A framework for addressing the information needs of catchment water quality management

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Abstract

The process of catchment water quality management must be built on sound philosophies and appropriate information. Over the last few years, the Department of Water Affairs and Forestry in South Africa has been reviewing and developing the philosophical support for catchment water quality management and has initiated a number of catchment plans. The translation of these philosophies into management information needs, which is supported by appropriate assessment of data obtained by monitoring the physical catchment, requires concomitant development. This paper provides a framework to anchor the scientific-technical support to catchment water quality management. The first part of the framework deals with the classification of the physical system, providing the conceptual "platform" for monitoring, assessment and management. This is based on the definition of four physical process elements representing the components of water quality management, namely **production, delivery, transport** and **use**. The second part of the framework involves the definition of an assessment "super-structure", building on these elements. This provides the link between the physical system and management information needs, through monitoring and assessment. The paper ends by providing an integrated framework, which indicates possible types of assessment associated with the different phases of the catchment water quality management process.

Introduction

The changing environment within which South Africa's water quality must be managed caused the Department of Water Affairs and Forestry (DWAF) to reassess water quality management philosophies over the last decade (DWAF, 1991). This has led to the adoption of a precautionary approach to water quality management, based on a hierarchy of management beginning with options to prevent and minimise pollution, followed by receiving water quality objectives, and only resorting to remediation of water bodies and treatment for use as a last resort (DWAF, 1994). Along with these developments has been the realisation that water quality (and all water resource) management must be tackled at a catchment scale, which is the philosophy behind catchment management (DWAF, 1995). The aim of catchment water quality management (as part of water resource management) is to ensure the availability of water of adequate quality (fit-for-use) to provide basic human needs and support economic production.

Integrated catchment management (ICM) attempts the holistic and sustainable management of socio-economic development and all resource utilisation within a catchment, which is the ultimate goal of water resource management. Therefore, catchment water quality management is a central component of ICM, as it provides an important linkage between the socio-political-economic and physical environments. Furthermore, it represents a major factor influencing the achievement of sustainable resource use, particularly in a water-scarce country such as South Africa, because water quantity and its quality represent the primary physically-based linkage between land, air and water resources. Catchment management must address all the elements of the physical catchment, focusing on the causes associated with the sources (i.e. catchment perspective), as well as the impacts on the receiving water bodies and their users (i.e. riverine perspective). This then provides the basis for holistic understanding and sustainable management of the physical environment, upon which catchment management should be based.

The purpose of this paper

Water resource managers are ultimately responsible to the social, political and economic values and concerns of the society which they serve. Therefore, water resource management philosophies should reflect societal goals. The definition of these philosophies is the responsibility of the DWAF and is continuously being attended to at appropriate levels of government (Van der Merwe and Grobler, 1990; DWAF, 1991 & 1995; Quibell et al., 1997). Such management philosophies imply information needs associated with the physical world (i.e. catchment) which they address, shown schematically in Fig. 1. Data are obtained through monitoring the natural catchment characteristics (e.g. slope and soils), anthropogenic influences (e.g. land use and demographics), hydrometeorology (e.g. rainfall and streamflow), water quality (e.g. physical, chemical and microbiological) and aquatic environment (e.g. habitat and biotic health). These data in themselves do not provide appropriate information for management purposes, but rather are the basis of the assessment and analysis which does provide this information.

This paper proposes a framework for the monitoring, assessment and management of the physical environment in support of catchment water quality management. It extends the point and nonpoint source-oriented framework presented by Pegram et al. (1995) and Pegram and Bath (1995) and supports the management approach presented by Quibell et al. (1997). The framework links the management information needs to the physical catchment through the assessment of monitored data. As such, it provides an integrated approach to the technical-scientific support for

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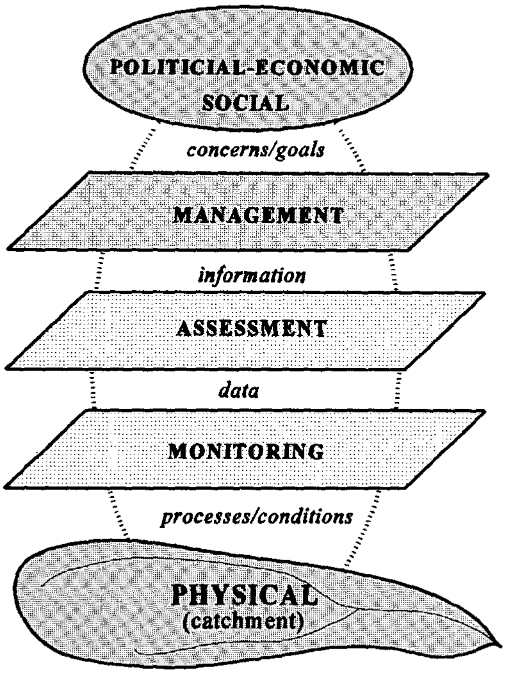

Figure 1
The relationship between the socio-economic-political and physical environments

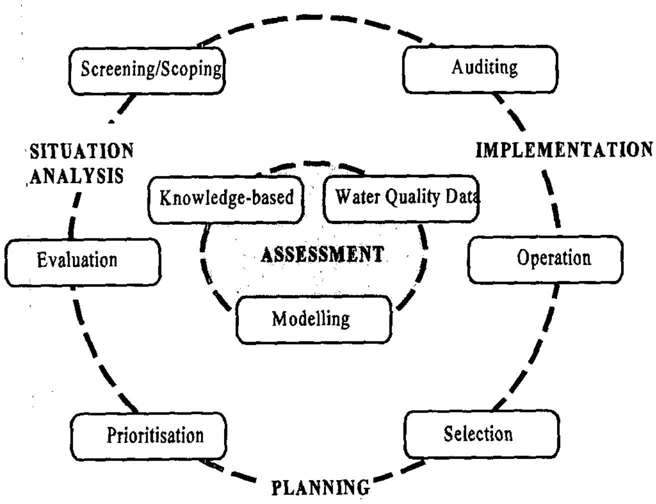

Figure 2
The cycle of assessment associated with the catchment management process

catchment water quality management. The framework grew out of the authors' need to link management needs and assessment requirements, during the development of the Mgeni Catchment Water Quality Management Plan (NSI, 1995a and 1995b). These ideas were further refined during an assessment of the current state of knowledge about nonpoint sources in South Africa, for the Water Research Commission (Pegram et al., 1996), and in-depth discussions with a number of water quality managers in South Africa. Although water quality has been emphasised in this discussion, the same concepts can and should be extended to water quantity issues to support effective catchment water resource management, as has recently been done for the extended Mgeni Catchment Management Plan (NSI, 1996a).

The reader needs to be cautioned that the framework is presented here in a highly conceptual and theoretical manner. NSI (1996b) anchors the framework in an actual study, using the Mgeni River catchment as a prototype. The first part of the framework deals with the classification of the physical catchment, providing the basic conceptual "platform" for monitoring, assessment and management. The second part of the framework involves the definition of an assessment "super-structure", to address management information needs. However, these components first need to be put into the management context, which is the goal of the next section.

The management information needs

The process of catchment management provides the context within which to evaluate the information requirements of water quality management. Various representations of this process have been outlined by other authors (Brown and Van Niekerk, 1995; Van Zyl, 1995), but they usually consist of similar components. Concerns about possible problems in a catchment may be raised through public perceptions or through the understanding and observation of water managers. This represents an interface between the socio-political and management environments (Fig. 1) and may result in the initiation of catchment management. While recognising that catchment management addresses all components of catchment functioning, and is grounded in public participation and institutional arrangements, the following discussion is narrowly limited to the scientific-technical support for three phases of water quality management: a situation analysis, a planning phase and an implementation phase, as represented in Fig. 2.

These three phases should be executed in parallel, thereby facilitating the incorporation of feedback from initial implementation into analysis and planning and enabling these phases to be oriented towards the people and organisations responsible for implementation. An indication of the types of information needs that water quality assessment must provide to assist decision-making during each phase of the management process is presented below.

Situation analysis

- what are the likely water quality problems (constituents)?
- how bad are they (fitness-for-use)?
- where do they occur (impacts)?
- when do they occur (periods and cyclicity)?
- what is causing them (processes)?
- where do they stem from (sources)?
- what should be managed to reduce the water quality problems (key issues)?

Planning

- what should be managed first (priorities)?
- how should it be managed (strategies)?
- what practices are available to prevent or reduce the problems (alternatives)?
- what is the impact of implementing one or more practices (scenarios)?
- what actions should be selected ("best management practices")?
- how should the selected actions be designed for effective implementation (design)?
- how should selected actions be "fine-tuned" to respond to changing conditions?

TABLE 1 THE ASSESSMENT ACTIONS SUPPORTING MANAGEMENT DECISIONS AT DIFFERENT LEVELS OF ASSESSMENT		
Management phase	**Level of assessment**	**Assessment action => management decision**
	Screening/scoping	preliminary overview of the existence and extent of a problem => the water quality issues to manage
Situation analysis	Evaluation	detailed investigation of the cause-and-effect relationships => key areas and constituents of concern
	Prioritisation	rank the problems and causes in terms of severity and manageability => priority sources and/or water bodies and management strategies
Planning	Selection	design and estimate the cost-effectiveness of possible actions => appropriate actions to achieve the specified strategies
	Operation	estimate the impacts of "real-time" actions => ongoing operational decisions
Implementation	Auditing	monitor the degree to which conditions are meeting objectives => reassessment, replanning or further implementation

Implementation

- what proactive operational actions should be taken to pre-empt potential problems?
- what reactive operational actions should be taken to mitigate observed problems?
- are selected actions being implemented as designed (programme auditing)?
- are discharges and yields from sources meeting goals (source compliance)?
- are receiving water quality objectives being met (in stream compliance)?
- is further analysis or planning required (reanalysis or replanning)?

The level of assessment

To ensure that a water quality assessment is cost-effective and appropriate to the issues and problems at hand, the features of the selected assessment techniques must suit the level of detail required for management decision-making. The appropriate level of assessment to support any phase of the management process depends upon the information needs to be addressed, the nature of the problem and the characteristics of the catchment. However, there are six basic levels of assessment reflecting the layers of information needs outlined above. They closely parallel the stages of the integrated environmental management (IEM) process (DEAT, 1992) and the theory of Water Resource Systems planning (Loucks et al., 1981). Table 1 indicates the type of assessment and management decisions required at each stage of the assessment process, which are associated with the phases in Fig. 2.

A start has been made with the establishment of catchment water quality management plans in a number of South African catchments (Howard et al., 1995; Ashton et al., 1995; Kapp et al., 1995). All these have different emphases in line with local needs and realities, but there seems to be a growing consensus that the responsibilities of a catchment management plan should not include the detailed action specification associated with selection and operation (Quibell et al., 1997). These are usually the legal jurisdiction of the relevant authorities, such as local authorities, bulk water suppliers, developers, local communities and farmers. The plan should identify the priority problems, causes, goals, objectives and strategies for management, and possibly outline appropriate regulations, guidelines or typical actions, rather than dictate particular practices to be implemented at individual sites. The onus is on those responsible for causing problems and thus implementing solutions to develop action plans.

The links between the management information needs and the assessment required for catchment water quality management have been outlined in the preceding discussion. The next step is to outline the linkage between the physical system and the monitoring and assessment required to provide appropriate information for management.

A characterisation of the physical elements of monitoring, assessment and management

Although socio-political and economic issues are at the root of water quality problems, the physical characteristics and processes in the catchment determine the actual nature of the problems. Thus, it is important to start with a conceptual view of the elements making up the physical system, taking account of the "Receiving Water Quality" management approach adopted by DWAF. The following characterisation is an extension of that presented by Pegram et al. (1995).

The processes through which constituents are generated at the source, are transported through the environment and by which they reach the users of water, have been conceptually separated into four elements, based on the location and processes governing constituent availability and movement, but taking account of the activities associated with monitoring, assessment and management. The characteristics of the four elements are described below and are shown in the schematic presented in Fig. 3. These

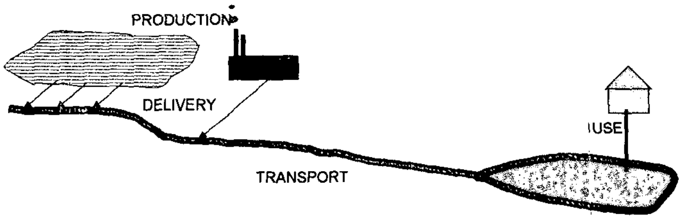

Figure 3
The physical elements of water quality management, assessment and monitoring

elements are not separate or discrete, but rather represent conceptually different points along a continuum. Therefore, there may be significant overlap in both the location and processes associated with different elements. However, this does not reduce their conceptual value for water quality assessment and ultimately management.

Quibell et al. (1997) adopt the same four generic elements, but interpret them from a management perspective by relating them to the DWAF's water quality management philosophy. Their interpretation requires the elements to be manageable, while the interpretation in this paper emphasises the physical processes underlying assessment. However, the similarity in the definition of the generic elements provides the basis for linking the management philosophy and assessment requirements.

Production at source (e.g. household, factory, waste disposal site or agricultural field):

- Governing processes include manufacturing processes, deposition, generation and application, as well as the natural availability and attenuation of constituents at the source.
- Monitoring and assessment include accounting of manufacturing process inputs and outputs, measurement of land surface application rates and availability, and surveying of physical catchment characteristics.
- Management requires prevention of pollutants from entering the effluent stream or nonpoint source discharge through isolation, reduction, recycling or removal of constituents at the point of production.

Delivery from source to receiving water body (e.g. conduits, over the land surface or through the soil matrix):

- Governing processes are point-source effluent discharges, surface runoff and washoff, interflow and percolation, with possible physical, chemical and/or biological attenuation during delivery.
- Monitoring and assessment are based on observation of concentrations, loads and toxicity of point-source effluent, surface runoff or percolate, and the hydrometeorological variables which govern these processes.
- Management requires the minimisation of impacts through interception, detention, treatment or increased assimilation of contaminants during delivery, before it reaches a water body.

Transport in the receiving water bodies (e.g. rivers, impoundments, wetlands and estuaries):

- Governing processes are advection, dispersion and diffusion, causing transport within and between water bodies, with various physical, chemical and/or biological processes governing the fate of constituents and the response of the aquatic environment.
- Assessment addresses the characteristics of the quality and quantity of water flowing through one or more water bodies, based on the sampling of streamflow, physical, chemical and biological water quality, as well as indices of the health of the aquatic environment.
- Management requires manipulation of the hydrodynamic regime through river-reservoir system operation and/or direct intervention in the water bodies to rehabilitate or enhance the physical, chemical or biological assimilation, which assists in meeting receiving water quality objectives and maintaining a healthy aquatic environment.

Use of water by the recognised users (i.e. domestic, industry, recreation, agriculture):

- Dominant processes involve the act of using water, either in the water bodies (e.g. bathing, recreation or stockwatering) or by abstraction (e.g. irrigated agriculture or bulk domestic and industrial water supply).
- Assessment involves water quality sampling and fitness-for-use assessment at the specific point or area of use based on appropriate water quality guidelines.
- Management requires the provision of water which is fit-for-use, by providing treatment after abstraction, or obtaining an alternative source, either permanently (e.g. provide formal water supply) or operationally (e.g. change the reservoir intake level), or by avoidance of use (e.g. by restricting recreational use).

The above conceptual differentiation illustrates the linkages between the various physical elements of water quality monitoring, assessment and management, based on the generic location and the governing processes. This characterisation clearly illustrates the issues involved with integrating monitoring, assessment and management of water quality. The precautionary principle for water quality management implies controlling contamination as close to the point of production as possible (Quibell et al., 1997). This protects the ecological health of the aquatic environment, by reducing the contamination it is required to assimilate. It is more appropriate in a water-scarce country such as South Africa, because the efficiency and cost-effectiveness of management actions are reduced with distance from the source, particularly when dilution or assimilation in the receiving water body is not possible or adequate.

The approach also enables analysts (and managers) to identify which particular element(s) they are addressing and thus what contribution their analysis is making to the understanding of the catchment for management purposes. This is particularly important as the location of most water quality monitoring is in the transport element, representing the combined impact of production, delivery and transport. This complicates the assessment of contributions from particular sources to an observed water quality problem. In order to disentangle the production, delivery and transport elements, the following definitions have been adopted:

- **Potential** is defined as the quantity (concentration or load) of a constituent available at the source for delivery, and represents the production element;
- **Yield** is defined as the quantity of a constituent being delivered from a source area to a receiving water body, representing the combined effect of production and delivery;

- **Export** is defined as the quantity of a substance leaving a catchment, which represents the combination of the production, delivery and transport elements.

Thus, the source delivery ratio represents the relationship between potential and yield. In practice, yield may include a small component of the transport element, so the differentiation between yield and export in a homogeneous catchment would depend upon the size of the catchment. Then, the relationship between the sum of the yields from all the sources in a catchment, and the export from the catchment is the transport delivery ratio, representing the assimilation associated with constituent fate in the transport element.

The above discussion has indicated the links between the physical elements and the assessment needs. The remainder of this paper builds on these elements and the levels of assessment to provide the assessment "super-structure" for the integrated framework.

Approaches to the assessment of water quality

As indicated above, water quality assessment should not be limited to the evaluation of sampled in-stream water quality against specified guidelines (fitness-for-use). Although this represents a fundamental component of the water quality assessment approach, other data and investigations are required to provide relevant information for the characterisation of contamination. Thus, water quality assessment should have an empirical quantitative component, based on hydrological, water quality and ecological data, and a more conceptual qualitative component, based on physical catchment characteristics. Modelling represents a third component, which provides the link between the conceptual understanding of the physical catchment characteristics and the empirical quantification of the hydrological, water quality and ecological response. These three complementary approaches to the assessment of water quality may be formalised as follows:

- **Knowledge-based assessment** provides a qualitative (expert) description of the possible water quality impacts associated with the natural catchment characteristics, the anthropogenic activities and water use. It may be used to indicate what, where and when water quality problems may occur in the catchment, and is particularly useful in the investigation of nonpoint source problems, as it can explicitly differentiate between individual sources and the different physical elements. This type of analysis can indicate transient water quality problems which may have been missed by even comprehensive water quality monitoring programmes. Knowledge-based assessment represents an important part of the screening/scoping level of assessment, it supports evaluation and prioritisation, particularly in data poor systems, and also provides the basis for developing heuristic rules during selection and operation (see Table 1).

- **Water quality data assessment** is based on monitored water quality, ecological and hydrological data. Sampled data are usually only available for point-source effluent discharges or receiving water bodies. However, this approach provides quantitative information on point-source delivery and catchment export, and is the basis for fitness-for-use assessment and assessment of the health of the aquatic environment, both of which can indicate water quality problems. However, the ability to differentiate between production, delivery and transport is limited, even in the most highly monitored systems. Furthermore, transient problems may be overlooked or underestimated, particularly when the assessment is based on grab-samples of water quality constituents. Water quality assessment plays an important role in screening/scoping, evaluation and auditing, and to a lesser extent prioritisation.

- **Modelling assessment** integrates the physical characteristics and/or observed water quality data to quantify the contribution from particular sources. Modelling can differentiate between production and delivery from different sources, can explicitly incorporate the processes governing transport and fate in the receiving water bodies and the impacts on the aquatic environment and recognised users. However, the calibration and verification of water quality models often requires intensive data monitoring to instil confidence in the results. Model application may be expensive and time-consuming to perform, and may not always be appropriate. A range of techniques exist for hydrological, water quality and ecological modelling, depending upon the information needs, data availability, temporal and spatial scale, source types, key constituents/variables, specific physical elements and mechanisms being evaluated. Modelling assessment is most appropriate for evaluation, prioritisation, selection and operation, and represents the only method of predictive quantification of the impacts of possible management actions and/or future development scenarios.

The issue of scale

The above discussion has indicated the broad approaches to water quality assessment. However, there are a number of techniques that fall under each of these general approaches. The appropriate technique is largely dependent upon the appropriate scale of analysis, which is related to the level of assessment, the nature of the problem and the characteristics of the catchment. Scale has a spatial and temporal component, for which the issues of appropriate scope and resolution must be addressed, before any technique can be selected.

Scope: refers to the extent/completeness of the investigation.

- Spatial scope may vary from a site-specific component analysis of a single process element (e.g. production) and/or site (e.g. source or water body), to a holistic system analysis covering an entire catchment or system (including inter-basin transfer).
- Temporal scope may vary from a single event-based analysis given initial conditions, to a continuous simulation over a period including a large number of events, which analyses longer-term impacts.

Resolution: refers to the degree of disaggregation of the area or time-frame defined in the scope of the analysis.

- Spatial resolution may range from a distributed approach, in which spatial variability is explicitly incorporated by dividing the area of analysis into a number of smaller homogeneous source areas and defining relationships between them, and/or a process-based approach, which separates the physical elements of production, delivery, transport and/or use, to a lumped approach, which treats the entire (possibly heterogeneous) area of analysis as a single entity combining the physical elements.
- Temporal resolution may range from the use of time-varying simulation, based on separate time-steps enabling the repre-

sentation of temporal variability, to single time-invariate estimates representing the average or equilibrium condition during the entire period of analysis.

The following issues influence the appropriate scale of a particular assessment; a number of investigations at various scales are required to support the catchment management process.

- **Level of Assessment**: Screening/Scoping only requires long-term assessment of the entire system at coarse resolution, whereas evaluation and prioritisation requires long-term assessment of subsystems at finer resolutions, and selection and operation requires component analysis at fine (possibly event-based) resolution, while auditing requires ongoing assessment at a range of scales. The resolution of any level should be consistent with the scope of the subsequent level, to reinforce continuity during the entire assessment process.

- **Degree of homogeneity**: High levels of catchment heterogeneity require fine spatial resolution, and possibly separate detailed component analysis of individual elements (e.g. feedlots or reservoirs), while greater process variability requires finer temporal resolution, to accurately describe the water quality response.

- **Nature of the water quality problem**: Acute (short-term), transient or event-driven problems with local impacts (e.g. faecal contamination) require subsystem assessment at finer spatial and temporal resolutions than cumulative (long-term) or time-invariant problems with regional impacts (e.g. sedimentation).

Scope and resolution are also applicable to the water quality problem, with scope referring to the number of problems being investigated (e.g. metal toxicity and/or faecal contamination) and resolution referring to the number of indicators used to investigate a particular problem (e.g. metal speciation or faecal indicators).

The choice of an assessment technique to support the information needs of the catchment management process in a particular catchment depends upon a range of issues, including the level and type of assessment and the availability of data and previous applications under similar conditions. These issues must be compared to the assumptions and limitations underlying a particular technique, in order to select the most cost-effective and appropriate analysis for a given application. NSI (1996b) presents an overview of the basic assumptions associated with various water quality assessment techniques, and links these to the needs of the different levels of assessment. The preceding discussion completes the outline of the individual components of the assessment framework.

An integrated framework addressing the needs of catchment water quality management

This section attempts to draw together all the strands outlined in this paper, to provide a possible template for the levels of assessment required to support the catchment water quality management process. NSI (1996b) illustrates an application of the framework to the Mgeni River catchment, providing examples and details about the particular techniques used to support each stage of the catchment water quality management process.

Situation analysis

Identify catchment-wide water quality issues (screening/scoping): This initial investigation should be based on a combination of a knowledge-based assessment of potential water quality impacts associated with the catchment characteristics and possible future development scenarios, and an assessment of the available water quality data. Concerns raised by local communities and managers should be incorporated into the investigation, while the requirements of existing and potential water users provide a point of reference against which the importance of water quality problems should be assessed. The investigation should be at a coarse subcatchment resolution, the definition of which should be based on areas of similar catchment characteristics, land use and water use, to support the knowledge-based assessment, as well as existing monitoring sites, to support the data investigation. This stage should result in the identification of existing and future water quality problems and the associated sensitive subcatchments, to be investigated in more detail.

Identify and describe key areas and constituents of concern (evaluation): The sensitive subcatchments should be investigated in more detail to provide information about the fitness-for-use of the water, when problems occur, the processes causing them to occur and the key areas causing the problems. This should be based on a combination of a fitness-for-use assessment of the available water quality data compared to user requirements and a modelling assessment to identify key areas associated with existing and future water quality problems, supported by knowledge-based assessment where data are not adequate. Lumped watershed export techniques may be used, particularly when applied to relatively homogeneous small watersheds with seasonal time-steps, although event-driven yield analysis provides more accurate information about the causes of problems. Descriptions of the relationships between transport processes and the health of the aquatic environment (resource base) are an important part of this investigation. As implied in the above discussion, the appropriate resolution requires disaggregation of subcatchments, although the scope is not necessarily the entire catchment. The identified key areas causing and receiving water quality problems and the behaviour of the associated constituents of concern should guide the planning phase.

Planning phase

Prioritise sources for management (prioritisation): The major sources associated with the constituents of concern in key areas are investigated in order to provide the detailed information required to identify management strategies. This requires the separation of the production, delivery and transport elements to indicate the contribution of each source to an identified water quality problem, and the processes which cause and/or mitigate the impacts. Modelling assessment, supported by expert-knowledge and water quality data, is necessary to provide information at the required spatial and process resolution, except in the case of monitored point sources when data analysis with some modelling of the transport element should suffice. The scope of the analysis is usually the key catchment area(s) upstream of an impacted area. Once the ranking of source contributions has been performed, sources need to be prioritised for management, based on the manageability of the source contribution. Assessment must indicate the impact of appropriate management strategies on the hydrodynamic, water quality and/or ecological response of the receiving water bodies and any source characteristics that may influence the effectiveness of management, such as the number of people involved, the existence of local political structures and site-specific physical attributes. In some cases, source or delivery management may not be possible, so transport management may be required. Once again, assessment is required to evaluate the effectiveness of the proposed strategies and/or to estimate how effective strategies need to be in order to achieve specified objectives. The prioritisation of sources and water bodies to be managed, identification of strategies for their management and specification of objectives that need to be achieved at critical sites in the system (after consultation with interested and affected parties), provide the technical basis of a management plan.

Evaluate and select management actions (selection): The strategies outlined in the prioritisation stage need to be converted to particular actions to be implemented by the people, communities and/or organisations responsible for management and/or development of the priority sources or water bodies. The site-specific management practices associated with the identified strategies must be designed and evaluated in terms of their efficiency and cost-effectiveness, by the responsible parties (or their agents). The scope of this analysis is usually very specific, concentrating only on the site and elements associated with the investigation (e.g. production and delivery from a priority source area or transport in a river reach or impoundment). The result of this evaluation should be a list of "Best Management Practices" which take into account other issues, such as social acceptability and long-term sustainability. The impacts of the combination of practices associated with all priority sources and water bodies should be evaluated against the strategies and objectives outlined in the management plan. This evaluation should guide the selection of practices to be implemented. These practices represent the basis of the specific action plan associated with the management plan, that must be carried through into the Implementation phase.

Implementation phase

Identify and select actions during implementation (operation): There are three groups of operational decisions that may be required during implementation, namely "fine-tuning" of actions to improve their effectiveness (based on feed-back from the auditing procedure or effective actions learnt through implementation), "reactive" operation to mitigate the impacts of problems that have occurred (e.g. unblocking sewers based on monitoring) and "proactive" operation to prevent problems from occurring (e.g. purging anoxic water from the impoundment hypolimnion). These operational actions are usually based on a combination of knowledge-based heuristics and detailed modelling assessments, supported by monitoring associated with the Auditing process. The assessment only addresses the pertinent elements and sites to be operated on a "real-time" basis, indicating specific actions to be taken

Monitor and evaluate the results (auditing): The implementation of the action plan and the effectiveness of the management plan must be audited, while ongoing monitoring is required to inform operational decisions, as well as possible future "reassessment" and "replanning" studies. Auditing the implementation of actions requires oversight of resource allocation, finance and programme management. The effectiveness of water quality management may be based on the comparison of sampled water quality data to the specified objectives, as in a fitness-for-use assessment. Monitoring of conditions in the catchment should include physical catchment information, hydrometeorological and water quality data, with appropriate methods to screen the data and present them in a form which is appropriate for operational management. The similarities or divergence between the developing catchment conditions and the assumptions underlying the situation analysis and planning assessments should be identified, to audit the degree to which the selected management strategies are addressing developing realities.

The cyclical nature of the management and assessment process was illustrated in Fig. 2. Screening/scoping represents the beginning of the process, while auditing feeds back into all of the other levels of assessment, thereby "closing the loop". It should be reiterated that the different stages in the management process do not need to be performed sequentially. Assessment associated with different stages may be performed simultaneously, possibly addressing different problems in separate parts of the catchment. This enables feedback between the various levels of assessment and phases of the management process, allows the preferences and constraints of implementation to guide planning, as well as encouraging those responsible for implementation to take an active role in understanding the behaviour of the catchment and planning appropriate solutions. In fact, the entire management process should be ongoing, with continual reassessment and replanning of priority issues and management strategies, based on the results of implementation.

NSI (1996b) describes the characteristics of particular assessment techniques associated with each stage of the catchment management process as applied to the Mgeni River catchment. This application should enable managers and analysts to identify how they may effectively use part or all of the framework outlined in this paper for catchment water quality management.

Conclusions and recommendations

This paper highlights the need for and presents a framework to integrate the investigation of the physical conditions and the monitored catchment and water quality (and to a limited extent the hydrological) data with the requirements of management and assessment. The first part of the framework addresses the physical system, dividing it into the conceptual physical elements associated with location and processes governing source **production**, **delivery**, water body **transport** and **use**, related to monitoring, assessment and management. The second part of the framework revolves around the process of assessment for management purposes, and is super-imposed on the physical framework. It addresses the need to provide management information at different levels of assessment: screening/scoping, evaluation, prioritisation, selection, operation and auditing. The linkages outlined through the framework should provide water quality managers and analysts, at various levels and pursuing different objectives, to identify with the holistic nature of catchment management. This will hopefully foster much needed communication between all those involved.

Knowledge-based, water quality data and modelling assessment provide three different but compatible approaches to address management information needs. Each has particular strengths which are appropriate for different levels of assessment. These assessment approaches are in turn associated with techniques having different assumptions and limitations, both in terms of the information they provide and the physical systems they represent. The appropriate assumptions and required spatial and temporal scale of analysis, which influences the choice of technique, is thus dictated by the required level of assessment and the water quality problem. Thus, the framework provides a means of identifying and selecting appropriate techniques to address the pertinent issues at all stages in the catchment water quality management process.

The framework presented in this paper has proved invaluable for the investigations required to support catchment water quality management (NSI, 1996a). This type of approach may be implemented and extended, to provide a conceptual reference point and process for water quality assessment in most catchment systems. It is particularly appropriate when this assessment must be performed within the DWAF "Receiving Water Quality" management approach, which requires simultaneous implementation of pollution prevention and/or minimisation, the setting and achievement of receiving water quality objectives, the sustainable maintenance of a healthy aquatic environment (resource base), and the provision of water which is fit-for-use by the recognised users in the system. However, catchment water quality management should not be divorced from the management of the entire water resource in a water-scarce country like South Africa. Thus, catchment management should address water quantity within the same framework as that presented in this paper, thereby providing a consistent approach to the management of the entire water resource.

Although the conceptual elements developed in this paper are derived from the needs of catchment water quality management, they are general enough to be extended to the other components of pollution management for which contamination is produced, delivered, transported, has an impact on the natural environment (resource base), and/or affects other users of these resources. This includes the management of the land surface and air, and as such provides a basic framework for management, assessment and monitoring associated with integrated pollution control (IPC), particularly if this is approached on a catchment scale. Catchment water quality management is appropriate for IPC, because water usually represents the major transport pathway for contamination.

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