQR of 30 was ascribed to this temperature value.

Finally, water temperatures of $30^{o}C$ and above would render a supply unsuitable for use in PWS and of only low economic value. Thus, a WQR of zero was given to this temperature value.

8.4.9. Chlorides (Cl, mgl^{-1}) (cf Figure 25)

Concentration (mgl^{-1})	WQR
0	100
50	90
200	60
300	30
600	15
3000	0

Rationale

Ideally, chlorides should be absent from potential PWSs (see Section 7.6.11). Thus a WQR of 100 was given to a zero chloride concentration.

A background concentration of 50 mgl^{-1} Cl would be indicative of an excellent quality PWS (McKee and Wolf, 1963; EPA, 1972).

Waters with this chloride concentration would require very little treatment thus, a WQR of 90 was allotted to this value.

The EEC (1975), WHO (E and I, 1970; 1971), Price and Pearson (1979) and the Bedford Ouse Report (1979), all agree that the MD chloride concentration for all potential PWSs should be equal to, or less than 200 mgl^{-1} Cl. Thus, the median WQR for all forms of treatment, a WQR of 60, was given to this chloride concentration.

No mandatory directive has been produced by the EEC for chlorides in PWSs. Those proposed by other authorities range between 250 mgl^{-1} Cl (McKee and Wolf, 1963; Bedford Ouse Report, 1979), 300 mgl^{-1} Cl (Price and Pearson, 1979), and 350 mgl^{-1} Cl (WHO E, 1970). Thus the use limiting WQR of 30 was given to the median of these three chloride concentrations.

Both the International and European WHO Committees recognise that chloride concentrations of 600 mgl^{-1} may be tolerated for a very limited period within PWSs. However, such waters would be of doubtful use. Thus a WQR of 15 indicating a median Class IV PWS was ascribed to this chloride concentration.

Finally, chloride concentrations of 3000 mgl^{-1} and above were given a WQR of zero as such levels would be indicative of severe pollution and low economic value.

8.4.10. Total Coliforms (MPN/100 mls at $37^{o}C$) (cf Figure 26)

Concentration (MPN/100 mls)	WQR
0	100
50	80
5000	60
50000	40
10^6	0

Rationale

Ideally coliforms should be absent from all PWSs. Thus a WQR of 100 was given to zero coliform counts.

All of the above total coliform counts relate to EEC (1975) guideline concentrations for PWSs receiving minor, conventional or advanced treatment. Thus the respective median WQRs were ascribed to each of these total coliform counts.

8.4.11. Sulphates (SO_4 mgl^{-1}) (cf Figure 27)

Concentration (mgl^{-1})	WQR
0	100
50	90
150	60
250	30
400	15
1200	0

Figure 26. Total Coliforms

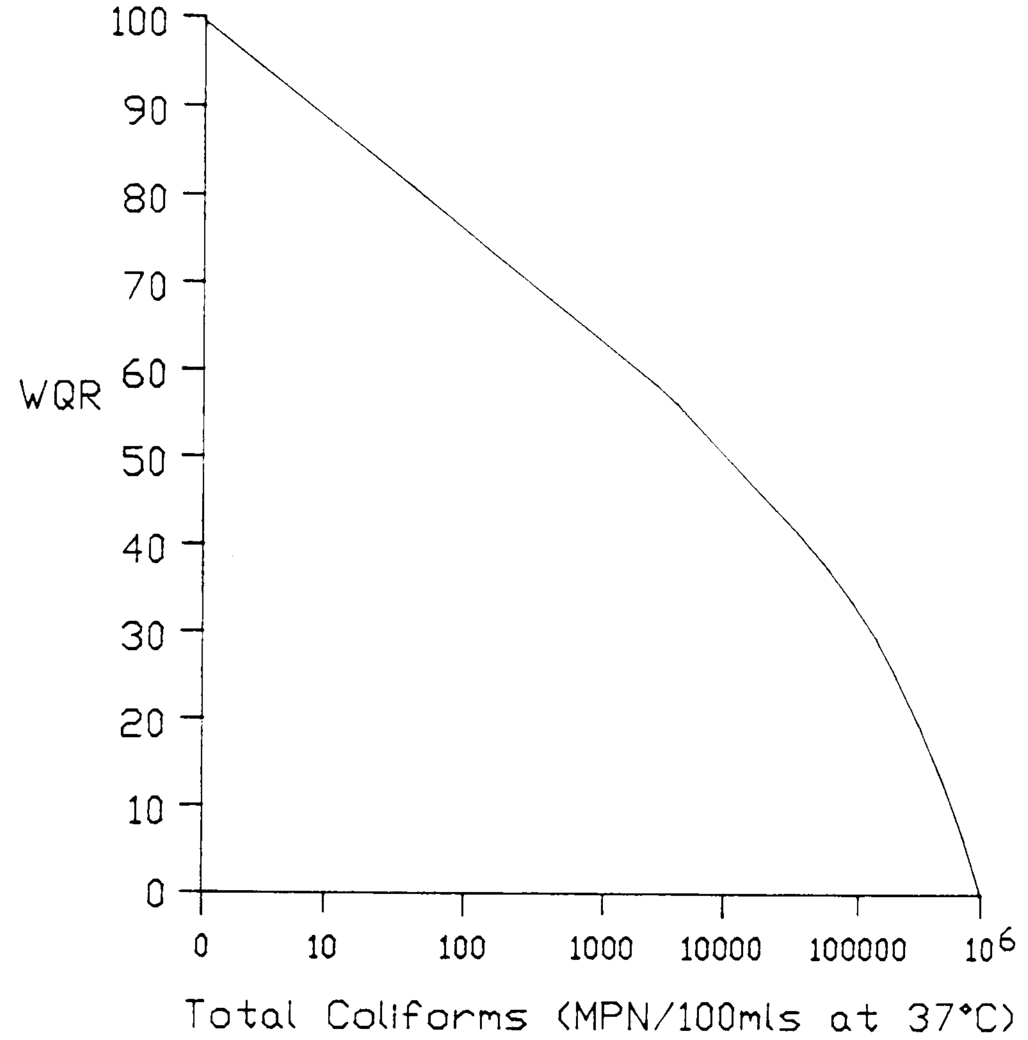
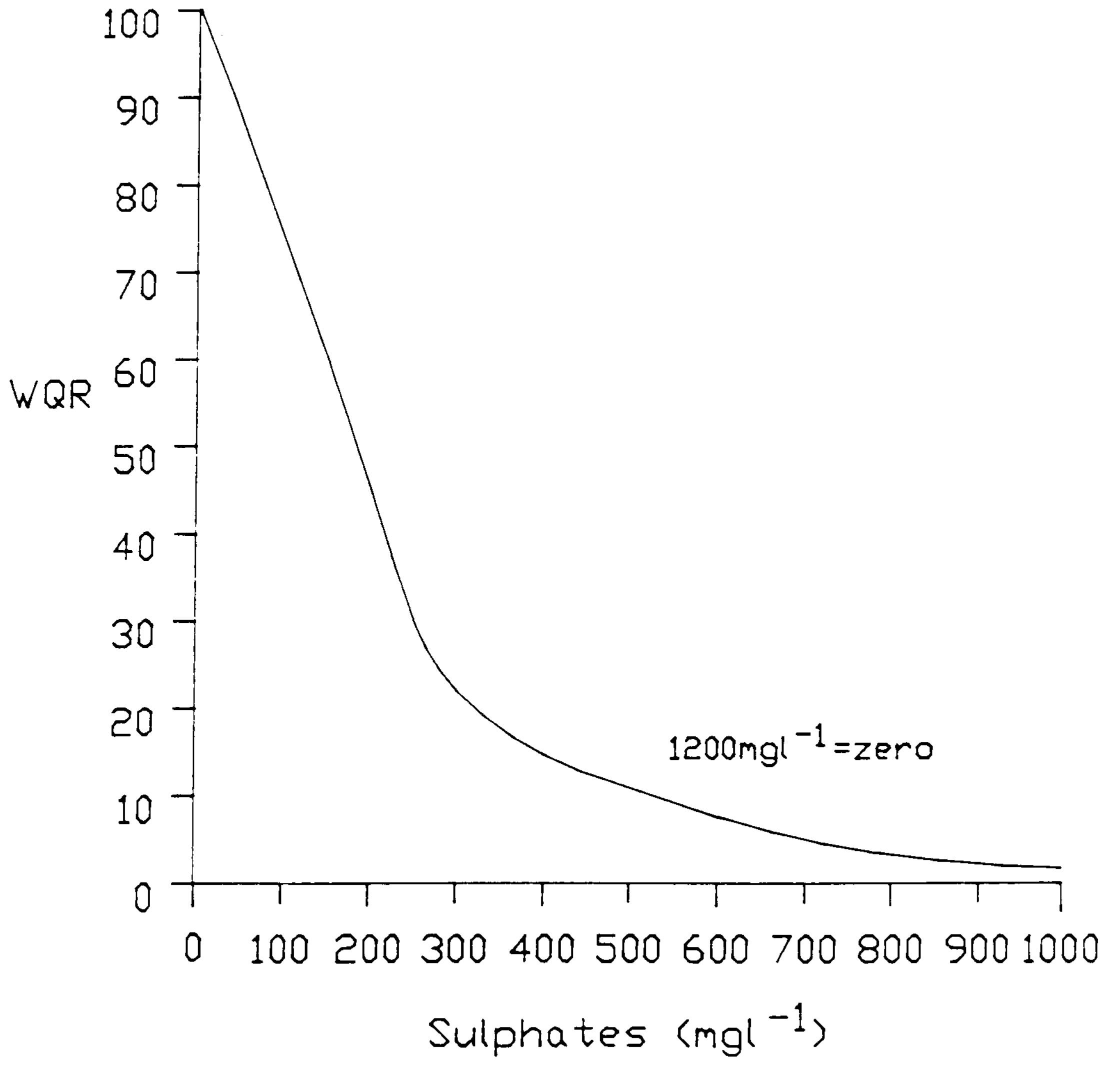


Figure 27. Sulphates



Rationale

Ideally sulphates should be absent from all PWSs (Section 7.6.12.). However, waters with a background concentration of 50 mgl^{-1} are still of excellent quality, requiring very little treatment, (McKee and Wolf, 1963). Therefore, WQRs of 100 and 90 were given to these sulphate concentrations respectively.

The EEC (1975) have proposed a guideline concentration of 150 mgl^{-1} SO_4 for all PWS abstractions for which treatment is required. Therefore, a WQR of 60, which is the median WQR for all methods of treatment, was given to this guideline concentration.

The EEC mandatory directive for the above is a sulphate concentration of 250 mgl^{-1}. This criterion has also been proposed by WHO E (1970), Train (1979) and the Ontario Water Resources Commission (1970). However, the WHO International Committee (1971) recognise that concentrations up to 400 mgl^{-1} SO_4 can be tolerated for short periods. As such waters would be of doubtful use in PWS, the use-limiting WQR of 30 was ascribed to SO_4 concentrations of 250 mgl^{-1} and a WQR of 15 to that of 400 mgl^{-1} indicating a median Class IV PWS.

Sulphate concentrations of 1200 mgl^{-1} and above would be indicative of severe pollution and low economic value. Thus a WQR of zero was given to this SO_4 concentration.

8.4.12. Dissolved Iron (Fe, mgl^{-1}) (cf Figure 28)

Concentration (mgl^{-1})	WQR
0	100
0.1	70
0.3	60
1.0	50
2.0	30
5.0	0

Rationale

Iron causes taste and staining problems beyond certain concentrations in waters used in PWS (Section 7.6.6.). Consequently a WQR of 100 was given to zero Fe concentrations.

The EEC (1975) guideline for PWSs receiving only minor purification is a concentration of 0.1 mgl^{-1} Fe. However, this has been proposed by WHO I and E (1971, 1970), and Price and Pearson (1979) as the MD for waters receiving conventional treatment. The WQRs for both these possible uses are 80 and 60 respectively. Thus, the median of these two WQRs, 70, was given to this Fe concentration.

The mandatory EEC directive for PWSs receiving minor purification is 0.3 mgl^{-1} Fe. However, this is the MP suggested by Train (1979) where only conventional treatment is available. The WQRs for both these criteria are 70 and 50 respectively, thus the median WQR of 60 was ascribed to this concentration.

The EEC guideline for PWSs receiving conventional and advanced treatment is 1 mgl^{-1} Fe, which is also the MP concentration

Figure 28. Dissolved Iron

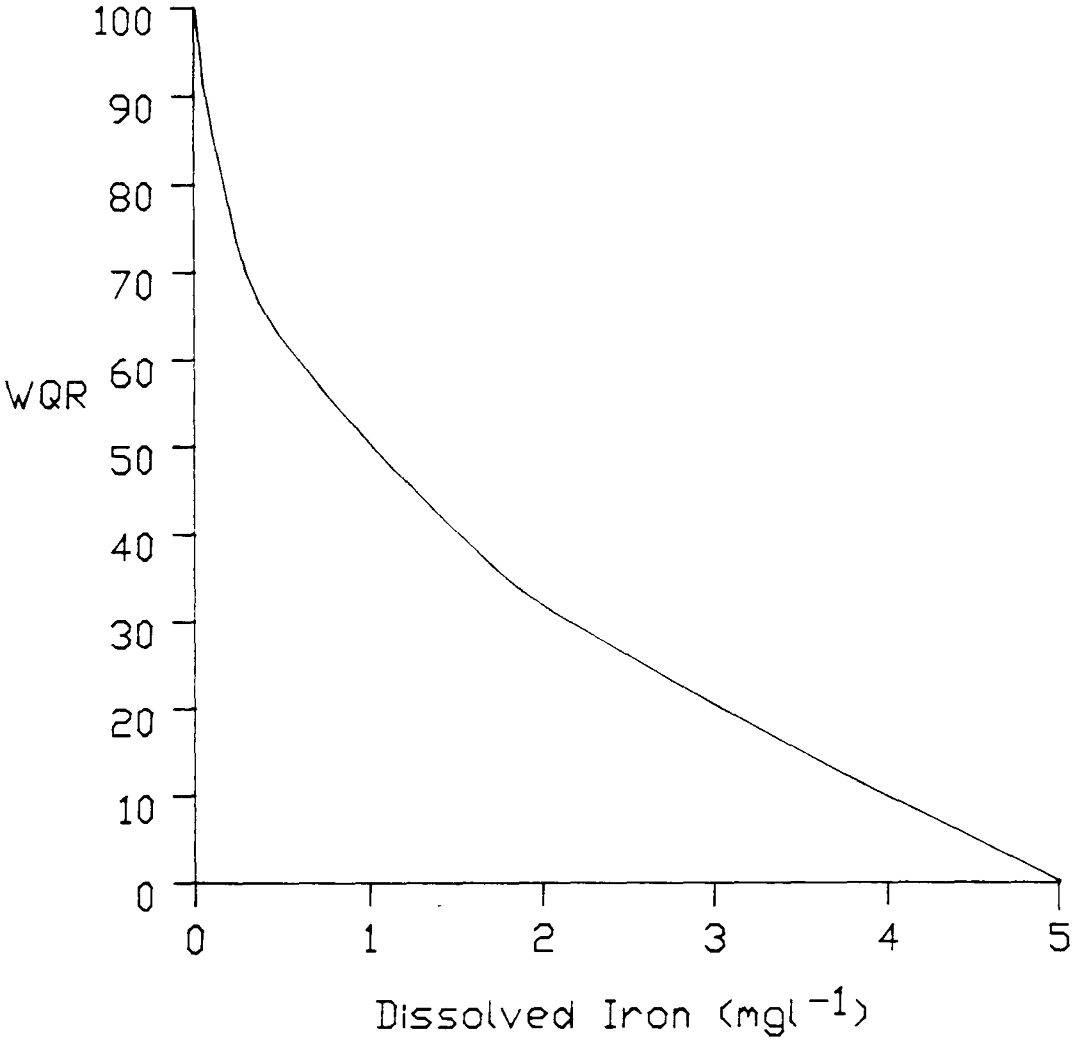
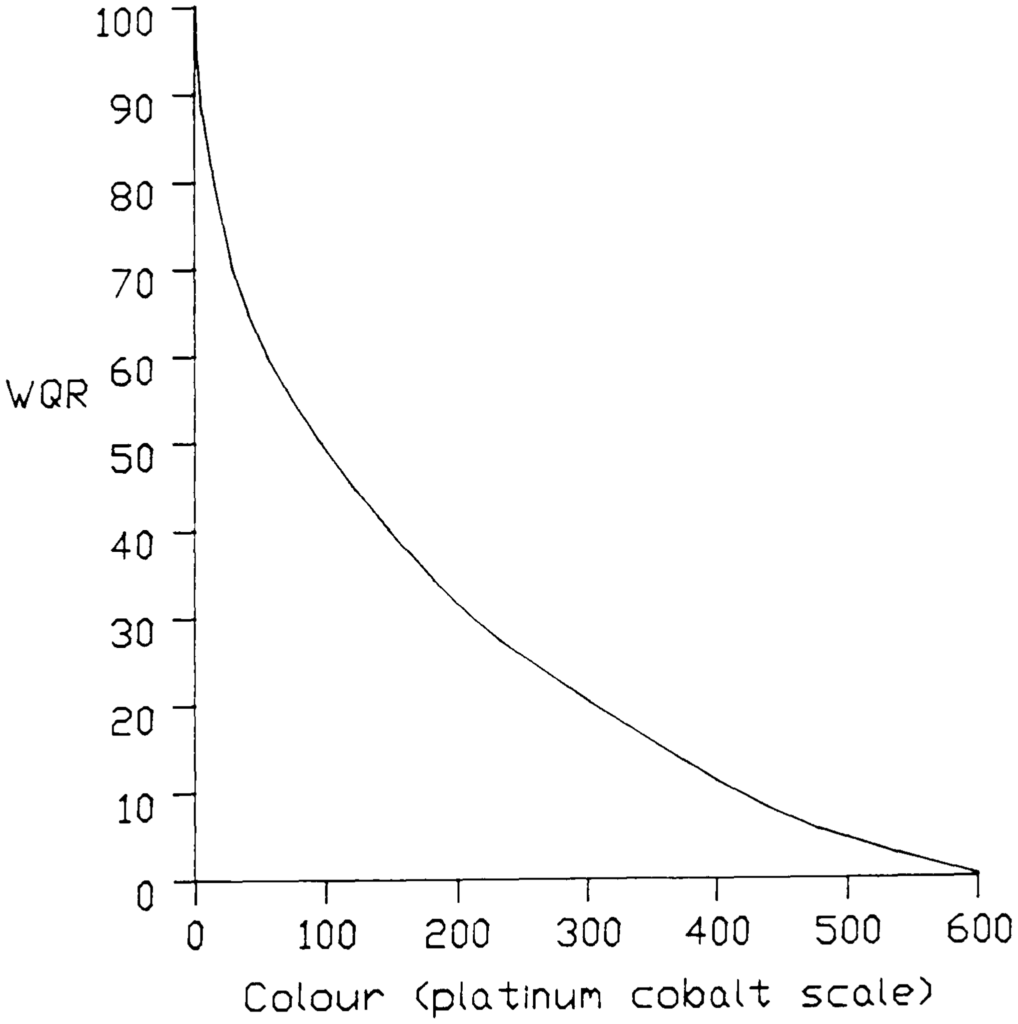


Figure 29. Colour



suggested by WHO I and Price and Pearson for the former. Thus, the WQR for these uses, 50, was given to this iron concentration.

The EEC (1975) mandatory directive for A2 waters is 2 mgl^{-1} Fe. However, no mandatory directive was proposed for situations in which advanced treatment was available. As this concentration is well in excess of other international recommendations (see Appendix II), a use limiting WQR of 30 was given to this Fe concentration.

Finally Fe concentrations of 5 mgl^{-1} and above would leave waters totally unsuitable for use in PWS and of only low economic value. Such concentrations were therefore given a WQR of zero.

8.4.13. Colour (units of platinum cobalt scale) (cf Figure 29)

Units (p.c.s.)	WQR
0	100
10	80
20	70
50	60
100	50
200	30
600	0

Rationale

Ideally PWSs should be free of any discolouration. Thus a WQR of 100 was ascribed to waters with zero units on the p.c.s.

The EEC (1975) guideline and mandatory values for PWSs receiving minor purification are 10 units and 20 units respectively on the platinum cobalt scale which is the same as that proposed by McKee and Wolf (1963). Thus the median and threshold WQRs for this form of treatment, WQRs of 80 and 70, were applied.

The EEC guideline and mandatory values for conventional treatment are 50 units and 100 units respectively on the platinum cobalt scale. The latter agrees with the criteria proposed by McKee and Wolf (1963). Thus the median and threshold WQRs for this form of treatment, WQRs of 60 and 50, were applied.

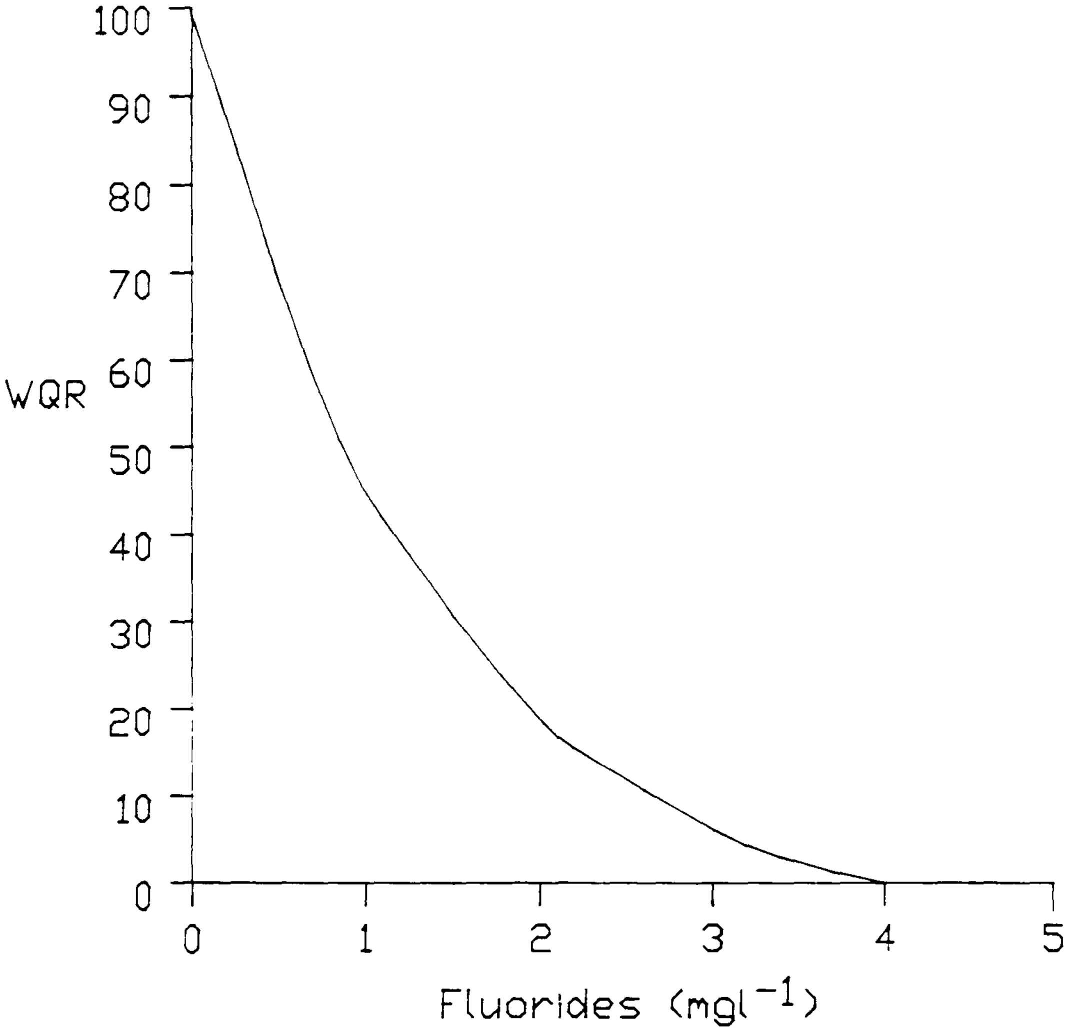
A value of 200 units on the platinum cobalt scale is the mandatory/MP proposed by the EEC and Price and Pearson (1979) respectively for PWSs regardless of the level of treatment provided. Thus a use limiting WQR of 30 was given to this level of discolouration.

Finally, waters with a reading of 600 units or more on the platinum cobalt scale would be totally unsuitable for use in PWS and of low economic value. Thus a WQR of zero was allocated.

8.4.14. Fluorides (F, mgl^{-1}) (cf Figure 30).

Concentration (mgl^{-1})	WQR
0	100
0.7	60
1.7	30
2.0	20
4.0	0

Figure 30. Fluorides



Rationale

There is an ongoing debate as to the desirable level of fluorides contained in waters used in PWS due to their potential benefits to dental health. Consequently, a WQR of 100 was given to a zero F concentration as fluorides may then be added if desired.

Fluoride concentrations of 0.7 mgl^{-1} and 1.7 mgl^{-1} are the lower and upper EEC (1975) guideline concentrations for all PWSs. The latter is also the MP concentration proposed by WHO E and I (1970; 1971) and the Ontario Water Resources Commission (1970). Thus the median and threshold WQRs for all forms of treatment, WQRs of 60 and 30, were applied to these fluoride concentrations.

The National Academy of Science (1972) suggested that waters with a F concentration of 2 mgl^{-1} could still be used in PWS. As this value exceeds those suggested by all other authorities, a WQR of 20, indicating a doubtful supply, was given to this fluoride concentration.

A WQR of zero was given to Fluoride concentrations of 4 mgl^{-1} and above and as such levels would be totally unsuitable for waters used in PWS.

The development of this curve was based on an annual average temperature of between 12.1°C and 14.6°C.

8.4.15. Summary

Thus, the curves developed for the PWSI have been designed in such a way as to reflect both general water quality and the suitability of water for use in potable water supply.

8.5. THE DEVELOPMENT OF RATING CURVES FOR THE AQUATIC TOXICITY INDEX (ATI)

8.5.1. Introduction

The inclusion of an index of toxicity to assist in the management of fish and wildlife populations is new to the development of water quality indices. Information on the potentially lethal effect of toxic determinands to fish is consistently being reviewed and updated. Hence, it is likely that the curves developed here will need to be adjusted as more knowledge is gained in the field. Thus, a zero rating from this index is indicative water which is unlikely to support healthy fish populations on the basis of existing water quality criteria and directives. However, this does not mean that it is of no economic value.

Toxic substances affect fish populations in many ways: they can reduce population size by affecting the fecundity of fish; they can reduce the actual size of fish by impairing growth; and affect rates of respiration. Those which do not normally affect the actual life cycle of fish e.g. phenols, may cause the flesh to become tainted and therefore inedible by man. However, even at low concentrations phenols can become toxic to both adult and immature organisms (EIFAC, 1973).

The toxicity to fish of some metals is influenced by water hardness, particularly calcium hardness ($CaCO_3$ mgl^{-1}). The concentration of metals in water with a low calcium hardness is likely to have a greater detrimental effect on fish populations than the same concentration in hard waters. For example, a chromium concentration of 0.05 mgl^{-1} would be acceptable in waters with a calcium hardness of 200 mgl^{-1} $CaCO_3$. However in soft water (50 mgl^{-1} $CaCO_3$), the same chromium concentration would be potentially lethal to salmonid fish (WRC, 1984). This is because in hard waters the metals combine with the calcium carbonate to form hydroxides or carbonates. In this form the metals are less toxic to fish. Of the twelve determinands included within this index, those for which the effects of hardness are most pronounced are copper, zinc, cadmium, chromium and lead. Thus, a series of curves has been developed for these determinands, (with the exception of cadmium, for which data were not available), relating their potential toxicity to fish with the hardness of the water.

Of the seven remaining determinands it was not possible to produce rating curves for three: hydrocarbons, PAHs and pesticides. No directives on the effect of these determinands to fish populations have, as yet, been produced. Thus if only an indication of pollution is required, the user may opt to use the PSI rating curves outlined in section 8.6. However, it is uncertain how applicable these curves would be to an assessment of the suitability of a water body to support healthy fish populations. Therefore their use is not recommended.

The nine determinands for which curves have been produced were developed in a similar manner to those of the WQI and PWSI. However, in addition to equating mandatory and guideline concentrations to the ATI range outlined in Table 39 and Figure 8, criteria for toxic substances and their effects on fish are also expressed as 50 percentiles and Annual Averages (AAs). The former were proposed by EIFAC and have been ascribed WQRs which are one third of the threshold value for either game or coarse fish as they are slightly less stringent than guideline criteria. The annual averages were proposed by WRC (1984) and have been treated as mandatory criteria. These have been adopted by the water authorities as RQOs for fisheries purposes. They were therefore ascribed threshold WQRs for each type of fishery. The curves were extrapolated to zero at double the mandatory or annual average concentrations. This can be justified in two ways. Firstly, a considerable safety factor is 'built-in' to the criteria proposed by all authors for the protection of fisheries. Secondly, fish are known to survive in waters which are far from ideal. However, although waters with determinand concentrations in excess of mandatory criteria could possibly support fish, they would nevertheless fall below accepted management objectives. Thus a score of between zero and 1.9 from this index indicates waters which require careful monitoring and management if they are to be used for fisheries purposes.

The determinands for which the rating curves have been developed are expressed as either total (T), dissolved plus particulate matter) or dissolved (D), concentrations. The Directives used are listed in Appendix III. The curves produced are outlined below and shown in Figures 31 to 39. Only one curve per determinand has been outlined in detail. These curves are for waters with a calcium hardness of between 200 mgl^{-1} to 250 mgl^{-1} $CaCO_3$. All other curves have been developed using the same methodology as outlined below. In all cases a WQR of 10 indicates waters which are free from toxic substances and therefore ideal for their intended management use.

8.5.2. Dissolved Copper(Cu. mgl^{-1}) (cf Figure 31)

Concentration (mgl^{-1})	WQR
0	10.00
0.01	7.33
0.04	4.00
0.10	zero

Figure 31. Dissolved Copper

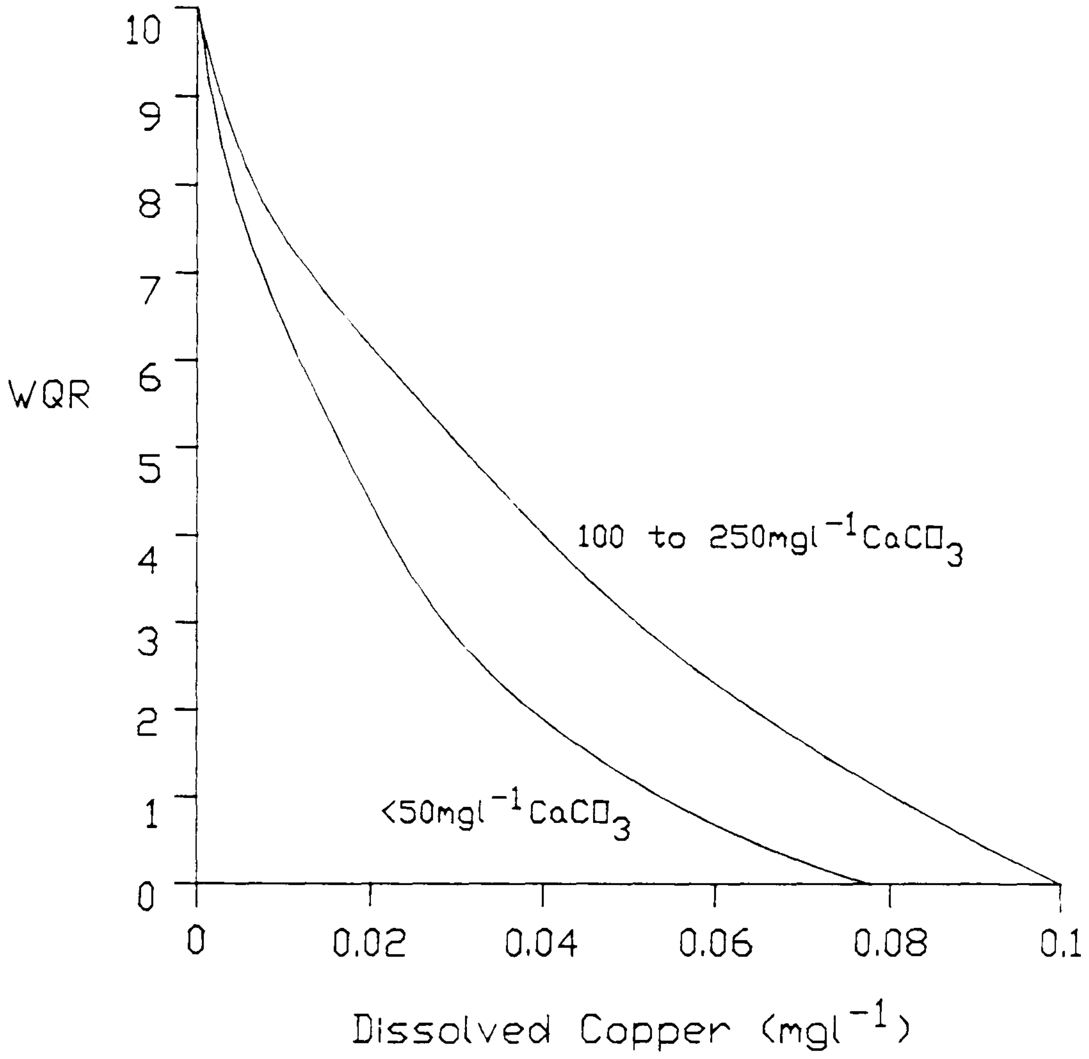
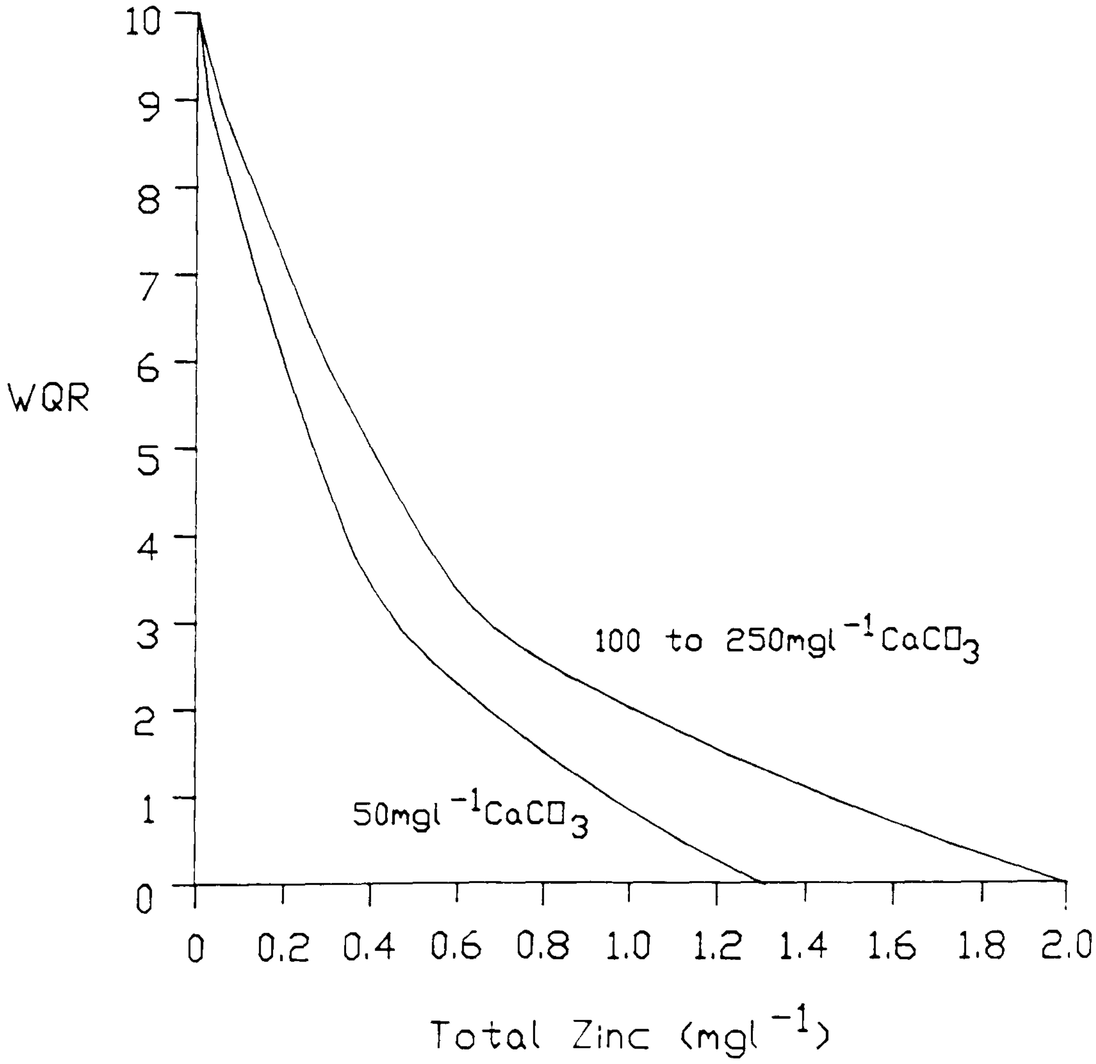


Figure 32. Total Zinc



Rationale

Copper is potentially toxic to fish, particularly in the early and juvenile stages of development. The toxicity of copper increases with a decrease in calcium hardness. Thus, the curve outlined here relates only to water with a calcium hardness of between 100 mgl^{-1} and 250 mgl^{-1} $CaCO_3$.

Only two criteria have been recommended on the amount of copper acceptable in waters intended to support healthy fish populations. The first of these, a dissolved copper concentration of 0.01 mgl^{-1}, was proposed as a 50 percentile value by EIFAC (1976). Thus a WQR of 7.33 which is one third of the index range referring to healthy fish populations (2.0 to 10.0) was ascribed to this concentration. The second, a guideline concentration of 0.04 mgl^{-1}, was suggested by the EEC (1978), EIFAC (1976) and Train (1979). This value was ascribed a WQR of 4.0 indicating a median A2 fishery.

The curve was extrapolated to zero at a dissolved copper concentration of 0.1 mgl^{-1}. This is two and a half times the guideline concentration, thus indicating water which fails to achieve its management objective, but is still of possible value as a low grade fishery.

8.5. Total Zinc (Zn. mgl^{-1}) (cf Figure 32)

Concentration (mgl^{-1})	WQR
0	10.00
0.075	8.66
0.30	6.00
1.00	2.00
2.00	zero

Rationale

Lethal concentrations of zinc are known to cause fish deaths by asphyxia (Skidmore, 1970). However, the toxicity of zinc varies with water hardness and lethal concentrations are lower in soft than hard water. Thus, the curve developed here is for application to water with a calcium hardness of between 100 mgl^{-1} and 250 mgl^{-1} $CaCO_3$.

EIFAC (1973) recommend a zinc concentration of 0.075 mgl^{-1} as a 50 percentile value for the protection of game fish. Thus a WQR of 8.66 which is one third of the index range relating to the protection of game fish was ascribed to this concentration.

Both EEC (1978) and EIFAC propose a mandatory concentration of 0.3 mgl^{-1} for water supporting game fish. Thus, a threshold WQR of 6.00 was given to this zinc concentration.

A threshold WQR of 2.0 was ascribed to a zinc concentration of 1.0 mgl^{-1} as this is the mandatory criterion proposed by both EEC and EIFAC for the protection of healthy coarse fish populations.

The curve was extrapolated to zero at a zinc concentration of 2.0 mgl^{-1} as this is both the MP concentration proposed by Price and Pearson (1979) for the use of water for amenity purposes and double the mandatory criterion proposed.

8.5.4. Total Arsenic (As mgl^{-1}) (cf Figure 33)

Concentration (mgl^{-1})	WQR
0	10.0
0.05	8.0
0.10	4.0
0.15	2.0
0.30	zero

Rationale

Arsenic has been shown to affect the survival and growth rate of fish. However, the effects of arsenic do not vary with hardness. Hence, the rating curve developed here is applicable to all waters.

An arsenic concentration of 0.05 mgl^{-1} has been suggested in the Canadian Water Quality Criteria (WQC, 1980) as a guideline for waters supporting game fish. Thus, a median WQR of 8.0 was ascribed to this concentration.

Concentrations of 0.1 mgl^{-1} and 0.15 mgl^{-1} have been proposed by Price and Pearson (1979) as MD and MP concentrations for the protection of coarse fish populations. Thus, median and threshold class A2 WQRs were ascribed to these values.

A WQR of zero was given to a total arsenic concentration of 0.3 mgl^{-1} as this is both the MP value suggested by Price and Pearson for the use of water for general amenity and double the mandatory value for the protection of fish.

Figure 33. Total Arsenic

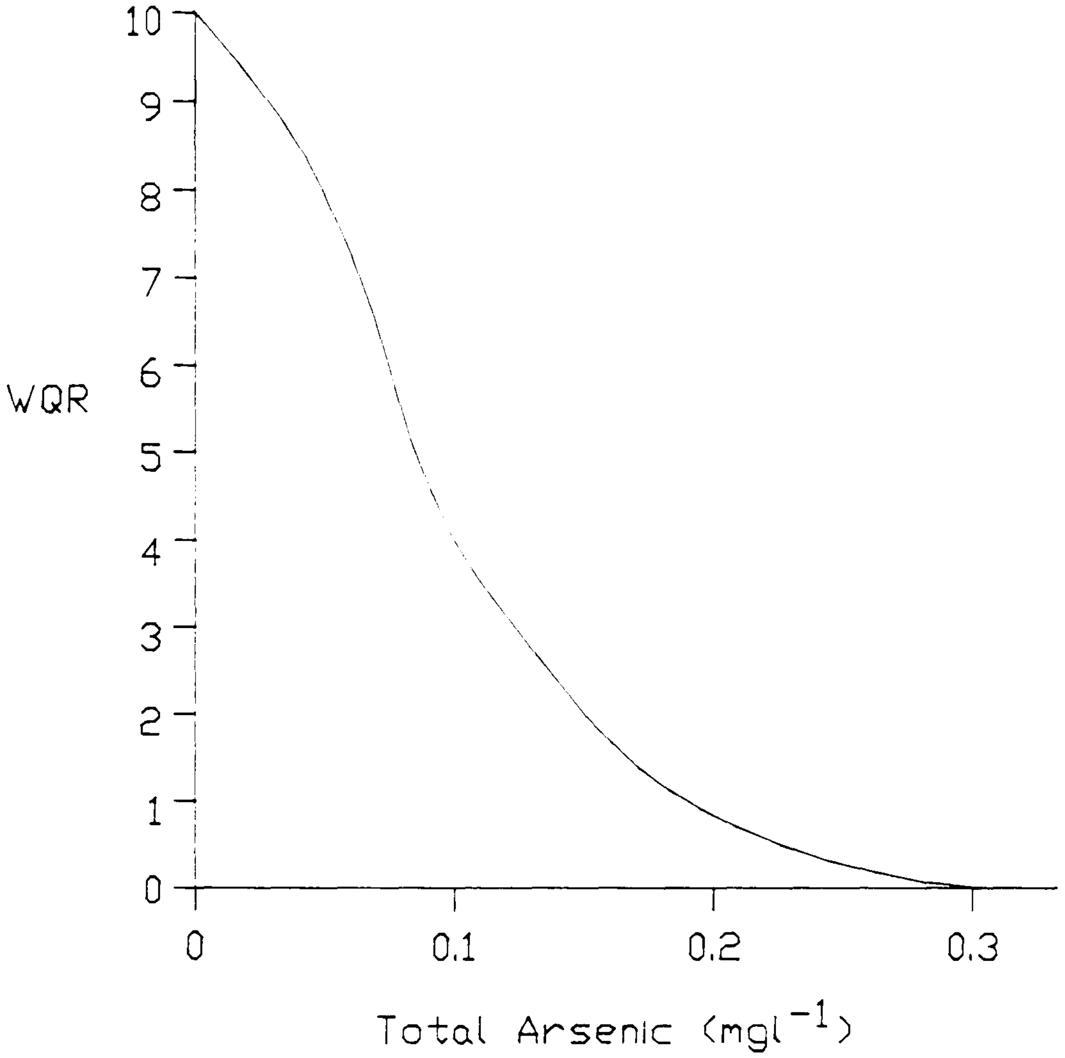
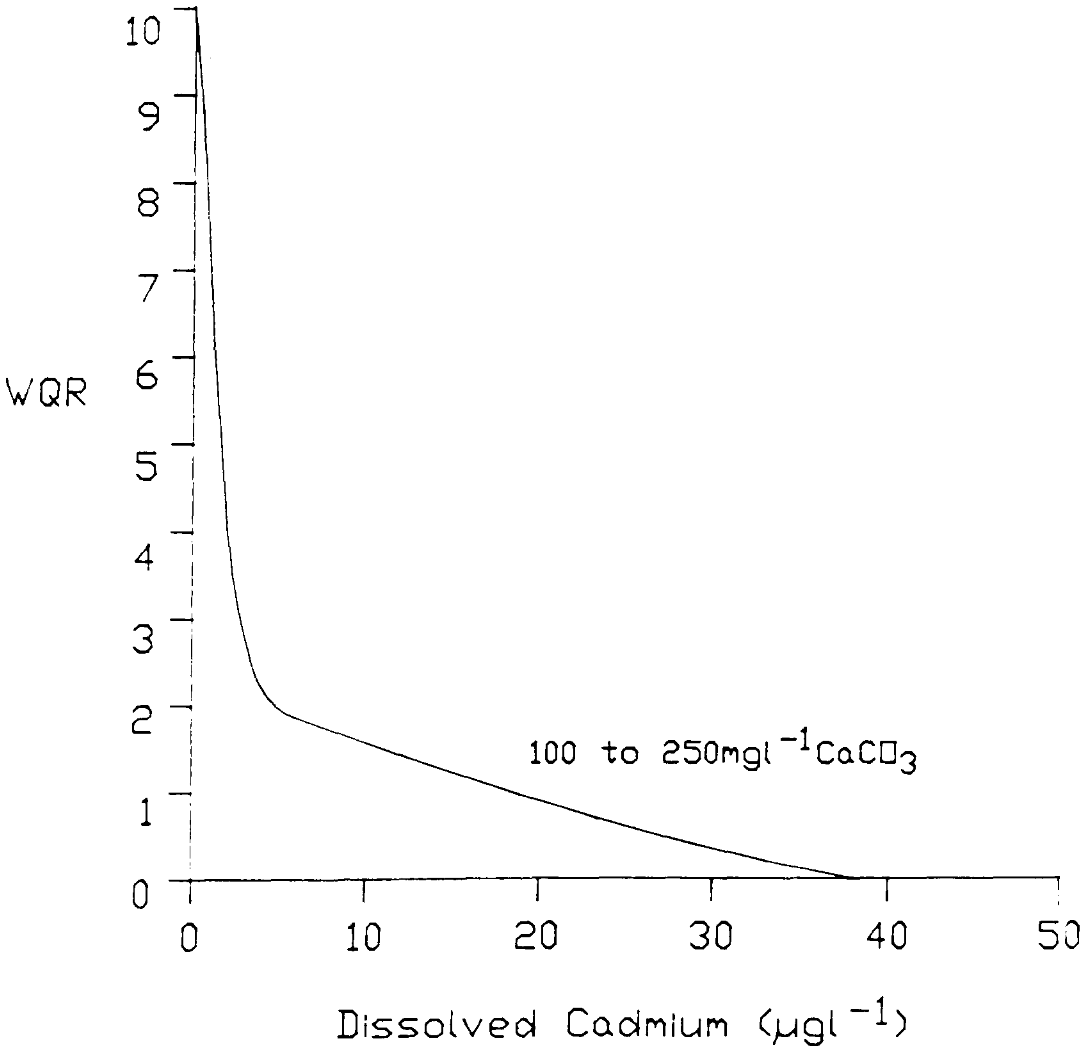


Figure 34. Dissolved Cadmium



8.5.5. Dissolved Cadmium (Cd. $\mu g l^{-1}$) (cf Figure 34)

Concentration ($\mu g l^{-1}$)	WQR
0	10.00
0.5	8.66
1.0	6.00
2.0	4.00
5.0	2.00
19.0	1.00
38.0	zero

Rationale

Fish, especially salmonid species, have been found to be sensitive to low levels of cadmium (Eaton, 1974a). Sub-lethal concentrations are known to cause damage to the gills, liver, heart and brain of fish (Ministry of Technology, 1970; 1973). However, the toxicity of cadmium decreases with an increase in water hardness (Benoit, 1980). Thus, the curve developed here is applicable to water with a calcium hardness of between 100 $mg l^{-1}$ and 250 $mg l^{-1}$.

Water with a dissolved cadmium concentration of 0.5 $\mu g l^{-1}$ or 1 $\mu g l^{-1}$ has been ascribed a WQR of 8.66 and 6.0 respectively as these concentrations are the 50 percentile and mandatory criteria proposed by EIFAC (1977) for the protection of game fish.

EIFAC have proposed a guideline concentration of 2 $\mu g l^{-1}$ for the protection of sensitive coarse fish such as pike; and WRC (1984) suggest an annual average concentration of 5 $\mu g l^{-1}$ for the protection of all species of fish. The latter is based on the EEC (1983) Directive relating to cadmium discharges into rivers. Thus, WQRs of 4.0 and 2.0 were ascribed to these concentrations.

Two additional criteria, MD and MP concentrations of 19 μgl^{-1} and 38 μgl^{-1} respectively, have been proposed by EIFAC for species such as perch which can tolerate much higher cadmium concentrations. These criteria have been ascribed WQRs of 1.0 and zero respectively as only very limited protection would be provided to most species.

8.5.6. Dissolved Chromium (Cr. mgl^{-1}) (cf Figure 35)

Concentrations (mgl^{-1})	WQR
0	10.00
0.025	8.66
0.05	6.0
0.10	4.66
0.25	2.00
0.40	zero

Rationale

Short-term exposure to chromium has been shown rarely to cause fish mortalities. However, less conclusive information is available on the effect of long-term exposure. Sub-lethal effects of chromium include a reduction in the rate of growth and an increase in the production of red blood cells which may in turn lead to various pathological conditions (Schiffman and Fromm, 1959). However, the toxicity of chromium varies with hardness, thus the curve outlined below is applicable to waters with a calcium hardness greater than 200 mgl^{-1}.

The criteria used for the development of this curve are the 50 percentile and annual average concentrations proposed by EIFAC (1983) and the WRC (1984) respectively. Therefore, WQRs which

Figure 35. Dissolved Chromium

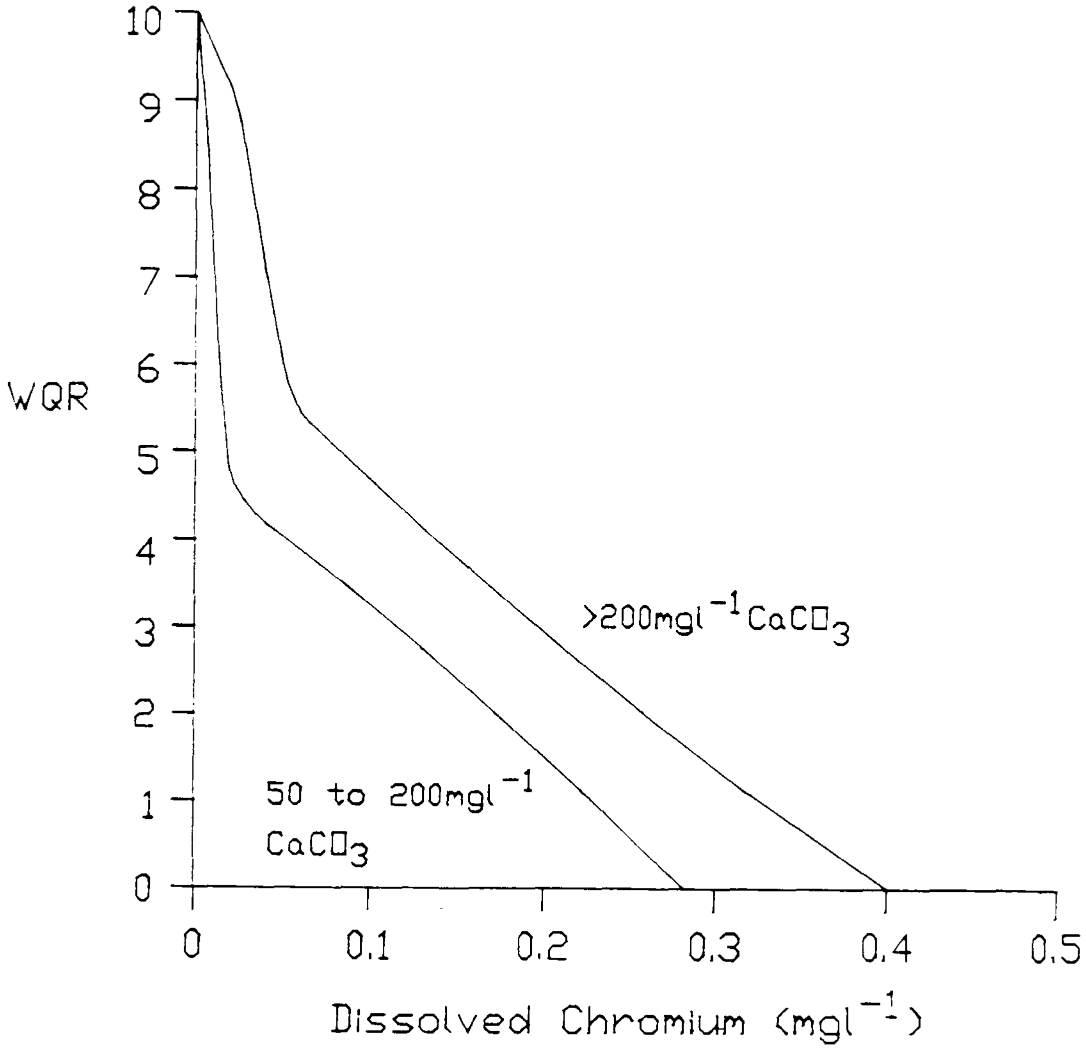
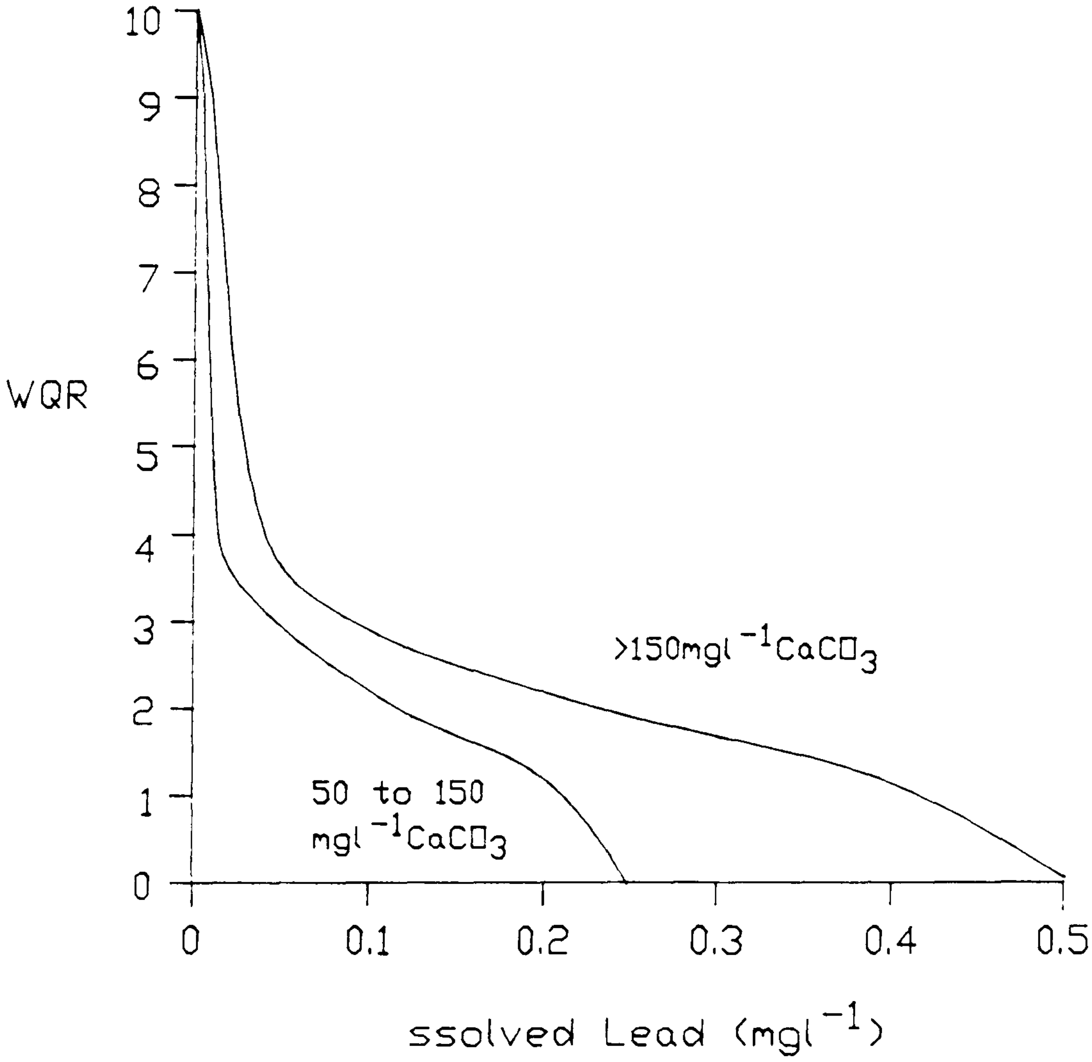


Figure 36. Dissolved Lead



are either one third of the index range or threshold values for either game or coarse fish were applied.

The curve was extrapolated to zero at a dissolved chromium concentration of 0.4 mgl^{-1} which is the MP concentration proposed by EIFAC for the protection of fish populations. This concentration was zero rated as it is greatly in excess of all other criteria, thus the level of protection afforded is questionable.

8.5.7. Dissolved Lead ($Pb.mgl^{-1}$) (cf Figure 36)

Concentration (mgl^{-1})	WQR
0	10.0
0.01	8.0
0.02	6.0
0.03	4.0
0.25	2.0
0.50	zero

Rationale

Lead can adversely affect the survival, growth and reproduction of fish (see Section 7.6.26). However, these effects vary with water hardness, thus the curve developed here is for application to water with a calcium hardness of between 150 mgl^{-1} and 250 mgl^{-1} $CaCO_3$.

The ratings ascribed above are either median or threshold WQRs as the criteria have been proposed as guideline and annual average concentrations within the Canadian WQC (1980) and the WRC (1984) respectively (See Appendix III).

The curve was extrapolated to zero at double the annual average concentration proposed by the WRC (1984).

8.5.8. Total Mercury (Hg. $\mu g l^{-1}$) (cf Figure 37)

Concentration ($\mu g l^{-1}$)	WQR
0	10.0
0.05	8.0
0.15	6.0
0.20	4.0
0.50	2.0
1.00	zero

Rationale

Mercury affects the survival, growth and reproduction of many fish species. However, its toxicity is unaffected by water hardness. Thus the curve developed is applicable to all waters.

A mercury concentration of 0.05 $\mu g l^{-1}$ has been proposed as the MD for water supporting game fish populations by the US EPA (1972). Thus a median A1 WQR of 8.0 was ascribed to this criterion.

Price and Pearson (1979) have suggested MD and MP concentrations of $0.15 \mu g l^{-1}$ and $0.2 \mu g l^{-1}$ for the protection of all fish species. These criteria are well within those proposed by Train (1979) and the WRC (1984). Hence, WQRs of 6.0 and 4.0 were ascribed to these mercury concentrations, the former being the median WQR for the protection of all fish species, and the latter indicating a median class A2 water body.

Concentrations of $0.5 \mu g l^{-1}$ and 1.0 $\mu g l^{-1}$ have been recommended by Train and WRC respectively as the MP and AA criteria for the

Figure 37. Total Mercury

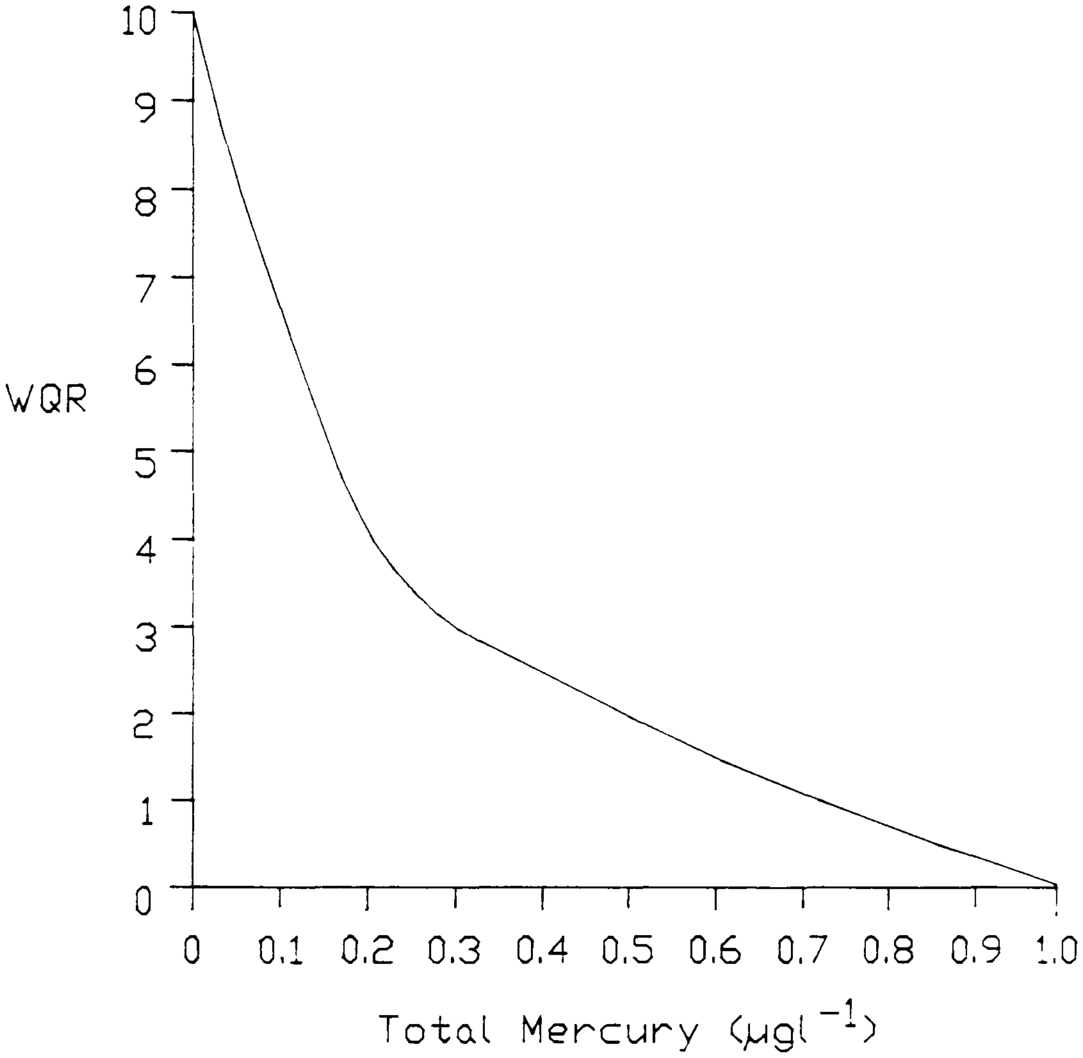
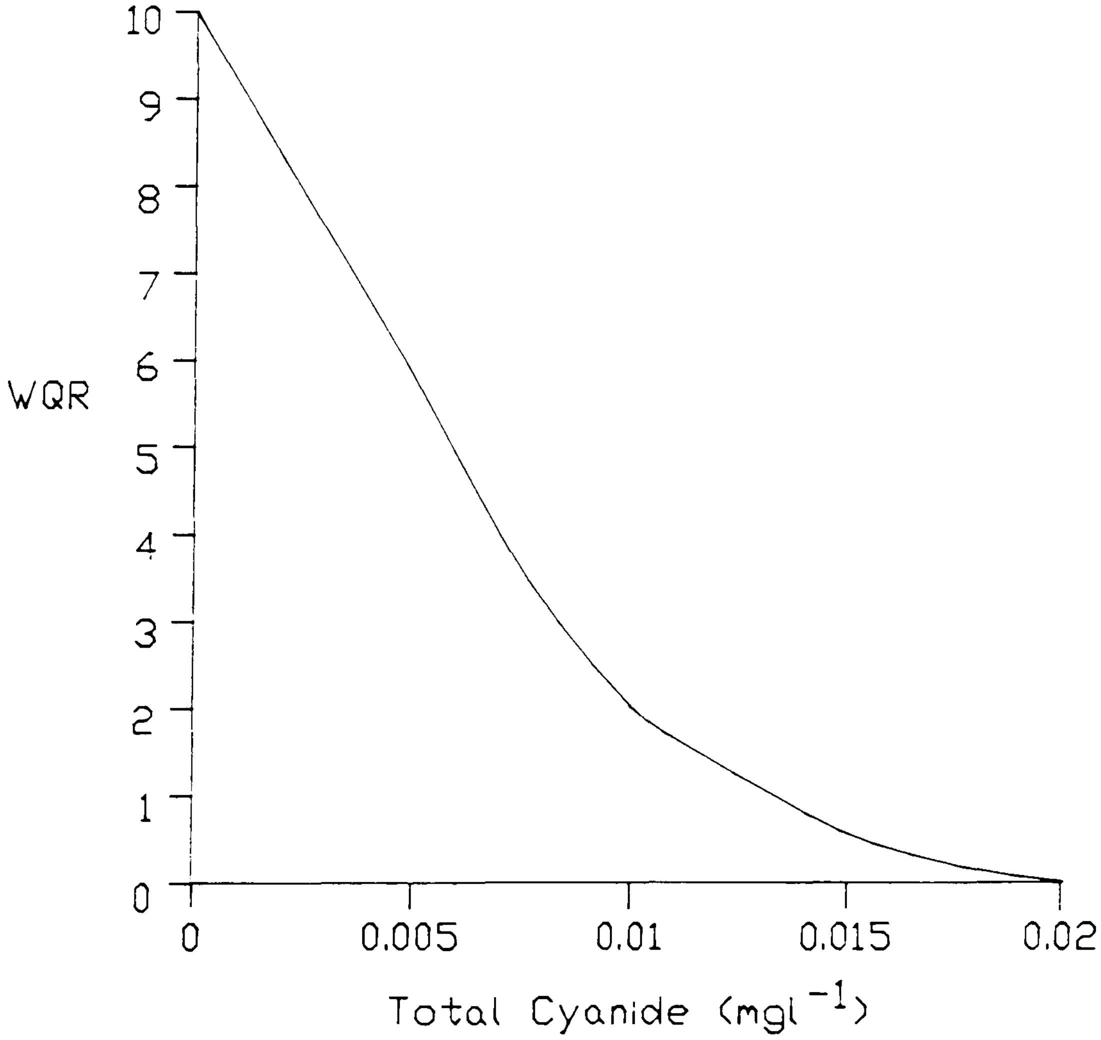


Figure 38. Total Cyanide



protection of all species of fish. The former was therefore assigned a WQR of 2.0 and the latter a WQR of zero as this is greatly in excess of all other criteria.

8.5.9. Total Cyanide (CN. mgl^{-1}) (cf Figure 38)

Concentration (mgl^{-1})	WQR
0	10.0
0.005	6.0
0.007	4.0
0.01	2.0
0.02	zero

Rationale

Free cyanide can be lethal to sensitive fish species (Doudoroff, 1966). More commonly, sub-lethal effects such as a reduction in the rate of growth and in swimming ability occur.

The toxicity of cyanide is unaffected by water hardness, thus the curve developed here is applicable to all waters.

Train (1979) has proposed a cyanide concentration of 0.005 mgl^{-1} for the protection of all species of fish. However, this criterion is half that suggested by Price and Pearson (1979). Thus, a WQR of 6.0, indicating a threshold class A1 water body, was ascribed to this concentration.

The MD and MP criteria proposed by Price and Pearson are cyanide concentrations of 0.007 mgl^{-1} and 0.01 mgl^{-1} respectively. Median and threshold class A2 WQRs were ascribed to these concentrations.

The curve was extrapolated to zero at a cyanide concentration of 0.02 mgl^{-1} which is both double the maximum permissible concentration for the protection of fish and the MP suggested by Price and Pearson for waters to be used for general amenity purposes.

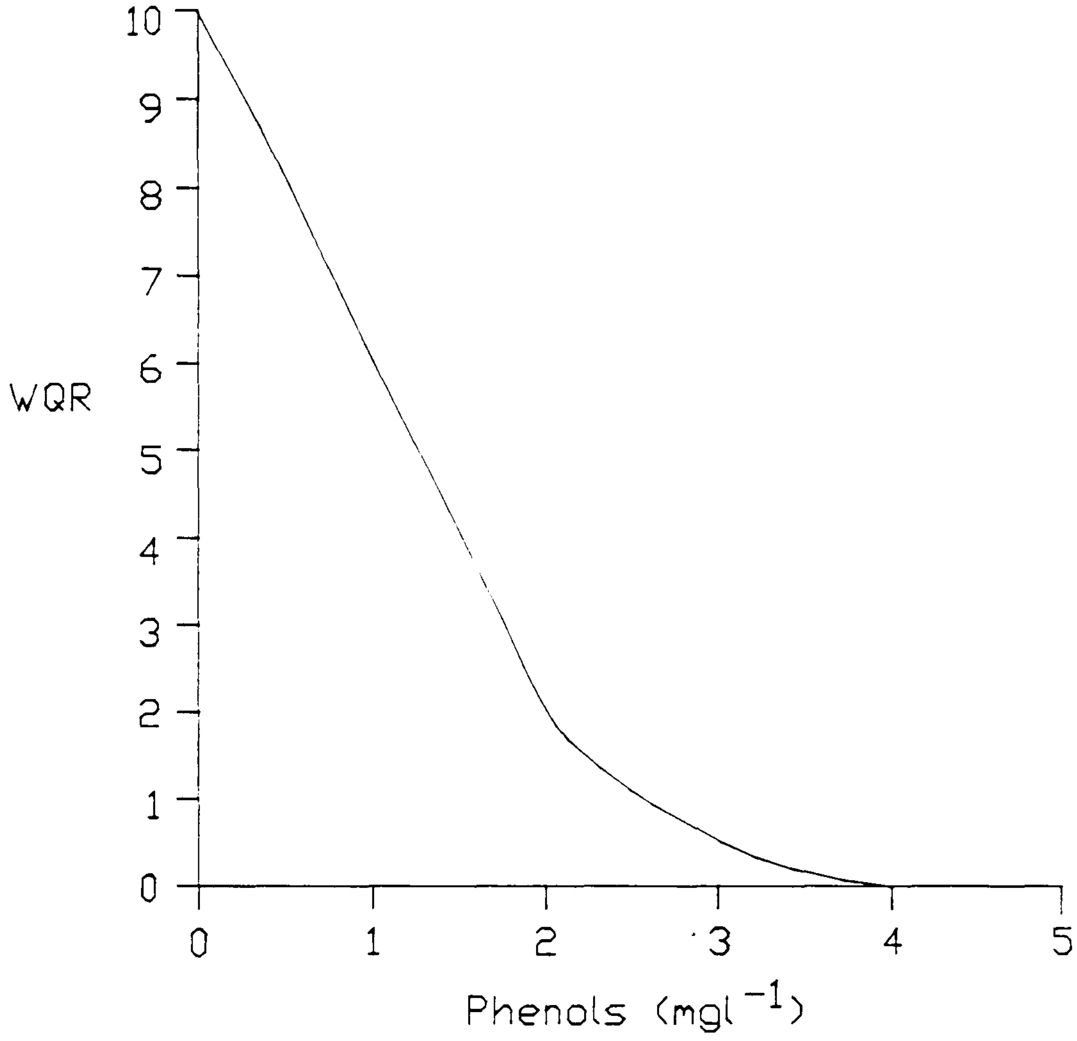
8.5.10. Phenols(mgl^{-1}) (cf Figure 39)

Concentration (mgl^{-1})	WQR
0	10.0
0.5	8.0
1.0	6.0
1.5	4.0
2.0	2.0
4.0	zero

Rationale

Phenols can be toxic to both adult and immature organisms at low concentrations (see Section 7.6.18). In addition, it can cause fish flesh to become tainted. Thus, ideally phenols should be absent from waters used for fisheries purposes. All points on the rating curve relate to MD and MP criteria proposed by either EIFAC (1973) or Price and Pearson (1979). Thus, in each case either a median or threshold A1 or A2 WQR was ascribed to the recommended limits.

Figure 39. Phenols



The curve was extrapolated to zero at a concentration of 4 mgl^{-1} as this is both double the MP concentration for the protection of fish, and the MP suggested by Price and Pearson for the use of water for amenity purposes.

8.5.11. Summary

Thus the curves outlined in sections 8.5.2. to 8.5.10 above are capable of reflecting water quality in terms of toxic determinands and provide a general indication of the use of such waters for fishery and amenity purposes.

8.6. THE DEVELOPMENT OF RATING CURVES FOR THE POTABLE SAPIDITY INDEX (PSI)

8.6.1. Introduction

This index has been developed to relate changes in water quality to its potential use as a potable water supply. It provides additional information to that produced by the PWSI because ten of the twelve determinands included within this index are potentially toxic to man and therefore require very careful monitoring. Thus a zero score from this index indicates water which is totally unacceptable for its management objective (Table 40 and Figure 8). However, this is not to say that such waters have no economic value. They may indeed be of value for some fishery or other amenity purpose.

Copper and zinc, although not toxic to man, may be objectionable when present in waters used in potable supply as they impart a bitter taste to the water when they occur in concentrations above those recommended. They are, however, toxic to fish in comparatively low concentrations. As one of the main indications of a good quality watercourse, and hence potentially good potable water supply, is that such waters support healthy fish populations, the inclusion of these determinands with those which are toxic to man will assist in evaluating the wholesomeless of the water.

Thus, the Potable Sapidity Index indicates the suitability of water for use in potable water supply in terms of its taste and wholesomeness. However, due to the toxic nature of many of the determinands included within this index, the potential use indicated by the final index score should only be considered as tentative and not definitive. When a score in the lower range of the scale is consistently recorded, (P3 and P4) the raw data must be evaluated more carefully. However, the index does accurately reflect changes in water quality and therefore the economic value of a water body.

These toxic determinands can, for the most part, be removed by effective water treatment. Consequently, the criteria proposed for most of the determinands vary with the level of treatment available. Thus, if a water body is classified as requiring conventional treatment then, assuming this level of treatment is available, any level of toxicity up to the specified load for that treatment process can be removed. Thus, following discussions with water quality experts at present involved in the management of surface waters used in PWS, it was recognised that rating curves per se were not essential to the operational management of such waters. For this reason step functions have been super-imposed onto the rating curves developed for these twelve determinands. These will either indicate the form of treatment required if surface waters are to be used in PWS, or the fact that water is unsuited to this use. This approach recognises the "lumped" nature of water quality intended for PWS, with each 'lump' having recognised threshold limits.

Rating curves have been used as the basis for defining these step functions because:

i) they are the most scientific way of relating published water quality directives and criteria on specific water use to changes in water quality;

ii) they can provide information on within class variations for those instances in which such information is required e.g. in areas which are in danger of being downgraded;

iii) they can accurately provide comparative information on which to base decisions on the selection of new sites to be used in potable water supply.

The twelve determinand curves have been developed as outlined in Section 8.3.1. However, in addition to mandatory (MP) and guideline (MD) criteria, Maximum Allowable Concentrations (MAC) have been recommended for this water use by the WRC (1984). This criterion relates to the maximum determinand concentration which must not be exceeded. Thus, these MAC values, where given, were ascribed a zero rating. By examining the directives and criteria listed in Appendix III, it is evident that these MAC values consistently relate to a concentration which is 1.5 times the mandatory or MP value. Hence, where these values have not been recommended the determinand curves have been zero rated at this concentration unless alternative criteria was available.

Some of the curves developed for this index are by necessity median curves. This was essential because of the variation which exists between guideline and mandatory criteria proposed by different authors. In instances where this occurred some weighting was attached to those proposed by the EEC (1975), WRC (1984) and Price and Pearson (1979). This is because the first of these are legal standards in Britain, and the latter two studies are based on work undertaken on British watercourses.

All of the determinands are expressed in terms of total concentrations which includes both dissolved and particulate fractions. The rationale for the development of each determinand curve is outlined below and the final curves produced are shown in Figures 40 to 51. In all cases a score of 10 indicates water which is ideally suited to its intended management use.

8.6.2. Total Copper ($Cu.mgl^{-1}$) (cf Figure 40)

Concentration (mgl^{-1})	WQR
0	10
0.02	8.5
0.05	5.5
1.00	2.5
1.50	1.0
3.00	zero

Rationale

A continuous intake of copper in water supply can cause liver damage. However, the main problem associated with copper in drinking water is that it may impart an objectionable taste (see Section 7.6.20). Thus ideally, copper should be absent in all potable water supplies (PWSs).

A concentration of 0.02 mgl^{-1} of copper is the EEC (1975) A1 guideline. Thus a WQR indicating a median P1 water supply was given to this concentration.

The EEC have proposed a concentration of 0.05 mgl^{-1} as both the mandatory A1 and guideline A2 value. The WRC (1984) agrees with both these values and the WHO I (1971) with the latter. However, the WHO (1970) and Price and Pearson (1979) believe this to be the MP concentration when only conventional treatment is available. The WQRs for each of these uses are 7.0, 5.5 and 4.0 respectively. Thus, the median WQR was given.

A concentration of 1 mgl^{-1} Cu is the MP suggested by Train (1979) and the Ontario Water Resources Commission (Ontario WRC, 1970) for waters receiving conventional treatment. However, the EEC (1975) and WRC (1984) respectively consider this concentration to be the guideline and mandatory value for advanced treatment. The WQRs for each of these directives are 4.0, 2.5 and 1.0 respectively. Thus, the median WQR was applied.

Concentrations of 1.5 mgl^{-1} and above can impart an undesirable taste to PWS regardless of the method of treatment available (WHO I 1971). Thus, a WQR of 1.0 was given to this copper concentration, indicating that such waters would be unsuitable for use in PWS.

This curve was extrapolated to zero at a copper concentration of 3 mgl^{-1}. This is the MAC value proposed by the EEC (1980) for water intended for human consumption. Thus, where this concentration is found in raw water it would indicate severe pollution and water which was unacceptable for use in PWS. This value exceeds the calculated MAC value outlined in 8.6.1. However it is considered justified in this instance because copper is not toxic to man. Thus, it would be inaccurate for a concentration below this level to result in a zero rating for the index as a whole. Thus by adopting this human consumption criteria, this determinand has been weighted inversely to the toxic determinands.

Figure 40. Total Copper

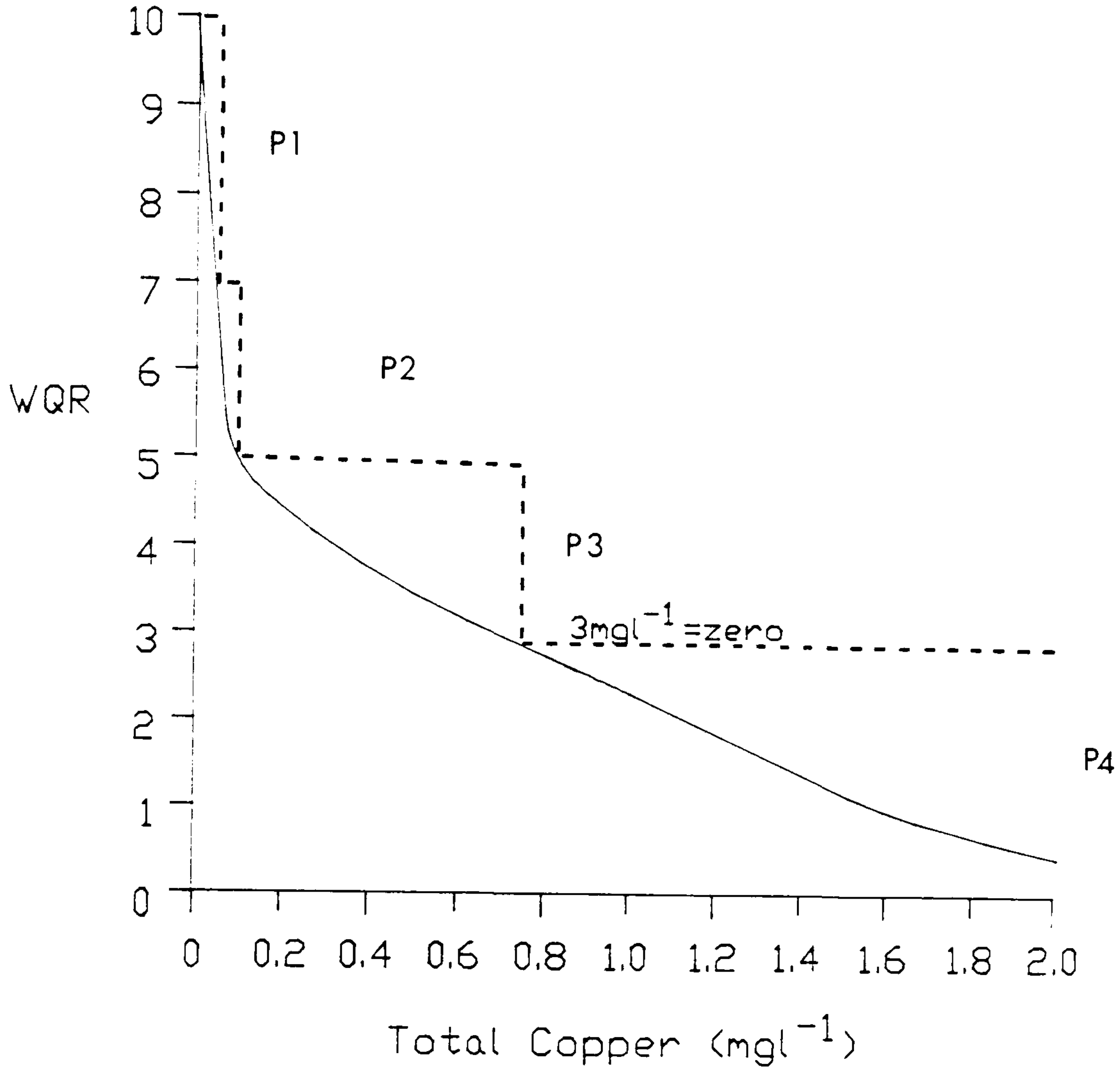
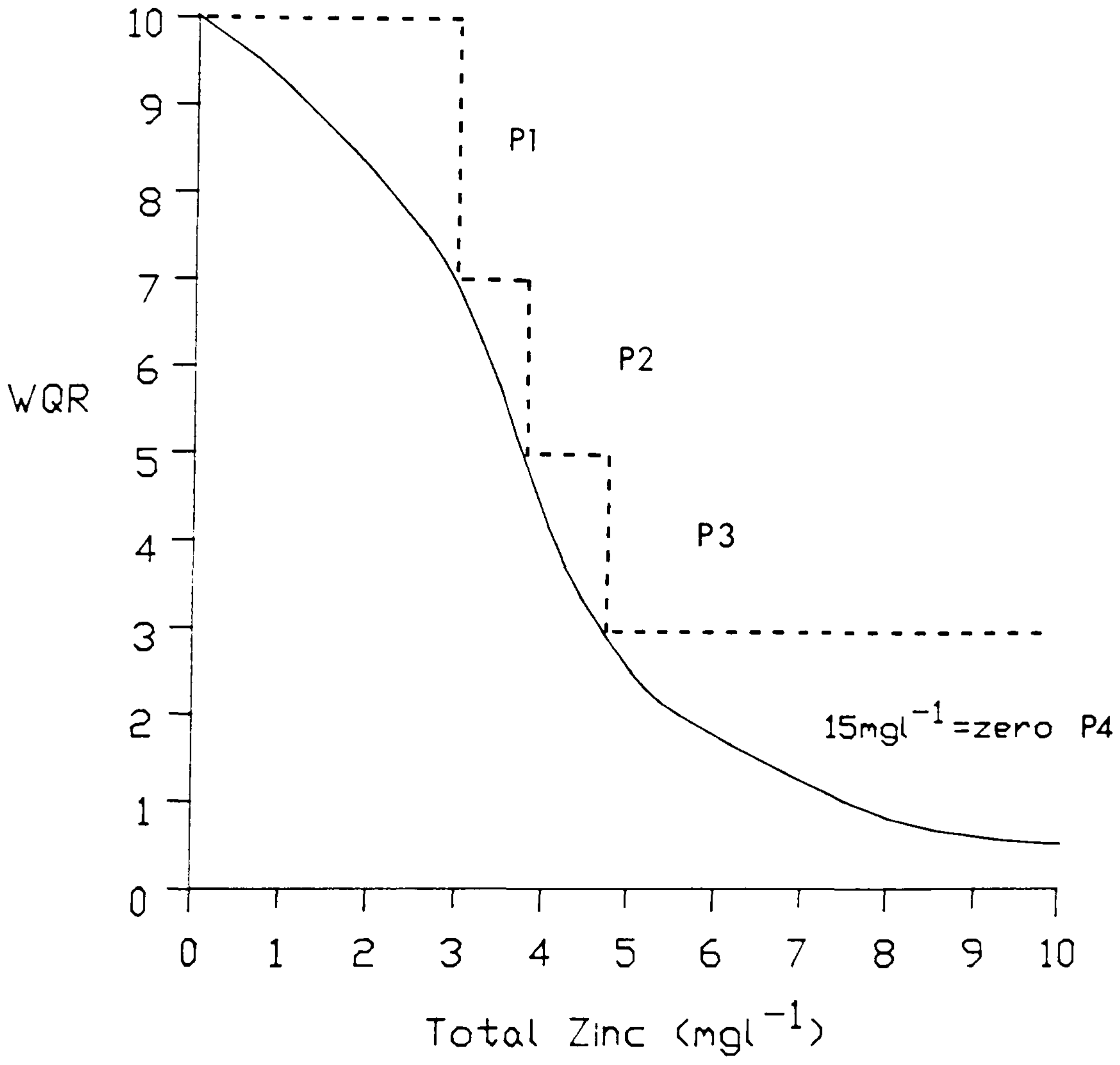


Figure 41. Total Zinc



8.6.3. Total Zinc (Zn. mgl^{-1}) (cf Figure 41)

Concentration (mgl^{-1})	WQR
0	10
3.0	7.0
5.0	2.5
7.5	1.0
15.0	zero

Rationale

As with copper, zinc can cause a bitter and objectionable taste in drinking water supplies (see Section 7.6.21). Thus a WQR of 10 is given to water in which zinc is totally absent.

A zinc concentration of 3 mgl^{-1} has been proposed by both the EEC (1975) and WRC (1984) as the mandatory value for PWSs receiving minor purification. Price and Pearson (1979) believe this to be the MD when conventional treatment is available. The WQRs for these authors' directives are 7.0, 7.0 and 5.5. Thus the median WQR of 7.0 was given.

Six of the eight authors to provide directives on zinc concentrations in drinking water propose a value of 5 mgl^{-1} as the mandatory or MP where only conventional treatment is available. However, two of them, the EEC and WRC, believe this to be the mandatory criteria regardless of the method of treatment available. Thus, the WQR's for both these forms of treatment are 4.0 and 1.0. Thus, a median between these two values of 2.5 was ascribed to this zinc concentration. Although, not strictly the median value, weighting was given to the criteria of the EEC and WRC for the reasons outlined in 8.6.1.

A zinc concentration of 7.5 mgl^{-1} is the MAC value proposed by the WRC (1984). However, a MP concentration of 15 mgl^{-1} has been suggested by the WHO I (1971) (see Appendix III). As zinc, like copper, is not actually toxic to man these concentrations have been ascribed WQRs of 1.0 and zero respectively. The former, indicating water which is unsuitable for use in PWS regardless of the method of treatment available; and the latter providing an inverse weighting to prevent zero ratings occurring on the basis of this determinand concentration alone.

8.6.4. Total Arsenic (As. mgl^{-1}) (cf Figure 42)

Concentration (mlg^{-1})	WQR
0	10
0.01	8.5
0.03	5.5
0.05	4.0
0.10	1.0
0.15	zero

Rationale

Arsenic constitutes a direct health hazard when present in drinking water. Thus a WQR of 10 was given to a zero concentration of arsenic.

The EEC (1975) guideline for waters receiving minor purification is 0.01 mgl^{-1} arsenic. Thus the median WQR for a P1 water supply was ascribed to this arsenic concentration.

Price and Pearson (1979) have suggested a MD concentration of 0.03 mgl^{-1} for PWSs receiving conventional treatment. All authors agree on a MP concentration of 0.05 mgl^{-1} for this form

Figure 42. Total Arsenic

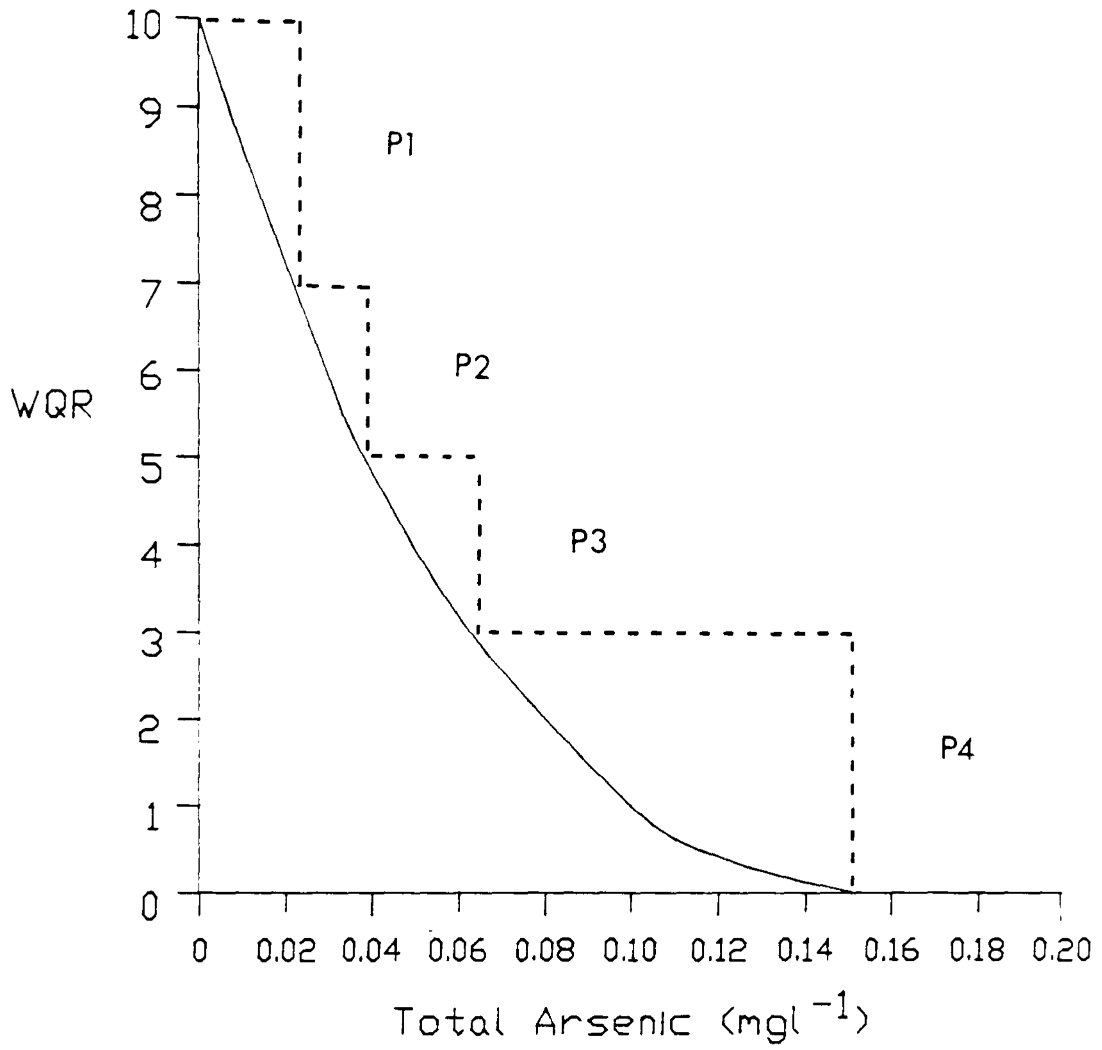
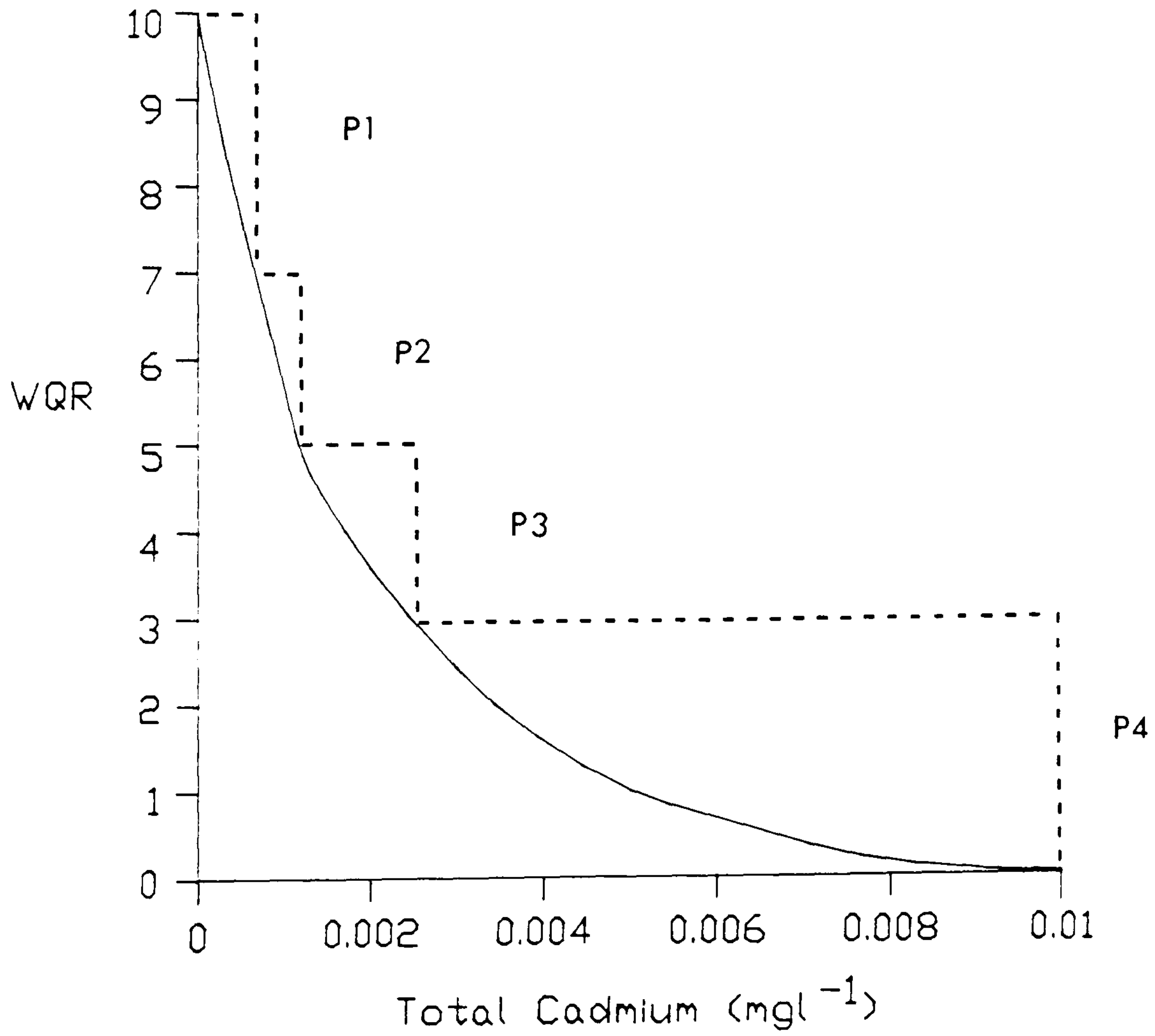


Figure 43. Total Cadmium



of treatment. Thus the median and threshold P2 WQRs were ascribed to these arsenic concentrations.

The EEC and WRC (1984) mandatory and MAC criterion for PWSs receiving advanced treatment is 0.1 mgl^{-1} and 0.15 mgl^{-1} respectively. Thus threshold P3 and P4 WQRs were applied to these concentrations.

8.6.5. Total Cadmium (Cd. μgl^{-1}) (cf Figure 43)

Concentration (μgl^{-1})	WQR
0	10
1	5.5
5	1.0
10	zero

Rationale

By comparing the above table for cadmium with that of arsenic it is interesting to notice that the former is considered by all authors to be considerably more toxic than the latter.

The ingestion of cadmium causes symptoms similar to food poisoning. Thus ideally cadmium should be absent in PWSs, and a WQR of 10 was equated to this situation.

The development of the remainder of this curve was made difficult by the fact that the EEC directive (1975) on total cadmium concentrations in PWSs is far more severe than those produced by all other authors (see Appendix III). However, it was thought necessary to be biased towards the EEC directive because of its legislative importance.

The EEC guideline and mandatory criteria for cadmium concentrations in PWS, regardless of the method of treatment are 1 μgl^{-1} and 5 μgl^{-1} respectively. Thus, WQRs of 5.5 (median for the PWS range) and 1.0 (threshold for use) were given to these concentrations.

The curve was extrapolated to zero at a concentration of 10 μgl^{-1} as this is the MP concentration proposed by all other authors.

8.6.6. Total Chromium (Cr mgl^{-1}) (cf Figure 44)

Concentration (mgl^{-1})	WQR
0	10
0.03	5.5
0.05	1.0
0.075	zero

Price and Pearson (1979) have suggested chromium concentrations of 0.03 mgl^{-1} and 0.05 mgl^{-1} as the MD and MP for PWSs receiving conventional treatment. However, the EEC (1975) believe the latter to be the mandatory value regardless of available treatment. The WRC (1984) have proposed a MAC value of 0.075 mgl^{-1}. Thus, the WQRs ascribed to these concentrations were 5.5, 1.0 and zero respectively with presidence being given to the criteria of the EEC.

Figure 44. Total Chromium

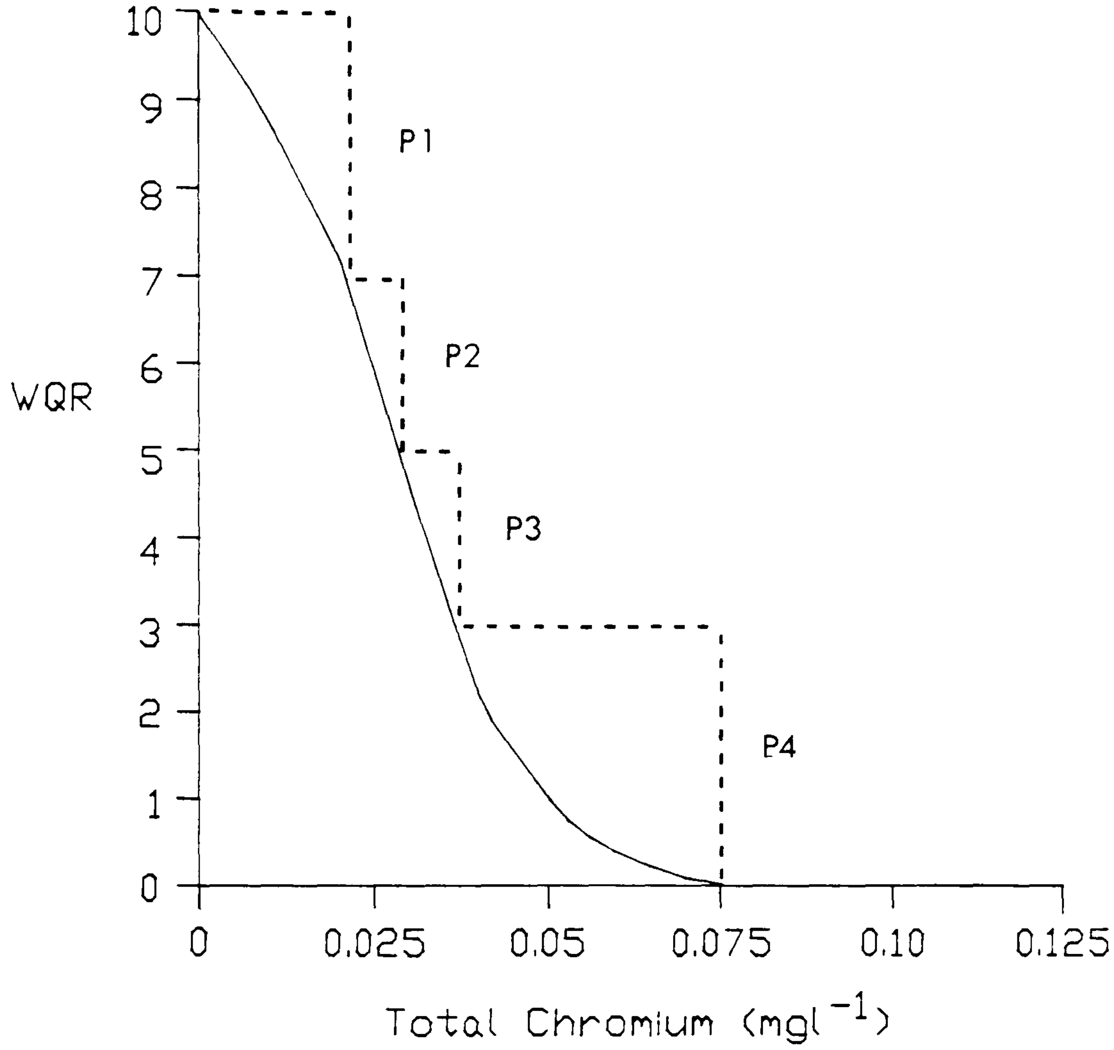
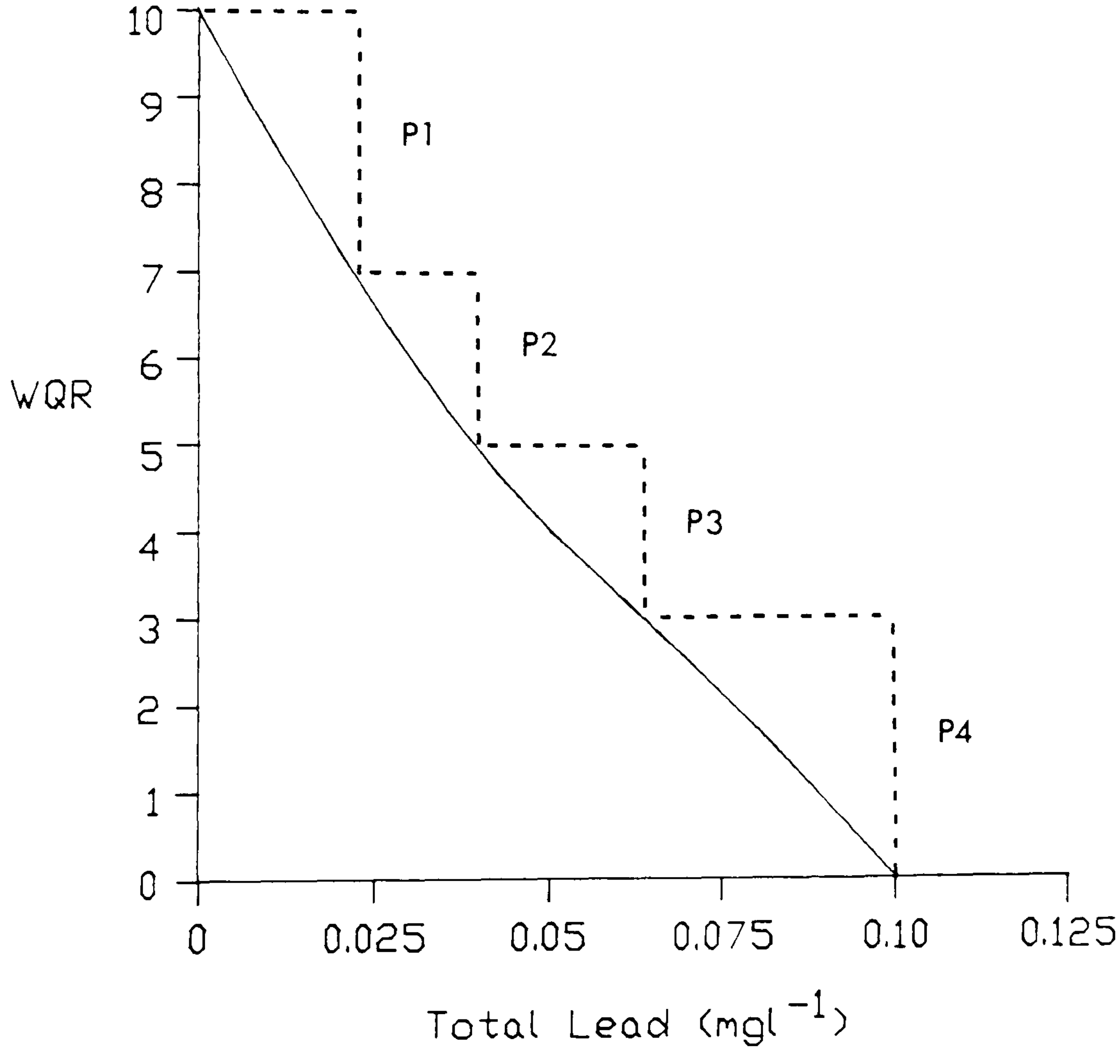


Figure 45. Total Lead



8.6.7. Total Lead (Pb. mgl^{-1}) (cf Figure 45)

Concentration (mgl^{-1})	WQR
0	10
0.05	4.0
0.07	2.5
0.1	zero

Rationale

Lead is a toxic metal which may accumulate in human tissues and cause brain damage (see Section 7.6.26). Thus, a WQR of 10 was given to zero lead concentrations.

The criterion proposed by the EEC (1975) on lead concentrations in PWS is extremely limiting and it would be impossible to develop a curve based on this one concentration alone (see Appendix III). Thus in this instance a median curve has been drawn which considers the criteria proposed by other authors in light of that of the EEC. For this reason, it may be necessary to omit lead from the final index calculation in instances in which the curve developed here is considered inappropriate.

The EEC propose a mandatory value of 0.05 mgl^{-1} for PWSs regardless of the method of treatment available. Train (1979) and the Ontario WRC (1970) have proposed this as the MP concentration for waters receiving conventional treatment; and Price and Pearson (1979) and the WHO (E (1970) and I (1971)) consider this value as the Maximum Desirable for this form of treatment. The respective WQRs for these three directives are 1.0, 4.0 and 5.5. Thus the median WQR was applied.

Price and Pearson have proposed MD and MP concentrations of 0.07 and 0.1 mgl^{-1} for waters receiving conventional treatment. WHO (E and I) agree with the latter. These directives should obtain WQRs of 5.5 and 4.0 respectively; however, as they are in excess of EEC recommendations, median P3 and use limiting WQRs of 2.5 and zero were awarded to these concentrations.

8.6.8. Total Mercury (Hg. µgl^{-1}) (cf Figure 46)

Concentration (µgl^{-1})	WQR
0	10
0.5	5.5
1.0	1.0
1.5	zero

Rationale

Mercury can be hazardous to human health (see Section 7.6.19) and consequently should be absent in PWSs. Thus a WQR of 10 was ascribed to this ideal.

A concentration of 0.5 µgl^{-1} has been suggested by the EEC (1975) as a guideline for all PWSs regardless of the method of treatment available. Thus a WQR of 5.5 was ascribed to this directive.

Both the WHO (1971) and Price and Pearson (1979) have proposed a MP concentration of 1.0 µgl^{-1} for PWSs receiving conventional treatment. However, the EEC believe this to be the mandatory concentration regardless of the method of treatment available.

Thus precedence was given to the EEC directive and a WQR of 1.0 was awarded.

Figure 46. Total Mercury

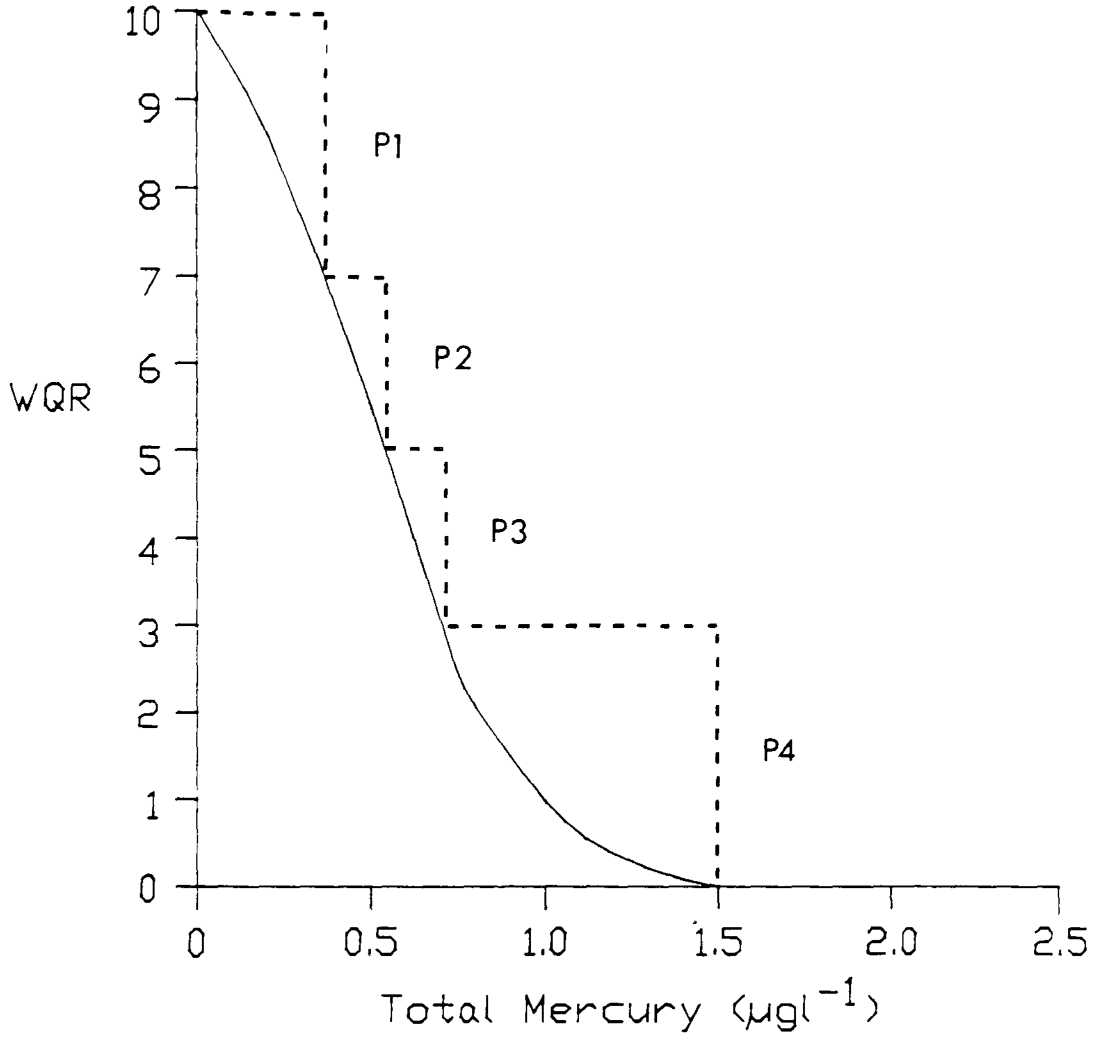
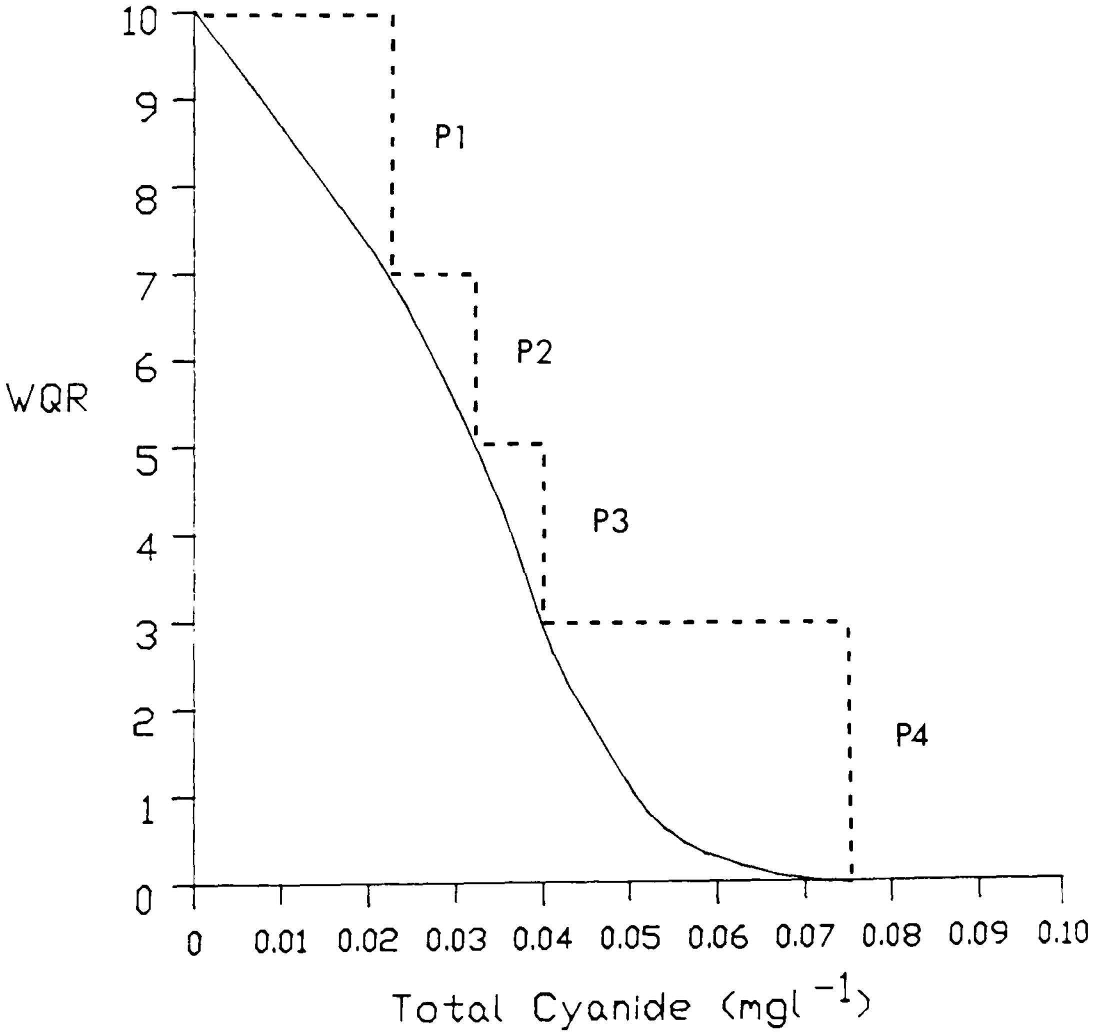


Figure 47. Total Cyanide



The curve was extrapolated to zero at a mercury concentration of 1.5 μgl^{-1} as this is the calculated MAC value (see Section 8.6.1.).

8.6.9. Total Cyanide (CN mgl^{-1}) (cf Figure 47)

Concentration (mgl^{-1})	WQR
0	10
0.03	5.5
0.05	1.0
0.075	zero

Rationale

Cyanide concentrations would have to be high to overwhelm human detoxifying mechanisms (see Section 7.6.27), although it should still, ideally, be absent in PWSs.

Price and Pearson (1979) suggest a MD concentration of 0.03 mgl^{-1} in PWSs receiving conventional treatment. Thus a WQR of 5.5, indicating a median class P2 water supply, was given to this cyanide concentration.

The EEC (1975) propose a mandatory criterion of 0.05 mgl^{-1} regardless of the method of treatment available. Thus, although most other authors believe this to be the MP when only conventional treatment is available, a use-limiting WQR of 1.0 was given to this concentration.

The curve was extrapolated to zero at a CN concentration of 0.075 mgl^{-1}, as this was the calculated MAC value (see Section 8.6.1).

8.6.10. Phenols (mgl^{-1}) (cf Figure 48)

Concentration (mgl^{-1})	WQR
0	10
0.001	5.5
0.005	4.0
0.01	2.5
0.10	1.0
0.15	zero

Rationale

Phenols may cause taste and odour problems when used in PWS as they cannot always be removed efficiently by conventional treatment (see Section 7.6.18). These problems may, in fact, be exacerbated by disinfection. In addition, phenols can become toxic to man (EEC, 1980). Thus, ideally, they should be absent in all PWSs.

The EEC (1975) propose a concentration of 0.001 mgl^{-1} as both the mandatory criterion for PWSs receiving minor purification and the guideline criterion for those receiving conventional treatment. However, Train (1979) and WHO E, (1970) suggest this concentration as the MP when only conventional treatment is available. The WQRs for these three directives are 7.0, 5.5 and 4.0 respectively. The median WQR of 5.5 was given to this phenols concentration, indicating a median P2 water supply.

The EEC mandatory criterion for PWSs receiving conventional treatment is a phenols concentration of 0.005 mgl^{-1}. Thus a use-limiting WQR of 4.0 was given to this concentration.

Figure 48. Phenols

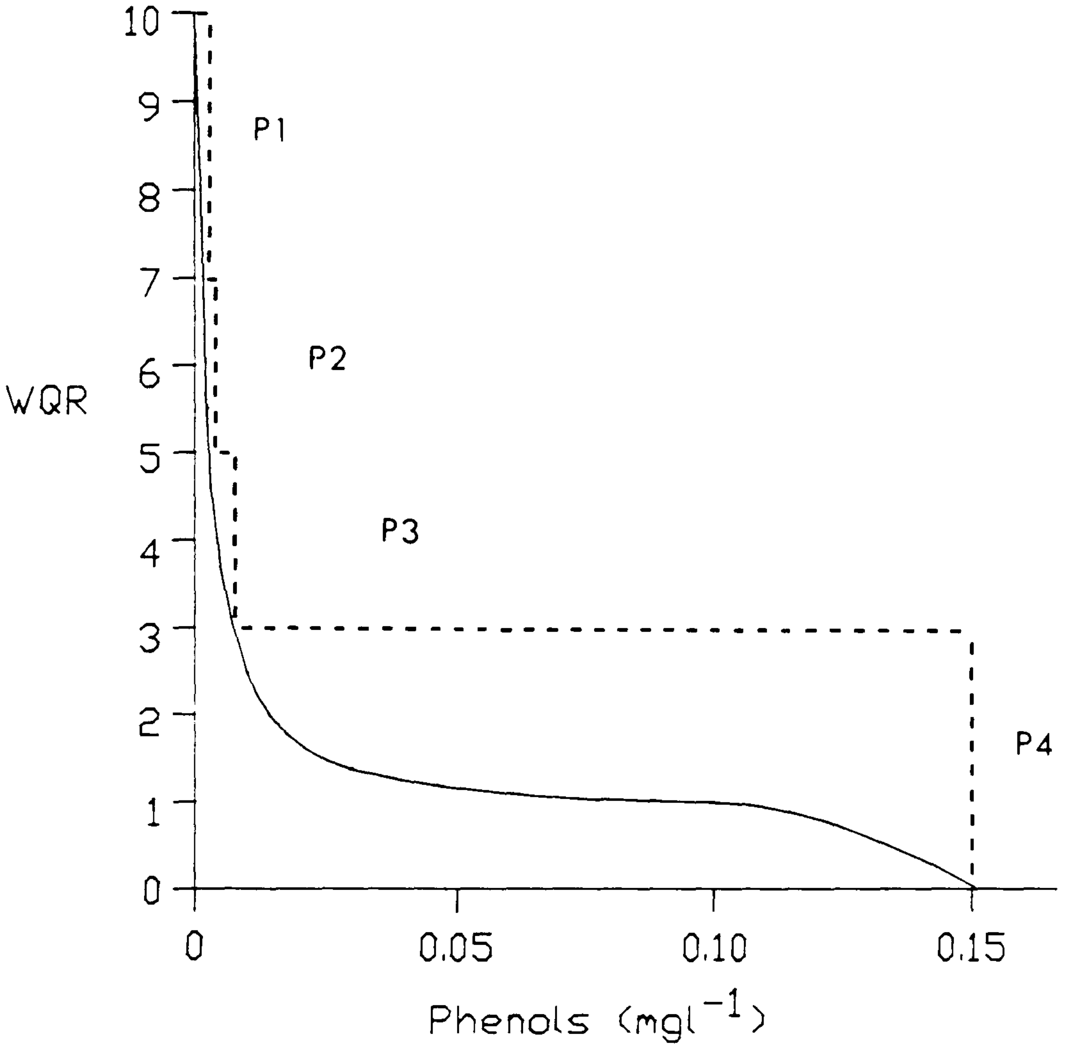
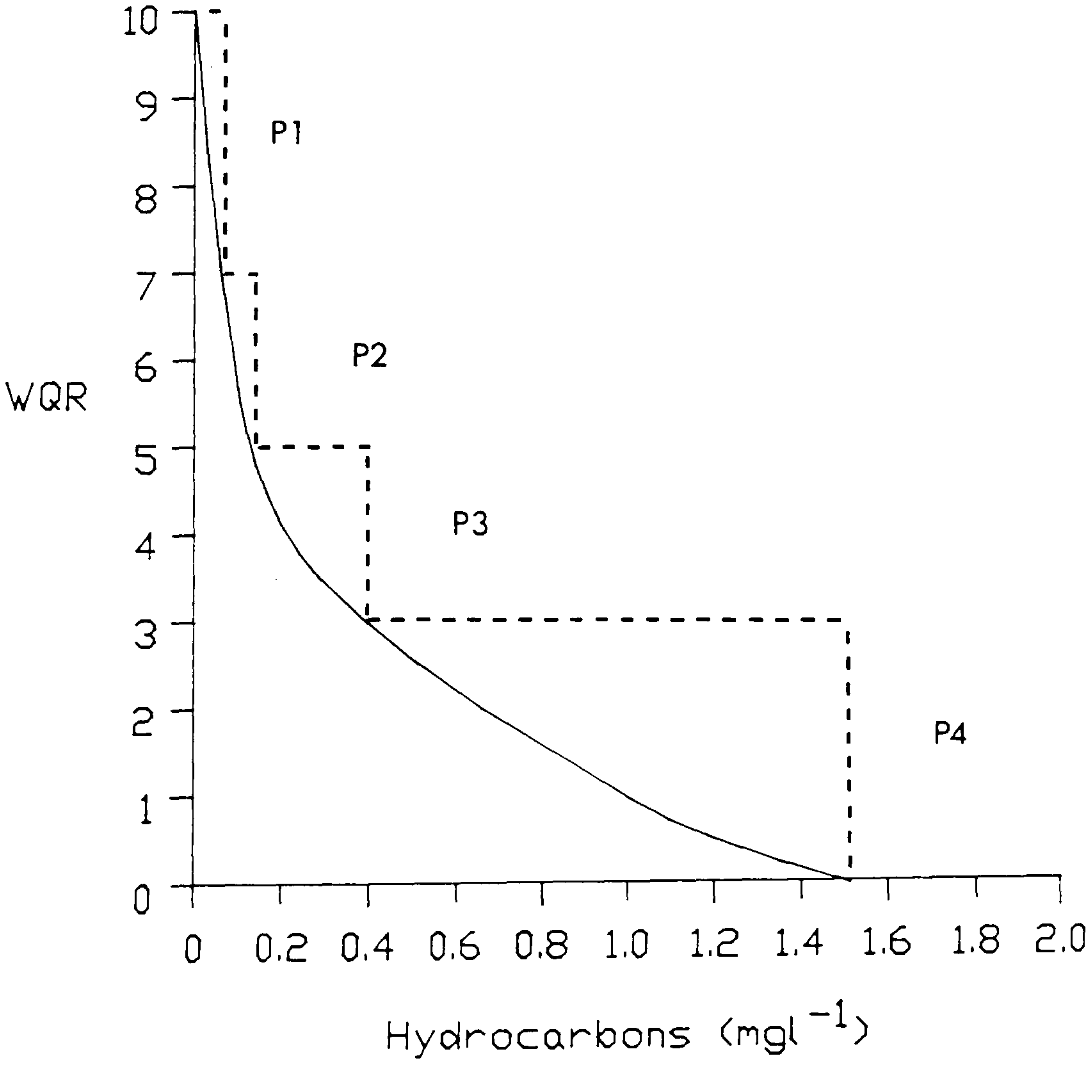


Figure 49. Hydrocarbons



The EEC guideline and mandatory criteria for PWSs receiving advanced treatment are phenol concentrations of 0.01 and 0.1 mgl^{-1} respectively. Hence median and threshold P3 WQRs were given to these phenol concentrations.

The curve was extrapolated to zero at a phenols concentration of 0.15 mgl^{-1} as this concentration is the calculated MAC value (see Section 8.6.1). However, such water could be of value for fishery and amenity uses.

8.6.11. Hydrocarbons (mgl^{-1}) (cf Figure 49)

Concentration (mgl^{-1})	WQR
0	10
0.05	7.0
0.10	5.5
0.20	4.0
0.50	2.5
1.00	1.0
1.50	zero

Rationale

Hydrocarbons should ideally be absent from all PWSs. Thus, a WQR of 10 was given to a zero concentration.

The EEC (1975) mandatory criterion for PWSs receiving only minor purification is a hydrocarbons concentration of 0.05 mgl^{-1}. Thus the threshold P1 WQR was ascribed to this value.

The Swedish Public Health Department (1976) suggest a MD hydrocarbon concentration of 0.1 mgl^{-1} in PWSs receiving conventional treatment. The EEC mandatory criterion for this form of treatment is a concentration of 0.2 mgl^{-1}. Thus, median and threshold P2 WQRs were given to these concentrations of hydrocarbons.

The EEC (1975) guideline and mandatory concentrations for PWSs receiving advanced treatment are 0.5 and 1.0 mgl^{-1} respectively. Therefore, median and threshold P3 WQRs were allotted to these concentrations.

The curve was extrapolated to zero at a concentration of 1.5 mgl^{-1} as this is the calculated MAC value and indicates water which is totally unsuitable for use in PWS.

8.6.12. Polyaromatic Hydrocarbons (PAH μgl^{-1}) (cf Figure 50)

Concentration (μgl^{-1})	WQR
0	10
0.2	4.0
1.0	1.0
1.5	zero

Rationale

Polyaromatic Hydrocarbons (PAHs) should ideally be absent from PWSs. Thus a WQR of 10 was ascribed to this concentration.

The EEC (1975) and WHO (E (1970) and I (1971)) mandatory criterion for PWSs receiving either minor or conventional treatment is a concentration of 0.2 μgl^{-1}). Thus a threshold P2 WQR was ascribed to this concentration.

Figure 50. P.A.H.

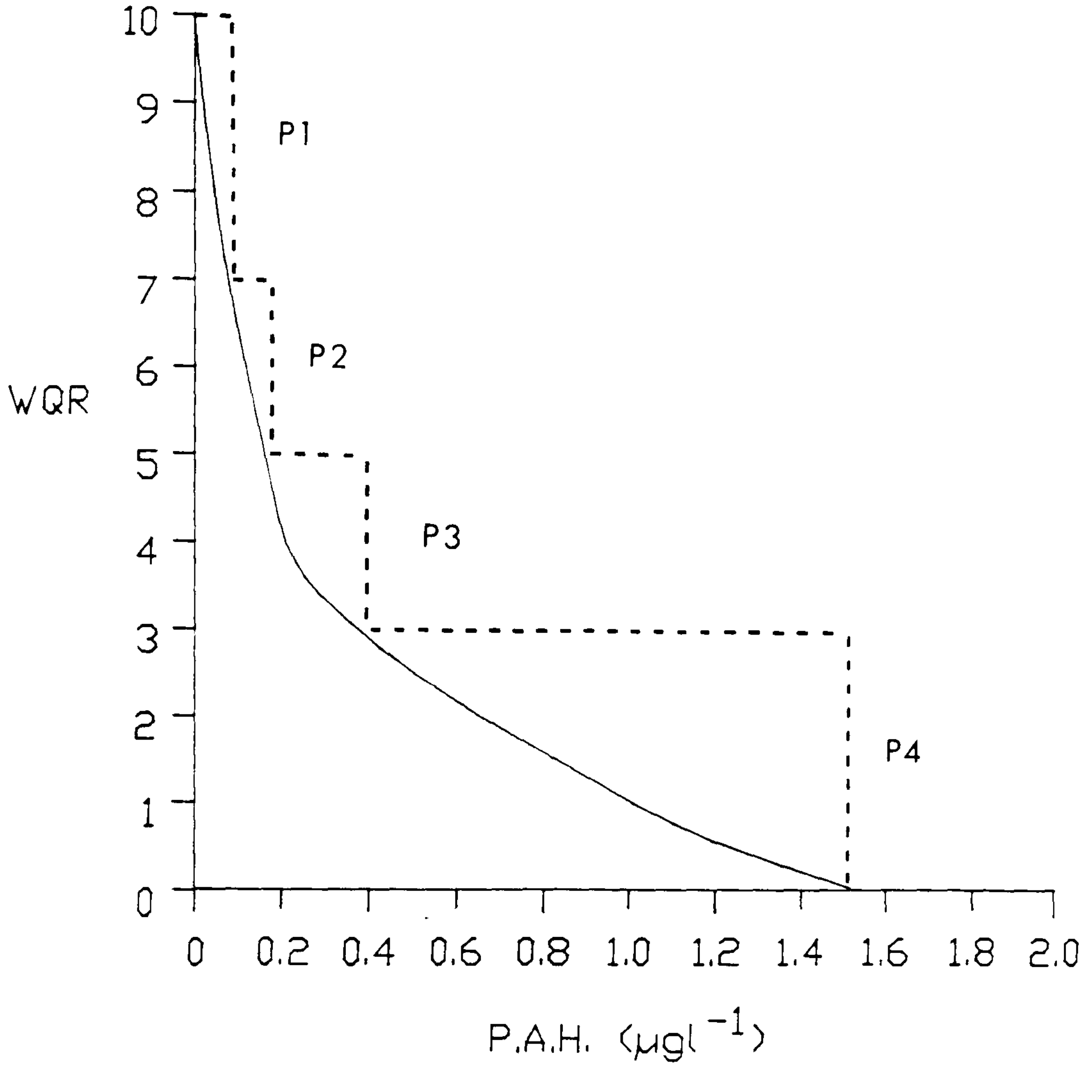
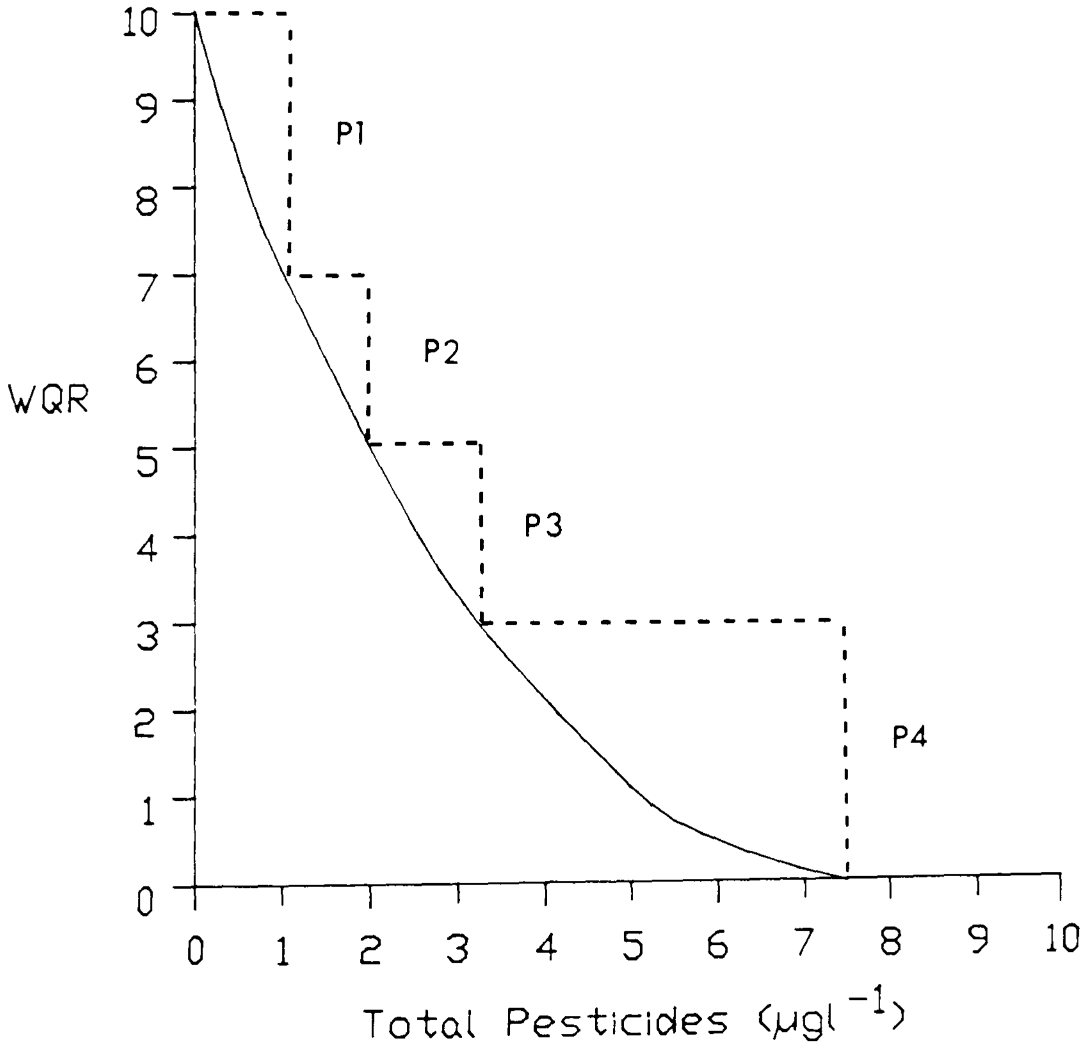


Figure 51. Total Pesticides



The mandatory criterion proposed by the EEC for PWSs receiving advanced treatment is a concentration of 1.0 μgl^{-1}. This was ascribed a use limiting WQR of 1.0.

Finally, the curve was extrapolated to zero at a PAH concentration of 1.5 μgl^{-1} as this is the calculated MAC value (See Section 8.6.1).

8.6.13 Total Pesticides (μgl^{-1}) (cf Figure 51)

Concentration (μgl^{-1})	WQR
0	10
1	7.0
2.5	4.0
5.0	1.0
7.5	zero

Rationale

A WQR of 10 was given to 0 μgl^{-1} Pesticides as ideally these should be absent from PWSs.

Concentrations of 1.0, 2.5 and 5.0 μgl^{-1} are the mandatory criteria produced by the EEC (1975) for potable water supplies receiving minor, conventional or advanced treatment respectively. Thus class-limiting P1, P2 and P3 WQRs were ascribed to these concentrations respectively.

The curve was extrapolated to zero at a total pesticides concentration of 7.5 μgl^{-1}. This concentration is within the criterion proposed by the Ontario WRC (1970) but is, however, 1.5 times that of the EEC. Thus such waters would be unsuitable for use in PWS.

8.7. SUMMARY

The rating curves outlined in this chapter have been developed in accordance with published water quality directives and criteria. Each index scale has been sub-divided into either four or three main classes of water quality. Each class provides a general description of water quality and relates this to possible water use. Determinand concentrations were transformed on to the index scales by ascribing mandatory or maximum permissible concentrations class limiting WQRs; guideline or maximum desirable concentrations median WQRs; and 50 percentile concentrations were ascribed WQRs which are one third of the class range. In this way, the curves were developed in a reasonably objective manner. Step functions were added to the final curves developed for the twelve determinands of the Potable Sapidity Index as information on within-class variations in toxicity are not required in this instance.

Thus, with the determinand transformations developed for the four proposed indices it is possible to proceed to the final stage in the development of these indices - the development of weightings and mathematical formulae.

CHAPTER 9

DETERMINAND WEIGHTINGS

9.1. INTRODUCTION

Water quality experts regularly attach weightings to individual determinands in their subjective assessment of water quality. This is because some determinands are considered to be either more indicative of pollution, or more detrimental to beneficial water use than others. Thus, they establish a 'pecking order' or hierarchy of determinands in the overall index score.

Investigations into the accuracy of index scores derived using both weighted and unweighted versions of a number of indices have been undertaken (Brown et al, (NSFI), 1970 to 1976; SDD, 1976; Anglian and Yorkshire Water Authority, Internal Reports, 1979; Dunnette, 1979). In all cases a more accurate assessment of water quality was obtained when weightings were applied (see Section 4.5.). For this reason weightings have been derived for the determinands included within the general and potable water supply indices developed as part of this research.

Weightings were not considered necessary for the Aquatic Toxicity or Potable Sapidity Indices because detrimental concentrations of these determinands are more likely to result from isolated pollution events such as storm run-off, or an accidental industrial spillage. Thus, both the occurrence of, and the problems associated with these determinands, vary on a national scale. In addition, where any one of these determinands occurs in concentrations in excess of recommended limits, both human and aquatic life can be endangered. Thus, it is impossible to single out any one determinand as being more important than any other, although locally one may be of greater concern than another. For example, arsenic is known to occur in concentrations at or near recommended levels in some catchments within the South West Water Authority, whereas mercury concentrations are of greater concern in some North West Water Authority catchments.

Two determinands for which the above is less applicable are copper and zinc, because they are not toxic to man at the concentrations generally encountered within UK surface waters. For this reason, these determinands have been inversely weighted to all other determinands during the development of rating curves for the Potable Sapidity Index (see Section 8.6.2. and 8.6.3.)

The approach to the development of weightings within previously developed indices has included:

i) the subjective assessment of weightings based upon the personal experience of individual authors (Horton, 1965; Inhaber, 1975; Ross, 1977);

ii) the subjective assessment of individual authors based upon published literature eg Water Quality Criteria (Dinius, 1972; Stoner, 1978);

iii) the use of statistical analysis to rank data (Shoji et al, 1966; Harkins, 1974; Joung et al, 1978);

iv) the development of weightings based upon those contained within previously developed indices (SDD, 1976); and

v) the development of weightings by means of a DELPHI opinion research technique (Brown et al, (NSF) 1970 to 1976; O'Connor, 1971; Deininger and Maciunas, 1971; SDD, 1976; Dunnette, 1979).

Often the combined use of two or more of the above methods has been advocated (SDD, 1976).

The use of either (i) or (ii) above was rejected in this instance due to the inherent subjectivity which results from either approach.

Weightings developed using statistical analysis are dependent upon the data used in their production. Previous workers using these techniques have based their calculations on data collected from a single river catchment, covering a limited time span (Shoji et al, 1966; Harkins, 1974; Joung et al, 1978). Consequently, index scores based on weightings developed in this way were not comparable in either space or time. If these techniques were to be used in the development of weightings for national application, as is required by the WQI and PWSI, data collected from all water authorities and river purification boards, covering a variety of quality conditions and treatment facilities, would have to be used. Even then the accuracy of weightings produced in this way would be questionable. Consequently, this approach to the development of weightings was rejected.

A consideration of weightings included within previously developed indices would be of doubtful value. All but two of these indices originate from outside the UK, where the emphasis placed by the respective water industries on certain determinands differs substantially from that of water experts in the UK, (see Section 7.2.). This has been highlighted by Deininger and Newsome (1984), who found that water experts from the UK and Brazil ascribed lower index scores to a range of water quality data than experts from the USA. This may, in part, be associated with different weightings being subjectively applied to individual determinands. In addition, the use of this approach in the development of weightings for the PWSI would be subject to further doubt, as only four such indices have been previously developed and two of these were developed by the same authors (Deininger and Maciunas, 1971). Thus, the use of weightings within previously developed indices was rejected.

Therefore, weightings were developed based upon the opinion of water quality experts from the UK water authorities and river purification boards. This involved the completion of two separate questionnaires, one for each index, by water quality officers (see Appendix IV and V). Respondents were asked to rank the determinands included within each index in descending order with the determinand considered to be the most important receiving the highest ranking. The results obtained from these questionnaire surveys are outlined below and shown in Tables 41 to 48.

9.2. THE DEVELOPMENT OF WEIGHTINGS FOR THE GENERAL WATER QUALITY INDEX (WQI)

It was hoped that weightings could be derived for this index using the rankings ascribed to these determinands by water authority officers within the questionnaire undertaken as part of the determinand selection procedure (see Section 7.4.). However, total coliforms were not included within this survey and, therefore, an additional questionnaire was undertaken (see Appendix IV).

Of the thirty five questionnaires originally despatched, twenty three were returned completed. Thus, a 66% response was achieved. Some of the incomplete questionnaires may be explained by a lack of awareness amongst water quality managers in Britain of, not only the use of indices, but on their existence. In addition, it was apparent from the interview programme (outlined in Sections 7.3 and 7.4) that some water authority officers were totally opposed to the use of indices in the management of surface water quality in Britain. In particular, concern was expressed over the use of an index to reflect water quality in terms of all potential water uses. Many felt that both the determinands selected and the weightings ascribed to them would fundamentally vary with potential water use.

The determinand rankings obtained from this questionnaire are shown in Table 41 with the range of rankings ascribed to each determinand given in the last column. These indicate the varied nature of expert opinion on the importance of certain determinands, particularly total coliforms and suspended solids. In addition, these results indicate the inherent danger of including the subjective assessment of determinand weightings within the use of existing classification systems. If expert opinion on the importance of certain determinands is indeed as diverse as the results in Table 41 suggest, the results produced by, for example, the National Water Council (NWC, 1978) classification are unlikely to be reproducible from one expert to another.

Mean, median and modal rankings were calculated for each determinand to assess the statistical distribution of the data and the most efficient way of using these rankings to develop determinand weightings (Table 42). It is evident from Table 42 that the use of modal values must be excluded from further consideration in the development of weightings due to the occurrence of bimodal values for total coliforms. However, by listing the determinands in rank order, it is evident that the nine index determinands can be sub-divided into a number of 'importance' categories on the basis of these mean, median and modal values (Table 43).

Table 41 The Rankings Obtained from the WQI Questionnaire Survey

Respondent Determinand	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	Range of Rankings
Suspended Solids	5	3	5	6	6	7	1	3	3	5	3	5	6	5	6	8	7	3	4	3	1	1	2	1-8
Chlorides	1	4	2	4	7	2	3	1	2	1	2	3	1	2	2	3	2	1	2	2	3	2	1	1-7
pH	4	2	4	2	2	4	4	5	5	7	4	4	3	4	4	7	6	4	6	6	4	6	6	2-7
Dissolved Oxygen	9	6	8	8	8	9	9	9	8	7	9	8	4	7	9	6	9	9	9	9	9	9	8	4-9
Total Coliforms	7	7	6	1	4	5	6	8	7	4	5	2	7	6	5	5	5	6	1	4	7	3	9	1-9
B.O.D.	6	9	7	9	5	8	7	8	9	8	8	9	9	9	8	9	8	8	8	8	6	8	5	5-9
Temperature	4	1	1	3	1	1	2	6	1	3	1	1	2	1	1	1	1	2	3	1	2	4	3	1-6
Ammonia	9	8	9	7	9	6	8	5	6	9	7	7	8	8	7	4	3	7	7	7	8	7	7	3-9
Nitrates	2	5	3	5	3	3	5	2	4	3	6	6	5	3	3	2	4	5	5	5	5	5	4	2-6

NB. The highest ranking has been ascribed to the determinand which is considered to be most indicative of water quality change or detrimental to potential water use.

Table 42. The Statistical Distribution of the WQI Questionnaire Data

Statistics Determinand												Median Ranking												Sum of Rankings	Mean Ranking
Suspended Solids	1	1	1	2	3	3	3	3	3	3	4	5	5	5	5	5	6	6	6	6	7	7	8	98	4.26
Chlorides	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	3	3	3	3	4	4	7	53	2.30
pH	2	2	2	3	4	4	4	4	4	4	4	4	4	4	5	5	6	6	6	6	6	7	7	103	4.47
Dissolved Oxygen	4	6	6	7	7	8	8	8	8	8	8	9	9	9	9	9	9	9	9	9	9	9	9	186	8.08
Total Coliforms	1	1	2	3	4	4	4	5	5	5	5	5	6	6	6	6	7	7	7	7	7	8	9	120	5.21
B.O.D.	5	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	9	9	9	9	9	9	9	179	7.78
Temperature	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	4	4	6	46	2.00
Ammonia	3	4	5	6	6	7	7	7	7	7	7	7	7	7	8	8	8	8	8	9	9	9	9	163	7.08
Nitrates	2	2	2	3	3	3	3	3	3	4	4	4	5	5	5	5	5	5	5	5	5	6	6	93	4.04

_ Denotes the modal values

Table 43. The Initial Sub-Division of the WQI Determinands Based on Mean, Median and Modal Rankings

Determinand	Mean Rankings	Median Ranking	Modal Ranking
Dissolved Oxygen	8.08	9	9
B.O.D.	7.78	8	8
Amm. Nitrogen	7.08	7	7
Total Coliforms	5.21	5	5/7
Suspended Solids	4.26	5	3
pH	4.47	4	4
Nitrates	4.04	4	4
Chlorides	2.30	2	2
Temperature	2.00	1	1
Total Ranking	45.22	45.00	

By examining the 'importance' categories outlined in Table 43, it is evident that all the determinands are similarly ranked, regardless of the statistical expression of the data selected, with the exception of suspended solids. These would be categorized into group two (ie of secondary importance) if the median rankings were applied; group three if the mean rankings were used and down to group four if the modal rankings were to be considered. This again reflects the varied opinion of experts as to the importance of certain determinands in the classification of water quality.

The median rankings were selected for the final calculation of the weightings for the WQI, because median values are generally considered best to reflect the range and distribution of a data set. Mean values simply produce an average - a number which ignores both the range and distribution of the data. In essence, the median rankings shown in Table 43 are the determinand weightings. However, in order to keep the index as simple as possible, it is desirable to have the sum of the weightings equal to one. In this way, if data on one or more of the nine WQI determinands is unavailable, the weightings can be recalculated and the precise 'pecking order' maintained. A formulae for the recalculation of weightings has been given by the SDD (1976) (see footnote to Section 4.8.).

Weightings based on these median rankings were calculated using:

$$w_i = r_{mi} \; (1 \div \sum_{i=9}^{n} r)$$

where w_i = the weighting of the ith determinand;
r_{mi} = the median ranking of the $_i$th determinand;
r = the ranking of the determinands
and n = the number of determinands

The weightings produced in this way are shown in Table 44. Weightings to only two decimal places are required, thus the intermediate weightings produced (column 2, Table 44) were rounded to the nearest figure (column 3, Table 44) in such a way as to maintain the unity of the sum of the weightings.

Thus the results suggest that dissolved oxygen, B.O.D. and ammoniacal nitrogen are considered by water quality experts in the UK to be the most indicative of pollution or detrimental to potential water use, with chlorides and temperature being substantially less significant.

Table 44. The Development of Weightings Based on Median Rankings

Determinand	1 Median Ranking	2 Intermediate Weighting	3 Final Weighting
Dissolved Oyxgen	9	0.19(9)	0.20
B.O.D.	8	0.17(7)	0.18
Amm. Nitrogen	7	0.15(5)	0.16
Total Coliforms	5	0.11(1)	0.11
Suspended Solids	5	0.11(1)	0.11
pH	4	0.08(8)	0.09
Nitrates	4	0.08(8)	0.09
Chlorides	2	0.04(4)	0.04
Temperature	1	0.02(2)	0.02
Total	45.00	0.95	1.00

1 ÷ 45.00 = 0.02222

9.3. THE DEVELOPMENT OF WEIGHTINGS FOR THE POTABLE WATER SUPPLY INDEX (PWSI)

In this instance twenty seven of the forty questionnaires originally despatched were returned completed; an additional six were returned incomplete. Thus, again, a 66% response was achieved. Of the incomplete returns, three had been partially completed; one by grouping the thirteen determinands into three main categories of importance and the other two by ranking a small selection of determinands only. The reasons given for the three remaining incomplete returns were similar to those outlined in Section 9.2. for the WQI. Thus, despite the fact that in this instance use had been specified, respondents still considered that it was inappropriate to attempt to place these determinands in any kind of rank order.

The format of this questionnaire was similar to that of the WQI (see Appendix V). The thirteen determinands were ranked in descending order; thus the determinand considered to be most important to the use of surface water in potable water supply received the highest ranking (Table 45).

An analysis of the range of rankings ascribed to each of these determinands again highlights the variability of expert opinion. Variation was particularly high in the rankings given for dissolved oxygen, B.O.D., chlorides, fluorides and temperature. Thus, the potential problems outlined in Section 9.2. concerning the use of subjective opinion are substantiated by the results obtained from this further questionnaire analysis.

The approach to the development of weightings on the basis of these rankings was the same as that employed for the nine WQI determinands. Mean, median and modal rankings were calculated for each determinand to assess the statistical distribution of

Table 45. <u>The Rankings Obtained from the PWSI Questionnaire Survey</u>

Respondent Determinand	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	Range of Rankings
Total Coliforms	7	13	13	13	13	13	11	13	8	13	13	13	10	13	13	13	13	11	12	13	11	13	1	13	12	13	13	1-13
Ammonia	6	7	3	12	7	9	13	6	12	11	5	12	12	5	8	8	5	13	13	9	12	12	13	9	11	4	8	3-13
Nitrates	8	5	7	11	10	12	4	12	13	8	8	7	11	11	11	7	9	12	9	7	5	8	4	11	13	11	6	4-13
B.O.D.	12	2	1	1	12	2	12	2	10	10	6	8	13	3	7	3	2	9	10	12	13	9	8	9	2	6	7	1-13
Fluorides	3	2	10	6	6	1	5	11	7	6	4	3	3	12	5	4	6	4	8	3	6	7	2	10	3	12	4	1-12
Suspended Solids	10	12	9	9	11	11	7	5	9	12	11	9	9	6	10	11	12	6	11	10	3	11	9	6	4	3	12	3-12
pH	9	11	11	8	8	7	6	8	5	7	12	6	8	2	9	13	10	5	7	5	8	5	12	12	10	10	10	2-13
Colour	11	7	4	10	11	10	9	7	11	4	10	11	4	8	12	11	11	8	3	8	7	10	6	9	5	1	11	1-12
Chloride	5	4	6	4	8	3	3	9	3	3	1	2	2	9	4	3	7	1	5	6	2	4	7	1	9	8	3	1-9
Iron	13	11	5	7	11	8	8	10	4	9	9	10	6	7	6	11	8	2	6	4	9	6	5	6	8	9	9	2-13
Sulphates	4	4	8	3	9	4	2	4	3	2	3	1	1	10	3	5	3	3	4	2	4	3	3	2	7	7	5	1-10
Temperature	1	11	2	2	7	5	1	3	1	1	2	4	7	4	1	1	4	10	2	1	1	2	10	6	1	2	1	1-11
Dissolved Oxygen	2	11	12	5	12	6	10	1	6	5	7	5	5	1	2	2	1	7	1	11	10	2	11	6	6	5	2	1-12

NB. The highest ranking has been ascribed to the determinand which is considered to be the most indicative of the potential use of water in potable water supply.

Table 46. The Statistical Distribution of the PWSI Questionnaire Data

Statistics Determinand														Median														Sum of Rankings	Mean Ranking
Total Coliforms	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	12	12	11	11	11	10	8	7	1	317	11.74
Ammonia	13	13	13	13	12	12	12	12	12	12	11	11	9	9	9	8	8	8	7	7	6	6	5	5	5	4	3	245	9.07
Nitrates	13	13	12	12	12	11	11	11	11	11	11	10	9	9	8	8	8	8	7	7	7	7	6	5	5	4	4	240	8.88
B.O.D.	13	13	12	12	12	12	10	10	10	9	9	9	8	8	7	7	6	6	3	3	2	2	2	2	2	1	1	191	7.07
Fluorides	12	12	11	10	10	8	7	7	6	6	6	6	6	5	5	4	4	4	4	3	3	3	3	3	2	2	1	153	5.66
Suspended Solids	12	12	12	12	11	11	11	11	11	11	10	10	10	9	9	9	9	9	9	7	6	6	6	5	4	3	3	238	8.81
pH	13	12	12	12	11	11	10	10	10	10	9	9	8	8	8	8	8	7	7	7	6	6	5	5	5	5	2	224	8.29
Colour	12	11	11	11	11	11	11	11	10	10	10	10	9	9	8	8	8	7	7	7	6	5	4	4	4	3	1	219	8.11
Chloride	9	9	9	8	8	7	7	6	6	5	5	4	4	4	4	3	3	3	3	3	2	2	2	2	1	1	1	121	4.48
Iron	13	11	11	11	10	10	9	9	9	9	9	8	8	8	8	7	7	6	6	6	6	6	5	5	4	4	2	207	7.66
Sulphates	10	9	8	7	7	5	5	4	4	4	4	4	4	3	3	3	3	3	3	3	3	2	2	2	2	1	1	109	4.03
Temperature	11	10	10	7	7	6	5	4	4	4	3	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1	1	93	3.44
Dissolved Oxygen	12	12	11	11	11	10	10	7	7	6	6	6	6	5	5	5	5	5	2	2	2	2	2	1	1	1	1	154	5.70
																												∑ mean values	92.94

_ Denotes the modal values

the data (Table 46). In this instance, four determinands were found to have bimodal rankings: dissolved oxygen, iron, suspended solids and fluorides. In each case, these bimodal rankings varied quite substantially, indicating that the level of disagreement which exists between water quality experts can be quite significant. Thus, modal values were excluded from further consideration in the development of weightings for this index. However, they were used in combination with the mean and median rankings to sub-divide the thirteen determinands into a number of 'importance' categories (Table 47).

By examining the 'importance' categories produced in each instance all three statistical expressions produce similar results. Even where bimodal rankings occur, at least one of the modes agrees with the ranking produced by the mean and median calculations. The major exception to this is B.O.D. which is rated twelfth in importance according to modal rankings, eighth by the means and joint third by median calculations.

The median rankings were again used in the calculation of the final determinand weightings. The method employed was that outlined in Section 9.2. for the WQI determinands, and the resultant weightings produced are shown in Table 48.

Thus, in this instance, where a particular water use has been specified, the weightings ascribed by water quality experts differ substantially from those given for the general water quality index. In this instance, the overall importance of total coliforms and nitrates is increased, while that of dissolved oxygen and B.O.D. is decreased.

Thus, water use appears to influence significantly the determinands selected for inclusion within an index (Section 7.7.); the rating curves used to transform determinand concentrations to

Table 47. The Initial Sub Division of the PWSI Determinands Based on Mean Median and Modal Rankings

Determinand	Mean Rankings	Median Rankings	Modal Rankings
Total Coliforms	11.74	13	13
Amm. Nitrogen	9.07	9	12
Nitrates	8.88	9	11
Suspended Solids	8.81	9	9/11
Colour	8.11	9	11
pH	8.29	8	8
Iron	7.66	8	6/9
BOD	7.07	8	2
Dissolved Oxygen	5.70	5	2/5
Fluoride	5.66	5	3/6
Chloride	4.48	4	3
Sulphate	4.03	3	3
Temperature	3.44	2	1
Total Ranking	92.94	92.00	

Table 48. The Development of Weightings Based on Median Rankings

Determinand	Median Rankings	Intermediate Weightings	Final Weightings
Total Coliforms	13	0.14 (1)	0.14
Amm. Nitrogen	9	0.09 (7)	0.10
Nitrates	9	0.09 (7)	0.10
Suspended Solids	9	0.09 (7)	0.10
Colour	9	0.09 (7)	0.10
pH	8	0.08 (6)	0.09
Iron	8	0.08 (6)	0.09
BOD	8	0.08 (6)	0.09
Dissolved Oxygen	5	0.05 (3)	0.05
Fluoride	5	0.05 (3)	0.05
Chloride	4	0.04 (3)	0.04
Sulphate	3	0.03 (2)	0.02
Temperature	2	0.02 (1)	0.02
Total	92.00	0.93	1.00

1 ÷ 92.00 = 0.01086

the same scale (Section 8.4.), and the weightings attached to each determinand by water quality experts.

9.4. SUMMARY

Weightings based on the opinion of water quality experts from the UK, were developed for the determinands included within the general and potable water supply indices. These were obtained by means of two separate questionnaire surveys. The final weightings produced are based on the median ranking ascribed to each determinand by a number of water quality experts. These weightings were developed in such a way that the sum of the weightings is equal to one, thus facilitating easy recalculation when data on all determinands is unavailable. From the results, shown in Tables 44 and 48 for the WQI and PWSI respectively, it is evident that water quality experts rate certain determinands very differently when the suitability of water for use in potable water supply is specifically stated as opposed to the more general statement of use implied by the WQI.

In addition, the results from both questionnaires highlighted the range in expert opinion which exists in the weighting of determinands (Tables 41 and 45), thus emphasising the danger of including the subjective assessment of determinand weightings within any classification system. However, despite this range of opinion, the median weightings developed here take into account the opinion of water quality experts from England, Scotland and Wales. Hence, when these weightings are included within an index, they allow data from all regions to be compared in a more meaningful and reproducible manner.

Weightings were not developed for either the Aquatic Toxicity or Potable Sapidity Indices as, in this instance, no one determinand can be singled out as being more important than any other as either an indicator of pollution or of potential water use.

Thus, having selected the determinands to be included within each index, and devised a series of ratings curves and weightings to be applied to these determinands, there only remains the selection of appropriate aggregation formulae to complete the development of the proposed indices.

CHAPTER 10

THE SELECTION OF APPROPRIATE AGGREGATION FORMULAE

10.1. INTRODUCTION

Aggregation formulae are used to combine information on the ratings and weightings of each individual index determinand to produce a single aggregated index score in an objective and reproducible manner.

These mathematically derived functions must be simple to manipulate manually, as many of the smaller divisional offices of the water authorities and river purification boards are still without access to computer facilities. They must be sensitive to changes in water quality and, in particular, capable of reflecting the effect of a single adverse determinand concentration. Finally, these aggregation formulae should produce index scores which show reasonable agreement with those produced subjectively by a group of water quality experts.

A number of aggregation formulae have been proposed within existing indices (Tables 49 and 50). These include both weighted and unweighted arithmetic, multiplicative and geometric formulae. In addition, modified arithmetic and root mean square techniques have been adopted (Tables 49 and 50). The index formulation most commonly advocated for use by previous workers has been the arithmetic weighted formulae (Table 50), proposed by Brown et al (1970), which produces a weighted linear summation of all determinand ratings.

Table 49. Aggregation Formulae Used Within Previously Developed Indices

INDEX / FORMULAE	(AU) Unweighted Arithmetic	(MU) Unweighted Multiplicative	(AW) Weighted Arithmetic	(MW) Weighted Multiplicative	(GW) Weighted Geometric	(SU.SW) Modified Arithmetic	(RMS) Root Mean Square
Horton (1965)						$X^{(w)}$	
Shoji et al (1966)			X				
NSFI (1970$^{(a)}$ 1973$^{(b)}$ to 1976$^{(c)}$)			$X^{(a)}$	$X^{(b)(c)}$	$X^{(b)}$		
Prati et al (1971)	X						
Deininger et al (1971)			X		X		
O'Connor (1971)			X				
Dinius (1972)						$X^{(w)}$	
MITRE Corp. (1972, 1975)			X				
McDuffie et al (1973)						$X^{(w)}$	
Landwehr NSFI, 1974)	X	X	X	X			
Nemerow et al (1974)			X				
Walski et al (1974)					X		
Inhaber (1975)							$X^{(w)}$
SDD (1976)	X	X	X	X	X	$X^{(w)(u)}$	
Ross (1977)						$X^{(w)}$	
Stoner (1978)$^{(d)(e)}$	$X^{(d)}$		$X^{(e)}$				
Dunnette (1979)			X	X			
Joung et al (1979)			X				

Footnote

(w) = weighted (d) = Type I determinands
(u) = unweighted (e) = Type II determinands

Table 50 Aggregation Formulae Employed Within Existing Indices

Unweighted Arithmetic, Modified Arithmetic and Multiplicative Formulae	Weighted Arithmetic, Modified Arithmetic and Multiplicative Formulae	Geometric Weighted Formulae and Mixed Expressions	
AU Prati et al (1971) Landwehr (1974) SDD (1976) $WQI = \frac{1}{n} \sum_{i=1}^{n} q_i$	AW Brown et al (1979) SDD (1976) Stoner (1978) $WQI = \sum_{i=1}^{n} q_i \ w_i$	GW Deininger et al (1971) Brown et al (1973) $WQI = \sqrt[n]{\prod_{i=1}^{n} q_i^{g_i}}$	Where: T_i = sub-index for the ith Type I pollutant variable q_i = the rating for the ith determinand w_i = the weighting for the ith determinand g_i = the geometric weighting for the ith determinand T = refers to transformation curve n = number of determinands
AU Stoner (1978) $WQI = \sum_{i=1}^{n} T_i$		Mixed Expression Brown et al (1973) $WQI = T\left[\sum_{i=1}^{n} q_i^{w_i}\right]$	
MU Brown et al (1973) SDD (1976) $WQI = \left[\prod_{i=1}^{n} q_i\right]^{1/n}$	MW Brown et al (1973) SDD (1976) $WQI = \prod_{i=1}^{n} q_i^{w_i}$		
SU SDD (1976) $WQI = \frac{1}{100}\left[\frac{1}{n} \sum_{i=1}^{n} q_i\right]^2$	SW SDD (1976) $WQI = \frac{1}{100}\left[\sum_{i=1}^{n} q_i w_i\right]^2$		

10.2. A COMPARISON BETWEEN AGGREGATION FORMULAE DEVELOPED WITHIN EXISTING INDICES

Comparative studies have been undertaken by various workers to assess the accuracy of a selection of aggregation formulae (Brown et al, (NSF), 1973; SDD, 1976, 1981; Bolton et al, (SDD), 1978; House and Ellis, 1980).

An arithmetic weighted formulation (AW) was originally proposed by Brown et al (1970; 1972) as the aggregation function for the NSFI. However, as part of the validation procedure for this form of the index (Brown et al, 1973), three additional aggregation functions were selected for assessment - the multiplicative and geometric weighted formulae (MW* and GW respectively) and a mixed expression (Table 50). Each version of the NSFI was applied to data collected from twenty-six sampling points in the Kansas River Basin. The results obtained from this comparative study indicated that the AW formulation had a tendency to over-estimate water quality throughout the index range by as much as 10 to 15 points (McClelland et al, 1973). In addition, the effect of a single adverse determinand concentration was not reflected in the final index score produced. These results were substantiated by the work of Bolton et al (1978) and House and Ellis (1980). The results of the latter study have been previously outlined in detail in Chapter 6 and are, therefore, only summarised at this point. Bolton et al (1978), the authors of the SDD (1976) index, applied a range of index formulations, including the AW and MW

Footnote

* MW This multiplicative weighted formulation has been called 'geometric weighted' by the SDD (1976). This was continued in the work by House and Ellis (1980).

formulations of the NSFI, to over 200 samples collected from the rivers Nith and Tweed. Although the AW formulation was found to be the easiest to use, requiring the minimum calculation time, it was again found to over-estimate water quality, particularly at the lower end of the quality scale. In addition, they concluded that this formulation was unlikely to produce an index score below 25 unless all determinand concentrations were uniformly poor. To overcome the problems inherent within the AW formulation, the SDD (1976) proposed a modified arithmetic weighted formulation known as the Solway weighted (SW) version (Table 50).

This version was found to be easier to calculate and allowed lower values to be recorded. However, House and Ellis (1980) found this index formulation to underestimate water quality towards the lower end of the index scale, thus overcompensating for the inadequacies of the AW formulation. In addition, both Bolton et al (1978) and House and Ellis (1980) found that the SW formula underestimated water quality at the upper end of the index scale. However, Bolton et al did not consider this underestimation to be a major problem. Thus, the results from these studies suggest that the weighted product index scores produced using an MW formulation agree most closely with the index scores subjectively awarded by a panel of water quality experts. When using this formula a zero score can occur due to the effect of a single adverse determinand concentration. This is essential if potential water use is to be inferred from the calculated index score (see Section 8.2.). Thus, both McClelland et al (1973) and House and Ellis (1980) concluded that a multiplicative weighted aggregation formula should be used for the calculation of water quality index scores. However, Bolton et al (1978) considered that, as both the SW and MW formulae provide a similar rating of water quality, the former should be used in preference to the latter because it was easier to calculate without access to computer facilities.

The Geometric weighted (GW) aggregation function proposed by Brown et al (1973) was first used by Deininger and Maciunas (1971) in the development of their potable water supply (PWS) index. In the latter instance, the GW version of the index was selected in preference to that of the AW. A multiplicative weighted version was not tested. It is important to note that the development of weightings and ratings for the GW version were similarly based on geometric calculations. Thus, the geometric version of the PWS index was entirely different from that of the arithmetic version, providing an additional explanation for the differences recorded. As the geometric weighted formulation was later abandoned by McClelland et al (1973) it must be assumed that the MW formulation was found to be superior.

Unweighted aggregation functions have been proposed either for those instances in which all determinands are equally weighted (Prati et al, 1971; Stoner, 1978), or to allow a comparison to be made between index scores derived using both weighted and unweighted formulae (Landwehr, 1974; SDD, 1976) (Tables 49 and 50).

Unweighted arithmetic (AU) formulations have been employed by both Prati et al (1971) and Stoner (1978) as the aggregation function for the unweighted determinands included within their respective indices.

However, Landwehr (1974), Landwehr and Deininger (1976) and the SDD (1976) employed unweighted aggregation functions for comparative purposes only. The first of these compared the index scores derived using both weighted and unweighted versions of the arithmetic and multiplicative formulae with those awarded by a panel of water quality experts for twenty river samples. Rank order correlation coefficients were calculated based on the mean index scores produced by each mathematical formula and the mean scores awarded by the water quality experts.

The results produced by the multiplicative formulations were found to agree most closely with expert opinion, with the multiplicative unweighted formulation achieving the highest level of agreement. However, all four correlations indicated a high level of agreement with expert opinion.

In the study conducted by the SDD, both weighted and unweighted versions of the Solway modified arithmetic formulation were included in addition to those listed above. In this instance, the results indicated that weightings should be retained, and either the SW or MW formula adopted.

On the basis of the arguments outlined within this section, it would appear that weighted and unweighted versions of the multiplicative and Solway modified formulae would be best suited for use within the proposed indices. However, the results produced by these aggregation functions within existing indices is, to a large extent, dependent upon the ratings and weightings ascribed to the individual index determinands. Thus, weighted and unweighted versions of the multiplicative, arithmetic and Solway modified arithmetic aggregation formulae have been applied to the proposed indices. The former will be used in the calculation of the general Water Quality and Potable Water Supply Indices and the latter for the calculation of the Aquatic Toxicity and Potable Sapidity Indices.

Thus, a comparison can be made between the results produced by each aggregation formula and the most appropriate selected.

10.3. SUMMARY TO PART TWO

Four water quality indices have been independently developed, each relating changes in water quality to possible water use.

Two indices are based on determinands which are recognised as being universal indicators of both potential water pollution and possible water use by officials from the water authorities and river purification boards of England, Wales and Scotland - the general Water Quality Index (WQI) and Potable Water Supply Index (PWSI).

The remaining two indices are based on determinands which are less frequently violated within UK surface waters, but are known to be a potential hazards to either human or aquatic life when found at concentrations in excess of recommended standards - the Aquatic Toxicity and Potable Sapidity Indices (ATI and PSI respectively).

The general WQI reflects water quality in terms of a range of possible water uses; whereas the PWSI, ATI and PSI are essentially use-specific, relating water quality in terms of its suitability for use in either potable water supply (PWSI and PSI) or for the protection of healthy fish and wildlife populations (ATI).

Each index has been developed in such a way as to conform to the eleven essential characteristics of an index outlined in Chapter 4. Determinand selection and the development of rating curves and weightings have been completed in as objective a manner as possible in relation to the requirement of water quality managers in the UK. To this end, determinand standards included within EEC Directives (1975; 1978; 1980), have been incorporated into each index because these have now been adopted as legal standards within the United Kingdom.

The final part of this thesis will deal with the validation of each index and include a consideration of the role of water quality indices in the management of surface water quality in the United Kingdom.

PART THREE

THE VALIDATION OF THE PROPOSED INDICES

CHAPTER 11

VALIDATING THE GENERAL WATER QUALITY INDEX (WQI)

11.1. INTRODUCTION

All four indices have been evaluated and validated against classificatory data published by a number of UK water authorities. One major problem in this calibration exercise was the difficulty of obtaining objectively a viable basis for comparison. The classification presently used by the water authorities and river purification boards of England, Wales and Scotland is that developed by the National Water Council (NWC, 1977). The problems associated with the use of this classification have been previously outlined in detail in Section 5.4. These problems basically arise from the classification being subjectively applied to extensive lists of water quality data. Hence, the accuracy and reproducibility of this method of water quality assessment is questionable. However, although it is far from being ideal, the NWC classification has been used as a basis for the validation of the WQI in the absence of a more acceptable alternative.

11.2 THE WQI VALIDATION PROCESS

The validation process entailed the application of the WQI to a total of three hundred and fifty five data sets collected from three water quality monitoring bodies - the Greater London Council, (GLC) and the Thames, (TWA) and Severn Trent Water Authorities, (STWA). In each instance the data had been previously classified using the NWC classification. It was considered important in this validation exercise to select data which had been collated and classified by a number of water authorities to ensure that the index is applicable under a variety of water quality conditions. In addition, the reproducibility of the NWC classification when used by a number of water quality managers can be assessed, as the application of the WQI, due to its mathematical format, will remain consistent throughout the validation process.

To facilitate these comparative studies the 10 to 100 index range was sub-divided according to the five NWC classes of water quality (Table 51). Hence, the calculated index scores could be similarly classified and the resultant classifications compared to those ascribed by the user of the NWC classification. However, the sub-divisions of the WQI outlined in Table 51 cannot be rigidly applied as the description of potential water use given within each of the NWC classes (Table 6) is often vague and wide-ranging when compared to that of the WQI range (Table 37).

Table 51. Sub-Divisions of the WQI Range

NWC Class	WQI Range
1A	91-100
1B	71-90
2	41-70
3	21-40
4	10-20

For example, water requiring conventional treatment before use in potable water supply (PWS) has been equated to that likely to support healthy game fish populations by the NWC classification (Table 6). Both these uses are recognised as requiring different quality water by the sub-divisions of the WQI range (Table 37). Hence it was necessary to introduce transition zones between each class of water. Thus, WQI scores of 86 to 90, 66 to 70, 41 to 45 and 21 to 25 were introduced as transition zones between class 1B/1A, 2/1B, 3/2 and 4/3 respectively.

Data on all nine WQI determinands were not available in any of the three data sets employed within the comparative studies. Determinand weightings were recalculated in each instance using the correction equation first used by SDD (1976) (see footnote to Section 4.8). Thus, the "pecking order" established within the development of determinand weightings was maintained.

Finally, index scores were calculated for each of the 355 data sets using the arithmetic, multiplicative and modified arithmetic weighted aggregation formulations. This enabled the most efficient of the proposed formulations to be evaluated.

11.3 THE APPLICATION OF THE WQI TO DATA COLLECTED FROM A SERIES OF WATER QUALITY MONITORING BODIES

The data selected for an initial comparative study between the WQI and NWC classification were those used by Aston et al (1979) in a study of quality changes during the 1970's of a number of Metropolitan watercourses within Greater London. These data were adapted in Chapter 6 for the comparative study between the SDD (1976) index and the NWC (1977) classification.

Data on only four of the nine WQI determinands were available from this study, thus determinand weightings had to be recalculated (Table 52).

Table 52. Determined Weightings for the GLC Data

Determinand	Weighting
Suspended Solids	0.17
Ammoniacal Nitrogen	0.24
Dissolved Oxygen	0.31
Biochemical Oxygen Demand	0.28
	1.00

WQI scores were calculated for fifty seven data sets collected from eight rivers for the years 1970 and 1977.

The Index was next applied to data relating to seventy two sampling sites within the Thames Water Authority (TWA) region for the fiscal year 1978/1979. The data were obtained from "Thames Water Statistics 1979" and were given in the form of mean concentrations. In this instance, in addition to classifying each river sampling site, sub-notations indicating future River Quality Objectives, (RQOs), were indicated.

Data on eight of the nine WQI determinands was available within this data set which again required the recalculation of the weightings (Table 53).

Table 53. Determinand Weightings for the TWA Data

Determinand	Weighting
pH	0.10
Suspended Solids	0.12
Biochemical Oxygen Demand	0.20
Temperature	0.02
Dissolved Oxygen	0.23
Ammoniacal Nitrogen	0.18
Chlorides	0.05
Nitrates	0.10
	1.00

Finally, the index was applied to 226 river samples located within the Severn Trent Water Authority (STWA) region. The data were divided into two sampling sets on the basis of the number of determinands for which data were available. The first related to 90 river samples and was based on the eight WQI determinands. Thus the weightings applied to this data set are those given in Table 53. The second related to 136 river samples and was based on seven of the nine WQI determinands. The recalculated weightings applied in this instance are given in Table 54. The data in both cases were given in the form of mean concentrations and covered a two year sampling period for the fiscal years 1978/1979 and 1979/1980. Data were abstracted from "Appendix 9 - River Quality" of the STWA Annual Report (STWA, 1980).

The results of this comparative study are of particular interest as data on dissolved oxygen concentrations - the determinand most heavily weighted by UK water quality experts (see Section 9.2) -

were not available. Thus the influence of this omission, if any, upon the calculated WQI scores could be assessed.

Table 54. Determinand Weightings for Data Set Two of the STWA Data

Determinand	Weighting
pH	0.13
Suspended Solids	0.16
Biochemical Oxygen Demand	0.26
Temperature	0.03
Ammoniacal Nitrogen	0.23
Chlorides	0.06
Nitrates	0.13
	1.00

The four data sets selected for this validation exercise have been derived from two of the largest water quality monitoring bodies in the UK and a Metropolitan area renowned for both its quality problems and reclamation work. Each embraces within its respective catchment areas a wide range of water quality conditions. In addition, the data sets vary in both size and the number of determinands on which they are based. Thus the role of all three factors in influencing the efficiency of the WQI can be tested.

11.4. THE RESULTS OF THE COMPARATIVE STUDIES FOR EACH OF THE WATER QUALITY MONITORING BODIES

WQI scores were calculated for each of the 355 data sets using the arithmetic, multiplicative and modified arithmetic weighted aggregation formulations (AW, MW and SW respectively). The derived index scores were then compared to the allocated NWC classifications and the efficiency of the WQI evaluated.

11.4.1. The Results of the Application of the WQI to a Series of London's Watercourses

An examination of the results obtained from this comparative study shows that the WQI scores, produced using the SW formulation, similarly classified forty nine of the fifty seven river samples prior to a consideration of scores which fall within the transition zones, (Table 55), and results in an 86% agreement with the NWC classification. This level of agreement was further increased to fifty four out of fifty seven cases (95%) by the introduction of transition zones (Table 56). Only two Class 2 and one Class 3 river remained not similarly classified. Both of the Class 2 rivers received WQI scores of 40 indicating borderline Class 3/2 quality. However, the Class 3 river, the River Brent upstream of the Grand Union Canal, does not appear, after analysis of the raw data, to deserve the low NWC classification ascribed to it. In fact, by reviewing more closely the results of this comparative study (Table 55), it is apparent that in at least three instances, the user of the NWC classification has downgraded the rivers by a full class whilst the calculated WQI scores for these rivers remained either the same, or indicated a marginal improvement in water quality over the recorded period. This suggests that either these rivers were classified on the basis of information which was unavailable for the WQI calculations or, alternatively, is reflecting the

Table 55. Results from the Comparative Study between the NWC Classification and the WQI for a Series of London Watercourses

Location	1970				1977			
	NWC Class	WQI Score			NWC Class	WQI Score		
		AW	SW	MW		AW	SW	MW
River Wandle								
Croydon Arm - Lower Reaches	3	63	40	60	-	-	-	-
Croydon Arm - Upper Reaches	3	62	39	58	1B	90	81	90
Carshalton Branch	3	57	33	51	1B	89	80	90
Goat Bridge - US of Beddington STW	3	65	42	60	1B	88	78	88
Watermeads - DS of Beddington STW	4	34	12	24	3	60	36	54
DS of Wandle Valley and US of Wimbledon STW	4	30	10	22	2	63	40	56
US of Tideway	4	34	11	23	2	65	43	59
Beverley Brook								
Beverley Brook - DS Worcester Park STW	4	35	13	24	3	50	25	43
Pyl Brook - DS of Sutton STW	3	56	31	51	3	52	27	46
Beverley Brook - US of the Tideway	3	52	27	43	2	70	49	67
River Darent and Cray								
River Darent - Upper Reaches	-	-	-	-	1B	88	77	87
River Darent - US of the Tideway	-	-	-	-	1B	89	80	89
River Shuttle	-	-	-	-	1B	83	69	83
River Cray - US of the Tideway	-	-	-	-	1B	86	74	85

Table 55 contd.....

River Ravensbourne

River Ravensbourne - US of the Pool	2	73	53	69	2	78	61	78
River Pool	2	70	49	64	2	82	68	82
River Quaggy	2	77	59	70	2	79	63	79
River Ravensbourne - US of the Tideway	2	68	46	64	2	82	66	81

River Crane and Duke of Northumberlands River

River Crane - US of the Duke's River	3	65	42	61	2	77	59	75
Duke's River - US of the River	2	77	60	73	2	80	63	79
River Crane - US of the Tideway	2	79	62	74	2	78	62	77
Duke's River - US of the Tideway	2	77	60	73	2	79	62	77

River Brent

Silk Stream	3	62	38	58	2	79	62	78
Dollis Brook	2	65	42	62	2	82	67	80
River Brent - DS of Welsh Harp	2	74	54	70	2	82	67	82
River Brent - US of Grand Union Canal	2	68	46	64	3	68	46	67
River Brent - US of Tideway	2	66	44	63	2	76	58	74

Grand Union Canal

Grand Union Canal - on entry to MPC Area	2	76	57	72	2	68	46	61
Grand Union Canal - US of the confluence with the River Brent	2	63	40	60	3	65	42	62
Paddington Arm	2	64	41	60	3	66	44	63
Regent's Canal - US of the Tideway	2	78	60	73	1B	85	72	84

NOTE: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification system.

DS = Downstream
US = Upstream
STW = Sewage Treatment Works
MPC = Metropolitan Pollution Control

inherent problem of using subjective methods of water quality classification.

The level of agreement achieved between the WQI and NWC classification was greatly reduced when the AW and MW formulations were applied (Tables 57 and 58). Only nineteen and twenty two of the WQI classifications produced by each formulation were found to agree with those of the NWC. These reflect agreements of only 33% and 39% respectively. This was increased to 49% for the MW formulation when the transition zones were applied.

The index scores recorded using the SW formulation covered a water quality range of between 10 and 81, leaving only nine points on the 10 - 100 index range unrecorded because no Class 1A rivers were sampled. The results produced by the WQI for Class 2 rivers, which embrace the widest range of water quality and potential water use, almost exactly cover the ascribed index range. Thus the index appears to be equally applicable to waters at both extremes of the water quality spectrum.

The index range covered by the AW and MW formulations was slightly reduced from that of the SW to 30 - 90 and 22 - 90 respectively. However, an analysis of the WQI range covered for each NWC class shows that both formulations have a tendency to overestimate water quality, particularly between an index score of 10 to 70. This tendency is shown most dramatically by the AW formulation which failed to classify correctly any of the eighteen Class 3 and 4 rivers. This tendency to overestimate water quality has resulted in a considerable degree of overlapping between the four classes of water quality sampled; a problem not encountered when using the SW formulation - with the exception of the one Class 3 sample discussed previously.

Table 56. The Results Obtained Using the SW Formulation

NWC Class	Number of Rivers in Each Class	WQI Classification	WQI Range
1B	8	7 (1)	69-81
2	31	29	40-68
3	14	9 (4)	25-46
4	4	4	10-13
	57	49 (54)	

Table 57. The Results Obtained Using the AW Formulation

NWC Class	Number of Rivers in Each Class	WQI Classification	WQI Range
1B	8	8	83-40
2	31	11	63-82
3	14	0	50-68
4	4	0	30-35
	57	19	

Table 58. The Results Obtained Using the MW Formulation

NWC Class	Number of Rivers in Each Class	WQI Classification	WQI Range
1B	8	8	83-90
2	31	14	56-82
3	14	0 (2)	43-67
4	4	0 (4)	22-24
	57	22 (28)	

Therefore, the results of this initial comparative study would tend to suggest that the SW index formulation is the most efficient of the proposed aggregation functions. Additionally, the WQI scores produced by this formulation can accurately detect changes in the quality of London's watercourses despite the fact that data on only four of the nine WQI determinands were available.

11.4.2. The Results of the Application of the WQI to TWA Data

An analysis of the results produced by this comparative study appear to confirm those outlined above (Tables 59 to 62). The index scores produced using the SW formulation show the best agreement with the NWC classification. Forty six and sixty of the seventy two river samples were similarly classified before and after the application of transition zones respectively (Table 60). Thus agreements of 64% and 83% were achieved. However after analysing the raw data it was apparent that at least six of the twelve river samples which had been mis-classified by the WQI did not merit the NWC classification ascribed (see Section 11.5.). If these six samples are ignored the level of agreement obtained would increase to 91% (sixty out of sixty six cases).

The results obtained using the AW and MW index formulations were less satisfactory. Only 44% and 46% of the WQI classifications agreed with those of the NWC (Tables 61 and 62).

The index scores derived by the SW formulation cover an index range of 26 to 88. Thus twenty eight points on the 10 to 100 index scale were unrecorded in this instance. These results indicate both a tendency to underestimate quality at the upper end of the quality spectrum and overestimate quality at the lower. The former tendency was noted by Bolton et al (1978) when

Table 59. Results From the Comparative Study Between the NWC Classification and the WQI for the TWA Data

Location	NWC	WQI Score		
	Class	AW	SW	MW
River Thames				
- Hannington Bdge	2/1B	79	62	78
- Buscot	2/1B	82	67	81
- Swinford	1B	83	69	83
- Days Lock	1B	79	63	79
- Caversham	1B	82	68	81
- Henley Bdge	1B	83	69	83
- The Cut	2	67	45	64
- Egham	1B	79	62	78
- Littleton	1B	82	68	82
- Walton	1B	80	64	80
- Teddington	2	74	55	73
- Swindon	2	79	62	78
- Cricklade	2	64	41	60
- Lechlade	1A	89	80	89
- Worsham	1B/1A	88	78	88
- Newbridge	1B/1A	87	77	88
River Cherwell				
- Grimsbury	1B/1A	84	71	83
- Twyford	3/2	71	50	68
- Upper Heyford	2/1B	82	68	81
- Fencott Road	3/2	64	41	56
- Marston Road	2/1B	84	70	84
River Ock	2/1B	82	67	82
River Colne				
- Denham	2/1B	85	72	84
- Thames	2/1B	70	48	55
River Mole				
- Horley Weir	3/2	66	43	60
- Sidlow Bdge	2/1B	69	47	65
- River Lane	2/1B	83	69	82
- Royal Mills	2	80	64	79
- Above Thames	2	79	63	78
- Hogsmill	4/3/2	61	37	51
River Lee				
- East Hyde	1B	82	68	82
- Road Bridge	2	66	44	63
- Wheathampstead	2	69	48	66
River Stort				
- Spellbrook	2/1B	80	63	78
- Roydon	1B	86	73	85
River Lee				
- Rye House	1B	88	78	88
- Dobbs Weir	1B	87	76	86
- Kings Weir	1B	87	76	87
- Lea Valley Rd	1B	86	73	85
- Navigation	2/1B	77	59	76
- Pymmes Bk.	3/2	70	49	67
- Springhill	3/2	64	41	62
- Carpenters Rd	2	74	56	71

Table 59 contd....

Location	NWC Class	WQI Score		
		AW	SW	MW
River Thame	1B	82	68	82
River Kennet	1A	93	88	93
River Blackwater				
- Farnborough	2/1B	63	39	59
- Whitewater	2/1B	78	60	76
- Swallowfield	2/1B	81	65	79
River Loddon				
- Arborfield Bdge	2/1B	82	67	81
- Twyford	2/1B	83	69	82
River Wye	2/1B	77	59	75
Beverley Brook				
- Motspur Park	3/2	55	30	46
- Priests Bridge	3/2	67	45	63

Location	NWC Class	WQI Score		
		AW	SW	MW
River Lambourn	1A	94	88	94
River Roding				
- Ongar Bridge	1B	86	74	85
- Abridge	2/1B	74	55	73
- Redbridge	3/2	68	46	64
R. Ingrebourne	3/2	71	50	68
River Beam	2	61	37	54
River Crane	1B	77	59	76
Duke of North.	2/1B	83	69	82
Pyl Brook	3/2	51	26	40
River Pool	2/1B	82	67	80
River Quaggy	2/1B	79	63	78
R. Ravensbourne	2/1B	83	69	83

Table 59 contd....

Location	NWC Class	WQI Score			Location	NWC Class	WQI Score		
		AW	SW	MW			AW	SW	MW
River Wandle									
- Goats Bdge	1B	85	72	84	River Darent				
- Watermeads	3/2	64	41	59	- Otford	1B	87	76	87
- Causeway	3/2	67	45	62	- Mill Pond Rd	1B	88	78	88
River Beck	2/1B	77	59	74	River Shuttle	2/1B	81	66	81

Note: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification system.

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using this formulation in the calculation of the SDD (1976) index. However, these results may be associated with the higher quality requirements of Class 1A waters as defined by the WQI, as opposed to the NWC classification, (see Section 11.2), and not with a forced function of the SW formulation. The upgrading of four Class 3 and one Class 4 rivers would suggest that the formulation is insensitive to a situation in which only one determinand achieves a low quality rating. This conclusion will be discussed in detail later in Section 11.5. Thus, the results in this instance suggest that, although WQI scores indicating lower Class 3 quality have been accurately recorded, residual problems may exist with the efficiency of the index in reflecting low quality waters.

Table 60. The Results Obtained Using the SW Formulations

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	3	0 (2)	80-88
1B	21	12 (6)	62-78
2	35	32	37-72
3	12	2 (6)	26-50
4	1	0	37
	72	46 (60)	

Table 61. The Results Obtained Using the AW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	3	2 (1)	89-94
1B	21	21	79-88
2	35	8	61-85
3	12	0	51-71
4	1	0	61
	72	31 (32)	

Table 62. The Results Obtained Using the MW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	3	2 (1)	89-94
1B	21	21	78-88
2	35	8	54-84
3	12	1	40-68
4	1	0	51
	72	32 (33)	

The index range covered by the AW and MW formulations highlights these problems, with scores of between 51 and 94 and 40 to 94 being recorded respectively. Thus, both formulations are responsible for producing gross overestimations of quality. Only eight and nine of the river samples previously classified as belonging to Class 4 to 2 respectively were correctly classified by each formulation (Tables 61 and 62).

Thus, on the basis of an analysis of the available raw data from this comparative study, the results again question the validity of a number of the NWC classifications . Both these results and the overestimation of five Class 3/4 rivers may be associated with either the increase in the number of data sets used or the greater number of determinands for which data were available. In either case, the overall results suggest that the SW version of the WQI most accurately detects a range of water quality conditions and highlights the problems of comparing an objectively derived index score with the subjectively derived NWC classification.

11.4.3. The Results of the Application of the WQI to Data Set One of the STWA Data

The results of this comparative study show that sixty four of the ninety river samples were classified similarly by both the WQI and NWC classification when the SW formulation was applied (Tables 63 and 64). It produced an agreement of 71%. However, an analysis of the raw data indicates that at least seventeen of the ninety river samples had been incorrectly classified by the user of the NWC classification or, alternatively, the classifications were based on data which were not available for the calculation of the WQI (see Section 11.5.). Thus the exclusion of the seventeen mis-classifications increased the level of agreement to 88%, whereas the level of agreement produced by the

Table 63. Results From the Comparative Study Between the NWC Classification and the WQI for Data Set One of the STWA Data

Location	1978/1979				1979/1980			
	NWC Class	WQI Score AW	SW	MW	NWC Class	WQI Score AW	SW	MW
River Severn								
- Caersws	1A	90	81	90	1A	92	85	92
- Llandrinio	1A	87	75	86	1A	88	78	88
- Shelton	1B	89	79	89	1B	89	80	89
- Atcham	1B	90	81	89	1B	88	77	87
- Buildwas	1B	89	79	88	1B	87	76	86
- Bridgnorth	1B	89	79	89	1B	86	74	86
- Bewdley	1B	86	73	85	1B	85	73	85
- Holtfleet	1B	85	72	84	1B	84	71	84
- Worcester	1B	86	74	85	1B	84	71	84
- Upton	1B	82	68	81	1B	84	70	83
River Clywedog								
- Brithdir	1A	94	89	94	1A	92	85	92
River Tern								
- Allscott Mill	2	69	47	65	2	74	55	71
- Atcham	2	73	53	68	2	72	53	69
River Meese	2	87	76	87	2	86	74	85
River Strine	2	79	63	78	2	79	62	77

Table 63 contd....

Location	1978/1979				1979/1980			
	NWC	WQI Score			NWC	WQI Score		
	Class	AW	SW	MW	Class	AW	SW	MW
River Stour								
- Lye	2	73	53	69	2	72	52	69
- Wordsley	3	64	42	60	3	64	41	59
- Stourton	3	63	40	58	3	66	44	62
- Stourport	3	62	39	57	3	57	32	51
- Smestow Brook	2	65	43	62	2	72	52	70
River Salwarpe								
- Wychbold	3	72	52	71	3	70	49	69
- Hawford	2	77	59	75	2	70	49	68
River Avon								
- Starebridge	3	80	64	80	3	82	67	81
- Portobello	2	74	56	71	2	78	61	74
- Castle Bdge	2	73	53	70	2	74	55	71
- New Banbury	2	73	54	70	2	75	57	73
- Stratford	2	76	57	74	2	77	59	75
- Evesham	2	75	56	74	2	77	60	76
- Tewkesbury	2	82	68	82	2	77	59	76
River Sowe								
- Baginton	2	80	63	79	2	80	65	80
- Stoneleigh	3	66	44	61	3	68	46	63
- Finham Brook	2	81	74	81	2	86	74	86
River Leam	2	85	73	85	2	87	75	87

Table 63 contd....

Location	1978/1979				1979/1980			
	NWC Class	WQI Score			NWC Class	WQI Score		
		AW	SW	MW		AW	SW	MW
River Tame								
- Perry Barr	4	50	25	40	4	48	23	37
- Lea Marston	4	61	37	54	4	58	34	52
- Chetwynd Bdge	3	64	42	59	3	64	41	60
- Wolverhampton	4	51	26	40	4	47	22	36
- Oldbury Tame	4	50	25	42	4	55	30	49
- Ford Brook	4	56	32	47	4	58	34	50
River Cole	2	78	61	78	2	81	65	80
River Blythe	1B	81	65	79	1B	81	66	80
River Bourne	1B	83	68	82	1B	86	75	86
River Dove	1A	89	79	89	1A	90	80	90
River Soar	2	73	53	70	2	71	51	70
Bottesford Beck	4	67	45	58	3	58	33	51

Note: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification system.

Table 64. The Results Obtained Using the SW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	8	0 (1)	75-89
1B	20	15 (4)	65-81
2	36	30	43-76
3	15	4 (6)	42-67
4	11	0 (4)	22-45
	90	49 (64)	

Table 65. The Results Obtained Using the AW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	8	3 (5)	87-94
1B	20	20	81-90
2	36	3	65-87
3	15	0	57-82
4	11	0	47-67
	90	26 (31)	

Table 66. The Results Obtained Using the MW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	8	3 (5)	86-94
1B	20	20	80-89
2	36	12	62-87
3	15	0	51-81
4	11	0	36-58
	90	35 (40)	

AW and MW index formulations decreased to 34% and 44% respectively (Tables 65 and 66).

An index range of 22 to 89 was covered by the SW version of the WQI which left twenty three points on the index scale unrecorded. The range was reduced to 47 - 94 and 36 - 94 by the application of the AW and MW formulations respectively. Both these formulations appeared to overestimate water quality for all but the highest quality waters. The results obtained for the SW formulation again reflected an underestimation of quality at the upper and an overestimation of quality at the lower end of the quality spectrum.

11.4.4. The Results of the Application of the WQI to Data Set Two of the STWA Data

In this instance 75%, (one hundred and two out of one hundred and thirty six river samples), of the classifications produced by the WQI using the SW formulation agreed with those of the NWC classification, (Tables 67 and 68). Despite the exclusion of dissolved oxygen from the WQI calculation and the increase in the number of data sets used, a high level of agreement was maintained. This level of agreement was further increased to 98% by an analysis of the raw data, which revealed that thirty two of the river samples had probably been mis-classified by the users of the NWC classification, or classified on the basis of additional information (see Section 11.5.). Thus, as the number of data sets increased, the accuracy of the subjective NWC classification became increasingly suspect.

Table 67. Results From the Comparative Study Between the NWC Classification and the WQI for Data Set Two of the STWA Data

	1978/1979				1979/1980			
Location	NWC Class	WQI Score			NWC Class	WQI Score		
		AW	SW	MW		AW	SW	MW
River Severn								
- Tewkesbury	1B	81	66	81	1B	82	67	81
- Hawbridge	1B	78	64	79	1B	78	61	78
- Sharpness Canal	1B	79	63	78	1B	79	63	79
River Clywedog	1A	96	92	96	1A	88	78	87
River Vyrnwy	1A	91	82	90	1A	90	81	90
River Perry	1B	82	67	81	1B	83	69	83
Rea Brook	1B	88	77	87	1B	86	74	86
River Roden	1B	81	65	80	1B	69	47	66
River Worfe	1B	84	70	83	1B	72	52	70
River Teme								
- Tenbury	1B	89	79	89	1B	86	74	86
- Powick	1B	80	64	78	1B	81	65	79
River Onny	1B	86	74	86	1B	83	69	83

Table 67 contd....

Location	1978/1979				1979/1980			
	NWC	WQI Score			NWC	WQI Score		
	Class	AW	SW	MW	Class	AW	SW	MW
River Corve	1B	86	74	85	1B	78	61	76
River Avon	1B	86	75	86	1B	88	77	88
River Arrow								
- Spernal Lane	2	69	48	67	2	64	41	61
- Alcester	2	75	57	74	2	71	51	70
- Salford Priors	2	79	62	78	2	80	63	79
- Badsey Brook	2	77	60	77	2	79	63	79
River Isbourne	1B	84	70	83	1B	80	65	79
Bow Brook	2	83	68	82	2	81	65	80
River Leadon	1B	82	67	82	1B	80	63	79
River Frome	2	83	69	83	2	83	69	82
River Trent								
- Hanford	3	66	43	63	3	65	42	62
- Stone	2	62	39	60	2	70	49	69
- Great Haywood	2	72	52	70	2	69	47	67
- Yoxall	2	75	56	74	2	76	58	75
- Walton	3	63	39	60	3	64	42	62
- Willington	2	68	47	66	2	71	50	69

Table 67 contd....

	1978/1979				1979/1980			
Location	NWC	WQI Score			NWC	WQI Score		
	Class	AW	SW	MW	Class	AW	SW	MW
River Trent contd.								
- Shardlow	2	73	53	72	2	75	56	74
- Sawley	2	75	57	74	2	77	59	76
- Nottingham	2	73	53	72	2	74	55	73
- Gunthorpe	2	73	53	70	2	74	54	71
- Kelham	2	72	51	70	2	73	53	71
- Dunham	2	75	56	74	2	75	56	74
- Gainsborough	2	69	48	67	2	69	47	64
- Fowlea Brook	3	57	33	53	3	58	34	53
River Penk	1B	74	55	73	1B	73	53	71
River Blithe	1A	84	71	83	1A	83	69	82
River Rea	2	67	44	65	2	54	29	46
River Anker								
- Leathermill Bdge	2	67	45	65	2	75	56	72
- Polesworth	2	67	45	61	2	70	50	64
- Ratcliffe Culey	2	76	58	75	2	82	67	81
River Mease	2	78	61	77	2	77	60	77

Table 67 contd....

Location	1978/1979				1979/1980			
	NWC Class	WQI Score			NWC Class	WQI Score		
		AW	SW	MW		AW	SW	MW
River Dove								
- Below Rocester	1B	85	73	85	1B	91	82	91
- Monks Bridge	1B	84	70	83	1B	86	74	86
River Manifold	1A	89	79	89	1A	91	83	91
River Churnet								
- Abbey Gn. Rd.	1B	80	64	78	1B	72	52	69
- Rocester	2	79	62	77	2	79	62	77
River Tean	2	65	42	62	2	78	61	78
River Derwent								
- Matlock Bath	1A	87	76	87	1A	92	84	91
- St Mary's Bdge.	2	85	72	84	2	87	77	87
- Wilne	2	78	61	77	2	82	67	81
River Wye	1A	89	79	89	1A	89	79	89
River Amber	2	69	48	67	2	72	51	70
Alfreton Brook	3	60	36	56	3	62	39	59

Table 67 contd....

Location	1978/1979				1979/1980			
	NWC Class	WQI Score			NWC Class	WQI Score		
		AW	SW	MW		AW	SW	MW
River Soar								
- Aylestone	2	71	51	69	2	72	52	71
- Wanlip	2	75	56	73	2	79	63	78
- Sileby	2	69	47	65	2	66	44	66
- Sence Confluence	3	63	40	58	3	64	41	60
River Wreake								
- Kirby Bellars	2	68	47	62	2	68	47	65
- Lewin Bridge	2	72	52	69	2	75	57	74
River Erewash								
- Trowell	2	60	36	55	2	58	34	54
- Confluence	3	56	31	50	3	54	30	47
River Leen	2	65	42	64	2	72	52	71
River Devon	1B	80	64	79	1B	81	66	80
River Idle/Maun								
- Whinney Hill	3	52	27	38	3	49	24	35
- Bawtry	2	74	55	72	2	79	62	77
River Torne	2	71	51	68	2	75	56	74

Note: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification.

Table 68. The Results Obtained Using the SW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	12	1	69-92
1B	38	11 (10)	47-82
2	72	66	29-72
3	14	10 (4)	24-43
	136	88 (102)	

Table 69. The Results Obtained Using the AW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	12	4 (6)	83-96
1B	38	36 (1)	69-91
2	72	22	54-87
3	14	0	49-66
	136	62 (69)	

Table 70. The Results Obtained Using the MW Formulation

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	12	3 (7)	82-96
1B	38	34 (3)	66-91
2	72	31	54-84
3	14	2	35-63
	136	70 (80)	

The level of agreement obtained by the use of the AW and MW formulations increased to 50% and 59% respectively (Tables 69 and 70). These improved results could be related to either the removal of dissolved oxygen from the index calculation, or the increased number of data sets employed.

The index range covered by each of the WQI formulations were 24 - 92 (SW), 49 - 96 (AW) and 35 - 96 (MW) respectively. Thus only eleven points on the WQI scale were left unrecorded because no Class 4 rivers were included within the data. The tendency of the SW formulation to underestimate high quality waters was still apparent, if not compounded. However, the results produced for Class 3 rivers almost perfectly cover the ascribed index range. Therefore, it is possible that the removal of dissolved oxygen from the index calculation removed the tendency of the SW formulation to overestimate quality at the lower end of the quality scale. Nevertheless, the results from this final study still reflected the tendency of the AW and MW formulations to overestimate water quality.

11.4.5. Summary of Results

The initial results from these comparative studies can be regarded as justifying the structure and efficiency of the proposed WQI method when the SW formulation is employed. The persistent problems of overestimation associated with the use of the AW and MW formulations mean that they must be rejected as aggregation functions for the proposed WQI.

The results produced by the SW formulation of the WQI for the three hundred and fifty five data sets have been summarised in Table 71. These show that two hundred and eighty of the three hundred and fifty five river samples were similarly classified by the WQI and NWC classification (79%), prior to an analysis of the raw data. The poorest results were undoubtedly obtained for Class 1A and Class 4 rivers, where agreements of only 17% and 50% respectively, were achieved. However, the range covered by the index was almost perfect (10-92) indicating that, despite the anomalies recorded, the index accurately reflected quality at both ends of the quality spectrum. The various over and under-estimations produced by the WQI can be explained by an examination of the raw data and the ratings ascribed to each determinand.

Table 71. The Initial Results Produced by the Validation Process

NWC Class	Number of Rivers In Each Class	WQI Classification	Level of Agreement	WQI Range
1A	23	4	17%	69-92
1B	87	66	76%	47-81
2	174	157	90%	29-76
3	55	45	82%	24-67
4	16	8	50%	10-45
	355	280	79%	

11.5. COMPARISON BETWEEN THE WQI SCORES AND THE DETERMINAND RATINGS

The classification given to a water body should reflect the range of Water Quality Ratings (WQRs) obtained by each determinand during the transformation process. Of particular importance is the class of water quality indicated by the lowest determinand rating. These ratings have been developed with reference to published water quality standards and criteria, many of which are now legal standards within the UK (Chapter 8). Thus, if the classification is applied rigidly, the classification given should be equal to that reflected by the lowest WQR. In some instances this may result in an underestimation of water quality. However, until the sensitivity of the WQI to unusually low determinand concentrations has been fully assessed, a review of the lowest ratings obtained by the mis-classified river samples is the most accurate way of determining the efficiency of the index.

Therefore, the lowest determinand rating obtained by the seventy five mis-classified river samples were reviewed and the quality class indicated by those ratings compared with those ascribed by both the WQI and the user of the NWC classification.

11.5.1. The Revised Results for the GLC Data

The classifications indicated by the lowest ratings for the three mis-classified river samples agreed with those produced by the WQI (Table 72). The results produced for the Grand Union Canal, (GUC) for 1970 showed the best level of agreement with only four

Table 72. Lowest Ratings and Classifications for the Rivers Incorrectly Classified Using the SW Formulation

Location	Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classification
River Wandle - DS of Wimbledon STW (1977)	23 (69)	40	2	3/2	3
River Brent - US of GUC (1977)	54 (57)	46	3	2	2
Grand Union Canal (1970)	36 (60)	40	2	3/2	3

Note: WQRs in parentheses indicate penultimate ratings points on the WQI scale separating the lowest rating and the calculated WQI score. However, the results produced for the River Wandle and the River Brent were less satisfactory. The calculated WQI scores were respectively seventeen points higher and eight points lower than the lowest ratings. The latter is a problem inherent within the SW formulation. It rarely produces results which vary by as much as a class but does indicate quality lower than that which actually exists. However, this is not considered to be a serious problem, although it is one which merits careful monitoring. The results for the River Wandle are the product of only one adverse determinand concentration. The second lowest determinand rating was 69, indicating a Class 2/1B quality. Thus the borderline Class 3/2 WQI score is a median between these WQRs.

Table 73. Results Obtained for the GLC Data After A Review of the Lowest Ratings

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1B	8	8	69-81
2	30	30	41-68
3	15	15	25-44
4	4	4	10-13
	57	57	

Therefore the results from this analysis of determinand ratings has increased the level of agreement to 100%, but has highlighted two potential shortcomings within the proposed WQI.

The revised results for the GLC data shown in Table 73 indicate almost perfect cover of each of the class sub-divisions of the WQI range.

11.5.2. The Revised Results for the TWA Data

Of the twelve data sets analysed, six of the classifications indicated by the lowest ratings agreed with those of the calculated WQI scores, five agreed with the ascribed NWC classifications and one was deemed to be of borderline quality to that defined by the WQI (Table 74). This resulted in six of the NWC classifications being downgraded and one being upgraded by one class. This increased the level of agreement between the two classifications to 92% (sixty six out of seventy two river samples).

The results obtained for the rivers which were similarly classified by the lowest rating and the calculated WQI score showed that in three cases a difference of less than six points was recorded on the index scale, with one result showing complete agreement. For the two remaining rivers a difference of nine and ten points was recorded. For a data set based on eight determinands these results reflect a good interpretation of the data. However, the revised sub-divisions of the WQI range still show two major anomalies (Table 75) - the overestimation of three Class 3 and two Class 4 rivers, one of which had been previously classified as Class 2 by the user of the NWC classification (Table 74).

Table 74. Lowest Ratings and Classifications for the Rivers Incorrectly Classified Using the SW Formulation

Location	Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classification
River Thames - Days Lock	68	63	1B	2	2
River Thames - Egham	52	62	1B	2	2
River Thames - Walton	64	64	1B	2	2
River Coln	76	80	1A	1B	1B
River Cherwell-Twyford	38(66)	50	3/2	2	3/2*
River Blackwater	30	39	2/1B	3	3
River Colne - Denham	65	72	2/1B	1B	2
River Hogsmill	19(30)	37	4/3/2	3	4/3*
Pymmes Brook	40(56)	49	3/2	2	3/2*
River Roding - Redbridge	31(56)	46	3/2	2	3/1
River Ingrebourne	45	50	3/2	2	2
River Beam	19(58)	37	2	3	4/3*

Note: Water quality classes which are underlined are those which place the rivers into the same class as that defined by the lowest determinand rating.

* Represents samples which are borderline between water quality classes.

Table 75. Results Obtained for the TWA Data After a Review of the Lowest Ratings

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	2	2	88
1B	19	19	68-80
2	37	36	41-72
3	12	9	26-50
4	2	0	37
	72	66	

In four of the five rivers these anomalies result from a situation in which one determinand concentration is of a considerably lower quality than the remaining seven determinands. (The penultimate determinand rating has been indicated in brackets in Table 74). For all rivers, with the exception of the River Hogsmill, the second lowest ratings indicate a change in quality from Class 4/3 for the lowest ratings to a median/upper Class 2. In each case the calculated WQI score results in a median between these two classifications. Whether this reflects a serious inaccuracy within the WQI can only be assessed by the further application of the index. However, the index would appear to maintain a balance between exceptionally high and low quality ratings, but favouring a balance towards the latter. Any greater bias than this would almost certain result in the underestimations of overall quality.

WQRs of between 19 and 97 were recorded for the River Hogsmill. Thus the calculated WQI score again reflects median quality.

Finally, the results for the River Colne at Denham indicate that although an upgrading in quality has been recorded by the WQI, a difference of only seven points was registered on the WQI scale. Such a result is considered as being a reasonable interpretation of the data.

Thus the sub-divisions of the WQI range show a good agreement with the classifications produced, particularly for Class 2 to 1A rivers. In addition, the nine similarly classified Class 3 rivers cover a quality range of 26 to 45 on the WQI range.

11.5.3. The Revised Results for Data Set One of the STWA Data

As a result of the analysis of the lowest ratings, seventeen of the river samples were re-classified to agree with the WQI classifications (Tables 76 and 77). This increased the level of agreement between the WQI and NWC classification to 90% (eighty one out of ninety cases) and resulted in six of the NWC classifications being downgraded and a further eleven upgraded.

Of the eleven rivers which were upgraded as a result of this study, eight of the WQI scores agreed very closely with the lowest WQR, indicating that the index accurately reflects overall water quality. However, three of the index scores, while similarly classifying the river samples, do appear to overestimate water quality. For example, the River Tame at Lea Marston and the Ford Brook achieved WQI scores of 37 and 34 respectively. However, the lowest WQRs reflect water of much lower quality (21 and 23 respectively). The penultimate ratings in each instance were 39 and 28 respectively. These relate more closely to the level of water quality recorded. Of the six rivers to be downgraded all of the WQI scores agreed closely with the lowest WQR. Thus, in at least fourteen of these seventeen re-classifications, it is obvious that the user of the NWC classification had mis-classified these rivers or done so on the basis of additional information not available to the WQI.

Of the nine sample dissimilarly classified by the WQI and lowest determinand ratings, those pertaining to the River Severn at Llandrinio had additionally been mis-classified by the user of the NWC classification by an even greater margin. The classification of 1B ascribed by the WQI reflects the median quality resulting from WQRs which indicate Class 2 to 1A quality. In addition, the calculated index scores for the River Meese were sufficiently close to the lowest WQRs to be of no concern, indicating Class 2/1B quality in each instance.

The index scores derived for the River Sowe at Stoneleigh, the Tame at Oldbury and the Bottesford Beck again reflect median scores between the lowest and penultimate water quality ratings (Table 76). However the results for the River Tame at Wolverhampton and the Ford Brook (1978) reflect median WQI scores associated with WQRs ranging from 11 - 100 and 20 - 100 respectively.

Table 76. Lowest Ratings and Classifications for the Rivers Incorrectly Classified Using the SW Formulation

Location		Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classification
R. Severn - Caersws	(1978)	80	81	1A	1B	1B
	(1979)	81	85	1A	1B	1B
- Llandrinio	(1978)	60	75	1A	1B	2
	(1979)	67	78	1A	1B	2
R. Clywedog - Brithdir	(1979)	81	85	1A	1B	1B
River Meese	(1978)	70	76	2	1B	2/1B*
	(1979)	69	74	2	1B	2/1B*
R. Salwarpe - Wychbold	(1978)	58	52	3	2	2
	(1979)	54	49	3	2	2
R. Avon - Starebridge	(1978)	67	64	3	2	2
	(1979)	71	67	3	2/1B	1B
R. Sowe - Stoneleigh	(1979)	28(55)	46	3	2	3
Finham Brook	(1978)	71	74	2	1B	1B
	(1979)	71	74	2	1B	1B
River Leam	(1978)	72	73	2	1B	1B
	(1979)	74	75	2	1B	1B

Table 76 contd....

Location		Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classification
R. Tame - Lea Marston	(1978)	21(39)	37	4	3	3/4*
	(1979)	23	34	4	3	3
- Wolverhampton	(1978)	11(23)	26	4	3	4
- Oldbury Tame	(1979)	20(33)	30	4	3	4/3*
- Ford Brook	(1978)	20(24)	32	4	3	4/3*
	(1979)	23(28)	34	4	3	3
River Blythe	(1978)	54	65	1B	2	2
River Dove	(1978)	81	79	1A	1B	1B
	(1979)	81	80	1A	1B	1B
Bottesford Beck	(1978)	15(64)	45	4	2	4

Note: Water quality classes that are underline are those which place the rivers into the same class as that defined by the lowest determinand rating.

* Represents samples which are borderline between water quality classes.

Table 77. Results Obtained for Data Set One of the SWTA Data after A Review of the Lowest Ratings

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	1	1	89
1B	29	29	67-85
2	38	34	43-78
3	14	13	32-46
4	8	4	22-45
	90	81	

From the revised sub-division of the WQI scale, it is evident that all but the four incorrectly classified Class 4 rivers show an accurate reflection of that expected (Table 77).

11.5.4. Revised Results for Data Set Two of the SWTA Data

In this final analysis, thirty of the thirty four classifications produced by the lowest ratings agreed with those defined by the WQI (Table 78), resulting in the downgrading of twenty eight and the upgrading of two river samples.

Thus the level of agreement between both classifications was increased to 97% (132 out of 136 cases). A review of the data for the re-classified rivers indicates that, in most instances, the calculated index scores closely reflect the lowest ratings obtained by the index determinands. The results from this study highlight most dramatically the problems associated with the use of subjective classifications like that of the NWC.

Of those remaining incorrectly classified, the results for the River Leadon, River Blithe and River Rea show that the calculated WQI scores are only separated by seven to nine points on the index scale from the lowest ratings ascribed, despite the final classification attained. The results for the River Clywedog again reflect a median score between the lowest and penultimate ratings.

Table 78. Lowest Ratings and Classifications for the Rivers Incorrectly Classified Using the SW Formulation

Location		Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classification
R. Severn - Hawbridge	(1978)	69	64	1B	2	2/1B
	(1979)	64	61	1B	2	2
- Sharp Canal	(1978)	60	63	1B	2	2
	(1979)	67	63	1B	2	2
River Clywedog	(1979)	60(92)	78	1A	1B	2
River Vyrnwy	(1978)	81	82	1A	1B	1B
	(1979)	80	81	1A	1B	1B
River Roden	(1978)	64	65	1B	2	2
	(1979)	43	47	1B	2	2
River Worfe	(1979)	55	52	1B	2	2
River Teme - Powick	(1978)	44	64	1B	2	2
	(1979)	51	65	1B	2	2
River Corve	(1979)	46	61	1B	2	2
River Isbourne	(1979)	55	65	1B	2	2

Table 78 contd....

Location		Lowest Rating	WQI Score	NWC Class	WQI Class	Correct Classi-fication
River Leadon	(1979)	71	63	1B	2	1B
River Stone	(1978)	40	39	2	3/2	3/2*
River Penk	(1978)	54	55	1B	2	2
	(1979)	48	53	1B	2	2
River Blithe	(1978)	64(86)	71	1A	1B	2
	(1979)	64	69	1A	2/1B	2
River Rea	(1979)	20(41)	29	2	3	4/3*
River Manifold	(1978)	81	79	1A	1B	1B
	(1979)	84	83	1A	1B	1B
R. Churnet-Abbey Gn Rd	(1978)	54	64	1B	2	2
	(1979)	45	52	1B	2	2
R. Derwent - Matlock	(1978)	77	76	1A	1B	1B
	(1979)	88	84	1A	1B	1B/1A
- St Mary's Bdge.	(1978)	72	72	2	1B	1B
	(1979)	81	77	2	1B	1B
River Wye	(1978)	81	79	1A	1B	1B
	(1979)	81	79	1A	1B	1B
R. Erewash - Trowell	(1978)	30	36	2	3	3
	(1979)	29	34	2	3	3
River Devon	(1978)	64	64	1B	2	2

Note: Water quality classes that are underlined are those which place the rivers into the same class as that defined by the lowest determinand rating.

* Represents samples which are borderline between water quality classes.

Table 79. Results Obtained for Data Set Two of the STWA Data After A Review of the Lowest Ratings

NWC Class	Number of Rivers In Each Class	WQI Classification	WQI Range
1A	1	1	92
1B	32	31	63-84
2	85	83	42-78
3	17	17	24-43
4	1	0	29
	136	132	

Thus, the revised sub-divisions of the WQI scale (Table 79) show, with the exception of the Class 4 river, almost complete agreement with those defined in Table 51.

11.6. COLLATION OF RESULTS

When the results from these comparative studies were collated they revealed that the WQI had accurately classified 336 of the 355 river samples previously classified by the NWC classification (Table 80). This produced an overall accuracy of 95%. Index scores of between 10 and 92 were recorded using the SW formulation leaving only eight points on the index range unaccounted.

The results clearly indicate the problems associated with the use of subjective methods of water quality classifications. At least fifty six of the river samples were shown to have been mis-classified by the users of the NWC classification on the basis of the lowest ratings obtained as part of the WQI calculations. These mis-classifications were shown to increase as the

Table 80. Results Produced by the WQI During the Validation Process

NWC Class	Number of Rivers In Each Class	WQI Classification	Level of Agreement	WQI Range
1A	4	4	100%	88-92
1B	88	87	99%	63-85
2	190	183	96%	41-78
3	58	54	93%	24-50
4	15	8	53%	10-45
	355	336	95%	

number of data sets increased. In addition, the interpretation of the NWC classification was seen to vary from one authority to another. This can be seen best by reviewing the results obtained for Class 3 rivers throughout the comparative studies. Class 3 was most accurately defined by the GLC where a WQI range of 25 to 46 was obtained. However, the results produced by the Thames and Severn Trent Water Authorities suggest that a more liberal view was taken, with WQI ranges of 26 to 50 and 24 to 67 respectively.

A review of the determinand ratings ascribed to the nineteen mis-classified rivers showed that ammoniacal nitrogen was the determinand most commonly to attain the lowest water quality rating. It is therefore possible that the lower end this rating curve requires modification. In addition, these results indicate that the high level of agreement obtained between the WQI and NWC classification for data set 2 of the Severn Trent Water Authority was not associated with the omission of dissolved oxygen from the index calculation.

The low average WQI scores obtained for the Class 1A rivers may reflect a tendency within the index to underestimate waters of high quality. However, this is likely to be associated with the higher quality requirements of a Class 1A river as defined by the WQI rating curves rather than the sub-divisions of the NWC classification. Familiarity with the use of the index could undoubtedly result in the lowering of the threshold score defining this quality class. Even without this modification, the higher quality requirements of the index should not impair its use by water quality managers, as Class 1A rivers are unlikely to require careful monitoring.

The results obtained from this validation exercise for Class 4 rivers are of more concern because they indicate a potential overestimation of quality. Whether these overestimations are real or apparent is difficult to assess at this stage. For example, a review of the definition given by the NWC for a Class 4 river suggests that it would be possible to modify the sub-divisions of the WQI scale to reflect more closely the range in the results produced. Thus, the index range relating to Class 4 rivers could be extended from 10 - 25 to 10 - 30 with scores of between 26 and 30 indicating waters of Class 4/3 quality. This would increase the number of Class 4 rivers correctly classified by the WQI to eleven. However, it is important to remember that an index number is, by definition, "... a form of average..." (SDD, 1976). As such, the index scores produced should reflect overall water quality as determined by the range of index determinands. In the case of the seven Class 4 rivers incorrectly classified by the WQI, only one determinand received a rating indicative of Class 4 quality in each instance. Of these, five of the rivers obtained borderline WQRs of 19 and 20. Thus, even the lowest ratings are indicative of marginal Class 4/3 quality. The second lowest and subsequent ratings in each instance reflect waters of Class 3/2 quality and above. Thus, the WQI scores of

26 to 37 calculated for each of these five river samples indicate a form of median quality and, as such, are likely to be accurate.

Thus the extremely high level of agreement obtained from this validation exercise indicates that the index is undoubtedly capable of reflecting both good and poor quality water in a simple and reproducible manner.

11.7. A COMPARISON BETWEEN THE WQI AND SDD (1976) INDEX

Finally, the results produced by the WQI were compared with those of the SDD (1976) index for the GLC data (Table 81).

Studies using the SDD index have shown indices to be a preferable form of water quality assessment to the use of subjectively applied classifications (Anglian and Yorkshire Water Authority, Internal Reports, 1978; House and Ellis, 1980). However, the SDD (1976) index was criticised as being biased towards water of high quality (see Chapter 6).

A comparison of the results produced by the SW formulations of the respective indices shows that both produce comparable results within an index range of 50 - 79. However, below this range the SDD index appears to underestimate grossly water quality (see Table 81). These findings are substantiated by an analysis of the index sub-divisions covered for each of the NWC quality classes (Table 82). Above an index score of 79, the WQI appears to underestimate quality slightly. However, the higher level of agreement achieved by the WQI and the increased cover of the index sub-divisions suggest that the WQI has overcome the problems associated with the use of the SDD index.

Table. 81. Results From the Comparative Study Between the SDD Index and the Proposed WQI

Location	1970					1977				
	NWC Class	WQI Score	SDD Index SW	AW	MW	NWC Class	WQI Score	SDD Index SW	AW	MW
River Wandle										
Croydon Arm - Lower Reaches	3	40	26	51	47		NO DATA			
Croydon Arm - Upper Reaches	3	39	27	52	47	1B	81	90	95	95
Carshalton Branch	3	33	21	46	37	1B	80	89	94	94
Goat Bridge - US of Beddington STW	3	42	31	56	49	1B	78	82	91	90
Watermeads - DS of Beddington STW	4	12	3	18	6	3	36	18	43	35
DS of Wandle Valley and US of Wimbledon STW	4	10	2	14	5	2	40	28	53	44
US of Tideway	4	11	1	15	11	2	43	32	57	47
Beverley Brook										
Beverley Brook - DS Worcester Park STW	4	13	3	18	6	3	25	12	35	26
Pyl Brook - DS of Sutton STW	3	31	18	43	38	3	27	14	38	30
Beverley Brook - US of the Tideway	3	27	15	39	29	2	49	38	62	58
River Darent and Cray										
River Darent - Upper Reaches		NO DATA				1B	77	81	90	90
River Darent - US of the Tideway		"	"			1B	80	86	93	92
River Shuttle		"	"			1B	69	69	83	83
River Cray - US of the Tideway		"	"			1B	74	77	88	87
River Ravensbourne										
River Ravensbourne - US of the Pool	2	53	52	72	65	2	61	65	80	79
River Pool	2	49	41	64	55	2	68	62	79	78
River Quaggy	2	59	56	75	63	2	63	61	78	76
River Ravensbourne - US of the Tideway	2	46	45	67	61	2	66	66	81	79
River Crane and Duke of Northumberland's River										
River Crane - US of the Duke's River	3	42	31	56	51	2	59	50	71	69
Duke's River - US of the River	2	60	54	74	67	2	63	60	77	76
River Crane - US of the Tideway	2	62	55	74	68	2	62	54	73	72
Duke's River - US of the Tideway	2	60	55	74	68	2	63	54	74	71
River Brent										
Silk Stream	3	38	24	49	44	2	62	55	74	72
Dollis Brook	2	42	30	55	50	2	67	62	79	77
River Brent - DS of Welsh Harp	2	54	46	68	63	2	67	64	80	79
River Brent - US of Grand Union Canal	2	46	32	57	52	3	46	33	57	56
River Brent - US of Tideway	2	44	29	54	50	2	58	50	71	68
Grand Union Canal										
Grand Union Canal - on entry to MPC Area	2	57	51	72	65	2	46	37	61	51
Grand Union Canal - US of the confluence with the River Brent	2	40	23	49	46	3	42	31	55	51
Paddington Arm	2	41	27	52	44	3	44	33	58	53
Regent's Canal - US of the Tideway	2	60	57	75	69	1B	72	77	88	88

TOTAL AGREEMENT 57 54 43 25 37

Note: Water quality index scores that are underlined are those which place the rivers into the same class as the NWC classification system.

Two additional criticisms of the SDD index were that it was not developed in relation to recognised standards or criteria and that no indication of potential water use was given (Anglian and Yorkshire Water Authority, Internal Reports, 1978). This Study has incorporated such standards and potential uses and therefore the WQI has met most of the criticisms of indices previously used within the UK.

Table 82. A Comparison Between the SDD Index and the WQI

NWC Class	Number of Rivers In Each Class	WQI Classification	SDD Classification	WQI Range	SDD Range
1B	8	8	8	69-81	69-90
2	31	29	22	40-68	23-66
3	14	13	9	25-46	12-33
4	4	4	4	10-13	2-3
	57	54	43		

11.8. THE IMPLICATIONS OF THE RESULTS

The high level of agreement between the WQI and NWC classification would suggest that a general WQI is at least as good as existing methods of water quality assessment. In fact, the adoption of a WQI would provide a number of positive advantages over the NWC classification in the operational management of surface water quality. It enables large quantities of data to be reduced to a single number in a reproducible manner, whereas it is not always possible for two water quality managers to agree on the classification of a water sample on the basis of the subjective assessment of a list of determinand concentrations. With an index, the use of mathematical formulae facilitates such reproducibility. In addition, an index is ideally suited to computerisation, thus reducing the time involved in the classification of surface water quality. It has been argued that in reducing large amounts of data to a single index number, information is lost or hidden, but this is true of all forms of classification and, as with any classification, the raw data are still available if additional information is required. However, an index actually provides more information on the quality of a river water than the NWC classification. As well as classifying a water body into a specific class, the use of index numbers can indicate the position of a sample within that class. Examples of both these and other advantages of the use of an index can be found within each of the sample data sets used as part of this validation study.

11.8.1. The GLC Data

Within-class variations have been highlighted by the use of the WQI in the analysis of the GLC data. The River Pool and the River Wandle upstream of the tideway (1977 data), were classified as Class 2 by the user of the NWC classification. However, the former received a WQI of 68 and the latter a WQI of 43 (Table 55). This indicates that both are at opposite ends of the same water quality class and will, therefore, possess very different economic potentials; a point which is totally overlooked by the NWC classification.

Thus, spatial variations in quality and economic potential become immediately apparent from the application of the WQI. The use of an index to determine the position of a water body within a specific quality class would also provide greater management flexibility as well as the information necessary to enable better operational management to be practised. Bearing in mind the recently emphasised accountability of future pollution control investments and improvements, an index provides 'harder' information on which to base investment decisions. In addition, water quality improvements associated with applied management strategies may be carefully monitored through time by the use of an index. For example, the influence of various management strategies employed to upgrade the quality of the Carshalton Branch of the River Wandle from a WQI of 33 in 1970 to 80 in 1977 could be monitored over various timescales and their efficiency and benefits assessed in monetary terms (Table 55). Similarly the quality change in the Dollis Brook over the same seven year period from a WQI of 42 to 67 may well have gone unnoticed, because the overall quality class remained constant throughout this period (Table 55). However, the economic potential will have changed significantly from a situation in which coarse fish might be present sporadically, to a potential appropriate for the introduction of game fisheries. Details of such secular water quality trends provides distinct advantages for the operational management of water quality.

Thus, the use of the WQI assists in pin-pointing river stretches which have changed significantly in quality, or identifies variations in quality which exist both within, and between, catchments.

11.8.2. The TWA Data

Further examples of the way in which an index can be used to highlight spatial variations in water quality can be cited from this data set. Additionally, the value of a numeric scale as opposed to the qualitative approximation of quality provided by the NWC classification can be assessed. For example, the quality of the River Cherwell at Grimsbury and Marston Road was assessed as being Class 1B and Class 2 respectively by the user of the NWC classification (Table 59). However, index scores of 71 and 70 were calculated for each river reach respectively. The River Thames at Cricklade and the River Cherwell at Fencott Road obtained identical index scores, but were classified as Class 2 and Class 3 respectively by the user of the NWC classification. In each instance, the ascribed NWC classification indicates waters of very different quality and potential economic value, which in reality would not appear to exist. Therefore an index reports on the specific quality of a river reach and produces results which are unambiguous, unlike those generated by subjective methods of classification.

11.8.3. The STWA Data

Examples of the way in which an index may be used to pin-point river reaches which have altered in quality can be cited from each of the data sets. For example, the quality of the River Tern at Allscott Mill and the River Avon at Tewkesbury changed significantly over the two year monitoring period. However, neither changed sufficiently for a change in class to be recorded (Table 63). The quality of the River Tern in fact increased from a WQI of 47 to 55, whilst that of the River Avon deteriorated from a WQI of 68 to 59. Although neither change reflects a change in the economic potential of these rivers, the former may result from applied management strategies which merit careful monitoring and assessment, whilst the latter may require causal investigations to be undertaken. In both cases, such changes may have gone unnoticed without the availability and use of an index.

Finally, spatial variations in the economic potential of water body can be assessed by using the WQI. For example, the River Clywedog obtained an index score of 92, reflecting water which could support a high class game fishery, or that which could be used as a potable water supply (PWS) after only disinfection

(Table 37). However, the Rea Brook with a WQI score of 77, whilst of similar high quality and able to support game fish populations would, as defined by the EEC (1975), require minor purification if this water was to be used in PWS. The lower quality reflected by an index score of 59 for the River Trent at Sawley indicates water of marginal quality for healthy game fish populations, but is adequate to support coarse fisheries whilst its use as a source of water for PWS would require conventional treatment (EEC, 1975). Finally, the Alfreton Brook, with a WQI of 39, would support only sporadic populations of coarse fish and require advanced treatment before use in PWS (EEC, 1975). Thus an index can be used to reflect spatial and temporal variations in the economic potential of a water body.

11.9. CONCLUSIONS

The results of this investigation highlight the variations which are bound to emerge when using subjective methods of water quality classification. However, the high agreement obtained between the WQI and NWC classification would suggest that an index can be used to monitor trends accurately in surface water quality.

The SW formulation of the WQI appears the most stable and consistent, showing a 95% agreement with the NWC classification. The index is based on legal standards and, as such, reflects precisely the legal requirements that water quality managers are aiming to achieve.

The specific advantages of a WQI may be summarised as follows:

i) it enables large amounts of data to to be reduced to a single index value in an objective, rapid and reproducible manner;

ii) an index can be used as a 'yardstick' with units which are stable, consistent and reproducible, thus allowing the comparison of water quality in space and time;

iii) it is an unambiguous way of communicating information upon trends in water quality, both within and between water quality classes. As such, it could promote a better understanding between laymen and operational management;

iv) it assists in pin-pointing river reaches which have altered significantly in quality. In this way, either the need for, or the value of, applied management strategies can be assessed;

v) the subdivision of the index to reflect potential water use provides an indication of the economic value of a watercourse and the gains and losses to that value which result from the implementation of management strategies;

vi) finally, it can provide considerable management flexibility in that it moves away from the strict categorisation of water quality in terms of defined classes to a numeric range which allows each river to be individually and independently classified in a reproducible manner. However, results may still be given in a classificatory form when information at the directorate level is required.

Hence, bearing in mind the compatibility of the WQI with existing classifications, it would suggest that optimal management practices would be capable of implementation by its adoption.

CHAPTER 12

VALIDATING THE POTABLE WATER SUPPLY INDEX (PWSI)

12.1. INTRODUCTION

The Potable Water Supply Index (PWSI) is use-specific and is intended to reflect water quality exclusively in terms of its suitability for use in potable water supply (PWS). Consequently, the results produced by the PWSI are not directly comparable to either the NWC (1977) classification or the general WQI. A comparison between the PWSI and NWC classification is particularly difficult because the latter ignores much of the PWSI scale. For example, the NWC classification does not recognise the potential use of water in PWS after only minor purification; thus PWSI scores in the range of 71 to 100 cannot be accurately evaluated.

Similar problems arise when comparing the index scores produced by the PWSI and WQI. The latter is, by design and definition, general use-related and, therefore, reflects a form of average quality covering a range of potential water uses. However, PWS is recognised as being of prime importance to water quality managers and was, therefore, given high priority as a potential water use within the development of the WQI, particularly at the middle-to-upper end of the quality spectrum. Both indices have been developed in the same rigorous manner, especially in regard to the construction of rating curves, which were based upon published water quality standards and criteria. In this respect, precedence was given in each case to the recommendations given by the EEC (1975) on the use of raw water in potable water supply. Thus, although the determinands, ratings and weightings differ between the PWSI and WQI, the way in which water quality is evaluated and recorded is similar. Therefore a reasonable basis for comparison exists. For the most part it is the interpretation of the scores produced by each index which may differ, due to the general applicability of the WQI (Tables 37 and 38).

Therefore, with no real base from which to compare the results produced by the PWSI, it cannot be directly validated. However, the PWSI can be instrumental in the further validation of the WQI, for although the WQI is not use-specific, it must be sufficiently sensitive to the way in which water quality trends affect major water uses such as PWS. In using the PWSI in this way one must be reasonably confident that the results produced by the index are, in fact, accurate. It is reasonable to assume a good accuracy for the PWSI because the design and development processes involved were the same as those used within the WQI, whose validation has been confirmed.

Thus, the results from a comparative study between the WQI and PWSI may provide an answer to the long-standing question about the need for both general and use-specific indices in the operational management of surface water quality.

12.2. A COMPARISON BETWEEN THE PWSI AND WQI

The PWSI was applied to the 129 data sets which had been previously classified by the Greater London Council (GLC) and Thames Water Authority (TWA) using the NWC classification. In addition, data relating to nineteen further sampling stations was selected from within the TWA Region where water is actually used in PWS. Although these data had not been classified using the NWC classification, it was known that conventional and advanced treatment, as defined by the EEC (1975), had been applied in the management of these waters.

Data which had been classified using the NWC classification were selected in order to evaluate the way in which a general water quality classification could be used to detect the suitability of water for specific purposes.

Five classes of raw water quality are recognised within the management of surface waters for use in PWS. These range between excellent quality, where waters require only minor purification prior to their use in PWS (Class I), through to waters which are totally unacceptable for this purpose (Class X). To facilitate these comparative studies, each index/classification was subdivided to reflect these five potable water quality classes (Table 83).

Table 83. Potable Water Quality Classes for the NWC Classification, WQI and PWSI

Potable Water Quality Class	NWC Class	WQI Score	PWSI Score
CLASS I (Minor Purification)	Not Included	71-100	71-100
CLASS II (Conventional Treatment)	1A + 1B	51-70	51-70
CLASS III (Advanced Treatment)	2	41-50	31-50
CLASS IV (Doubtful Quality)	3	21-40	11-30
CLASS X (Unacceptable Quality)	4	10-20	0-10

In addition, the weightings given to both the WQI and PWSI determinands were re-calculated, as outlined within the WQI validation exercise, because data on only a selection of the index determinands were available (Tables 84 and 85) within each of the data sets.

Table 84. Re-calculated Weightings of the WQI and PWSI for the TWA Potable Water Supply Data

Determinand	WQI Weighting	PWSI Weighting
pH	0.18	0.12
Ammoniacal Nitrogen	0.33	0.14
Chlorides	0.08	0.05
Nitrates	0.18	0.14
Total Coliforms	0.23	0.19
Colour		0.14
Sulphates		0.04
Fluorides		0.06
Iron		0.12
	1.00	1.00

Table 85. Re-calculated Weightings of the PWSI for the GLC and TWA Data

Determinand	GLC Data Weightings	TWA Data Weightings
Ammonical Nitrogen	0.30	0.17
Suspended Solids	0.30	0.17
Biochemical Oxygen Demand	0.26	0.15
Dissolved Oxygen	0.14	0.09
pH		0.15
Temperature		0.03
Chloride		0.07
Nitrates		0.17
	1.00	1.00

Finally, the PWSI was calculated for each of the 148 data sets using the arithmetic, multiplicative and modified arithmetic index formulations (AW, MW and SW respectively). The classifications produced by the PWSI were then compared to those of the WQI and NWC classification where applicable.

12.3 THE RESULTS FROM THE COMPARATIVE STUDIES BETWEEN THE PWSI, WQI AND NWC CLASSIFICATION

The results from each comparative study are presented in Tables 86 to 91. However, those produced by the PWSI using the AW and MW formulations are not given, because both formulations were found to substantially overestimate water quality, a tendency recognised during the validation of the WQI. The only exceptions to these overestimations of quality were recorded by the MW formulation when a zero rating was attained by any one of the

PWSI determinands. This occurrence resulted in a zero index score. The significance of these results is discussed in Section 12.3.2 and 12.3.3. Thus, the results outlined in Tables 86 to 91 relate to the use of the SW formulation in the calculation of both the PWSI and WQI.

12.3.1. The Results for the TWA Potable Water Supply Data

The results from this comparative study show almost complete agreement between the potable water quality classifications produced by the WQI and PWSI (Table 86). The scores produced by each index range between 47 - 70 and 44 - 67 respectively. Thus, both indices appear not only similarly to classify, but also similarly rate water quality, with a maximum difference of only nine points recorded on the index scales. Eighteen of the nineteen river reaches are classified as Class II (requiring conventional treatment) by the calculated PWSI scores. These scores almost perfectly cover the index range ascribed to this water quality class. Thus, the PWSI would appear to detect the range in quality conditions requiring this form of treatment (Table 87). The WQI similarly classified seventeen of these eighteen Class II river reaches, indicating a large degree of similarity in the way both indices relate water quality to the potential use of surface water in potable water supply. The quality of the River Thames at Culham was underestimated by the WQI thus indicating the problem of accurately defining potential water use by a general index. However, the River Eden at Bough Beeches was similarly classified as Class III by both indices.

The results from this initial comparative study suggest that both indices similarly detect trends in surface water quality and that the WQI is capable of accurately reflecting the suitability of water for use in potable water supply, despite its general use development format. However, these results are not altogether

Table 86. Results from the Comparative Study Between the PWSI and WQI for the TWA Potable Water Supply Data

Location			WQI Score	PWSI Score	WQI Class	PWSI Class
River Kennet	-	Fobney	70	63	II/I	II
	-	Southcote	68	62	II	II
River Thames	-	Walton	60	52	II	II
	-	Datchet	60	52	II	II
River Lee	-	New Gauge	61	54	II	II
	-	Chingford	64	55	II	II
River Tillingbourne			70	61	II/I	II
River Thames	-	Farmoor	58	59	II	II
Sor Brook	-	Bodicote	62	60	II	II
River Cherwell	-	Grimsbury	61	61	II	II
River Coln	-	Lechlade	66	67	II	II
River Thames	-	Buscot	56	58	II	II
River Windrush	-	Worsham	63	62	II	II
River Thames	-	Culham	47	56	III	II
River Eden	-	Bough Beech	49	44	III	III
River Thames	-	Egham	58	55	II	II
	-	Chertsey	59	54	II	II
	-	Walton	58	53	II	II
	-	Sunnymead	59	54	II	II

Note: Quality Classes that are underlined are those which similarly classify water quality to the PWSI.

Table 87. Breakdown of the Results for the TWA Potable Water Supply Data

Potable Water Quality Class	PWSI Classification	WQI Classification	PWSI Range	WQI Range
I				
II	18	17	52-67	56-70
III	1	1	44	47-49
IV				
X				
	19	18		

surprising because, in most cases, the data reflect waters of high quality and it is at this end of the quality spectrum that both indices are most similar in their development and interpretation.

12.3.2. The Results for the GLC Data

The results produced by the PWSI for the GLC data were compared with both the WQI and NWC classifications. The former achieved an agreement of 81%, with forty six of the fifty seven river samples similarly classified to the PWSI. A maximum of only eight points separated the calculated PWSI and WQI scores indicating a high level of agreement in the way in which both indices interpret water quality (Table 88). Index scores of 5 - 75 and 10 - 81 were recorded for the PWSI and WQI respectively compared with Classes 4 - 1B in the NWC classification assigned by Aston et al in 1979.

Table 88. Results from the Comparative Study Between the PWSI, WQI and NWC Classification for the GLC Data

Location	1970 Data					1977 Data				
	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Wandle										
Croydon Arm - Lower Reaches	40	39	IV/III	III	3	ND	ND	ND	ND	ND
Croydon Arm - Upper Reaches	39	37	IV	III	3	81	75	I	I	1B
Carshalton Branch	33	33	IV	III	3	80	74	I	I	1B
Goat Bridge - US of Beddington STW	42	40	II	III	3	78	72	I	I	1B
Watermeads - DS of Beddington STW	12	8	X	X*	4	36	33	IV	III	3
DS of Wandle Valley and US of Wimbleton STW	10	5	X	X*	4	40	37	IV/III	III	2
US of Tideway	11	9	X	X*	4	43	39	III	III	2
Beverley Brook										
Beverley Brook - DS Worcester Park STW	13	10	X	X*	4	25	24	IV	IV	3
Pyl Brook - DS of Sutton STW	31	31	IV	III	3	27	25	IV	IV	3
Beverley Brook - US of the Tideway	27	21	IV	IV	3	49	51	III	II/III	2
River Darent and Cray										
River Darent - Upper Reaches	ND	ND	ND	ND	ND	77	71	I	I/II	1B
River Darent - US of the Tideway	ND	ND	ND	ND	ND	80	72	I	I	1B
River Shuttle	ND	ND	ND	ND	ND	69	66	II/I	II	1B
River Cray - US of the Tideway	ND	ND	ND	ND	ND	74	69	I	II	1B
River Ravensbourne										
River Ravensbourne - US of the Pool	53	54	II	II	2	61	62	II	II	2
River Pool	49	43	III	III	2	68	63	II	II	2
River Quaggy	59	53	II	II	2	63	58	II	II	2
River Ravensbourne - US of the Tideway	46	47	III	III	2	66	63	II	II	2
River Crane & Duke of Northumberland's River										
River Crane - US of the Duke's River	42	42	III	III	3	59	57	II	II	2
Duke's River - US of the River	60	61	II	II	2	63	60	II	II	2
River Crane - US of the Tideway	62	60	II	II	2	62	60	II	II	2
Duke's River - US of the Tideway	60	59	II	II	2	62	61	II	II	2
River Brent										
Silk Stream	38	39	IV	III	3	62	58	II	II	2
Dollis Brook	42	42	III	III	2	67	62	II	II	2
River Brent - DS of Welsh Harp	54	57	II	II	2	67	63	II	II	2
River Brent - US of Grand Canal	46	48	III	III	2	46	49	III	III	3
River Brent - US of Tideway	44	46	III	III	2	58	56	II	II	2
Grand Union Canal										
Grand Union Canal - on entry to MPC Area	57	56	II	II	2	46	41	III	III	2
Grand Union Canal - US of the confluence with the River Brent	40	40	IV/III	III	2	42	43	III	III	3
Paddington Arm	41	46	III/IV	III	2	44	45	III	III	3
Regent's Canal - US of the Tideway	60	60	II	II	2	72	69	I	II/I	1B

NOTE: Quality Classes that are underlined are those which similarly classify water quality to the PWSI.

DS = Downstream STW = Sewage Treatment Works
US = Upstream MPC = Metropolitan Pollution Control
* = Indicates PWSI scores which are zero related when the MW formulation is used.

A breakdown of the results indicates that the WQI has a tendency to underestimate waters requiring advanced treatment before use in potable water supply (Class III) and, slightly, to overestimate the quality of those requiring conventional treatment (Class II, Table 89). These results are contrary to the findings of the WQI validation study, which indicated the tendency of the WQI to underestimate quality at the upper end and overestimate quality at the lower end of the quality spectrum. The overestimation of Class II rivers by the WQI is associated with the additional consideration of the quality requirements of game and coarse fisheries, which are similarly classified by the WQI scale (Table 37). The underestimation of Class III rivers is similarly associated with the consideration of additional potential water uses. Thus, some difference in the index scores recorded by the respective indices was to be expected. However, these results again reflect a strong similarity in the way in which both indices record and interpret water quality.

Table 89. Breakdown of the Results for the GLC Data

Potable Water Quality Class	PWSI Classification	WQI Classification	NWC Classification	PWSI Range	WQI Range	NWC Range
I	5	5	5	71-75	77-81	1B
II	24	21	3	51-69	49-74	2-1B
III	21	13	10	31-49	31-49	3-2
IV	3	3	3	21-25	25-27	3
X	4	4	4	5-10	10-13	4
	57	46	25			

Nevertheless, the results produced by the user of the NWC classification were less satisfactory, with only twenty five of the fifty seven river samples similarly classified to the PWSI (Table 89). The user of the NWC classification would appear consistently to underestimate quality. This is undoubtedly associated with the exclusion of minor purification from the NWC classification and the fact that the design of the classification is biased towards the protection of game and coarse fisheries (Table 6).

The index range covered by the PWSI for Class II and Class III rivers almost perfectly covers the ascribed index range of 31 to 70. In addition, the calculated index scores of 5-10 for Class X rivers indicates the ability of the PWSI to detect waters which are totally unacceptable for use in PWS when using the modified arithmetic formulation. The ability to detect waters of very low quality is generally recognised as being the main attraction of the multiplicative weighted formulation. Each of the four Class X rivers attained zero index scores when the MW formulation was applied. However, the scores achieved by the SW formulation indicate that this version of the PWSI is sufficiently sensitive to low quality ratings to reflect waters which are unsuitable for use in PWS.

Thus, the WQI and PWSI similarly rate and classify surface water quality over a range of quality conditions.

12.3.3. The Results for the TWA Data

The results from the application of the PWSI to the TWA data revealed that fifty four of the seventy two river samples were similarly classified by the PWSI and WQI (Table 90), with a difference of twelve points being recorded between the two index scores. However, in most instances, both indices similarly rated water quality. The range covered by each index was extended to 24 - 83 and 26 - 88 for the PWSI and WQI respectively (Table 91). Thus both indices are capable of detecting waters of high quality, requiring only minimal treatment. The results again indicate the tendency of the WQI to overestimate the quality of Class II rivers, with eleven of the rivers incorrectly classified as Class I. The results produced by the WQI for Class III rivers were less consistent, with two of the incorrectly classified rivers receiving overestimated and the remaining three underestimated quality classifications. Thus again, it would appear that the WQI, far from underestimating waters of high quality, is either overestimating or at least accurately reflecting water quality.

The results produced by the NWC classification were slightly improved from those in the previous study; the ascribed classes again showing a marked tendency to underestimate quality, particularly the quality of Class II rivers requiring conventional treatment (Table 91).

The results produced by the PWSI again cover a wide range in water quality conditions, with Class I to Class IV quality recorded. The results for Class II rivers perfectly cover the ascribed index range.

Table 90. Results from the Comparative Study Between the PWSI, WQI and NWC Classification for the TWA Data

Location	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Thames					
Hannington Bridge	62	62	II	II	2/1B
Buscot	67	63	II	II	2/1B
Swinford	69	64	II	II	1B
Days Lock	63	56	II	II	1B
Caversham	68	57	II	II	1B
Henley Bridge	69	63	II	II	1B
The Cut	45	48	III	III	2
Egham	62	51	II	II	1B
Littleton	68	63	II	II	1B
Walton	64	58	II	II	1B
Teddington	55	48	II	III	2
Swindon	62	61	II	II	2
Cricklade	41	42	III	III	2
Lechlade	80	73	I	I	1A
Worsham	75	69	I	II	1B/1A
Newbridge	77	68	I	II	1B/1A
River Cherwell					
Grimsbury	71	63	I	II	1B
Twyford	50	52	III/II	II	3/2
Upper Heyford	68	63	II	II	2/1B
Fencott Road	41	53	III	II	3/2
Marston Road	70	66	II/I	II	2/1B
River Ock	67	64	II	II	2/1B

Table 90 contd....

Location	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Thame	68	63	II	II	1B
River Lambourn	88	83	I	I	1A
River Kennet	88	81	I	I	1A
River Blackwater					
Farnborough	39	45	IV	III	2/1B
Whitewater	60	61	II	II	2/1B
Swallowfield	65	64	II	II	2/1B
River Loddon					
Arborfield Bridge	67	66	II	II	2/1B
Twyford	69	65	II	II	2/1B
River Wye	59	57	II	II	2/1B
River Colne					
Denham	72	66	I	II	2/1B
Thames	48	43*	III	III	2/1B
River Mole					
Horley Weir	43	46	III	III	3/2
Sidlow Bridge	47	50	III	III/II	2/1B
River Lane	69	68	II	II	2/1B

Table 90 contd....

Location	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Mole contd.					
Royal Mills	64	64	II	II	2
Above Thames	63	62	II	II	2
Hogsmill	37	34	IV	III	4/3/2
River Lee					
East Hyde	68	68	II	II	1B
Road Bridge	44	44	III	III	2
Wheathampstead	48	45	III	III	2
River Stort					
Spellbrook	63	63	II	II	2/1B
Roydon	73	67	I	II	1B
River Lee					
Rye House	78	69	I	II	1B
Dobbs Weir	76	67	I	II	1B
Kings Weir	76	68	I	II	1B
Lea Valley Road	73	62	I	II	1B
Navigation	59	55	II	II	2/1B
Pymmes Brook	49	44	III	III	3/2
Springhill	41	43	III	III	3/2
Carpenters Road	55	48	II	III	2

Table 90 contd....

Location	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Roding					
Ongar Bridge	74	62	I	II	1B
Abridge	55	52	II	II	2/1B
Redbridge	46	44	III	III	3/2
R Ingrebourne	50	50	III/II	III/II	3/2
River Beam	37	35	IV	III	2
River Crane	59	54	II	II	2/1B
Duke of Northumberland's River	69	64	II	II	2/1B
Pyl Brook	26	24	IV	IV	3/2
Beverley Brook					
Motspur Park	30	30	IV	IV	3/2
Priests Bridge	45	44	III	III	3/2
River Wandle					
Goats Bridge	72	65	I	II	1B
Watermeads	41	37	III	III	3/2
Causeway	45	41	III	III	3/2

Table 90 contd....

Location	WQI Score	PWSI Score	WQI Class	PWSI Class	NWC Class
River Beck	59	60	II	II	2/1B
River Pool	67	64	II	II	2/1B
River Quaggy	63	58	II	II	2/1B
R. Ravensbourne	69	62	II	II	2/1B
River Darent					
Otford	76	71	I	I	1B
Millpond Road	78	72	I	I	1B
River Shuttle	66	63	II	II	2/1B

Note: Quality Classes that are underlined are those which similarly classify water quality to the PWSI

* Indicates PWSI scores which are zero rated when the MW formulation is used.

Table 91. Breakdown of the Results for the TWA Data

Potable Water Quality Class	PWSI Classification	WQI Classification	NWC Classification	PWSI Range	WQI Range	NWC Range
I	5	5	5	71-83	76-88	1B-1A
II	46	33	19	51-69	41-78	3-1B
III	19	14	10	34-50	37-55	3-2
IV	2	2	2	24-30	26-30	3
X	-	-	-			
	72	54	36			

12.4. SUMMARY

The results from these three comparative studies suggest that both the WQI and PWSI similarly classify and rate water quality. The combined results of them show that 118 of the 148 river samples were similarly classified by the WQI and PWSI; an agreement of 80% (Table 91a). A maximum of twelve points separated the index scores produced by the WQI and PWSI. In total, each covered an index range of 10 - 88 and 5 - 83 respectively leaving only twelve and twenty two points unrecorded on the 10 - 100 and 0 - 100 index scales. Therefore, both indices can detect water quality trends and relate these trends to the suitability of water for use in potable water supply.

Table 91a. Collated Results from the Comparative Studies Between the PWSI, WQI and NWC Classification

Potable Water Quality Class	PWSI Classification	WQI Classification	NWC Classification	PWSI Range	WQI Range	NWC Range
I	10	10	10	71-83	76-88	1B-1A
II	88	71	22	51-69	41-78	3-1B
III	41	28	20	31-50	31-55	3-2
IV	5	5	5	21-30	25-30	3
X	4	4	4	5-10	10-13	4
	148	118	61/129			

Spearmans Rank correlation coefficients were calculated for the WQI and PWSI scores recorded within the three data sets. Correlation coefficients of 0.63, 0.98 and 0.93 were attained for each data set respectively indicating a significant relationship at the 99% confidence level between the index scores recorded. Thus both indices similarly classify water quality. However, the over and under estimations recorded by the WQI for Class II and III rivers show that the potential use indicated by the WQI can only be considered as being an indication and not definitive which, in fact. it was never envisaged as being. Thus, despite the good agreement shown in the way both indices record water quality, where the use of water in PWS is of exclusive interest to water quality managers, the PWSI should be used.

In conclusion, these comparative studies again appear to highlight the shortcomings of the NWC classification which consistently underestimates the suitability of water for use in

PWS. At the same time, it confirms the ability of the WQI to reflect water of both ideal and doubtful quality for this use.

Until the PWSI is itself officially validated, the WQI can be used in the operational management of surface waters used in PWS. Moreover, both indices can be used to monitor the economic gains and losses that might accrue from a reduction or increase in the level of treatment required for the continued use of water in potable supply.

CHAPTER 13

VALIDATING THE AQUATIC TOXICITY (ATI) AND POTABLE SAPIDITY (PSI) INDICES

13.1. INTRODUCTION

It was not possible directly to validate either the Aquatic Toxicity (ATI) or Potable Sapidity (PSI) indices because both are use-specific and based upon determinands which are potentially toxic to human and/or aquatic life. However, consideration of toxic determinands for which guideline and mandatory criteria have been proposed by the EEC (1975; 1980) and EIFAC (1964-1983) is implicit within the quality criteria for each class of the National Water Council (NWC, 1977) classification. Hence, where data on both routinely monitored and toxic determinands are available, a subjective assessment of water quality has to be made on over 45 determinand concentrations. The problems associated with the subjective use of the NWC classification have been fully outlined previously (Sections 5.4 and 11.5). However, additional problems arise where management objectives require the careful monitoring of toxic determinands.

The single class notation assigned to a water body by the use of the NWC classification combines the influence of both general physico-chemical and biological determinands with those of potentially toxic determinands. This severely limits the causal interpretation of the resultant quality by any water quality manager. In addition, it makes a comparison between the NWC classification and the calculated ATI/PSI scores unacceptable for the purposes of validation. However, both indices can be considered, to a certain extent, to be self-validating because the results produced by each of the aggregation formulations can be compared with the lowest determinand ratings ascribed to each data set as outlined within the WQI validation procedure (see Section 11.5). It is, therefore, considered possible to assess the value of these indices to the operational management of surface water quality by applying them to a range of water quality data.

The availability of data for the evaluation of the ATI and PSI was greatly reduced when compared with the available data base for the WQI and PWSI studies because the ATI and PSI determinands are not monitored on a regular basis by either the water authorities or river purification boards. Data were particularly sparse for dissolved concentrations of heavy metals which are essential to the calculation of the ATI and were completely unavailable for pesticides, hydrocarbons and polyaromatic hydrocarbons which must be monitored as part of the PSI. A further problem affecting the availability of data was the fact that many water authorities present data about these determinands in terms of a 'less than' some predetermined level - usually a legal standard. Data presented in this fashion cannot be used for the calculation of index scores as it is ambiguous and imprecise. Consequently, only 64 and 105 of the 355 data sets used within the validation of the WQI contained data suitable for the calculation of the ATI and PSI respectively. Each of these data sets relates to river reaches from within the Severn Trent Water Authority (STWA) catchment area. All data were expressed as mean concentrations for the fiscal years 1978/1979 and 1979/1980. However, even within these data sets, information on only three to five of the ATI and PSI determinands was consistently available viz. copper, zinc, chromium, lead and cadmium.

Nevertheless, ATI and PSI scores were calculated for each data set using the arithmetic, modified arithmetic and multiplicative unweighted index formulations (AU, SU and MU respectively). Thus the most accurate of these aggregation formulations could be tested. In addition, each of these data sets has been classified using the WQI, PWSI and NWC classifications and hence it is possible to assess the additional management flexibility provided by the calculation of ATI and PSI scores. For example, although index scores based on routinely monitored physico-chemical and biological determinands may indicate waters which are ideally suited to their proposed management objective, ATI or PSI scores may indeed reflect potentially toxic situations and lead to the downgrading of water quality. A consideration of toxic determinands may also help to explain the apparent anomalies found between the classifications ascribed by the user of the NWC classification and the calculated WQI and PWSI scores. Of course, it has to be recognised that these NWC classifications may have been based on a consideration of toxic determinands not included within either the WQI or PWSI calculations.

13.2. AN EVALUATION OF THE ATI AND PSI

The final score produced by any index should closely reflect the lowest determinand rating ascribed within the transformation process. This is of particular importance in the evaluation of the ATI and PSI, because concentrations in excess of legal limits may be harmful to either aquatic or human life. Thus, the production of median scores becomes less satisfactory as greater accuracy is required. Hence, the classifications produced by each version of the ATI and PSI were compared with those indicated by the lowest determinand ratings. In this way the most accurate of the three index formulations could be ascertained.

13.2.1. A Discussion of the Results Obtained for the Aquatic Toxicity Index

The ATI was applied to data relating to sixty four river reaches within the STWA for which data were available. The results were based predominantly upon the concentration of dissolved copper, chromium, lead and total zinc.

The aim of the ATI is to reflect the suitability of water for the promotion and protection of healthy fish and wildlife populations. Therefore, the 0 - 10 ATI scale was sub-divided to reflect three categories of water quality (Table 92), thereby enabling both index scores and classifications to be compared.

Table 92. The Sub Divisions of the ATI Scale

Class	Index Range	Comment
A1	6.1-10.0	Water which can support all fish and wildlife populations.
A2	2.1-6.0	Water which can support only coarse fish and reduced wildlife populations.
A3	zero-2.0	Water which is incapable of supporting healthy fish and wildlife populations.

The results of this comparative study indicated that the index scores produced using the SU formulation agreed most closely with the lowest determinand ratings ascribed in all but four cases (Table 93). Less than 0.5 of a point separated these scores on

Table 93. The Results Produced by the ATI When Applied to the STWA Data

Location	1978/1979				1979/1980			
	Lowest	ATI Scores			Lowest	ATI Scores		
	Ratings	AU	SU	MU	Rating	AU	SU	MU
River Stour								
- Smestow Brook	4.8	7.0	**4.9**	6.8	4.8	7.0	**5.0**	6.8
River Avon								
- Portbello					4.0	6.9	**4.8**	6.6
River Sowe								
- Baginton	6.0	7.0	**4.9**	6.9	4.8	7.3	**5.4**	7.1
- Stoneleigh					3.0	6.5	**4.3**	6.0
River Tame								
- Perry Barr					1.4	4.8	2.3	3.8
- Lea Marston	2.3	6.0	**3.6**	5.2	2.3	5.9	**3.5**	5.3
- Chetwynd Bridge	4.0	6.6	**4.4**	6.3	4.0	6.9	**4.7**	6.5
- Wolverhampton	1.4	3.6	**1.3**	3.1	4.0	6.1	**3.7**	5.7
- Oldbury Tame	4.0	6.1	**3.7**	5.7	4.0	5.1	**2.6**	5.0
- Ford Brook	0.0(6.0)	5.0	2.5	0.0	0.0(6.3)	5.3	2.8	0.0
River Cole					4.8	6.5	**4.2**	6.3

Table 93 contd....

Location	1978/1979 Lowest Ratings	1978/1979 ATI Scores AU	1978/1979 ATI Scores SU	1978/1979 ATI Scores MU	1979/1980 Lowest Rating	1979/1980 ATI Scores AU	1979/1980 ATI Scores SU	1979/1980 ATI Scores MU
River Soar					6.0	8.1	6.5	7.9
River Avon								
- Clifton					6.0	7.8	6.1	7.6
River Arrow								
- Spernal Lane					6.0	7.2	5.2	7.1
- Alcester					6.0	7.6	5.7	7.4
- Salford Priors	6.0	7.6	5.8	7.5				
- Badsey Brook					6.0	7.8	6.1	7.6
River Trent								
- Hanford					7.3	8.2	6.6	8.1
- Stone					7.3	8.3	7.0	8.3
- Great Haywood					6.0	8.0	6.4	7.9
- Yoxall					6.0	8.1	6.6	8.0
- Walton					6.0	7.8	6.0	7.6
- Willington					6.0	8.0	6.4	7.9
- Shardlow	6.0	8.1	6.4	7.9	6.0	8.0	6.4	7.8
- Nottingham					6.0	8.0	6.4	7.9
- Gunthorpe					6.0	8.1	6.6	8.0

Table 93 contd....

Location	1978/1979				1979/1980			
	Lowest	ATI Scores			Lowest	ATI Scores		
	Ratings	AU	SU	MU	Rating	AU	SU	MU
River Trent contd.								
- Kelham					6.0	8.1	6.5	7.9
- Gainsborough					5.6	7.3	5.3	7.1
- Fowlea Brook	6.8	7.9	6.2	7.8	6.0	7.5	5.7	7.4
River Penk	3.6	5.6	3.1	5.1				
River Anker								
- Leathermill Bridge					7.3	8.5	7.2	8.5
- Polesworth					7.3	8.6	7.4	8.5
- Ratcliffe Culey					7.3	8.8	7.8	8.7
River Meese					7.3	8.7	7.6	8.6
River Derwent								
- Wilne	7.3	8.1	6.5	8.1	6.0	8.0	6.4	7.9
River Amber					7.3	8.7	7.6	8.6
Alfreton Brook					6.0	8.2	6.8	8.1
River Soar								
- Aylestone	7.3	8.6	7.4	8.5	7.3	8.8	7.7	8.7
- Wanlip					6.0	8.2	6.8	8.1
- Sileby	7.3	8.6	7.5	8.6	7.3	8.6	7.4	8.5
- Sence Confluence	6.0	8.2	6.7	8.0	7.3	8.7	7.6	8.6

Table 93 contd....

Location	1978/1979				1979/1980			
	Lowest	ATI Scores			Lowest	ATI Scores		
	Ratings	AU	SU	MU	Rating	AU	SU	MU
River Wreake								
- Kirby Bellars					7.3	8.6	**7.4**	8.5
- Lewin Bridge	7.3	8.8	7.7	8.7	7.3	8.7	**7.6**	8.6
River Erewash								
- Trowell					7.3	8.1	**6.6**	8.0
- Confluence					6.0	8.1	6.6	8.0
River Devon	7.3	8.8	7.8	8.7	7.3	8.8	**7.8**	8.7
River Idle/Maun								
- Bawtry					6.0	8.1	6.6	8.0
River Torne	7.3	8.2	6.8	8.2	7.3	8.2	6.8	8.2

Note: 8.4 Indicates index scores which agree most closely with the lowest determinand ratings.

8.4 Indicates those SU index scores which additionally classify the rivers in accordance with the lowest ratings.

the 0 - 10 index scale in many instances. Index scores of 1.3 - 7.8 were recorded, thus reflecting all three classes of water quality. Forty four of the index scores similarly classified the river reaches to the lowest determinand ratings, with a further eighteen, although incorrectly classified, separated by less than one point on the 0 - 10 index scale and ten of these by less than 0.5 of a point. Thus, sixty two of the ATI scores produced using the SU formulation showed very good agreement with the lowest determinand ratings.

The results produced by the AU formulation appeared to overestimate water quality throughout the index range, a point first noted within the validation of the WQI. Similar results were obtained for the MU formulation of the ATI with only five of the index scores showing a good agreement with the lowest determinand ratings. However, the zero scores produced by the MU formulation for the Ford Brook indicate determinand concentrations in excess of legal standards or criteria and therefore would constitute a potential hazard to aquatic life. These zero scores are the result of the zero water quality ratings assigned to the dissolved copper concentrations for both monitoring periods. The detection of such conditions is of the utmost importance to operational managers responsible for the quality of surface waters. However, index scores of 2.5 and 2.8 were recorded by the SU formulation of the ATI. These index scores reflect a median quality between the lowest and penultimate determinand ratings indicated in brackets on Table 93. Thus, although they suggest the ability of water to support sporadic populations of species of coarse fish, such waters should not be used for this purpose if, indeed, it were possible in the first place. The ability of the SU formulation to reflect waters which exceed the legal requirements for the protection of fish and wildlife populations may be improved by raising the upper threshold for this situation from 2.0 to 3.0. However, the best solution to the detection of low quality waters would be the combined use of both the SU and MU formulations with the results produced by the latter adopted in situations in which zero scores are recorded.

Despite the problems found at the lower end of the quality spectrum, the use of the SU formulation in the calculation of the ATI allowed a number of river reaches which had changed significantly in quality over the recorded period to be identified. For example, the quality of the River Tame at Wolverhampton changed dramatically from a situation in which fish and wildlife populations would be virtually absent (an index score of 1.3) to one in which lower coarse fish species could be present (an index score of 3.7). Hence, the use of an index allows the success of applied management strategies to be evaluated and future improvement in quality monitored. Furthermore, the source of potential pollutants may be traced through the application of the index upstream of the sampling station, or in adjoining tributaries.

Finally, spatial variations in toxicity may be assessed by the application of the ATI, as can 'within class' variations in quality. For example, the results for the River Trent indicate river reaches of Class A1 to A2 quality. However, those for the River Tame reflect waters of much lower quality varying between Class A2 to A3. These river reaches require particularly careful monitoring and management if their use as a fishery is to be maintained or improved. Thus, indices can help to detect river reaches in which applied management strategies are required, or those which indicate an economic gain or loss as a result of quality improvements or deteriorations.

The results produced by the ATI can be seen accurately to reflect the ability of water to support fish and wildlife populations when the SU and MU formulations are used. Moreover, a new dimension to the management of water quality has been added, with the influence of toxic determinands being independently monitored and assessed.

13.2.2. A Discussion of the Results Produced by the Potable Sapidity Index

The Potable Sapidity Index, like the PWSI, reflects water quality in terms of the form of treatment required for water to be used in potable water supply (PWS). As a treatment process must be applied to the water before it is piped into the distribution system, many water quality managers argue that 'within class' variations are of little importance except when scores are approaching threshold values (Table 94).

However, there are also instances, such as investigative studies to determine future sources of PWS, where both within and between class variations may have a significant influence upon the selection process. Hence, the ability of the index to detect a range in water quality conditions is of importance. Thus, index scores were calculated for the one hundred and five river reaches for which data were available. The results are based predominantly upon the concentration of total copper, zinc, chromium, lead and cadmium present within each river reach.

The results showed that the SU version of the PSI produced index scores which agreed most closely with the lowest determinand ratings assigned within the transformation process (Table 95). Eighty four of the index scores produced using this formulation similarly classified the rivers to the lowest determinand ratings or, alternatively, produced borderline agreement with index scores and lowest ratings separated by only 0.2 - 0.4 of a point on the 0 - 10 index scale. A further four rivers, although not similarly classified, achieved index scores indicating an

Table 94. The Sub Divisions of the PSI Scale

Class	Index Range	Comment
P1	7.1-10.0	Minor Purification required before use in potable water supply.
P2	5.1-7.0	Conventional treatment required before water used in potable water supply.
P3	3.1-5.0	Advanced treatment required before water can be used in potable water supply
P4	zero-3.0	Water which is of doubtful to totally unacceptable quality for use in potable water supply.

underestimation of quality of only 0.8 of a point or less. The quality of an additional three rivers was overestimated by between 1.1 - 2.0 points, the latter being recorded for the River Derwent at Matlock Bath. The tendency of the SU formulation to overestimate quality was most apparent at the lower end of the quality spectrum where an additional fourteen river reaches were incorrectly classified. These misclassifications are the result of zero determinand ratings ascribed to the total cadmium concentrations, which were in excess of recommended limits. These were accurately reflected by the index scores calculated using the MU

Table 95. The Results Produced by the PSI When Applied to the STWA Data

Location	1978/1979 Lowest Rating	1978/1979 PSI Scores AU	1978/1979 PSI Scores SU	1978/1979 PSI Scores MU	1979/1980 Lowest Rating	1979/1980 PSI Scores AU	1979/1980 PSI Scores SU	1979/1980 PSI Scores MU
River Stour								
- Lye	4.0	7.4	5.5	6.9				
- Smestow Brook	0.0(5.5)	5.8	3.3	0.0	5.0	6.9	**4.8**	6.7
River Avon								
- Portobello	5.4	8.0	**6.4**	7.7	5.5	7.8	**6.1**	7.6
River Sowe								
- Baginton	7.2	8.2	6.8	8.1	0.0(6.5)	6.2	3.9	0.0
- Stoneleigh					0.0(5.3)	5.7	3.3	0.0
- Finham Brook					0.0(5.7)	5.8	3.4	0.0
River Tame								
- Perry Barr	0.0(2.2)	4.6	2.1	0.0	0.0(2.2)	4.4	2.0	0.0
- Lea Marston	5.2	6.6	**4.4**	6.4	0.0(5.0)	5.1	2.6	0.0
- Chetwynd Bridge	5.4	7.5	**5.6**	7.3	0.0(5.3)	5.7	3.3	0.0
- Woverhampton	0.0(5.3)	5.7	3.2	0.0	0.0(4.9)	5.4	2.9	0.0

Table 95 contd....

Location	1978/1979				1979/1980			
	Lowest Rating	PSI Scores			Lowest Rating	PSI Scores		
		AU	SU	MU		AU	SU	MU
River Tame contd.								
- Oldbury Tame	5.0	6.9	4.7	6.6	0.0(5.3)	5.7	3.2	0.0
- Ford Brook	0.0(2.2)	4.4	2.0	0.0	0.0(4.3)	5.1	2.6	0.0
River Cole	6.0	7.5	5.6	7.3	6.0	7.5	5.6	7.3
River Blythe					6.5	7.9	6.2	7.8
River Bourne					7.2	8.2	6.8	8.1
River Soar	7.2	8.6	7.3	8.5	8.5	8.9	7.9	8.9
Bottesford Beck	7.2	8.7	7.6	8.7	7.2	8.2	6.8	8.2
River Trent								
- Hanford	5.0	8.0	6.4	7.7	5.0	8.0	6.4	7.8
- Stone	5.0	8.0	6.4	7.8	6.0	8.3	6.8	8.1
- Great Haywood	6.0	8.3	6.8	8.1	5.0	8.0	6.4	7.8
- Yoxall	7.2	8.5	7.3	8.5	7.2	8.3	6.9	8.2
- Walton	5.5	7.5	5.6	7.3	6.5	7.7	6.0	7.6
- Willington	7.5	8.7	7.5	8.6	7.5	8.7	7.5	8.6
- Shardlow	7.4	8.4	7.0	8.3	6.0	7.7	5.9	7.6

Table 95 contd....

Location	1978/1979 Lowest Rating	1978/1979 PSI Scores AU	SU	MU		1979/1980 Lowest Rating	1979/1980 PSI Scores AU	SU	MU
River Trent contd.									
- Sawley	7.5	8.7	7.5	8.6		7.2	8.0	6.4	7.9
- Nottingham	7.2	8.3	6.9	8.2		7.2	8.3	6.9	8.2
- Gunthorpe	5.5	7.5	5.7	7.4		8.5	9.0	8.1	9.0
- Kelham	6.0	7.7	5.9	7.6		7.2	8.0	6.4	7.9
- Dunham	7.2	8.6	7.3	8.5		7.2	8.0	6.4	7.9
- Gainsborough	6.0	8.0	6.3	7.8		6.0	7.7	5.9	7.5
River Penk	6.5	8.2	6.8	8.0	0.	0(7.5)	5.8	3.4	0.0
River Rea						5.0	7.2	5.2	6.9
River Anker									
- Leathermill Bridge	7.4	8.9	7.9	8.8		7.4	8.9	7.9	8.8
- Polesworth	7.2	8.5	7.1	8.4		7.4	8.6	7.4	8.6
- Ratcliffe Culey						8.6	9.3	8.6	9.3
River Meese	8.6	9.3	8.6	9.3		8.6	9.1	8.3	9.1

Table 95 contd....

Location	1978/1979				1979/1980			
	Lowest	PSI Scores			Lowest	PSI Scores		
	Rating	AU	SU	MU	Rating	AU	SU	MU
River Dove								
- Below Rochester	8.5	9.0	8.2	9.0				
- Monks Bridge					8.5	9.0	8.1	9.0
River Churnet								
- Rochester					7.5	8.7	7.5	8.6
River Tean	8.5	9.0	8.1	9.0	8.5	9.0	8.1	9.0
River Derwent								
- Matlock Bath	3.3	7.2	5.3	6.5	7.2	8.8	7.7	8.7
- St Mary's Bridge	6.0	8.4	7.1	8.2	7.2	8.8	7.7	8.7
- Wilne	5.0	7.8	6.1	7.5	7.2	8.6	7.3	8.5
River Wye					8.6	9.3	8.6	9.3
River Amber	7.2	8.3	6.8	8.2	7.4	8.6	7.4	8.6
Alfreton Brook	7.2	8.4	7.0	8.3	7.4	8.6	7.4	8.6
River Soar								
- Aylestone	5.5	8.1	6.6	8.0	8.5	8.9	7.1	8.8
- Wanlip	6.0	8.0	6.3	7.8				
- Sileby	7.4	8.8	7.7	8.8	7.4	8.6	7.4	8.6
- Sence Confluence	7.4	8.6	7.4	8.6	7.4	8.6	7.4	8.6

Table 95 contd....

Location	1978/1979				1979/1980			
	Lowest Rating	PSI Scores			Lowest Rating	PSI Scores		
		AU	SU	MU		AU	SU	MU
River Wreake								
- Kirby Bellars	8.6	9.3	8.6	9.3	8.6	9.1	8.3	9.1
- Lewin Bridge	7.4	8.9	7.9	8.8	8.5	8.9	8.0	8.9
River Erewash								
- Trowell	8.5	9.0	8.1	9.0	7.4	8.6	7.4	8.6
- Confluence	8.5	9.0	8.1	9.0	7.5	8.7	7.5	8.6
River Leen	5.0	7.8	6.1	7.5	8.5	9.0	8.1	9.0
River Devon	8.5	8.9	8.0	8.9	7.4	8.6	7.4	8.6
River Idle/Maun								
- Whinney Hill	8.6	9.3	8.6	9.3	7.2	8.5	7.3	8.5
- Bawtry					8.5	8.9	7.9	8.9
River Torne	7.4	8.6	7.4	8.5	8.5	8.9	7.9	8.9

Note: 8.4 indicates index scores which agree most closely with the lowest determinand ratings

8.4 indicates those SU index scores which additionally classify the rivers in accordance with the lowest ratings.

formulation which otherwise appears to have overestimated water quality throughout the index range. The index scores obtained for these river reaches by the SU formulation ranged between 2.0 - 3.9, which reflect waters requiring advanced treatment before use in PWS. These results could be marginally improved by raising the lower threshold for advanced treatment from 1.1 to 2.1, thereby increasing the ability of the SU formulation to detect waters which are unsuitable for use in PWS. However, the most effective solution would again entail the combined use of both the SU and MU aggregation formulations with the latter used to record waters of unacceptable quality for use in PWS.

The results produced by the AU formulation of the PSI were, as expected, the least satisfactory, with gross overestimations in quality recorded throughout the index range. Thus the AU formulation was not considered further within the use of the PSI.

The results produced using both the SU and MU versions of the PSI highlight both temporal and spatial variations in the suitability of water for use in PWS. For example, the quality of the River Trent at Shardlow decreased from an index score of 7.0 to 5.9 during the sampling period whilst that of the River Trent at Gunthorpe showed an improvement in quality with the recorded index score increasing from 5.7 to 8.1. Both these changes in quality, although occurring at the upper end the quality spectrum, are of considerable economic significance because the level of treatment required changes from minor purification to conventional treatment and vice versa. The changes recorded for the River Tame at Lea Marston and Oldbury are of much greater significance with scores of 4.4 and 4.7 decreasing to zero in the second year of the sampling programme. These deteriorations in quality may have resulted from a sudden pollution event or as a result of a gradual accumulation of cadmium within the water body and contained sediments. If it were the latter, then the use of an index would also enable gradual deterioration in quality to be recorded. Similarly, the improved quality of the Smestow Brook on the River Stour from Class P4 in 1978/1979 to an index score of 4.8 (indicating borderline Class P3/P2) in 1979/1980, can be monitored and the efficiency of any applied management strategies assessed.

The results from these comparative studies show that both the ATI and PSI successfully monitor variations in the toxicity of water. The ability to do this is of great value to those involved in operational water quality management, enabling them to be knowledgeably aware of the prevailing toxicity and to monitor the effect of applied management strategies aimed at reducing the toxic load of the surface water body.

13.3. THE COMBINED USE OF THE WQI, ATI AND PSI IN THE CLASSIFICATION OF WATER QUALITY

Where the management of surface water quality requires a general assessment of both water quality and potential water use to be undertaken, the best management practice (BMP) would almost certainly be afforded by the combined use of the WQI, ATI and PSI. Where the management objective for a particular river reach is exclusive to the abstraction of water for use in potable supply, then the results of the PWSI and PSI should be considered. Alternatively, any one of the four proposed indices may be used independently as and when required.

The results produced by the WQI, ATI and PSI for the 113 river reaches of the Severn Trent Water Authority for which data on two or more of these indices were available, were therefore combined to produce an overall picture of water quality for the region (Table 96).

Table 96. The Combined Results of the WQI, ATI and PSI for for the SWTA Data

	1978/1979				1979/1980			
Location	NWC Class	WQI Class	ATI Class	PSI Class	NWC Class	WQI Class	ATI Class	PSI Class
River Stour								
- Lye	2	II		P2				
- Smestow Brook	2	III	A2	P4	2	II	A2	P2
River Avon								
- Portobello	2	II		P2	2	II	A2	P2
River Sowe								
- Baginton	2	II	A2	P2	2	II	A2	P4
- Stoneleigh					3	III	A2	P4
- Finham Brook					2	I		P4
River Devon	1B	II	A1	P1	1B	II	A1	P1
River Tame								
- Perry Barr	4	IV		P4	4	IV	A3	P4
- Lea Marston	4	III	A2	P2	4	III	A2	P4
- Chetwynd Bridge	3	III	A2	P2	3	III	A2	P4
- Wolverhampton	4	IV	A3	P4	4	IV	A2	P4
- Oldbury Tame	4	IV	A2	P2	4	IV	A3	P4
- Ford Brook	4	III	A3	P4	4	III	A3	P4
River Cole	2	II		P2	2	II	A2	P2
River Blythe					1B	II		P2
River Bourne					1B	I		P2
River Soar	2	II		P1	2	II	A1	P1
Bottesford Beck	4	III		P1	3	III		P2
River Avon								
- Clifton					1B	I	A1	
River Arrow								
- Spernal Lane					2	III	A2	
- Alcester					2	II	A2	
- Salford Priors	2	II	A2					
- Badsey Brook					2	II	A1	

Table 96 contd....

Location	NWC Class	WQI Class	ATI Class	PSI Class	NWC Class	WQI Class	ATI Class	PSI Class
River Trent								
- Hanford	3	III		P2	3	III	A1	P2
- Stone	2	III		P2	2	III	A1	P2
- Great Haywood	2	II		P2	2	III	A1	P2
- Yoxall	2	II		P1	2	II	A1	P2
- Walton	3	III		P2	3	III	A2	P2
- Willington	2	III		P1	2	III	A1	P1
- Shardlow	2	II	A1	P2	2	II	A1	P2
- Sawley	2	II		P1	2	II		P2
- Nottingham	2	II		P2	2	II	A1	P2
- Gunthorpe	2	II		P2	2	II	A1	P1
- Kelham	2	II		P2	2	II	A1	P2
- Dunham	2	II		P1	2	II		P2
- Gainsborough	2	III		P2	2	III	A2	P2
- Fowlea Brook	3	III	A1		3	III	A2	
River Penk	1B	II	A2	P2	1B	II		P4
River Rea					2	IV		P2
River Anker								
- Leathermill Bridge	2	III		P1	2	II	A1	P1
- Polesworth	2	III		P1	2	III	A1	P1
- Ratcliffe Culey					2	II	A1	P1
River Meese	2	II		P1	2	II	A1	P1
River Dove								
- Below Rochester	1B	I		P1				
- Monks Bridge					1B	I		P1
River Churnet								
- Rocester	2	II			2	II		P1
River Tean	2	III		P1	2	II		P1

Table 96 contd....

Location	NWC Class	WQI Class	ATI Class	PSI Class	NWC Class	WQI Class	ATI Class	PSI Class
River Derwent								
- Matlock Bath	1A	I		P2	1A	I		P1
- St Mary's Bridge	2	I		P1	2	I		P1
- Wilne	2	II	A2	P2	2	II	A1	P1
River Wye					1A	I		P1
River Amber	2	III		P2	2	II	A1	P1
Alfreton Brook	3	III		P2	3	III	A1	P1
River Soar								
- Aylestone	2	II	A1	P2	2	II	A1	P1
- Wanlip	2	II		P2	2	II	A1	
- Sileby	2	III	A1	P1	2	III	A1	P1
- Sence Confluence	3	III	A1	P1	3	III	A1	P1
River Wreake								
- Kirby Bellars	2	III		P1	2	III	A1	P1
- Lewin Bridge	2	II	A1	P1	2	II	A1	P1
River Erewash								
- Trowell	2	III		P1	2	III	A1	P1
- Confluence	3	III		P1	3	IV	A1	P1
River Leen	2	III		P2	2	II		P1
River Idle/Maun								
- Whinney Hill	3	IV		P1	3	IV		P1
- Bawtry					2	II	A1	P1
River Torne	2	II	A1	P1	2	II	A1	P1

Note: WQI and NWC classifications that are underlined are those which must be downgraded on the basis of PSI and/or ATI classifications.

The results were given in classifactory terms to provide a general assessment of water quality. The classifications used are those given in Section 8.2 and not those adopted for a comparison with the NWC classification. The NWC classifications assigned to each river reach were, nevertheless, included within this study to compare the value of the information provided by this classification with that of the combined use of water quality indices.

The results showed that eleven of the WQI classifications had to be downgraded as a result of the scores produced by either the ATI or PSI. Although this affects only a small proportion of the data sets, the results are significant, indicating the need to include a consideration of toxic determinands within routine water quality monitoring programmes. The most interesting results were obtained for Finham Brook and the River Penk which received WQI classifications of I and II respectively. However, the final classification for each river reach was reduced to Class IV on the basis of the PSI results, thus indicating waters which are totally unsuitable for use in PWS. However, this does not mean that these waters have no potential use or economic value. These waters may still be of excellent quality capable of supporting high class game and coarse fisheries. Hence, as long as there is no desire to use these rivers for abstractions for PWS the rivers may be managed in such a way to preserve their present use and amenity value. Alternatively, if the use of this water for PWS was to be the defined management objective for these rivers, the attention of the water quality manager would be immediately directed to the presence of toxic determinands which would impede its use for this purpose. The combined use of the WQI and PSI in this instance provides more information than the assigned NWC classification of Class 2 and 1B respectively, as these fail to recognise the presence of excessive concentrations of cadmium and therefore indicate waters of much higher quality than actually exists.

The results for the Ford Brook section of the River Tame are more extreme, indicating water which is suitable only for navigation, sewage transport and very limited non-contact recreational uses. These results indicate a situation in which immediate remedial action is required. Similarly, the resultant index scores for the Oldbury Tame show the way in which water quality will continue to decline if action is not initiated in an attempt to alleviate the problem.

The assigned NWC classifications again provide a cause for concern for, despite the inclusion of toxic determinands within the quality criteria of each quality class, seven of the assigned classifications had to be downgraded on the basis of calculated ATI and PSI scores.

Finally, where ATI and PSI scores are in accord with, or indicate a higher level of water quality than the WQI classification, the user may proceed with the planned management objectives assuming the WQI classification is also favourable. Hence, a complete picture of the quality conditions which prevail within a catchment may be obtained by the combined use of the WQI, ATI and PSI. Thus operational managers may select an appropriate course of action and BMP is ensured.

13.4. THE COMBINED USE OF THE PWSI AND PSI IN THE CLASSIFICATION OF WATER QUALITY

The PWSI and PSI can be applied in situations in which water quality is managed exclusively for use in potable water supply. In order to assess the additional information provided by the combined use of these indices it was necessary first to calculate

PWSI scores for the 105 river reaches previously classified using the PSI.

Data on only eight of the thirteen PWSI determinands were available from this data set, thus the determinand weightings were recalculated as outlined in Chapter 11,(Table 97).

Table 97. Recalculated Weightings for the PWSI

Determinand	Weighting
pH	0.15
Suspended Solids	0.17
Biochemical Oxygen Demand	0.15
Temperature	0.03
Dissolved Oxygen	0.09
Ammoniacal Nitrogen	0.17
Chlorides	0.07
Nitrates	0.17
	1.00

Ten of the resultant classifications had to be downgraded on the basis of calculated PSI scores (Table 98), with nine of these indicating waters which were in excess of legal requirements for use in PWS. Hence, it is again apparent that BMP will be assured by the combined use of the PWSI and PSI in the selection, monitoring and management of rivers used within potable water supply because they provide the maximum amount of information to operational managers.

Table 98. The Combined Results of the PWSI and PSI for the STWA Data

Location	1978/1979		1978/1979	
	PWSI Class	PSI Class	PWSI Class	PSI Class
River Stour				
- Lye	II	P2		
- Smestow Brook	III	P4	II	P2
River Avon				
- Portobello	II	P2	II	P2
River Sowe				
- Baginton	II	P2	II	P4
- Stoneleigh			III	P4
- Finham Brook			II	P4
River Devon	II	P1	II	P1
River Tame				
- Perry Barr	IV	P4	IV	P4
- Lea Marston	III	P2	III	P4
- Chetwynd Bridge	III	P2	III	P4
- Wolverhampton	IV	P4	IV	P4
- Oldbury Tame	IV	P2	III	P4
- Ford Brook	III	P4	III	P4
River Cole	II	P2	II	P2
River Blythe			II	P2
River Bourne			II	P2
River Soar	II	P1	II	P1
Bottesford Beck	III	P1	III	P2
River Trent				
- Hanford	II	P2	II	P2
- Stone	III	P2	II	P2
- Great Haywood	II	P2	III	P2
- Yoxall	II	P1	II	P2

Table 98 contd....

Location	1978/1979		1978/1979	
	PWSI Class	PSI Class	PWSI Class	PSI Class
River Trent contd.				
- Walton	III	P2	III	P2
- Willington	II	P1	II	P1
- Shardlow	II	P2	II	P2
- Sawley	II	P1	II	P2
- Nottingham	II	P2	II	P2
- Gunthorpe	II	P2	II	P1
- Kelham	II	P2	II	P2
- Dunham	II	P1	II	P2
- Gainsborough	III	P2	III	P2
River Penk	II	P2	II	P4
River Rea			III	P2
River Anker				
- Leathermill Bridge	III	P1	II	P1
- Polesworth	III	P1	II	P1
- Ratcliffe Culey			II	P1
River Meese	II	P1	II	P1
River Dove				
- Below Rochester	I	P1		
- Monks Bridge			I	P1
River Churnet				
- Rocester			II	P1
River Tean	III	P1	II	P1
River Derwent				
- Matlock Bath	I	P2	I	P1
- St Mary's Bridge	I	P1	I	P1
- Wilne	II	P2	II	P1
River Wye			I	P1

Table 98 contd....

Location	1978/1979		1978/1979	
	PWSI Class	PSI Class	PWSI Class	PSI Class
River Amber	III	P2	II	P1
Alfreton Brook	III	P2	III	P1
River Soar				
- Aylestone	II	P2	II	P1
- Wanlip	II	P2		
- Sileby	III	P1	III	P1
- Sence Confluence	III	P1	III	P1
River Wreake				
- Kirby Bellars	III	P1	II	P1
- Lewin Bridge	II	P1	II	P1
River Erewash				
- Trowell	III	P1	III	P1
- Confluence	III	P1	III	P1
River Leen	III	P2	III	P1
River Idle/Maun				
- Whinney Hill	III	P1	III	P1
- Bawtry			II	P1
River Torne	II	P1	II	P1

Note: PWSI classifications that are underlined are those which must be downgraded on the basis of PSI classifications.

13.5. SUMMARY AND CONCLUSIONS

The results from these studies indicate that both the Aquatic Toxicity and Potable Sapidity Indices accurately reflect variations in the toxic quality of water where both the modified arithmetic and multiplicative unweighted aggregation formulations are applied. The former can be used to indicate quality for all but the extreme lower end of the quality spectrum and the latter for the detection of concentrations in excess of legal limits. Thus each index can detect waters of varying degrees of acceptability for their respective uses.

An indication of the level of quality impairment resulting from toxic determinand concentrations is of particular importance to the management of water quality as the nature of water pollution becomes more complex, with accidental discharges and spillages from industry, rural areas, mining wastes and urban runoff increasing each year. Therefore, the quantification of such transient pollution events allows the initial effect, aftermath and recovery to be carefully monitored and assessed, further ensuring that BMPs can be pursued.

Prior to the development of the ATI and PSI, a very limited picture of toxicity was available to water quality managers, with only the presence or absence of determinand concentrations in excess of legal standards included within previously developed indices used in the United Kingdom. Thus, spatial and temporal variations in quality may have been overlooked. As these variations have been shown to be substantial and of condiderable economic significance, a knowledge of them can only add to the potential for the management of such waters.

The independent construction of these indices provides an added element of flexibility as the results can be viewed either in isolation, or as part of a larger basin-wide study of water quality within an area. In either case, the interpretation of the results is not complicated by the amalgamation of numerous index scores, thus the information provided remains clear and precise. This information has been shown to be hidden by the subjective application and use of the NWC classification, in which adverse concentrations of toxic determinands were often ignored or, alternatively, their occurrence was masked within a single classification.

'Within class' variations have been highlighted by the application of both the ATI and PSI to a range of water quality data, thereby allowing direct comparisons to be made and improvements or deteriorations in quality to be monitored. These variations become of particular importance as class thresholds are approached. Classifications are often used in the development of river quality objectives (RQOs) and it is important, therefore, that the precise classification is known in the first instance, thus reducing the risk of setting of unrealistic objectives.

Therefore, the ATI and PSI may be used to set and monitor the compliance with, or progress towards, RQOs; they can be used to pin-point river reaches which have changed in quality over the recording period, or trace the source of a pollutant, allowing remedial action to be taken at the appropriate point.

The combined use of the ATI and PSI with the WQI provides a new dimension and degree of flexibility to the management of surface water quality. It allows data on up to twenty one determinands to be reduced to a single classification, which can then be interpreted in terms of water quality or potential water use in an accurate and reproducible manner. At the same time it highlights the sources of potential problems, particularly those relating to toxicity.

The combined use of the PWSI and PSI serves to provide a complete picture of the suitability of water for use in PWS and facilitates detailed comparisons of the qualities of rivers of potential value for this use.

All four indices, either in combination or used independently, provide significantly greater amounts of information than the NWC classification, or any other classification or index to have been developed and used in the United Kingdom. Index scores could be calculated for any river reach, using one or more of the proposed indices, depending upon the aims and objectives of the particular study and the data available. Thus, if they were to be utilised, management flexibility would be enhanced and the basis of decision-making processes in the operational management of water quality could be considerably improved. Moreover, the need for, and success of, applied management strategies could be more accurately assessed and evaluated, and an indication of the cost and benefits accruing from the implementation of such strategies could be obtained.

CHAPTER 14

CONCLUSIONS AND RECOMMENDATIONS

14.1. CONCLUSIONS

(i) In the initial stages of the development of a new water quality index it became apparent that what was required by operational management in the UK water industry was a general water quality index which would reflect water quality in a simple and reproducible fashion whilst providing an indication of potential water use and, hence, the economic value of a water body.

(ii) To be of maximum value, the index would have to be based on existing legal standards and published criteria and include information on toxic determinands and provide additional management flexibility.

(iii) However, due to the combination of determinands selected within Stage 1 of the index development process (Figure 52), it became apparent that it would not be possible to develop one index of general water quality which covered all potential water uses and included toxic determinands directly within its structure (see Chapter 8).

(iv) Thus four indices were developed - WQI, PWSI, ATI and PSI - each of which could be used independently or in combination with one another. Each index was developed in the same objective and rigorous manner (Figure 52).

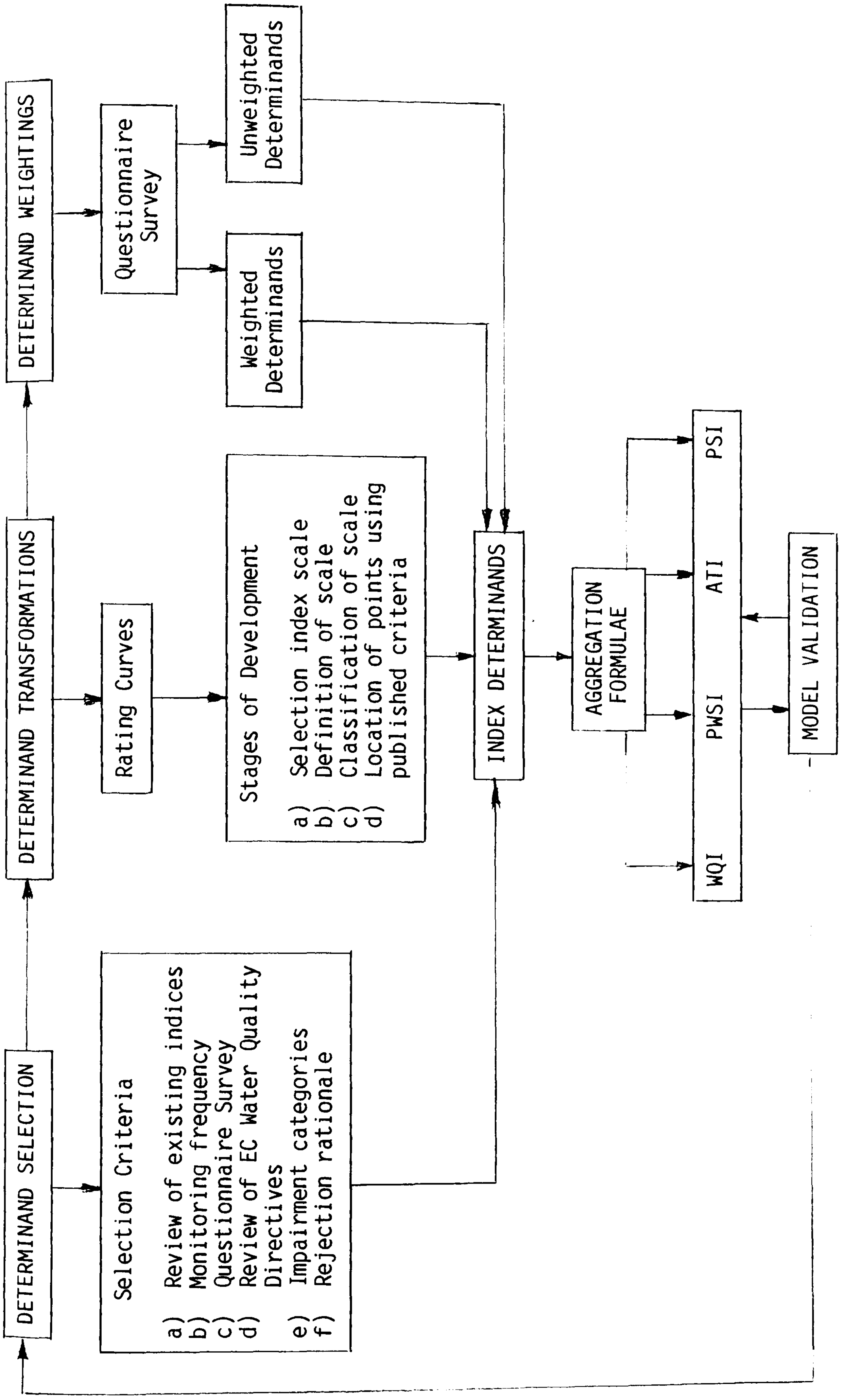

Fig. 52 Stages in the Development of a Water Quality Index

(v) The accuracy of these indices was assessed by the application of each index to a range of data from a selection of water quality monitoring bodies. The results produced by the WQI were compared with previously assigned NWC (1977) classifications and a 95% agreement was achieved, with an index range of 10 - 92 recorded. Thus, the index was found to reflect accurately changes in surface water quality when the weighted modified arithmetic formulation was utilised (see Chapter 11).

(vi) The WQI was, in turn, used in the evaluation of the PWSI. An 80% agreement was reached between the two indices thereby indicating a high degree of similarity in the way in which both indices recorded water quality. This was substantiated by the calculation of Spearman's Rank correlation coefficients which revealed a significant relationship between the results produced by each index at the 99% confidence limit. Nevertheless, the use of the PWSI is recommended where the potential of water for potable water supply is the exclusive use under investigation (see Chapter 12).

(vii) The ATI and PSI were applied both independently and in combination with the WQI and PWSI to data collected by the Severn Trent Water Authority. Each index was found to reflect accurately variations in the toxic quality of surface waters, where both the unweighted, modified arithmetic and multiplicative formulations were applied. In addition, the combined use of these indices and/or the WQI and PWSI highlighted situations in which waters, although achieving index scores indicative of high quality and economic potential on the basis of WQI and PWSI determinands, were, in fact, toxic and totally unacceptable for high value uses (see Chapter 13). However, both these indices require further validation as at present no base exists from which an accurate evaluation of the results can be made.

(viii) The application of the indices to data which had been previously classified using the NWC Classification highlighted a number of advantages associated with the use of an index as opposed to a subjectively applied classificatory system.

a) As index scores are derived mathematically, they are objective and therefore reproducible, thereby avoiding the misclassification of river reaches on which the NWC Classification was used (see Chapter 11).

b) Because of the numeric scale, an index can provide information on 'within class' variations of quality which are of particular importance where class or use threshold values are approached. In this way an index can be used to pin-point reaches which have altered significantly in quality, but insufficiently to merit a change of class within the NWC Classification.

c) In addition, index scores are unambiguous, precisely indicating quality, rather than the close approximation provided by the classificatory system. This is of considerable importance because the final classifications produced by a water quality monitoring system may be used in the development of river quality objectives. If these are to be realistic and meaningful, they must be based on an accurate assessment of current water quality.

d) Due to their objective derivation, each index may be used to detect spatial and temporal variations in surface water quality in a precise and reproducible manner.

e) An index may be used to assess the economic potential of a water body by the potential water use associated with its index score. Similarly, a change in the economic potential of a water body resulting from an increase or decrease in quality, and hence use, may be evaluated. Such information is of considerable value in the operational management of water quality because it allows management decisions to be based on both quality and monetary considerations.

f) As each index has been developed in accordance with recognised, and often legally accepted, water quality standards and criteria, they may be used by operational management to identify surface waters requiring priority action.

g) Indices may also be used at the directorate level or for the provision of information to the layman in simple, but precise terms by dividing the index scores into broader classes, while at the same time maintaining the initial precision.

h) The provision of both general and use-related indices, together with the development of indices of toxicity, make available a complete and precise picture of water quality to operational management.

Thus, the indices developed in this research provide a precise picture of water quality, provide additional management flexibility and facilitate the development of best management practices.

14.2. RECOMMENDATIONS FOR THE APPLICATION OF THE INDICES IN PRACTICE

(i) It is recommended that the WQI be used in the general water quality monitoring programmes of the water authorities of England and Wales and the river purification boards of Scotland. As more of these monitoring bodies are turning to telemetric sampling systems, where vast quantities of data are collected on a routine basis, it is essential that an accurate and reproducible method of data assimilation be adopted. This will reduce the task of analysis and ensure that the data collected are fully utilised. Where management objectives are more specific, either in terms of water use or in terms of simply requiring a more detailed evaluation of water quality, the employment of one or more of the use-related indices will provide the additional information with little additional effort.

(ii) Indices may be used to great advantage:

- to detect improvements in water quality associated with applied management strategies;
- to determine the source of deteriorations in water quality resulting from an unusual industrial or sewage outfall discharge;
- to assess the effects of water quality in adjoining tributaries;
- to determine the effect of agricultural runoff and accidental spillages;
- in comparative studies to select potential new locations for fisheries or potable water supplies.

(iii) With the NWC classification only being generally applied on a five yearly basis for the purpose of management at directorate level, it is considered that the use of water quality indices would add an extra dimension to the operational management of the quality of surface waters and fill an obvious gap in the system. Indices allow all data to be interpreted in an objective manner, thus allowing direct national comparisons of surface water quality to be made.

14.3. FUTURE RESEARCH

Future research into the use of the proposed indices should include their further validation by means of detailed pilot studies undertaken by a selection of water authorities and river purification boards to incorporate their use in situations such as those outlined in Section 14.2. In addition, the use of water quality indices in cost-benefit analysis studies to assess the economics of water quality management is of considerable importance. Although the potential water use indicated by the calculated WQI scores can only be considered as tentative due to the average quality assessments produced, they are considered to be sufficiently accurate to allow the economic gains associated with water quality improvements to be assessed against the costs incurred in their achievement.

Finally, more research is urgently required into the potential for the development of a form of Planning Priority Index as outlined by Greeley et al (1972). Given the present constraints on capital expenditure for water quality improvements, it is essential that resources be invested in areas in which the greatest benefits will accrue. To that end, best management practices should be adopted whenever and wherever possible.

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APPENDIX I

APPENDIX I

QUESTIONNAIRE ON THE SELECTION OF DETERMINANDS FOR INCLUSION WITHIN A WATER QUALITY INDEX

Aims

The overall aim of this research is to develop a water quality index for use in the management of urban catchments. Although this index is to be one of general water quality, it should contain those parameters which are of the greatest importance to all major uses of water.

No general water quality index to date has included toxics such as heavy metals, pesticides or hydrocarbons directly within an index. Therefore it is intended to develop a sub-index of toxicity which would have a greater influence on the final water quality index score than the more routine water quality index parameters. For example, where the sub-index of toxicity produces a score indicative of serious pollution, this would nullify a good score produced by the routine sub-index. This sub-index of toxicity would only be used where the parameters included within the sub-index are regularly monitored, or where they are causing significant pollution problems. By using the sub-index in this way it is hoped that areas of different types of pollution can be directly compared.

Instructions for Completion

a) Tick those parameters which you consider to be of value for inclusion within an index as outlined above. Additional parameters may be included if considered necessary.

b) Give a _brief_ outline of your reasons for including/excluding these parameters in the space provided on the form.

c) Rank the parameters you have selected for inclusion on the basis of their relative importance to one another in terms of overall water quality. Rank the parameters included within the sub-index of toxicity separately. These rankings will assist in the development of weightings in the final index.

_NB_

Under a) Y = Yes, N = No, P = Possibly

POTENTIAL LIST OF PARAMETERS FOR INCLUSION WITHIN A WATER QUALITY INDEX

Parameters	Include			Reason	Rank
	Y	N	P		
Dissolved Oxygen					
B.O.D.					
C.O.D.					
T.O.C.					
Alkalinity					
Iron					
Manganese					
Ammonia					
Nitrate					
Nitrite					
T.O.N.					
Ortho-Phosphate					
Chloride					

Potential list of parameters contd....

Parameters	Include			Reason	Rank
	Y	N	P		
Sulphate					
pH					
Temperature					
Conductivity					
Turbidity					
Suspended Solids					
Colour					
Transparency					

Sub-Index of Toxicity

Parameters

Phenols					
Synthetic Detergents					
Hydrocarbons					

Potential list of toxicity parameters contd....

Parameters	Include			Reason	Rank
	Y	N	P		
Pesticides					
Chlorophyll A					
Poly. Arom. Hydro.					
Hg.					
Cu.					
Zn.					
As.					
B.					
Cd.					
Ni.					
Pb.					
CN					
Total Annual Toxicity Fraction (Brown & Alabaster)					

APPENDIX II

APPENDIX II

PUBLISHED WATER QUALITY DIRECTIVES AND CRITERIA FOR THE DETERMINANDS INCLUDED WITHIN THE WQI AND PWSI

In Appendix II, the following notation is used:

A1 - Minor purification; simple physical treatment and disinfection (EEC A1, 1975).

A2 - Conventional treatment; normal physical treatment, chemical treatment and disinfection (EEC A2, 1975).

A3 - Advanced treatment; intensive physical and chemical treatment and disinfection (EEC A3, 1975).

G - Guideline concentration as defined by the EEC

I - Mandatory concentration as defined by the EEC

0 - May be exceeded in exceptional climatic or geographical conditions

MD - Maximum Desirable concentrations as defined by the respective authors

MP - Maximum Permissible concentrations as defined by the respective authors

(a) - minimum values

(b) - WHO(I), 1963

Published Water Quality Directives and Criteria for Dissolved Oxygen
(Values as DO % saturation. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	<70% (G)								
	A2	<50% (G)			<70% (a) (MD) <50% (a) (MP)					
	A3	<30% (G)								
FISHERIES										
GAME										
COARSE										
LOWER THRESHOLD										
DIRECT CONTACT RECREATION		80%-100% (G)								
INDUSTRY										
HIGH QUALITY					(a) 70-120%					
AVERAGE QUALITY					(a)40-70% or >120%					
POOR QUALITY					(a) <40%					
AMENITY										
HIGH										
GENERAL										

Published Water Quality Directives and Criteria for BOD
(Values in mgl^{-1}. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	3 (G)								
	A2	<5 (G)		6(b) (MP)	3 (MD) 6 (MP)					
	A3	7 (G)								
FISHERIES										
	GAME	<3 (G)			3 (MD) 5 (MP)					
	COARSE	<6 (G)			4 (MD) 6 (MP)					
	LOWER THRESHOLD				5 (MD) 8 (MP)					
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				<2					
	AVERAGE QUALITY				2-6					
	POOR QUALITY				>6					
AMENITY										
	HIGH				3-5 (MD) 4-8 (MP)					
	GENERAL				5-7 (MD) 8-12 (MP)					

Published Water Quality Directives and Criteria for Ammoniacal Nitrogen
(Values in mgl-1 NH_4-N. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	0.05 (G)								
	A2	1.0(G) 1.5(I)	0.05(MP)	(b) 0.5(MP)	0.5(MD) 1.0(MP)					<0.01(MD) 0.5(MP)
	A3	2.0(G) 4.0(IO)								
FISHERIES										
	GAME	<0.04(G) <1.0(I)				0.045 (MD) 0.22 (MP)				
	COARSE	<0.2(G) <1.0(I)								
	LOWER THRESHOLD									
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				<0.25					
	AVERAGE QUALITY				0.25-2.0					
	POOR QUALITY				>2.0					
AMENITY										
	HIGH				1 (MD) 2 (MP)					
	GENERAL				3 (MD) 5 (MP)					

Published Water Quality Directives and Criteria for Nitrates
(Values in mgl-1 as N . All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	5.6(G) 11.3(I)								
	A2	11.3(IO)	11.3(MD) 22.6(MP)	10.0(MP)	11.3(MD) 22.6(MP)		10			
	A3	11.3(IO)								
FISHERIES										
GAME					75(MD) 100(MP)		90			
COARSE					75 100		90			
LOWER THRESHOLD					75 100		90			
DIRECT CONTACT RECREATION										
INDUSTRY										
HIGH QUALITY										
AVERAGE QUALITY										
POOR QUALITY										
AMENITY										
HIGH										
GENERAL										

Published Water Quality Directives and Criteria for Suspended Solids
(Values in mgl^{-1} . All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	25(G)								
	A2									
	A3									
FISHERIES										
	GAME	<25 (GO)			25(MD) 40(MP)	25		25(MD)		
	COARSE	<25 (GO)			25(MD) 80(MP)	25-80		80(MD)		
	LOWER THRESHOLD				80(MD) 400(MP)	25-100		400(MP)		
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				<10					
	AVERAGE QUALITY				10-30					
	POOR QUALITY				> 30					
AMENITY										
	HIGH				25(MD) 80(MP)					
	GENERAL									

Published Water Quality Directives and Criteria for pH
(Values as pH units. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	6.5-8.5 (G)								
	A2	5.5-9.0 (G)		7.0-8.5 (MD) 6.5-9.2(MP)	(a) 7.0-8.5 (MD) (a) 6.5-9.2(MP)		5.0-9.0		6.0-8.5	
	A3	5.5-9.0 (G)								
FISHERIES										
	GAME	6.0-9.0 (OI)			(a)6.5-9.0(MD) (a)6.0-9.5(MP)	6.5-9.0(MD) 5.3-9.0(MP)	(a)6.5-9.0	6.5-8.5(MD)	6.5-8.5	
	COARSE	6.0-9.0 (OI)			(a)6.5-9.0(MD) (a)6.0-9.5(MP)	4.5-9.5	(a)6.5-9.0	6.0-9.0(MD)	6.5-8.5	
	LOWER THRESHOLD				(a)6.5-9.0(MD) (a)6.0-9.5(MP)	4.0-9.5	(a)6.5-9.0	5.5-9.5(MP)	6.5-8.5	
DIRECT CONTACT RECREATION		7.4 (Ideal) 6.9 (I)						7.4 (Ideal) 6.5-8.5 (MD) 5.0-9.0 (MP)		
INDUSTRY										
	HIGH QUALITY				(a)7.0-8.5					
	AVERAGE QUALITY				(a)6.0-9.0					
	POOR QUALITY				(a)<6.0 or >9.0					
AMENITY										
	HIGH				(a)6.5-8.5(MD) (a)6.0-9.0(MP)					
	GENERAL				(a) 6.0-9.0 (MD) (a) 6.0-10.0 (MP)					

Published Water Quality Directives and Criteria for Temperature
(Values in °C. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	22(G) 25(OI)								
	A2	22(G) 25(OI)			20(MD) 25(MP)		20			
	A3	22(G) 25(OI)								
FISHERIES										
	GAME	21.5(IO)			20(MD) 22(MP)	20				
	COARSE	28(IO)			23(MD) 26(MP)	30				
	LOWER THRESHOLD				25(MD) 28(MP)	30				
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				< 20					
	AVERAGE QUALITY				20-25					
	POOR QUALITY				>25					
AMENITY										
	HIGH				25(MD) 28(MP)					
	GENERAL				25(MD) 30(MP)					

Published Water Quality Directives and Criteria for Chloride
(Values in mgl^{-1}). All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	200(G)						<50 Excellent	<50 Excellent	
	A2	200(G)	200(MD) 600(MP)	200(MD) 600(MP)	200(MD) 300(MP)			50-250(MD) >250(MP)	50-250(MD) >250(MP)	25(MD) 250(MP)
	A3	200(G)								
FISHERIES										
	GAME				1000(MD) 1500(MP)					
	COARSE				1500(MD) 2000(MP)					
	LOWER THRESHOLD				2000(MD) 2500(MP)					
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				<50					
	AVERAGE QUALITY				50-200					
	POOR QUALITY				>200					
AMENITY										
	HIGH				1500(MD) 2000(MP)					
	GENERAL				2000(MD) 3000(MP)					

Published Water Quality Directives and Criteria for Total Coliforms
(Values as MPN/100 mls at 37°C. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	50(G)						50-100 (Excellent)	50-100 Excellent	
	A2	5000(G)						50-5000 (MD)	50-5000 (MD)	100(MD) 5000(MP)
	A3	50000(G)						>5000	>5000	>5000
FISHERIES										
	GAME									
	COARSE									
	LOWER THRESHOLD									
DIRECT CONTACT RECREATION		500(G) 10000(I)								
INDUSTRY										
	HIGH QUALITY									
	AVERAGE QUALITY									
	POOR QUALITY									
AMENITY										
	HIGH									
	GENERAL									

Published Water Quality Directives and Criteria for Sulphates
(Values in mgl^{-1} . All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	150(G) 250(I)								
	A2	150(G) 250(I)	250(MP)	200(MD) 400(MP)	200(MD) 350(MP)		50(MD) 250(MP)	500 (MP)		50(MD) 250(MP)
	A3	100(G) 250(I)								
FISHERIES										
	GAME									
	COARSE									
	LOWER THRESHOLD									
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				100					
	AVERAGE QUALITY				100-200					
	POOR QUALITY				>200					
AMENITY										
	HIGH									
	GENERAL									

Published Water Quality Directives and Criteria for Dissolved Iron
(Values in mgl^{-1} . All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	0.1(G) 0.3(I)								
	A2	1.0(G) 2.0(I)	0.1 (MD)	0.1 (MD) 1.0 (MP)	0.1 (MD) 1.0 (MP)		0.3 (MD)			
	A3	1.0(G)								
FISHERIES										
	GAME									
	COARSE									
	LOWER THRESHOLD									
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY				<0.2					
	AVERAGE QUALITY				0.2-2.0					
	POOR QUALITY				>2.0					
AMENITY										
	HIGH									
	GENERAL									

Published Water Quality Directives and Criteria for Colour
(Values on platinum cobalt scale. All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	10(G) 20(OI)							0-20 (MP)	
	A2	50(G) 100(OI)		5(MD) 50(MP)	20(MD) 200(MP)		75		20-150 (MP)	
	A3	50(G) 200(OI)							>150(MP)	
FISHERIES										
	GAME									
	COARSE									
	LOWER THRESHOLD									
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY									
	AVERAGE QUALITY									
	POOR QUALITY									
AMENITY										
	HIGH									
	GENERAL									

Published Water Quality Directives and Criteria for Fluorides
(values in mgl^{-1} . All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	McKee + Wolf	ONTARIO WRC
POTABLE WATER SUPPLY	A1	0.7-1.0 (G) 1.5(I)								
	A2	0.7-1.7 (G)	0.6-0.9 (MD) 0.8-1.7(MP)	0.6-0.9 (MD) 0.8-1.7(MP)	0.8(MD) 1.5(MD)					1.0(MD) 1.3-1.7(MP)
	A3	0.7-1.7 (G)								
FISHERIES										
GAME										
COARSE										
LOWER THRESHOLD										
DIRECT CONTACT RECREATION										
INDUSTRY										
HIGH QUALITY										
AVERAGE QUALITY										
POOR QUALITY										
AMENITY										
HIGH										
GENERAL										

APPENDIX III

APPENDIX III

PUBLISHED WATER QUALITY DIRECTIVE AND CRITERIA FOR THE DETERMINANDS INCLUDED WITHIN THE ATI AND PSI

In Appendix III, the following notation is used:

A1 - Minor purification; simple physical treatment and disinfection (EEC A1, 1975).

A2 - Conventional treatment; normal physical treatment, chemical treatment and disinfection (EEC A2, 1975).

A3 - Advanced treatment; intensive physical and chemical treatment and disinfection (EEC A3, 1975).

G - Guideline concentrations as defined by the EEC

I - Mandatory concentrations as defined by the EEC

O - May be exceeded in exceptional climatic or geographical conditions

MD - Maximum Desirable concentrations as defined by the respective authors

MP - Maximum Permissible concentrations as defined by the respective authors

D - Dissolved fraction only

T - Total concentration (dissolved plus particulate concentration)

AA - Annual Average

Published Water Quality Directives and Criteria for Total and Dissolved Copper

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	CANADA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1 (T)	0.02(G) 0.05(IO)							0.05(I)		
	A2 (T)	0.05(G)	0.05(MP)	0.05(MD) 1.5(MP)	0.03(MD) 0.05(MP)		1.0(MP)	0.5(MP)	0.05(G)	1.0(MP)	
	A3 (T)	1.0(G)							1.0(I)		
Hardness: $100mgl^{-1}$ $250mgl^{-1}$ $CaCO_3$ FISHERIES											
	GAME	D 0.04(G)			0.04(MD) 0.05(MP)	D 0.01(50% ile) 0.04(95% ile)	0.04		EEC		
	COARSE	D 0.04(G)			0.02(MD) 0.03(MP)	D 0.01(50% ile) 0.04(95% ile)	0.04		EEC		D 0.04(MD) 0.17(MP)
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.02(MD) 0.03(MP)						
	GENERAL				0.04(MD) 0.06(MP)						

Published Water Quality Directives and Criteria for Total Zinc

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	CANADA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.5(G) 3.0(I)						5.0(MP)	3.0(I)		
	A2	1.0(G) 5.0(I)	5.0(MP)	5.0(MD) 15.0(MP)	3.0(MD) 5.0(MP)		5.0(MP)	10.0(MP)	5.0(I)	5.0(MP)	
	A3	1.0(G) 5.0(I)							5.0(I) 7.5(MAC)		
Hardness: 100 mgl^{-1} to 250 mgl^{-1} CaCO$_3$ FISHERIES											
	GAME	0.3(I)			0.2(MD) 0.3(MP)	D 0.075(50% ile) 0.30(MP)			0.075(AA) 0.3(I)		
	COARSE	1.0(I)			0.75(MD) 1.0(MP)	D 0.25 (50% ile) 1.0(MP)			0.25(AA) 1.0(I)		D 0.4(MD) 1.6(MP)
DIRECT CONTACT RECREATION									50.0		
INDUSTRY											
	HIGH QUALITY								3.0		
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.75(MD) 1.00(MP)						
	GENERAL				1.5(MP) 2.0(MP)						

Published Water Quality Directives and Criteria for Total and Dissolved Arsenic

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

	EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	CANADA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY A1 (T)	0.01(G) 0.05(I)							0.05(I) 0.075(MAC)		
A2 (T)	0.05(I)	0.05(MP)	0.05(MP)	0.03(MD) 0.05(MP)		**0.05(MP)**	0.05(MP)	0.05(I) 0.075(MAC)	0.05(MP)	
A3 (T)	0.05(G) 0.1(I)							0.1(I) 0.15(MAC)		
Hardness: Regardless										
FISHERIES										
GAME				0.6(MD) 0.75(MP)		0.05(MD) 0.13(MP)	T 0.05	D 0.05(AA)		
COARSE				0.1(MD) 0.15(MP)		0.05(MD) 0.13(MP)		D 0.05(AA)		
DIRECT CONTACT RECREATION								T 0.5		
INDUSTRY										
HIGH QUALITY								T 0.5		
AVERAGE QUALITY										
POOR QUALITY										
AMENITY										
HIGH				0.1(MD) 0.15(MP)						
GENERAL				0.2(MD) 0.3(MP)						

Published Water Quality Directives and Criteria for Total Cadmium

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.001(G) 0.005(I)									
	A2	0.001(G) 0.005(I)	0.01(MP)	0.01(MP)	0.007(MD) 0.01(MP)		0.01(MP)	0.01(MP)		0.01(MP)	
	A3	0.001(G) 0.005(I)									
Hardness: Regardless Except EIFAC. 100 mgl^{-1} CaCO$_3$ FISHERIES											
	GAME				0.001(MD) 0.002(MP)	D 0.0005(50% ile) 0.001(MD)		0.003(MD) 0.03(MP)	0.005(AA)		
	COARSE				0.004(MD) 0.005(MP)	D 0.019 (50% ile) 0.038(MD)		0.003(MD) 0.03(MP)	0.005(AA)		D 0.0015 0.003
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.004(MD) 0.005(MP)						
	GENERAL				0.008(MD) 0.01(MP)						

Published Water Quality Directives and Criteria for Total and Dissolved Chromium

(Values as mgl^{-1} All values are 95 percentiles unless otherwise stated)

		EEC	WHO.E	WHO.I	PRICE & PEARSON (Hexavalent)	EIFAC	TRAIN	EPA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1 (T)	0.05(I)							0.075(MAC)		
	A2 (T)	0.05(I)	0.05(MP)	0.05(MP)	0.03(MD) 0.05(MP)		0.05(MP)		0.075(MAC)	0.1	
	A3 (T)	0.05(I)							0.075(MAC)		
Hardness: Greater than 200 mgl^{-1} $CaCO_3$ FISHERIES											
	GAME				0.07(MD) 0.10(MP)	D 0.025(AA) 0.01(MP)	0.1	0.05	D 0.05(AA)		
	COARSE				0.07(MD) 0.10(MP)	D 0.1(AA) 0.4(MP)	0.1	0.05	D 0.25(AA)		D 0.05(AA) 0.20(MP)
DIRECT CONTACT RECREATION										0.1	
INDUSTRY											
	HIGH QUALITY									0.1	
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.07(MD) 0.10(MP)						
	GENERAL				0.15(MD) 0.20(MP)						

Published Water Quality Directives and Criteria for Total and Dissolved Lead

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1 (T)	0.05(I)									
	A2 (T)	0.05(I)	0.1(MP)	0.1(MP)	0.07(MD) 0.1(MP)		0.05(MP)			0.05(MP)	
	A3 (T)	0.05(I)									
Hardness: Greater than 150 mgl^{-1} $CaCO_3$ FISHERIES											
	GAME				0.4(MD) 0.5(MP)			D 0.03(MP)	D 0.02(AA)		
	COARSE				0.4(MD) 0.5(MP)			D 0.03(MP)	0.25(AA)		D 0.05(MD) 0.10(MP)
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.4(MD) 0.5(MP)						
	GENERAL				0.8(MD) 1.0(MP)						

Published Water Quality Directives and Criteria for Total Mercury

(Values as $\mu g l^{-1}$ All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	**EPA**	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.5(G) 1.0(I)									
	A2	0.5(G) 1.0(I)		1.0(MP)	0.7(MD) 1.0(MP)		2.0	2.0(MP)			
	A3	0.5(G) 1.0(I)									
Hardness: Regardless											
FISHERIES											
	GAME				0.15(MD) 0.20(MP)		0.5(MP)	0.05(MD) 0.2(MP)	1.0(AA)		
	COARSE				0.15(MD) 0.20(MP)		0.5(MP)		1.0(AA)		D 1.0(AA)
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.15(MD) 0.20(MP)						
	GENERAL				0.30(MD) 0.40(MP)						

Published Water Quality Directives and Criteria for Cyanide

(Values as mgl^{-1} All values are 95 percentiles)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.05(I)									
	A2	0.05(I)	0.05(MP)	0.05(MP)	0.03(MD) 0.05(MP)					0.2(MP)	
	A3	0.05(I)									
Hardness: Regardless											
FISHERIES											
	GAME				0.007(MD) 0.01(MP)		0.005(MP)				
	COARSE				0.007(MD) 0.01(MP)		0.005(MP)				0.02(MD) 0.1(MP)
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				0.07(MD) 0.01(MP)						
	GENERAL				0.015(MD) 0.02(MP)						

Published Water Quality Directives and Criteria for Phenols

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	**EPA**	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.001(I)									
	A2	0.001(G) 0.005(I)	0.001 (MP)	0.001(MD) 0.002(MP)	0.001(MD) 0.0015(MP)		0.001(MP)				
	A3	0.01(G) 0.1(I)									
Hardness: Regardless FISHERIES											
	GAME				0.4 (MD) 0.5 (MP)	0.5(MD) 1.0(MP)		0.1(MP)			1.0(MD) 5.0(MP)
	COARSE				1.5(MD) 2.0(MP)	2.0(MP)		0.1(MP)			
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH				1.5(MD) 2.0(MP)						
	GENERAL				3.0(MD) 4.0(MP)						

Published Water Quality Directives and Criteria for Hydrocarbons

(Values as mgl^{-1} All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	CANADA	WRC	ONTARIO WRC	SWEDISH CRITERIA
POTABLE WATER SUPPLY	A1	0.05(I)									
	A2	0.2(I)		0.01(MD) 0.3(MP)							0.1(MD)
	A3	0.5(G) 1.0(I)									0.3(MD)
FISHERIES											
	GAME				NO	DATA					
	COARSE				NO	DATA					
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH										
	GENERAL										

Published Water Quality Directives and Criteria for PAH

(Values as $\mu g l^{-1}$ All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	CANADA	WRC	ONTARIO WRC	Y.W.A. (1982)
POTABLE WATER SUPPLY	A1	0.2(I)									
	A2	0.2(I)	0.2(MP)	0.2(MP)							
	A3	1.0(I)									
FISHERIES											
	GAME					NO DATA					
	COARSE					NO DATA					
DIRECT CONTACT RECREATION											
INDUSTRY											
	HIGH QUALITY										
	AVERAGE QUALITY										
	POOR QUALITY										
AMENITY											
	HIGH										
	GENERAL										

Published Water Quality Directives and Criteria for Total Pesticides

(Values as $\mu g l^{-1}$ All values are 95 percentiles unless stated otherwise)

		EEC	WHO.E	WHO.I	PRICE & PEARSON	EIFAC	TRAIN	EPA	WRC	ONTARIO WRC
POTABLE WATER SUPPLY	A1	1.0(I)								
	A2	2.5(I)								17.0
	A3	5.0(I)								
FISHERIES										
	GAME					NO DATA				
	COARSE					NO DATA				
DIRECT CONTACT RECREATION										
INDUSTRY										
	HIGH QUALITY									
	AVERAGE QUALITY									
	POOR QUALITY									
AMENITY										
	HIGH									
	GENERAL									

APPENDIX IV

APPENDIX IV

QUESTIONNAIRE SURVEY TO ASSIST IN THE DEVELOPMENT OF WEIGHTINGS FOR THE NINE WQI DETERMINANDS

OBJECTIVES

The objectives of this index are twofold :

i) to reflect general water quality on a scale of 10 - 100;

ii) to indicate potential water use over a range of water quality.

METHOD

Rank the nine determinands in descending order giving the highest rank (9) to the determinand you consider to be most significant as an indicator of water quality and potential use.

Determinand	Rank
Suspended Solids	
Chlorides	
pH	
Dissolved Oxygen	
Total Coliforms	
B O D	
Temperature	
Ammoniacal Nitrogen	
Nitrates	

APPENDIX V

APPENDIX V

QUESTIONNAIRE SURVEY TO ASSIST IN THE DEVELOPMENT OF WEIGHTINGS FOR THE THIRTEEN PWSI DETERMINANDS

OBJECTIVE

The objective of this index is to reflect the suitability of surface waters for use in potable water supply.

METHOD

Rank the determinands in order of importance giving the highest rank of 13 to the determinand(s) you consider to be most important for water used in potable water supply.

Determinand	Rank
Fluorides	
pH	
Colour	
Dissolved Oxygen	
Chlorides	
Iron	
Total Coliforms	
Nitrates	
Temperature	
Sulphates	
Ammoniacal Nitrogen	
Suspended Solids	
Biochemical Oxygen Demand	