The development of water quality methods within ecological Reserve assessments, and links to environmental flows

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Abstract

In the South African National Water Act (NWA, No 36 of 1998), the ecological Reserve is defined as the quality and quantity of water required to ensure appropriate protection of water resources, so as to secure ecologically sustainable development and use. Aquatic ecosystems are recognised as the core location of water resources, and although considerable progress has been made in developing methods for quantifying environmental flow requirements, this paper describes and discusses the first agreed method for quantifying environmental water quality requirements in an ecological Reserve assessment. Integration of flow and water quality is emphasised, and is based on the philosophy that environmental flows should be motivated to provide ecologically important flow-related habitat, or geomorphological function, but should not be motivated to solve water quality problems by dilution. Water quality is multivariate, and not all variables can be considered in an ecological Reserve assessment, but core water quality variables include: system variables (salts, dissolved oxygen, turbidity, temperature), nutrients (phosphate, nitrite, nitrate) and toxic substances (those listed in the South African Water Quality Guidelines for Aquatic Ecosystems, including toxic metal ions, toxic organic substances, and/or substances from a chemical inventory of an effluent or discharge). In addition, biological indicator data (e.g. SASS data), chlorophyll-*a* (e.g. phytoplankton and periphyton data) and toxicity test data may be used. For each variable, a concentration range or response is linked to a class within a water resource classification system, where classes range from minimally to severely modified. There are five main stages in the environmental water quality method:

- Initiate study and determine scope of assessment.
- Delineate water quality sub-units.
- Select sites and collect data and information.
- Determine benchmarks, including generic boundary values (literature-based concentrations related to classes); the unimpacted, natural or reference condition; the present ecological state; and the contribution of water quality to the overall ecosystem importance and sensitivity.
- Provide quantified and qualitative water quality objectives for each ecosystem health class, and each variable in each resource unit. These steps are integrated with environmental flow assessment procedures. After environmental flows have been recommended to achieve a selected level of protection (class), flow-concentration relationships are modelled, and the likely water quality consequences of modified flows are provided to resource managers, who then decide on whether to allocate water for dilution and/or to address the pollution problem directly using source controls.

Keywords: environmental water quality, environmental flow requirements, ecological Reserve, water resource management

Introduction

The ecological Reserve

The two founding principles of the South African National Water Act (No. 36 of 1998) (NWA) are "sustainability" and "equity" (NWA, 1(1)(xviii)(b)). These principles are supported by acknowledging that the water cycle is an integrated process and should be managed as such. Particular attention should be paid to integration between water quality and quantity; ground- and surface water; and between rivers, impoundments, wetlands and estuaries. In the NWA there are only two rights to water:

- Water for drinking, cooking and hygiene
- Water for sustainable ecosystems.

All other water (for industry, agriculture, domestic use and waste disposal) is allocated to water resource users by licence or general authorisation. The two water rights are provided for by the *Reserve,* comprising the basic human needs Reserve and the ecological Reserve, and this paper deals only with the latter.

Environmental goods, services and classification

In any developing country, the optimal use of natural resources for sustainable economic activity is essential (Howarth and Farber, 2002). It is therefore necessary to provide people with choices, and information about the goods and services offered by aquatic ecosystems (Palmer et al., 2002; 2004). The NWA provides for a water resource classification system, and a preliminary classification is being used in ecological Reserve determinations (Jooste and Rossouw, 2002; DWAF, 2004; Hughes, 2004). The classification system aims to optimise sustainable water resource use, by providing an organised basis for identifying and selecting "ecological health", and for setting descriptive and quantified resource quality objectives. Each class can be

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TABLE 1
River health and integrity classes in relation to ecological and management perspectives (Roux, 2004)
(This is the personal opinion of Roux. It is not generally accepted and used in the technical determination of the ecological Reserve and is provided as an example study only. The RDM documentation (Vers 1.0; DWAF, 2003) does provide information on the ecological and biological integrity/health levels based on biological responses)

Class	Ecological perspective	Management perspective
Natural	Minimal or negligible modification of in-stream and riparian habitats and biota. The best Natural rivers are in the Reference or unmodified condition.	Protected rivers; relatively untouched by humans; no effluent discharges or impoundments.
Good	Ecosystems essentially in good state; biodiversity largely intact.	Some human-related disturbance but mostly of low impact potential.
Fair	A few sensitive species may be lost; lower abundances of biological populations are likely to occur, or sometimes, higher abundances of tolerant or opportunistic species occur.	Multiple disturbances associated with need for socio-economic development, e.g. impoundment, habitat modification and water quality degradation.
Poor	Habitat diversity and availability have declined; mostly only tolerant species present; species present are often diseased; population dynamics have been disrupted (e.g. biota can no longer breed or alien species have invaded the ecosystem).	Often characterised by high human densities or extensive resource exploitation. Management intervention is needed to improve river health (e.g. to restore flow patterns, river habitats or water quality).

linked to a range of goods and services including: water supply; waste transport, processing and dilution; natural products (e.g. reeds, fish, medicinal plants); nature and biodiversity conservation; flood control; recreation; aesthetic needs; and sites for religious rituals or spiritual needs (Palmer et al., 2002; 2004). Aquatic ecosystems can, if managed appropriately, continue to supply people with these goods and services into the future, and therefore implementation of the NWA involves "resource protection to ensure sustainable resource use" (DWAF, 1997).

However, aquatic ecosystems cannot offer the whole range of goods and services at the same time in the same place. For example, if heavy use is made of water supply and waste disposal – then the ecosystem is unlikely to provide well for nature conservation, recreation or "a sense of place". Therefore people need to be able to choose which services they want from which ecosystems in time and space. The degree of "naturalness' of an ecosystem is equated with ecosystem integrity and health, where ecological integrity is "the full range of elements and processes expected in the natural habitat of the region" (Karr, 1996) and ecosystem health goes further, and incorporate human uses and values (Downes et al., 2002). The underlying assumption is that completely natural systems have the highest possible level of ecosystem integrity in terms of both structure (habitat and species composition) and function (processes such as carbon breakdown, photosynthesis and respiration) (Allan, 1995). Use of aquatic ecosystems, especially for water abstraction and waste disposal, generally results in a deterioration of ecosystem integrity and health. The classification system spans ecosystem integrity from "natural" to "degraded" and provides an objective framework for recommendations and preferences to be articulated by stakeholders, managers and specialists, and for decisions to be made by government (as the custodian of the resource), about the kinds and degrees of aquatic ecosystem use.

A variety of classification approaches have been reviewed (Uys, 1994). The classification system currently in use ranks ecosystem health along a continuum, or gradient, from natural/excellent to poor. "Fuzzy" boundaries are imposed to categorise the gradient, and descriptions are provided of the central characteristics of four classes/categories: Natural/Excellent, Good, Fair and Poor (Jooste and Rossouw, 2002; DWAF, 2004; Hughes, 2004). Each of the classes is associated with a level of ecosystem health and integrity (Table 1), and the potential to offer a particular range of goods and services (Palmer et al., 2002; 2004). This classification is related to the A - F categories used in early ecological Reserve determinations (DWAF, 2001). In the ecological Reserve determination process for water quality, each class is quantified by boundary values distinguishing adjacent classes (Palmer et al., 2004). There are also classification procedures for macroinvertebrates, fish, aquatic plants, geomorphology, and flow (DWAF, 1999; 2003). Where data do not allow quantified ranges, qualified descriptors may be included.

Water quality in an ecological Reserve assessment

The task of the flow component of an ecological Reserve assessment is to provide both quantified and descriptive information about the pattern and reliability of environmental flows, with information on frequency, magnitude and duration, so that an entire modified flow regime can be provided (King et al., 2000). However methods for quantifying environmental water quality still focus on only magnitude (concentration), and frequency and duration are only taken into account via flow-concentration modelling (Malan and Day, 2002; Malan and Day, 2003; Malan et al., 2003). During an ecological Reserve assessment, the ecological Reserve for water quality is provided as class boundary-value concentrations for each variable (for example, Table 2 shows the default boundary values for salts). From the many possible water quality variables, the initial suite to be considered in South Africa includes: inorganic salts (sodium chloride, sodium sulphate, magnesium chloride, magnesium sulphate, calcium chloride, calcium sulphate); nutrients (phosphate as PO_4^{-3}, and total inorganic nitrogen); physical variables (turbidity, pH, oxygen, and temperature); and those toxic substances listed in the *South African Water Quality Guidelines for Aquatic Eco-*

systems (DWAF, 1996). In addition, bioassessments such as the aquatic invertebrate index SASS (Chutter, 1998; Dickens and Graham, 2002), algal abundance (Barbour et al., 1999) and toxicity tests (Slabbert et al., 1998; Slabbert, 2004; Palmer and Scherman 2000; Scherman et al., 2003), will be undertaken (Palmer et al., 2004).

TABLE 2
The default benchmark category boundaries for inorganic salts (Jooste and Rossouw, 2002; Palmer et al., 2004, Appendix 1). Any concentration higher than the Fair boundary value would be considered as "Poor" and management response would be to manage towards an improvement to at least to a Fair state.

Variables	Natural boundary (mg/ℓ)	Good boundary (mg/ℓ)	Fair boundary (mg/ℓ)
$MgSO_4$	16	27	37
Na_2SO_4	20	36	51
$MgCl_2$	15	33	51
$CaCl_2$	21	63	105
NaCl	45	217	389
$CaSO_4$	351	773	1195

General

The products of an ecological Reserve assessment are quantified and descriptive resource quality objectives (RQOs). These endpoints are linked to the complexity of ecosystem structure and function through components that assess habitat (hydraulic and geomorphological), biota (fish, invertebrates, vegetation - riparian and in-stream), and the responses of biota to the stress of altered flow and chemical variables (O'Keeffe et al., 2002). Although environmental flows are commonly provided for in many countries (King and Tharme, 1994), the effects of reduced, or altered flows, in relation to stable or increasing waste discharge and non-point source pollution are seldom considered. The most common approach to environmental water quality protection is through protective water quality guidelines (Hart et al., 1999). The new *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC and ARMCANZ, 2000) do allow for the selection of levels of resource protection, but do not link these to environmental flows. One aim of this paper is to outline a preliminary approach by which environmental water quality requirements can be managed in conjunction with environmental flows to achieve sustainable water resource management.

Water quality procedure

The procedure outlined here was derived from the DWAF (1999) draft manual, further developed by the DWAF ecological

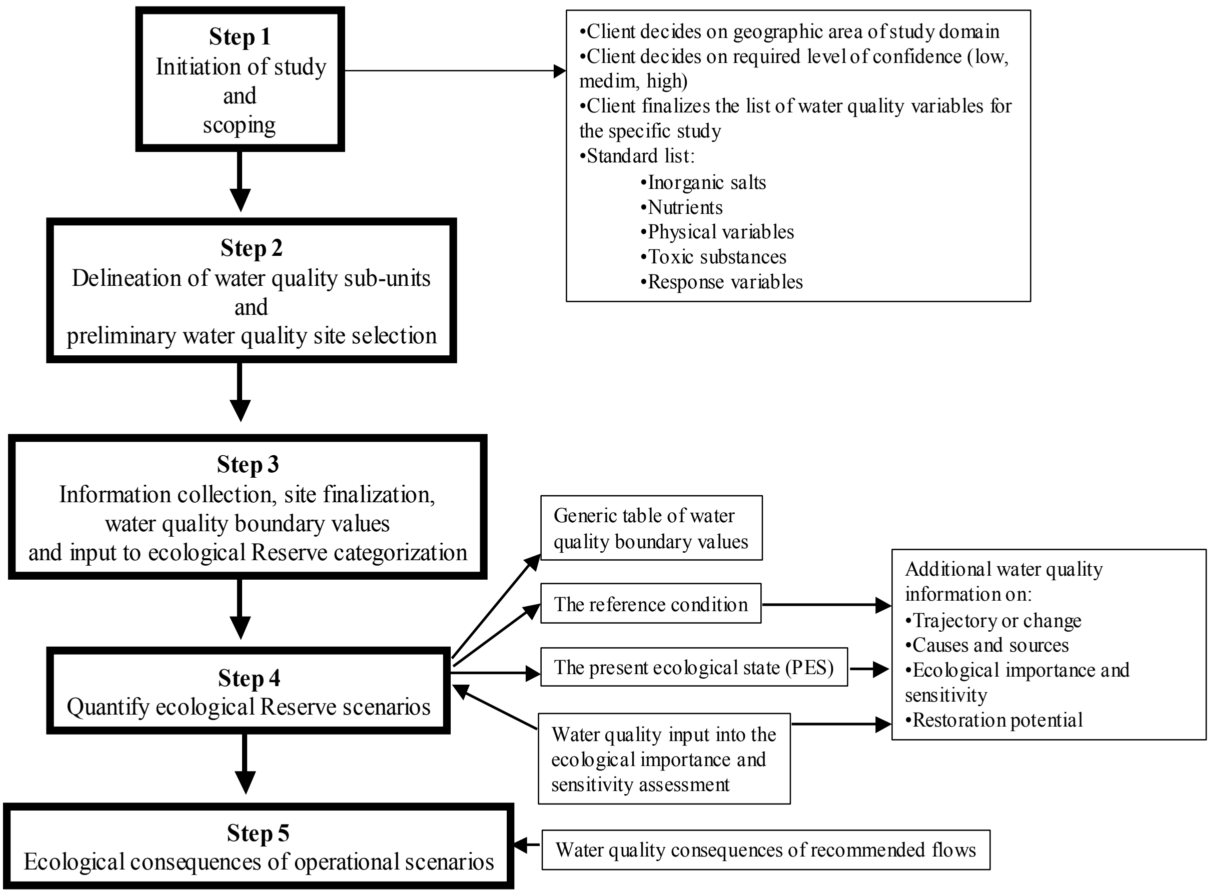

Figure 1
Roadmap of the five key steps for assessing water quality in an ecological Reserve assessment for rivers

Reserve water quality team over several ecological Reserve studies and will appear in the next methods manual. The detailed methods currently in use are provided in Palmer et al. (2004), and the general ecological Reserve process is outlined in the *Resource Directed Measures (RDM) Module 1: Introductory Module* (DWAF, 2003). The assessment of water quality in ecological Reserve assessments for rivers requires that each water quality constituent is described according to the method below (outlined in Fig. 1) and followed by a step-wise summary of water quality data analysis.

Step 1 Initiate study and scoping

Study domain

This is the geographic scope of the study area, including the length of river, and the tributaries to be considered. It is important to include tributaries with water quality that is naturally or anthropogenically different from the main stem of the river since poor water quality can cause "hot spots", and good water quality can provide biotic "refugia" and recolonisation sources (DWAF, 2001). For example, in the Olifants River (Gauteng and Mpumalanga), the Wilge and Blyde Rivers act as refugia, respectively protecting the main stream from the polluting effects of low pH, metal toxicity and salinisation in the upper catchment, and the landscape degradation effects of salinisation and turbidity in the lower catchment. Further abstraction of water from, or additional discharges into, the Wilge or the Blyde Rivers would significantly threaten the ecological health of the Olifants River. In the case of the Blyde River this has implications for the Olifants River as it flows through the Kruger National Park (DWAF, 2001).

Level of confidence (high, medium, low)

The results of an ecological Reserve assessment can have differing levels of confidence, depending on the quality and extent of the available data. The quality of the data depends on the regularity and accuracy of monitoring programmes; the capacity to collect additional field and/or laboratory data specifically for the ecological Reserve assessment; and the availability of appropriate modelling tools. Depending on the constraints of the budget, available time and the quality of existing data, ecological Reserve assessments can be undertaken so as to produce high, medium or low confidence results. The criteria for confidence are provided in Palmer et al. (2004).

Finalisation of water quality variables for the specific study

The standard suite of variables is usually considered: inorganic salts (sodium chloride, sodium sulphate, magnesium chloride, magnesium sulphate, calcium chloride, calcium sulphate); nutrients (total inorganic nitrogen and soluble reactive phosphorus); system variables (dissolved oxygen, turbidity, temperature); toxic substances (those listed in the *South African Water Quality Guidelines for Aquatic Ecosystems* (DWAF,1996) and/or substances from a chemical inventory of an effluent or discharge); and biological indicator data (e.g. SASS data), chlorophyll-*a* (phytoplankton and periphyton data) and toxicity test data (Palmer et al., 2004). There may be additional specific variables of concern, for example, because of local geology, or because of discharges and impacts. Additional variables, such as pesticides, can be motivated on a site-specific basis.

Step 2 Delineation of water quality sub-units and preliminary water quality site selection

A water quality sub-unit is a length of river for which a single description of water quality can be given. This needs to apply both to natural, unimpacted streams and to impacted streams. For example, the natural water quality of the upper reaches of rivers is often different from the lower reaches, and therefore eco-regions and different eco-region levels (Kleynhans, 1999), are used to indicate water quality sub-unit boundaries. Additional water quality sub-unit boundaries are needed because certain impacts change the present water quality, and therefore dams, tributaries, towns and pollution point-sources need to be considered as appropriate sub-unit boundaries. Preliminary water quality monitoring points are identified.

Step 3 Information collection, site finalisation, water quality boundary values and input to ERC categorisation

Sites for data and information collection within water quality sub-units are verified and mapped, and each water quality sub-unit is described by a set of water chemistry and bioassessment data. Where there are inadequate data that are appropriate to that sub-unit then data from another water quality sub-unit that is judged to be sufficiently similar are used. For example in the Olifants River, adjacent sub-units were amalgamated and considered as a longer water quality sub-unit with the same resource quality objectives (DWAF, 2001). Alternatively, water quality data from an adjacent catchment can be used provided it is in the same ecoregion.

Step 4 Quantify ecological Reserve scenarios

Benchmarks (or boundary values) comprise the key quantitative values, and qualitative narrative descriptions, that comprise the water quality component of an ecological Reserve assessment. The generic benchmark boundary values are used to evaluate reference condition and present ecological states to quantify the ecological Reserve scenarios.

Generic class / boundary value tables

These are a set of generic tables, derived from the literature, which describe and/or quantify the boundary values between classes for each water quality variable (Jooste and Rossouw, 2002; Palmer et al., 2004). These generic values will be most accurate where the reference or natural state is consonant with the generic value. Where the natural state is different, the difference must be ascertained and the boundary value changed appropriately (refer to section on water quality data analysis). If the generic tables are used without checking their similarity to the natural state of the study area the ecological Reserve assessment will have a low confidence.

Reference condition

The reference, or natural, condition provides the benchmark against which to judge the class boundaries, and the present state, of each aspect of the water quality of the water quality sub-unit (refer to section on water quality data analysis). The reference condition is the first benchmark to be adjusted on a site-specific basis after site-specific data are checked against the generic boundary value tables. The reference or natural condition is described using either pre-impact data, or using data from unimpacted sites. The natural boundary equals the reference condition.

In many water quality sub-units, and particularly in the lower reaches of rivers, there are no unimpacted sites, and reference conditions are difficult to infer. Data may be used from neighbouring catchments within the same ecoregion or any acceptable approximation of the natural condition.

Present ecological state (PES)

The PES is the measured, current water quality for each water quality sub-unit and provides the point of departure for the development of any management objectives (refer to section on water quality data analysis). Chemical and biotic response data are linked to a class (Natural, Good, Fair, or Poor). Preferably data from 1 to 3 years prior to the assessment of the PES are used. If the data record is poor (e.g. less than monthly sampling frequency), then data from up to, but no longer than, 5 years prior to the assessment can be used.

Classification on the basis of the water chemistry may be misleading because water chemistry data are not continuous. Bioassessments offer a time-integrated indication of possibly unmeasured chemical conditions. For example, excessive algal growth (indicated by periphyton and phytoplankton chlorophyll-*a* concentrations) is indicative of nutrient enrichment and poor macroinvertebrate diversity (e.g. indicated by poor SASS scores) may indicate instream toxicity (Palmer et al., 2004).

If the results of the bioassessments are not consistent with the water chemistry (i.e. they indicate a different ecosystem health class), then there is a need for interpretation and adjustment of the concentration-class relationship. For example, if the presence of algal growth indicates a lower class than is indicated by the measured nutrient values, then nutrients should be described by the lower class; and/or in any water quality sub-unit where an SASS class is lower than the class indicated by water chemistry variables, an instream toxicity assessment is needed. If there is an indication of toxicity from response data, or from a chemical inventory, then a full toxicity assessment should be undertaken (DWAF, 2001).

Ecological importance and Ecological sensitivity

If an ecosystem is deemed to be of specific ecological importance or sensitivity this provides motivation for the selection of a management class with a higher level of ecological integrity (for example, Good or Natural condition). Water quality data are used in the importance and sensitivity procedures of Kleynhans (1999), where the value of the natural water quality in relation to conservation status of the river, and its role in society, are assessed.

Step 5 Describe ecological specifications for each class

Quantitative specifications (boundary values)

The quantitative ecological specification is a table that specifies the water quality for a water quality sub-unit (refer to section on water quality data analysis). Details in the table include: the Natural/Excellent, Good, Fair and Poor boundary values for each variable examined in the assessment; the level of confidence (low, medium or high) associated with each variable; and any comments required to clarify the boundary values that have been specified for the level of confidence for each variable.

Qualitative specifications

The qualitative ecological specifications are a narrative description that links the quantitative ecological specifications to site-specific information. During the assessment of the ecological water quality requirements, the water quality specialists gain insights about the water quality behaviour of the river system (for example, the role of refugia and hot spots in tributaries or from point sources (DWAF, 2001). These insights may not be captured in the quantitative ecological specifications for water quality, and this step provides the opportunity to document these insights in a descriptive but concise manner.

Water quality data analysis

The data analysis protocol for undertaking an ecological Reserve assessment for water quality is detailed in Palmer et al. (2004, Appendix A), and summarised in the list of steps that follows. These steps can be followed independently or using "SPATSIM" (Spatial and Time Series Information Modelling) software (Hughes, 2004; currently SPATSIM assumes that data are obtained from DWAF and the software designed to analyse data obtained in this format).

1 **Obtain relevant water quality data:**

- A water quality assessment requires that all available water quality data be assessed for inclusion in the Reserve study. However, not all monitoring point data are suitable or appropriate for inclusion in an assessment: sampling frequency, knowledge of the catchment and professional judgement are used to assess whether data from particular monitoring points are to be included.
- Include monitoring points in all water quality sub-units.
- Water quality data required to undertake a water quality ecological Reserve assessment are:
  - o Calcium, magnesium, potassium, sodium, chloride, sulphate, ammonia, nitrate and nitrite, phosphorus, pH, dissolved oxygen, turbidity, temperature, toxic substances listed in the South African Water Quality Guidelines for Aquatic Ecosystems (DWAF 1996), including toxic metal ions, toxic organic substances, and/or substances from a chemical inventory of an effluent or discharge, biological indicator data (e.g. SASS data), chlorophyll-*a* (phytoplankton and periphyton data) and toxicity test data.
  - o Not all the above listed variables will be available for all water quality monitoring points and not all water quality variables are obligatory for an ecological Reserve assessment for water quality.
  - o Although not a requirement for comprehensive ecological Reserve assessments, it may be useful to obtain conductivity (EC; mS/m) and total dissolved salt (TDS; mg/ℓ) data.
  - o It may be appropriate to include water quality data from dams, especially if water samples are taken from the outflow of the dam.
- Data recorded as below detection limits (denoted by a "<") should not be considered as missing data. Statistically, it is deemed appropriate to convert these data to half the detection limit value.
- Total inorganic nitrogen (TIN) values need to be calculated.
- Individual salt concentrations (obtained by reconstituting ion data) need to be calculated. A model for doing this can be obtained from DWAF (Jooste, 2004).

TABLE 3
Water quality data requirements to undertake the water quality component of an Ecological Water Requirements (Rivers) assessment (EWR: Rivers) (Palmer et al., 2004). (*indicates that the water quality variable is optional for an EWR: Rivers)

Water quality variables	Reference condition	Present ecological state
Inorganic salts:		
Data: Ca, Mg, K, Na, Cl, SO_4 **Calculate inorganic salt concentrations:** $MgSO_4$, Na_2SO_4, MgCl, $CaCl_2$, NaCl, $CaSO_4$ **Data analysis:** $MgSO_4$, Na_2SO_4, MgCl, $CaCl_2$, NaCl, $CaSO_4$	Calculate 95% of reference data.	Calculate 95% of present state data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Nutrients:		
Data: NH_4, NO_2+NO_3, PO_4 **Calculate TIN** (NH_4+NO_2+NO_3) **Data analysis:** TIN and SRP	Calculate 50% of reference data.	Calculate 50% of present state data.
	Compare to default boundary values.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Adjust accordingly using Chl-*a* data. Calculate confidence level.
System variables:		
DO	Calculate 5% of reference data.	Calculate 5% of present state data.
	Compare to default boundary values.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
pH	Calculate 5% and 95% of reference data.	Calculate 5% and 95% of present state data.
	Compare to default boundary values.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Turbidity*	Method not yet developed.	Method not yet developed.
Temperature* **Data:** If no water temperature available, calculate daily water temperature from air temperature	Calculate monthly 10% and 90% of reference data.	Calculate monthly 10% and 90% of present state data.
	Calculate the upper and lower boundaries of the categories.	Compare to boundaries obtained for reference condition.
	Summarize results in benchmark table.	Assign category. Calculate confidence level.
TDS / EC	Method under development.	Method under development.

2 **Ascertain which monitoring points and relevant data are to be used for reference condition assessment and which data are to be used for present ecological state assessment:**

- Ecological Water Requirements (Rivers) assessments for water quality require that an assessment be made of reference (unimpacted) condition. This is to benchmark the default boundary values provided in the methods (Palmer et al., 2004, **Appendix 1**) for the categories and determine whether natural background levels are different from those values provided. In the event that they are, the values in the benchmark tables need to be recalibrated so that an accurate assessment of the present ecological state can be undertaken.
- Data obtained from water quality monitoring points are used to determine both reference condition and present ecological state. The confidence level of the assessment is determined by the sample size and the method describes a statistical procedure to calculate this.
    - o Data obtained from water quality monitoring points which have been operational for several decades may be

TABLE 3
(continued)

Toxic substances:		
Data: NH_3 (calculate from NH_4 data), Al, As, Atrazine, Cd, Cr, Cu, Cyanide, Endosulfan, F, Pb, Phenol, Hg	Calculate 95% of reference data.	Calculate 95% of present state data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Biological response variables		
SASS **Data:** SASS scores and ASPT scores	Assess whether ASPT score from Reference site is >5% different to default Natural boundary.	Compare ASPT scores from resource unit with relevant boundary table.
	Recalibrate boundary if necessary.	Assign category.
CHL-*a** **Data:** Phytoplankton (µg/ℓ) and periphyton (mg/m²)	Calculate 50% of reference data	Calculate 50% of periphyton data and mean of phytoplankton data.
	Compare to default boundary table.	Compare to relevant boundary table.
	Recalibrate boundary table if necessary.	Assign category. Calculate confidence level.
Toxicity	Method not yet developed.	Method not yet developed.

appropriate for reference condition assessment. This can be ascertained by plotting the concentrations of appropriate water quality variables over time and determining whether there is a detectable trend over time. If there is a trend, the earlier part of the record may be appropriate for reference condition determination (i.e. pre-impact data) while the more recent data record may be appropriate for a present ecological state assessment.

- o There may be a water quality monitoring point upstream of any impacts in the resource unit which may be suitable for reference condition assessment. In this case, the more recent data record can be used.
- o Assess whether it is necessary, and appropriate, to use water quality data from dam outflow.
- o Although not specified by the method, box-and-whisker plots of monthly medians, 25% and 75% of selected water quality variables provide a useful visualisation of seasonal changes, and provides the necessary information required for flow-concentration modelling.

3 **Undertake the necessary calculations and analyses:**
A list of the necessary analyses to be undertaken in an ecological Reserve assessment for water quality is summarised Table 3, alongside the necessary water quality variable requirements.

4 **Report results:**
It is important that all procedures, results and scientific decisions are recorded for future reference.

Integration of water quality with environmental flow assessment

In South Africa, there are three accepted methods for ecological/environmental flow assessments for rivers, the Building Block Methodology (BBM) (King et al., 2000); the Downstream Response to Imposed Flow Transformations (DRIFT) method (King et al., 2003) and the flow stressor-response (O'Keeffe and Hughes, 2004). The water quality assessment procedure fits into all three methods (Fig. 2).

The results of Steps 4 and 5, including water quality data analysis are used to write a water quality starter-document, for use in the ecological Reserve workshop. Simple flow-concentration modelling can also be undertaken (Malan and Day, 2002). The BBM, stressor-response and DRIFT reports will include the relationship between flow and concentration, medium- to long-term trends in concentrations; the probable causes of water quality impacts; possible water quality management options, and the likely ease of implementation. The BBM and stressor-response methods require quantitative and qualitative objectives for water quality, related to each ecosystem health class; and the DRIFT method requires a list of water quality variables and a systematic classification of how each variable can change in relation to flow changes.

At the workshop, a group of specialists (in hydrological modelling, hydraulic modelling, geomorphology, riparian and in-stream habitat integrity, fish ecology, aquatic invertebrate ecology, riparian vegetation, social anthropology and water quality) collaborate to define the flow and water quality requirements for river resource units to function at different level of ecosystem health. The water quality specialist provides information on the probable water quality consequences that result from particular flow reductions or increases. These consequences are reported in terms of chemical, biotic and toxicological responses to flow changes. In each resource unit, a modelled modified flow regime (Hughes, 2001; 2004) is provided for each ecosystem health class. An ecosystem health class that is attainable through management, and is consistent with the ecological sensitivity and importance of the unit, is recommended as the management goal for each resource unit.

Modified flow regimes are modelled with different flow assurances, which are also related to water quality consequences.

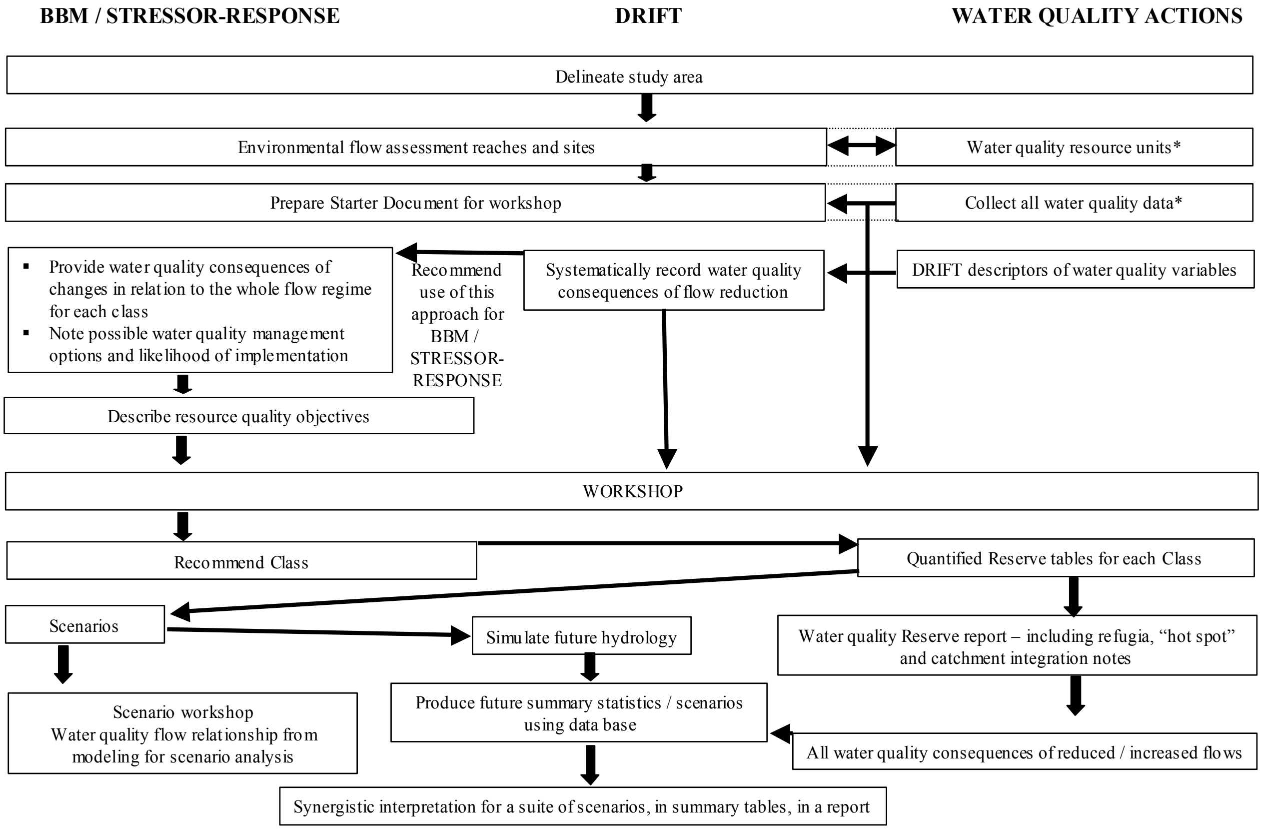

Figure 2
Water quality actions (steps) feed into environmental flow assessment methods (DRIFT King et al., 2003), BBM (King et al., 2000) and flow stressor-response (O'Keeffe et al., 2004), and result in an integrated ecological Reserve assessment.
**The steps for the identification of water quality sub-units and the procedure for data collection are described in the text.*

In the BBM and stressor-response methods these alternatives are evaluated at a scenario workshop; in the DRIFT approach, alternative scenarios are extracted from the systematic database that is created during the workshop.

The final water quality report provides all the information from the starter document, together with qualitative and quantitative water quality objectives for each resource unit, for a range of ecosystem health classes (DWAF, 2001).

Discussion

Pollution control – an essential management tool

An environmental flow regime is generally recommended at specific sites (extrapolated to river reaches) and takes account of riverine habitat integrity, geomorphology, and the needs of riparian vegetation, fish, and aquatic invertebrates (King et al., 2000; King et al., 2003; Hughes, 2004). Once an instream flow recommendation is agreed upon, the water quality team considers the consequences to water quality of the recommended flows. If a situation arises where the natural water quality were to be impacted by recommended flows, then higher environmental flows would be recommended (for example, if a stream had a naturally high salinity and low flows would result in increased salinity to unacceptable levels). However, environmental flows are not recommended to address anthropogenic water quality impacts. This is important because the ecological flows are motivated to meet specific biological objectives, which would be obscured by adding flows to solve water quality problems.

However, severely polluted rivers are at risk if only the recommended environmental flows remain in the river without stringent application of waste discharge (DWAF, 1995) and non-point source pollution (Pegram and Görgens, 2001) controls. Pollution control is imperative if the resource is to be adequately protected. Where such controls may take time to implement, water resource managers should be alerted to river reaches that require intervention management, for example the use of dilution, to solve water quality problems that threaten resource health and integrity.

Refugia and "hot spots"

In most catchments there are reaches and tributaries with particularly good water quality, which play a vital role in the improvement of downstream water quality conditions, and potentially act as refugia for biota from adjacent, more impacted, reaches (DWAF, 2001). In the integrated management of the catchment the critical role of these good quality river reaches should not be under-estimated, nor the dependence of downstream river health on them overlooked.

Likewise, there are often reaches and tributaries that are severely impacted and have very low water quality; these negatively impact either on receiving impoundments, or on downstream reaches. These have been termed "hot spots" (DWAF, 2001). Effective source-directed controls in these reaches would significantly improve catchment water quality.

Risk and hazard

At present, the flow conditions that potentially allow an ecosystem to exist in each of the classes can be described in terms of the frequency, magnitude and duration (Hughes, 2001; 2004). However, for water quality variables, most class descriptions are in terms of magnitude (usually concentration) only, with duration and frequency only indirectly considered, if at all. Because of considering mainly magnitude, the present method is based on hazard descriptions, whereas future assessments may be risk-based (Jooste et al., 2000). (Hazard is a potentially negative impact, such as a high concentration of a pollutant, whereas risk is the likelihood of the hazard actually happening.)

Conclusion

Compared with the assessment of environmental flows, the development of methods for environmental water quality assessments, and the integration of water quality with flow in protective water resource management, is in its infancy. Most of the elements of the procedure described here are currently being further researched, but we suggest that environmental water quality assessment and management are crucial for sustainable river management. Priorities for future attention include: water user and management review of methods presented in this paper; inclusion of turbidity and/or total suspended solids (TSS) monitoring and a method for their assessment, further development of the assessment of nutrients, with more attention to response variables such as algal growth, and formal integration of toxics and toxicity monitoring in the ecological Reserve process.

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