A water quality index for use with diatoms in the assessment of rivers

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Abstract

Water quality is commonly reported with respect to the minerals that comprise the total dissolved solids, often together with COD, BOD, pH and other components. For ease of use by consumers, the quality parameters are mostly related to usage, i.e. water quality for domestic use, livestock or irrigation, etc. When diatom populations are used as water quality indicators a different system is necessary because diatoms are mostly good indicators of the total dissolved solids. A system to report water quality as an index or class is proposed using data collected from the Swartkops River system, which has pristine headwaters but which becomes progressively polluted downstream. The data included in the index encompass water quality values that cover more than 90% of the 212 river sites sampled from all the phytogeographical areas of South Africa.

Keywords: epipelic diatoms; river water quality; water quality index

Introduction

There is a great need for good quality water throughout the world and this is no different in South Africa. Consumption is beginning to exceed supply in many areas as the population grows, with industrial and agricultural requirements increasing in proportion. Most rivers in South Africa have been modified, primarily by weirs and dams, to increase their year-round ability to supply water for agriculture, industry, municipal and human purposes. Many of these modifications have resulted in a reduction of water quality within the rivers because return flow from irrigated agricultural lands and sewage purification works has increased the total dissolved solids in many rivers. Due to agricultural activities, erosion has become a problem and this has increased the already naturally high turbidity of many rivers.

The Department of Water Affairs and Forestry (DWAF) at Resource Quality Services monitors the water chemistry of many rivers in South Africa. However, the chemistry at any given time is a snapshot of the water quality at the time of sampling. The temporal variation of most water quality variables is usually high in lotic environments (France and Peters, 1992; Chambers et al., 1992; Cattaneo and Prairie, 1995) and biological monitors can be beneficial if they can accurately assess the water quality with a lower degree of variability than can the snap-shot samples at different sites and of specific water quality variables (Stevenson and Pan, 1999).

In 1996 DWAF, the Water Research Commission (WRC) and the Department of Tourism, Environmental and Economic Affairs (DTEEA) initiated the National Biomonitoring Programme for Aquatic Ecosystems (NBPAE). The objective was to design a programme to monitor the health of aquatic ecosystems throughout the country and to provide information that might be used to manage water systems (Hohls, 1996). Arrays of biological indices have, and are, being tested for practical use and interpretation. These indices include the South African Scoring System Version 5 (SASS5, based on macroinvertebrates), the Index of Biotic Integrity (IBI based on fish) and the Riparian Vegetation Index (RVI). A suite of secondary indices is also used to interpret the biological indices. These include habitat assessment indices, the Hydrological Index, the Water Quality Index (WQI) and geomorphological indices.

The use of benthic diatoms in South Africa for water quality assessment has been briefly considered, but until recently the shortage of expertise in identification made a diatom index unsuitable for use (Uys et al., 1996). Despite this, in South African river systems, diatoms have been studied extensively since the early 1950s (e.g. Cholnoky, 1953; Cholnoky, 1960; Cholnoky, 1968; Archibald, 1983) and efforts have been made to relate diatom associations to water quality (e.g. Archibald, 1983; Schoeman, 1979; Schoeman and Archibald, 1986). However, none of these has included the complete suite of parameters routinely measured by Resource Quality Services. Hence, these earlier observations are incomplete by present-day standards.

The distribution of benthic algae in a river is the result of a complex series of interactions between hydrological, water quality and biotic factors. Short-term differences in community composition are driven by immigration of cells, differences in growth rate between populations and loss processes such as death, emigration, sloughing and grazing. Poulin and Williams (1998) estimated that there are 10 million diatom species world-wide of which only about 11 000 have been identified to date. However, Bate et al. (2004) have shown during an extensive survey of South African rivers that the number of dominant benthic diatom species is remarkably low. Lange-Bertalot (2000) suggested that part of the international species pool is cosmopolitan and Bate et al. (2004) have confirmed this because most of the dominant species found in the South African rivers were already recorded in the international literature.

Benthic microalgae become abundant where water systems are impacted by anthropogenic influences. Diatom autecology has been studied in various parts of the world and diatom indices for the assessment of water quality have been developed (e.g. Prygiel and Coste, 1993; Kelly and Whitton, 1995). Various researchers have been able to infer successfully the trophic conditions at a sampling

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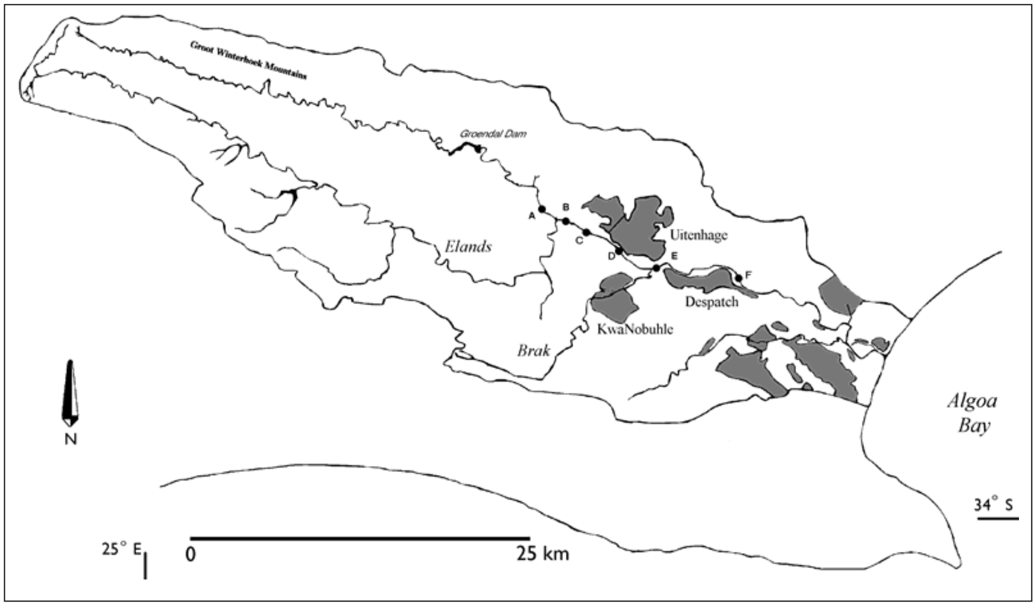

Figure 1
Map of the Swartkops River catchment with the sampling sites A to F and the position of Metropolitan Port Elizabeth

site from the composition of benthic diatom assemblages at that site (e.g. Van Dam et al., 1994; Kelly and Whitton, 1995). This indicates that trophic conditions do have an influence on species composition, but that it is hard to distinguish specific nutrients causing the effect. Nutrient kinetic studies and multivariate statistics are promising approaches to study the effect of nutrients on benthic algal species composition (Borchardt, 1996).

The assessment of water quality conditions in freshwater habitats with benthic diatoms has a long history. Diatoms are used as bioindicators in Europe (Kelly et al., 1998; Prygiel et al., 1999), North America (Stevenson and Pan, 1999; Lowe and Pan, 1996), South America (Lobo et al., 1998; Loez and Topalian, 1999), Australia (John, 1998; Chessman et al., 1999) Asia (Lobo et al., 1995; Rothfritz et al., 1997) and Africa (e.g. Schoeman, 1979; Pieterse and Van Zyl, 1988; Gasse et al., 1995). Some of these approaches are focused on inferring past hydrochemical characteristics in lakes (e.g. Fritz et al., 1991; Gasse et al., 1995), while others are designed to monitor present-day conditions in rivers and streams (e.g. Prygiel and Coste, 1999).

Currently in South Africa an array of biological indices is being tested for practical use in the interpretation of water quality. These indices are not used uniformly throughout South Africa because the different assessments are fragmented into usage characteristics. For example "hard water" is water with certain characteristics; water suitable for the different kinds of livestock in the country has certain characteristics while water quality suitable for a sustainable ecosystem must have a quality variance that should not exceed a percentage of the natural values. Clearly these latter indices are unsuitable for use where diatoms are used to express the quality of natural river water.

A water quality index, in the context of this report, is a set of numerical values to indicate the concentration of chemical constituents present in river water. A water quality class is a numerical value that can be used with diatoms to indicate the average of all the chemical constituents present in river water at the site where a species was found. The components of the final index provide a rapid assessment of how the final class is calculated. The WQI is "arbitrary" in the sense that the values have no biological or chemical reason for being used, but simply reflect a case for comparison.
Bate et al. (2004) have reported on the relationships between water quality and the dominant benthic diatom flora in a great many of South Africa's rivers. The water quality values used by these authors included the normal suite assessed by Resource Quality Services. This present paper describes a numerical index system that indicates how the dominant diatom species found at a site indicates the water quality.

Materials and methods

Water quality: Swartkops River

The data from which the water quality index is derived were taken from the Swartkops River in the Eastern Cape South Africa. The main part of the catchment of the Swartkops River lies in the "Groot Winterhoek Mountains" (Fig. 1). The total catchment area is ca. 1 354 km^2 with a mean annual runoff of 84.2 x 10^6 m^3. The largest obstruction to river flow in the catchment is the Groendal Dam. This reservoir has a storage capacity of ca. 12 x 10^6 m^3, which is 45% of the mean annual runoff from that part of the catchment. The Elands River is the largest tributary to the Swartkops and has two small dams in its catchment. These dams tend to have little effect on the river flow (Baird et al., 1986). The part of the Swartkops River that was studied is a 2^{nd} to 3^{rd} order stream (Strahler method in Gordon et al., 1992) based on a 1:250 000 scale map. The climate in the catchment is largely warm temperate with all months between 10 to 22^{o} C and with at least 60 mm of rain monthly (Köpke, 1988). Six sites (A to F) were selected along the river that was regularly sampled as part of a monitoring programme run by DWAF. The locations of the sites are given in Table 1. Figure 1 illustrates the catchment area and sampling sites.

The water quality of the Swartkops River is severely impacted by several anthropogenic sources (Baird, 1986; Mackay, 1993; Binning, 1999). There is a persistent gradient of water quality, ranging from virtually pristine conditions just upstream from the town of Uitenhage (Sites A and B), to heavily degraded water quality at Sites C to F. The sources of impact include: agriculture, a wool-processing factory, three sewerage treatment works, runoff from informal settlements and discharges from light industries (e.g. leather tanning).

The sampling sites were visited monthly between May 1997 and April 1999 and the full suite of major inorganic water quality variables was analysed by the RQS of DWAF. The details of these sites are shown in Table 1.

Water quality: Rivers of South Africa

River samples for water quality and dominant epipelic diatoms were collected in the Western Cape, Free State, Northern Cape, KwaZulu-Natal, Northern Province, Eastern Cape, Kruger National Park, Durban Metro area and DWAF Rand Water area. Full details of the 212 sampling sites, GPS co-ordinates and date of sampling are given in Bate et al., 2004.

Water quality analyses

The water samples (250 mℓ) were taken by the DWAF representative present during the collection, preserved with $HgCl_2$ (8 mg·ℓ^{-1}) and analysed at the laboratories of the Resource Quality Services, Department of Water Affairs and Forestry, Pretoria, South Africa (National Laboratory Accreditation Service, Accredited Laboratory No. T0073). The samples were analysed for NH_4, NO_2+NO_3, F, alkalinity as $CaCO_3$, Na, Mg, Si, PO_4, SO_4, Cl, K, Ca and total dissolved solids (TDS). *In situ* dissolved oxygen (WTW, Oxi 330), electrical conductivity (YSI model 30 conductivity meter), pH (UniFet 100 pH meter) and temperature (read from the conductivity meter) were measured. In those cases where the samples were taken by Rand Water, Durban Metro and Umgeni Water, the water samples were handled and treated in their own prescribed manner.

TABLE 1
Sampling sites on the Swartkops River indicating the site designation, its name and the location co-ordinates

Site	Name	Location	
		South	East
A	Springfontein	33°44'10.5"	25°19'11.3"
B	Bulmer Drift	33°45'07.6"	25°20'33.4"
C	Gubb & Ingg's	33°45'51.2"	25°22'32.9"
D	Niven Bridge	33°46'19.5"	25°23'16.5"
E	Nic Claasen Bridge/Brak River	33°47'33.1"	25°24'48.4"
F	Despatch Bridge	33°47'25.2"	25°29'18.6"

Calculation of the Swartkops River water quality classes and water quality index for diatoms

The presentation of diatom data as an indication of water quality can be by simply showing the actual water quality values of the sites in which the diatom species were found. The problem with that approach is that the reader is left without any perspective of where the species lies in the context of all South African water quality values. If an index of water quality were to have been constructed from all the water quality data collected in this project, the spread would be great and therefore not very useful. For this reason the choice was made to construct an arbitrary index but one using real data from the Swartkops River. The Swartkops River data are useful because they represent a consecutive 13-month collection of water samples from sites with consistently different water quality. Sediment samples were collected at the same time that the water samples were collected and the dominant diatoms from each site were related to the water quality in the river (Bate et al., 2004). The minimum and maximum values for each water quality parameter was calculated for the Swartkops River and compared with all the South African river sites. Five water quality classes were compiled using the Swartkops water quality data. To determine the water quality index for a diatom species the average water quality value is calculated and a water quality class (i.e. 1 to 5) assigned. There are too few replicated diatom data at present to use this water quality index system as more than a guide.

TABLE 2
Minimum and maximum values for each of the parameters measured at the Swartkops River sites together with the minimum and maximum values measured at all the sites sampled in South Africa during the study. The data show the maximum value from the Swartkops River sites as a percentile of the "all South Africa" maximum value measured. The values given are those provided by WQS.

Component	SR WQ Min Value	SR WQ Max Value	All RSA WQ Min Value	All RSA WQ Max Value	SR WQ max. as a %ile
Ca	2	90	1	504	94.9
Cl	40	1577	<10	6844	99.3
F	0	0.5	<10	0.7	96.4
K	0.6	34.2	0	242.6	94.3
Mg	3	129	1	690	98.8
Na	24	899	<0.02	3645	99.4
NH_4	0	3.8	<0.04	295	99.4
NO_3+NO_2	0	6.2	<0.04	340	96.8
pH	6.81	8.8	4.2	9.6	97.9
PO_4	0.01	7	<0.01	336	93.1
SiO_2	0	8.9	0.5	47	92.8
SO_4	0	514	2.1	2114	98.1
Alkalinity	7	851	6	851	100
TDS	95	3380	26.1	14139	99

Results

The water quality data taken from the Swartkops River are shown in Table 2 and illustrate that the ranges between minimum and maximum values for these data are narrower than for the "all South Africa" (RSA) data. To construct an index from the wide-ranging data set from all the RSA data results in lower sensitivity.

Of importance is the fact that the data in Table 2 show that the maximum values of the Swartkops River data cover 90 to 100% of all the values taken from 212 river sites in all the obvious phytogeographical regions of South Africa.

An analysis of the water quality values obtained for all the South African sites (Bate et al. 2004) showed that the data, with the exception of pH, were not normally distributed. Rather they were made up of many low values with very few high values. The data for TDS are shown in Fig. 2.

In compiling water quality classes using the Swartkops River quality data, a decision was taken that 5 classes would be adequate. The determination of a class is that Class 1 begins at the lowest value of a water quality component found from the Swartkops River data shown in Table 3, while a Class 2 has the range (Class 2 minus Class 1)/2. The same principle applies to the other classes.

Anomalies occur where the water quality at a site is either below

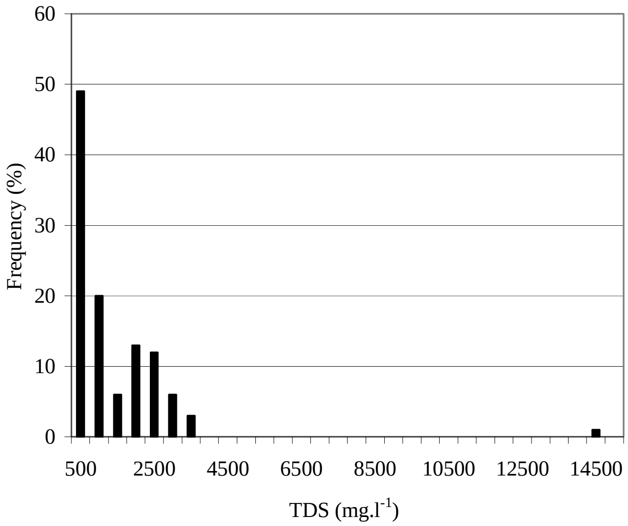

Figure 2
Frequency distribution of total dissolved solids from all the rivers sampled in South Africa

the minimum of the index range or above its maximum. This can be accommodated logically in cases where the number is higher than the maximum in the Swartkops classes, by applying a suffix to the class value, where relevant. Hence, it is possible to have a Class 1- or a Class 5+. In the event that a site value exceeded the upper Class 5 value by an order of magnitude, a Class 5++ would be indicated. Hence, in the case of TDS, values falling between 95.0 and 505.63 were allocated Class 1, whereas values > 505.63 to 1326.88 were allocated Class 2 and so on. If a TDS value was found to be > 3 380 mg·ℓ$^{-1}$ (Table 2) then it was classified as 5+. The actual calculations were undertaken using MS Excel using nested conditional statements.

To determine the water quality index (WQI) for a diatom species, the average water quality values for the site where the species was found were calculated for each component as shown in Table 4. Hence the WQI for a diatom species would comprise the average value of the water quality components. An example is shown in Table 4 for the diatom with the code name AMPHPEDI (*Amphora pediculus* (Kutzing) Grunow). Code names were allocated according to the rules determined by Bate et al. (2004). An example of this calculation is provided with reference to Tables 3 and 4. In Table 4, AMPHEDI is shown to have been found at a site where the Ca^{++} concentration was 69 mg·ℓ$^{-1}$. This value falls between 57 and 79 (Table 4) and thus a Class 4 is allocated for Ca^{++}. Similarly, the Cl^- concentration was 463 mg·ℓ$^{-1}$, which falls between 232 and 616, thus placing Cl^- in Class 2.

The average value on the last line of Table 4 indicates that all values are included in the calculation except pH. The reasons for excluding pH are that:

- The pH data were the only ones that were normally distributed
- A low or high pH value does not necessarily indicate good or poor water quality.

The calculation of the average class includes EC and TDS. It might be argued that EC should be excluded since it is a measure of TDS and thus TDS is included twice. The data for all the water quality data across South Africa (Bate et al., 2004) showed that the TDS could be calculated as EC x 6.49 with the range 3.74 to 9.27. The majority of the TDS/EC values were very close to 6.5. The reason for including EC into the diatom WQI is that Resource Quality Services normally include it in their reports and the class is the same as that for TDS.

Because the final WQI is the mean of the components, the influence of including EC is almost negligible. A number of examples were calculated (data not shown) before this procedure was followed.

TABLE 3
Water quality class ranges for each water quality component. Data taken from the Swartkops River at 5 sites over a period of 13 months. In each class range, "Low" represents the lowest value measured while "High" represents the highest value measured (mg·ℓ$^{-1}$ for mineral elements; mS.m^{-1} for EC; pH units).

Component	Class 1 Range		Class 2 Range		Class3 Range		Class 4 Range		Class 5 Range	
	Low	High	Low	High	Low	High	Low	High	Low	High
Ca^{++}	2.00	13.00	>13	35.00	>35.00	57.00	>57.00	79.00	>79.00	90.00
Cl^-	40.00	232.13	>232.13	616.38	>616.38	1000.63	>1000.63	1384.88	>1384.88	1577.00
EC	17.30	128.01	>128.01	349.44	>349.44	570.86	>570.86	792.29	>792.29	903.00
F^-	0.00	0.05	>0.05	0.15	>0.15	0.25	>0.25	0.35	>0.35	0.40
K^+	0.60	30.85	>30.85	91.35	>91.35	151.85	>151.85	212.35	>212.35	242.60
Mg^{++}	3.00	18.75	>18.75	50.25	>50.25	81.75	>81.75	113.25	>113.25	129.00
Na^+	24.00	133.38	>133.38	352.13	>352.13	570.88	>570.88	789.63	>789.63	899.00
NH_4^+	0.00	0.48	>0.48	1.43	>1.43	2.38	>2.38	3.33	>3.33	3.81
$NO_2^- + NO_3^-$	0.00	0.78	>0.78	2.33	>2.33	3.89	>3.89	5.44	>5.44	6.22
pH	6.81	7.07	>7.07	7.58	>7.58	8.10	>8.10	8.61	>8.61	8.87
$H_2PO_4^-$	0.01	0.88	>0.88	2.62	>2.62	4.36	>4.36	6.10	>6.10	6.97
SiO_2	0.00	1.11	>1.11	3.34	>3.34	5.56	>5.56	7.79	>7.79	8.90
SO_4^{++}	0.00	64.25	>64.25	192.75	>192.75	321.25	>321.25	449.75	>449.75	514.00
Alkalinity	7.00	112.50	>112.50	323.50	>323.5	534.50	>534.5	745.50	>745.50	851.00
TDS	95.00	505.63	>505.63	1326.88	>1326.88	2148.13	>2148.13	2969.38	>2969.38	3380.00

TABLE 4
Calculation of the diatom WQI for the single diatom species with the code name AMPHEDI (*Amphora pediculus* (Kutzing) Grunow)

AMPHPEDI Component	Quantity ($mg \cdot \ell^{-1}$)	DiatomWQ Index
Ca^{++}	69	4
Cl^-	463	2
EC ($mS \cdot m^{-1}$)	238	2
F^-	0.5	5
K^+	8.9	1
Mg^{++}	46	2
Na^+	319	2
NH_4^-	0.02	1
NO_3^-	0.02	1
pH	8.35	4
$H_2PO_4^-$	0.043	1
SiO_2	2.4	2
SO_4^{--}	245	3
Alkalinity	196	2
TDS	1391	3
AVE CLASS WITHOUT pH		2.21

TABLE 5
Mean and modal values calculated for each of the components of the WQI for NAVIHEIM (*Navicula heimansii* Van Dam & Kooyman*)*

NAVIHEIM n=12	$mg \cdot \ell^{-1}$ Mean	Class Mean	($mg \cdot \ell^{-1}$) Mode	Class Mode
Ca^{++}	2.67	1	3.00	1
Cl^-	42.83	1	42.00	3
EC (mS.m-1)	45.64	1	-	1
F^-	0.05	2	0.10	1
K^+	0.75	1	0.70	1
Mg^{++}	3.83	1	4.00	1
Na^+	26.17	1	28.00	2
NH_4^-	0.00	1	0.00	1
NO_3^-	0.02	1	0.00	1
pH	7.21	2	-	2
$H_2PO_4^-$	0.03	1	-	1
SiO2	2.28	2	2.10	1
SO_4^{--}	9.50	1	7.00	1
Alkalinity	12.17	1	14.00	2
TDS	100.83	1	-	1
Mean class without pH		1.14		1.29

To construct an index from the wide-ranging data set from all the RSA data results in lower sensitivity. On the other hand, some of the Swartkops maximum values are as high as or almost as high as the maximum values from all the RSA rivers sampled. It might therefore appear unnecessary to use the Swartkops River data. As mentioned, however, the component values from all RSA rivers had a few very high values. In the case of TDS the greatest TDS value from the Swartkops River was 3 380 $mg \cdot \ell^{-1}$ whereas the highest value from all RSA sites was 14 139 $mg \cdot \ell^{-1}$.

The use of a Water Quality Index allows one to assess rapidly the overall water quality of the site where the diatom species was found. At the same time, the quality of the water for each of the components can also be rapidly determined.

Discussion

A water quality index, in the context of this study, is a set of numerical values to indicate the concentration of chemical constituents present in river water. This water quality index is a numerical value that can be applied to diatoms indicating the average of all the chemical constituents present in river water at the site where the species was found. The WQI is "arbitrary" in the sense that the values have no biological or chemical reason for being used, but simply reflect a case for comparison. The water quality index values chosen in this study were taken from the Swartkops River in the Eastern Cape, South Africa, because those data were the most comprehensive available. More particularly, they represent water quality data from a system that has a wide variation in water quality from headwaters to the head of the estuary.

We believe that the water quality index reported here is a valuable addition to the description of river water quality as well as to the uses to which water can be put. For example, where domestic water is considered to have a target TDS of 0 to 450 $mg \cdot \ell^{-1}$, this implies that the target water quality index value would be Class 1. For livestock, the TDS classes might be Class 2 for dairy animals, pigs and poultry, Class 3 for non-dairy cattle and up to Class 5 for sheep.

In biomonitoring river water quality using diatoms, reference to an actual water component concentration in units of $mg \cdot \ell^{-1}$ is not very useful because TDS comprises up to 4-digit whole numbers whereas ammonium normally falls into values of a single whole number. When a WQI value is used, a Class 3 is the same for all water quality components. The same applies to other uses. If a user is aware that there are 5 water quality classes, then a reported WQI has immediate interpretative value.

Bate et al. (2004) have reported the WQI values for all the dominant benthic diatoms located thus far in the rivers of South Africa. If an epipelic diatom is dominant at a river site then the WQI for that species immediately indicates the average WQ for the site at which it was collected. There are too few data at present to use this WQI system as more than a guide and because the values are not likely to be normally distributed until more data are collected. We have calculated both the mean and modal water quality values for a number of species. As n for each species increases, so the mean and mode merge. However, until more data are available, both the mean WQI and the modal WQI should be reported with their respective standard errors. An example of the difference between the mean and modal WQC values is shown in Table 5. The data in Table 5 show that in the case of NAVIHEIM (*Navicula heimansii* van Dam and Kooyman*)*, both the mean and modal classes were rather similar, but not identical.

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