The development of an aquatic toxicity index as a tool in the operational management of water quality in the Olifants River (Kruger National Park)

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The development of an aquatic toxicity index and its application is described. In this index the protection of aquatic life is always referred to in terms of toxic effects of different water quality variables to fish, as health indicators of the aquatic ecosystem. The final index score is produced by means of standard additive techniques as well as by using the water quality variable giving the lowest index score (minimum operator). The minimum operator is employed in order not to conceal important water quality information. The aquatic toxicity index development has been linked to toxicological data, international water quality standards and South African guidelines. The index provides valuable information concerning toxic effects of a specific variable on fish should the threshold level for normal maintanence of aquatic life be exceeded. This index is intended as an aid in the interpretation of water quality information in order to facilitate management decisions.

Key words: Water quality, development, aquatic toxicity index, environmental management, Olifants River, Kruger National Park.

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Introduction

By virtue of its position on the eastern border of South Africa, the Kruger National Park receives the flow of six main rivers, each of which has different proportions from the specific catchment in the park itself. The Olifants River has the largest catchment area both in size and in proportion of catchment area beyond the park boundaries (Walmsley & Davies 1991). The increased competing demand for water by the urban, industrial, mining and agricultural sectors within the catchment boundaries of the Olifants River has focused attention on the ecological water requirements of the river.

When one considers the demand for water by the Kruger National Park it is evident that water is required for more than one use, i.e. for potable use, game watering and ecosystem (aquatic and riparian) maintenance (Moore 1990b). In order to facilitate proper water quality management it is necessary to develop a comprehensive water quality management plan for the river. According to Van der Merwe & Grobler (1990) the development of such a plan requires a thorough understanding of the fate and effects of pollutants in the environment. It is furthermore important to have reliable information on the trends and status of important water quality determinants in these systems.

In the field of water management, scientists, engineers and managers are often confronted with a large array of data which can be totally overwhelming. In order to convey the interpretation of the data in a simplified manner, a set of numbers or a single number may be devised to integrate the data pool (Smith 1990). This number is known as a water quality index. The use of a water quality index (WQI) would make it possible to bridge the gap between the extremes of water quality monitoring and reporting (House 1989).

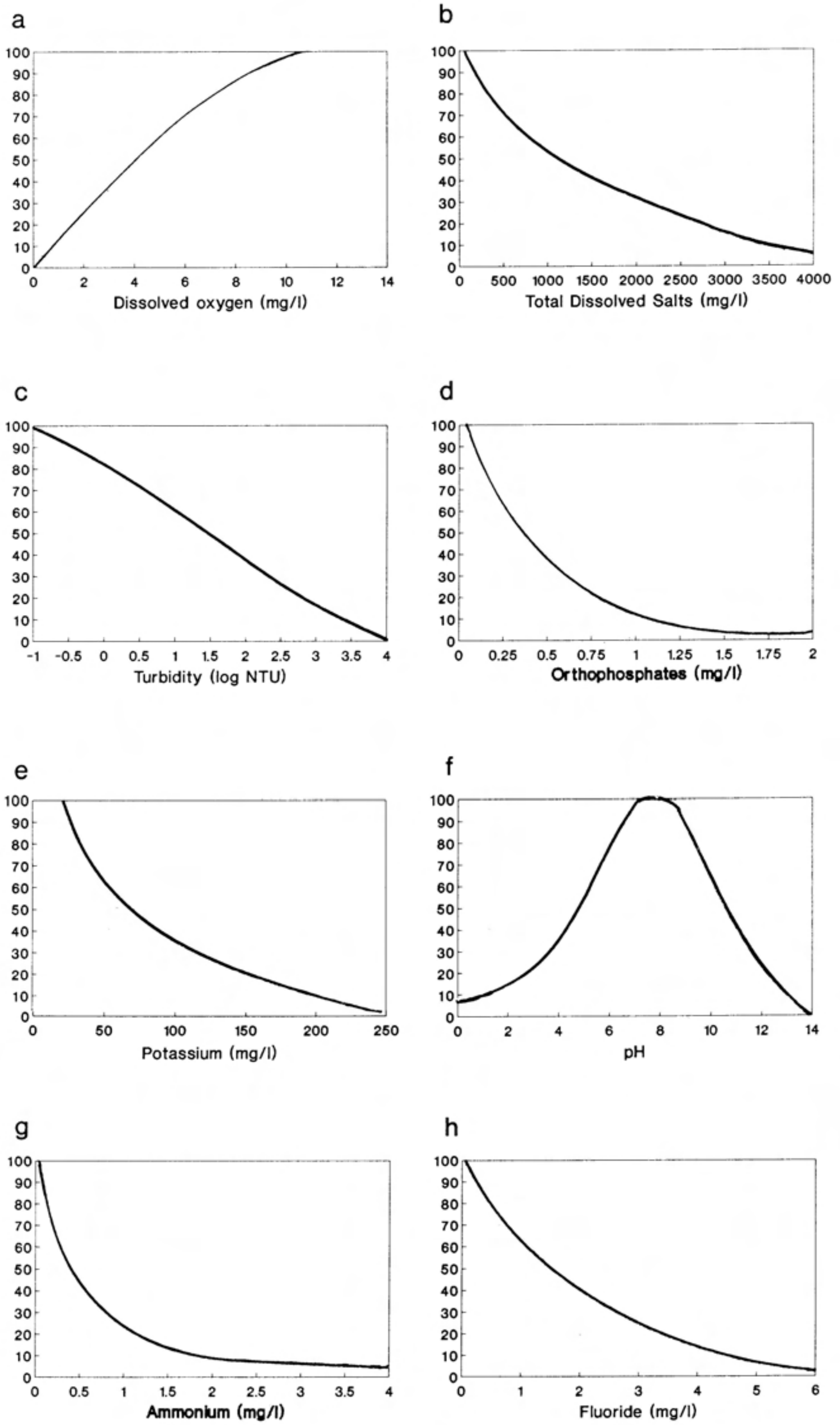

Fig. 1. Index rating curves of the aquatic toxicity index: a. dissolved oxygen; b. total dissolved salts; c. turbidity; d. orthophosphates; e. potassium; f. pH; g. ammonium; h. fluoride.

Classification and zoning of rivers form an integral part of water pollution control programmes (Bhargava 1983). A river may be classified into various grades indicating the beneficial use(s) to which it may be put. The grades are based on the permissible limits or guidelines of the relevant water quality set by the various authorities. Depending on the quality of water in the river, it can be zoned according to its suitability for a specific beneficial use (e.g. maintanence of the aquatic ecosystem).

It is the purpose of this paper to provide the theoretical basis underlying the development of a WQI, or more specifically, an aquatic toxicity index intended for use as a tool in the operational management of the water quality in the Olifants River within the Kruger National Park boundaries. With the development of such a WQI emphasis was placed on the development of an index reflecting the toxicological effects of selected water quality variables on the aquatic environment. An aquatic toxicity index (ATI) was therefore developed to reflect the effect of the water quality on a specific water use i.e. the aquatic environment.

Development of an Aquatic Toxicity Index

The term water quality is seldom defined and in many instances the water quality index produced is an attempt to pool several aspects of water uses, including pollution (House & Ellis 1980), the reason for this being that different water users have different water quality requirements. In the development of the current index the toxic effects of the water quality on aquatic organisms, specifically fish, were taken into account. The index was only developed for fish because of the extensive toxicity data base available for fish. We envisage incorporating the toxic effect of the chosen water quality variables on aquatic invertabrates into the ATI in the future.

The question that was addressed when developing the ATI was, "how suitable is the water for the continued existence of the fish populations in the Olifants River?". The three stages in the development of a water quality index (House 1989) that were followed during the development of the current ATI were: determinant selection; determinant transformation; determinant aggregation.

Determinant selection

The determinants that were chosen comprised some of the most commonly measured attributes of natural water as measured by the Department of Water Affairs and Forestry (DAWF). The determinants chosen included physical, chemical and potentially hazardous trace and heavy metals. Each determinant had to conform to three basic requirements i.e.: (a) was the determinant data readily available at frequent intervals, (b) are the determinants considered important indicators of water quality change and (c) were there maximum permissible water quality criteria available for the determinants.

The physical water properties selected were pH, dissolved oxygen and turbidity. The chemical determinant included ammonium, total dissolved salts, fluoride, potassium and orthophosphates while the potentially hazardous metals chosen were total zinc, manganese, chromium, copper, lead and nickel concentrations. All the above-mentioned variables conformed to the requirements set and from a management point of view these determinants could be limited in effluents in receiving waters.

Determinant transformation

The most efficient method of transforming information on individual determinant concentrations is to select or obtain rating curves for each determinant (Walski & Parker 1974; House 1989; Smith 1990). Before developing a rating curve it was necessary to define the scale on which the ATI was to operate.

a) Defining an ATI scale

An ATI scale similar to the WQI scale proposed by Smith (1990) for salmonid spawning was used. A

Table 1
The interpretation and classification of the ATI scale

ATI scale	Interpretation
60-100	Indicates water of suitable quality for all fish life
51-59	Indicates quality of water suitable only for hardy fish species e.g. adult *Oreochromis mossambicus* and adult *Clarias gariepinus*
0-50	Indicates water quality which is totally unsuitable for normal fish life

scale of 10-100 was selected with a score of 10 reflecting water which is totally unsuitable for fish life and that of 100 akin to pristine conditions. The interpretation and classification for the aquatic toxicity WQI scale is given in Table 1.

b)Selecting ATI rating curves

Three different methods were followed when selecting the ATI rating curves:

(i) Use of existing WQI rating curves

The existing curves used were those for dissolved oxygen (Smith 1990) (Fig. 1a), total dissolved salts (Fig. 1b), turbidity (Fig. 1c) (Moore 1990a), orthophosphates (Fig. 1d) (Walski & Parker 1974) and potassium (Fig. 1e) (Workshop: Sensitive fish species 1991).

(ii) Modification of existing WQI rating curves

Existing curves for pH and ammoniacal nitrogen were modified in order to take into consideration the highly mineralised conditions that occur in the Olifants River (Van Veelen 1991). In existing curves the 100 rating score for pH was at a pH of 7,2 whereas the median pH for the Olifants River for the period 1983-1992 was 8,0 (Van Veelen 1991; Wepener *pers. obs.*). The modified pH rating curve (Fig. 1f) showed a steep gradient. This is to because the Olifants River is a fairly well buffered river system. In the unlikely event of the pH differing with more than one pH unit the resultant altered toxicity of ammonium and heavy metals, due to speciation changes, will be taken into consideration. The NH_4^+ rating curve (Fig. 1g) was adapted from NH_3 toxicity data to reflect the effect of a higher pH value (pH 8 - 9) and temperature (25 - 30 °C) on the toxicity of NH_4^+ to fish (Thurston *et al.* 1983; Hellawell 1986).

(iii) Development of ATI rating curves

The rating curves were obtained as follows: Blank graph formats were taken on which the y-axis represented the suitability-for-use (index rating score) and ranged from 0-100. The x-axis represented the range of determinant concentrations or values likely to have an effect on fish. In all the cases the curves were to be plotted through a fixed point, i.e the index rating score of 60 and the x-axis value representing the water quality standard for that determinant; this corresponds with the lowest value in the "suitable for all fish life" category (see Table 1). The rest of the concentrations of the specific determinants and their corresponding rating scores were plotted on the graph by employing current toxicity data in the form of LC_{50} and no observed effect concentration (NOEC) values.

Rating curves for fluoride (Fig. 1h), zinc (Fig. 2a), manganese (Fig. 2b), copper (Fig. 2c), chromium (Fig. 2d), lead (Fig. 2e) and nickel (Fig. 2f) were obtained by the above-mentioned method. All the LC_{50} and NOEC values were obtained from existing toxicological data in literature (Smith *et al.* 1985; Hellawell 1986; Mance 1987; Van de Meent *et al.* 1990). Only toxicological data corresponding with the basic water properties of the Olifants River were used, i.e. pH between 7,8 and 9, water hardness 120 mg/l as $CaCO_3$, and temperature between 20 °C and 30 °C. In most of the cases the toxicological data used were obtained using the same fish species. These fish species included *Lepomis macrochirus* (bluegill), *Pimephales promelas* (fathead minnow), *Oncorhynchus gairdneri* (rainbow trout), *Ictalurus punctatus* (channel catfish) and fish species found in Southern Africa e.g. *Oreochromis mossambicus* (Mozambique tilapia). The concentration on the x-axis for the index rating score of 60 (y-axis value) for each determinant was derived by combining and aggregating the water quality standards of the United Kingdom (Gardiner & Zabel 1989), Netherlands (Van de Meent *et al.* 1990), Australia (Hart 1974), Canada (Environment Canada 1987), European Inland Fisheries Advisory Commission (EIFAC) (1980) and South African guidelines (Kempster *et al.* 1980), as well as water quality guidelines for the Olifants River (Moore *et al.* 1991; Workshop: Sensitive fish species 1991). The rating score of 60 is regarded as the minimum ATI value where the water quality is suitable for all fish species. When a water quality standard was above or below available toxicity data, that specific standard was not taken into consideration when deriving the x-axis value.

To illustrate the development of an index rating curve, the rating curve of zinc is described. All the LC_{50} and NOEC values were plotted on the x-axis. In order to determine the NOEC value, the LC_{50} value was multiplied by a factor of 0,01 (United States Environmental Protection Agency 1984). The lowest NOEC value, in this case 16 μg/l, was given an index rating of 100 (Mance 1987; Van Meent *et al.* 1990). The median water quality standard or guideline for zinc as set by the above-mentioned countries was taken as 200 μg/l and the rating score of 60 was attained. The zero rating was taken as the lowest LC_{50} i.e. 1 400 μg/l (Mance 1987). The rest of the NOEC values were awarded corresponding rating scores of between 61 and 99 according to the toxicity of zinc to the aforementioned fish species. The plotted points were connected with a curved line. When the curve did not join all the points smoothly, a trend line was drawn resembling an inverted LC_{50} curve.

Determinant aggregation

The values obtained from the rating curves had to be aggregated in some way to produce a final index score. For the ATI the aggregation technique employed was the Solway Modified Unweighted Additive Aggregation function (House & Ellis 1980):

$$I = 1/100.(1/n\sum_{i=1}^{n} q_i)^2 \qquad (1)$$

where I is the final index score, q_i is the quality of the ith parameter (a value between zero and 100) and n is the number of determinants in the indexing system. This function is similar to the aggregation technique developed by the Scottish Development Department

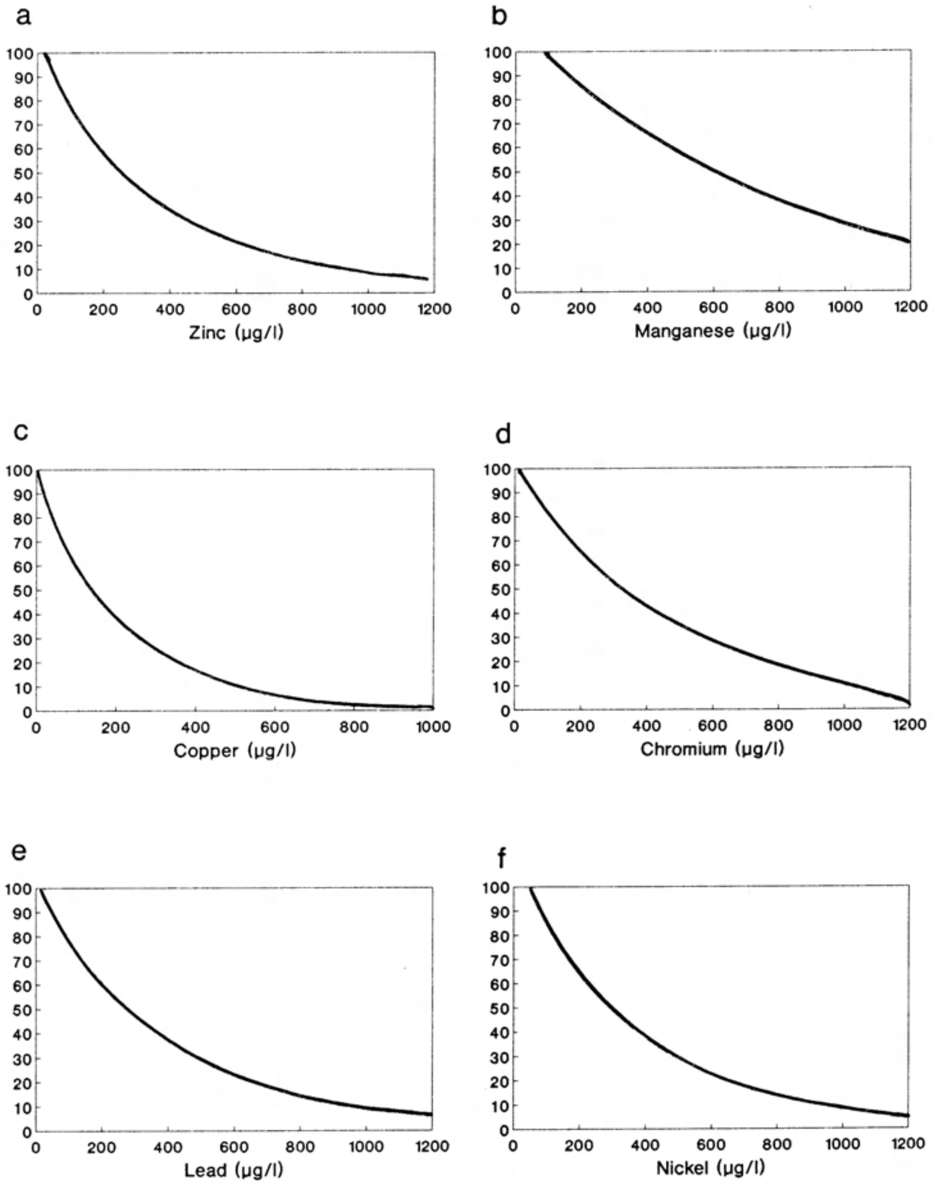

Fig. 2. Index rating curves of the aquatic toxicity index: a. zinc; b. manganese; c. copper; d. chromium; e. lead; f. nickel.

(SDD) (1976) and which is being advocated for use in England (Tyson & House 1989). The only difference between the technique employed in this study and the technique used by the SDD is that the latter has a weighted value (an indication of perceived importance) attached to each determinant. No weighted system was applied to the determinants in the current study as the authors felt that too little is known about the importance of one determinant compared to another under local conditions. Furthermore, it is not possible to compare factors which have a direct and interactive effect on one another, e.g. pH and heavy metals, and apply a weighted system whereby it is implied that the relative importance of one parameter over another is known. It will, however, be possible to develop a weighted system when

Table 2
Equations for the determination of index rating values

Determinant	Index Rating Equation
Dissolved Oxygen	$0 \leq DO \leq 5$; y=10(DO) $5 < DO \leq 6$; y=20(DO)-50 $6 < DO \leq 9$; y=10(DO)+10 DO >9 ; y=100
pH	$y=98 \exp[-(pH-8{,}16)^2(0{,}4)]$ $+17 \exp[-(pH-5{,}2)^2(0{,}5)]$ $+15 \exp[-(pH-11)^2(0{,}72)] +2$
Manganese	$y=a\ \exp^{-c}\ \exp^{(Mn)b} +d$ a=0,115; b=0,0013; c=0,05; d=5
Nickel	y=-c ln (a (Ni+b)) +d a=1; b=-10; c=28; d=211
Fluoride	y=-c ln(a (F+b))+d a=0,001; b=2,5; c=71; d=-235
Chromium	y=-c ln(a (Cr+b))+d a=0,1; b=150; c=40; d=210
Lead	y=-c ln(a (Pb+b))+d a=0,1; b=-30; c=27; d=148
Ammonium	$0{,}02 \leq NH_4^+$; y=100 $0{,}02 < NH_4^+ \leq 0{,}062$; $y=-500(NH_4^+)+110$ $0{,}062 < NH_4^+ \leq 0{,}5$; $y=40/(NH_4^+ +0{,}65)^2$ $NH_4^+ > 0{,}5$; $y=-5{,}8(NH_4^+)+32{,}5$
Copper	y=-c ln(a (Cu+b))+d a=1; b=-18; c=26; d=180
Zinc	y=-c ln(a (Zn+b))+d a=0,001; b=-20; c=22; d=16
Ortho-phosphates	y=a exp(P)b a=100; b=-2,4
Potassium	$y=a\ \exp^{-b(K)} +c$ a=150; b=-0,02; c=-8
Turbidity	y=-c ln(a ln(NTU)+b)+d a=0,001; b=30; c=220; d=-689
Total dissolved salts	$y=a\ \exp^{-b(TDS)} +d$ a=117; b=0,00068; d=-7

more information concerning the chemistry of the system as a whole (including synergistic/antagonistic effects) becomes available.

It is, however, a problem when deriving a final index score through an aggregation technique, because it tends to conceal the most valuable piece of information, namely the identity of the determinant which limits the water's "suitability-for-use" and the degree to which this occurs (Smith 1990). It was therefore decided to use an aggregation function which would not conceal valuable, information in addition to the use of function (1). This function uses the lowest determinant index score to produce the final index score and it is known as the "minimum operator" function:

$$I = \text{minimum}\ (q_1, q_2, ..., q_i) \qquad (2)$$

In order to minimise the laborious task of determining the index score of each determinant from an index rating curve and then to calculate the final ATI score, a computer software package (WATER) was developed. The curve of each determinant was plotted and fitted and an equation for each curve was determined by means of numerical calculations and Pascal (see Table 2). All the equations were incorporated into a computer program which was written in Pascal with "Turbo Pascal Version 6". The program is able to compute both the additive and the minimum operator final index values. In addition to computing the final index values the program provides valuable information on the harmful effects that the different determinants would have on fish should the "suitable-for-use" concentration limit be exceeded.

Application of the ATI by employing the WATER computer software program

An example of how the computer program is applied to obtain an ATI score for the Olifants River is demonstrated in Figure 3. Aquatic toxicity index values are represented by both the aggregation functions discussed. Data used in the example were collected at Mambaweir (Department of Water Affairs sampling site number B7M15) in October 1991 during a bimonthly sampling trip to the Olifants River. In the following article we will use the ATI to discuss the water quality of the Olifants River for the period February 1990 to June 1992.

Discussion

In the past, water quality indices were criticised for the loss of information due to the aggregation of a number of determinants. This was overcome by the implementation of a minimum operator function in deriving a final ATI value. The ATI can further provide information on the determinant concentrations in terms of quality criteria legislation (when implemented in South Africa) for aquatic life as the standards for the different determinants were used in the development of the individual determinant rating curves.

The ATI is an efficient method to monitor trends in water quality since it enables the reduction of large amounts of data to a single index value in a highly reproducible way. It is, however, important to keep into consideration that should the number of determinants included in each index application vary, the results obtained may be misleading.

In order to implement an ATI successfully it is necessary to have access to the different determinants in the index at frequent intervals. The National Parks Board is in the fortunate position that it has access to frequently sampled chemical data on 22 localities in the six main rivers from which water is supplied to the Kruger National Park (Van Veelen 1991). Physical determinants are obtainable by employing portable field instruments which are easy to handle. The trace metal concentrations in the water can be determined by means of portable diagnostic kits which are freely available. The trace metal concentrations obtained in this manner are not necessarily one hundred percent accurate, but they enable the researcher is able to obtain a very good idea of the concentration range is and if there are any changes in concentrations. Should a drastic change in trace metal concentrations be found, the water sample could be sent away for very accurate and detailed atomic absorption spectrometry analyses.

The data obtained by the researcher would then be fed into the WATER computer program and an ATI value for the specific locality could be produced. In this way the status of the water quality for different localities in the Olifants River could be kept up to date on a biweekly or monthly basis.

The advantages of using a computerised ATI in the operational management of surface river water may be vested in the fact that a number of determinants can be interpreted immediately and the resultant index value will enable the game ranger or researcher to pinpoint deteriorating water quality and even the possible source of the decreased water quality. A further advantage of this ATI is the information which is provided concerning the toxicological effects of the determinants on aquatic life. This would aid water management by the Parks Board when establishing water quality guidelines for upstream users. It is also possible to update the program should recent and more relevent toxicological data become available.

House (1989) summarises the advantages of a WQI as follows:

- it is able to demonstrate annual cycles and trends in water quality, even at low concentrations, in an efficient and timely manner;
- it is able to highlight river reaches which have shown a change in quality over a specified period;
- it can be applied to unpolluted as well as polluted rivers and enables managers to place rivers into ranked order, thus indicating spatial variation in water quality;
- it indicates possible water use in terms of guideline values (or legally adopted water quality standards contained within legislative directives to be implemented in the future); and
- it assists in the evaluation of benefits which may accrue from investment capital schemes.

We would like to stress the fact that this aquatic toxicity index is designed specifically for fish in a water system with a hardness greater than 120 mg/l as $CaCO_3$ and pH > 7,8 such as the Olifants River in the Kruger National Park. The authors conclude that the Aquatic Toxicity Index can be applied in an objective manner and the results obtained would be reproducible and repeatable both temporally and spatially.

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Determinants to be measured	*Values obtained*	*Rating values*
Dissolved oxygen (mg/l)	9,3	100
pH	8,8	85,67
Manganese (µg/l)	23	100
Nickel (µg/l)	< 10	100
Fluoride (mg/l)	1,9	60,25
Chromium (µg/l)	< 6	100
Lead (µg/l)	154	69,36
Ammonium (mg/l)	0,04	90
Copper (µg/l)	20	85,4
Zinc (µg/l)	36	100
Phosphates (mg/l)	0,04	89,98
Potassium (mg/l)	34,1	83,84
Turbidity (NTU)	9,3	66,67
Total dissolved salts (mg/l)	1117	47,74

Final Index Score

Solway equation: 70,92
Minimum operator:
47,74 due to TDS

Suitability-for-use

Suitable for all fish species but more research is needed on the effect of high TDS values

Fig. 3. An example of how an aquatic toxicity index score is obtained.

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