

A Framework for Point and Nonpoint Pollution Analysis

GC Pegram¹, AB Ottermann¹ & J Howard²

¹ Ninham Shand Inc., PO Box 95262, Waterkloof 0145

² Umgeni Water, PO Box 9, Pietermaritzburg, 3200

Introduction

The apparent deterioration of the quality of South African surface waters has drawn the attention of water managers and planners during the last decade. The Department of Water Affairs and Forestry (DWAF) is currently involved in a process of evaluating and adapting its water quality management strategies to address the threat of deteriorating water quality. Legislation and compliance monitoring has improved the control and quantification of point source contamination. The more recent adoption of a *User-based Receiving Water Quality* approach, underlying *Integrated Catchment Management Planning*, requires the understanding, analysis and management of nonpoint source contributions, as they represent the dominant contributing source in some catchments.

DWAF and Umgeni Water (UW) have to ensure the water resources of the Mgeni catchment are managed to meet the quantity and quality requirements of all users, as well as protect and maintain the ecological functioning of the aquatic environment, which is the resource base upon which all other users depend. Increasing population growth, with the associated domestic, agricultural and industrial activity has led to the resources of this system becoming highly stressed. In response to these conditions, Ninham Shand Inc. was appointed by DWAF and Umgeni Water to develop a water quality management plan for the Mgeni catchment, namely the Mgeni Catchment Water Quality Management Plan (MCWQMP). One of the major components of this study was the investigation of the sources of contamination, to provide the information necessary to prioritise and manage the causes of water quality problems, rather than the symptoms in the receiving water bodies.

The diversity of source types, the range of delivery mechanisms, the variability in water body responses and the variety of users in the Mgeni catchment results in an extremely complex system, both in terms of analysis and management. This complexity indicated the necessity to develop a framework within which the Situation Analysis of the MCWQMP could be performed. This framework was largely developed to support the point and nonpoint source analysis for purposes of integrated management and is consistent with DWAF's hierarchical approach to water quality management (Quibell, 1995), beginning with minimizing impacts from the source and ending with the definition of receiving water quality objectives.

This paper outlines the adopted framework and illustrates its value for water quality assessment and management planning (Pegram & Ottermann, 1995). The first part of the framework deals with the classification of the physical system, providing the basic

conceptual "platform" for water quality assessment and management. The second part of the framework involves the definition of an assessment "super-structure", to address management information needs. The issues surrounding theoretical assumptions and scale of analysis are discussed with reference to this assessment framework, which provides links to both the physical and management environments.

The Management Focus

Any analysis designed to support the development of a management plan should be oriented towards the needs of management. Therefore, a paper of this type should begin with an overview of the information needs of the various components of water quality management.

The assessment of water quality for management purposes requires the description and analysis of the sources (cause) and impacts (symptom) of water quality contamination (Quibell, 1995). It should also provide sufficient management information to enable problems to be prioritised and to allow decisions to be made to address those problems in places where the water resources are not fit-for-use. Finally, ongoing assessment involves the auditing of contaminant sources and receiving water bodies, to determine whether the specified objectives are being achieved. Issues that a water quality assessment should attempt to address include:

Impact (or Symptom):

- what are the problems (constituents)?
- where do they occur (impacts)?
- when do they occur (periods)?
- how bad are they (fitness-for-use)?

Source (or Cause):

- what is causing them (processes)?
- where do they stem from (sources)?

Management:

- what should be managed to reduce the problems (key issues)?
- what should be managed first (priorities)?
- what options are available to mitigate the impacts (actions)?
- what is the impact of implementing one or more actions (scenarios)?

Auditing (or Monitoring):

- are discharges and yields from sources meeting specified goals (sources)?
- are the specified receiving water quality objectives being met (impacts)?

The management focus of a water quality analysis may consist of one or more of the above listed issues and is characterised by the nature of the problem and the detail of the information required. To ensure that an analysis is cost-effective and appropriate to the issues and problems at hand, the features of the selected analysis techniques must suit the level of detail required for management. The following levels of analysis represent distinct management foci associated with different phases of assessment:

- Screening*: provides a preliminary overview of the extent of a problem
- Evaluation*: provides detailed information about the causes of the problem
- Planning*: prioritises the components of the problem for management
- Operational*: estimates the impacts of implementing management decisions
- Auditing*: monitors the degree to which conditions are meeting objectives

The first two are associated with the *Assessment* phase of a management plan, the second two support the *Decision Making* (or *Development*) phase, while the last evaluates the *Implementation* of the plan. The highly complex and interrelated nature of water quality issues, requires a framework within which to address the analysis of point and nonpoint sources. This framework needs to bridge the gap between the management components of the plan and the elements of the physical system.

The Physical Elements of Water Quality Assessment and Management

Although socio-political and economic issues are at the root of water quality issues, the physical characteristics and processes in the system determine the nature of the water quality problems. Thus, it is important to start with a conceptual view of the elements making up the physical system, taking account of the *User-based Receiving Water Quality* approach adopted by DWAF.

The physical processes through which constituents become available at the source, are transported through the environment and reach the users of water, can be conceptually separated into four elements, to assist the assessment, monitoring and management of water quality problems. Figure 1 illustrates the relationship between the four management elements, while Table 1 outlines their relationships to the management information needs, physical processes, monitoring, management options and water quality assessment tasks.

The definition and characteristics of the four elements are:

- the **source**, including the availability, generation, application and attenuation of constituents;
- delivery** to water bodies, through transport processes (point discharge, surface runoff, groundwater discharge or adsorbed to sediment);
- water body** response, including transport processes (eg. advection, dispersion and diffusion) and the fate of constituents (eg. assimilation and transformation);

- use* of water, either in the aquatic environment or through abstraction.

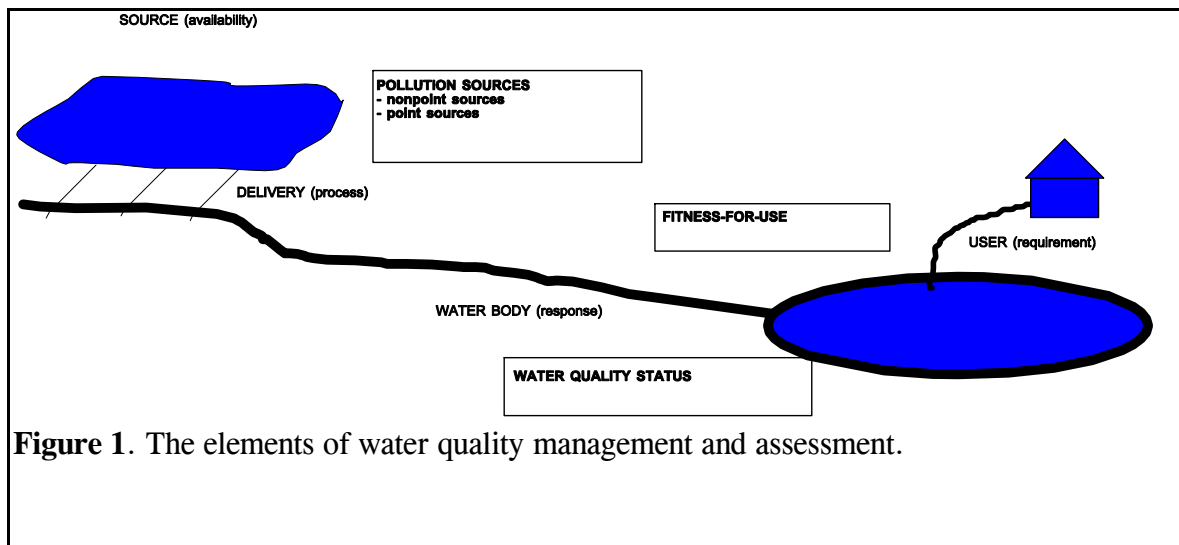


Figure 1. The elements of water quality management and assessment.

Table 1. The general characteristics of the management elements.

	Info Needs	Processes	Monitoring	Management	Assessment
Source	where from?	availability application generation attenuation	physical availability application generation	land management application timing runoff reduction	Pollution Source (NPS & PS)
Delivery	when? why?	discharge washoff percolation attenuation	discharge washoff groundwater toxicity	interception ecological assimilation treatment	
Water Body	what? where? how bad?	transport fate ecological assimilation	river reservoir estuary ecological	biotic assimilation system operation isolation	WQ Status
					Fitness-for-use
User		fitness-for-use assimilation abstraction	ecological water body bulk supply	abstraction treatment	User Requirement

These elements provide the context for a water quality Situation Assessment and were related to the specific tasks of the MCWQMP as follows:

- *Pollution Sources* are associated with the **source** itself and the **delivery** to the water body;
- *Water Quality Status* are concerned with the response of the **water body**;
- *User Requirements* are related to the **use** of water and the associated water quality guidelines;
- *Fitness-for-use* compares the water quality of the **water body** and the requirements of **users**.

The assessment and auditing of water quality problems is based on monitoring of:

- substances applied, generated and attenuated at the **source**, and the physical catchment characteristics which govern the availability of contaminants;
- the quality of water in surface runoff or groundwater discharge during **delivery**, and the

- meteorological variables which control the delivery processes;
- quality of water in the receiving *water bodies* (rivers and impoundments), and the hydrology, ecology and morphology which determine the water body response;
- quality of water available for *users* and the aquatic environment, either in the water bodies themselves or during the abstraction and treatment process.

Finally the appropriate approaches to the management of water quality problems are also related to the four management elements, because efficiency and effectiveness of management reduces with dilution and distance from the source. Management practices include:

- control of contaminant application and generation at the *source*;
- interception, treatment or reduction of *delivery* of contaminants to the receiving water bodies;
- river-reservoir system operation or improved assimilation within the receiving *water bodies*;
- management of the quality of water within the natural environment or abstraction and treatment for *users*.

A Definition of Contaminant Sources for Water Quality Management

The analysis of contaminant sources should provide management oriented information. This implies that the sources should be investigated according to the most appropriate management practices, which in turn are based on the source characteristics (eg. areal extent), contaminant availability (eg. deposition, application or production) and delivery mechanisms (eg. discharge or export). Based on these differences, pollution sources can be grouped into four categories.

i. *Point Sources* discharge from a single point (pipe, drain or canal). These may include industrial manufacturing process or waste water treatment effluent with relatively continuous discharge and are usually managed through detention, treatment or dilution.

Nonpoint Sources include all other sources. They can be characterised as follows:

ii. *Diffuse Sources* contribute to air, surface and groundwater contamination over a widespread area, with intermittent and highly variable export occurring during hydrometeorological events. Management of diffuse sources is usually related to land use management, although delivery reduction and/or treatment may be used.

iii. *Concentrated Sources* export from a localized area, such as mines, feedlots or dairies, with discharges occurring during hydrometeorological events or artificial surface washing. The confined nature of the sites allow for either treatment or containment at source, similarly to point source control, or require land management, as with diffuse sources.

iv. *Incident Sources* are accidental spills, so discharges occur infrequently at unspecified locations. Management is based on reducing the risk of accidents and improving the clean-up response.

The categories are not absolute as diffuse sources may be collected and discharged as pseudo-point sources (eg. storm water runoff collection), or point sources may be applied to create concentrated or diffuse sources (eg. irrigated effluent). The differentiation between diffuse and concentrated sources should be based on the requirements for analysis and management. The following questions should help clarify whether a source should be defined as concentrated:

- should the source be represented as a point, rather than an area, in the integrated analysis ?
- does it require alternative analysis techniques to the diffuse sources ?
- is it feasible to collect and manage the runoff or leachate as a point source ?

Approaches to the Assessment of Water Quality Problems

The analysis of water quality problems should not be limited to the evaluation of sampled instream water quality against specified guidelines (fitness-for-use). Although this represents a fundamental component of the water quality assessment approach, other data and analysis is required to provide relevant information for the characterisation of contamination. Thus, water quality analysis should have an empirical quantitative component, based on hydrological and water quality data, and a more conceptual qualitative component, based on physical catchment characteristics. Modelling represents a third analysis component, which provides the link between the conceptual physical catchment characteristics and the empirical hydrological and water quality response. These three complementary approaches to the analysis of water quality may be formalised into:

- A ***Knowledge-based Assessment*** provides a *qualitative* (subjective) description of the possible water quality impacts associated with the natural basin 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. This type of analysis can indicate transient water quality problems which may have been missed by even comprehensive water quality monitoring programmes.
- A ***Water Quality Assessment*** based on monitored water quality and hydrological data. Sampled water quality data is usually only available in the water bodies, which reflects the combined impact of heterogeneous areas with multiple point and nonpoint sources and the transport to the sampling site. Despite these problems, this approach provides quantitative data on the contributions from monitored point sources and the condition of a catchment, and indicates many of the important water quality problems. *Statistical* and *stochastic*

timeseries approaches are most suited to this type of analysis.

- A **Modelling Assessment** which integrates the physical characteristics and/or observed water quality data to quantify the contribution from particular sources. Modelling differentiates between the contributions from different sources, and incorporates the impacts of transport and fate in the receiving rivers and impoundments. A variety of analysis techniques exist for water quality assessment, depending upon the management focus, data availability, temporal and spatial scale, source types, key constituents and main transport mechanisms being evaluated. *Deterministic* and *stochastic simulation*, and/or *empirical relationships* represent the most widely used water quality modelling approaches.

Assumptions and Limitations Associated with Analysis Approaches

All analysis approaches have assumptions and limitations which affect their applicability in addressing management questions under different conditions. These assumptions also determine the choice of scale and data requirements. The major issues which need to be investigated before an appropriate analysis technique can be selected, include the relevance of:

- a *qualitative* approach which enables ordinal evaluation based on an understanding of the causative processes, and/or *quantitative* analysis enabling cardinal ranking and evaluation.
- a *physically-based* approach, which explicitly represents the processes causing contamination, and/or *empirical* approach, which is based on observed impacts.
- a *transferable* approach, which may be applied to unmonitored conditions, or a *calibrated* model, which depends upon observed hydrological and/or water quality data.
- a *deterministic* approach for which inputs, relationships and outputs are represented with certainty, and/or *probabilistic* approach, which explicitly incorporates uncertainty.

These classes provide a practical method for classification of existing models, which are based on several assumptions. The appropriate approach, with acceptable assumptions and limitations, for a particular analysis is depended upon:

- the *focus of management*, indicating the detail and accuracy required;
- the *data availability*, both in terms of physical and water quality data;
- the existence of *previous applications* under similar conditions.

The Spatial and Temporal Scale of Analysis

In terms of spatial and temporal scale, two issues must be addressed in identifying an appropriate analysis technique for the assessment of the causes (sources) of water quality problems.

Firstly, the *level of detail* (or holism):

- spatially, whether to use a holistic *systems* approach over the entire catchment, or a site-specific *component* analysis of a single source.
- temporally, whether to use an *event-based* approach, representing a single event given initial conditions, or a *continuous* simulation of the long-term impacts of a number of events.

Secondly, the *degree of resolution* (or disaggregation):

- spatially, whether to use a *distributed* approach, in which the spatial variability is explicitly incorporated, or a *lumped* approach, which treats heterogeneous areas as a single entity.
- temporally, whether to use separate *timesteps* (ranging from hourly to monthly), to reflect temporal variability, or whether *long-term averages* are adequate.

The spatial and temporal scale appropriate for a particular analysis depends upon:

- the *focus of management*, with screening possible at coarse scales, while planning and operational assessment require finer resolution;
- the *degree of homogeneity*, with high levels of heterogeneity requiring finer spatial resolution to accurately describe the response;
- the *location of the impacts*, with short-term (acute) local impacts requiring finer spatial resolution than long-term (cumulative) regional impacts;
- the *nature of the problem*, with acute and/or variable event-driven impacts requiring shorter timesteps than cumulative and/or time-invariant impacts;
- the *analysis technique*, with stochastic methods being constrained by the sampling sites, while deterministic methods can conceptually disaggregate source, delivery, transport and fate;
- the *resolution of the available data*.

The nonpoint source area concept is based on the definition of homogeneous areas with similar physical, hydrological and water quality characteristics. It may be extended to individual point sources to assist the integrated assessment of all sources. The concept of source areas is useful for management purposes in that it allows the disaggregation of source, delivery and water body response and provides a means to compare the contribution from different sources. When source areas are associated with a (distributed) physically-based approach describing the processes causing contamination, the relative contributions associated with the various transport processes from different sources during separate events and seasons may be estimated. The advent of Geographic Information Systems (GIS) technologies has increased our ability to store and access detailed spatially referenced data, allowing complex physically-based analyses to be conducted at fine spatial and temporal resolutions, where the input data is sufficiently detailed.

The Analysis Requirements for the Different Levels of Management

In the past few decades, many different water quality models have been developed. These range from simple screening tools to complex research oriented models. The above discussion helps to categorise and differentiate the various models, even though many of these classes are better represented as a continuum than by discrete categories. Accepting that choice of technique is based on management focus, the requirements of different levels of analysis are outlined below.

Screening

This overview requires coarse resolution investigation of all possible problems in the entire study area (catchment), based on simple quantitative and/or qualitative analysis of observed data. Appropriate analyses include *knowledge-based assessment* of catchment conditions (assisted by GIS databases), together with *statistical analysis* of monitored water quality data.

Evaluation

This more detailed assessment should address problems and key sub-catchments (or areas) identified during the screening stage. The spatial and temporal resolution is finer, allowing disaggregation of the different events associated with the various sources, delivery and transport processes. The effort required to perform more detailed *water quality modelling* is warranted, because this is the most cost effective way to obtain information about source contributions. The whole range of modelling approaches may be used, including deterministic simulation, stochastic analysis and empirical approaches. The choice of model depends upon data availability and the existence of previous applications. This modelling analysis should be supported by information provided by detailed *knowledge-based assessment* and *water quality data analyses*.

Planning

This level of analysis requires fine spatial and temporal resolution, which usually depends upon *water quality modelling*, rather than analysis of intensive monitoring. Therefore, transferability is important, which indicates the use of deterministic, physically-based models. Empirical approaches may be used, where applications have been performed under similar conditions. Key sources identified during the evaluation phase should be investigated in more detail, to provide information and enable prioritisation of the sources and processes for management.

Operational

The effectiveness of a management action should be evaluated at the site of that action, whether it is at the source, during the delivery or in the water body. This requires very detailed *modelling analysis* of that component, based on transferable, physically-based models or probabilistic analysis. Empirical *knowledge-based assessment* may be used to support this analysis, or even replace it in data-poor situations when expert opinion is available.

Auditing

This task should assess compliance with specified goals, so is usually based on *water quality data analysis* with reference to a guideline or objective. The auditing of nonpoint sources should however be related to the land surface, in which case, detailed *modelling analyses* similar to those used for operational assessment may be used to evaluate the likely impact of a monitored condition at the source (eg. contaminant concentrations in the soil).

An Application to the Formulation of a Management Plan

The process of formulating the MCWQMP has a number of tasks, many of which are associated with water quality assessment. The nature of water quality management, dictates that the (point and nonpoint) sources of contamination have a central role in this assessment, both as the most appropriate site of control and as the causative component of water quality problems. The following task list outlines the process of developing a management plan, and indicates the appropriate types of water quality assessment associated with each task. An illustration of the type of information provided by each task is also presented for the Mgeni catchment.

The Mgeni catchment was divided into 13 management sub-catchments, based on representative monitoring sites and relatively homogeneous physical characteristics, landuse and water use. These represent the basic unit of management and facilitated assessment.

Identify catchment-wide water quality issues

This Screening task involved a *knowledge-based assessment*, based on natural and anthropogenic physical catchment characteristics, as well as climatic and hydrological information, and a *water quality assessment*, based on Umgeni Water's monitoring program.

- Faecal contamination, phosphorus and sediment were identified as the major water quality issues in the Mgeni catchment, with possible isolated metal and pesticide problems.

Identify sensitive sub-catchments

The identification of sensitive management sub-catchments was initiated during the Screening phase and was based on *knowledge-based* and *water quality assessments*. The Evaluation phase entailed the use of the catchment-wide ACRU water quality model (Kienzle *et al*, 1995) for sediment and phosphorus yield, which supported the identification of sensitive sub-catchments.

- For faecal contamination, the Pietermaritzburg sub-catchment in the Msunduze catchment was identified as the major contributing area.

Identify key areas and constituents

The major contributing areas within the sensitive sub-catchments and the associated key constituents were identified, based on *modelling analyses* and *water quality data assessments*

performed during the Evaluation and Planning phases. The ACRU model, other models and estimates of contaminant application (mass-balance) were used. *Knowledge-based assessment* supported the investigation of areas or constituents which were not modelled or monitored.

- Within Pietermaritzburg sub-catchment, the Baynesspruit, Slangspruit, Edendale valley and Dorpspruit catchments had the greatest *E.coli* (faecal contamination) problems.

Prioritise point and nonpoint sources

This task was based on detailed fine-resolution *modelling analyses* and *knowledge-based assessment* associated with the Planning phase. The impacts on local surface and ground water resources were estimated, in terms of both contaminant availability and yield.

- The major sources associated with these areas were leaking and failing sewers in Imbali, Sobantu and central Pietermaritzburg, and inadequate sanitation in the informal settlements of Cope's Folly, Slangspruit/Wilgefontein and Sweetwaters.

Identify and evaluate management options

Potential management strategies for addressing the critical water quality problems and pollution sources in key areas need to be identified during the Operational Assessment. This evaluation should provide an indication of the manageability and cost-effectiveness of using an option for a specific source, based on detailed *modelling analysis*.

- Detailed assessments should be performed to estimate the implications of improving sanitation in these areas, as opposed to reducing delivery in detention ponds and wetlands.

Monitor the results

A major task associated with the implementation of a management plan involves Auditing the impacts of actions, to determine whether goals are being achieved. This will largely be based on *water quality assessment* of monitored data, although monitoring of catchment characteristics and *modelling assessment* may support the auditing of nonpoint sources.

- Monitoring of the rivers downstream of the major sources should provide sufficient data to evaluate the results of any actions taken to improve this problem.

This process should be repeated for all problems and source areas throughout the Mgeni catchment. The definition of acceptable receiving water quality objectives should be informed by the above assessments, but emphasis should always be on minimising the causes of contamination (source and delivery management), rather than instream mitigation of the symptoms.

Conclusions and Recommendations

The analysis of point and nonpoint sources for the MCWQMP highlighted the need for a framework to integrate the investigation of the physical conditions and available catchment, hydrological and water quality data with the requirements of management and assessment.

The first part of this framework addressed the physical system, dividing it into the elements *source* production, *delivery* processes, *water body* transport and fate, and *user* requirements. Sources of contamination were further classified as *point*, *diffuse*, *concentrated* and *incident*, based on the requirements for management and assessment.

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 detail, associated with five management foci: *Screening*, *Evaluation*, *Planning*, *Operational* and *Auditing*.

Knowledge-based, *water quality data* and *modelling* assessment provide three different but compatible approaches to address the issues for any management focus. Each of these assessment approaches have a range of analysis techniques with different assumptions and limitations, both in terms of information they provide and the physical system they represent. The appropriate assumptions and required spatial and temporal scale of analysis, which influences the choice of analysis technique at any stage in the assessment process, is dictated by the focus of management. Thus, the framework provides a means of identifying and selecting appropriate techniques to address the pertinent issues throughout the assessment process.

The framework presented in this paper proved invaluable for the investigation of point and nonpoint sources of contamination in the highly diverse and complex Mgeni catchment. Furthermore, it provided the point of reference for the other water quality assessment tasks and the required links to the identification and selection of management options the Mgeni Catchment Water Quality Management Plan.

This type of approach may be implemented and extended, to provide a conceptual reference point and process for water quality assessment in any complex system, particularly when this must be performed within the *User-based Receiving Water Quality* management approach, which requires simultaneous implementation of pollution prevention and/or minimisation and the definition and achieving of receiving water quality objectives.

Acknowledgements

The authors wish to acknowledge the Department of Water Affairs and Forestry and Umgeni Water for permission to publish this work, which was largely developed for the Mgeni Catchment Water Quality Management Plan. Extensions to the framework are being

performed under a contract to the Water Research Commission, involving the development of a guide for nonpoint source assessment, and this contribution is acknowledged. Mr Gavin Quibell of the Institute of Water Quality Studies (DWAF) and Prof. Andre Görgens of the University of Stellenbosch are thanked for their valuable insights.

References

Kienzle, S W, Lorentz, S A & Schulze R E (1995). **Hydrological and Water Quality Modelling of the Mgeni System**, Draft Report to the WRC by Dept. of Ag. Eng (UNP).

Pegram, G C & Ottermann, A B: NSI (1995). **Pollution Sources**, report to DWAF and UW for the Mgeni Catchment Management Plan, DWAF report # WQ U200/00/0995

Quibell, G (1995). **Personal Communication**, Institute of Water Quality Studies (DWAF)