Substance-specific water quality criteria for the protection of South African freshwater ecosystems: methods for derivation and initial results for some inorganic toxic substances

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Freshwater ecosystems form the resource base on which water users, such as the agricultural, recreational, domestic and industrial sectors, depend. These essential resources therefore need to be protected and maintained in a healthy state. The Department of Water Affairs and Forestry is currently developing water quality criteria for the protection of South African freshwater ecosystems, to complement the existing National Water Quality Guidelines for domestic, industrial, agricultural and recreational use. This paper describes the methodology for the derivation of in-stream water quality criteria for inorganic toxic substances. Criteria are calculated from the results of acute and chronic toxicity tests on a number of representative species, using local data where available, and relying on international databases to supplement local information. Conservative numerical criteria are provided for aluminium, ammonia, arsenic, boron, cadmium, chlorine, chromium, copper, cyanide, fluoride, lead, manganese, mercury, molybdenum, selenium, vanadium and zinc. For each toxic substance, threshold levels at which chronic and acute toxicity effects on aquatic biota can be expected are indicated. The criteria can be applied in water quality evaluation, impact assessment, and in the setting of discharge permit conditions.

In terms of the policy of the Department of Water Affairs and Forestry, aquatic ecosystems are considered to be 'the base from which the [water] resource is derived' (draft White Paper, 1994). This implies that management and protection of the resource base must be effective to ensure the maintenance of fitness for other uses (such as agricultural, domestic, recreational and industrial water use).

A variety of instruments are critical to the effective and efficient management of freshwater resources. One such instrument is a set of numerical criteria, for specific substances, that indicate the levels at which protection of sensitive components of aquatic ecosystems can be ensured. In this respect, water quality criteria for the aquatic environment represent an important source of information to support resource management decisions.

Until recently, little progress had been made with the development of guidelines for managing aquatic ecosystems. The lack of a generally accepted set of water quality criteria for local application forced scientists and managers to make use of various substitutes. Overseas standards, for example the Canadian, American and Australian water quality criteria,[2-4] or locally produced summaries of such criteria,[5,6] were commonly used. The South African General Effluent Standards and Special Effluent Standards were, unfortunately, also used as representative of allowable environmental concentrations, even though these amounts bear little or no environmental relevance. This shortcoming is now being addressed through a project dedicated specifically to the development of water quality criteria and water quality management guidelines for protecting South African freshwater ecosystems.

The Department of Water Affairs and Forestry has decided to *develop* criteria for South African aquatic ecosystems, rather than to adopt or modify existing international criteria. The reasoning behind this is, first, that it is important to establish the know-how of criterion development locally, and second, that devising local criteria, while based on internationally accepted procedures, can take cognisance of factors of local importance, for example key species and specific water characteristics. Moreover, the development of environmental management guidelines and associated criteria is an evolving field. Any set of values derived from a single project should be seen as interim, to be used and tested under local conditions, and to be modified or complemented from the results of ongoing research. The availability of new research findings and additions to the existing data bases may at any time require modifications to the approach and/or to the criteria for particular variables.

This paper provides the background and general overview of the philosophy and procedures used to derive criteria for selected inorganic toxic substances in the aquatic environment. Initial results are presented for aluminium (Al), ammonia ($NH_{3(aq)}$), arsenic (As), boron (B), cadmium (Cd), chlorine (Cl_2), chromium (Cr), copper (Cu), cyanide (CN), fluoride (F), lead (Pb), manganese (Mn), mercury (Hg), molybdenum (Mo), selenium (Se), vanadium (V) and zinc (Zn).

Quality criteria for the protection of aquatic ecosystems

An aquatic ecosystem can be defined as a coherent entity encompassing shore, water, biota and bottom sediment, including the physical, chemical and biological components.[7] Terrestrial animals, such as fishing owls, crocodiles, hippopotami and otters, which depend on aquatic ecosystems for essential life support, are included in this definition.[8]

Water quality criteria for the aquatic environment should, if adhered to and given appropriate hydrological and habitat conditions, allow for the sustainable functioning of healthy and balanced aquatic ecosystems. The philosophy behind the derivation of water quality guidelines for these ecosystems is significantly different from that used in the preparation of guidelines for domestic, agricultural, industrial and recreational use.[1] The latter are stated in terms of the effects on the users of given concentration ranges for a particular water constituent. These users can make a decision on their water quality requirements which is based on quantitative knowledge of the physiological, aesthetic or economic effects of worsening or improving water quality. Mitigating actions would be tempered by technical feasibility and the costs of offstream treatment.

For aquatic ecosystems, however, a protective approach has

been followed in the derivation of water quality criteria. This is intended to minimize the risk of unforeseen, possibly irreversible, damage to the resource base. The approach followed here is, in principle, similar to those which have been adopted and are being applied in the United States, Canada and the Netherlands.[2,3,7] Since criteria to protect whole ecosystems cannot focus on each and every species associated with it, use is made of key indicator species representative of different trophic groups. The philosophy is that if representative key species are protected, other biota will enjoy protection as well.

Through the derivation of numerical criteria for the protection of aquatic biota, some measure of protection can also be extended to aquatic habitats and ecological processes. However, to deal effectively with the integrated nature of ecosystems, numerical values based on chemical constituents on their own are not enough. For this purpose measures for the protection of aquatic ecosystems have been categorized broadly into three classes, namely:

- *substance-specific criteria* where a numerical value(s) for each substance of concern represents an acceptable level of ecological risk associated with that substance;
- *whole-effluent criteria* where the whole-effluent toxicity (WET) testing approach is followed to evaluate complex mixtures which contain several constituents and where the individual effect of each substance on the environment cannot be resolved;[9]
- *biological criteria* — either numerical values or narrative expressions that quantitatively describe the desired state and ecological integrity of aquatic ecosystems, usually region-specific and based on the best attainable conditions in that region.

Methodologies for whole-effluent and biological criteria still need to be established for South Africa, and are not further discussed here. Substance-specific criteria for the aquatic environment focus on in-stream concentrations and are intended for national application. Criteria may be modified, however, where appropriate, as a result of site-specific considerations. The idea is not for the numerical values to be enforceable by themselves, but to guide and assist in the development of effluent standards for point-source pollutants, and in the formulation of effluent discharge permits, which can be enforced.

In this project, the selected water quality variables were divided into logical groups, namely, inorganic toxic substances (e.g. trace metals), organic toxic substances, nutrients and driving variables (e.g. oxygen, temperature, pH, hardness). For each category of variables, a procedure specifically applicable to it is followed for deriving numerical criteria.

Glossary

water quality criteria for aquatic ecosystems: numerical values or narrative statements that are calculated from experimental data and based on expert opinion, with the aim of protecting the aquatic environment.

substance-specific criteria: numerical values that indicate the concentration of the substance of concern at or below which the aquatic environment will be safeguarded against adverse ecological effects.

water quality guideline: a scientifically based set of prescriptions to provide a management framework for implementing water quality criteria, including the criteria, background information, information on the fate and effects of the substance, specifications for monitoring and analyses, possible treatment options, etc.

toxic substance: a natural or synthetic chemical substance which can cause adverse effects on living organisms even when present at low concentrations.

The approach for toxic substances

For toxic substances an estimate of the risk associated with each chemical should be part of the process of formulating criteria. One way of achieving this goal is to assess the toxicity of a substance and, depending on the degree of uncertainty associated with the source data, to extrapolate to a 'safe' level. Single-species toxicity tests are currently the most widely used and most reliable means of estimating environmental damage from exposure to toxic substances.[10] Numerical water quality criteria are, therefore, usually developed from laboratory concentration–response data, as derived from toxicity tests with single species. These tests can, on the basis of the exposure duration, be divided into short-term (acute) and long-term (chronic) tests. Accordingly, criteria for the aquatic environment are specified to protect against acute and chronic effects, where each level of protection is expressed in terms of allowable concentrations.

The selection of an end-point for toxicity data has an implication for interpreting the criteria derived from that information. For this project, the end-point used for acute data was mortality, rather than some physiological or enzymatic inhibition. A consequence of this selection is that the resulting criteria reflect an irreversible effect. They do not, therefore, allow for ambiguous interpretation, even when short duration excursions above the standard occur.

In contrast, a particular end-point was not selected for chronic toxicity data. The intention with the chronic criteria is that no adverse effect of any kind should be discernible. Since the standards are intended to be precautionary, the reversibility of effect, although possible, is not considered.

Although the toxicity of individual substances often depends on several environmental factors in a water body, such as hardness, pH, suspended solids and temperature, it is intended that national water quality criteria should be set at levels which will protect all or most water bodies. The use of national criteria attempts to provide a reasonable and adequate amount of protection with only a small possibility of considerable overprotection or underprotection. National criteria for each toxicant of concern are expressed as two numerical values, respectively termed an acute effect value (AEV) and a chronic effect value (CEV).

The AEV refers to the concentration at and above which a statistically significant acute adverse effect is expected to occur. If exceedance of the AEV is limited and lasts for a short period only, aquatic organisms and their uses should, however, not be affected permanently and populations will recover. The AEV is not a target value or compliance concentration, but rather a danger or reaction level, indicating where acute adverse effects can be expected. The AEV can, for example, be used to guide decision making when a toxic spill occurs. Calculation of the AEV is primarily based on results of acute toxicity tests.

The CEV refers to the concentration limit which is safe for all or most populations even during continuous exposure. It can also be termed the 'no-unacceptable-biological-effects' concentration for long-term or permanent exposure. If the CEV is exceeded, fish, invertebrates, phytoplankton and aquatic plant communities in freshwater ecosystems (streams, rivers, lakes and reservoirs) may not be protected against unacceptable long-term and short-term effects. As the CEV is increasingly exceeded, the risk of ecosystem damage rises, and also the uncertainty regarding the nature and extent of the effects of such change.

Some adverse effects, such as reduction in growth or reproduction of *a specific species*, may occur at, and even below, the CEV. If maintained continuously, however, any concentration above

the CEV is expected to cause an ecologically unacceptable effect. On the other hand, the concentration of a substance in a body of water can be above the CEV without producing an unacceptable effect if:

- the magnitude and duration of the exposures above the CEV are limited, and
- there are compensating periods of time during which the concentrations are below the CEV.

Calculation of the CEV is based on results of chronic toxicity tests and/or the ratios of acute and chronic results.

Derivation of numerical criteria

The derivation of a CEV and AEV for a particular toxic substance entails a rigorous calculation procedure, based largely on the methodology developed by the US Environmental Protection Agency.[11] The method relies upon data generated from the results of toxicity tests on a representative range of aquatic organisms. Since our aim was to produce criteria specific to the South African situation, local source documents and research findings were used where possible. Locally derived data are, however, very limited and lacking for many indigenous species, especially fish. This study subsequently had to rely mainly on international toxicity findings, of which the ASTER and AQUIRE data bases formed the main sources.[12,13] These references contain data from peer-reviewed publications, with enough supporting information to indicate that acceptable test procedures were employed and that the results are reliable.

Data base requirements

Quantity and quality of laboratory toxicity data play an important role in determining whether numerical criteria can be developed for a specific substance. Confidence in a criterion usually increases with the amount of available data. The more comprehensive and representative the information gathered, the less the chance of deriving standards that are severely overprotective or underprotective.

National criteria are derived only if adequate and appropriate data are available to provide reasonable confidence in such values. If experimental results are not adequate, then tentative standards are proposed using the available information. Safety factors are applied at points in the calculation procedure to compensate for lacking data (discussed in more detail later). These tentative criteria can be reviewed as more information becomes available. No safety factor was incorporated if the knowledge about a specific substance complied with the following minimum requirement:

- Results of acute toxicity tests on at least one species of freshwater animal in at least eight different families such that all of the following are included:[11]
  - — a representative of the cold-water fishes, e.g. from the family Salmonidae in the class Osteichthyes;
  - — any family of freshwater fishes in the class Osteichthyes to represent the warm-water fishes (e.g. Cichlidae, Cyprinidae, Clariidae);
  - — planktonic crustaceans (e.g. cladoceran, copepod, etc.);
  - — benthic crustaceans (e.g. ostracod, isopod, amphipod, crayfish);
  - — insects (e.g. mayfly, dragonfly, damselfly, stonefly, caddisfly, mosquito, midge);
  - — a family in a phylum other than Arthropoda or Chordata (e.g. Rotifera, Annelida, Mollusca).

Only data on freshwater species were used. Information on cold- and warm-water fish includes species of which wild populations reproduce in southern African waters. If not indigenous to southern Africa, the species were selected on the basis of their local commercial or recreational importance. Species used under this specification include: Rainbow trout, Brown trout, Largemouth bass, Smallmouth bass and Common carp.

- Results of chronic toxicity tests or acute–chronic ratios (ACRs) of species of aquatic animals in at least three different families are used, provided that of the three species:
  - — at least one is a fish, and
  - — at least one is an invertebrate.

Due to the general shortage of chronic toxicity data, ACRs for any freshwater fish in the class Osteichthyes were used. Although data on species specified under the acute test requirements were preferred, ACRs of other species were used for some metals.

- Results of at least one test with a freshwater alga or a vascular plant. If plants are among the aquatic biota that are most sensitive to the substance, results of a test with a plant in another phylum (division) should also be available.

Two sets of criteria were calculated: i) when results on cold- water fish species were excluded and ii) when findings on cold- water fish species were included in the data set. Values derived when excluding the information on cold-water species were regarded as the criteria for national application. If, however, the inclusion of cold-water species data resulted in a significant lowering of the calculated values, the latter are given additionally as site-specific modifications for areas where endemic or exotic cold-water-adapted species occur.

The following selection criteria were used in the collection and collation of data:[11]

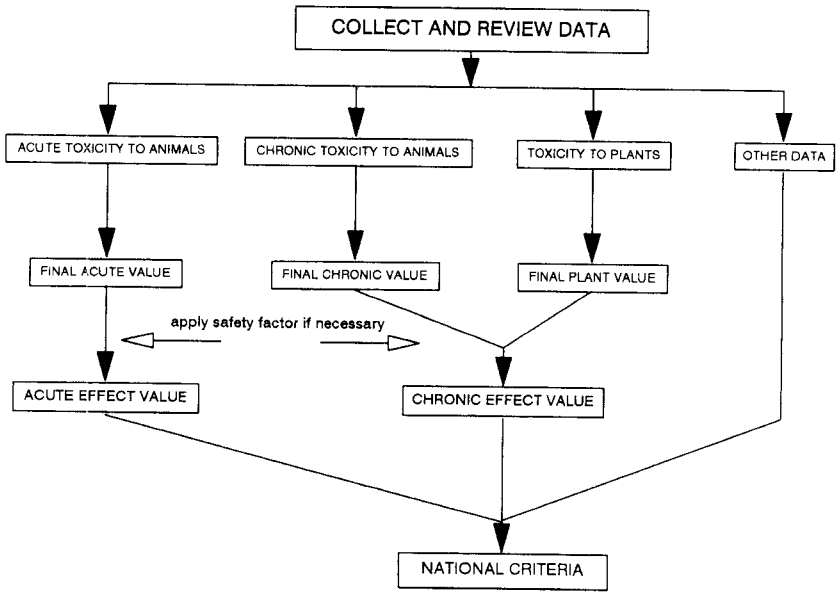

Fig. 1. Diagrammatic presentation of the process of deriving national criteria for toxic substances. This process has been modified from the US Environmental Protection Agency's methodology.[11]

Table 1. Descriptions of the final values used in the derivation of criteria for toxic substances.

Value	Abbreviation	Description
Final acute value	FAV	Calculated from the EC_{50}* values of acute toxicity tests on genera as per the prescribed data base requirements
Final chronic value	FCV	Calculated from either (i) results of chronic toxicity tests (LOEC or NOEC)**, or (ii) acute–chronic ratio (ACR)
Acute-chronic ratio	ACR	Ratio of geometric mean of acute values to geometric mean of chronic values
Final plant value	FPV	Lowest result of toxicity test on an important alga, or chronic toxicity test on an important vascular plant
Acute effect value	AEV	One-half of the FAV
Chronic effect value	CEV	Lowest value of the FCV and FPV

* EC_{50} is the toxicant concentration which corresponds to a cumulative probability of 50% of an adverse effect at a specific time of observation. Where the desired effect is mortality, the term LC_{50} (lethal concentration) is used.

** The LOEC (lowest observed effect concentration) is the lowest concentration used which led to an adverse response statistically different from the control. The NOEC (no observed effect concentration) is the highest concentration which led to no adverse effect statistically different from the control. Statistical significance was measured at the 95% confidence level.

- For each metal, all available information concerning toxicity to, and bio-accumulation by, aquatic animals and plants were collected.
- Questionable data were rejected. This included results from tests:
  - — that did not contain a control treatment;
  - — in which too many (usually >10%) organisms in the control treatment died or showed signs of stress or disease;
  - — in which distilled or deionized water was used as the diluent without addition of appropriate salts;
  - — with organisms that were previously exposed to substantial concentrations of the test substance or other contaminants; and
  - — where there was insufficient agreement of toxicity data within and between species.
- Data on technical grade substances were used where appropriate, but findings involving formulated mixtures and emulsifiable concentrates of the material of concern were not employed. All results are expressed in terms of the concentration of the metal of concern, and not of the test compound.

Final values used in the derivation of criteria

Figure 1 shows schematically how the criteria for toxic substances were derived. Table 1 lists and defines the final values which are used in the process illustrated in the figure.

Procedures for calculating factors used in the derivation of numerical criteria

Final acute value

For the purpose of deriving national criteria, it is necessary to find a single figure to represent the plethora of acute toxicity data. A single acute toxicity value is usually presented as the nth percentile of acute effect concentrations (EC_n). The test organisms include many different species in a number of different genera. The toxicity data for a species can be represented by its mean acute value (SMAV). Where SMAVs for more than one species within a genus are available, the genus mean acute value (GMAV) is calculated.

The final acute value (FAV) is an estimate of the fifth percentile of a statistical population represented by the set of GMAVs for which acceptable acute tests have been conducted on the substance.[14] If, however, the SMAV of a commercially or recreationally important species is lower than the calculated FAV, then the smaller SMAV replaces the FAV in order to provide protection for that important species.

The procedure developed by the US Environmental Protection Agency was followed in calculating the FAVs.[11] This procedure involved five steps (Fig. 2):

Step 1: Suitable toxicity data were reduced to standard benchmark formats, such as LC_{50} values, to produce one value per test. For acute tests use was made of a dose–response curve, which plots the concentrations of the substance against organisms' response. The concentration which corresponds to a cumulative probability of 50% for death (LC_{50}) of the test population was then calculated. The benchmark formats are reported in the AQUIRE data base.[11]

Step 2: The species mean acute values were calculated from individual toxicity test results. Such results have usually been found to conform to skewed distributions. However, there were often insufficient data to calculate a mean or modal value, and the geometric mean was used to approximate the distribution mean. This step produced one value to represent the tolerance of each selected species.

Step 3: This step involved the calculation of a genus mean acute value from the relevant species mean acute values. Here, as in Step 2, the geometric mean was used to approximate the distribution mean. This produced one value to represent the tolerance of the genus. Where data for only one species per genus could be found, the SMAV became the GMAV.

Step 4: Although the GMAVs often fitted a lognormal distribution, or even a Weibul distribution, it was found that the calculation of the FAV was best served by assuming a log triangular distribution.[14] The FAV was then calculated by:

- Assigning to each GMAV the cumulative probability, P, calculated from $P = R/(N+1)$
  where R = rank and N = the number of GMAVs or SMAVs;
- fitting a line to the ln(GMAV) versus P data set using the four points where P is closest to 0.05 and employing the geometric mean functional relationship to estimate the slope (the factor of 0.05 was selected to give criteria that seemed neither too high nor too low in comparison with the sets of data from which they were calculated); and
- calculating the FAV as the concentration corresponding to $P = 0.05$ on this line.

Step 5: The AEV was calculated as FAV/f, where f was the safety factor (Table 2). Where no safety factor was applicable, f had the value of 2.

Where there were enough data to demonstrate that acute toxicity to two or more species is similarly related to environmental characteristic(s) other than the toxic substance (e.g. hardness, temperature or pH), then the SMAV (or GMAV) was calculated as follows:

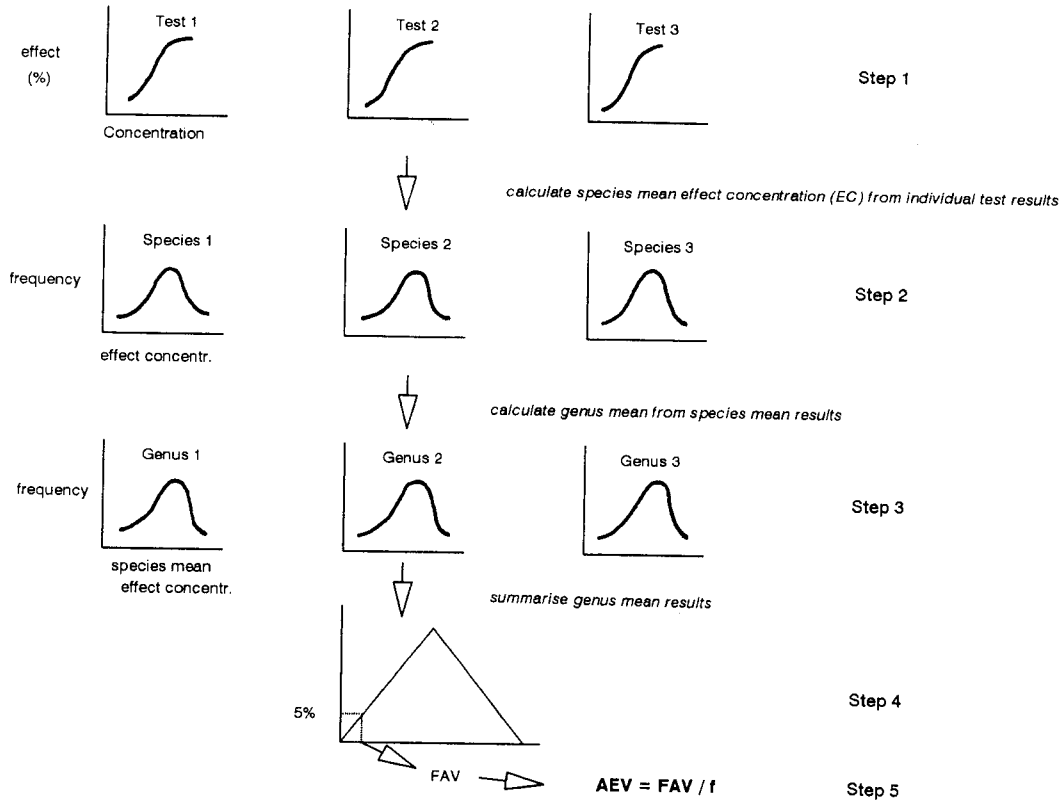

Fig. 2. Diagrammatic presentation of the steps involved in deriving the final acute value (FAV) and the acute effect value (AEV).

- For each species the SMAV at a selected value, Z, of the water quality characteristic was calculated by:

$$SMAV = e^{[\ln W - V(\ln X - \ln Z)]}$$

where W is the geometric mean of the acute toxicity values, X is the geometric mean of the water quality characteristic and V is the slope of the pooled normalized toxicity data of a species on the pooled normalized concentration of the water quality characteristic.

- The Final Acute Equation is written as:

$$FAV = e^{[V \cdot \ln(\text{water quality characteristic}) + \ln A - V \cdot \ln Z]}$$

where A is the value of ln (GMAV) corresponding to $P = 0.05$.

- In addition to the general criteria for acceptance of data, data were rejected when:
  - the range of the pertinent environmental characteristic was not sufficiently wide to be useful,
  - acute values adjusted for the water quality characteristic for a species or genus differed by more than a factor of 10,
  - correlation for at least one fish and one invertebrate was not available,
  - slopes from regression analysis of the pertinent environmental characteristic for different species were too dissimilar, or
  - too few data were available.

Final chronic value

The final chronic value (FCV) was either calculated from available chronic toxicity data or was derived from the acute:chronic ratio. Where there are enough chronic exposure test data available, the species mean chronic value (SMCV), mean genus chronic value (MGCV) and FCV were calculated in a manner analogous to SMAV, GMAV and FAV.

In the case of having sufficient data, the following rules applied:

- Results of flow-through or renewal tests, i.e. where flowing-water tanks were used or when water was replaced during the course of the experiment, were included.
- Survival, growth and reproduction of the control had to be acceptable for the species.
- If the total organic carbon (TOC) or suspended solids (SS) in the dilution water exceeded 5 mg l^{-1}, a relationship of either TOC or SS to chronic toxicity had to be known — whether there was an effect or not.

Table 2. The guidelines that were followed in applying safety factors for deriving AEVs, where safety factors are applied to the FAV.

Scenario	Acute data base description	Safety factor
1	Each of the six specified groups has at least one representative species, and the species mean can be calculated from at least two results for at least one species in at least three of the groups	1
2	Each of the six specified groups has at least one representative species, but the intra-species representation is less than in scenario 1	3
3	Only four or five of the specified groups have at least one representative species, and the species mean can be calculated from at least two results for at least one species in at least three of those groups	6
4	Only four or five of the specified groups have at least one representative species, and the intra-species representation is less than in scenario 1	15
5	The inter-species and/or intra-species representation is less than in scenario 4. Even one acute result for one species can be used if the test procedures (including control and replicate tests) are adequate	100

- Chronic values were based on end-points and exposures appropriate to the species. Full life-cycle tests were selected in preference to partial life-cycle tests.

The chronic value for a particular test was obtained from the geometric mean of the LOEC and the NOEC. In the case where there were insufficient chronic exposure data available to calculate a FCV, an ACR was computed as follows:

- For each chronic value for which there is a corresponding acute value, i.e. the same species and the same substance, the ACR was calculated as:

$$\text{ACR} = \frac{\text{Geometric mean of acute values}}{\text{Geometric mean of chronic values}}$$

and the FCV was calculated as:

$$\text{FCV} = \frac{\text{FAV}}{\text{ACR}}.$$

- For acute and chronic values to correspond, water similarly diluted in both cases had to be used.
- If there was no apparent correlation between the ACR and the SMAV values, and the intra-species ACR differed by less than a factor of 10, with no ACR less than 2, the final ACR was calculated as the geometric mean of the species ACRs.
- If the ACR appeared to be correlated to the SMAV, then the ACR was calculated for species whose SMAVs were close to the final acute value.
- If a species ACR was less than 2 it was interpreted to mean that acclimation had probably taken place and, in order to ensure adequate protection in field situations, it was adjusted to 2.

If none of the above applies, toxicological mechanistic differences probably render the calculation of a meaningful final acute-chronic ratio invalid.

Final plant value

A final plant value is the lowest result of a 96-hour test on an alga or a chronic toxicity test on a vascular plant. In the case of metals, concentrations of strong complexing or chelating agents above about 0.7 μmol l^{-1} were considered to invalidate the results.

Rounding off

For calculation purposes the data were used as reported and no rounding off was performed before the final result was calculated. The criterion values were rounded down to the same number of significant figures as the lowest number of significant figures in the data set.

Application of safety factors

Data generated with the prescribed list of test organisms do not exist for all toxic substances or even for all trace metals. Safety factors — also termed application or extrapolation factors — are selected to compensate for the uncertainties associated with missing information. In the derivation of interim criteria for substances for which data were inadequate, the final values, for example the FAV and FCV, were divided by the safety factor. The fewer data available, the higher the safety factor needs to be.

For the purpose of this study, safety factors were applied in the derivation of national criteria where the available data did not meet the specified data base requirements. Safety factors were mainly applied where the following issues arose:

- lack of data to evaluate inter-species variability;
- lack of information to evaluate intra-species variability;
- lack of adequate chronic toxicity data.

Although safety factors are sometimes used where a lack of data does not allow the evaluation of variability among different organism life stages, this application is not considered here. The majority of fish and invertebrate acute data that were used were for early life stages, and indications are that these stages are generally the more sensitive ones. The degree to which a specific substance is accumulated by aquatic organisms or persists in the aquatic environment is, however, not reflected in the calculation or the application of safety factors for national criteria.

Example: deriving criteria for cadmium

Table 4 contains the toxicological data used for calculating criteria for cadmium, as summarized at the genus level. The data in the table were compiled from species-level information obtained from the AQUIRE data base.[13]

Using the data in Table 4 and applying the procedure in Fig. 2, the following final acute values were calculated:

FAV (excluding cold-water fish) = 13.5 μg l^{-1}
FAV (including cold-water fish) = 5.75 μg l^{-1}

The final chronic value was calculated from the GMCVs. This resulted in FCVs of 0.5 (excluding cold-water fish) and 0.2 μg l^{-1} (including cold-water fish). Since the data set in Table 4 meets with the scenario 1 requirements (Tables 2 and 3), the safety factors for deriving an AEV and CEV are both equal to 1. Therefore the AEV and CEV for cadmium are respectively 6 (13.5/2) and 0.5 μg l^{-1}.

As the effect of water hardness and alkalinity on acute and chronic toxicity to aquatic organisms has been demonstrated, cadmium criteria were calculated in terms of water hardness, according to the following equations:

AEV (excluding cold-water fish) = $e^{(1.128[\ln(\text{hardness})] - 3.284)}$
CEV (excluding cold-water fish) = $e^{(0.7852[\ln(\text{hardness})] - 4.226)}$
AEV (including cold-water fish) = $e^{(1.128[\ln(\text{hardness})] - 4.020)}$
CEV (including cold-water fish) = $e^{(0.7852[\ln(\text{hardness})] - 5.143)}$

Subsequent recommended criteria for cadmium for waters of different hardness are presented in Table 5.

Criteria for some inorganic toxic substances

Changes in hardness, temperature and pH have been accounted for in the derivation of criteria. Where sufficient

Table 3. The guidelines that were followed in applying safety factors for deriving CEVs, where safety factors are applied to the FCV.

Scenario	Chronic data base description	Safety factor
1	ACRs or chronic exposure data are available for at least one species each from at least three different groups (including at least one fish)	1
2	ACRs or chronic data are available for at least one species each from at least three different groups *not* including a fish species	10
3	ACRs or chronic data are available for species from one or two groups	incl. fish – 10 excl. fish – 100
4	Only acute animal or plant data are available (factor applicable to the calculated FAV or FPV)	1000

Table 4. Genus-level chronic and acute toxicity data for cadmium as selected and summarized from AQUIRE.

Taxonomic grouping	GMAV (μg l^{-1})	GMCV (μg l^{-1})	ACR
Cold-water fish			
Oncorhynchus	5.01	3.67	1.37
Salmo	7.37	3.59	2.05
Other fish			
Carassius	8 325		
Cyprinus	215.5		
Gambusia	7 685		
Poecilia	3 570		
Pimephales	30.5	15.2	2
Planktonic crustaceans			
Daphnia	9.9	0.135	65
Moina	40.8		251.
Simocephalus	43.7		9
Benthic crustaceans			
Gammarus	62.6		
Hyalella	204.9		
Insects			
Chironomus	1 200		
Ephemerella	2 130		
Paraleptophlebia	322.8		
Unidentified damselfly	8 100		
Unidentified caddisfly	3 400		
Rotifera, Annelida and Mollusca			
Aplexa	104	4.841	21.
Branchiura	3 018		48
Limnodrilus	2 137		
Physa	157		
Quistradrilus	4 024		
Tubifex	4 024		
Amnicola	3 800		
Nais	1 700		
Algae and plants			
Anabaena flos aquae	120		
Ankistrodesmus	2500		
Chlorella	153		
Euglena	5000		
Lemna	10		
Microcystis	70		
Navicula	310		
Nitzschia	480		
Salvinia	10		
Scenedesmus	168		
Selenastrum	113		

supportive information was found, values were calculated for a range of hardness concentrations. No attempt was made to account for chemical speciation. For mercury, however, it has been assumed that 10% of the total mercury is present in the form of dimethyl mercury(II).

National criteria, that is, criteria for nationwide application, and criteria for cold water-adapted species that were derived in this study are presented in Table 5.

Proposed implementation of national criteria

Analyses and sampling frequency

Toxic substances occur in different forms in water, e.g. in the dissolved state, adsorbed onto suspended particles and as complexes with inorganic and organic substances. Careful attention should, therefore, be paid to the analytical techniques used to measure the concentrations of the substances in water. Inorganic toxic materials can be expressed as acid-soluble or dissolved concentrations. The national criteria are stated as the acid-soluble concentration of the metals present in a grab water sample. This is based on the premise that the acid-soluble fraction of the metals will approximate the total recoverable metal concentration. Since the toxic forms of individual substances often constitute a smaller fraction of the acid-soluble concentration present in water, this approach also provides a safety margin because it assumes that all of the analytically recoverable substance is 'available' to aquatic biota.

Ecological impact is determined not only by the degree with which a substance exceeds its criterion, but also by the frequency and duration of exceedance. It is, however, extremely difficult and often impossible to integrate these factors and quantify their collective effect on the environment. As a rule of thumb, and to retain the protective character of criteria, it is suggested that 90% of measured results should be at or below the CEV, and that concentrations should never exceed the AEV. Non-exceedance of the national criteria should be assessed on the basis of a statistically sound sampling frequency, considering:

- whether sites are outside or within zones of ecological influence of any point-source or diffuse-source discharges;
- the variability in the quantity and quality of such discharges; and
- the hydrological characteristics of the receiving stream.

Site-specific modifications

Under some local conditions, the application of national criteria may not be appropriate. It might be desirable to derive site-specific criteria by modification of national criteria to reflect local conditions, such as water quality, temperature, suspended solid content and ecologically important species. Derivation of site-specific criteria might be required where, for instance:

- Untested locally important species might be sensitive to the material of concern.
- Aquatic organisms in field situations might be stressed by diseases, parasites, predators, other contaminants, contaminated or insufficient food, and fluctuating or extreme conditions of flow, water quality and temperature.
- Some substances might degrade to more toxic materials.
- Important ecosystem functions or species interactions might be adversely affected by concentrations lower than those that affect individual species.
- Natural background concentrations may be higher than the national criteria.
- Socio-economic considerations may dictate that national criteria are not practically achievable.

Natural geological and physical characteristics of an area affect the concentrations and the transportation of substances in the aquatic environment. Generally, South African rivers are highly turbid, compared with rivers in the Northern Hemisphere, where most of the available toxicity data have been generated. Standard test waters generally are more representative of clear waters than of the more turbid South African examples. Modifications to the national criteria may, therefore, be allowed on a site-specific basis to take account of locally elevated levels of suspended sediments.

However, it must first be conclusively proved through field and laboratory studies that the local water quality characteristics will lead to a decreased bioavailability of the metal of concern, through, for example, increased adsorption on particulate matter. Furthermore, it has to be proven that such a decrease in bioavailability holds for the river farther downstream and is not brought

Table 5. Criteria for protecting aquatic ecosystems in South Africa. Values in parenthesis indicate the safety factors that were applied to compensate for lacking data.

Substance	Hardness (mg $CaCO_3$ l^{-1})	National criteria (µg l^{-1}) AEV	National criteria (µg l^{-1}) CEV	Criteria for cold-water-adapted species (µg l^{-1}) AEV	Criteria for cold-water-adapted species (µg l^{-1}) CEV
Al	90	10	1(10)	10	1(10)
NH_3(aq)	90	100	30	50	10
As	90	130	20	130	20
B	90	10(1000)	1(1000)	10(1000)	1(1000)
Cd	<60	3.0	0.30	1.8	0.15
	60–119	6.0	0.50	2.8	0.19
	120–180	10	0.70	5.1	0.29
	>180	13	0.80	6.2	0.34
Cl_2	90	1(6)	0.1	1(6)	0.1
Cr(III)	90	340(3)	24	340(3)	24
Cr(VI)	90	200	14	200	14
Cu	<60	1.6	0.53	1.6	0.53
	60–119	4.6	1.5	4.6	1.5
	120–180	7.5	2.4	7.5	2.4
	>180	12	2.8	12	2.8
CN	90	110	4	35	1
F	90	7 000	100(10)	7 000	100(10)
Pb	<60	4.0	0.50	4.0	0.50
	60–119	7.0	1.0	7.0	1.0
	120–180	13	2.0	13	2.0
	>180	16	2.4	16	2.4
Hg	90	1.7	0.08	1.7	0.08
Mn	90	1 300	370	1 300	180
Mo	90	439 (100)	40	439 (100)	40
Se	90	30(3)	5	30(3)	5
V	90	1120 (100)	662	1120 (100)	662
Zn	90	36	3.6(10)	36	3.6(10)

about through some unique set of physical or chemical conditions peculiar to the point of measurement.

Where the application of site- or case-specific modifications can be justified, a 'water-effect ratio' should be calculated for the specific substance tested. The water-effect ratio is the acute (or chronic) value of a substance in the local site water divided by the acute (or chronic) value found in the laboratory water. This factor can either increase or decrease the water quality criterion. At least one fish and one invertebrate species, and approved testing procedures, should be used for the calculation of water-effect ratios.[15]

Discussion

Numerical water quality criteria represent a first step in estimating the concentrations of toxic substances that may be tolerated by aquatic ecosystems. These criteria are intended to be used independently of water quality management policy, in combating pollution through evaluating the condition of water bodies and deriving discharge standards.[16]

Whereas criteria are based on the results of scientific experimentation and a rigid calculation procedure, the development of effluent discharge standards might have to take into account additional factors. Social, legal, economic and hydrological considerations, environmental and analytical chemistry of the substance, extrapolation from laboratory data to field situations and relationships between species for which data are available and species in the body of water of concern may have to be considered.

The fact that criteria for the protection of aquatic ecosystems are derived from the results of biotoxicity tests provides a degree of environmental realism and applicability. A number of limitations are, however, associated with the use of the numerical values. These limitations relate primarily to pharmacodynamic and environmental interaction effects, and include:[17–19]

- mechanistic similarities between different substances which will result in additive, synergistic or antagonistic effects;
- the relationship between the level and duration of exposure and the resulting effect, which is necessary to quantify the allowable excursions above the criteria;
- the environmental partitioning under various chemical and physical water conditions which induce change in the bio-availability of a substance and hence in the ecological risk associated with that substance;
- photo- and chemical degradation/transformation processes which may increase or decrease the toxicity of a substance (this in more applicable when dealing with organic compounds);

Further limitations relate to the design of toxicity tests and the nature of the resulting toxicological data. These may arise when:

- Data from a limited number of species, often determined by their ease of laboratory culturing, are used.
- Single-species rather than multi-species or community responses are used.
- Sediment–water interactions and the quality of bottom sediment are ignored (sediments are as a rule not incorporated into experiments).
- The joint toxic action of related and unrelated substances on aquatic species are not addressed. The understanding of the kinetics and dynamics involved when organisms are exposed to mixtures is limited.
- The impact of persistent or bio-accumulative substances on predator species, including man, feeding on other aquatic species is not fully addressed.

Even with their limitations, numerical criteria provide some of the best management tools available to water quality managers. In terms of aquatic ecosystems, however, they are of limited use since they address the water column alone, which forms only one compartment of the system. For the effective management of aquatic ecosystems, all these compartments, including bottom sediment, in-stream habitat and riparian zones must be accounted for. Several relevant monitoring and management instruments are currently under development in South Africa. These include in-stream biological monitoring, toxicological assessments of whole-effluent and estimation of in-stream flow requirements. Only the successful integration of these instruments and the correct application of the resulting information will ensure the sustainable use of the country's water resources.

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Research Letters

The incidence of IgA deficiency amongst blood donors in KwaZulu-Natal

The development of three immunoassays to assess the IgA and anti-IgA status of the KwaZulu-Natal blood donor population is reported. IgA deficiency was detected using a competitive enzyme-linked immunoassay and a quantitative ELISA was used to determine the IgA concentration. A third immunoassay was used to establish the incidence of antibodies to this immunoglobulin in the plasma of IgA-deficient donors. This survey showed that 0.1% of donors had an IgA concentration of less than 20 mg l^{-1}, that is, IgA deficient, and this frequency was similar for all race groups. Antibodies to IgA were detected in 19% of the deficient donors. These immunoassays may be used to establish a special IgA-deficient donor panel should the need arise.

Selective IgA deficiency is not uncommon, varying from 1:440 to 1:6500 in different population groups,[1] and is one of several manifestations reflecting a basic defect in the immunoregulatory system.[2] People deficient in IgA are at risk of producing anti-IgA antibodies after receiving blood or blood products and subsequent exposure to these products may result in anaphylactic reactions.[3] Obviously, individuals at risk should be identified where possible but, to our knowledge, the incidence of IgA deficiency in South Africa has never been studied.

In order to carry out such a survey, assays for the detection of IgA deficiency and its quantitation were initially developed. Since it is the presence of anti-IgA in the circulation of IgA-deficient patients which actually triggers anaphylactic shock, we also developed an assay to detect these antibodies specifically and used it to establish the anti-IgA status of our IgA-deficient donors.

One of the major problems when considering screening for anti-IgA is the production and availability of purified IgA protein as a test antigen. However, by exploiting the specificity of the lectin jacalin O for IgA1 (IgA1 comprises about 90% of total IgA in human blood), we were able to provide a facile tool for the isolation of this immunoglobulin. The highly purified IgA was then utilized in two ways; in the development of an ELISA to detect antibodies to IgA and, secondly, to raise monoclonal and polyclonal antibodies against IgA. The monoclonal antibodies were used to develop a competitive enzyme-linked immunoassay (CELIA) for the screening of IgA in donated blood. A conventional ELISA employing both the monoclonal and polyclonal anti-IgA was established to quantify the very low levels of IgA sometimes present in these specimens.

Materials and methods

Cobalt-irradiated 96-well microtitre plates (Greiner) were obtained from Laboratory and Scientific, Durban, and horseradish peroxidase, suitable for conjugate production, was a product of Boehringer Mannheim. Pristane (2,6,10,14-tetramethylpentadecane) was from Aldrich Chemical Company and α-D-galactose from Sigma Chemical Company. Protein A insolubilized on 4% agarose was a product of Bioprocessing, Durham, UK. Polyclonal sheep anti-human IgA was obtained from the Natal Institute of Immunology. All other chemicals used were of analytical grade.

Isolation and insolubilization of jacalin. Seeds from the jackfruit tree (*Artocarpus integrifolia*) were collected from trees growing in the Botanical Gardens, Durban, and jacalin was extracted as follows: Jackfruit seeds (410 g) were homogenized in 1350 ml 0.05 M phosphate–0.1 M NaCl buffer, pH 7.2 (PBS), and stirred overnight at 4°C. The homogenate was clarified by centrifugation for 30 min at 5000 × *g*. The crude jacalin was precipitated from the supernatant by adding solid ammonium sulphate to a final concentration of 2.4 M. The precipitate was recovered by centrifugation at 5000 × *g* for 30 min and dissolved in 450 ml of distilled water. Redissolved precipitate was dialysed extensively against several changes of distilled water and a brown precipitate removed by centrifugation and the supernatant lyophilized (yield 5.5 g).

The jacalin (750 mg) was insolubilized onto 150 ml of cyanogen bromide-activated Sepharose CL-4B according to the method of March *et al.*[4]

Isolation of IgA. Jacalin-agarose (150 ml) was packed into a glass chromatography column (2.5 × 50 cm) and equilibrated in