

Linking Land Use to Water Quality for Effective Water Resource and Ecosystem Management

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

1. PROJECT BACKGROUND

This project is primarily about understanding the influence of land use, in all its forms, on the quality of water in our water resources. This knowledge, if made accessible, has the potential to soundly inform both water quality management and land use management. This will hopefully reverse some of the alarming trends currently apparent in respect of water quality in our rivers, dams and groundwater.

To date attempts to manage the linkage between land use and water quality through *ad hoc*, disconnected projects, operating in isolation from one another have failed. The state of our rivers is testimony to this failure. This research project was a multi-organisational response which called for a break from the past and a focus on a future that is already effectively mandated. The research involved the development of a sound foundation that will serve to integrate the efforts of scientists within stakeholder sectors. It is envisaged that such socio-technical approaches will greatly assist multi-stakeholder co-development of appropriate options and recommendations in any given land use/water quality impacts context. In brief the research is fully supportive of both the spirit and the letter of the 1998 National Water Act (NWA) and the institutional arrangements which are being implemented to support that legislation and in so doing support integrated water resources management.

OVERALL OBJECTIVE

Recognising the strong relationship between water quantity and quality, the objective of this project is to better understand the implications of particular land uses for water quality and to test tools that improve spatially explicit decision making about water resource and aquatic ecosystem management at catchment level.

The aims of the project are to:

1. Identify and critically review land use classification system/s currently available in South Africa for their applicability and utilisation within the project (Chapter 4).
2. Review and categorise land use types within the selected land use classification system with regards to their potential impacts on water resource and ecosystem health (Chapter 3 and Chapter 4).
3. Develop tools and guidelines to guide and improve decision making by relevant management stakeholders with regards to the potential impacts of different land uses on water quality (Chapter 2 and Chapter 3).
4. Test and refine the developed tools through two case study catchments to improve the decision making of management stakeholders (Chapter 5).
5. Build the capacity of the relevant management stakeholders at catchment and national level to improve Integrated Water Resource Management.
6. Recommend priority areas for future research within the scope of the effects of land use management on water resource quality (Chapter 6).

Throughout this project we have made the case that a new paradigm is needed because of the complexity, the dynamics, the multiple stakeholders and the widespread paucity of data plus the urgent need for behavioural change with regard to land use and its effect in water quality. As such in addition to assessing and implementing technical models designed to predict land use impacts on water quality, the project team has focussed on fundamental shifts in mindset required to make the most of available tools and to facilitate the development of an installed modelling and information management system run transparently and continuously by stakeholder sector advisors. The technical thrust investigated and applied the range of tools available for linking land use to water quality, with a view to assessing the tools as well as applying them in case study catchments. Closely linked to these activities was the review of available land use classification systems in South Africa and the availability and quality of data required to implement models that make predictions of land use impacts on water quality.

2. CONCEPTUAL BASIS

As highlighted in the introduction, instead of focussing only on software and models that link land use and water quality that facilitate decision making, the project also took cognisance of the broader operating environment in which such decisions and reasoning take place. This includes the general absorptive capacity of the organisations involved. This is the set of organisational processes by which an organisation acquires new knowledge, assimilates that knowledge, transforms (itself), and exploits knowledge to produce a dynamic organisational capability. The shift in focus to the environment “receiving” the technical tools (e.g. software tools) is also a deliberate attempt to lay the basis for a post project sustainability plan aimed at improving the uptake of project outputs, irrespective of the exact nature of the technical tools.

As such the project took an uncompromisingly national and long-term perspective. It acknowledges (a) a serious existing problem, and (b) that business as usual cannot be the way forward. Yet there is optimism that change is possible. This is embedded in the knowledge that there are approaches and mindsets that potentially allow South Africans to tackle the seemingly intractable complexities of land use management in relation to water quality. Many of the concepts that underlie these approaches and mindsets are at the forefront of international research, thinking and application. They include, among others, the following:

- **Acceptance of Strategic Adaptive Management for IWRM.** “*The practice of Strategic Adaptive Management (SAM) as a framework for IWRM in complex social-ecological systems*”, will characterise interactions amongst stakeholders.
- **Recognition of dynamic complexity.** There is already some evidence of a growing recognition of the complex nature of the systems in which we live, in particular the inherent unpredictability associated with complexity. Indeed, this is the primary motivation for adaptive management.
- **Acceptance of post-normal science paradigms.** Post-Normal Science is the methodology that is appropriate when (a) facts are uncertain, (b) values are in dispute, (c) stakes are high and (d) decisions are urgent. Typically integrated catchment management has these attributes.

- **Acceptance of dangers posed by systemic risk.** Issues relating land use and water quality are intertwined in complicated and complex ways that create inherent systemic risk.
- **Focus on developing absorptive capacity.** Absorptive capacity is a set of organisational routines and processes, by which firms acquire, assimilate, transform and exploit knowledge to produce a dynamic organisational capability.
- **Recognition that socially robust knowledge generation is imperative.** This is knowledge that is socially acceptable on which people are prepared to act. It is a context-specific integration of reliable knowledge and social knowledge.
- **Recognition of need to evolve appropriate institutional forms.** Socially robust institutional forms are needed to build socially robust knowledge and strategies. Socially robust institutional forms require at least a policy, legal and ethical framework.
- **Use of participatory agent-based social simulation modelling.** This kind of modelling directly involves those actors who themselves will later use the model. The model captures subjective perceptions and expectations and the social and human elements of water resource management. The purpose of agent-based modelling is to aid intuition.
- **Need to develop resilience in society.** Resilience is the ability to bounce back after disaster strikes. Diversity plays a significant role in developing resilience.
- **In-kind financial and skills contributions to make IWRM affordable.** Our national policies pave the way for in-kind contributions. Many entities can make such contributions and many have the implicit mandate to do so by their water-related responsibility. A very wide variety of in-kind contributions can potentially be made, depending on the specific entity.

These concepts are by no means mutually exclusive. Indeed, on the contrary, they all dovetail into a mindset in which uncertainty, individual subjectivity, and empathy mix seamlessly with traditional science.

3. TOOLS THAT LINK LAND USE AND WATER QUALITY FOR EFFECTIVE ECOSYSTEM MANAGEMENT

At a basic scientific level, managing and or mitigating the effects of land use activities on water quality requires the identification and quantification of sources of pollutants linked to specific land use activities. Identifying and quantifying pollution derived from nonpoint sources in particular is very challenging. This is because nonpoint source pollution is derived from a large surface area which is often heterogeneous in terms of the land use activities taking place in the catchment. Furthermore, the magnitude of nonpoint source pollution is influenced by a number of geographical factors which can vary from one catchment to another, which can make the process of linking land use activities to water quality impacts particularly challenging.

In response to these challenges, a number of tools and models have been developed that rely on different levels of technical/scientific/information input (from low to high detail), depending on the

nature and type of decision that needs to be made. An example of a low level of scientific input is using the literature to make simple qualitative, generic links between land use activities and water quality and the different kinds of potential impact associated with that water quality. For example, elevated concentrations of sulphate are a well-known consequence of coal mining. This basic knowledge enables decision makers to make generic statements of how water quality is likely to be impacted by a future land use or to identify land use practices that should be prioritised and investigated in further detail. Further detailed analysis of land use impacts on water quality requires a more quantitative estimation of pollution.

This chapter investigated a number of modelling software packages and approaches with a core objective of better understanding the application of these models in the context of making decisions related to impacts of land use on water quality. Principle and philosophical issues relating to models, modelling, shells, frameworks and platforms and data and information are discussed. In other words this chapter says:-

- these are the issues,
- these are the available frameworks, platforms, shells and models,
- this is when you use them, and
- this is how you use them.

A range of tools and methods are introduced and tested (some through use within the case study catchments) which can inform decision making, from simple lookup tables to complex modelling. As a first tier, lookup tables covering *water quality impacts per land cover*, and then *typical impacts and effects on downstream users* are presented. A literature review of typical land use – water quality links, interactions and impacts was translated into lookup tables based on the NLC2000 land cover dataset, with land use classes categorised up to Level 1 and Level 2 (in line with SANS 1877:2004). To effectively cover the range of land use – water quality interactions the NLC2000 land cover classes were supplemented to include land uses relevant to the assessment of water quality impacts but which cannot typically be distinguished by remote sensing. As the first tier of investigation, these lookup tables can direct where further analysis or monitoring is required. Four water users are considered, namely the natural environment, agricultural/industry, drinking water, and recreation.

The more complex modelling approaches and technologies that were assessed included:-

- A review of typical water quality impacts associated with land use in South Africa
- Export coefficients, which included
 - the pollution load estimator (PLOAD), a US EPA supported public domain product;
 - a methodology to develop export coefficients for local South African conditions;
- Bayesian Modelling systems;
- The BASINS 4.0 modelling shell;
- Specific hydrological land use and water quality models, including;
 - the Soil Water Assessment Tool (SWAT) a USDA supported public domain product;
 - The Hydrological Simulation Program Fortran (HSPF) a flagship model in the BASINS 4 framework supported by the US EPA;
 - MIKE SHE which is part of the DHI suite which includes MIKE ZERO; MIKE BASINS; MIKE 11. The MIKE suite is available to Universities in South & southern Africa and

also to the Water Research Commission (WRC) and the Council for Scientific and Industrial Research (CSIR) free of charge.

- AQUATOX a biological water quality model supported by the US EPA and which is in the public domain;

Each of the modelling approaches was evaluated in terms of the outputs they provide, the data they require and their general advantages and disadvantages. Each approach varies in terms of their ease of use and complexity. It was recognised that one component of any such learning process is the ability to efficiently transfer the knowledge gained to those that follow. Accordingly, a supplementary technical report on the software is available on the CD attached with this report. A primary output of this evaluation was the development of a Land Use and Water Quality Tool Evaluation Matrix, which assessed the models explored in this project against a number of criteria including, amongst others, information that can be elicited, operational considerations and water quality parameters addressed by the models.

The assessment of the modelling approaches found that suitable technologies and processes exist and we have the absorptive capacity in South Africa to engage them successfully and sustainably. The latter statement is subject to the proviso that the multiple stakeholders truly engage both the spirit and the letter of the 1998 NWA. In other words the technology and the human dynamic needed for co-construction of actionable land use and water quality knowledge are inextricably linked.

4. LAND USE CLASSIFICATION AND DATA SOURCES

The literature was reviewed to assess how land use relates to water quality modelling. A distinction is made between land use, associated with management practices influencing water quality, and land cover, which can be observed and mapped through earth observation technologies. Examples of country-wide land use/land cover (LULC) classification systems are tabulated followed by the limitations of land cover classification maps or data. Empirical relationships between land uses and water quality are shortly discussed as well as how land cover data is used in water quality models. The level 1 land cover classes of the South African standard for land cover classification (SANS1877) is tabulated in comparison to those of National Land Cover (NLC) datasets of 1996 and 2000. The SANS1877 level 1 classes are also compared to land cover classes used in water quality modelling software, such as GIRAS, HSPF, and those of the United States of America. Export coefficients for phosphates, nitrate and suspended solids are tabulated for levels 1 and 2 of SANS1877 as available from South African and international literature. We listed shortly some general information of geospatial data to the user to improve their understanding and knowledge of geospatial data pertaining to water quality modelling, with metadata of nationally-available geospatial datasets available in South Africa for water quality modelling in Appendix A.

The existing levels 1 and 2 of SANS1877 are particularly useful in water quality modelling. Any national or provincial dataset complying with these categories will be appropriate for use in water quality modelling. Some geospatial datasets were difficult to obtain and there are still a number of point-source datasets not available at national level. We proposed a centralised portal for accessing or referring users to geospatial data sets. Export coefficients for phosphates matched the level 1 and 2 categories of SANS1877 better than those for nitrates and suspended solids. We suggest that the user community be consulted through a stakeholder engagement workshop or consultation process to consider their needs in expanding on these coefficients for South Africa, as well as to further discussion on improvements to geospatial data and funding thereof.

Included in this report is a guideline to sources of national geospatial datasets in South Africa for use in water quality modelling and prediction. It is structured according to the geospatial data categories used in the US EPA BASINS shell, namely base cartographic data, environmental background data, environmental monitoring data, and point sources/loading data. Metadata are also listed.

5. CASE STUDIES

In order to facilitate detailed input and testing of project concepts and models, two case study catchments were chosen. These were the upper uMngeni River and upper Olifants River catchments. These catchments were used as focus areas for catchment-based stakeholder and institutional engagement as well as testing of the models identified in Chapter 3.

Investigation of Water Quality Drivers and Trends

In meeting the requirement for stakeholder engagement, capacity building, and refining and testing of the developed tools, alternative approaches in the investigation of links between land use and water quality were included under the research project. The investigation of water quality drivers and trends within a critical water supply catchment within KwaZulu-Natal was provided as a case study. The study combined two methods, the first being the analysis of historical water quality records to distinguish sub catchment water quality trends, with the second involving the simple mapping of water quality drivers (land use activities) within the sub catchments. In this way the water quality status of each sub catchment in relation to the land use activities within the catchment, could then be easily interpreted visually by stakeholders. It was found that the approach was useful in determining water quality hot spots across the sub catchments, and identifying potential sources and drivers of the water quality. The inter relationships between catchment size, water quality status and the intensity and extent of land use activities impacting water quality could be interrogated. These understandings then inform where resources must be prioritised, such as initiating further investigation or monitoring, or in terms of ensuring activities are correctly regulated, licensed, managed or maintained.

Export Coefficients

Export coefficients are typically associated with nonpoint pollution sources. They represent the total mass (kg) of a constituent per hectare (ha) of land that enters a water resource via surface runoff per year. For example, a phosphate export coefficient of 0.01 kg/(ha.yr) means that the land uses in the catchment to which the export coefficient applies are such that, on average, 0.01 kg of phosphate will enter the local water resource from each hectare each year. Detailed modelling of a catchment, such as performed using the SWAT, potentially gives more detail on constituents such as phosphate entering the local water resource. On the other hand, an export coefficient is easier to obtain and gives some insight into which catchments are likely to be the most problematic, i.e. contribute the most to downstream loads. However, they do not typically indicate the likely source. Nevertheless, they are potentially useful and relatively straightforward indicators of potential nonpoint source impacts of land use on water quality. Export coefficients can be gleaned from the literature, and a lookup table of available export coefficients covering phosphates, nitrates and suspended solids is provided. However mass of pollutant exported can vary greatly based on local variables, such as climate, soils and management, such that universal application has limitations. Thus, a method to calculate export coefficients is presented as a case study, with data requirements also listed. This study was undertaken in the upper Olifants catchment. Predicted

values (based on land cover data) were compared with measured values (determined at DWA water quality monitoring stations). Differences could be explained, for example, by the presence of large impoundments or significant point sources. The investigation confirmed that the use of export coefficients is potentially a useful tool in catchment-level planning for identifying land uses with high pollution potential.

Application of the SWAT model in the upper Olifants Catchment

Given the concerns of eutrophication in Loskop and other dams in the upper Olifants catchment, the hydrological and water quality model, SWAT (Soil Water Assessment Tool), was used to: a) identify the spatial and temporal trends in nutrient loading in the system, b) determine the relative contribution of point and nonpoint sources to phosphate loading in the system, and c) to test the impact of phosphate reduction scenarios on loading of Loskop, Middelburg and Witbank dams. The SWAT model was able to provide good simulations of flow (particularly in catchments located in close proximity to the weather stations) and nutrient loading processes. The model successfully identified catchments responsible for high ortho-phosphate loading as well as point sources and land use activities responsible for high phosphate input (i.e. agriculture and mining). The model also identified temporal processes (i.e. an extended dry period that led to low dam levels followed by high nonpoint source input at the beginning of a relatively wet period) leading to the onset of eutrophication in Loskop Dam. The model simulated load reductions in major dams associated with the implementation of the 1 mg/l ortho-phosphate standard at WWTWs and identified dams and also identified the main sources (i.e. point source versus nonpoint source) and land use activities responsible for phosphate loading. A number of factors were identified for improving the model. Incorporation of additional weather stations as model input could provide a far more accurate representation of spatial weather conditions which will undoubtedly improve flow simulations in sub-catchments across the main catchment. Improved knowledge of sediment loads and concentrations could help improve calibration of phosphate loading. Automated calibration as opposed to manual calibrations (which is extremely time-consuming) may also help to refine model input parameters. Improved knowledge of dam releases (and daily extraction volumes from each dam) could provide more accurate simulations of phosphate concentrations in the dams. Finally, a sensitivity analysis of input parameters would allow for further improved calibration by identifying those parameters that have the greatest influence on model outputs and ensuring that the information used for these parameters is as accurate as possible.

Bayesian Networks

Water resource management is complex, and should ideally be a co-operative, stakeholder-driven problem-solving process. Addressing real-life problems relating to water quality management requires as much attention to quantitative detail (such as in the type of deterministic catchment modelling described above) as it does to the kind of mindset with which problem solving is approached. Stakeholder participation is now widely recognised as critical to successful management. One participatory tool that is increasingly being used to facilitate this process is the use of Bayesian networks. The upper uMngeni catchment in the province of KwaZulu-Natal, eastern South Africa, is a key water resource area, characterised by looming water quality problems. The high number of stakeholders involved with a Catchment Management Forum provided a suitable environment for testing the development of a Bayesian network of the relationship between water quality problems and stakeholders in this area. Through engagement with stakeholders at quarterly meetings during 2011, and collation and analysis of water quality time series, qualitative and quantitative data were successfully translated into a Bayesian network

for water quality improvement in the study area. The model demonstrated that certain water quality variables (for example, waste water treatment works compliance; cumulative housing developments in the catchment) were more likely to be the cause of problems than others, and that these should be addressed as the greater priority. A number of management interventions were objectively assessed, with wetland rehabilitation as a suitable option in the context of this study. Such an approach highlighted the value of involving stakeholders in a co-operative process.

6. CONCLUSIONS

1. This project demonstrates that tools, techniques and expertise required to lead modelling efforts designed to illuminate socially robust (i.e. actionable) options with respect to land use impacts on water quality are present in South Africa.
2. However, this project also revealed that without continuous multi-sector stakeholder modelling engagement the socially robust (i.e. actionable) knowledge to required take us forward will not be generated.
3. Post-normal science paradigms are therefore crucial to adopt if we are going to utilise the available technologies in a manner that leads to socially robust (i.e. actionable) knowledge.
4. Monitoring systems by various stakeholders need to be harnessed in concert with one another for ongoing model use and implementation of agreed courses of remedial and preventative action by the stakeholders.
5. While data and information for the pursuit of modelling land use impacts on water quality are often not complete and, in many cases, sparse, societal actors need to utilise modelling to enhance their scientific conversations.
6. The team was successful in implementing a variety of modelling approaches in the case study catchments. All models varied in their application context and had strengths and weaknesses. The assessment of these models provides a guideline on their suitability for making decisions related to water quality impacts on land use. Ultimately, the choice of model is generally dependent on the nature of the problem and the level of detail required to make a decision.
7. Through the application of different modelling approaches, the project team concludes that it is not necessary to develop new models. There are a number of freely (open source) and commercially available options that have undergone intensive research and development and have been proven to be effective in making decisions related to land use impacts on water quality throughout the world.
8. This project showed unequivocally that the areas for future research are not technical but relate to how the technology is engaged by the multi-stakeholder sectors. This includes a need for a deeper understanding of the use of 'models', 'modellers' and 'modelling' in helping make better decisions related to managing the impacts of land use on water quality.

7. RECOMMENDATIONS

- The data paucity and the value laden nature of the issues make it imperative to work according to the paradigms present in post-normal science and those which seek to generate socially robust knowledge in a context of 'wicked' problems. The priority areas for future research are therefore in using these technologies in participatory agent-based social simulation modelling within the world class policy, legal and institutional frameworks which South African's have created since 1994.
- In this respect the development and implementation of a national business model that promotes the use of common software and common databases across multiple sectors and stakeholders is essential with regards to generating socially robust knowledge.
- While data was available for running more complex hydrological models with high data requirements, it was often spread across multiple domains and was often difficult to source and obtain. While an entire project could focus on populating the SWAT databases for easier use in South African conditions, in general, it is recommended that a central point (e.g. database) be established to serve as a portal for users to link to relevant institutions or online data to ease access for water quality modelling initiatives.
- The completeness and sufficiency of the available geospatial datasets for water quality modelling in South Africa remains to be evaluated. It is recommended that this evaluation be conducted within the context of the development of a national business plan that promotes the use of common software and common databases across multiple sectors and stakeholders.
- Export coefficients were identified as a useful first tier assessment of identifying land use impacts on water quality. However modelling applications in the case study areas relied on international values. Mass of pollutant exported can vary greatly based on local variables, such as climate, soils and land management, such that universal application has limitations. A method to export coefficients was successfully implemented in the upper Olifants catchment and consideration should be given to applying this method more widely to develop local, catchment specific export coefficients for South Africa.
- In the interests of promoting continuous multi-sector stakeholder modelling engagement that generates socially robust (i.e. actionable) knowledge to take us forward, it is recommended that a workshop involving top level executives and their water advisors needs to be held. The participants should be the calibre of people who are involved in water/food/energy Nexus conversations and those who are involved in Systemic Risk conversation. The messages to stimulate discussion in this workshop need to be those contained in this Executive Summary.

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GLOSSARY

Absorptive Capacity. A set of organisational routines and processes by which organisations recognise the value, acquire, transform or assimilate, and exploit knowledge to produce a dynamic organisational capability.

Base cartographic data. “BASINS’ base cartographic data include administrative boundaries, hydrologic boundaries, and major road systems. These data are essential for defining and locating study areas and defining watershed drainage areas.” (BASINS Help Files)

Community of Practice. A community of practice is a group of people who share a passion and meet regularly and informally to learn and practice how to do things better. A community of practice typically emerges in a bottom-up sense. Their usefulness and adaptability fundamentally depend on this ability to self-organise. However, this property does make them vulnerable to heavy-handed top-down management. Useful constructive communities of practice must be nurtured.

Complex. Refers to systems that are self-organising and adaptive. System-wide behaviours or properties emerge which can be unpredictable. These emergent properties are maintained by feedback mechanisms. Examples: Social systems, ecosystems.

Complicated. Refers to systems of many individual parts whose individual interactions are understood sufficiently well to be able to predict and understand the overall behaviour of the system. Examples: Aircraft; clock; computer.

Deduction/deductive reasoning. Reasoning from the general to the particular (cause to effect).

Ellipsoid. Refers to a smooth mathematical surface that best fits the shape of the geoid and is the next level of approximation of the actual shape of the earth. A **spheroid** is a shape that is generated by rotating an ellipse around one of its axes.

Emergence. See Complex.

Environmental background data. Environmental background data provide information to support watershed characterisation and environmental analyses. These data include information on soil characteristics, land use layers, and the stream hydrography. This information is used in combination with modelling tools to perform more detailed assessment of watershed conditions and loading characteristics.

Environmental monitoring data. Refers to environmental data products developed from existing national water quality databases for use in BASINS. In BASINS “these databases were converted into locational data layers to facilitate the assessment of water quality conditions and the prioritization and targeting of water bodies and watersheds. These data can be used to assess the current status and historical trends of a given water body and also to evaluate the results of management actions.”

Geodetic datum. A Geodetic datum consists of a defined geodetic reference ellipsoid, and a defined orientation, position and scale of that Geodetic Datum in space. <http://www.ngi.gov.za/index.php/Geodesy-GPS/datums-and-coordinate-systems.html>

Geoid. A smoothed representation of the earth’s irregular shape used for computational purposes. <http://www.ngi.gov.za/index.php/Geodesy-GPS/datums-and-coordinate-systems.html>

Geospatial data. Refers to spatial features pertaining to the earth.

Inference/inductive reasoning. Reasoning from an observation to a general statement (effect to cause).

OpenMI Standard. The Open Modelling Interface Standard is an open source standard which defines an interface that allows time-dependent models to exchange data at run-time. It was created with the intent to facilitate model integration which contributes to an integrated approach to environmental management. The OpenMI standard allows any OpenMI compliant model to exchange data with any other compliant model. It defines a standardised way to exchange data between models and allows them to run simultaneously, with data being exchanged between models at run time.

Point Source/Loading data. “BASINS also include information on pollutant loading from point source discharges. The location, type of facility, and estimated loading are provided. These loadings are also used to support evaluation of watershed-based loading summaries combining point and nonpoint sources.” (BASINS Help Files)

Projected coordinate systems. These use metric space to refer to the position of features in geospace. Examples include metres from the equator and central meridian. Projected coordinate systems are used in geospatial analyses and measurements.

Social learning. “Social learning theory” is the theory that people learn new behaviour through observational learning of the social factors in their environment. If people observe positive, desired outcomes in the observed behaviour, then they are more likely to model, imitate, and adopt the behaviour themselves. It derives from work that proposed that social learning occurs through close contact, imitation of superiors, understanding of concepts, and role model behaviour. (See

http://en.wikipedia.org/wiki/Social_learning_theory)

Socially robust knowledge. Knowledge that is socially acceptable on which people are prepared to act. It should be distinguished from “reliable scientific knowledge” which, although objective and agreed on by scientists (which should always be strived for), may sometimes fail to impress those outside the scientific community. It is a context-specific integration of reliable knowledge and social knowledge. It is usually the product of intensive (and continuous) interaction between results and interpretation, people and environments, applications and implications (Nowotny, Scott & Gibbons, 2001).

Topology. Refers to the recognition of connectivity of features in a database. Examples: two road or river arcs should be connected with only one node. If not connected, no topology exists, and the two features would not be seen as connected. Two polygons should share a single boundary and the database should register their location relevant to the shared boundary. Otherwise adjacency cannot be detected.

Unprojected coordinate systems ...use locational information to refer to the position of features in geospace. Examples include latitude and longitude references such as degrees, minutes and seconds, or decimal degrees. Unprojected systems are used for small areas to indicate location.

ACRONYMS

ACRU	Agricultural Catchments Research Unit
AMD	Acid Mine Drainage
ARC-ISCW	Agricultural Research Council's Institute for Soil Climate and Water
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BMP	Best Management Practice
CGS	Council for Geoscience
CMA	Catchment Management Agency
CMF	Catchment Management Forum
CoP	Community of Practice
CSI	Committee for Spatial Information
CSIR	Council for Scientific & Industrial Research
DAFF	Department of Agriculture, Forestry and Fisheries
DEM	Digital Elevation Model
DRDLR	Department of Rural Development and Land Reform
DRDLR-NGI	Department of Rural Development & Land Reform's National Geo-Spatial Information Directorate
DUCT	Dusi-Mgeni Conservation Trust
DWA	Department of Water Affairs
ESRI	Environmental System Research Institute
ET	Evapotranspiration
FAO	Food and Agricultural Organisation (FAO)
GDEM	Global Digital Elevation Model
GIS	Geographic Information System
GPS	Global Positioning System
GWP	Global Water Partnership
HSPF	Hydrologic Simulation Program – Fortran
ISRIC	World Soil Information organisation
IWRM	Integrated Water Resources Management
LAI	Leaf Area Index
LDADA	Land Degradation Assessment in Drylands
LULC	Land use/land cover
LUMS	Land Use Management System
MDB	Municipal Demarcation Board
NGI	National Geo-Spatial Information
NWM4	National Wetland Map v.4
NWRS	National Water Resources Strategy
PLOAD	Pollutant Loading

RD	Root Depth
SAC	Satellite Application Centre (former unit of the CSIR)
SANBI	South African National Biodiversity Institute
SANS	South African National Standard
SANSA	South African National Space Agency
SASDI	South African Spatial Data Infrastructure Act
SASS	South African Scoring System
SAWS	South African Weather Services
S & CRHP	Schools & Citizens River Health Program
SRTM	Shuttle Radar Topography Mission
SSA	Standards South Africa
SWAT	Soil & Water Assessment Tool
SWMM	Storm Water Management Model
TMDL	Total Maximum daily Load
UNEP	United Nations Environment Programme
US EPA	United States Environment Protection Agency
USGS	United States Geological Survey
WGS84	World Geodetic System of 1984
WMA	Water Management Areas
WMS	Water Management System
WRC	Water Research Commission
WWTW	Wastewater Treatment Works

CHAPTER 1: PROJECT BACKGROUND

1.1 INTRODUCTION

Water is a limited resource in South Africa and hence strong competition exists between different land use practices. This inherently poses challenges in the way that water and land is managed. Each land use has specific requirements in terms of water quantity and quality and specific outputs that in turn influence water quantity and quality. For example, the mining sector which makes a significant contribution to the South African economy represents approximately 6% of the total water requirements, yet by virtue of the nature of their operations runs the risk of delivering effluents and high loads of dissolved salts and heavy metals to local water resources (Ongley, 1996). Urban land-use requires water of adequate quantity and quality to support processing to potable and industrial standards yet generates effluent (stormwater, sewerage) that ultimately is returned to the stream network and thus has the potential to alter natural water quality. Similarly other land use practices may exert direct and indirect influences on local or even regional water resource quality.

The key then is to understand the relative influence that land use practice has on water quality and then manage the risks accordingly. Until recently such responsibility has been spread amongst different authorities with sometimes varied perspectives, which have caused major challenges in effective governance. For the combined benefit of the various economic, social and environmental sectors, a holistic perspective to both land and water management must be adopted. This, however, is not a simple task as multivariate factors influence the reasoning and decision-making process, which ultimately should rest with an informed, impartial and knowledgeable body or entity. With the advent of the CMA and CMF there is a move towards a more streamlined approach in catchment management and ultimately water quality. For CMAs to fulfil their mandate, however, it becomes critical that they are armed with the necessary integrated knowledge and tools that encompass all relevant catchment data and management requirements of not only themselves, but environmental authorities and other stakeholders. This ensures that all CMAs, which manage integrated water systems, are working with an integrated system understood and trusted by all. Such a system would allow data and knowledge sharing, knowledge equity and transparency among all stakeholders, data compatibility across institutions and would secure institutional knowledge and memory and methodologies within a framework, rather than allowing them to rest on the shoulders of a few individuals.

For effective water resources management it is impossible to separate land use, human behaviours, water quality and water quantity issues. They are all integral aspects of an integrated and interconnected, complex system. The study, management and use of such systems require that stakeholders acknowledge their inherent unpredictability and learn the predictable behaviours of such systems and the consequences of human behaviours. Our water and environmental policies and laws recognise this and mandate that water and environmental systems be managed as an integrated whole. They also detail the required institutional arrangements.

1.2 OBJECTIVE AND AIMS

This project specifically addresses the link between land use and water quality in water resources. The strong competition between land use practices because of water limitations poses difficult challenges for how both resources are managed. One key aspect that can contribute to such management is a sound understanding of how land use can affect water quality and how this in turn can affect, and indeed, determine, downstream land use. This project attempts to provide the necessary social learning processes and technologies to develop and use this critical knowledge to the point that it becomes socially robust and hence engenders wise management actions.

Recognising the strong relationship between water quantity and quality, the objective is to better understand the implications of particular land uses for water quality and to develop tools that improve spatially explicit decision making about water resource and aquatic ecosystem management at catchment level.

The aims of the project are to:

1. Identify and critically review land use classification system/s currently available in South Africa for their applicability and utilisation within the project.
2. Review and categorise land use types within the selected land use classification system with regards to their potential impacts on water resource and ecosystem health.
3. Develop tools and guidelines to guide and improve decision making by relevant management stakeholders with regards to the potential impacts of different land uses on water quality.
4. Test and refine the developed tools through two case study catchments to improve the decision making of management stakeholders.
5. Build the capacity of the relevant management stakeholders at catchment and national level to improve Integrated Water Resource Management.
6. Recommend priority areas for future research within the scope of the effects of land use management on water resource quality.

1.3 PROJECT APPROACH

Given the broad and diverse nature of the land use – water quality nexus, the choice of tools and guidelines aimed at facilitating improved and more informed decision making is inherently a difficult one. There are many relevant issues ranging from technical to environmental, social, economic, and potentially political. Specifically, tools are envisaged as modelling software platforms or shells as they are sometimes referred to. It must be able to address:

- The increasingly urgent need for more effective land use and water quality management;
- The wide variety of potential application contexts; and
- The need for the development and sustainable use of the platform/shell to make financial sense in the short- and long-term.

The approach in achieving the objectives of this project focussed on two significant thrusts. The first is centred around the technical and scientific relationships that exists between land use practice and in-stream water quality, (i.e. knowledge of the way the natural system functions and a reasonable assessment of how perturbations in this system are interpreted). These relationships

are generally captured in the form of predictive models that attempt to elicit/predict/estimate the likely impact of land use or land management practices on water quality. These models typically vary in their complexity, data requirements and uncertainty related to predictive outputs (i.e. small to large uncertainty).

The second and critically important thrust is the integration of the predictive outputs of these models in a manner that *is objective yet transparent* enough to develop a reaction plan or *forward thinking perspective* that is embraced by *all stakeholders*, initially at the catchment level, which may then be up-scaled to the regional or national platform. Thus the gap between science and management needs to be closed in pursuit of an integrative yet robust reasoning platform that is understood and endorsed by all. Thus, throughout this project we have made the case that a new paradigm is needed because of the complexity, the dynamics, the multiple stakeholders and the widespread paucity of data plus the urgent need for behavioural change with regard to land use and its effect in water quality. If the objective of a technical modelling exercise is merely to assess how closely the model output for particular variables predict the observations of these variables in observed data, then we are faced with a very technocratic data-driven approach. However, when models are being used to enhance and guide co-reasoning about future possible consequences of past, present or future actions the view on data, models, modellers and modelling must become more mature and nuanced. What we mean by this is that if societal actors are to only move into “spaces” where there is already plentiful sound data then we are going to be “inhabiting” a few research plots at best and no places at worst. The truth is that we have to learn to reason in extremely data scarce environments. Our existing monitoring networks are declining, so if we wait for monitored data we can only look backwards and as the trends in data collection show, to increasingly small geographical site-specific areas. A key to this new paradigm is the notion of post-normal science and socially robust knowledge which is also known as actionable knowledge. Data and how the stakeholders view data is at the centre of this paradigm change. Concerned stakeholders will never get the funds and certainly not the time to monitor all the necessary variables until we have a full observed data set for the models which are so vital to our learning, institutional memory, dialogues, surfacing of assumptions and integrated insights that will engender action imperatives. This is where post-normal science paradigms are so vital to adopt. We need to use default values to start the multi-stakeholder engagement, dialogue, thinking and learning processes. We then need to use values that are estimates surfaced in our imaginations to feed into our systems thinking, primarily via the models, to enhance our learning towards behavioural change.

There is no doubt that more site-specific data collection is needed as stakeholders move into the future. However, if stakeholders run around aimlessly spending large sums of money collecting data which multi-stakeholder funding bodies cannot justify then the funding for such efforts will soon be cut off, as indeed it is at present. Stakeholders need to use models to guide their data collection efforts and in this regard sensitivity analyses that are greatly assisted by modelling are crucial. Translating this into practical operations, wisely guided data collection is highly dependent on answers to the “*what if*” question posed to the multiple stakeholders as they co-model. Co-modelling in other words is not an academic playground but a hard-nosed operational necessity for stakeholders who wish to tread into the future with their eyes and minds open.

A related project, largely in response to the same issues and concerns on impacts of land use on water quality, is currently being undertaken by the Institute of Natural Resources, Pietermaritzburg, on behalf of the Department of Water Affairs. The project, titled ‘*Assessing the impact of land-*

based activities on water resources' is a practical response to Chapter 3, Section 12 of the National Water Act of 1998, which enables regulation of land-based activities to protect the water resource. The project considers impacts on water quality by nonpoint and point pollution sources, water quantity by volumes of water used, with additional consideration given to biota and habitat in very broad terms. The DWA project is complementary to this current WRC project, in that its aim is to act as a screening tool for prioritizing quaternary catchments for further monitoring and water quality modelling."

1.4 REPORT STRUCTURE

Chapter 1

Introduction: This chapter includes the project background, aims and approach

Chapter 2

This section describes the techno-social dynamics that water quality and land use models need to accommodate. The purpose is to explore and describe the ultimate ideal institutional and technical landscape to ensure modelling efforts are properly focussed and result in meaningful inputs to decision making.

Chapter 3

The purpose of this chapter is to introduce users to philosophical concepts behind modelling and the types of tools available for decision making. Examples of the application of all modelling tools presented here are presented in Chapter 5 (reference to these case studies is made in information boxes). This chapter is intended to guide users on the type of model they may wish to use, depending on the data they have available or the type of decision that needs to be made. This can be facilitated by use of the Reasoning Support System matrix presented in Appendix A of this report.

Chapter 4

In Chapter 4 we explore the literature to assess how land use relates to water quality modelling, in response to the first aim of this project. A distinction is made between land use, associated with management practices influencing water quality, and land cover, which can be observed and mapped through earth observation technologies. We listed shortly some general information of geospatial data to the user to improve their understanding and knowledge of geospatial data pertaining to water quality modelling, with metadata of nationally-available geospatial datasets available in South Africa for water quality modelling in Appendix B.

Chapter 5

This chapter describes applied modelling exercises carried out in two case study catchments (the upper uMngeni and upper Olifants river catchments) during the course of the project using models/systems described and discussed in the preceding chapters. These exercises provided hands-on contexts in which various models and approaches could be tested. They are described in detail so that the reader can achieve deeper insight into the necessary processes and the kind of problems that can be encountered.

Chapter 6

Conclusions and Recommendations

CHAPTER 2: LAND USE IMPACTS ON WATER QUALITY – THE NATIONAL CONTEXT

2.1 INTRODUCTION

Building institutional capacity implies the need for the development of a sustainability plan, which explicitly recommends how the application of the outcomes and outputs of this project, can be made sustainable after the project ends. It was evident to the project team, from the outset, that if the project outcomes and outputs were at variance with the emerging and evolving National context in which land use and its effect on water quality was going to have to be addressed then the outcomes and outputs of this project would be ignored by the multiple stakeholders and hence the outcomes and outputs of the project would not be sustainable.

This Chapter 2 sketches the National Context which is constructed from a mixture of facts held together by what we consider to be a soundly reasoned matrix of informed speculation. It has been necessary to create this clearer vision of the emerging National Context, the key points of which are explained briefly in Sections 2.3 to 2.6 below, because it is in the light of this National Context that the sustainability of the outcomes and outputs of this project need to be assessed.

2.2 INFORMED DECISION MAKING

The ultimate aim of this project is to enable a better understanding of the interrelationships between land use and water quality to form in the collective mind of appropriately skilled agents acting on behalf of each of the major sectors in a catchment. It is envisaged that this will improve land use planning, water quality management, and ultimately water resource management in the Water Management Areas (WMAs) in South Africa.

Given that such planning and management is not currently happening to the extent necessary, it is also envisaged that to achieve the above a significant mindset and associated behaviour change will be necessary. This has significant implications for how and how quickly the vision might be achieved.

2.3 INTEGRATED WATER RESOURCES MANAGEMENT (IWRM)

There is wide spread recognition for the IWRM imperative, as the following few extracts from UN sources indicate.

“The traditional fragmented approach is no longer viable and a more holistic and coordinated approach to water management is essential. This is the rationale for the Integrated Water Resources Management (IWRM) approach that has been accepted internationally as the way forward for efficient, equitable and sustainable development and management of the world’s limited water resources”.

<http://www.undp.org/water/priorityareas/resource.html>

“At the 4th World Water Forum in Mexico (2006) it was reported that out of 95 countries examined, 74 percent either had IWRM strategies in place or had initiated processes for the formulation of such strategies”.

UNESCO (2009)

IWRM involves complex socio-economic & socio-ecological processes that require healthy interaction from a full range of stakeholders, each of whom only have an element of knowledge on part of the complex systems involved. IWRM does not happen simply because stakeholders are knowledgeable. It depends intimately on processes of interaction between those stakeholders. In particular, social integration processes must be engaged continuously, transparently and honestly to transfer knowledge and translated it into realised IWRM capacity. In our case this is specifically actionable or socially robust knowledge on land use impacts on water quality.

2.4 AN ENABLING INSTITUTIONAL ENVIRONMENT

The exact nature of the institutional environment will be critical to the uptake and on-going effective use of a shell. There are two core components to this environment. First, there are the players themselves. Second, there is the institutional environment in which they operate. These are not entirely mutually exclusive. The players themselves, in particular their behaviour, can contribute significantly to the overall enabling environment.

Ideally the “enabling environment” should be one that is conducive to self-organisation and the emergence of a national “community of practice” closely connected to the existing and growing international community of practice. Its core interest is better land use and associated water quality management through the application of agreed processes and technologies.

One thing that can help create enabling conditions is a degree of common language. It should help different stakeholders communicate with each other, which in turn improves the diversity of thinking so necessary in the complicated and complex land use – water quality arena.

2.5 WALKING TOGETHER

It is obvious that no single individual, organization, sector, government department, scientific discipline will have the ability (nor the required absorptive capacity) to succeed on its own. It is imperative that we stop working in fragmented isolation. The Dinokeng Scenarios made it clear that “Government, Business & Civil Society Must Walk Together”.

The migration of knowledgeable people in South Africa, first articulated by DWAF/UNESCO/WMO (1998), can be perceived as a problem. However, the 1997 National Water Policy and the 1998 National Water Act provide the policy framework for bringing dispersed water-related skills back into integrated focus. They do this specifically through the CMAs and their Boards. The latter should have access to, and be advised by their “sector advisors” who form one component of the migrated “knowledgeable people”. Within this model, DWA plays an oversight role for the multi-sector stakeholder engagement process and makes final decisions based on reasoned, triple-bottom-line-compliant options that emerge from these processes. DWA is also intimately guided by the National Water Resources Strategy (NWRS). These sector advisors could play critical roles (e.g. “gatekeeping”) in creating and maintaining the necessary absorptive capacity generally, and specifically in respect of a frameworks approach.

Evidence is beginning to appear that sectors are making increasing use of consultants to perform water-related work that is crucial both to their resource needs and their corporate social responsibility imperatives. There are also tangible signs that these advisors are coming into contact with one another more frequently and on water issues of increasing gravity. A new transformational dynamic in the intellectual underpinning of South Africa's budding CMAs is also emerging. This offers hope and direction for fulfilment of the dreams of the visionaries who created our 1997 National Water Policy and 1998 National Water Act.

These advisors, other stakeholders in their sectors and the CMAs can all comprise the network of the players referred to above which can self-organise for maximum effectiveness if their institutional environment is sufficiently enabling to allow this. The insights and guidance that emerge should feed directly into an effective and efficient DWA and ultimately cabinet and hence properly functioning water ecosystems and a better quality of life for all.

2.6 SUMMARY

The analysis presented in the supplementary Preliminary Conceptual Basis Report shows a national context characterised by growing recognition and acceptance of a variety of approaches and mindsets. The greater the degree of acceptance the more ideal the enabling environment will be for addressing the fundamental issues associated with a unified national approach to the land use and water quality nexus.

- **Acceptance of Strategic Adaptive Management for IWRM.** *“The practice of Strategic Adaptive Management (SAM) as a framework for IWRM in complex social-ecological systems”* Rogers and Luton (2012), will characterise interactions amongst stakeholders.
- **Recognition of dynamic complexity.** There is already some evidence of a growing recognition of the complex nature of the systems in which we live, in particular the inherent unpredictability associated with complexity. Indeed, this is the primary motivation for adaptive management.
- **Acceptance of post-normal science paradigms.** Post-Normal Science is the methodology that is appropriate when (a) facts are uncertain, (b) values are in dispute, (c) stakes are high and (d) decisions are urgent. Typically integrated catchment management has these attributes.
- **Acceptance of dangers posed by systemic risk.** Issues relating land use and water quality are intertwined in complicated and complex ways that create inherent systemic risk.
- **Focus on developing absorptive capacity.** Absorptive capacity is a set of organisational routines and processes, by which firms acquire, assimilate, transform and exploit knowledge to produce a dynamic organisational capability.
- **Recognition that socially robust knowledge generation is imperative.** This is knowledge that is socially acceptable on which people are prepared to act. It is a context-specific integration of reliable knowledge and social knowledge.

- **Recognition of need to evolve appropriate institutional forms.** Socially robust institutional forms are needed to build socially robust knowledge and strategies. Socially robust institutional forms require at least a policy, legal and ethical framework.
- **Use of participatory agent-based social simulation modelling.** This kind of modelling directly involves those actors who themselves will later use the model. The model captures subjective perceptions and expectations and the social and human elements of water resource management. The purpose of agent-based modelling is to aid intuition.
- **Need to develop resilience in society.** Resilience is the ability to bounce back after disaster strikes. Diversity plays a significant role in developing resilience.
- **In-kind financial and skills contributions to make IWRM affordable.** Our national policies pave the way for in-kind contributions. Many entities can make such contributions and many have the implicit mandate to do so by their water-related responsibility. A very wide variety of in-kind contributions can potentially be made, depending on the specific entity.

2.7 A POSSIBLE NATIONAL BUSINESS MODEL

The success of any venture that aims to introduce land use and water quality processes and technologies into the South African market will depend on the business model that prevails in the minds and in the actions of the role players. In other words, the processes and technologies for assessing the effects of land use on water quality will need to generate useful services and products and the provision of those services and products will need to make good business sense to the many service providers, catchment management stakeholders and government entities involved. A classic approach in business is to employ what is known as the Porter's 5 Forces Model to help shape the reasoning that underpins the strategic choice of a sensible business model to guide the role players.

In this section a preliminary analysis of the strategic business forces that will influence the choice of processes and technologies that are likely to be applied to land use and water quality matters, is conducted in terms of the Porter's 5 Forces framework. Porter identified five strategic forces that influence any industry. The core force is (1) the intensity of competitive rivalry within the industry. This is directly affected by the other four forces, namely (2) the threat of substitute services or products, (3) the threat of the entry of new competitors, (4) the bargaining power of buyers, and (5) the bargaining power of suppliers.

Some explanation of terms is required at this stage, to help make the link between the generic explanation of Porter's 5 Forces that is found in text books and academic journals and the specifics of the case involving multiple water stakeholders:-

- **Industry.** The "industry" in this case is made up of the set of role players, processes and technologies that provide the scientific services to the IWRM processes, in which land use and water quality matters are addressed, in the multi-stakeholder engagement spaces mandated by the 1998 National Water Act.
- **Products.** These are the outputs of the technology. Two kinds are envisaged:

- Un-interpreted basic (direct) outputs (maps, graphs, numbers, etc.) which typically the buyer would interpret.
- Interpreted (indirect) outputs (e.g. insights gained from modelling exercises that in effect add value to the model outputs). In this case the interpretation is done by the supplier and the buyer (top expertise in each of the engaging sectors).
- **Suppliers.** These are the ‘technology operators’ who are independent consultants and/or expert advisors who are employed in government, business and civil society organisations that are themselves stakeholders in the IWRM process in catchments. In the case of CMA stakeholder sectors that are closely connected within their sectors and across sectors, up to national level, these could be ‘in-kind’ contributions.
- **Buyers.** These are the leaders in the multiple stakeholder sectors (government, business, civil society) who are mandated to infuse the CMA engagement space with their sector’s contribution, which will include processes and products emanating from this WRC project.

The greater the competitive intensity the more attractive the market will be in the sense of overall industry profitability. However, this is the traditional profit-making view of business. While the potential for profit-making will be important at some levels in the above national scenario, it must be tempered by the fact that since the buyers and suppliers are, mostly, from the same organisations, the ultimate purpose is not profit-making but rather more aligned with the overall national interest of improved water quality at an affordable cost. The profit-making and the associated competition must be able to exist at the level of the suppliers. The following examines how the Porter’s 5 Forces Model might operate within the multi-stakeholder water engagement scenario described above.

- **The threat of substitute services or products.** There are presently, and will be in future, selected software products that will be able to provide substitute products (either un-interpreted or interpreted) in specific contexts, for example, a specific kind of map or model. There are a number of possible scenarios.
 - The substitute product is only a subset of the overall potential products scope of the chosen integrated modelling platform. There are two possible outcomes:
 - The substitute product will not be used because use of the equivalent existing component of the integrated platform is preferred (possibly because it is within such an integrated system).
 - The substitute product is incorporated into the integrated platform thus providing an alternative module to the existing product.
 - The substitute product is another comprehensive integrated modelling platform. There are two possible outcomes.
 - The new product is preferred by the multi-stakeholder market players and takes over as the preferred platform.
 - The new product is not adopted by the market because of the sunk costs in the existing product. These sunk costs could include information on rainfall and other climate factors, soils, land use, abstractions, return flows and their quality, dam operating rules, stream channel configurations and wetlands.
- **The threat of entry of new competitors (i.e. suppliers).** The more profitable the industry the more attractive it will be to new entrants. The most attractive market segment (for profit-making) will be one in which entry barriers are high (which make it difficult for new

entrants) and exit barriers are low (making it easy for non-performers to exit). If emphasis is placed on the interpreted (e.g. modelling) outputs, then good modellers could create a high entry barrier, thus maintaining their market share soundly on the basis of a better value-added product. However, the large potential size of the market means that new entrants could differentiate themselves from existing suppliers on the basis of the kind of modelling they do. This could create a healthy degree of competition. On the other hand, the size of the market could also create opportunities for a number of suppliers who provide un-interpreted (basic) products although they would probably only compete with one another on the basis of the geographical location and proximity to individual buyers.

- **The bargaining power of buyers.** The buyers (government, business and civil society sector role players in the CMA engagement space) will prefer a single effective platform so that sunk costs in its development (software as well as data and model-generated information sets) are not lost. However, they will prefer the costs of using the platform to produce the products, either un-interpreted or interpreted, to be more market-based so that they can choose between suppliers.
- **The bargaining power of suppliers.** Suppliers can sometimes be in a position to exert pressures on the buyers who they supply when there are few substitute suppliers. A healthy situation exists when there are many suppliers competing for the buyer's business. In the CMA engagement space scenario, the wide range of supporting data potentially required by the integrated platform creates an environment in which many suppliers could exist. For example, some organisations may be able to produce better quality monitoring data or more accurate and reliable modelling parameters than others. There is therefore potential for healthy competition between suppliers.
- **Intensity of competitive rivalry.** Each of the above four factors can affect the intensity of competitive rivalry. It is evident that competitive rivalry can exist between suppliers. This potentially healthy situation bode well for a successful business model within which the processes and products recommended in this project will be important.

An example of a modelling shell which strongly supports fundamental issues required to develop a successful national business can be viewed in Chapter 3 of this document:

Chapter 3.8.1 BASINS 4.0

2.8 ABSORPTIVE CAPACITY ISSUES

The project team will need to be cognisant of the inherent capacity of envisaged stakeholders to adopt and effectively use a framework. This capacity, and specifically the possible lack of it, will have implications for uptake by those organisations and hence the potential success of this project. This is known as 'absorptive capacity'. This section describes some of the issues.

2.8.1 What is absorptive capacity?

Absorptive capacity has been defined as “a set of organisational routines and processes by which organisations recognise the value, acquire, transform or assimilate, and exploit knowledge to produce a dynamic organisational capability” (Todorova and Durisin, 2007). Dynamic capabilities reflect “a firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments” (Teece et al., 1997).

In the current context the project team will want individuals and organisations to “recognise the value” of the knowledge embedded in the frameworks suggested. We will want them to “acquire” that shell (and hence knowledge), “transform” it if necessary to their specific circumstances or “assimilate” it into their “routines and processes” and “exploit” it. In so doing they should be able to “produce a dynamic organisational capability” that is better placed to address the challenges of dealing with the land use – water quality nexus.

The construct was first introduced over 20 years ago (Cohen and Levinthal, 1990) and has been acclaimed as one of the most important constructs to emerge in organisational research in recent decades (Lane et al., 2002). It has been reconceptualised at least twice in which the link with a “dynamic organisational capability” was made and strengthened (Zahra and George, 2002; Todorova and Durisin, 2007).

Zahra and George (2002) identified a variety of components of absorptive capacity, an important one being *understanding*. The current project is ultimately about facilitating informed decision making. The latter is only achieved by increasing the understanding of decision makers of underlying reasons for, and possible consequences of their decisions. The full nature of “understanding” and how it emerges are elusive, as indicated by the following:

“Efforts at analysis, i.e. focusing on the parts, lose the ability to highlight their emergent properties. Knowledge can come from analysis of the parts. But understanding comes from synthesis and a systems approach. There is a danger with emergence that people will begin to treat emergent properties as discrete elements or parts. That trend leads back to fragmentation and the loss of attention to the whole. But a full understanding of the whole escapes us. It will always be partial and subjective. It escapes at this point into mystery. Systems thinking is thus always struggling to balance mystery and mastery, between failing to understand anything of significance and claiming to understand everything.”
Morgan (2005)

Zahra and George (2002) also noted that one component of the exploitation of knowledge is *implementation*. Thirteen years after the National Water Act was enacted, there is clear evidence that Integrated Water Resource Management will not just happen because there are good policies, laws & better knowledge of the science. Implementation will depend on absorptive capacity, itself likely to be an emergent phenomenon.

2.8.2 Creating a receptive institutional environment

Of particular importance to the project team is that creating and maintaining absorptive capacity has a number of important considerations (Murray et al., in press). They all relate to nature of the

capacity, and its creation, in the institutional environment within which a shell is envisaged to operate.

- First is the importance of “in-house prior related knowledge”. This means that the ideal situation is that some knowledge already exists in the individual and organisation that is related to what a software package or system has to offer, for example, some knowledge relating to GIS and water resource modelling would be useful.
- Second is the importance of informal knowledge transfer. Social integration mechanisms and the associated social learning opportunities they create will be important considerations to supplement typical formal mechanisms (such as training courses). It must be recognised that face-to-face communication in a social context is an important alternative knowledge transfer mechanism.
- Third is the need for motivation and intensity of effort on behalf of the stakeholder. This should not be underestimated. In effect, this is a “no pain, no gain” message.
- Finally, the importance of ‘gatekeepers’ should be acknowledged. These people typically serve as an interface between the internal system and the external knowledge sources and will be critical to advocating the value of a system within their organisations. They often need to be people with special talents.

These issues are particularly important for aim number 5 of the project, namely “*Build the capacity of the relevant management stakeholders at catchment and national level to improve Integrated Water Resource Management*”. The issues give explicit focus for engagement with stakeholder organisations.

2.9 GUIDING PROFOUND CHANGE

The task of improving land use and water quality management in the nation’s interest is a demanding one. The project team will, in effect, be playing a leadership role in this respect. While the above few principles will be useful in guiding some aspects of stakeholder engagement, a more fundamental philosophy may be useful. Accordingly, the team will acknowledge “Theory U” originally developed by Otto Scharmer and described on the web site of the Presencing Institute (PI) <http://www.presencing.com/index>. The PI is a global awareness based action research community for profound societal innovation and change. The reader is encouraged to examine this site and the available downloads. The following is taken mainly from this web site.

Presencing, a blend of the words “presence” and “sensing”, refers to the ability to sense and bring into the present one’s highest future potential—as an individual and as a group”. Figure 2.1 illustrates the presencing journey. One moves:

1. Down one side of the U (connecting to the world that is outside of our institutional bubble)
2. To the bottom of the U (connecting to the world that emerges from within) and
3. Up the other side of the U (bringing forth the new into the world).

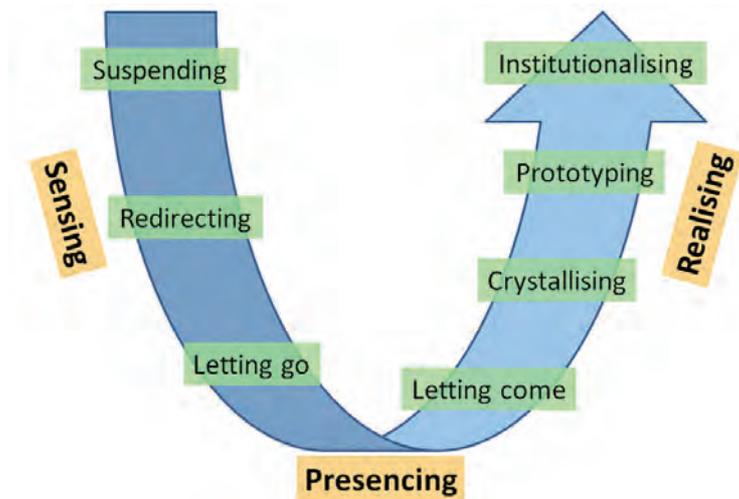


Figure 2.1: The core stages and required leadership capacities of Theory U (after Senge et al., 2005).

Although Figure 2.1 is the barest summary of the theory (it has evolved in some detail, for example, in Senge et al., 2005), its essence is clear. Leadership requires suspending preconceptions, listening to stakeholders with empathy, listening carefully to one's inner voice, inevitably letting go of previous ways of doing (perhaps by both "them" and "us"), allowing the new to emerge, crystallising it, prototyping (modelling) it and institutionalising it.

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CHAPTER 3: TOOLS THAT LINK LAND USE AND WATER QUALITY FOR EFFECTIVE ECOSYSTEM MANAGEMENT

3.1 INTRODUCTION

One of the main objectives of this project is to enable relevant stakeholders to make better informed decisions on the impacts of land use on water quality through providing an assessment of tools that integrate principles of cooperation, transparency and inclusivity amongst relevant stakeholders, with sound science that links land use and water quality. These scientific tools and methodologies describe the nature of land use and water quality interactions at a catchment level, thereby improving the ability of water resource managers to systematically make informed water management decisions and informed inputs to various land use based policies and strategies.

At a basic scientific level, managing and or mitigating the effects of land use activities on water quality requires the identification and quantification of sources of pollutants linked to specific land use activities. Ideally this is done through monitoring water quality downstream of specific point sources or land use activities. In terms of point sources this is a relatively simple logistical task as the location of discharge outlets of, e.g., waste water treatment works, are generally well known. Identifying and quantifying pollution derived from nonpoint sources is however far more complicated. This is because nonpoint source pollution is derived from a large surface area which is often heterogeneous in terms of the land use activities taking place in the catchment. Furthermore, the magnitude of nonpoint source pollution is influenced by a number of geographical factors which can vary from one catchment to another, which can make the process of linking land use activities to water quality impacts particularly challenging.

Given the broad and diverse nature of the land use – water quality nexus, the choice of ‘reasoning support system’ to facilitate more informed decision making is inherently a difficult one. There are many relevant issues ranging from technical to environmental, social, economic, and potentially political. In response to these challenges, a number of tools and models have been developed that rely on different levels of technical/scientific/information input (from low to high detail), depending on the nature and type of decision that needs to be made. These tools must be able to address:

- The increasingly urgent need for more effective land use and water quality management;
- The wide variety of potential application contexts; and
- The need for the development and sustainable use of the platform/shell to make financial sense in the short- and long-term.

An example of a low level of scientific input is using the literature to make simple qualitative, generic links between land use activities and water quality and the different kinds of potential impact associated with that water quality. For example, elevated concentrations of sulphate are a well-known consequence of coal mining. This basic knowledge enables decision makers to make generic statements of how water quality is likely to be impacted by a future land use or to identify land use practices that should be prioritised and investigated in further detail. Further detailed analysis of land use impacts on water quality requires a more quantitative estimation of pollution.

Quantitative estimates of land use-derived pollutant loading can be made through complex hydrological modelling programmes (e.g. SWAT, HSPF, etc.). These models typically integrate large amounts of spatial, climate and management data in an attempt to predict realistic pollutant inputs at a high level of detail (i.e. on an hourly, daily, monthly or annual time-step basis). These models are typically data intensive and time-consuming but have a relatively higher level of certainty associated with their outputs. Land use export coefficients provide a far simpler quantitative estimation of pollutant loading and are expressed as the quantity of pollutant derived per surface area unit of a specific land use per year (i.e. kg/ha/yr). These coefficients can simply be multiplied by the surface area of a specific land use in a catchment so as to derive the pollutant loading from that land use in the catchment.

Export coefficients are particularly attractive alternatives to complex models due to their limited data requirements, ease of use and their sensitivity to temporal changes in land use and management practices. While this technique does not indicate the specific mechanisms causing surface runoff and pollutant transport, it can be used to indicate dominant land areas and/or activities significantly contributing to nonpoint source pollution. Information on these contributing sources can then be used in watershed-level planning for identifying "hot-spots" and promoting management practices for land uses or areas that are major contributors of nonpoint source pollution.

This chapter proposes a specific software shell as the main framework on which to proceed and it examines its pros and cons. Importantly, it also suggests a possible national business model within which it could flourish. This chapter also looks briefly at other related local models (as opposed to shells) and at the role Bayesian networks could play.

3.2 OBJECTIVES

The purpose of this chapter is to introduce users to

- basic concepts behind modelling,
- typical water quality problems associated with different land uses
- and the types of tools available for decision making.

Examples of the application of all modelling tools presented here are presented in Chapter 5 (reference to these case studies is made in information boxes). It is intended to guide users on the type of model they may wish to use, depending on the data they have available or the type of decision that needs to be made. This decision can be facilitated by use of water quality and land use tool evaluation matrix presented in the Appendix A of this report. In other words this report says:-

- these are the issues,
- these are the available frameworks, platforms, shells and models,
- this is when you use them, and
- this is how you use them.

The models and processes technologies that were assessed *inter alia* by means of small case studies were:-

- Export coefficients and the pollution load estimator (PLOAD), a US EPA supported public domain product;
- Bayesian Modelling systems;
- The BASINS 4.0 software shell;
- AQUATOX a biological water quality model supported by the US EPA which is in the public domain;
- MIKE SHE which is part of the DHI suite which includes MIKE ZERO; MIKE BASINS; MIKE 11. The MIKE suite is available to Universities in South & southern Africa and to the Water Research Commission (WRC) and the Council for Scientific and Industrial Research (CSIR) free of charge.
- The Hydrological Simulation Program Fortran (HSPF) a flagship model in the BASINS 4 framework supported by the US EPA;
- the Soil Water Assessment Tool (SWAT) a USDA supported public domain product;

These models vary in terms of their complexity and data requirements and are addressed in order from simple (i.e. few data requirements and high uncertainty related to outputs) to more complicated models (i.e. large number of data requirements and lower level uncertainty associated with outputs).

3.3 IMPORTANT CONCEPTS RELATED TO MODELS AND MODELLING

3.3.1 Selling Modelling Versus Selling Models

Good modelling producing value-added outcomes and outputs could play an important role in the sustainable uptake and use of a frameworks approach in South Africa. This raises the issue of the receptiveness of our envisaged target audience to the usefulness of modelling and therefore the possible need for the project team to actually “sell” (i.e. motivate) modelling as a useful tool in some circumstances.

Selling modelling should be contrasted with selling models. Models are motivated for very different reasons. They are motivated on the basis of the data they need, data availability, the calculations they do, how difficult it might be to set up and run the model, etc. Selling modelling is different. It does depend on the nature of the model being used, however it also involves a human element with important subtleties.

Experience of the project team members has shown that receptiveness to modelling can vary considerably. At the one extreme there are those who are very comfortable with modellers, models and what they can produce. At the other extreme there are those who have no time for these whatsoever. Sadly, in both of these camps, the perceived usefulness (or uselessness) of modelling is sometimes based on a lack of appreciation of what “good” modellers can actually do. It is worthwhile to reflect briefly on this issue so that project team members can present a consistent and accurate message to target audiences when necessary.

A very common misconception is that a “good model” is one that can *quantitatively* reproduce (or predict) the behaviour of a real system of interest. While this might often be an aim of modelling, this is an extremely demanding definition. It is proposed that the project team adopt the following definition:

3.3.1.1 Modelling point 1

A good model is any construct that helps one think usefully about the real system.

This is a very broad definition that could include simple diagrams or concepts (as well as quantitative modelling) that help one understand the system better.

Sometimes even modellers themselves do not fully appreciate what a modelling exercise has achieved. Often a modelling program is used to try to reproduce a quantitative field (or laboratory) observation (e.g. the nitrate concentration was X mg/l or the flow at that point in the river was Y m³/s), or even more demanding, predict it. Sometimes (and in some contexts, often) the modellers are unable to calculate values that agree well with quantitative observations. However, the very process of modelling often reveals insights into the behaviour of the system. It is also not uncommon that the modeller is unaware of this new knowledge. This is a kind tacit knowledge that *you only know you know when you need to know it*. This is sometimes only revealed when the modeller is presented with some related question and finds that they suddenly have something to contribute. This is a subtle modelling outcome.

The more important point of the above issue is that if the modeller's themselves sometimes do not know what they know, how can we expect our target audience to know what modellers can do with the modelling systems assessed in this report? The answer lies partly in the following:

3.3.1.2 Modelling point 2

Modelling will improve understanding of the land use – water quality nexus.

With good modelling, this can almost always be guaranteed. This is well aligned with Point 1 above and implies that modelling will improve decision making by making it better informed (which is explicitly assumed here to mean decision making is based on a better understanding of the **reasons** for the decision and the possible consequences).

This raises another point:

3.3.1.3 Modelling point 3

This project is not only about what the models can do. It is also about what the modellers can do.

What non-modellers (and perhaps sometimes modellers themselves) are sometimes not aware of is that modellers either consciously or subconsciously model in three distinct steps.

1. **Real world-to-model interpretation.** The modeller listens to the “real world” question and interprets it (or, in effect, translates it) into often simpler and well-defined questions they know they can answer using their model. The real world question might be “is land use X acceptable or not?” The modelling questions will be related to how land use X might affect water quality and how this might affect downstream users. A similar question relating to flow could also be posed.
2. **Running the model.** The modeller runs the model or models, making multiple assumptions along way, so that the modelling questions are answered as well as possible.

3. **Model-to-real world interpretation.** The modeller examines the modelling outputs (the numbers, the graphs, etc.) and uses tacit knowledge that may have emerged during the modelling exercise and translates them into a “yes”, “no”, “not very likely”, “definitely under these circumstances but not under those”, or other similar real world (non-modelling) language.

Decision makers very rarely pose their questions (nor want answers) directly in terms of the model that is used. If they do, the modeller should be wary. The decision makers are very likely to be asking the wrong questions. They are trying to do Step 1 themselves. This is dangerous if they are not very familiar with the models. This interpretive role of modellers illustrates why this project is as much about what the modellers can do as what models can do.

This section serves to remind us, and readers, that this project is not only about motivating for a particular software system. It is also about understanding how such a system is best used. The ultimate target users must understand (a) the advantages, and especially the limitations, of the models *and* importantly, (b) what modelling *per se* can bring to the table. This is no easy task because of the often subtle nature of modelling. The possible, indeed likely misconceptions of some of the ultimate target users in respect of modelling need to be constantly borne in mind in engagements with them.

3.3.1.4 Modelling point 4

Good scientific modelling can become an art that goes well beyond numbers and graphs.

Modelling has been referred to as the art of making implicit assumptions explicit (Senge et al., 1990). In a very real sense therefore models can become the repositories of a connected, systemic story that links and relates the assumptions of stakeholders.

3.4 WHAT'S THE LIKELY WATER QUALITY PROBLEM?

To inform certain decisions regarding land use and water quality it may not be necessary (or feasible from a time and cost perspective) to utilise water quality modelling. In certain cases low-level, scientific input can be provided to inform decision making through the illustration of simple, qualitative, generic links between land use activities, their impacts on water quality and the resultant effects on downstream users. To address this need a literature review of typical land use – water quality links (refer to Chapter 4 on the review of land use/land cover classification systems from a water quality perspective), interactions and impacts were translated into spreadsheet format. The developed spreadsheet and tables can be utilised as a guideline reference, or be manipulated to feed into a modelling framework.

The structure adopted is in line with the South African National Standard (SANS) 1877 (SSA, 2004), with land use classes categorised into Level 1 (e.g. Built up land/Urban) and Level 2 (e.g. Industrial: Heavy). The type of information contained, which can form a quick reference guide for land use planners, includes the typical water quality impacts per land cover (Table 3.1) and typical effects on downstream water users (Table 3.2). Export coefficients of key water pollutants per land use category (Table 4.5) can feed reasoning support systems or modelling frameworks. As the land use-water quality matrix spreadsheet is too big for print, the three tables (Table 3.1, Table 3.2

and Table 4.5) show extracts of key data. The preliminary investigation through the various tables can lead to further investigation of literature, or lead to utilisation of various modelling tools

Table 3.1: Typical problematic water quality determinants or impacts per land cover.

Land cover class (Based on NLC2000 Level 1)	Water quality determinants or impacts
Natural vegetation and degraded classes	<ul style="list-style-type: none"> Sedimentation Nutrients Organic matter
Plantations	<ul style="list-style-type: none"> Sedimentation Salinity Pesticides Nutrients Organic matter
Water-bodies	<ul style="list-style-type: none"> Sedimentation[†] Nutrients[†] Organic matter[†] Toxicants[†]
Wetlands	<ul style="list-style-type: none"> Nitrates* Phosphates* Sediments (including organic matter)* Toxicants*
Bare rock and soil	<ul style="list-style-type: none"> Sedimentation Salinity
Cultivated (and agriculture)	<ul style="list-style-type: none"> Nitrates Phosphates Pesticides Sedimentation Microbial contamination and pathogens Salinity Heavy metals Hydrocarbons Man-made/synthetic organic chemicals Persistent bioaccumulative organic pollutants Organic matter Air pollution settlement/atmospheric deposition

Land cover class (Based on NLC2000 Level 1)	Water quality determinants or impacts
Urban/Built up (including transport, industrial and smallholdings)	Hydrocarbons Heavy metals Phosphates Microbial contamination and pathogens Salinity Water Temperature pH Man-made/synthetic organic chemicals Pesticides Persistent bioaccumulative organic pollutants Water temperature Solid waste/litter Air pollution settlement/atmospheric deposition Organic matter Sedimentation Accidental spills of contaminants Tyre, brake and mechanical wear Wear of road surface – tar/concrete Roadside herbicides
Mining	Sulphates Acid Mine Drainage Heavy metals Sedimentation pH Salinity Hydrocarbons Air pollution settlement/atmospheric deposition

[†]Factors such as water body type, habitat condition and extreme events determine if water-bodies are sinks or conduits (including remobilisation) of these water pollutants.

*Wetlands act as sinks for these water pollutants, but they can be mobilised if the wetland is degraded/eroded.

Source: Adapted from Ross (2010) and supplemented by Pegram and Görgens (2001) and Dallas and Day, (2004), with transport impacts supplemented by GSA (2011) and mining impacts supplemented by Heath et al. (2004) and Ashton et al. (2001).

The typical effects of the water quality determinants and impacts in Table 3.1 on four classes of water users are summarised in Table 3.2.

Table 3.2: Typical effects of water quality determinants or impacts on four classes of water users

Legend	Low impact	Moderate impact	High impact			
Water quality determinant or impact	Typical effects on water users		Aquatic environment	Agriculture/industry	Drinking water	Recreation
Acid Mine Drainage	Negative impacts on water pH, temperature and concentrations of sulphates and metals resulting in direct impacts to all water use classes					
Heavy metals	Toxic to aquatic organisms and water consumers					
	Contamination of groundwater					
Hydrocarbons	Low concentrations may result in a decrease in the diversity, richness & composition of aquatic species present, with high concentrations resulting in death of aquatic biota					
	Health risks to humans through water contact, water recreation and water consumption					
	Water treatment problems					
Microbial contamination and pathogens	Health risks to humans through water contact, water recreation and water consumption					
	Health risks to fauna and livestock					
	Contamination of agricultural products with associated health and financial risks					
	Increased costs of water treatment					
Nitrates	Overgrowth of vascular plants					
	Algal blooms					
	Depletion of dissolved oxygen					
	Mass killing of aquatic fauna					
	Contamination of groundwater, with nitrates being the world's most widespread groundwater contaminant					
Phosphates	Overgrowth of vascular plants					
	Algal blooms					
	Depletion of dissolved oxygen					
	Mass killing of aquatic fauna					
	Taste and odour problems for water consumption and potable water treatment					

Linking Land Use to Water Quality

Water quality determinant or impact	Typical effects on water users	Aquatic environment	Agriculture/industry	Drinking water	Recreation
Persistent bioaccumulative organic pollutants	Range of toxic effects, ranging from death in organisms to effects in humans which include cancer and developmental, learning and memory effects	Red	Red	Red	Red
Pesticides	Man-made organic chemicals which are toxic to natural life, generally do not occur naturally and do not break down as readily as natural compounds	Red	Red	Red	Red
	interference with food chains/ecosystems through growth inhibition and reproductive failure	Red	Red	Red	Red
	Pesticides leach into soils, polluting sediments and groundwater	Red	Red	Red	Red
	Bioaccumulate up the food chain	Red	Red	Yellow	Yellow
pH	Low pH tends to impact young organisms	Red	White	White	White
	Low pH can mobilise metals from natural soils, allowing rise to toxic concentrations	Red	Red	Red	Red
Salinity	High salinity impacts aquatic biota, affecting metabolic function and oxygen saturation levels	Red	White	Yellow	White
	Rising salinity can alter riparian and emergent vegetation, affecting wetlands and decreasing habitat for some aquatic species	Red	White	Red	Yellow
	High salinity reduces agricultural productivity and crop yields	White	Red	White	White
Sedimentation	Impacts to natural physical, chemical and biological processes	Red	Yellow	Yellow	Red
	Decrease in primary productivity within aquatic systems	Red	White	White	White
	Decrease and impair fish spawning habitat, fish, plants and benthic invertebrates	Red	White	White	White
	Sediments provide binding agent for nutrients and toxic contaminants such as pesticides	Red	Red	Red	Red
	Sedimentation of dams and water supply/reticulation infrastructure	Yellow	Red	Red	Yellow
	Damage to water treatment and reticulation infrastructure	White	White	Red	White
	Damage to irrigation pumps, pipes and sprinklers	White	Red	White	White
	Increased water treatments costs for potable water and agricultural use	White	Red	Red	White
	Pollutants, such as pesticides and phosphates, adsorb to sediment particles with the result that	Red	Red	Red	Red

Water quality determinant or impact	Typical effects on water users	Aquatic environment	Agriculture/industry	Drinking water	Recreation
	sediment deposits and sediment laden waters are contaminated	Red	Red	Red	Red
Solid waste	Solid waste can introduce other pollutants to water either directly or during decomposition/chemical breakdown	Red	Red	Red	Red
	Solid waste can cause a physical disturbance to aquatic biophysical habitats, resulting in erosion, scour, destruction of habitat and disruption of species movement	Red	Yellow	Yellow	Yellow
	Solid waste can also result in ill health effects or death of living organisms within or utilising the water resource through ingestion, trapping, drowning, etc.	Red	White	Red	Red
	Solid waste can cause blockage and damage to water treatment infrastructure as well as sewer systems (with resultant sewage surcharge likely to pollute watercourses)	Red	Red	Red	Red
Sulphates	An essential component of natural waters, but which at elevated levels forms sulphuric acid which has devastating effects on aquatic ecosystems and downstream water users	Red	Red	Red	Red
Temperature	Impact on metabolic rates, reproduction, growth and population size of aquatic biota	Red	Yellow	Yellow	Yellow

Source: Ross (2010), DWAF (1996) and Dallas and Day (2004)

3.5 EXPORT COEFFICIENTS

3.5.1 Overview

Export coefficients are estimates of the amount of pollutant loaded into a system per unit area of a particular land-use (Reckhow et al., 1980; Pegram and Görgens, 2001) and are reported as a mass of pollutant per unit area per annum; usually kg/ha/yr (Enongene and Rossouw, 2007). Export coefficients can be applied to areas of a similar land use to estimate the potential pollutant load to a system from a particular catchment area. There are two methods of obtaining export coefficients for a particular land use: one is from the literature and studies of similar land use types and another is to calculate actual export coefficients for a particular catchment from in-stream water quality monitoring data (US EPA, 2002; Shrestha et al., 2008).

Climate, topography, geology, soil type, vegetation and land use management practices (Enongene and Rossouw, 2007) affect the export of pollutants from a land area. Brylinsky (2004) details the following climate and soil factors which influence rates of phosphate export from land areas:

- Warm climates with high rainfall have higher export coefficients than those with colder, dryer climates.
- The amount, intensity and duration of precipitation have a large influence on phosphorus export coefficients.
- Sandy soils overlying granitic igneous formations tend to have high nutrient export.
- Loamy soils contain more nutrients and are more subject to erosion than sandy and gravelly soils and tend to have higher export coefficients.
- Clay soils are highly erosive, have poor water infiltration and a high capacity to adsorb phosphorus which results in high export.
- Organic soils have high nutrient contents, poor infiltration capacity, limited phosphorus retention capacity and high export.

3.5.2 Application context

Export coefficients can be used to investigate the impacts of land use and land management on water quality by estimating the pollutant loads contributed by the land parcels under the various land use or land management scenarios. The proportion of pollutant load contributions from different parcels of land within a catchment can also be investigated. As a result the impacts on water quality as a result of land use change or change in activity management can also be estimated. However, it must be remembered that export coefficients are better applied in the estimation of water pollutant loads which are cumulative in nature (such as sediment, nutrients, organic matter and metals), with non-cumulative pollutants, such as microbiological contamination, better accounted for by probability distributions (Pegram and Görgens (2001).

A case study on the use of export coefficients can be viewed in the following sections in Chapter 5 of this document:

5.3 *Load Modelling – Phosphate in the upper uMngeni*

3.5.3 Advantages and disadvantages

The limitations of export coefficients are that they do not account for seasonal and climatic variations, nor do they account for physical features of the catchment which affect contaminant transport processes (Pegram and Görgens, 2001). Brylinsky (2004) states that (a) unless export coefficients have been measured in the catchment being modelled, the choice of the most appropriate export coefficient to use remains somewhat subjective, and that (b) it is very important to attempt to match climate, geology, soil and vegetation type as closely as possible when estimates are based on studies that have been carried out in other areas. As a result there is high variation in the range of export coefficients quoted in the literature within a certain land use.

Regarding the estimation of export coefficients through case studies in South Africa, Pegram and Görgens (2001) stated that *“there is considerable variation in the reported values, which significantly complicates the selection and application of appropriate coefficients”*. These statements illustrate that the ideal scenario is the calculation of export coefficients for the particular catchment. However, given the range of land use classes, and the time and cost associated with

gathering the required water quality data, export coefficient calculation is not appropriate for rapid catchment water quality modelling applications.

Section 4.7 of Chapter 4 includes a table of available export coefficients (Table 4.5) for phosphates, nitrates and suspended solids for the level 2 land use classes of SANS 1877 from a review of both national and international literature.

The advantage of export coefficients is that they can be used for rapid estimates of pollutant loads from catchments or land use areas, and can rapidly give an indication of the potential impact of land use or management changes on water quality without the requirement for detailed site and pollutant data. Export coefficients are also a universally utilised 'index' which can feed into a variety of pollutant load models, but can also be used in rapid, on-the-fly calculations.

3.5.4 Data requirements

Depending on the land use activity and type of investigation being undertaken, data required to calculate export coefficients typically includes the following:

- Detailed water quality data.
- Flow data.
- Land use parcels.
- Area of land use contributing the pollutant.
- Area of the catchment/catchment boundary.
- Remote sensed imagery of the catchment.
- Land use treatment and management practices.
- Point sources of pollution and effluent discharges.

Flow and water quality monitoring data at a sufficient level of detail to inform the investigation form the most important data requirement.

3.5.5 Calculating export coefficients

Export coefficients are typically calculated by estimating the load of a pollutant at a point and expressing this load (i.e. kg) as a function of the total area of a land use (i.e. ha) upstream of that point so as to get an idea of the total amount of pollutant exported per unit of land area (i.e. kg/ha). The main data required for calculating export coefficients are therefore flow and water quality monitoring data at a sufficient level of detail to enable the calculation of reasonably accurate annual loads. This data is readily available from the DWA Google Earth website.

A common challenge associated with calculating accurate export coefficients is that monitoring stations where water quality and flow data are routinely collected are typically downstream of catchments that comprise a number of different land use activities. It is therefore difficult to isolate the contribution of a specific land use to loads measured at a monitoring point.

The following provides a brief summary of a methodology used to calculate export coefficients (more details on the methodology can be viewed in McFarland and Hauck, 2001):-

1. Identify appropriate monitoring stations where reliable water quality and flow data are available and use this data to calculate annual loads of the pollutant of interest (kg/yr)
2. Delineate the catchment area of each of the selected monitoring stations using Geographical Information Systems (GIS).
3. Quantify the total area (ha) of each of the land cover categories within each delineated sub-catchment.
4. Calculate the total pollutant export coefficient per sub-catchment per year by dividing the total annual load by the total area of the catchment (i.e. kg/ha/yr)
5. To isolate the loading contribution of different land cover categories to the total export coefficient, use a multiple regression techniques were used to develop the phosphate export coefficients for the major land cover categories. The dependent variable is the average annual nutrient loading at each site on a per hectare basis, while the independent variables is the fraction of the drainage area above each site represented by each land cover category. The coefficients from the resulting multiple regression models define optimised export coefficients across all sites for each land cover category for the time period evaluated. All multiple regression models should be developed using a forced zero intercept, thus, giving a loading of zero when all independent variables equal zero.
6. An example of how to calculate the uncertainty associated with the derived export coefficients is provided in the case study in Chapter 5.

With regards site selection, one should focus on monitoring stations where both flow and water quality data are available in the catchment. This allows for the calculation of the total quantity of a pollutant (i.e. kg) exiting a sub-catchment over a specific time period (i.e. a year). For each monitoring station, the catchment area contributing to the station must be delineated using Geographical Information Systems (GIS) and a Digital Elevation Model (DEM). The purpose of this exercise is to identify the extent of the catchment area that drains into each of the selected monitoring points and identify major land use activities taking place in the sub-catchment. Using the delineated sub-catchment map and GIS, it was possible to quantify the relative proportion of each of the major land cover categories falling within each sub-catchment.

Loads are calculated at each gauging station in the study area, by way of example, to calculate total export coefficient per catchment, for each selected station and for each year average monthly phosphate concentrations can be calculated. These concentrations are multiplied with the monthly flow for that particular month to derive a monthly phosphate load:

$$PO_4load = [PO_4] \times F \times 1000$$

Where [PO₄] is the average phosphate concentration for the month (mg/l) and F is the monthly flow in (m³). For each year, the sum of the average monthly loads can be used to estimate the total annual phosphate load (kg/year).

A case study on the use and development of export coefficients can be viewed in the following section in Chapter 5 of this document:

5.4 *Method for Calculation of Phosphate Export Coefficients in the Upper Olifants Catchment*

3.6 BAYESIAN NETWORKS

3.6.1 Overview

The soundest management plans often fail if they are developed without participation of local individuals (Cain et al., 2000). For this reason it is becoming increasingly obvious that stakeholder participation is critically important in successful water resources management (Zorilla et al., 2010). Even with these pitfalls catered for, scientific knowledge forms only a small component of available knowledge from stakeholder groups (Smith and Bosch, 2004), with decisions based on perceptions rather than absolute reality (Zorilla et al., 2010). Clearly, suitable tools which involve stakeholders in discussions and a creative process and which enhance capacity to consider complexity are required (Cain et al., 2000; Zorilla et al., 2010). A key issue in choosing such tools is their capacity to capture perceptions and utilise non-scientific information in a structured, logical form.

Bayesian probabilities are based on subjective degrees of belief (Crilly, 2007) which offer a robust approach for dealing with uncertainty. Bayesian Networks provide a method of representing relationships between variables, even if the relationships involve uncertainty, unpredictability or imprecision (Batchelor and Cain, 1999). They are also viewed as a strong tool for visualising complexity and engaging stakeholders (Zorilla et al., 2010). Bayesian probability theory and Bayesian networks (BNs) are discussed in more detail in Section 5.5. For this section, what is of relevance is that there is a rising interest in BNs as tools for water resource modelling (Kragt, 2009, Uusitalo, 2007, both citing a number of authors), even though their use in environmental sciences is still scarce (Aguilera et al., 2011). Only 4.2% of a total number of papers dealing with Bayesian statistics reviewed over a twenty year period (1990-2010) were from the environmental sciences, and of these, less than 25% were for water resources (30 papers) (Aguilera et al., 2011). In other words, while there is considerable potential for application of BNs in water resources management, use is still limited (Aguilera et al., 2011). BNs are a useful tool for assessing land use impacts on water quality in that they allow assessment of relative changes in outcome probabilities linked to management actions, and because they offer a comprehensive way to portray complex system interaction (Kragt, 2009). Furthermore, BNs are able to represent the catchment system as a whole.

A case study on the development of Bayesian for key variables affecting water quality in the upper uMngeni catchment (focussing on the area around the Mpophomeni township) is available in Chapter 5 of this document:

5.5 *Bayesian Decision Networks – Decision making in the Upper uMngeni*

The case study demonstrates the use of a BN as a management tool, which could be adopted for facilitating negotiations between various stakeholders represented by a Catchment Management Forum (CMF); as such, the “client” would be the CMF.

3.6.2 Application context

The use of inference is a powerful approach when faced with partial knowledge of an effect, and where the causes are multiple and complex. Management of water quality problems within a catchment typically involves multi-objective problems resulting from complex biophysical and socio-economic processes (Kragt, 2009). Thus, for example, it is difficult to attribute measured water quality parameters to particular multiple contributing land uses (Zobrist and Reichert, 2006). A deterministic approach may involve non-trivial modelling using a suitable nonpoint source pollution model such as SWAT. In a more generalised context, tools are typically limited to either biophysical models or economic models (Kragt, 2009). Deterministic models using only quantitative data are not useful when data are limited. This requires an integrated rather than reductionist approach to problem-solving. However, a major challenge is the synthesis of knowledge from many different areas and disciplines.

An alternative is to use Bayesian inference, and Zobrist and Reichert (2006) successfully estimated export coefficients for a range of parameters for different land use categories over a prolonged (24 years) time period. Such an approach also allows for testing the effects of land use changes to contributions of measured concentrations at catchment measurement points. Model development starts with setting an objective, which is followed by developing a conceptual system model (qualitative component), parameterising the model with data (quantitative component), and then model evaluation and scenario analyses (Kragt, 2009). Model evaluation requires feedback from experts and stakeholders. BNs are particularly useful when incorporating cost-benefit nodes, where problems have environmental, social and economic consequences (Kragt, 2009). Through this approach, stakeholders can easily assess trade-offs from different management actions.

3.6.3 Advantages and limitations

BNs are a useful addition to the toolkit of environmental scientists, and likely to become established as a standard method of analysis in problems dominated by uncertainty (Uusitalo, 2007). The use of BNs in water resources management offers a number of very strong advantages, although the choice of embarking on such an approach should not be made before the study objectives have been assessed against the perceived outcomes, to ensure that using BNs will be a suitable vehicle to meet these ends.

Advantages

- The simple graphical representation of BNs helps stakeholders understand and visualise complex problems (Kragt, 2009). Additionally, and even before data are required, the process of constructing the model allows stakeholders to determine dependence (or independence) of relationships, and to see which variables are relevant to the problem (Aguilera et al., 2011). Potentially, complex situations with many variables can be modelled relatively quickly.
- As a control, the probabilistic presentation of knowledge prevents over-confidence in the strength of responses (Uusitalo, 2007), i.e. model limitations are recognised explicitly.
- BNs can accommodate a variety of knowledge sources and data types (Kragt, 2009); with incorporation of quantitative and qualitative data of a range of accuracies.
- The explicit recognition of uncertainty helps decision makers identify risks associated with different management actions (Kragt, 2009; Aguilera et al., 2011).
- The process of BN construction helps represent current knowledge and identify knowledge gaps.
- Since BNs are a visual decision support tool, the transparent representation of causal relationships between system variables facilitates stakeholder buy-in.
- BNs are good at handling missing observations (Kragt, 2009; Aguilera et al., 2011 citing various authors). Use of prior knowledge reflects the state of knowledge before the research was undertaken and as the study progresses these will be subsequently updated as knowledge expands (Uusitalo, 2007). Even where data for prior probabilities are relatively poor, posterior probability distribution estimates are almost as accurate as when derived from extensive data (Goddard, N.D.), i.e. Bayesian networks are relatively “forgiving” of poor input data. Thus, this approach is free from the arguments of “too little data” and BNs show good prediction accuracy even using small sample sizes (Uusitalo, 2007).
- Structural and parameter learning, and new evidence can be incorporated (Kragt, 2009; Uusitalo, 2007). Various learning algorithms are used within the different software packages, which are beyond the scope of this report. One such example is the use of case files in Netica (see section below on data requirements), where conditional probabilities are derived from cases (where each case represents an example of the observed effect and the variable states of the parent nodes). This approach was used successfully by Hiestermann and Rivers-Moore (2012) to calculate conditional probabilities of wetland occurrence in KwaZulu-Natal, based on case data.
- Since numbers are attached to variables, it is possible to compute the probability of a particular hypothesis relatively quickly (Uusitalo, 2007).
- Because of the nature of Baye’s theorem, it is possible to calculate probability values of child nodes given the values of parent nodes (i.e. cause to effect) and vice versa (effect to cause) (Uusitalo, 2007).

Limitations

A number of limitations in the use of BNs exist, although none of these should preclude using this approach in water resources management. Certain of these limitations are not problematic when BNs are used with other tools, while the remaining limitations are merely constraints to be borne in mind when using BNs.

- Much data, especially in water management, is continuous (Aguilera et al., 2011), and BNs do not allow for the direct use of continuous data. Rather, there is generally a need to

reduce the data into discrete states, which invariably results in data loss (Kragt, 2009; Uusitalo, 2007). States can be of different types: numerical values, intervals, probability distribution or categorical definition. It is also informed by the type of data available and level of model parsimony required (Kragt, 2009).

- Spatial and temporal dynamics are not explicitly handled by BNs. Instead, they may be handled by developing a separate network for each site or time period, which are run separately, or at best, set up in series, where the links in networks are considered as the effect of time. This can add significantly to model complexity (Aguilera et al., 2011).
- No feedback loops (Kragt, 2009, Uusitalo, 2007)
- Developing a BN relevant to the problem at hand requires the model developer to have skills in stakeholder consultation and eliciting expert knowledge, i.e. the model is only as good as the data-eliciting and stakeholder engagement processes (Kragt, 2009, Uusitalo, 2007). Therefore potential pitfalls to bear in mind are that there may be difficulty in reaching agreement on the BN structure with experts, and in populating the conditional probability tables based on expert opinion

3.6.4 Data requirements

Data requirements to develop BNs are as intensive as require by the user. Because model development is relatively quick, investment time is not a major consideration in using this approach. In general, data requirements will be low, and the greatest investment is time in identifying and engaging with stakeholder groups.

Developing and using a BN should not be seen in isolation, but rather that BNs are coupled with other modelling approaches, e.g. process-based models to provide input into the models. Thus, for example, spatial GIS layers can be used to derive inputs for BNs (Johnson et al., 2011). Similarly, outputs from BNs can be applied to raster images, to provide a likelihood surface (Johnson et al., 2011). For example, in a recent study covering KwaZulu-Natal, the likelihood of wetland occurrence has been mapped for the province. Here, outputs from a Bayesian network model estimating likelihood of wetland occurrence based on a number of environmental drivers were converted to a spatial map (Hiestermann and Rivers-Moore, 2012).

Thought should also be given to the data requirements for model validation, since it has been noted that a high percentage of studies have not validated the models. It is necessary to choose the most appropriate validation technique (Aguilera et al., 2011).

Calculating conditional probabilities can be a non-trivial undertaking, even though these do not require high levels of computing power. A BN will typically be developed within a dedicated BN software package. A number of (commercial) software packages are available for developing BNs. The list below includes packages which range from being freely downloadable to offering free demo versions, which offer full functionality but limit the number of nodes on the BN.

- Analytica (www.lumina.com)
- Netica (<http://norsys.com/>) is widely used (Uusitalo, 2007), and supports the use of decision and utility variables. This software was used in this study, and is freely downloadable as a

limited mode (15 nodes with 3 states). The limited mode has full functionality, and payment for an upgrade provides a password which enables larger BNs to be constructed.

- Hugin (<http://www.hugin.com>). A free limited version (Hugin Lite) is available, which can handle up to 50 states (e.g. 25 variables with 2 states). One advantage with this software is that extensive tutorials are available online, and an associated book (Kjaerulff and Madsen, 2008).
- GeNIe (<http://genie.sis.pitt.edu/>) – This was developed through the University of Pittsburgh, and a full version is downloadable at no cost, which includes commercial use (Uusitalo 2007).
- Samlam (Sensitivity Analysis, Modelling, Inference and More) (<http://reasoning.cs.ucla.edu/samiam/>). This was developed through the University of California, and a full free version is downloadable. This software allows imports other BN software (for example, Netica).

Based on a review by Aguilera et al. (2009), the majority of studies (34.2%) used Netica, followed by Hugin (20.2%).

3.6.5 Theory

Uncertainty and complexity have traditionally been dealt with by excluding qualitative data and focussing only on quantitative frequency data to derive probabilities. Conversely, Bayesian probabilities are based on subjective degrees of belief (Crilly, 2007), and offer a robust approach for dealing with uncertainty. Bayesian networks are based on cause-and-effect relationships ($X \rightarrow Y$), where Y often takes the role of an observable effect of X . Bayesian analysis presents a way of dealing with subjective probabilities (i.e. prior probabilities) and how they may be updated based on new evidence. Conditional (posterior) probabilities are calculated from single or multiple prior probabilities and the accuracy of the prediction is a function of the reliability of the prior probabilities (Crilly, 2007). In this system, prior probabilities (parent node) modify the probability of a posterior (child node) event occurring (Figure 3.1). This could be written out as: “If stakeholder 1 does action y to change the state of variable x , stakeholder 2 will most likely experience this as...”.

In Bayesian theory, conditional probabilities are calculated according to the form of Equation 1:

$$P(a | b) = x \quad [1]$$

i.e. given event b (observation), the conditional probability of a is x .

A key focus is the calculation of posterior probabilities based on evidence. We derive the posterior probability distribution, given the observation $Y = y$ and using the prior distribution $P(X)$ and the conditional probability distribution $P(Y|X)$, based on Equation 2, known as Baye’s Theorem. This theorem is central to statistical inference, with the probability of a cause being inferred when its effect has been observed (Kjaerulff and Madsen, 2008).

$$P(X | Y = y) = \frac{P(Y = y | X)P(X)}{P(Y = y)} \quad [2]$$

where X is a cause of Y , with observation y .

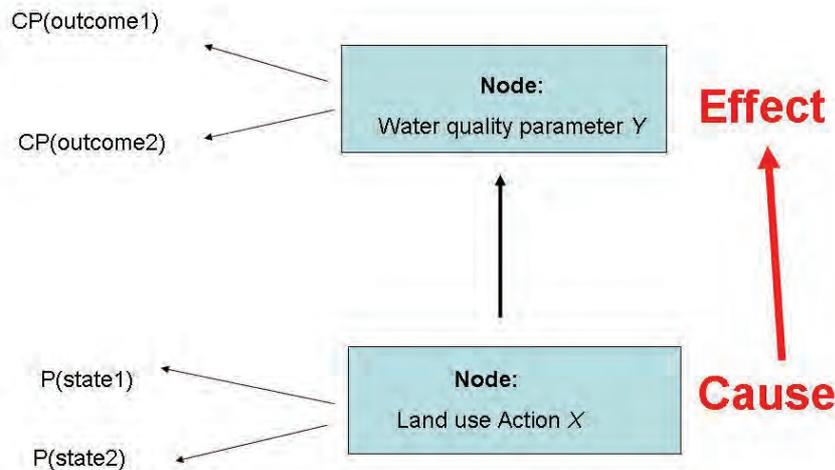


Figure 3.1: Cause (parent) and effect (child) nodes which form the basic building blocks for a Bayesian network.

A Bayesian network is termed an directed acyclic graph (DAG) with elements (V,E) (where V = variables and E = events or states), and representing cause-and-effect relationships. There are two steps to defining a Bayesian network, viz.:

- Quantitative component: Identification of variables, states (events) and causal relations between them = DAG + states;
- Qualitative component: Knowledge on causal relations, conditional (joint) probabilities and utilities (preferences) associated with decision options.

Thus, each node has system states, with associated conditional probabilities which may be derived using either qualitative or quantitative data. Nodes in a Bayesian network are of three possible types, which can either be discrete or continuous. Discrete nodes are populated by a well-defined finite set of possible values, while a continuous node can take on a value between any other two values:

- Chance
- Decision (discrete data only)
- Utility (continuous)

Combining these elements results in a Bayesian network (Figure 3.2). Once constructed, the parameters of a Bayesian network may be continuously updated as new information arrives. Most of the outputs of interest of a Bayesian network are the posterior probabilities (effects). These are often combined with decision variables and costs/benefits (utilities), which changes the Bayesian network into an influence diagram to provide a Decision Support System. Through this, the decision with the highest expected utility is therefore selected. Bayesian networks and influence diagrams are applicable for a large range of domain areas with inherent uncertainty (Kjaerulff and Madsen, 2008).

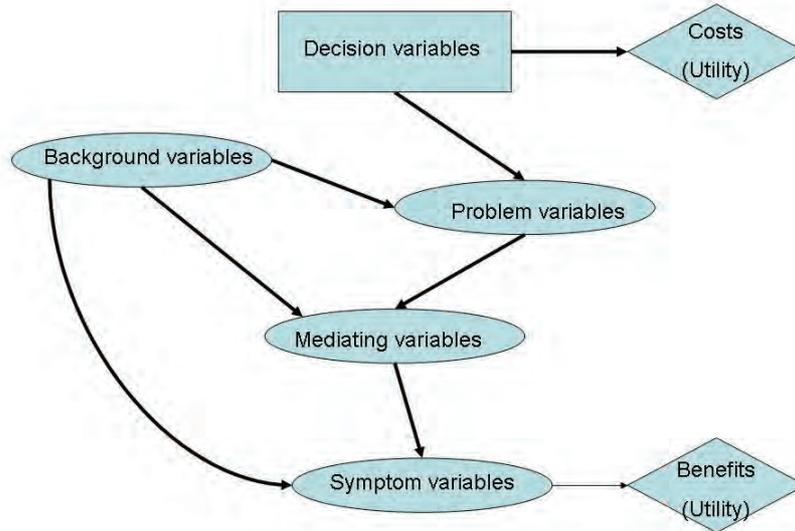


Figure 3.2: Diagram of key components of a Bayesian network (after Kjaerulff and Madsen 2008).

3.6.6 Worked example

This example demonstrates conditional probabilities based on observation (food experience) used to infer the guilty chef, and has been ‘unpacked’ based on an exercise from Kjaerulff and Madsen (2008): “Peter and Eric are chefs at Restaurant Bayes. Peter works six days a week while Eric works one day a week. In 90% of the cases Peter’s food is high quality while Eric’s food is high quality in 50% of the cases. One evening Restaurant Bayes serves an awful meal.”

Is it fair to conclude that Eric prepared the food that evening?

The first step in the process is to identify the variables from the description, define variable states, and quantify the information. Here, variables are “Chef” and “Taste” and variable states are (Peter, Eric) and (Tasty, Bad meal) respectively. Quantifying the problem involves defining parent prior probabilities (Table 3.3 and child node prior probabilities (Table 3.4). Next, this information is used to calculate conditional (posterior) probabilities to solve the problem, according to Equations 3a,b.

Table 3.3: Parent node prior probabilities – P(x).

	Peter	Eric
On-duty: P(x)	6/7 (85.714%)	1/7 (14.286%)

Table 3.4: Child node prior probabilities.

	Chef	Tasty meal	Bad meal
Peter		90	10
Eric		50	50

If
$$P(X | y) = \frac{P(X) * P(Y | X)}{P(Y)}$$
 [3a]

then
$$P(\text{Eric} | \text{Bad}) = \frac{14.2 * 0.5}{15.67}$$
 [3b]

which gives a 45.45% chance that Eric cooked the meal. It is not fair to assume Eric cooked the meal!!

The same approach is used to represent the data in a Bayesian network. In this example, the observation (bad meal) is used to infer the most likely cause of the problem, based on the conditional probabilities (Figure 3.3). Using the same conditional probability information, but without the benefit of an observation, it is possible to deduce that on any given night, there is an 85.7% chance that Peter will be cooking, and that there is an 84.3% chance that the meal will be tasty (Figure 3.4).



Figure 3.3: Representation of the problem statement as a Bayesian network, showing variables and variable states, and associated probabilities of belief based on the observation that the meal was not a good one.

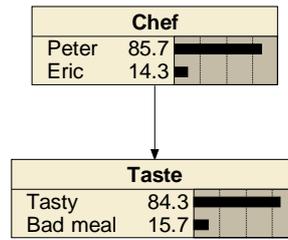


Figure 3.4: Representation of the problem statement as a Bayesian network, showing variables and variable states, and associated probabilities of belief, in the absence of any observations.

3.7 HYDROLOGICAL LAND USE AND WATER QUALITY MODELS

3.7.1 Overview

The purpose of this section is to provide an overview on hydrological land use models and their application in linking land use to water quality impacts. This section will also provide an overview of differences and similarities between three well know models (**HSPF, MIKE-SHE and SWAT**) to help users make an informed choice on which model to use. This section will not critically evaluate which model performs better than another with respect to simulated outputs.

Hydrological land use models are:

- Complex models, requiring a relatively high level of data input, that provide detailed predictions of flow and water quality with a higher degree of certainty associated with outputs, when compared to modelling approaches previously discussed in this chapter (e.g. export coefficients).
- They typically operate within a Geographical Information System (GIS) interface and integrate geographical information, weather data and land management information (e.g. agricultural practices) to provide spatial and temporal predictions of hydrology, point and nonpoint source pollution, from field to large catchment scales at daily, monthly or annual time-steps.
- While user-friendly interfaces make these models relatively easy to get running, calibration of the model so as to provide reliable and realistic outputs is particularly challenging and time-consuming.

3.7.2 Application context

Effective catchment management and decision making typically require detailed knowledge of the catchment area and a good understanding of the relationships between anthropogenic activities and sources of point and nonpoint source pollution, both at a spatial and temporal scale. Hydrological water quality models were developed with an emphasis on attempting to understand the impacts of land use on nonpoint source pollution. Their main emphasis is therefore on predicting nonpoint source pollution and they are therefore very useful in terms of evaluating the impacts of land use, land use management and land use change on hydrology, nonpoint source pollution and resulting water quality.

Possibly the most attractive motivation for using such models is that once it has been established that they provide estimates or predictions that simulate reality (i.e. they have been calibrated), they can:

- provide an estimate of hydrology and water balance within a catchment (including ungauged catchments);
- provide an estimate of spatial and temporal loadings and concentrations of nonpoint source pollutants in a catchment;
- identify specific land uses responsible for high pollutant loading;
- spatially identify areas or sub-catchments (i.e. hotspots) responsible for high nonpoint source pollution (including areas where routine monitoring does not take place);
- provide insight into drivers of pollution (e.g. geographical factors such as slope or soil characteristics, or land management practices such as crop fertilization, tillage operations, etc.) in hotspot areas;
- spatially and temporally quantify the relative contribution of point source and nonpoint source pollution in a catchment.

Furthermore, a calibrated model can be used to run scenario analyses that can provide a realistic prediction of changes in hydrology or nonpoint source pollution as a result of:

- land use change (e.g. crop production to mining);
- change in management practices (e.g. agricultural management practices such as alternative tillage or fertilizer application regimes);
- Best Management Practices (BMPs) that improve hydrological conditions or mitigate nonpoint source pollution;
- climate change (i.e. increased temperature or reduced rainfall, etc.).

This type of information is very useful for making catchment management decisions, such as:

- quantifying maximum allowable loads of pollutants so as not to exceed specific in-stream water quality standards;
- whether to focus on point or nonpoint source pollution with respect to improving water quality;
- identifying appropriate best management options for reduction of nonpoint source pollution in a catchment (i.e. BMP prioritisation);
- identifying most appropriate area(s) (sub-catchments) to implement mitigation or management strategies for reduction of nonpoint source pollution in the catchment (i.e. hotspot prioritisation);
- whether or not to allow a specific development in a specific catchment;
- whether or not to approve the change of an existing land use to another (e.g. allowing agricultural land to be mined).

3.7.3 Uncertainty and Calibration

To increase the amount of certainty associated with the model output it is important to calibrate the model and ensure that the model output (prediction) approximates as closely as possible measured field values.

Calibrating a catchment model over a large area (i.e. primary or secondary catchment) is an extremely challenging process, particularly in highly managed watersheds, where natural processes may in many instances play a secondary role. Without the knowledge of detailed management data, calibration of the model may not be possible. Management of dams and associated releases, use of water from these dams, irrigation and water transfers will all significantly impact on the natural flow of water. Particularly in a large catchment, it is difficult to obtain all this detailed information and often expert opinion or assumptions will need to be used. Over a large surface area there is bound to be a high degree of uncertainty associated with model outputs. These uncertainties stem from conceptual, input and parameter uncertainty (Abbaspour, 2011).

Conceptual model uncertainty could be as a result of

- a) simplifications in the conceptual model (e.g. assumptions in the universal soil loss equation (USLE) for estimating sediment loss),
- b) processes occurring in the catchment that are not included in the model (e.g. wind erosion effecting mobilization of particulates from the soil surface),
- c) processes that are included in the model but are unknown to the modeller (e.g. the magnitude of dam releases, water transfers and irrigation) and
- d) processes unknown to the modeller that are also not included in the model (e.g. dumping of waste material and chemicals into the river and sewage or chemical spills).

Input uncertainty is as a result of errors in input data (i.e. rainfall and/or) the extension of this point data over a large catchment area. In a large catchment, considering the number of individual farms (each with their own management regimes) and the inherent variability in input parameters, it is thus inevitable that there is a large amount of uncertainty associated with the input parameters and the resulting model output.

In large catchments it may be impossible to accurately calibrate the model. In these instances however the model can still be effectively used to make relative spatial or temporal comparisons (e.g. expressed as a greater or lesser proportional contribution to pollutant loads) or to assess relative change (e.g. expressed as a percentage increase or decrease) in outputs as a result of changes in input (e.g. tillage vs. no-tillage, implementation of filter strips, etc.).

3.7.4 Advantages and disadvantages

The disadvantages associated with using more complex hydrological land use models include:

- *Time consuming:* Collecting and preparing data, setting up and running the model and finally calibrating the model all take up large amounts of time.
- *Data intensive:* These models generally require large amounts of data which often needs to be formatted to a specific format. In many instances data may not be available or may be too expensive to acquire.

- *Technical Support:* Technical support is often related to the cost of the model. In general freely available models do not have a dedicated technical support while commercial models will tend to have better technical support
- *Cost:* While freely available open source models available, there is often a large cost implication associated with using these models. Many models operate within a GIS interface and may require commercial GIS software (e.g. ArcGIS) as well as expensive add-on tools (e.g. Spatial Analyst).

Considering these limitations on the running and maintaining such models, the following skill requirements are recommended:

- Good background knowledge of the catchment, including land use activities, land management practices;
- An understanding of geographic, climatic and land management factors that influence nonpoint source pollution;
- A basic understanding of Geographical Information Systems;
- Patience; setting up and calibrating such models is very time-consuming;
- Persistence; due to the complex nature of the models and the large number of input parameters required, models can often produce unexpected results. Good problem solving skills are recommended.

3.7.5 Data requirements

Hydrological water quality models are characterised by their extensive data requirement, which include geospatial data (normally in the form of GIS raster or shapefiles), weather data, monitoring data (flow and water quality) and point source data (refer to Appendix B for a list of geospatial data sets available at national scale). These data are normally sufficient to get the model running, however it is important to emphasise that additional data parameters that characterise biophysical processes and land use management practices are also required to calibrate the model to an acceptable level of accuracy. Such information is generally obtained by having an in depth knowledge and understanding of the catchment.

3.7.5.1 Geospatial data

Geospatial data provide information to support watershed characterization and environmental analyses. These data include information on soil characteristics, land use layers, and the stream hydrography and are typically required as rasters or shapefiles. This information is used in combination with modelling tools to perform more detailed assessment of watershed conditions and loading characteristics.

3.7.5.2 Weather Data

Hydrology and nonpoint source pollution is heavily influenced by climatic conditions and models typically require daily rainfall, temperature, humidity, wind speed and solar radiation as input parameters as well as the location (co-ordinates) of weather stations where weather data is recorded.

A Note on Rainfall

Rainfall data is probably the most variable across a catchment area, particularly in areas such as the highveld, where summer rains can be highly variable across a relatively small spatial area. Simulations can be significantly improved by including data from as many weather stations as possible.

3.7.5.3 Monitoring Data

Flow and water quality data (e.g. sediment, nutrient concentrations, etc.) are required to compare model outputs against so as to determine whether the model is providing realistic output. Monitoring data are therefore an important part of the calibration and validation procedure. These data can be used to assess the current status and historical trends of a given water body and also to evaluate the results of management actions.

Calibration vs. Validation

Calibration is the process of finding the optimum set of parameters that would help the model to reproduce observed data within the desired accuracy. This involves adjusting model parameters so as to produce output that provides an accurate simulation of observed data. **Validation** is the step where the capabilities of the calibrated model in simulating acceptable results could be confirmed. This involves comparing the output of the calibrated model to observed data that was not used in the calibration procedure. For example assume that observed time series data is available for the year 2000 to 2012. The calibration procedure may make use of the time series from 2000 to 2006 to help in calibrating the model. Once the model is calibrated for this time period the model could be run to simulate the years 2007 to 2012 and compared to observed data for the same time period. If the model output provides an acceptable simulation of the observed time-series, then the model would be considered to be validated.

The DWA has extensive records of flow (daily, monthly and annual) and water quality (weekly, to bi-weekly to monthly) data at a number of monitoring stations located across the country. Data is available for:

- Flow
- Major Ions (Ca^{+2} , K^{+2} , Mg^{+2} , CO_3^{-2} , Cl^- , Na^- , SO_4^{-2})
- Nutrients (NO_3^{-2} , NH_4^{+1} , PO_4^{-2})
- In-situ field measurements (pH, Dissolved Oxygen, Electrical Conductivity, Temperature)

Data is not available for:

- Sediments
- Metals
- Pesticides

A Note on Units

It is very important to use consistent units when comparing model outputs (e.g. flow) to observed data (e.g. from DWA flow gauge stations). For example SWAT expresses monthly flow measurements as average monthly flow in m³/s. Monthly flow data available from DWA is in total m³ for the month. For comparison purposes it is therefore very important to convert average monthly flow (m³/s) to total flow for the month (m³):

$$m^3 = m^3/s \times 60 \times 60 \times 24 \times n$$

where n is number of days in a month

Other units that may be required to be converted for making comparisons between observed and measured data include concentration and load values.

3.7.5.4 Point Source Data

Most hydrological water quality models can incorporate pollutant loading from point source discharges. The location, type of facility, and estimated loading are essential. These loadings are also used to support evaluation of watershed-based loading summaries combining point and nonpoint sources.

Examples of the applications of these models are numerous and in particular in countries where they have been developed, are an integral component of water resource management. Current applications include:

3.8 COMPARISON OF HYDROLOGICAL LAND USE AND WATER QUALITY MODELS

When weighing up whether to use these models over simpler models (i.e. export coefficients) it is important to consider practical advantages and limitations of the model, data requirements and availability, data output and skill requirements. Furthermore it is important to note that there are many models available, all of which perform a similar function. The choice of model is largely determined by user preference and other factors such as cost, user support, ease of use, etc. This section addresses the following models:

HSPF: <http://water.epa.gov/scitech/datait/models/basins/index.cfm>

MIKE-SHE: www.dhi.com

SWAT: <http://swatmodel.tamu.edu>

This chapter does not advocate the use of one model over another – rather it merely highlights some of the models that are available. HSPF and MIKE-SHE were explored to the point of getting the models to work without calibration or verification of the model outputs. These models will be discussed to the point of simply getting them to work. The SWAT model was investigated in more detail to the point of calibration and will therefore be assessed in more detail.

HSPF

HSPF (Hydrologic Simulation Program-Fortran) is a distributed watershed model that simulates precipitation- and snowmelt-driven movement of water through the basin via overland flow, interflow, and baseflow. Kinematic routing of the unidirectional flow through a receiving network of well-mixed channel reaches is also simulated. The transport of a wide variety of constituents through the watershed and the receiving network can be simulated. Time scales from storm events to many years can be simulated. Simulation of the physical, chemical, and biological processes included in the model is based on many theoretically- and empirically-developed relations. The resulting model is comprehensive and flexible, but also very complex and requires a large number of parameters.

MIKE-SHE

MIKE SHE is a distributed, physically based hydrologic modelling system for the simulation of all major processes occurring in the land phase of the hydrologic cycle, including interception, evapotranspiration, overland and channel flow, snow melt, unsaturated and saturated zone flow, and surface water/groundwater interactions. MIKE SHE is applicable on spatial scales ranging from a single soil profile (infiltration studies) to large regions that include several river catchments.

SWAT

SWAT (Soil and Water Assessment Tool) is physically based continuous simulation model useful for predicting the impact of land management practices on water, sediments, and different agricultural parameters for watersheds of various scales and complexities. OpenSWAT provides an extensive GIS interface for SWAT through the BASINS GIS application. A catchment simulation through SWAT is achieved by subdividing the watershed into Hydrological Response Units (HRUs). HRUs are basically homogeneous sub-basins having similar soil, land use, and slope properties. Main input parameters are grouped into categories such as weather, land cover, soil, and management within sub-basins, plus ponds/reservoirs, ground water, and the main channel or reach. More information about SWAT can be downloaded

Table 3.5: Summary of three catchment scale hydrologic and nonpoint-source pollution models (from Borah and Bera, 2003).

Description	HSPF	MIKE-SHE	SWAT
<i>Model components/capabilities</i>	Runoff and water quality constituents on pervious and impervious land areas, simple and complex (process-based) WQ options, and water and constituents in stream channels and mixed reservoirs. Currently, part of the US EPA BASINS modelling system with user interface and ArcViewGIS platform.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation, and user interface with pre- and post-processing, GIS, and UNIRAS for graphical presentation.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the US EPA BASINS modelling system with user interface and ArcView GIS platform.
<i>Temporal scale</i>	Long term; variable constant steps (typically hourly, but can range from 5-min to daily).	Long term and storm event; variable steps depending numerical stability.	Long term; daily steps.
<i>Watershed representation</i>	Pervious and impervious land areas, stream channels, and mixed reservoirs; 1-D simulations.	2-D rectangular/square overland grids, 1-D channels, 1- D unsaturated and 3-D saturated flow layers.	Sub-basins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
<i>Rainfall excess on overland/water balance</i>	Water budget considering interception, ET, and infiltration with empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
<i>Runoff on overland</i>	Empirical outflow depth to detention storage relation and flow using Chezy-Manning equation.	2-D diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.
<i>Subsurface flow</i>	Interflow outflow, percolation, and groundwater outflow using empirical storage and recession relations.	3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model (Sloan et al., 1983), and groundwater flow using empirical relations.

Linking Land Use to Water Quality

Description	HSPF	MIKE-SHE	SWAT
<i>Runoff in channel</i>	Routing based on 'storage' or 'kinematic-wave' methods; All inflows assumed to enter upstream end, and outflow is a depth-discharge function of reach volume or user-supplied demand. Flexible options to handle time and volume varying demands, and multiple outflow points.	Uses MIKE-11 model with optional full (St. Venant) or 1-D diffusive wave equations solved by an implicit finite-difference scheme. Both complex and simple hydrologic methods available.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.
<i>Flow in reservoir</i>	Same as channel, with flexibility to handle user-defined reservoir operations and structures.	Same as channel, with wide range of capabilities to handle hydraulic structures and operations.	Water balance and user-provided outflow (measured or targeted).
<i>Overland sediment</i>	Rainfall splash detachment and wash off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	2D overland flow model drives MIKE SHE SE (soil erosion) model.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) expressed in terms of runoff volume, peak flow, and USLE factors.
<i>Channel sediment</i>	Non-cohesive (sand) sediment transport using user-defined relation with flow velocity or Toffaleti or Colby method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	Hydraulic in MIKE-11 simulation drives both cohesive and non-cohesive sediment transport, including suspension, re-suspension, settling.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with bed erodibility and channel cover factors (for vegetation), and deposition based on particle fall velocity.
<i>Reservoir sediment</i>	Same as channel.	Same as channel.	Outflow using simple continuity based on volumes and concentrations of inflow, outflow, and storage.

Description	HSPF	MIKE-SHE	SWAT
<i>Chemical simulation</i>	Soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic N, phosphate, organic P, pesticides in dissolved, adsorbed, and crystallized forms, and tracer chemicals chloride or bromide to calibrate solute movement through soil profiles. Detailed instream water quality simulation, including sediment transport (sand, silt, clay) with sediment-chemical interactions with both water column and bed; BOD/DO, nutrient and algal simulation (phytoplankton and multiple benthic algal species); and parent-daughter formulations for pesticides and other organic chemicals.	Dissolved conservative solutes in surface, soil, and ground waters by solving numerically the advection-dispersion equation for the respective regimes. MIKE-11 water quality capabilities used for surface water quality.	Nitrate-N based on water volume and average concentration, runoff P based on partitioning factor, daily organic N and sediment adsorbed P losses using loading functions, crop N and P use from supply and demand, and pesticides based on plant leaf-area-index, application efficiency, wash off fraction, organic carbon adsorption coefficient, and exponential decay according to half lives.
<i>BMP evaluation</i>	Nutrient, pesticide, and irrigation management by parameter changes, or simple BMP module with removal efficiencies.	Extensive BMP capabilities expected for the process-based land modules.	Agricultural management: tillage, irrigation, fertilization, pesticide applications, and grazing.

3.8.1 BASINS 4.0

A particular software ‘shell’ that has considerable potential to address the requirements noted in the introduction of this chapter is BASINS. ‘BASINS’ is an acronym for *Better Assessment Science Integrating Point and Nonpoint Sources*. It was originally developed by the US Environmental Protection Agency (EPA) to determine Total Maximum Daily Loads (TMDLs) in 1994 as BASINS 1.0. Its continuous development is supported by the US EPA, the US Geological Survey (USGS), leading Universities and consultants in the USA.

The BASINS shell concept has long been recognised as a powerful one for managing catchments (Battin et al., 1998). They specifically demonstrated that the BASINS shell and the models and utilities it houses can be used for:

- Facilitating examination of environmental information;
- Providing an integrated catchment and modelling framework; and
- Supporting analysis of point and nonpoint source management alternatives.

The BASINS shell is an open-source, public domain, multi-purpose environmental analysis system that integrates a number of geographical information systems ((including GRASS, ArcGIS and

MapWindows GIS), national catchment data, and state-of-the-art environmental assessment and modelling tools into one convenient package

(<http://water.epa.gov/scitech/datait/models/basins/index.cfm>).

3.8.1.1 *Total Maximum Daily Loads (TMDLs)*

A TMDL is a regulatory term used in the US Clean Water Act describing the value of the maximum amount of a pollutant that a water body can receive while still meeting downstream water quality requirements. In its simplest form such a calculation does not require knowledge of land use.

However, in the last ten years there has been increasing emphasis on TMDL management. This includes management of the catchment in such a way that (a) amounts of pollutants discharged are allocated to dischargers (whether point or nonpoint source) and (b) catchment strategies are developed to attain established targets. The latter clearly requires detailed knowledge and understanding of catchment-scale issues (like land use). More information on TMDLs can be obtained from the following website:

http://en.wikipedia.org/wiki/Total_maximum_daily_load

The following puts TMDLs in a South African context. If TMDLs were required to be determined for a water quality constituent X for a South African water resource, the following are required:

Downstream resource quality objectives (RQOs) (specifically those relating to constituent X);
Upstream existing water quality in the water resource (specifically constituent X); and water flow data.

With this information it is possible to calculate how much (i.e. the load, kg/day) of constituent X can potentially be discharged into the water resource (upstream of the point at which the RQOs are set) so that the RQOs are not exceeded. This information is fundamental to setting discharge limits (and hence water use licence conditions) for point sources of constituent X.

The TMDL concept and multi-stakeholder processes that utilise the BASINS 4.0 shell are engaged extensively in the USA in support of nonpoint source pollution management and the determination of agricultural best practices.

3.8.1.2 *Potential advantages*

The following are some reasons why the BASINS 4.0 shell has been so successful in being widely adopted in the USA.

- **Avoidance of duplication.** The whole catchment modelling community focusses their efforts on creating datasets and information sets and developing models that potentially everyone else can use. This avoids the duplication ('wheel re-invention') that would occur if different modelling shells were in use.

- **Accommodation of “no size fits all”.** Even though the same software shell is in use throughout the country, the BASINS 4.0 shell allows individual users to include datasets and models that are specific to the needs of their water management area.
- **Open-source.** BASINS 4.0 is based on open-source GIS software making it independent of any proprietary GIS platform. It uses the free public domain MAPWindows GIS although also accommodates other GIS software platforms (e.g. ArcGIS and GRASS). The BASINS 4.0 stewards (i.e. the US EPA and USGS) are committed to migrating it to the OpenMI Standard interface for integrating time-dependent models. The US EPA and USGS have publically and strongly stated their commitment to embracing Open MI.
- **Modularity.** Modularity is a fundamentally sound principle in any software development. BASINS 4.0 is a highly modular shell with four main parts:
 - **Data.** These can include political boundaries, monitoring data, hydrography, land use, elevation data, soils data, meteorological data, etc.
 - **Tool and utilities.** These can include catchment reports, catchment delineation, parameter estimation, etc.
 - **Modelling.** There is a variety of models (a) linking land use and water quality, (b) estimating loads, and (c) for instream water quality.
 - **Decision making and analysis.** Post-processing (presentation of results), catchment management, sensitivity analysis, climate analysis tool, nutrient management, source water protection, total maximum daily loads (TMDLs), etc.
- **Multi-functional modelling.** The BASINS 4.0 shell contains a variety of models, including the following:
 - **Models linking land use and water quality.**
 - HSPF (Hydrologic Simulation Program – Fortran) is a catchment-scale model for estimating instream concentrations resulting from loadings from point and nonpoint sources.
 - SWAT (Storm Water Management Model) is a catchment-scale model that predicts the impacts of land management practices on water, sediment and agricultural chemical yields in catchments with varying soils, land uses and management conditions over long periods of time.
 - SWMM (Storm Water Management Model) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The routing portion of SWMM transports this runoff through a system of pipes, channels, storage/treatment devices, pumps, and regulators.
 - **Load estimation models.**
 - PLOAD (Pollutant loading estimation) estimates annual average loads from nonpoint sources of pollution for user-specified pollutants using either the export coefficient or simple method approach.
 - **Instream water quality models.**
 - AQUATOX predicts the fate of pollutants, such as nutrients and organic chemicals, and their effects on the ecosystems, including fish, invertebrates, and aquatic plants.
 - WASP is a dynamic compartment-modelling program for aquatic systems including both the water column and underlying benthos.

- **Online data availability.** When installing BASINS 4.0 and building a project, data is pulled in from freely available, centralised data sets.
- **Integrative.** The BASINS 4.0 shell allows a wide variety of datasets to be used in an integrated way. It can also specifically integrate point and nonpoint source data.
- **Broad international experience base.** BASINS 4.0 has been extremely widely used and tested in a wide variety of contexts. This means that there can be high level of trust in the system. The following website illustrates the enormous emphasis given by the USA to TMDLs and hence the BASINS 4.0 shell.

<http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/index.cfm>

- **Attractive national business model.** Healthy competition within the scenario of a single comprehensive integrated modelling platform/shell used nationally bodes well for a successful business model (see Chapter 2).

Key concepts required to develop an attractive national business model are described in Chapter 2 of this report:

Chapter 2.7 A Proposed National Business Model

3.8.1.3 Access to support

In business terms, what one is buying with software is an expectation of future value. Support and ongoing developments that are aligned to major trends are a critical component of that expected future value.

One major trend is the move to the internet for online use and support. With software development there is an ever-present danger that different groups, with similar modelling interests, develop different software systems. Each may have its own assumptions, datasets, input and output formats, etc. However, there may well be more fundamental approaches in any one system that distinguishes that system from the others. As a potential user who may recognise that software system A is fundamentally the one of choice, but who may also want to investigate the use of software system B, because that has advantages in another area, the level of investment required to set up both systems can be prohibitive. There can also be a host of issues created by the underlying assumptions and software design that prevent an easy comparison between the results of each system.

A powerful solution to the latter problem is the use, by both systems, of a common “shell”, in which all have agreed to certain assumptions and standards. Support relating to these common components is now centralised. The advantages to the user are obvious. (Indeed, the advantages to the software developers are also obvious. Someone else has already made the necessary design decisions. They just have to “plug in”.)

Even if those who provide the technical support for BASINS 4.0 may be located overseas, there are sound reasons why strong relationships can be built up with these people and organisations. If South Africa adopts BASINS 4.0 as the shell of choice and there is demonstrable multi-stakeholder support, this in itself will get the attention of the developers of the models within the BASINS shell. Indeed, there already has been, and is, some limited contact. There is also an existing enormous and ever-growing BASINS user and development communities that provide a wide variety of potential contacts of potential mutual benefit. (The interest in South African water-related problems and solutions in the international water community, particularly since the National Water Act came into being in 1998, is but one factor that could improve the degree of mutual benefit.)

The whole issue of creating and maintaining the kind of strong relationships with model developers anywhere in the world is one that must receive careful attention. A specific strategy with this objective in mind must be developed. One component of such a strategy could be creating an enabling environment in which communities of practice are allowed to develop.

3.8.1.4 BASINS 4.0 Systems Overview

The assessment reports on BASINS 4.0, AQUATOX, HSPF, should be read in conjunction with the two comprehensive supplementary reports (see CD attached to this report), namely:

Preliminary Conceptual Report VI

Preliminary Technical Report VI

Better Assessment Science Integrating Point and Nonpoint Sources, version 4.0 (or BASINS 4.0) integrates GIS modelling and data analysis, designed to assist TMDL (total maximum daily load) management and watershed based analysis (EPA, 2007). There are several components to BASINS 4.0 shown in Figure 3.5, integrating GIS layers, tools and utilities, models and the decision making and analyses of the output generated from the models. Models in the BASINS 4.0 framework are plugins, which are continuously being updated in new BASINS versions. SWAT, PLOAD and AQUATOX are the three models from within the BASINS 4.0 framework that came through our assessment with recommendation for further use and research.

From our work certain limitations became apparent, for example; the different units (US English/Imperial units versus RSA Metric units) were initially time-consuming with models associated with BASINS 4.0, particularly the HSPF and PLOAD models. However, unit differences were not perceived as insurmountable. Within the WinHSPF model (*the Windows version of HSPF inside the BASINS 4.0 shell*), the user has the option to specify the input and output units as English or Metric. For PLOAD, output units are automatically generated in pounds and acres. The addition of a new field in the shape file's attribute table, along with a calculation to convert, for example, from pounds to kilograms, was a workable solution. Another unfortunate aspect of BASINS 4.0 is file paths. At times, the software is quite particular about where it searches for files, and if a file is located at a different file path, it will not find it. Also, for certain aspects of BASINS

BASINS 4.0 System Overview

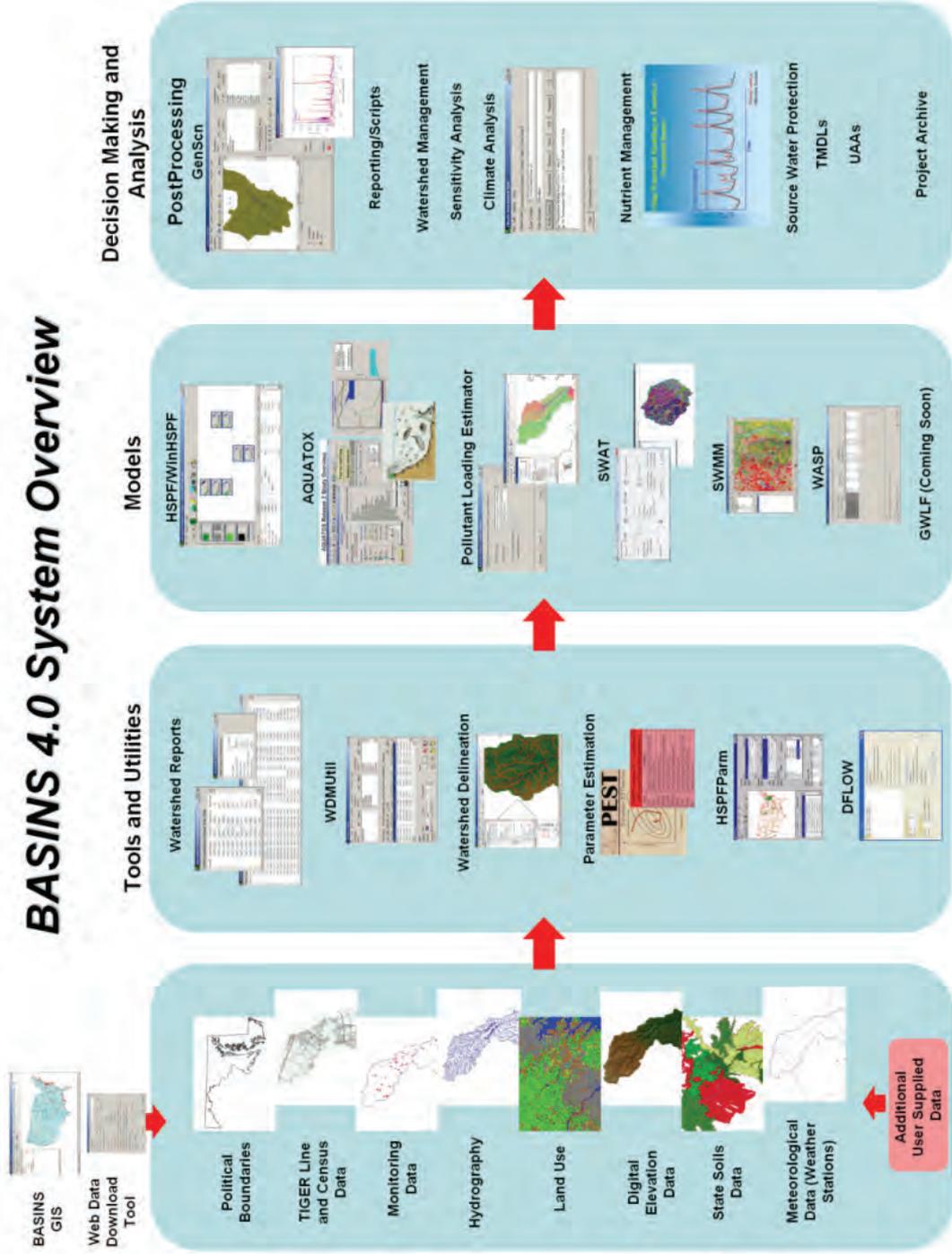


Figure 3.5: BASINS 4.0 system overview (EPA, 2010)

4.0 (e.g. WDMUtil and WinHSPF), file paths cannot be read if there are more than 70 characters in the pathname. A further issue was data projection, initially, models, e.g. PLOAD were run or tools, e.g. automatic and manual watershed delineation, were used, where the output did not make logical sense. The problem arose that the shape files or DEMs were not in a projected format. However, once this problem was solved, meaningful outputs were generated. Despite these limitations the notion that BASINS 4.0 is difficult to work with and takes excessive time to learn and understand the steps and procedures of the models, was found to be over stated.

Models in the BASINS 4.0 framework are plugins, which are continuously being updated in new BASINS versions. SWAT, PLOAD and AQUATOX are the three models from within the BASINS 4.0 framework that came through our assessment with recommendation for further use and research.

3.8.2 AQUATOX

AQUATOX is “...a simulation model for aquatic systems. AQUATOX predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants. AQUATOX is a valuable tool for ecologists, biologists, water quality modelers, and anyone involved in performing ecological risk assessments for aquatic ecosystems” (Clough, 2009). This definition is more easily explained by the processes diagrammed in Figure 3.6.

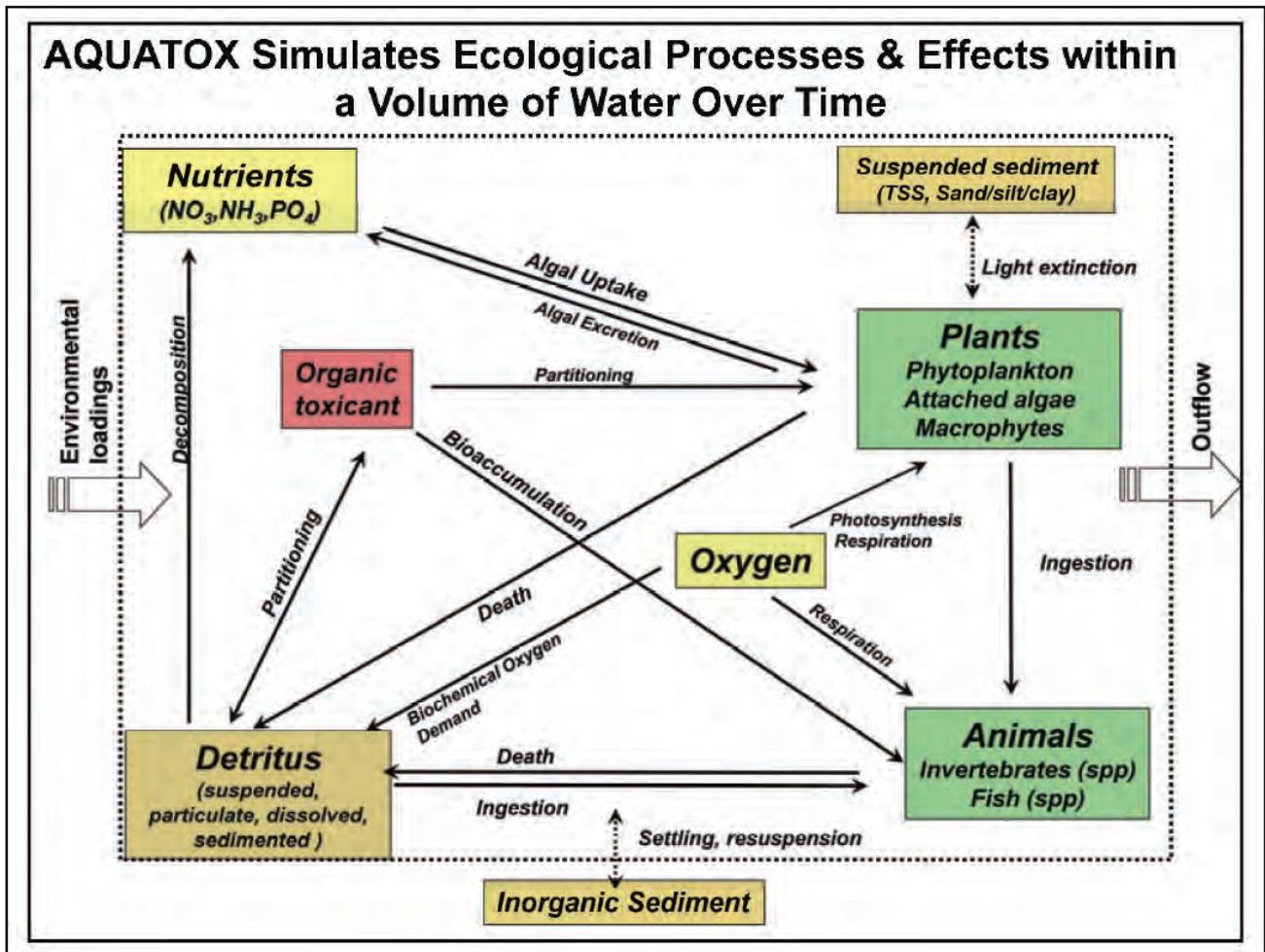


Figure 3.6: Biotic and abiotic processes effects within AQUATOX

For instream ecosystems modelling AQUATOX was chosen as it is one of the most comprehensive models of its kind. It simulates the ecological process and the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates, and aquatic plants, within a volume of water over time. The assessment of AQUATOX is based on a number of activities. These are outlined below and help the reader to form confidence in our assessment of the AQUATOX modeling system. The AQUATOX modeling work was carried out by two Masters students under the supervision of two project members. In so doing the capacity building aspects of the project are progressed well as an operational understanding of the overall BASINS 4 modelling framework. This was achieved by modelling the current aquatic ecosystem health of the Mpophomeni catchment, based on data obtained from the National River Health Bio-Monitoring database, and knowledge gained by participatory-agent based social interactions within the team and with a fellow Masters student who has completed detailed bio-monitoring fieldwork on the above streams. What has been found so far is that AQUATOX does have certain limitations but in each case a reasonable work around is feasible. For example :-

AQUATOX limits the number of species which can be modeled. When selecting within a group, e.g. sediment feeders, a maximum of two species may be selected. However, whilst working on observed data, three or more sediment feeders may be present. A possible solution is to employ trials which use different combinations of species. However this is time consuming, especially if many species are present. Species should not be based purely on abundance and indicator species should be given preference. A group of similar species could possibly be modeled as one 'representative' species. Furthermore, AQUATOX does not take into account which species may be present in the future. During the input phase, if five species are entered into the AQUATOX system, only those five species are modeled for the duration of the simulation. No new species are introduced into the system. In the observed data set six species were found at a site in the study area in 2002 and eight species were observed at the same site in 2012. The additional species were not introduced automatically, within the model, bearing in mind the two species per group limitation mentioned above. A possible solution is to set species which one anticipates will be present in the future to a very low value. This allows AQUATOX to model that species without a direct effect on initial values of species present. It must be stressed that this requires specialist knowledge of species dynamics as one cannot introduce all species which may possibly be present (due to the limit on the number of species, in a group, that may be modeled at any one time).

As is the case with many models, unit conventions need to be strictly adhered to. For example water flow rate input data needs to be in cubic meters per day, whereas hydrological models generally report flow rate in cubic metres per second. Caution also needs to be exercised with respect to AQUATOX animal mass data. The animal library within AQUATOX requires mean wet weight whilst modelling requires dry weight per cubic meter. This may be a limitation depending on the user. The dry weight is easy to calculate however the mass per square meter is not always known. It is difficult to determine the average mass per meter squared based on literature due to varying mass in different areas. A possible solution is that expert knowledge may be used to determine relative abundance within an area or to undertake field work may to determine the average number of individuals per square meter.

Compatibility between versions of AQUATOX and versions of Microsoft Windows has been problematic. There is an option to select compatibility mode on the latest version of AQUATOX

R3.1 to work with the older version of Windows (XP). Possible solutions: For optimum use of the AQUATOX modelling system, AQUATOX R3.1 works best with Windows 7. AQUATOX R 3 works best with Windows XP.

Despite the above cautionary note AQUATOX does have a number of advantages. The AQUATOX model software is in the public domain and is free to download from the internet, whilst the graphical user interface (GUI) is exceptionally intuitive, making it user friendly to the first time user as well as being fast and flexible for experienced users. Time varying data may be included within the modelling process. Not all time dependent variables or the parameters are required to be completed while using AQUATOX. One is able to interpolate missing time series data and uses default values for many of the parameters in the absence of input values. Certain parameters are calculated from surrogate relationships for example day light hours may be calculated using latitude. Complex interactions such as trophic interactions are considered within the background modelling process. AQUATOX links multiple simulations to obtain an increased understanding of interrelated processes. AQUATOX is a useful in modelling cause-effect relationships. Flexible and well-designed output graphs allow one to visualise and examine cause-effect relationships, easily. Statistics and daily/monthly parameter and variable values may be viewed within the output window, this allows the user to examine modeled changes at each time step and is useful in the analysis process.

The methods of assessment of AQUATOX have been tailored towards developing a working knowledge of the key elements of its use in participatory-agent based social simulation modeling. So far there have been no problems which would lead the research team to conclude that AQUATOX cannot be used in an exploratory process role, designed to deepen multi-stakeholder understanding into land use impacts on aquatic ecosystems, when used within strategic adaptive management (SAM) paradigms and processes. Our confidence in AQUATOX as an aid to learning grows as we combine the above in a manner consistent with the selected social learning theory, detailed in Deliverable 4 and work towards a series of controlled tests with knowledgeable volunteers from the aquatic science community in the greater Pietermaritzburg area.

This positive assessment of the AQUATOX modelling software and the modellers capability enhancement has been made against a social and technical backdrop which recognizes that it is not a simple matter to convincingly link nonpoint sources of pollution to instream water quality at points far-downstream of the pollution sources. In addition, there are often multiple sources of nonpoint source pollution and this, combined with the uncertainty, leads to shifting of blame. This malady is particularly prevalent when remediation costs are high and individuals and organisations are seeking to avoid change and costs. Stakeholders are most likely to contest taking responsibility for their pollution that affects aquatic ecosystems. It is important for stakeholders to change their behaviour with respect to land use activity, which is detrimental to water quality. To make the required behavioural changes stakeholders will need to understand and accept their contribution to water quality and aquatic ecosystem problems through their land use processes.

In summary the assessment has shown that AQUATOX addresses a core problem facing society and that is how to develop and assess a structured set of processes to advance collective stakeholder reasoning that leads to wise operational decision making with respect to land use effects on aquatic ecosystem health. The assessment reveals the potential for integration of

advanced stakeholder reasoning that allows for optimum management strategies for integrated water resource management.

This research is seeking to link the efforts of experts on aquatic ecosystems through the AQUATOX system to the efforts of land use related water quality experts working with the MIKE-SHE system. In this exploratory study, into participatory agent-based social simulation modelling, the MIKE-SHE system, discussed below, will be used for the rainfall/runoff/water quality simulations up to and in the stream leading to the stream segments in which AQUATOX simulations are performed.

3.8.3 DHI MIKE system

The DHI MIKE system was assessed against a range of criteria (Appendix A) and was selected, along with the SWAT model (component in the BASINS 4.0 suite), as the recommended model for the land use part of the water quality challenge. A factor which featured in the assessment was that we anticipate that the SA Water Partnership Network will seek to create an installed modelling system. This they are likely to do for many of the catchments within their sphere of influence and interest. In addition, it is likely that the DHI suit will form the basis of the modelling software strategy of the Alliance for Water Stewardship and the SA Water Stewardship Council Trust as they develop synergies and closer working arrangements between them as their members engage in a common virtual working space. As part of our assessment we constructed the diagram shown in Figure 3.7, to illustrate the main points of our argument in favour of using models such as AQUATOX; SWAT and the DHI MIKE suite.

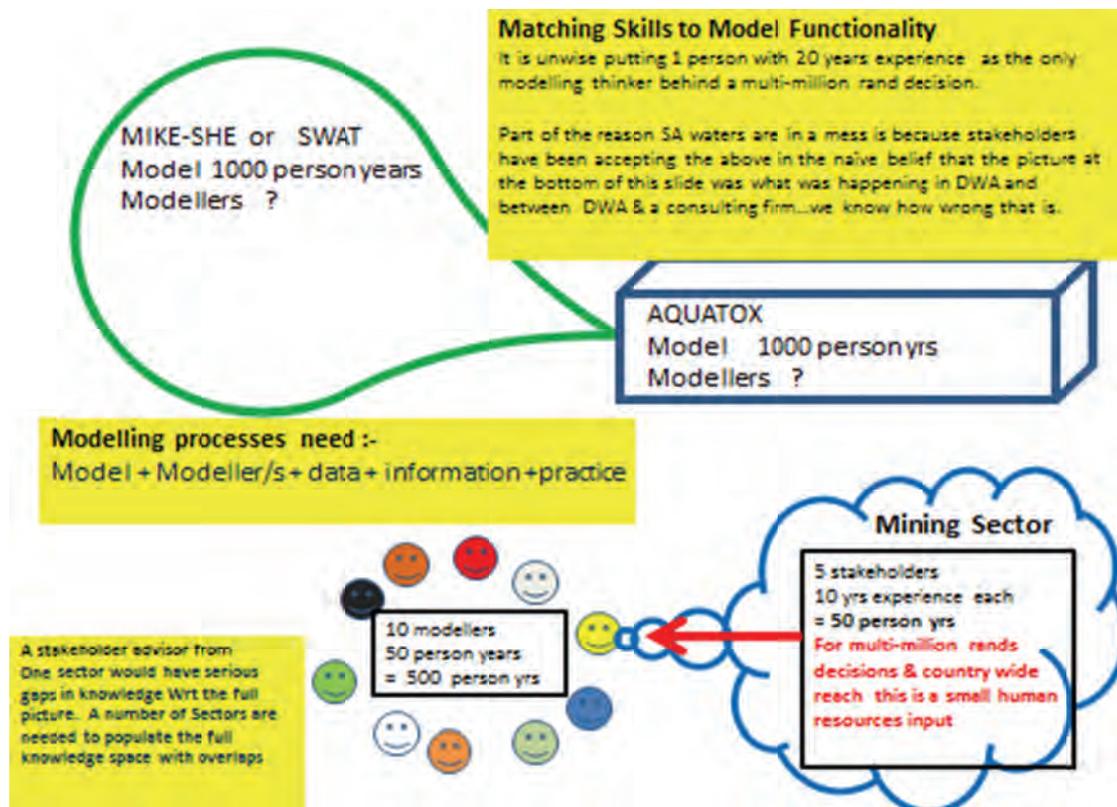


Figure 3.7: Illustrates the value of matching skills to model functionality in these complex systems.

MIKE SHE is a “dynamic modelling system for integrated groundwater and surface water resources. MIKE SHE is a unique software package for the simulation of all the major processes in the land phase of the hydrological cycle. It is a dynamic, user-friendly modelling tool for a wide range of water resources and environmental problems related to surface water and groundwater and can be applied on scales ranging from local infiltration studies to regional watershed studies” (MIKE by DHI, 2011).

As part of the assessment, MIKE SHE was used to simulate stream flow for the Mpophomeni catchment study area. The Mthimzima stream, in the Mpophomeni catchment once had a working gauging weir (from 1988 to the end of 1992), but unfortunately it has not been operational for the past 19 years. The observed flow from this short period was used to calibrate the MIKE SHE model to simulate stream flow for the same period, where the year 1992 was used to calibrate the model. Once the model was calibrated, stream flow was simulated for a more recent time period, between October 2010 and July 2011. This period coincides with the study period an MSc project outside of this WRC project, where streamflow was required to aid the explanation of the presence of macro invertebrates found in a SASS process.

There are various specifications of water movement that one can select in MIKE SHE, depending on what they intend modelling. The available types of water movement include the following: overland flow, rivers and lakes, unsaturated flow, evapotranspiration and saturated flow. MIKE 11 is used in conjunction with MIKE SHE, with regards to the river network and cross-sections. Thus, it is important that one sets up a MIKE 11 simulation first prior to attempting a MIKE SHE simulation. This can be selected under the ‘Rivers and Lakes’ section in MIKE SHE.

Land use data can be represented in grid format (Figure 3.8), where there is an option to include paved areas (for built-up land use) and irrigation (for agricultural land use). For each land use type, there is an option for the user to include seasonal leaf area index (LAI) and root depth (RD), by specifying the temporal distribution as a vegetation property file (extension .etv) (Figure 3.9 – note, the LAI and RD values used in this example are not actual seasonal values, but merely estimated values to have as input into the model for it to work). For land uses (or land-cover types) which do not usually have LAI or RD, for instance, built up dense settlement (Figure 3.5), the user has the option of specifying the temporal distribution as constant, where the LAI and RD values become negligible. The area covered by the land use type is displayed, where the area under ‘Annual commercial crops dryland’ is shaded in red (Figure 3.5).

Linking Land Use to Water Quality

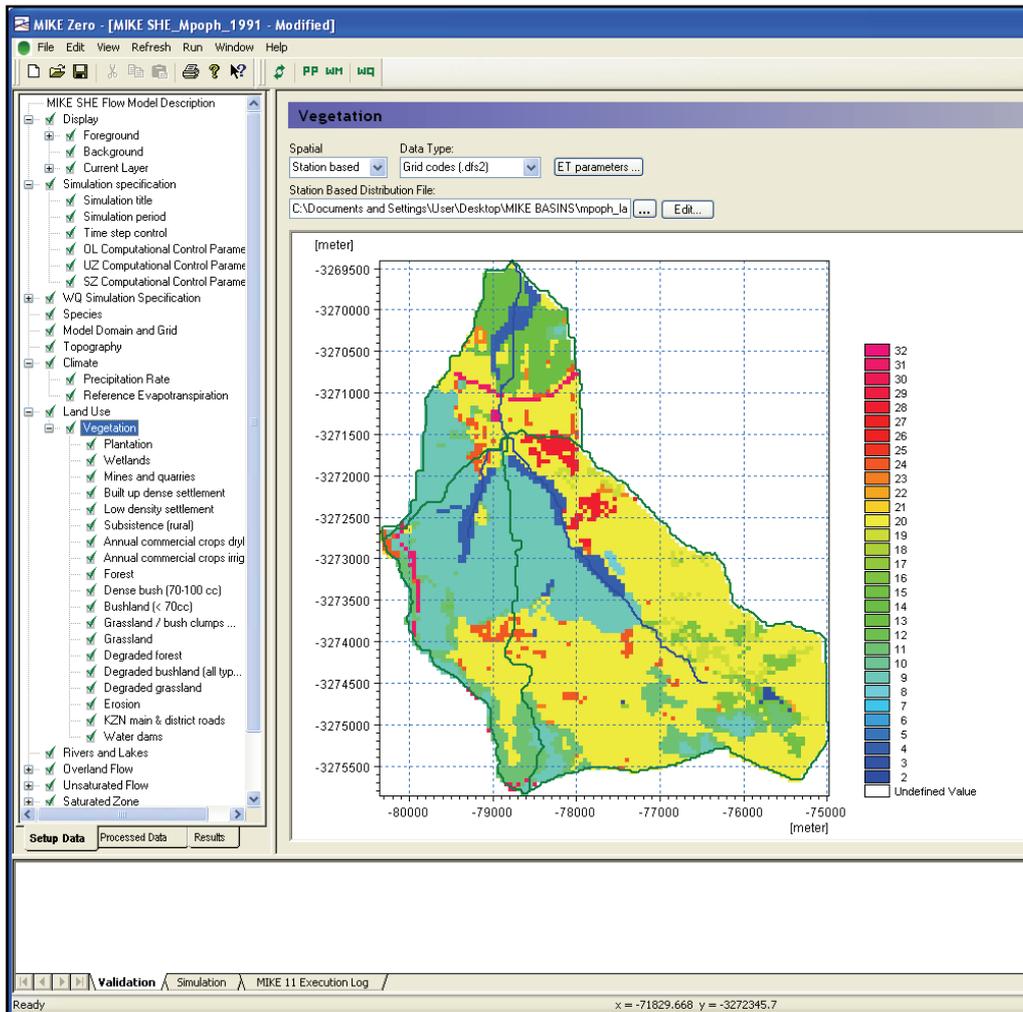


Figure 3.8: Land use colour-coded grid (extension .dfs2).

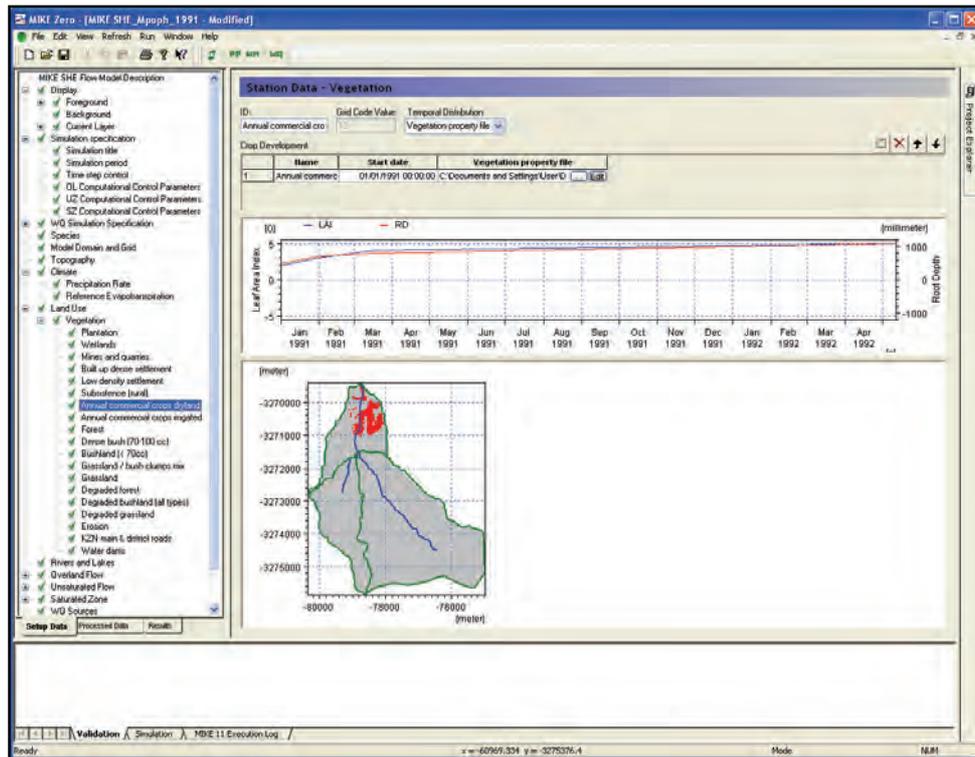


Figure 3.9: Example of a land use type (Annual commercial crops dryland), indicating the area in the catchment under use, as well as the seasonal LAI and RD associated with the land use practice.

A further important layer to include into the MIKE SHE model (*if unsaturated zone flow – UZ, is selected in the simulation specification*) is soils data. This is specified spatially under the unsaturated flow layer, where several soil attributes are required. Soil layers can be represented as spatially distributed, where grid codes are used to differentiate the various soil types from one another. A unique name can be assigned to the layers, for example, various texture classes (*sandy loam, clay, sandy clay*), but for this example, numbers between 1 and 5 have been used (Figure 3.10 and Figure 3.11). When selecting one of the layers under the sub-menu on the left-hand side, a variety of soil properties are visible, which can be edited by the user.

If the saturated zone (SZ) is enabled under the simulation specification, several options are available to the user. Depending on the option specified (Figure 3.12, depending on which boxes are ticked and which radio buttons are enabled), the required fields to edit are altered. For example, in Figure 3.9, different options have been enabled compared to Figure 3.8. The model informs the user that additional fields need attention, where the sub-menu on the left of the screen now shows additional sub-menus that do not contain green ticks (Figure 3.13).

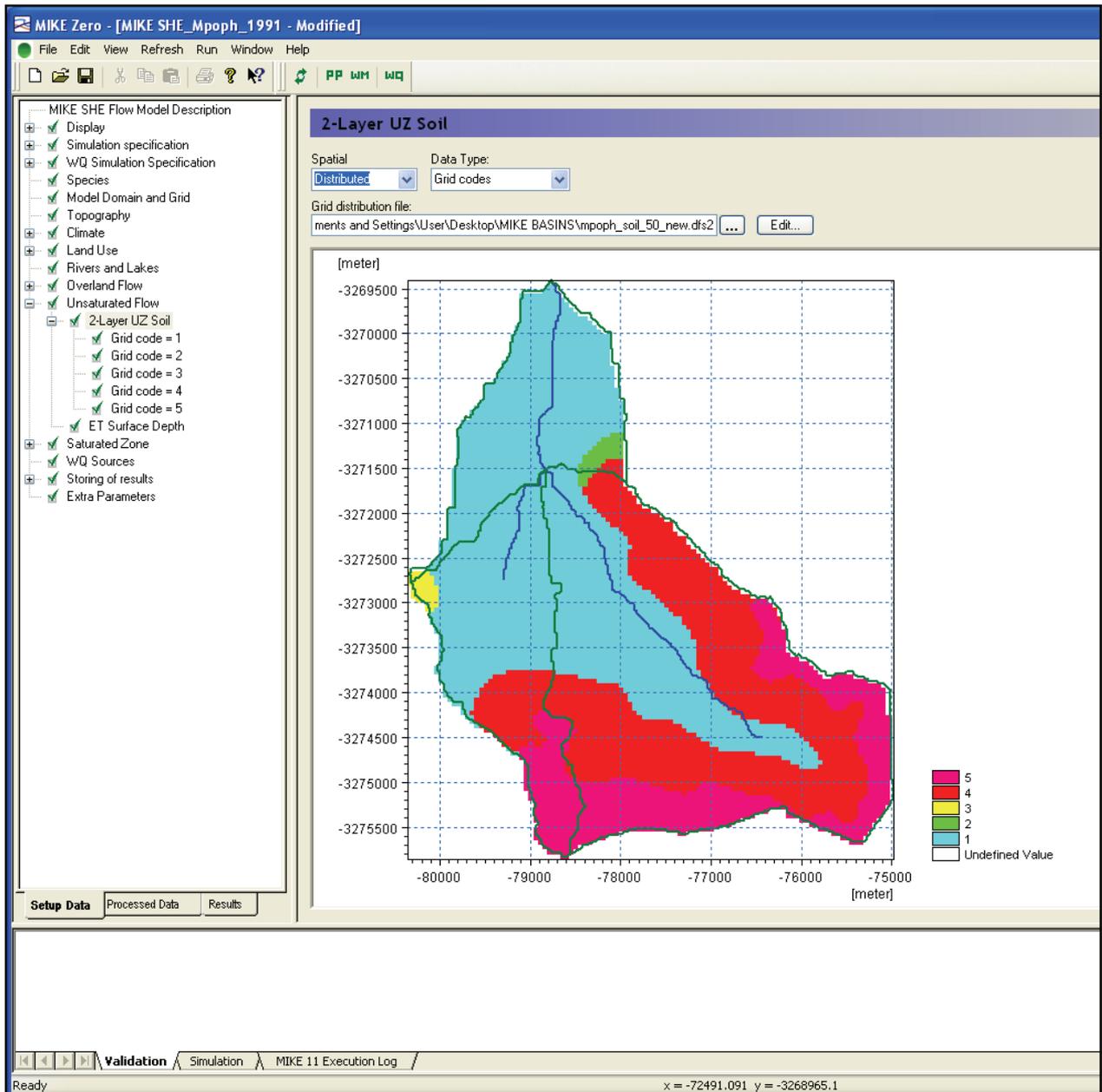


Figure 3.10: Spatial distribution of the various soils present in the study catchment.

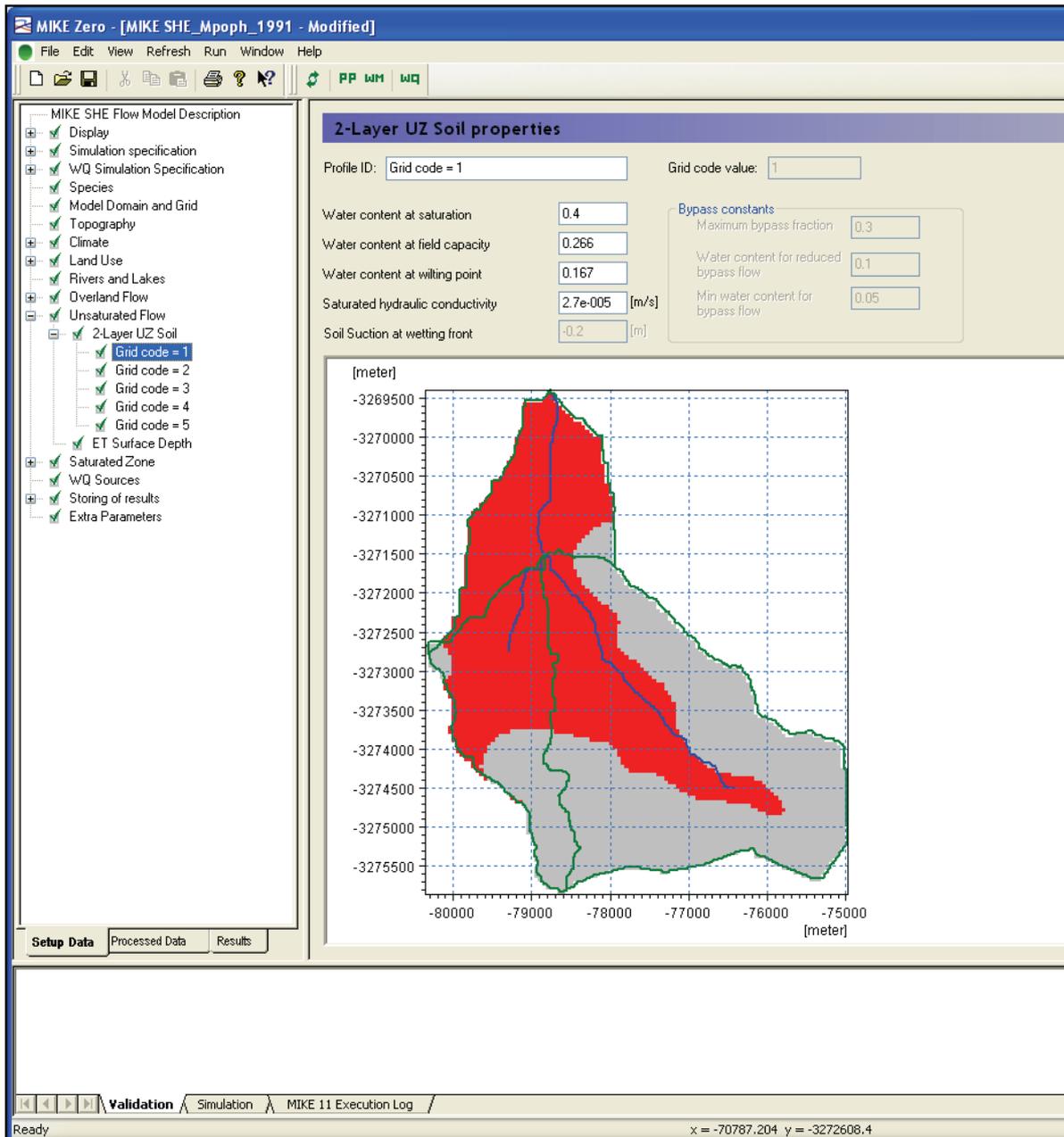


Figure 3.11: The various soil properties associated with each soil type.

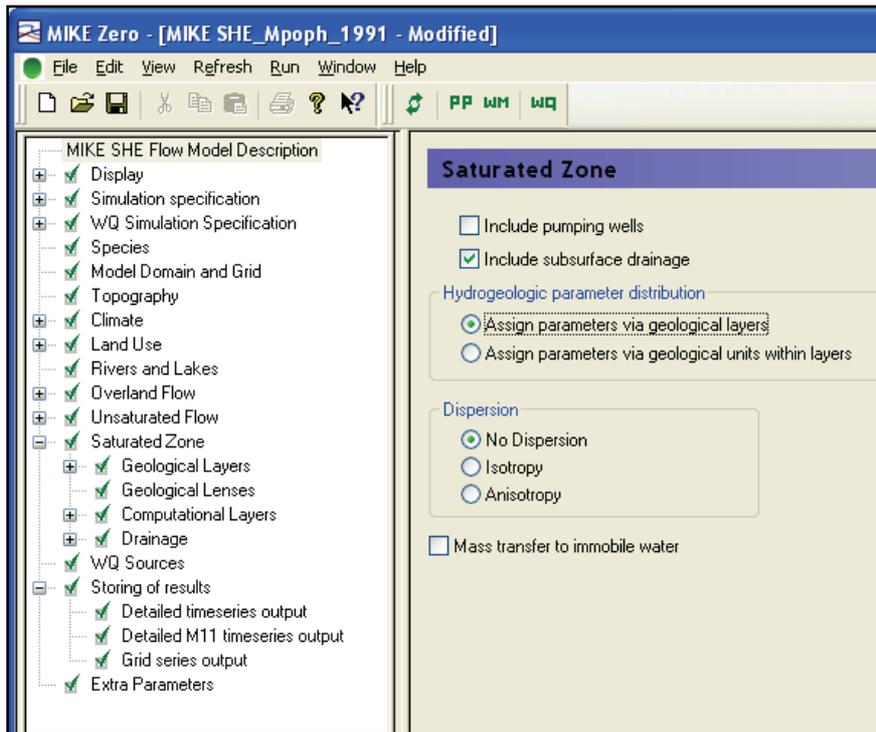


Figure 3.12: Options available for the saturated zone.

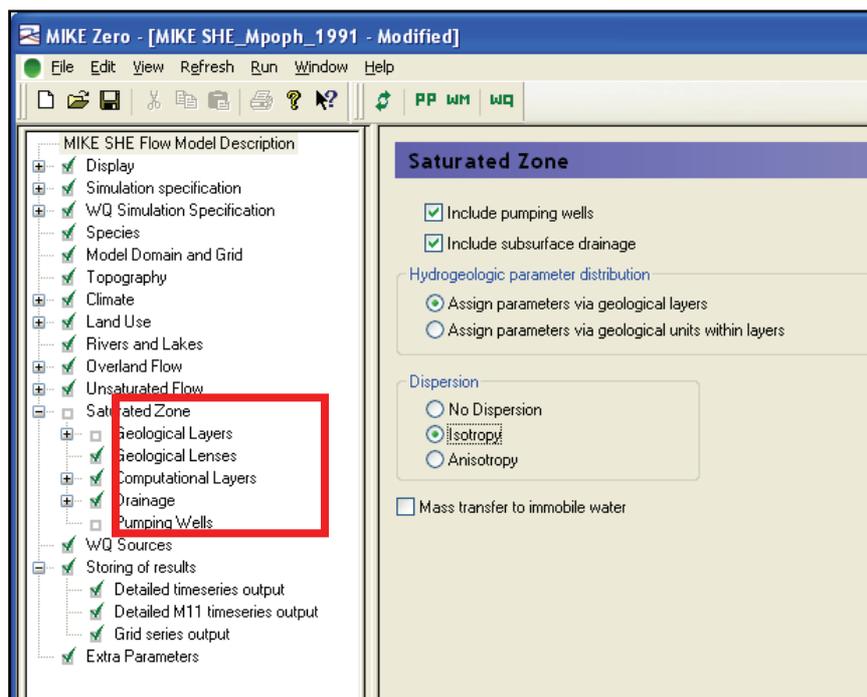


Figure 3.13: Adjustments made to the saturated zone sub-menu, where the user is informed of additional fields to edit (emphasized by the red box).

The user has a variety of options for the type of results required from the model. One of the features of MIKE SHE is that various discharge simulations can be made at various points on a stream from one model run. This is specified in the 'Storing of results' section, where branch name and chainage numbers (obtained from the network file in the rivers and lakes section, from MIKE 11) can be adjusted. For example, streamflow can be simulated at the end of two different

tributaries, immediately after the two tributaries meet, and at the outlet of the stream, thus four different streamflow simulations from a single run of MIKE SHE (Figure 3.14).

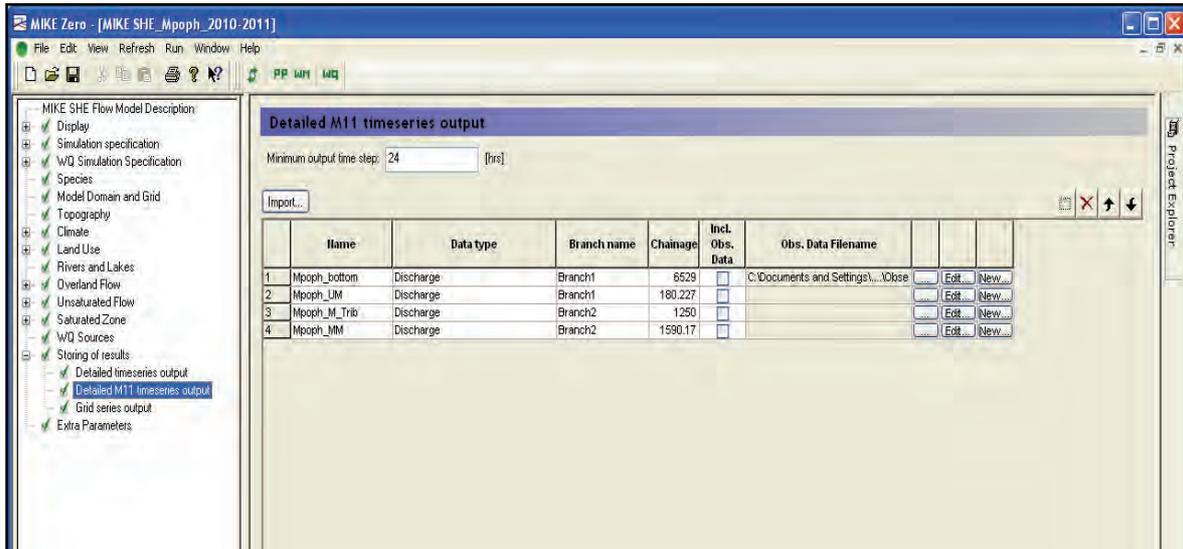


Figure 3.14: Storing of result section in MIKE SHE, where the user has the option to simulate several discharges at various points on a stream from a single simulation.

The simulated output from this MIKE SHE project is evident (Figure 3.15), where the R^2 between simulated and observed was 0.846.

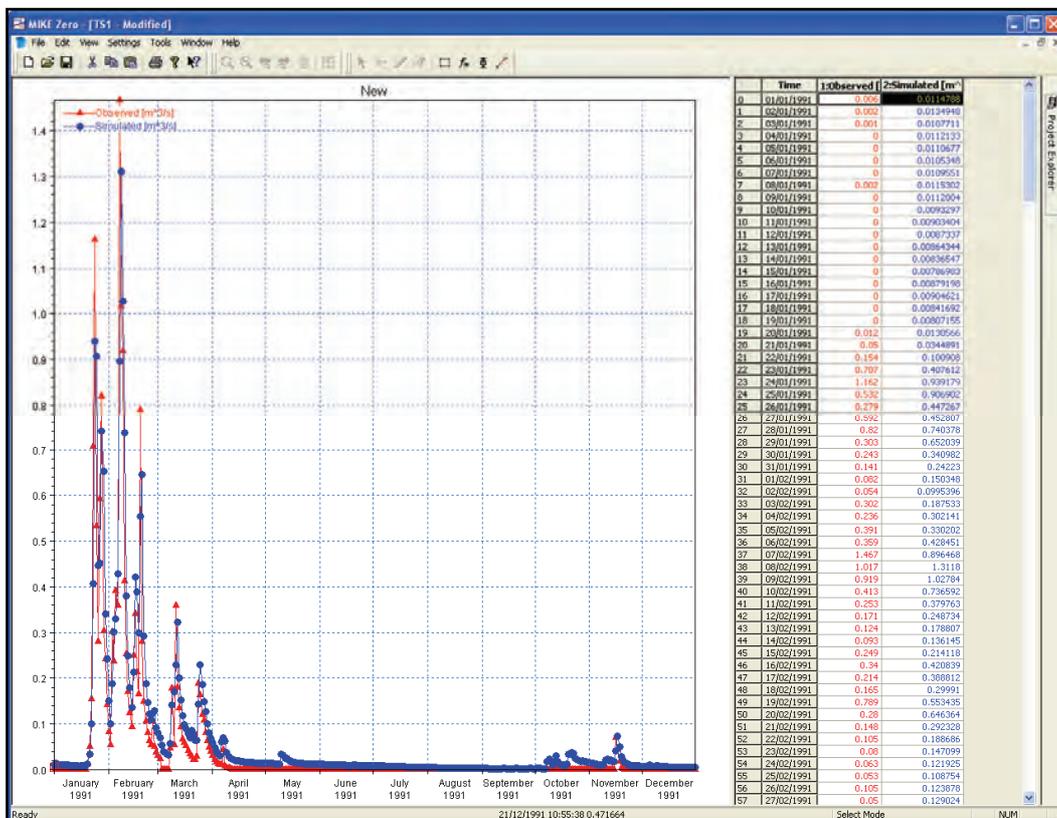


Figure 3.15: Illustrations of observed versus estimated discharge, for calibration of the MIKE SHE model.

This calibrated model was used to simulate streamflow for the study period (October 2010-July 2011). Precipitation rate and reference evapotranspiration were the primary adjustments that were made. The output for this is evident (Figure 3.16), where four different points in the catchment were used to generate discharge.

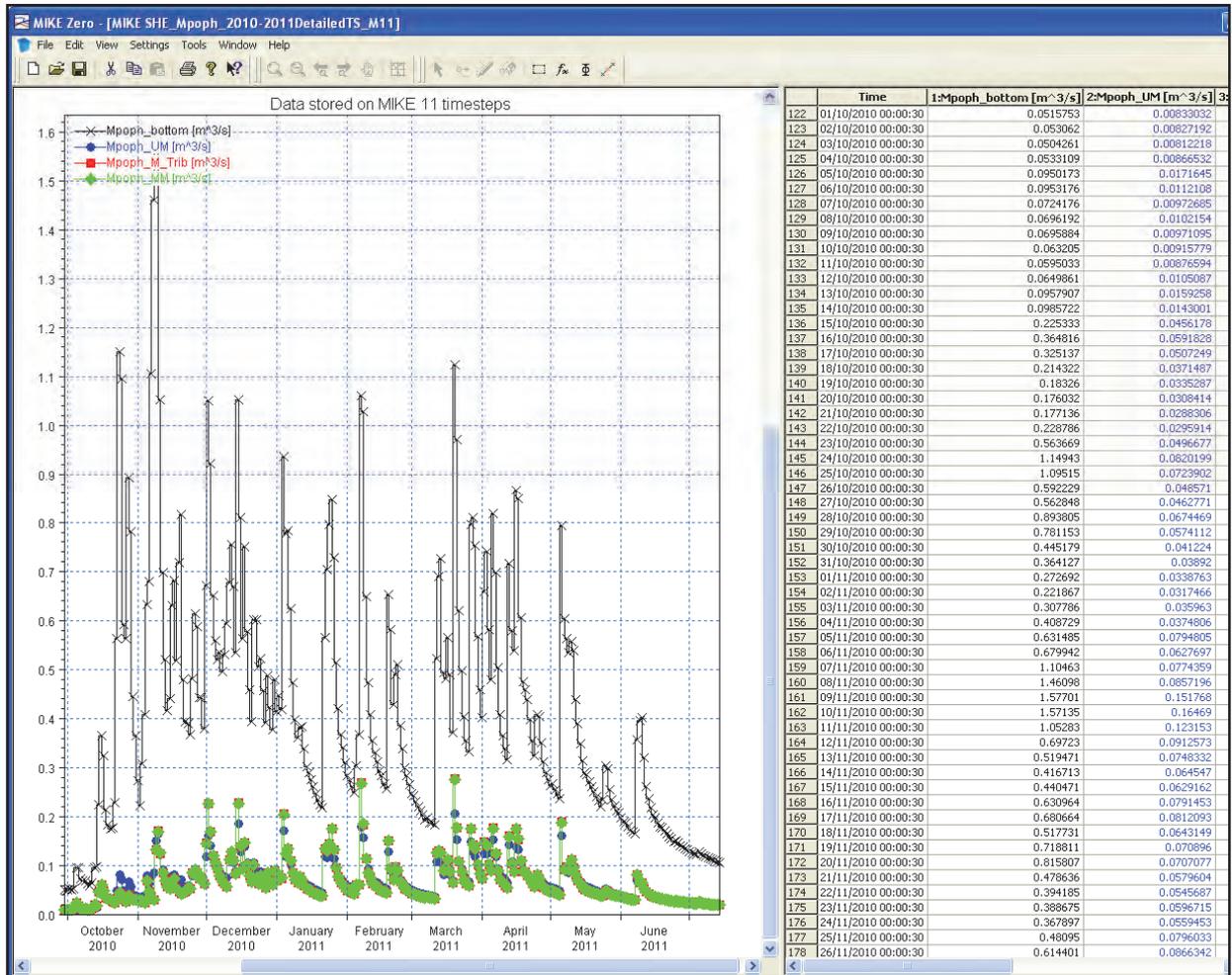


Figure 3.16: Final discharge output from the MIKE SHE model for four different points in the catchment.

3.8.4 Hydrological Simulation Program in FORTRAN (HSPF)

A detailed analysis of HSPF is available in the Preliminary Technical Software Report (see CD attached to this report). Whilst it is recognised that HSPF is a popular and powerful model in the BASINS 4.0 system and is extremely widely used particularly in the TMDL programme in the USA, it is not well supported in South Africa and it is not OpenMI compliant. Therefore, despite having considerable merits and a wide range of functions as the HSPF system is not recommended predominantly on the basis of available support and regularity of updating.

3.8.5 SWAT

3.8.5.1 Assessment of the SWAT Model

The purpose of this section is to describe how to use or run the model. The freely available user guides supplied with the model provide detailed and well explained information on how to install and use the model. The purpose is also not to describe the technical quality of the model. The purpose of this section is to provide an assessment of the model based on its use and application by a first time user in a South African catchment and to highlight advantages and limitations of the using the model that are not necessarily obvious to a first time user.

A case study on the application of the SWAT model in the upper Olifants catchment is available in Chapter 5 of this document:

5.6 SWAT (Soil Water Assessment Tool) – Phosphate in the Olifants

Eutrophication is becoming more prominent in Loskop Dam and the case study applies SWAT to assess point and nonpoint sources of phosphate in the catchment.

3.8.5.2 Applications

SWAT is a public domain model. One of the main strengths of the model is the fact that it is freely available as an extension for a number of commercial and open source GIS software packages (Table 3.6). As a result, the model has been widely used across the world and a number of peer-reviewed scientific papers and reports on the use of SWAT have been published. The developers of SWAT have maintained a database of publications that have used SWAT which is freely available online at <http://swat.tamu.edu/publications/> (all listed publications are freely available for download). This assessment refers to the ArcSWAT version of the model.

Table 3.6: Versions of SWAT model currently available

SWAT Version	Description
AVSWAT	ArcView extension and graphical user input interface for SWAT
ArcSWAT	ArcGIS-ArcView extension and graphical user input interface for SWAT
MWSWAT	Open source interface to SWAT using the GIS system MapWindow
SWAT (Basins)*	BASIN 4.0 integrated version of SWAT based on a MapWindow interface

3.8.5.3 Data requirements

SWAT has relatively high data requirements, including spatial GIS data, temporal weather data and specific land cover, soil and other parameters contained in a database that are used for modelling (Table 3.7)

Table 3.7: Minimum data requirements for running ArcSWAT

Data	Source
Spatial Data <i>DEM (raster)</i> <i>Land Cover (raster or shapefile)</i> <i>Soil (raster or shapefile)</i>	http://www.ngi.gov.za/ NLC 1996 (CSIR), 2000 (ARC) 2009 (SANBI) WR2005
Daily Weather Data <i>Rainfall</i> <i>Temperature</i> <i>Humidity</i> <i>Wind Speed</i> <i>Solar Radiation</i>	Weather SA (www.weathersa.co.za) ARC (www.arc.agric.za) SAPWAT (extensive weather data files associated with programme for locations across the country)
Point Source Data <i>Location</i> <i>Daily Loading</i>	DWA Water Quality Data Exploration Tool. (http://www.dwa.gov.za/iwqs/wms/data/000key.asp)
Monitoring Data <i>Flow</i> <i>Water Quality</i>	DWA Water Quality Data Exploration Tool. (http://www.dwa.gov.za/iwqs/wms/data/000key.asp)

NOTE On Data Requirements:

A draw back with SWAT, as with other hydrological land use models is that it is data intensive. Applying SWAT in South African conditions was challenging from a data collection perspective. However in most instances data was available but was simply spread out across many domains. A useful research project for the future would be one that gathers widely dispersed data and populates SWAT databases. This would ensure easier use and wider uptake of the model in South Africa.

3.8.5.4 SWAT Database

SWAT looks up data for land use and soil classes (added as geospatial data) from the SWAT database. When initially downloaded the SWAT database contains information specific to the USA. This means that users of SWAT outside of the USA have to populate the database with relevant information for the country or area of interest. The database is fully editable and new country specific soil and land use information can be added or existing information (e.g. land use) can be edited to be more representative of local conditions.

The SWAT model uses weather generator data for weather stations located in the study area. Weather generator data for these weather stations needs to be entered into the SWAT database. This requires the calculation of mean monthly values as well as specific rainfall statistics (these statistics can all be calculated easily using the software programme pcpSTAT – see Table 3.10)

The physical properties of soil govern the movement of water and air through the profile and have a significant impact on the cycling of water within the Hydrological Response Units defined by the model. Specific soil data required is:

- Number of soil layers
- Hydrological Group
- Maximum Rooting depth of soil profile
- Fraction of porosity from which anions are excluded

For each soil layer:

- Depth from soil surface to bottom of layer
- Moist bulk density
- Available water capacity of the soil
- Organic carbon content
- Saturated hydraulic conductivity
- Percentage clay, silt, sand and rock content
- Moist soil albedo
- USLE equation soil erodability factor
- Electrical conductivity

Table 3.8: Useful data sources for populating the soil database within the SWAT database

Data Source	Description	Reference
ARC Natural Resources Atlas	This online atlas provides spatial and background data on soils occurring in South Africa	http://www.agis.agric.za/agisweb/nr_atlas
Water Resources of South Africa (WR2005)		http://www.wrc.org.za
Soils of South Africa	<p>The book arranges more than seventy soil forms into fourteen groups and provides the following information that was helpful in</p> <ul style="list-style-type: none"> • maps showing their distribution and abundance throughout South Africa • descriptions of morphological, chemical and physical properties • a detailed account of classification and its correlation with international systems • illustrative examples of soil profiles with analytical data and accompanying interpretations. 	Fey, M. (2010) Soils of South Africa. Cambridge. University Press

As many of the land cover and plant growth types included in the SWAT database are common to those occurring in South Africa the existing SWAT database could be used. However it is preferable to update the database with local data (see Table 3.9 for potential sources of data) to reduce uncertainty associated with input parameters. Specific land cover and plant growth data required is:

- Biomass to energy ratio
- Harvest index
- Maximum leaf area index

- Fraction of the growing season corresponding to the 1st and 2nd point on the optimal leaf area development curve
- Fraction of the maximum leaf area index corresponding to the 1st and 2nd point on the optimal leaf area development curve
- Fraction of the growing season when the leaf area index starts declining
- Optimal temperature for plant growth
- Minimum temperature for plant growth
- Fraction of nitrogen and phosphorus in harvested biomass
- Fraction of nitrogen and phosphorus in plant at emergence, half way to maturity and maturity
- SCS runoff curve numbers for the plant or land cover per hydrologic soil group (A, B, C and D)

Table 3.9: Useful data sources for populating the land cover/plant growth database within the SWAT database

Data Source	Description	Reference
Department of Agriculture	DAFFs online website provides detailed guides on the cultivation on most crops produced in South Africa. These guides provide detailed information for updating plant production characteristics contained in the SWAT database	http://www.nda.agric.za/
SAPWAT 3	While designed as a programme for estimating water requirements of crops, the built in databases contain information useful for updating the land cover/plant growth database in SWAT	http://www.wrc.org.za
Visual SCS-SA	This programme and associated manual provides detailed information on SCS Curve numbers derived for different hydrologic soil groups per land cover category.	SCHOOL OF BIORESOURCES ENGINEERING AND ENVIRONMENTAL HYDROLOGY UNIVERSITY OF KWAZULU-NATAL PIETERMARITZBURG CAMPUS PRIVATE BAG X01, SCOTTSVILLE, 3201 SOUTH AFRICA Tel: ++27-(0)33-2605490 Fax: ++27-(0)33-2605818 E-mail: BEEH@ukzn.ac.za

3.8.5.5 Running SWAT – ARCSWAT or SWAT in BASINS

ArcSWAT is relatively easy to use and the user manual provides extensive step by step guidance on data requirements, formatting input data, setting the model up and running the model. In

addition there are a number of internet based user groups for technical support and supplementary programmes that have been developed to help with data preparation, model calibration and data visualisation (Table 3.10).

3.8.5.6 Advantages and Disadvantages

Advantages

- *Open Source:* The model is freely available for use with commercial (i.e. ArcGIS) and open-source (i.e. Map Windows) GIS software.
- *Excellent Support Documentation:* There is extensive, freely available literature on operating the model interface (i.e. manuals), theory behind calibrating model outputs as well as the theory behind the development of the model.
- *Support software:* There are a number of freely available software specifically designed for preparing data (pcpSTAT), calibrating (SWATCUP) and visualising (SWATPlot and VIZSWAT) SWAT output data.
- *Community Support:* There are a number of user forums on the internet providing access to common queries and solutions commonly experienced by international SWAT users. The forums allow users to interact with users across the world.
- *User Friendly Interface:* Once input data had been prepared in the correct formats, use of the interface to integrate data components and run simulations is relatively simple
- It is easy to add and edit relevant information on South African soil types to the SWAT databases
- *Good Water Quality Simulation Capabilities:* Apart from phosphates, the model is capable of performing simulations for other common water quality parameters including nitrogen, sediment, bacteria, dissolved oxygen and pesticides.

Disadvantages

- *Data Preparation:* A significant amount of data preparation (i.e. weather data, point source location) is required prior to input into the model. Preparation of data input is tedious as specifically formatted text or DBF files need to be created.
- *SWAT Databases:* The built-in SWAT databases used to provide information on soil, crop, land use, etc. characteristics contain information relevant to the USA only. While it is easy to add data for South African conditions, a significant effort would be required to set up a relevant database of South African conditions (i.e. a database that contains information on all soil types, crops and land uses across the country) to make the model readily and easily usable across the country.
- *Model Calibration:* For this study, manual calibration techniques were used to improve model simulations. This process was the most time consuming component of the project and manual calibration is not recommended. Familiarisation with auto-calibration software (i.e. SWATCUP) is highly recommended for calibration of the model. Additionally

identification of input parameters most influential on output parameters using a sensitivity analysis is highly recommended.

- *Auto-calibration Tool:* The SWAT model has an auto-calibration tool built in to the software to help in performing sensitivity and uncertainty analysis to help with calibration of the model. Literature and manuals on the use of this application are few and lack sufficient detail and consequently the application could not be run successfully. Preliminary investigation of the SWATCUP software proved this software to be significantly easier to use and yielded very promising and useful outputs.
- *Data Visualisation:* An attractive output of models is the ability to produce maps that provide colourful representation of – for example – nutrient sources or nutrient loading. SWAT does not have a built in data visualisation feature that allows one to quickly and easily produce such maps based on the model output. SWAT output is stored in an MS-Access database and the only option of producing such maps – apart from purchasing VizSWAT – is to extract relevant data from the database and link it to either the watershed or river shapefile produced during the catchment delineation procedure in SWAT. VizSWAT has been developed to perform such a function but it is not freely available.
- *Lack of Sediment Data:* While this is not a problem specific to the SWAT model, the calibration procedure recommends calibrating sediment outputs prior to calibrating nutrient outputs. This is because nutrients – especially phosphorus – are transported into surface waters through attachment to sediment. South Africa does not currently routinely monitor in-stream sediment loads, making calibration of phosphate inputs more challenging.
- *Hidden Costs:* While the ArcSWAT interface and software is free it operates as an extension to ArcGIS and requires Spatial Analyst for the catchment delineation procedure. These are expensive software to acquire if not already part of an organisations IT infrastructure.

Table 3.10: Sources of support to help in running and calibrating the SWAT model and interpreting and visualising SWAT output.

Description	Cost	Description	Source
SWAT User Manuals	Free	A step by step user guide, providing detailed information on how to set up and run the model	http://swatmodel.tamu.edu
Theoretical Documentation	Free	Extensive document detailing the equations, etc. used to model	http://swatmodel.tamu.edu
User Groups	Free	Google groups where users share problems and solutions with using the SWAT programme	groups.google.com/group/arcswat groups.google.com/group/swatuser
pcpSTAT	Free	Software designed to calculate rainfall statistics used by the weather generator of the SWAT	Software: www.findthatzip.com/.../winrar-winzip-download-pcpstat.zip.htm Manual:

Description	Cost	Description	Source
		model	http://www.brc.tamus.edu/swat/manual_pcp_STAT.pdf
SWAT CUP	Free	Software designed to assist in the calibration of the SWAT model	http://swatmodel.tamu.edu
SWAT Plot	Free	Extracts output data from SWAT runs. Observed data (if available) can also be included for comparative purposes.	www.waterbase.org/download_swatplot.html
SWATGraph	Free	Visualises the output from SWATPlot, displaying the data as histograms or line graphs.	www.waterbase.org/download_swatplot.html
VizSWAT	Free	Software designed to visualise SWAT outputs either as maps or graphs.	http://swatmodel.tamu.edu

3.8.6 ACRU

ACRU is a hydrological model that predicts runoff from rainfall. It uses a daily time step and is based on a soil water budget and can take account of agricultural management practices. ACRU does not address water quality.

A recent WRC report (Pott et al., 2008) summarised as follows:

“ACRU is a daily time step rainfall runoff model which has been developed by the School of BioResources Engineering and Environmental Hydrology at the University of KwaZulu-Natal. The acronym ACRU is derived from the Agricultural Catchments Research Unit. The development of the ACRU model is a long term project which has enjoyed generous funding from the Water Research Commission. ACRU, which is continually being developed and improved as our understanding of the physical processes within the Hydrological Cycle is enhanced, has been used in many projects throughout South Africa, the neighbouring states as well as overseas.”

“The ACRU agrohydrological modelling system is defined as being a physical conceptual model. As such, the model is not a parameter optimising model and the parameters that are used in the model are generally estimated from the physical characteristics of the catchment that is being simulated. ACRU also runs on a daily time step and revolves around a multi-layer soil water budget which results in ACRU being a versatile total evaporation model. This attribute makes the ACRU soil water budget sensitive to any changes in climate and land use. It can also be adjusted to take into account any agricultural management practices such as different irrigation applications and soil tillage practices. A further advantage of the ACRU model is that it can be used at different levels of complexity depending on the purpose of the application and the availability of suitable data. Therefore it is flexible in its scope of application.”

“The ACRU model is very data intensive and can take a long time to set up depending on the level of complexity of the catchment and the particular scenario that is being modelled. This, coupled with a lack of readily available data, has contributed to relatively long set up times for an initial base run and consequently the model has possibly not been utilised to its full potential in the South African environment.”

3.8.7 PITMAN

The Pitman model is a model that predicts monthly runoff from rainfall. It does not address water quality.

The Pitman model, originally developed in 1973 (Pitman, 1973) comprises three conceptual storages (interception, soil moisture and groundwater) and simulates infiltration-excess flow, saturation-excess flow, direct overland flow and groundwater flow. It is a conceptual, semi-distributed, monthly rainfall-runoff model that uses monthly rainfall data and monthly estimates of evapotranspiration as input (Kapangaziwiri and Hughes, 2008).

Pott et al. (2008) note that water resource planners in South Africa currently make use of the Water Resources Yield Model (WRYM), a node-and-channel-network model, which is fed with streamflow generated from the Pitman model.

They also note that the above-mentioned ACRU-MIKE BASIN linkage provides an alternative to the Pitman-WRYM combination, and has some advantages over the Pitman-WRYM. The time-step that the models operate on is daily (as opposed to monthly). Also, ACRU is a process-based hydrological model, which allows various land use and management practice scenarios to be considered which are not suited to the Pitman modelling framework since it is a regression model.

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CHAPTER 4: LAND USE CLASSIFICATION AND DATA SOURCES

4.1 INTRODUCTION TO LAND USE/LAND COVER CATEGORIES REQUIRED FOR WATER QUALITY MONITORING

Fluctuations in surface water quality are highly correlated with land use changes. Land use practices associated with agriculture, mining and urban areas include tillage, addition of fertilizers, spraying of pesticides and extraction of water. These alter the quality and quantity of available usable downstream water in a catchment. The structure and phenology of natural vegetation in a catchment also impact on hydrological processes and dynamics through changes in infiltration rate, evapotranspiration and ultimate runoff to downstream catchments. Some high impact land uses are increasing in spatial extent and some land use practices are intensifying. Those that transform the landscape and impact the natural hydrological cycle make modelling the impact of land use on water quality extremely important for water resource management (DeFries & Eshleman, 2004).

The relationship between land use and water quality has been demonstrated and modelled at particular scales in various parts of the world. Indeed, the TMDL Programme in the United States of America (USA) has played a central role in exactly this. There are also many land use – water quality modelling programmes around the world. However, modelling the impact of land use changes and climate to explain observed water quality parameters and predict future scenarios at an appropriate scale remains a challenge (Niehoff et al., 2002; Tong and Cheng, 2002). It has been noted that “hydrological responses are highly sensitive to and dependent upon land use and its change” (Schulze, 2002). In Africa, insufficient spatial and temporal hydrological data make regional scale studies inadequate for water resource management (Legesse et al., 2003). Abrupt local land use changes have a more significant impact on hydrological responses (Schulze, 2002).

The past few decades have seen a proliferation of software models aimed at modelling historical land uses in relation to water quality parameters. Current and future land use scenarios have also been developed to predict water quality trends based on current or potential land use practices with the aim of implementing land use best management practices (BMPs) that mitigate negative impacts on water quality and quantity (DeFries & Eshleman, 2004). In addition, there has been increased use of operational space-borne imagery for mapping of country-wide land cover and vegetation phenology. This has enabled not only a broader view of regional patterns of land cover change but, with higher spatial resolution imagery, it has also improved the ability to study land cover changes at a macro, meso and micro scale. Water quality models have also incorporated the ability to proxy land use practices, imperviousness and associated water quality constituents to mainly first-level land cover classes.

South Africa has produced two National Land Cover (NLC) data sets from satellite imagery:

1. National Land Cover 1996 (NLC1996) (Thompson, 1996; Fairbanks et al., 2000); and
2. National Land Cover 2000 (NLC2000) (Van den Berg et al., 2008).

A four-level nested hierarchical land cover standard, the South African National Standard (SANS) 1877 (SANS1877) (SSA, 2004), was developed after NLC1996 and adopted for the classification of NLC2000. Similar to many other international land cover classification systems, the classes and hierarchies are based on the ability of the remote sensing technology (sensor and software) to distinguish between various land covers. An increase in spatial and spectral resolution of the sensors will bring an increase in the ability to detect more detailed land cover classes (detectability) and improved methods to separate between them (separability). However, a critical question remains within the context of water quality modelling and scenario generation: how appropriate is the current land cover classification system for South Africa for water resource management?

The current land cover classification system of South Africa is therefore reviewed particularly in respect of linking land use to water quality. The objectives of the review are to:

- Distinguish between land cover and land use in order to understand the terminology related to a land use or land cover classification system;
- Investigate the land cover classes and hierarchies resulting from earth observation;
- Broadly assess the land cover classes and land use practices used for water quality modelling at a catchment level;
- Evaluate the ability of the South African land cover classification system to be used in catchment-based water quality modelling; and

4.2 LAND USE AND LAND COVER – DIFFERENCE IN TERMINOLOGY

Land cover is the biophysical or physical cover visually detectable through remote sensing, e.g. the vegetation or crop type. Land use on the other hand “is characterised by the arrangements, activities and inputs people undertake in a certain land cover type to produce, change or maintain it.” (FAO, 2003:3). Land use activities and associated management practices impact directly on water quality in a catchment.

While land use practices primarily impact on water quality, these are not easily mapped as they are not always visible from a space-borne platform (Table 4.1). This is even less so for the quantifiers necessary to describe the land use practice. For example, patterns of tillage (a land use activity) are visible on satellite imagery. However, quantification of the temporal frequency and duration require high frequencies of sensor revisit and much post-processing and interpretation. Neither the amount of fertilizer added or pesticide used in agriculture (including the placing in the soil profile, and the timing), the micro-management of runoff on or near the surface, nor the full extent of underground mining activities, can be detected with remote sensing. All the aforementioned can impact on water quality even when the land cover is designated to be the same.

Table 4.1. The relationship between land cover, land use and water quality.

	Land cover data	Land use data
Amenability to use of remote sensing	High	Very low for many land uses
Cost of thorough data collection and mapping	Relatively cheap	Expensive (can be highly labour intensive)
Practical usefulness for understanding the effects on water quality	Low	High

On the other hand, land cover, as mapped by satellite imagery, offers a country-wide perspective of the landscape and can serve as a proxy for land use practices. However, the real challenge lies in accurate modelling of this at the appropriate scale. In many instances it may not be possible to change land cover but it is always possible to change land use practices. For example, while the extent of agricultural cropland may remain the same, the impact on water quality may change with different land use practices, such as the way in which farmers till and apply fertilisers, pesticides and herbicides.

4.3 LAND COVER CLASSIFICATION THROUGH EARTH OBSERVATION

Since the launch of the Landsat satellite sensor in 1972, Earth Observation (EO) technologies have enabled the automation of land cover classification over large areas and inventories at country-wide scales (Goldewijk & Ramankutty, 2004). Initial land cover attempts were focused on providing inventories or pictures of land features. However, the increased use of EO for land cover mapping created the possibility of time-series comparisons from a country-wide to global scale. This required a more consistent approach to the use of land cover classes (Bartholomé and Belward, 2000; Goldewijk & Ramankutty, 2004).

A number of country-wide land cover classification systems are used internationally. Table 4.2 shows a representative though not exhaustive list. The use of land cover classification datasets has infiltrated into all levels of government, research councils, the private sector and other users (Jansen & Di Gregorio, 2002). The range of application of these datasets is broad. It includes feature inventorying, land use planning, resource monitoring to historical change detection (Bartholomé and Belward, 2000; Goldewijk & Ramankutty, 2004).

Table 4.2. Examples of some international country-wide land cover classification systems.

Land cover classification system name	Country	Reference/website
Land Use and Land Cover Classification System for the United States of America (USA)	United States	Anderson et al., 1976 and modifications thereafter
The Australian Collaborative Land Use Mapping Programme (ACLUMP)	Australia	Australian Government Bureau of Rural Science, 2006
UK National Land Use Database	United Kingdom	LandInform Ltd, 2006
Coordination of Information on the Environment (CORINE)	Europe	CEC, 1995
National Land Cover Classification system for South Africa	South Africa	NLC1996 (Thompson, 1996; Fairbanks et al., 2000) NLC2000 (Van den Berg et al., 2008) SANS1877 (SSA, 2004)
Land Cover Classification System (LCCS) for African countries	African countries	Hosted by the United Nations Food and Agriculture Organisation (UN-FAO): http://www.africover.org/system/africover_data.php or http://www.africover.org/LCCS.htm

A consistent continental approach to land cover classification and mapping allowed the first global land cover dataset to be generated in 2000 (Bartholomé and Belward, 2000). However, comparability and compatibility remain the biggest challenges in up- and down-scaling of land cover maps for resource monitoring (Herold et al., 2006). Owing to the use of EO in land cover classification, structural classifiers of land cover, such as vegetation life form, density, height, leaf type and longevity are often used in definitions of land cover classes (Herold et al., 2006:5). Ensuring compatibility between the precise meanings of terminology used in different land cover classification systems is critical when comparing land cover datasets (Feng and Fleweling, 2004; Herold et al., 2006).

Compatibility problems can also result from improvements in sensor capabilities in terms of spectral, spatial and temporal resolution (Goldewijk and Ramankutty, 2004; Herold et al., 2006). Phenology changes, changes in agricultural cycles and the hydrological cycle itself also present difficulties in detecting land cover change (Goldewijk and Ramankutty, 2004).

Another feature of comparability between land cover classification systems and datasets is scale. Ideally this should be accommodated through various levels in a nested hierarchy (Jansen and Di Gregorio, 2002). Understanding the scale at which features were mapped and the minimum mapping unit (MMU) facilitate appropriate comparisons and decision making (Herold et al., 2006). Current trends generally lead in the direction of global monitoring of resources (Bartholomé & Belward, 2000) and towards finer scale research and comparisons (Tong and Chen, 2002). For

example, higher resolution data have been found to provide higher accuracy in the relationship between water quality and land use (Gassman et al., 2007). The appropriate scale to be used in an application will depend on the purpose of the application, the spatial extent and available data.

The following are some specific limitations in land cover classification:

- Not all land use activities can be directly related to land cover types (Anderson et al., 1976);
- Seasonality and processes need to be accounted for such as hydrological and agricultural cycles (Anderson et al., 1976);
- Underground (e.g. mining) activities may only be partially recognisable with remotely sensed imagery;
- Multiple land cover classes and uses may be present at the same point. For example, mining land may be covered with trees or grasses as part of remediation but also used for subsistence grazing and crop production. In such a case, the largest contributor or most significant water quality contaminant needs to be considered;
- Transition from one land use to another can happen quickly. Multi-temporal EO imagery has limitations in monitoring these changes; and
- Better accuracy imagery and datasets are usually more expensive, as well as data/image acquisition and *in situ* ground-truthing.

More recently users have expressed a need for land use classification systems (Briassoulis, 2000). Combined land use-land cover (LULC) classification systems and datasets resulted but these had inconsistencies (Jansen and Di Gregorio, 2002). In other applications, land use activities and associated parameters have been related to land cover classes for modelling purposes (IPCC, 2006). Changes in modelling parameters can also hinder comparability for historical change detection.

The manner in which land use is imbedded in LULC classification systems or how it relates to land cover classification systems need to be explored further specifically within the context of water resources management.

4.4 LAND COVER & LAND USE LINKS TO WATER QUALITY

This sub-section examines the use of land cover classes and land use practices in relation to water quality management at a catchment scale. Two sources of information were explored to assess how nonpoint source runoff water quality relates to land uses:

1. Research empirically determining the statistical relationship between water quality constituents and the percentage land use within a catchment; and
2. Models relating water quality to land uses.

Some examples of applications and models are briefly discussed to demonstrate the relationship between LULC and water quality.

4.4.1 Empirical relationships between land cover and water quality

A number of research case studies have related high levels of inorganic constituents, volatile organic components, pesticides, bacteria and/or suspended sediments to land use practices associated with land covers in the catchment (e.g. Eckhardt and Stackelberg, 1995; Mattikalli and Richards, 1996; Johnson et al., 1997; Ahearn et al., 2005; Rothenberger et al., 2009). These land uses related mainly to agriculture, urban areas and forestry.

A number of preliminary observations were made:

- **Catchment-scale land use correlation with water quality.** Two studies specifically found that water quality was better explained by considering land use at a catchment scale compared with land use within a 100-200 m river buffer (Hunsaker and Levine, 1995; Sliva and Williams, 2001).
- **Surface water quality correlation with land use.** In most cases surface water quality correlated well with land use. However, Eckhardt and Stackelberg (1995) found that upper-level groundwater quality samples also correlated well with the land use surrounding a monitoring well.
- **Seasonal fluctuations correlated with point sources.** Seasonal fluctuations of water quality variables were correlated with point sources such as Waste Water Treatment Works (WWTWs) and confined animal feed operations (CAFOs) (Rothenberger et al., 2009).
- **Classification of land uses in terms of nature of runoff.** Land use practices may be considered as either resulting in nonpoint source runoff, point source runoff or a combination of the two (Ongley and Broekhoven, 1978).
- **Site characteristics (e.g. slope, soil type, etc.) affect the land use – water quality relationship.** Such factors affect hydrological infiltration and runoff which, combined with land use, ultimately determine water quality.

None of the above-mentioned studies established empirical relationships between mining activities and water quality variables.

The generality and usefulness of the above observations will need to be tested during the project. They also raise the question of the need for empirical relationships that are specific to South African conditions, an issue that will be considered later.

4.4.2 How is land cover used in water quality models?

Various software systems used for hydrological modelling use land cover as one input dataset. These include the US EPA's BASINS 4.0 which is an integrated software shell that provides a wide variety of modelling tools and the locally-developed ACRU (both described further in Chapter 3). The models that specifically link land cover or land use to water quality have typically been used in three contexts:

1. Facilitating hydrological modelling to assess sedimentation and water quality as a result of land use practices related to land cover in a catchment (e.g. Legesse et al., 2003; Schulze 2000);
2. Linking historical land cover changes with historical water quality records (Mattikalli and Richards, 1996); and

3. Generating future land use scenarios and their impact on water quality (e.g. Tang et al., 2005; Gassman et al., 2007; Eberhard et al., 2009; Idowa et al., 2010).

Catchment models in the BASINS 4.0 shell use standard land cover classes developed for the USA (Anderson et al., 1976) or modifications thereof. Modifications and additions to these land cover lookup tables can be customised by the user. The land cover classes can also be subdivided by the percentage area of each of these classes based on an impervious rating that the user assigns. Management practices in terms of fertilisation, addition of pesticide, tillage and the time period associated with these are then linked with the defined land cover classes. The models also allow integration of point-source models with the runoff from nonpoint sources. The BASINS 4.0 shell also expands scenario modelling capabilities through additional plug-ins with other modules such as climate change scenario generators, groundwater, ecological and farm economical models (Gassman et al., 2007). Interoperability is possible with proprietary (e.g. ArcGIS) and open source software (e.g. GRASS and MapWindowsGIS).

4.4.3 Is it better to use land cover or land use in water quality monitoring?

It is apparent that most of the models and literature support the use of land cover classes in linking nonpoint source runoff to water quality. Land use practices and associated quantifiers are linked to land cover classes as parameters/coefficients in the models (as the default settings). However, in some models it is possible to simulate various forms of land use practices by changing parameter/coefficients settings in the model input data sets. The BASINS 4.0 shell currently houses both of these types of model. The South African land cover classification system will therefore be reviewed in this light.

4.5 THE SOUTH AFRICAN NATIONAL LAND COVER SYSTEM

4.5.1 Historical development of the South African Land Cover classification system

Following the first national land cover data set in 1996 (Thompson, 1996; Fairbanks, 2000), a South African National Standard (SANS), SANS1877 (SSA, 2004) for land cover mapping was developed. SANS1877 defines land cover classes and nested groupings thereof at four levels. The standard was used in the classification of NLC2000 (Van den Berg et al., 2010). The past decade has seen more investment in provincial land cover datasets and it is unclear whether a NLC dataset is envisaged as a separate product to the provincial land cover datasets, or whether the amalgamation of provincial data sets is planned by the Department of Rural Development and Land Reform (DRDLR).

In response to an increasing need of land use categories reflected in the land cover data sets by municipal land use planners, a workshop was held in 2008 to determine user's needs of land use categories (GTI, 2008; NGI, 2009). It was apparent that the dominant sector input came from the local scale (municipal) land use planning institutions, as opposed to national-level decision makers, and users from sectors such as the water sector. Similar to ACLUMP (Australian Government Bureau of Rural Science, 2006), land uses will be considered for incorporation into the land cover classification scheme but to which level and degree is not yet known. A pilot study is under way to test the capturing of the proposed land uses in the Eastern Cape (Parker, 2010).

The South African land cover datasets, like other land cover datasets in the world, serve a multi-organisational user community who use them in many applications for different purposes and at a variety of scales. A level-1 comparison of the South African NLCs (using SANS1877) is given in Table 4.3. It is apparent that most of the classes at level-1 are comparable and very few classes differ between the standard and NLC datasets.

Table 4.3. Possible congruencies of level-1 classes of the South African National Land Cover classification standard and datasets.

SANS1877	NLC1996	NLC2000
Natural		
Forest and woodland	Forest	Forest
	Forest and Woodland	Woodland
Thicket, bushland, scrub forest and high fynbos	Thicket & bushland	Thicket, Bushland, Bush Clumps, High Fynbos
Shrubland and low Fynbos	Shrubland and low Fynbos	Shrubland and low Fynbos
Herbland	Herbland	Herbland
Grassland	Improved grassland	Planted grassland
	Unimproved grassland	Natural grassland
Water bodies	Water bodies	Water bodies
Wetlands	Wetlands	Wetlands
Barren rock	Barren rock	Barren rock
Transformed		
Mines & quarries	Mines & quarries	Mines & quarries
Forest plantations	Forest plantations	Forest plantations
Cultivated land	Cultivated	Cultivated
Built-up land	Urban	Urban/Built-up
Other		
	Degraded	Degraded
	Dongas & sheet erosion scars	Dongas & sheet erosion scars

4.5.2 Comparing LULC categories of RSA with those in the BASINS 4.0 shell

Table 4.4 shows a comparison of the South African standard (SANS1877) with the land cover classes used by models in the BASINS 4.0 shell. It is apparent that level-1 classes match fairly well.

One particular advantage is that a clear differentiation is made in SANS1877 between mining land and barren land, recognising the one being transformed land and the other being natural. SANS1877 however does not distinguish sub-groups within “Mines and quarries”. This may be

problematic from a water quality point of view because different mines (e.g. gold, uranium and coal) can have different water quality impacts.

It is evident that using the level-1 categories of NLC1996 and NLC2000 is appropriate for water quality modelling in BASINS.

Table 4.4. Possible congruencies of SANS1877 land cover classes with those used in water quality models linking land use and water quality.

SANS1877	GIRAS	HSPF (USGS)	NLCD	MRLC	MRLC2001
Natural					
Forest and woodland				Natural Forested Upland	Mixed Forest
Thicket, bushland, scrub forest and high fynbos				Non-Natural Woody Herbaceous Upland Natural/Semi-Natural Vegetation Grassland/Herbaceous	Shrub/Scrub
Shrubland and low fynbos			Upland Shrub Land	Shrubland	Sedge/Herbaceous
Herbland					
Grassland			Grass Land	Other Grasses (Urban/recreational; e.g. parks, lawns)	Grassland/Herbaceous
Water bodies	Wetlands/Water	Water	Water/Wetlands	Water Open Water	Open Water
Wetlands		Waterlands		Wetland per type	Wetland per type
Barren lands	Barren Land	Barren Land	Barren or mining*	Bare Rock/Sand/Clay Barren Bare Soil	Barren Land
Transformed					
Mines and quarries			Barren or mining*	Quarries/Strip Mines/Gravel Pits	
Forest plantations	Forest Land	Forest Land			Forest
Cultivated land	Agricultural Land	Agricultural Land	Agriculture - cropland	Planted/Cultivated (orchards, vineyards, groves) Herbaceous Planted/Cultivated Pasture/Hay Row Crops Small Grains	Cultivated Crops
	Range Land		Agriculture - rangeland		Pasture/Hay

Table 4.4 (cont). Possible congruencies of SANS1877 land cover classes with those used in water quality models linking land use and water quality.

SANS1877	GIRAS	HSPF (USGS)	NLCD	MRLC	MRLC2001
Built-up land	Urban or Built-up Land		Urban		Developed
Other					
		Unknown	Transitio- nal	Perennial Ice/Snow Unclassified Transitional	Perennial Ice/Snow Unconsolidated Shore Lichens, Moss

* Transcends both natural and transformed land cover categories

4.5.3 Issues of scale of land cover classes in water quality modelling

Land cover categories used in hydrological modelling (like those in Table 4.4) do not reflect land use practices such as conservation, tillage or addition of fertilizers and pesticides. Instead the quantity of pollutant per surface area associated with a land use category is saved as default coefficient factors in a look-up table in the software (see Chapter 3, Section 3.4). The default factors may be modified and potentially factors associated with land use (as opposed to default factors associated with land cover) may be better incorporated in the hydrological modelling of water quality using proxies to land cover. The scale at which the hydrological models are tested is very important. Modelling at different scales of extent and data mapped at different extents will most probably have result, yet will not necessarily improve understanding or decision making.

Although additional higher resolution data sets are available for South Africa, these are captured inconsistently and infrequently. They are therefore not easily compared. The advantage of the BASINS 4.0 shell to users in the USA is the immediate availability of datasets available online when creating a new project. A similar situation could be created in South Africa to link the primary data and information suppliers, who are generally government departments, to users of models in the BASINS 4.0 shell.

While the NLC1996 and NLC2000 offer sub-categories of land cover at levels 2 to 4, default factors of pollutant loads for land cover categories are only available at level 2 for phosphates and partly for nitrate and suspended solids (Section 4.8 of this Chapter). It is possible to develop unique pollutant load factors for South Africa to be used in conjunction with SANS1877 levels 1 and 2, or even refine land cover categories and factors of levels 2-4 or beyond. The need for investing in such detail should be considered in the light of improving understanding within the context of efficiency of decision making. Furthermore, not all hydrological or water quality models can accommodate the details of SANS1877 at level 2 (Section 4.8 of this Chapter), however can accept the basic land cover classes at level 1. We therefore consider the current categories of level 1 and to a degree those of level 2 of SANS1877, as used in South Africa, to be appropriate for use in water quality modelling and related scenario generation.

4.6 THE SOUTH AFRICAN NATIONAL LAND COVER DATASETS AND HYDROLOGICAL MODELLING

At the time of writing the National Land Cover 2000 (NLC2000) (Van den Berg et al., 2008) was the latest available South African land cover which distinguishes nested land cover classes up to level 2, along the lines of those specified within the South African National Standard (SANS)1877 (SSA, 2004) for land cover mapping. The 49 Level 2 land cover classes of NLC2000 are particularly useful in the context of pollutant load modelling utilising export coefficients or event mean concentrations (such as the PLOAD model), as the high number of classes allows more accurate representation of nonpoint source areas generating pollution. The NLC2000 coverage (Van den Berg et al., 2008) distinguishes 17 unique 'urban/built up' land cover classes at level 2 (Table 4.5), providing improved potential for the modelling of urban catchment areas (particularly in conjunction with modelling ability to enter point source inputs).

However, with regards to land cover datasets, the accuracy of catchment water quality modelling is also reliant on the accuracy and resolution of the land cover dataset. Regional land cover datasets, such as those at municipal or conservation area level, are commonly compiled at higher resolutions, which may facilitate more accurate water quality modelling. A case in point is the 2008 KwaZulu-Natal land cover dataset commissioned by Ezemvelo KZN Wildlife (EKZNW, 2010). However, while the vegetation class mapping of this coverage is at a high resolution and distinguishes multiple vegetation classes, all urban land cover classes are lumped into a single category which potentially limits the accuracy of export coefficient or event mean concentration water quality modelling in urban catchment areas. As the NLC2000 is a national coverage, most closely meets the SANS1877 standard, and disaggregates multiple urban, natural and agricultural land cover sub classes, the land cover proved appropriate for use in the pollutant load modelling within the uMngeni case study catchment (Chapter 5).

4.7 POLLUTANT LOAD EXPORT COEFFICIENTS USED WITH LAND COVER CLASSES FOR WATER QUALITY MODELLING

Export coefficients for phosphates, nitrates and suspended solids for the level 2 land use classes of SANS1877 (SSA, 2004) were extracted from a review of both national and international literature (Table 4.5). Local export coefficients (estimated from South African data/catchments) were given priority; however, where these were unavailable for a particular land use international literature was consulted. Obtaining nitrogen and suspended solids export coefficients down to the disaggregated level 2 land use classes set out in the SANS1877 principles proved challenging and in some cases export coefficients could only be found for the Level 1 land-use classes (i.e. wetland as opposed to separate coefficients for channelled and unchannelled wetlands).

Two key reports utilised to populate Table 4.5 with regard to nutrient export coefficients were "*Investigation of the positive and negative consequences associated with the introduction of zero-phosphate detergents into South Africa*" (Dickens et al., 2010) and "*Collation and development of nutrient export coefficients for South Africa*" (Enongene & Rossouw, 2007). Simpson and Stone (1988) and Simpson (1991, 1998) were useful sources of South African export coefficients having undertaken studies of urban catchments and runoff water quality, the effects of land-use on runoff water quality and the runoff water quality from a disused feedlot, respectively. Wimberley and Coleman (1993) estimated export coefficients for urban land-uses in Alexandra and Sunninghill Park (South Africa). In a study of the Hennops Valley, Hoffman (1995) estimated export coefficients for several urban land-use classes – formal settlement, informal settlement and mixed industrial and commercial. Enongene and Rossouw (2007) provide a useful compilation of export

coefficients (based on international literature; Reckhow et al., 1980 and Athayde et al., 1983) and estimate export coefficients for several South African catchments. However, South African studies of nitrogen and suspended solids export coefficients for all the land-use classes specified at level 2 of SANS1877 (SSA, 2004) are not available; for certain land use classes even international export coefficient estimates proved difficult to obtain.

To fill gaps in Table 4.5, default export coefficients for nitrates and suspended solids provided within the PLOAD model were extracted where possible from the range of default land use classes supplied within the model. The land use classes provided as default within PLOAD do not distinguish the full range of land use classes detailed under level 2 of SANS1877 (SSA, 2004). However the export coefficient and land use look up tables utilised by PLOAD are fully editable, and as such the range of land use classes and export coefficients can be tailored to any level of classes. One limitation is the units used by the PLOAD model, requiring that export coefficients fed into the model are converted to pounds per acre per year.

With the rate of export being dependent on local factors, particularly climate and soils, the export coefficients compiled may not perfectly represent the catchment, but should be seen as the best currently available. At the least it provides a plausible starting point for stakeholder interaction in the quest to find more realistic estimates. Brylinsky (2004) states that (a) unless export coefficients have been measured in the catchment being modelled, the choice of the most appropriate export coefficient to use remains somewhat subjective, and that (b) it is very important to attempt to match climate, geology, soil and vegetation type as closely as possible when estimates are based on studies that have been carried out in other areas. As a result there is high variation in the range of export coefficients quoted in the literature within a certain land use. Regarding the estimation of export coefficients through case studies in South Africa, Pegram and Görgens (2001) stated that *“there is considerable variation in the reported values, which significantly complicates the selection and application of appropriate coefficients”*. However, in the present study it must be re-emphasised that the context within which we are assessing approaches is a multi-stakeholder interaction process which seeks to generate socially robust knowledge that is sufficiently accepted to engender integrated actions.

What is apparent when reviewing these South African reports and other international sources, is that the majority of export coefficients provided within recent literature are quoted from studies performed as far back as the 1980s and 1970s. Research into appropriate export coefficients has likely dwindled in recent years as researchers delve into complex, physically based models simulating pollutant transport. However, export coefficients still have an important role to play in regional and catchment scale management, and are attractive alternatives to complex modelling due to their limited data requirements (Enongene and Rossouw, 2007).

Chapter 5 includes the description of pollutant load modelling undertaken within the chosen case study catchments as a component of the testing and refining of tools to improve the decision making of management stakeholders. The PLOAD modelling on the uMngeni River compares results between the use of model default phosphate export coefficients gathered from international literature, and the predominantly local phosphate export coefficients compiled within Table 4.5. The export coefficients provided within Table 4.5 will need to be refined and verified during further case studies and catchment investigations within the context of the emerging Catchment Management Agency engagement spaces in South Africa.

Table 4.5: Phosphate, nitrate and suspended solid export coefficients for each of the land cover/use classes.

Land cover/use class (NLC2000)		Phosphate export coefficient (kg/ha/yr)	Source	Nitrate export coefficient (kg/ha/yr)	Source	Suspended solid export coefficient (kg/ha/yr)	Source
Level 1	Level 2						
Forest	Forest (indigenous)	0.02	Dickens et al. (2010)	0.16*	Simpson (1991)	303*	Simpson (1991)
Woodland/Bushland	Woodland (previously termed 'Forest and Woodland')	0.02	Dickens et al. (2010)	0.041	Enongene & Rossouw (2007)		
	Thicket, Bushland, Bush Clumps & High Fynbos	0.02	Dickens et al. (2010)				
Shrubland	Shrubland and Low Fynbos	0.08	Dickens et al. (2010)	0.29	Enongene & Rossouw (2007)		
Herbland	Herbland	0.02	Dickens et al. (2010)	2.24	PLOAD default	56	PLOAD default
Natural Grassland	Natural Grassland (Previously termed 'Unimproved Grassland')	0.1	Dickens et al. (2010)	0.9	Wali et al. (2011)	303*	Simpson (1991)
Planted Grassland	Planted Grassland (Previously termed 'Improved Grassland')	0.1	Dickens et al. (2010)				
	Forest Plantations (Eucalyptus spp)						
	Forest Plantations (Pine spp)			108	Reckhow et al. (1980)		
Plantations	Forest Plantations (Acacia spp)	0.02	Dickens et al. (2010)			250	Jeje (2006)
	Forest Plantations (other/mixed species spp)			1.8	Enongene & Rossouw (2007)		
	Forest Plantations (clear-felled)						
Water-bodies	River	0	Dickens et al. (2010)				
	Dam						
	Lake			8.0	Harper (1998)	21.0	Harper (1998)
Wetlands	Un-channelled wetland	0	Dickens et al. (2010)	4.4	Harper (1998)	27.7	Harper (1998)
	Channelled wetland						
	Bare rock and soil (natural surfaces)	0	Dickens et al. (2010)				
Bare rock and soil	Bare rock and soil (soil erosion surfaces: dongas/gullies)			0.14	Wali et al. (2011)		Wali et al. (2011)
	Bare rock and soil (soil erosion surfaces: sheet)						

Land cover/use class (NLC2000)		Phosphate export coefficient (kg/ha/yr)	Source	Nitrate export coefficient (kg/ha/yr)	Source	Suspended solid export coefficient (kg/ha/yr)	Source
Level 1	Level 2						
Degraded	Degraded Forest and Woodland	0.02	Dickens et al. (2010)				
	Degraded Thicket, Bush Clumps & High Fynbos	0.02	Dickens et al. (2010)				
	Degraded Shrubland and Low Fynbos	0.08	Dickens et al. (2010)				
	Degraded Herbland	0.02	Dickens et al. (2010)				
	Degraded Natural Grassland	0.1	Dickens et al. (2010)				
Cultivated (and agriculture)	Cultivated, permanent, commercial, irrigated	1.2	Dickens et al. (2010)	6.69-9.8	Lin (2004)	2240	PLOAD default
	Cultivated, permanent, commercial, dryland	0.1	Dickens et al. (2010)				
	Cultivated, temporary, commercial, sugarcane	0.12	Dickens et al. (2010)				
	Cultivated, temporary, commercial, irrigated	1.2	Dickens et al. (2010)				
	Cultivated, temporary, commercial, dryland	0.08	Dickens et al. (2010)				
	Cultivated, temporary, subsistence, dryland	0.1	Dickens et al. (2010)	2.85	Wali et al. (2011)		
	Cultivated, temporary, subsistence, irrigated	1.2	Dickens et al. (2010)				
	Cultivated, temporary, subsistence, irrigated	1.2	Dickens et al. (2010)				
	<i>Beef farm/livestock open</i>	0.2	Jeje (2006)				
	<i>Feedlot</i>	250-300	Brylinsky (2004) and Jeje (2006)	2900	Enongene & Rossouw (2007) and Jeje (2006)		
Urban	<i>Dairy</i>	220	Enongene & Rossouw (2007)	2900	Enongene & Rossouw (2007)		
	Urban/Built-up	5	Dickens et al. (2010)	2.1 [#]	Simpson & Stone (1988)	1223.7	Simpson & Stone (1988)
	Urban/Built-up: rural cluster	5	Dickens et al. (2010)				
	Urban/Built-up: residential: formal suburbs	5	Dickens et al. (2010)				
	Urban/Built-up: residential, flatlands	0.1	Dickens et al. (2010)				
	Urban/Built-up: residential mixed	5	Dickens et al. (2010)	7.5	Enongene & Rossouw (2007)		
	Urban/Built-up: residential, hostels	5	Dickens et al. (2010)				

Land cover/use class (NLC2000)		Phosphate export coefficient (kg/ha/yr)	Source	Nitrate export coefficient (kg/ha/yr)	Source	Suspended solid export coefficient (kg/ha/yr)	Source
Level 1	Level 2						
	Urban/Built-up: residential, formal township	0.5-4	Pegram & Görgens (2001)	16.85	Hoffman (1995)	67.52	Hoffman (1995)
	Urban/Built-up: residential, informal township	na		9.26	Hoffman (1995)	1128.1	Hoffman (1995)
	Urban/Built-up: residential, informal squatter camp	1-3	Pegram & Görgens (2001)				
	Urban/Built-up: Commercial – mercantile	1.7	Dickens et al. (2010)				
	Urban/Built-up: Commercial – educational, health, IT	1.7	Dickens et al. (2010)				
	Urban/Built-up: Industrial/transport – heavy	2.7	Dickens et al. (2010)				
	Urban/Built-up: Industrial/transport – light	2.7	Dickens et al. (2010)	4.73	Hoffman (1995)	1163.4	Hoffman (1995)
	Waste Water Treatment Works (WWTW)	7.7	Jeje (2006)				
	Landfills /refuse disposal	na					
	Urban/Built-up: smallholdings – Woodland	0.02	Dickens et al. (2010)				
	Urban/Built-up: smallholdings – Thicket, Bushland, Bush Clumps, etc.	0.02	Dickens et al. (2010)				
Small-holdings	Urban/Built-up: smallholdings – Shrubland and Low Fynbos	0.08	Dickens et al. (2010)				
	Urban/Built-up: smallholdings – Natural Grassland	0.1	Dickens et al. (2010)				
	Mines & Quarries (underground/sub-surface mining)						
Mining	Mines & Quarries (surface-based mining)	0.8	Dickens et al. (2010)	8.6	Jeje (2006)	22.4	PLOAD default
	Mines & Quarries (mine tailings, waste dumps)						

* Export coefficient calculated for a parcel with a mix of indigenous forest and grassland

Organic nitrogen

Level 2 land uses in italics have been supplemented to expand the NLC2000 land cover classes to account for key land uses impacting water quality.
These line and point shapefiles supplement the land cover (polygon shapefile/grid) data.

The available export coefficients were matched to the SANS1877 level 1 and 2 categories (Table 4.6). It is evident that phosphate export coefficients are mostly sufficient for water quality modelling in South Africa, however, export coefficients for nitrates and suspended solids need expansion.

Table 4.6: Percentage of export coefficients matching South African land cover categories (SANS1877) at level 1 and 2.

Export coefficient (kg/ha/yr):	Phosphate		Nitrate		Suspended solids	
	Nr. Of matches per land cover class	% match	Nr. Of matches per land cover class	% match	Nr. Of matches per land cover class	% match
SANS1877:						
Level 1 (15 classes)	15	100.00	12	80.00	10	66.67
Level 2 (49 classes)	39	79.59	27	55.10	24	48.98

4.8 SOUTH AFRICAN GEOSPATIAL DATASETS AVAILABLE FOR WATER QUALITY MODELLING

A number of geospatial datasets are available in South Africa to be used in water quality monitoring, ranging from those generated at country-wide scale, to provincial and quaternary catchment scale. These data sets are mostly funded and generated by a wide variety of organisations on an *ad hoc* basis, and at various scales and time intervals. Understanding the limitations, options and characteristics of datasets and their collection is important when sourcing data for use in water quality modelling:

- **A single datasets may have multiple purposes and multiple users:** the classification of the data may therefore not have water quality in mind and therefore may not be appropriate for use, unless modified.
- **Government should fund all geospatial datasets required by all users:** There are many user communities requiring frequently updated, highly accurate data at a high spatial scale or resolution. It is not feasible or realistic that the South African Government should fund all of these data sets. Organisations involved in water quality monitoring could identify the most important geospatial data sets and their criteria required for improved water quality modelling in South Africa.
- **Datasets required for water quality modelling should all be fundamental data sets:** – As mentioned, the South African Government Departments will realistically not be able to meet all the requirements of users for geospatial data. Through the South African Spatial Data Infrastructure (SASDI) Act, a Committee for Spatial Information (CSI) has been in operation for the past three years, investigating the fundamental or core datasets for South Africa. Sub-committees discuss more specific criteria and needs of data types, e.g. rivers and wetlands. It would be up to the water quality community to ensure their needs are addressed through involvement and representation on the relevant sub-committees.
- **Geospatial data is collected consistently geographically:** The distribution of monitoring points is often biased based on accessible location and not representative of all locations. Statistical models can adjust for these inconsistencies; however the limitations of the data should be understood when used in water quality modelling. For example, very few rainfall stations are located on the Lesotho highlands, which are in fact, the water factory of South Africa. Similarly gauging stations are not equally distributed in all catchments of South Africa.
- **Datasets has different temporal resolutions:** referring to the time interval between data sampling periods. Similarly there may be a lag period between data collection and publication, as is the case of the NLC datasets where the imagery dates a few years back from the actual date of publication.
- **Appropriate spatial resolution & scale:** The use of satellite imagery of 1 km resolution or 1:500 000 at country-wide scale is appropriate, though would be inappropriate at local or quaternary catchment scale. At quaternary catchment scale 1:10 000-1:50 000 scale or

10-50 m resolution may be appropriate, depending on the extent of the quaternary catchment.

- **Attributes information associated with geospatial classes:** Many attributes may be associated with the geospatial features of a dataset, for example, soil carbon, depth and type to soil classes.
- **Geospatial data can be generated or derived in future:** The availability of new space-borne sensors such as RapidEye and WorldView, which includes a red edge band, provides new opportunities for deriving LAI, N:P ratio of vegetation and other phenological characteristics through Earth Observation methods.

A list of geospatial data sets that could be used in water quality modelling and prediction is listed in Appendix B in addition to recommendations on their use and preparation. It is structured according to the geospatial data categories used by water quality models in the United States Environmental Protection Agency (US EPA), as listed in Table 4.7.

Table 4.7: List of South African geospatial datasets categories for water quality models as used by the US EPA (See Appendix B for full metadata).

Base cartographic data	Environmental background data	Environmental monitoring data	Point sources/loading data
Political boundaries: <ul style="list-style-type: none"> • Provincial boundaries • Municipal boundaries • Ward boundaries 	Water management areas Ecoregions	Water quality monitoring data	WWTW
Infrastructure: <ul style="list-style-type: none"> • Road, railway lines and railway stations 	Soils	Weather stations: <ul style="list-style-type: none"> • SAWS • ARC 	Power stations
Urban areas: <ul style="list-style-type: none"> • Polygon extent of urban areas • Extent of communities, villages, etc. • Dwelling units • (NLC categories) 	Hydrographic dataset: <ul style="list-style-type: none"> • Rivers • Waterbodies • Wetlands 		Mines Ownerless and derelict mines database
Census information: <ul style="list-style-type: none"> • Statistics & demographics 	Digital Elevation Models (DEMs)		Feed lots
Hydrological units (catchment boundaries): <ul style="list-style-type: none"> • Primary - quaternary 	National Elevation Dataset: <ul style="list-style-type: none"> • Contour lines Spot heights		Dairy
	Land use /Land cover datasets: <ul style="list-style-type: none"> • NLC1996 • NLC2000 • NLC2009 		Landfills/refuse disposal
	National Protected Areas		

4.9 KNOWN SHORTCOMINGS OF THE SOUTH AFRICAN GEOSPATIAL DATASETS FOR WATER QUALITY MONITORING

Based on the experiences of the team members of this project, we compiled a list of shortcomings and related recommendations in Table 4.8. We suggest that these be expanded in future with the knowledge of a wider community, ideally through a stakeholder workshop.

Table 4.8: Shortcomings of South African geospatial data sets for water quality monitoring

Dataset	Shortcomings	Recommendations
Base cartographic data		
No issues noted.		
Environmental background data		
Soils	Not all attributes required are available	
Hydrology	The DWA data does not provide classification on channelled or unchannelled wetlands.	NFEPA (Nel et al., 2011) modelled channelled and unchannelled wetlands in RSA at country-wide scale. Local or provincial studies may also have included these categories in their datasets.
DEMs and elevation data	All DEMS and contour/spot data must be evaluated for gaps/sinks, errors in elevation attributes, or sensor errors, e.g. some ASTER DEM scenes erroneously shows island within waterbodies. A DEM needs some improvement before it can be used.	Consider the use of the hydrologically improved SRTM DEM by Weepener et al., 2012.
Land cover data	Does not include Beef farm/livestock information Management practices not included for all agricultural categories	
Environmental monitoring data		
Water quality monitoring	Distribution not consistent throughout South Africa	
Weather stations	Distribution not consistent throughout South Africa	
Point sources/loading data		
Feedlots	Not easily accessible for users	
Dairy	Not easily accessible for users	

4.10 CONCLUSION AND RECOMMENDATIONS FOR IMPROVING WATER QUALITY MODELLING THROUGH IMPROVING GEOSPATIAL DATA

This Chapter reviewed the appropriateness of the South African land cover classification system to be used in water quality modelling. We found levels 1 and 2 of SANS1877 in line with international classification systems used in water quality modelling software accessible through the BASINS 4.0 Shell. Most of the pollutant load export coefficients used in water quality modelling softwares in association with land cover classes are available for phosphates to level 2 of SANS1877. The majority of these are South African values, supplemented by international coefficients. Pollutant

load export coefficients for nitrate and suspended solids are however not complete for level 1 of SANS1877 (80% for nitrate; 67% of LULC categories for suspended solids), and even less so for level 2 of SANS1877 (55% for LULC categories for nitrate and 49% for suspended solids).

In general, geospatial datasets were difficult to obtain by project members in this study, or is not even available at national level (Appendix B). The team propose that a centralised point serve as a portal for users to link to relevant institutions or online data to ease access (e.g. <http://www.wrc.org.za/Pages/ResourcesAndTools.aspx>). The land cover datasets that follow the SANS1877 land cover classification will therefore be appropriate for use in water quality modelling (see Appendix B for more information). Users should keep in mind that there are many other supplementary data that could be used in water quality modelling, including line and point shapefiles of, for example, rivers and point-source information.

The completeness and sufficiency of the available geospatial datasets for water quality modelling in South Africa remains to be evaluated, hence we propose a number of topics for further discussion at a suitable stakeholder engagement workshop, including i.a.:

- The need to development South African export coefficients for remaining land use categories of level 1 or 2 of SANS1877 as per Table 4.5.
- How South African export coefficients can be made available in a general format to be used in most water quality modelling software.
- Geospatial data generation or improvements:
 - Which datasets are essential to generate that does not yet exist (e.g. point-source pollution data)?
 - Which datasets can be generated, but are not essential for water quality monitoring, though would be nice-to-haves?
 - Which datasets are available but are insufficient in accuracy, attributes or scale for quaternary catchment scale modelling?
- Whether there is a need to extend current water quality and weather rainfall stations in South Africa.
- Whether the community consider a Cost Benefit Analysis (CBA), where the advantages and cost of improving geospatial data sets are compared to the extension of monitoring stations, necessary.
- Long-term funding opportunities and responsible organisations for geospatial datasets required for water quality monitoring.

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CHAPTER 5: CASE STUDIES

5.1 INTRODUCTION

The following sections describe the application of models/systems described and discussed in the preceding chapters. These exercises provided hands-on contexts in which various models and approaches could be tested. They are described in detail so that the reader can achieve deeper insight into the necessary processes and the kind of problems that can be encountered. In order to facilitate detailed input and testing of project concepts and models, two case study catchments were chosen, which served as focus areas for catchment-based stakeholder and institutional engagement as well as testing and development of modelling approaches investigated in this project.

5.2 UMNGENI RIVER CATCHMENT

5.2.1 Catchment characterisation

The upper uMngeni catchment forms the main water catchment for the water supply dams of the Pietermaritzburg-Durban development node, the second most important economic complex in South Africa after Gauteng. Due to the high water demands of this urban node, the water supply of the uMngeni catchment is already supplemented by an interbasin transfer from the adjacent Mooi River catchment to the north, with additional interbasin transfers planned in the future (WRC, 2002).

The rainfall within the 4 416 km² catchment is strongly seasonal with more than 80% falling between October and March. The Mean Annual Precipitation across the catchment ranges from 410 to 1 450 mm between the lowest and highest rainfall areas respectively. Across the catchment Mean Annual Runoff ranges from 72 to 680 mm with Mean Annual Evaporation from 1 360 to 2 040 mm (WRC, 2002).

The headwaters of the uMngeni catchment are comprised of mountain streams draining upland farming areas of the KwaZulu-Natal Midlands. The region has an average altitude of 1 600 m and is characterised by undulating hills and low to high mountains reaching above 2 000 m, with vegetation dominated by highland sourveld. A significant feature of the headwater catchment is the uMngeni Vlei, the principal source of the uMngeni River and which produces a sustained yield of high quality water. The core of the Vlei covers an area of approximately 300 ha, with the broader network of wetlands being over 950 ha in extent. The entire catchment of the Vlei falls within protected areas, with the Vlei itself being a proclaimed nature reserve. This is in recognition of the valuable ecosystem services it provides, most notably that of water production and biodiversity conservation. The Vlei is home to numerous threatened and endemic species, and forms the most important Wattled Crane breeding site in the country (EKZNW, 2008).

The uMngeni River is approximately 255 km long and drains to the sea at Durban on the KwaZulu-Natal coast. The uMsunduzi River, which drains the Pietermaritzburg urban area and surrounds, forms the most significant tributary of the uMngeni River. Four key dams are utilised to manage the water supply requirements of the Pietermaritzburg-Durban development node: Midmar, Albert Falls, Nagle and Inanda Dams.

Domestic users comprise the single largest water use within the uMngeni River catchment, with system losses (i.e. evaporation) and distribution losses utilising a combined 22% (Figure 5.1).

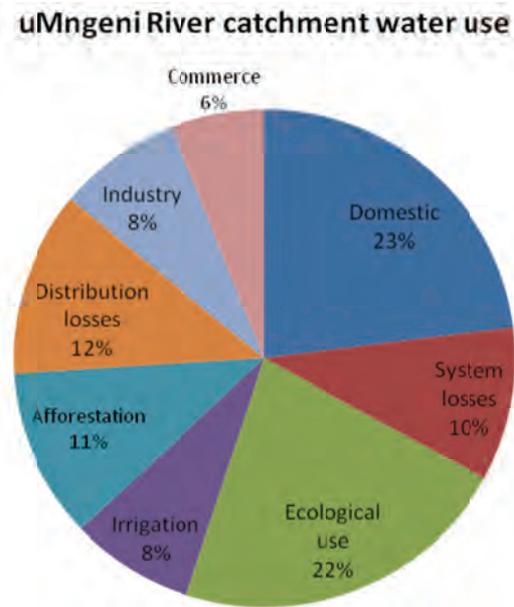


Figure 5.1: Water use within the uMngeni River catchment (after WRC 2002).

Due to the strategic importance of the uMngeni catchment water resource, the high demands on the system and the costs of interbasin transfer, it is essential that the relationship between the water quality of the rivers and dams of the catchment and the drivers thereof, is understood. This will inform appropriate management and long term security of good water quality.

5.2.2 Land cover

In terms of transformed land use, cultivated lands cover 19% of the catchment with forestry having transformed another 17%. Eight percent of the catchment is developed by urban areas (Figure 5.2). Cultivated areas and forestry plantations are located predominantly within the headwaters and upper reaches of the catchment, with the KwaZulu-Natal midlands forming important areas for commercial crop production and forestry. The majority of the urban areas within the catchment are situated along the uMsunduzi River tributary (Pietermaritzburg and surrounds) and the lower reaches of the uMngeni River extending from the outlying urban and industrial areas of Durban, to the river mouth in central Durban. However, informal and formal settlements and urban areas also fall within the upper uMngeni Catchment, most notably Howick and surrounding settlements.

Correct management of land use activities and services infrastructure, and the protection of water resources within the upper uMngeni River catchment areas is essential to maintain and improve the quality and quantity of water supplying the downstream urban and industrial areas. The management of water quality, quantity and sediment regimes is also essential to maintain the biophysical and ecological status of the mangroves and other ecological services assets associated with the uMngeni River mouth and estuary.

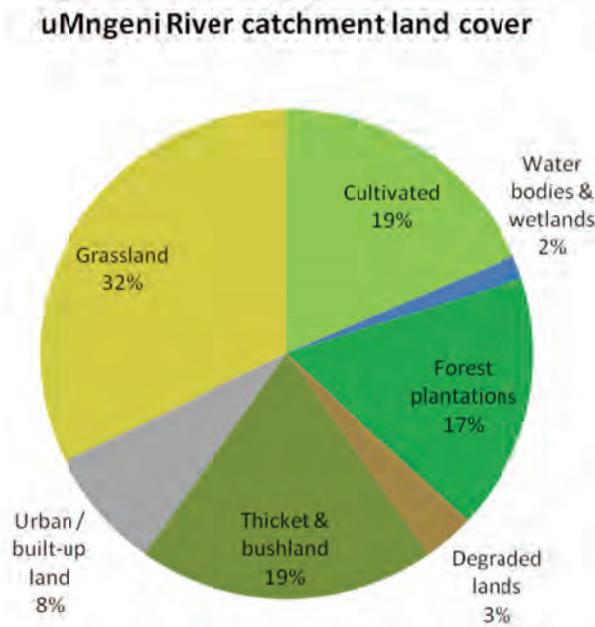


Figure 5.2. Land cover areas of the uMngeni River catchment (after DEAT and EKZNW, 2008).

5.2.3 Typical water quality impacts and drivers

5.2.3.1 Upper uMngeni River catchment

Within the upper uMngeni catchment nutrients from agricultural activities, most notably crop fertilization, dairy operations, piggeries and feedlots, introduce excess nutrient loads (and sediments) to the uMngeni River. The critical headwater areas have been significantly impacted by the historical drainage of wetland areas for cultivation, grazing and forestry (WRC, 2002). The farming and forestry areas also contain a considerable number of small dams which, in conjunction, regulate streamflows and reduce flow volumes. Investigations have shown that the small farm dams within the upper uMngeni catchment collectively result in up to a month's delay in the summer flow response as the dams successively refill, capturing the first rains of the wet season (Schulze, 2011, pers. comm.). A study of the water quality and quantity impacts of small dams on South African rivers found that low flows were significantly reduced and certain physico-chemical water quality determinants were negatively impacted (Mantel et al., 2010), illustrating that the cumulative impact of small dams must not be underestimated. The many small dams within the upper uMngeni catchment have also inundated wetland and riparian areas which would have otherwise provided valuable ecological goods and services. Poor land and catchment management, particularly of wetland and riparian areas, remains a challenge. Partly due to the long history of forestry within the area, Invasive Alien Plants are a significant problem within the region, further impacting on stream flows and riparian habitat integrity.

As significant as these predominantly nonpoint source impacts collectively are within the upper catchment, it has been found that per unit area the water quality impacts of urban and settlement areas are significantly higher (GroundTruth, 2010a). In a study of pollution loads entering Midmar Dam from 1999 to 2009, it was found that while the sub catchment containing the Mpophomeni low cost housing settlement adjacent to Midmar Dam comprised only 2.4% of the dams' catchment area, it contributed 50.9% of the *E. coli* loads and 15% of the Soluble Reactive Phosphorous loads

(GroundTruth, 2010a). This impact was predominantly as a result of defective and surcharging municipal sewer systems within settlement areas. Examination of historical and current aerial imagery shows that informal settlements, with no formal sewage infrastructure, are expanding within the upper uMngeni catchment, draining into the critical water supply of Midmar Dam (GroundTruth, 2010a).

Downstream of Midmar Dam significant impacts include the Howick Waste Water Treatment Works and other point discharges from urban and industrial areas surrounding Howick, which discharge to the uMngeni River.

5.2.3.2 uMsunduzi River catchment

The uMsunduzi River tributary of the uMngeni River is impacted by point and nonpoint pollution from informal settlements, low cost housing, formal urban and industrial areas, and the Darvill WWTW servicing Pietermaritzburg. The source and upper catchment areas of the uMsunduzi River contain informal and low cost housing areas which contribute a high level of litter, sediments and nutrient loads to the uMsunduzi River, particularly following rainfall events. Illegal and unregulated discharges from industrial areas surrounding Pietermaritzburg are shown to have a significant impact on the water quality of the uMsunduzi River downstream of tributaries draining the industrial areas. Before reaching the uMngeni River the uMsunduzi River flows through rural areas with relatively low population densities, with the river aquatic health shown to improve within this section (GroundTruth, 2010b).

Both the Pietermaritzburg (Darvill) and Howick WWTW operate close to capacity with the result that during intense rainfall events the works are regularly inundated by the storm flows and surcharge untreated sewage directly to the receiving rivers.

5.2.3.3 Lower uMngeni River catchment

During state of rivers assessments in 2006 and 2007 it was found that spills and illegal discharges form the most significant impact to rivers flowing through Durban. Illegal discharges from industrial areas contribute a variety of pollutants to the uMngeni River. Chief amongst spills are the leaking and surcharging sewer mains and the failure of sewer reticulation infrastructure, such as pump stations. Another significant impact is the poor quality of treated effluent discharged from the various WWTW servicing Durban and surrounding areas (GroundTruth, 2007). The uMngeni River and associated tributaries within the Durban area are heavily impacted by both licensed and illegal sand mining operations. The mining of topsoil and sands from rivers and banks is resulting in significant impacts to river channel form and riparian vegetation. Illegal solid waste dumping and poor litter servicing are also seen to have a significant impact (GroundTruth, 2007).

Throughout the uMngeni River catchment the informal use of detergents in rivers through the washing of clothes, tents and vehicles has a cumulative impact on aquatic biota and eutrophication levels.

5.2.4 Ecological and water use effects

The water quality pollutants of the uMngeni River detailed above manifest in the following impacts:

- **Eutrophication:** Trend analyses of historical Total Phosphorus concentrations indicate that by 2019 Midmar and Albert falls Dams will reach Eutrophic classification (utilising ranges given by van Ginkel et al., 2001), with Nagle Dam almost reaching Hypertrophic classification (GroundTruth, 2010c).
- **Water treatment problems:** Taste & Odour and Filter Clogging algal genera are problematic for water treatment plants as they increase the costs of water treatment and can result in taste and odour problems. Release of toxins from these algal cells can result in health problems to water consumers. Predications are that at current rates of increase, Taste & Odour genera will comprise 67% and 82% of the total algal counts within Albert Falls and Nagle Dams respectively by the year 2017. It is predicted that by the same year raw water abstracted for the critical water supply of the Durban Heights Water Treatment Plant will show an 89% dominance by these problematic algal genera.
- **Water hyacinth and aquatic weed infestation:** As a result of the high nutrient loads accumulating within the uMngeni River, the prolific growth of Water Hyacinth and other aquatic weeds is becoming an increasing problem within the lower uMngeni River, particularly in the vicinity of Nagle Dam. This is illustrated by organisers of the Dusi canoe marathon and supporting NGOs having to spend ever increasing sums of money each year on clearing paths through the aquatic weeds. The aquatic weeds present a danger to adjacent communities and recreational users by providing potential habitat for Bilharzia carrying snails, and by presenting an increased drowning risk to people and livestock. This impact is exacerbated by sand mining which creates unnatural pools and backwaters, with slow flow velocities, which are readily colonised by aquatic weeds.
- **Health of water users and surrounding communities:** Within the Durban area numerous sites sampled during 2006 and 2007 showed *E. coli* concentrations which would have a significant likelihood of causing gastrointestinal illness through human recreational contact with the water. Young children playing in the waters at one polluted site within Durban reportedly had welts and sores on their skin, which may be as a result of exposure to highly polluted waters. The uMngeni River and tributaries are used for washing, fishing, recreation, cattle watering and various cultural and spiritual activities, posing a risk to communities particularly within Durban and surrounds (GroundTruth, 2007).
- **Impacts on river health and biodiversity:** The range of pollutants and other impacts which the uMngeni River and tributaries are expected to have a negative impact on the health and biodiversity of aquatic and riparian habitat, particularly within the lower reaches passing through Durban and surrounds.

5.2.5 Future prospects

The dominant impacts on the uMngeni River illustrate management opportunities in the form of appropriate land use and sewer/waste infrastructure management, and land use planning. The impact from the presence of poorly serviced low cost housing areas adjacent to water supply dams and watercourses can clearly be seen. The impact of feedlots, dairy operations and intensive cultivation in proximity to watercourses and rivers will need to be vigilantly managed with new applications carefully planned. Nature reserves and buffers of riparian and wetland habitats, as well as certain low impact rural areas, are shown to improve water quality within rivers and mitigate impacts of adjacent high impact land uses. The conservation and formal protection of catchment source area and river buffer areas currently protecting water resources and ameliorating water quality must be integrated with land use planning.

5.2.6 Catchment stakeholders

Table 5.1 shows the key stakeholders and affiliations. The Department of Water Affairs (DWA), as the constitutional custodian of our water resources, is represented by the KwaZulu-Natal regional office of DWA. The stakeholders in the table typically engage in the integrated water management discourse under the oversight of DWA.

Table 5.1. The uMngeni catchment stakeholders, their sectors and their national affiliations.

Stakeholder	Sector	National affiliation
Umgeni Water	Water	SA Association of Water Utilities (SAAWU)
eThekweni and Msunduzi municipalities	Local Government	SA Local Government Association (SALGA)
The KwaZulu-Natal Department of Agriculture, Environmental Affairs and Rural Development	Agriculture, Environment, Rural Development	Department of Agriculture Department of Environment Affairs
The Duzi-Umgeni Conservation Trust (DUCT)	Conservation	Department of Environmental Affairs
The Upper uMngeni Catchment Management Forum	Water	Most stakeholder groups in the Forum have National Affiliates
The uMsunduzi Catchment Management Forum	Water	Most stakeholder groups in the Forum have National Affiliates
The Lower uMngeni Catchment Management Forum	Water	Most stakeholder groups in the Forum have National Affiliates
Forestry	Forestry	Forestry SA & Department of Agriculture, Forestry and Fisheries (DAFF)
Farmers	Agriculture	Various National Agricultural Organisations; Department of Agriculture, Forestry and Fisheries
Industry	Trade & Industry	Various National Business Organisations; Department of Trade & Industry
EKZN Wildlife	Conservation	Department of Environmental Affairs

At present the Upper uMngeni Catchment Management Forum is the most active forum, with the uMsunduzi Catchment Management Forum in Pietermaritzburg gaining momentum. The Lower uMngeni Catchment Management Forum is the newest of the forums and faces great challenges within Durban's urbanised and industrial catchment areas of the lower uMngeni River. The Duzi-

uMngeni Conservation Trust (DUCT) is very active within Pietermaritzburg, Howick and Durban with the clearing of invasive alien plants and clean-up of litter within rivers and riparian zones. Through additional support and funding their area of influence within the catchment is spreading. Key to optimising catchment stakeholder engagement and partnerships are tools to investigate land use scenarios and their impact on water quality to inform effective and key interventions required to best improve water quality, catchment management and land use planning.

5.3 OLIFANTS RIVER CATCHMENT

5.3.1 Catchment characterisation

The upper Olifants River catchment covers an area of 11 464 km² in the headwaters of the Olifants Water Management Area (WMA). The mean annual precipitation is 683 mm, the mean annual runoff, 10 780 million cubic metres, and the mean annual evaporation, 1 580 mm (Midgley et al., 1994). The Olifants River originates from the east of Johannesburg and initially flows northwards before curving eastwards towards the Kruger National Park where it is joined by the Letaba River before flowing into Mozambique.

The proposed study area for this project is the upper Olifants catchment, upstream of Loskop Dam. The Upper Olifants River catchment comprises the drainage areas of the Olifants River, Klein Olifants River and Wilge River with tributaries down to the Loskop Dam. The headwaters of these rivers are located along the Highveld Ridge in the Secunda-Bethal area and the rivers then flow in a northerly direction towards Loskop Dam. The major tributaries are the Steenkoolspruit, Klein Olifants River and Wilge River.

It has large urban centres located in the Emalahleni (Witbank), Steve Tshwete (Middelburg) and also a number of smaller urban centres such as Bronkhorstspuit, Kriel, Hendrina, Kinross and Trichardt. Satellite townships are also associated with most of the mining operations and power stations. The natural rivers and streams have been extensively dammed with the result the stream flow is now highly regulated. The major impoundments upstream of Loskop Dam include Witbank Dam, Middelburg Dam, Bronkhorstspuit Dam and Premiere Mine Dam. Many smaller farm dams and water supply structures associated with the mining operations have also been constructed in the catchment. Power generation comprises the largest single use of water in the upper catchment (Figure 5.3).

Olifants River catchment water use

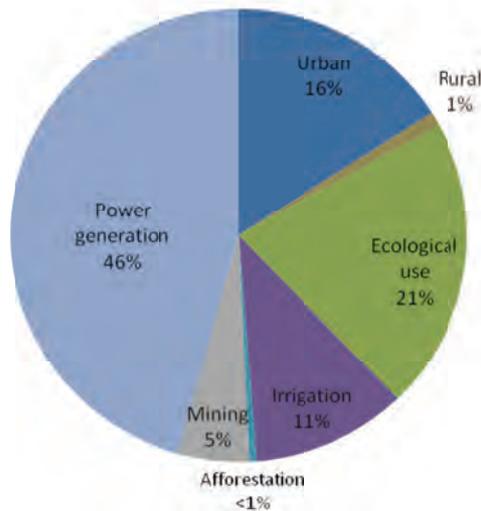


Figure 5.3. Water use within the upper Olifants catchment (DWAF, 2004).

5.3.2 Land cover

The land use in the upper part of the Upper Olifants (Witbank and Middelburg Dam catchments) is characterised by extensive coal mining, coal fired power stations, the urban centres of Middelburg and Witbank, steel manufacturing industries and agriculture (Figure 5.4 and Figure 5.5). The Wilge River catchment is more rural in nature with the main activity being agriculture with the main towns of Bronkhorstspuit and Delmas. The coal mining, previously concentrated in the Olifants and Klein-Olifants catchments, is expanding into the Wilge River catchment as the coal reserves in the Middelburg and Witbank Dam catchments are insufficient to meet demands. Agriculture, both dryland and irrigated, is another important land use in the catchment with many areas in the southern and central portions producing high yields of maize. The Loskop Dam supplies water to the Loskop Irrigation Scheme, the second largest in the country, where a number of commercial crops, including citrus, cotton, wheat, tobacco, groundnuts and vegetables are cultivated.

Further downstream from the upper catchment, the Olifants River eventually flows through the Kruger National Park and into Mozambique. Thus, provision of water of sufficient quality and quantity to meet ecological requirements is one of the controlling factors in the management of water resources throughout the water management area. Considering that most mining, industrial and urban activity takes place in the upper Olifants catchment, the effective management of this section of the catchment is crucial with regards to minimising impacts on downstream users.

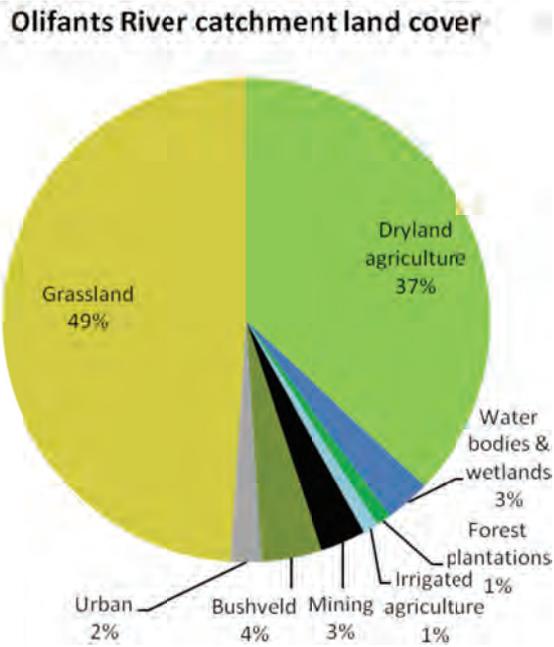


Figure 5.4. Proportion of major land cover categories represented in the upper Olifants River catchment.

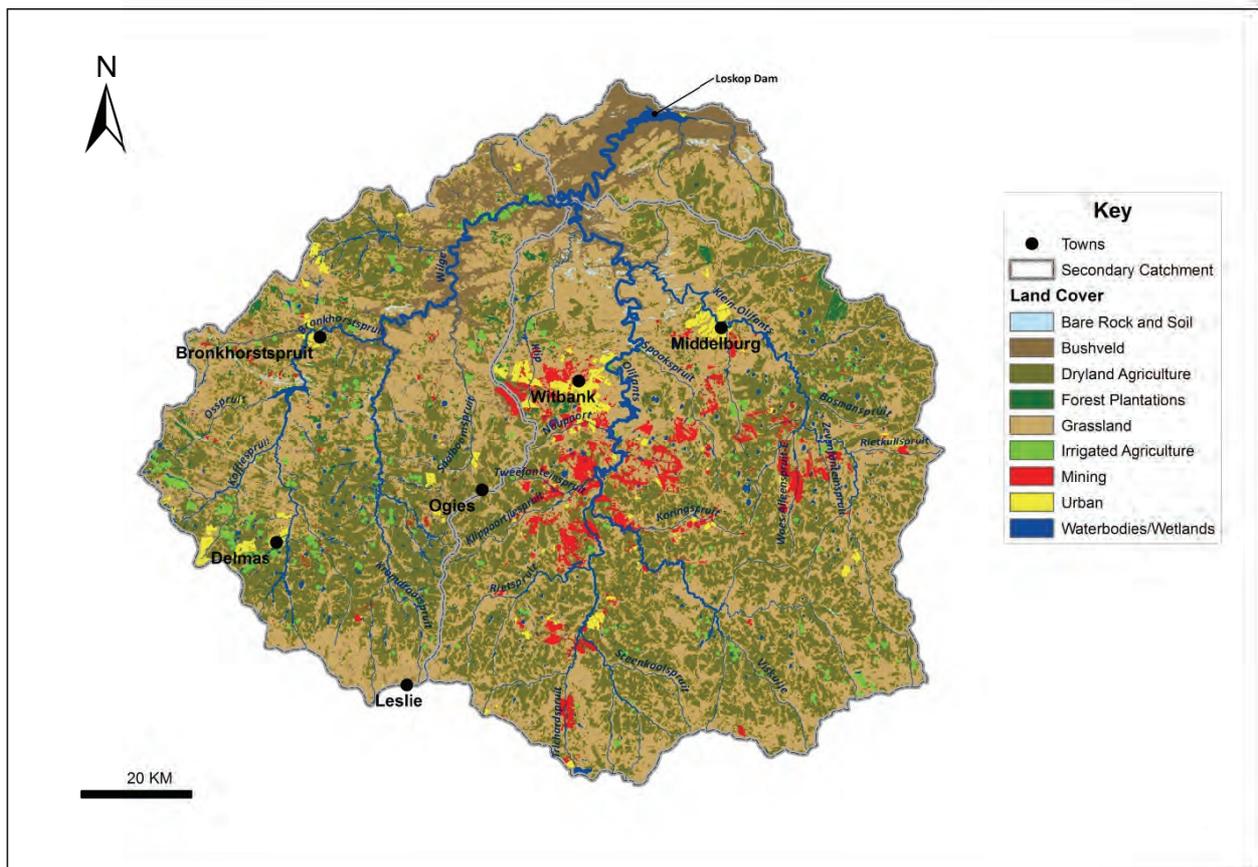


Figure 5.5. Map illustrating land cover of the upper Olifants River catchment (NLC2000).

5.3.3 Typical water quality impacts and drivers

The number and variety of land and water use activities in the upper Olifants River system are of strategic importance to South Africa (e.g. mining, agriculture, power generation, etc.). These activities rely heavily on a variety of goods and services that they derive from the aquatic ecosystems in the area to sustain their processes. However, the Olifants River has been described as one of the most polluted rivers in southern Africa because of the number of anthropogenic stressors that are present, particularly in the upper catchment.

The water quality of the water resource is under threat from a number of sources, particularly the coal mining industry, urban development and poorly performing municipal wastewater treatment plants. Pollutants and processes generated by these activities include a general acidification of the system and the input or mobilisation of heavy metals and sulphates and other contaminants via acid mine drainage (Gray, 1998), potential acid rain (resulting from poor air quality; Rodhe et al., 2002), industrial effluent containing a variety of potential pollutants; excessive nutrient inputs (phosphorus and nitrogen) from agricultural activities and sewage effluent (Hart et al., 2004; Jarvie et al., 2006); and microbiological pollution from intensive agriculture (e.g. feedlots) and sewage effluent. There has been a steady deterioration in the water quality of the major dams since the 1970s. The deterioration has largely been arrested in the Witbank and Middelburg Dams with the introduction of the controlled mine water release scheme and its associated water use licensing, complemented by the improvement in pollution source controls on the mines.

5.3.3.1 Mining

South Africa's coal mining industry is the second largest mining sector after gold, contributing to 16% of export revenue in 2003 (Hobbs et al., 2008). Together with the Ermelo and Highveld coalfields, the Witbank coalfield represents the largest conterminous area of active coal mining in South Africa, producing coal for power generation, export and domestic consumption. With seven coal-fired power stations situated in the region, the upper Olifants catchment accounts for approximately 50% of the country's total power generation capacity.

Mining results in large-scale physical disturbance to the landscape and the exposure of large quantities of sulphide mineral ores to atmospheric oxygen and water. This promotes oxidation of the sulphides to oxidised forms such as sulphate, an increase of which is a typical indicator of mining impacts in water quality. De Villiers et al. (2009) analysed long-term water quality monitoring data and showed that sulphates have increased in Loskop Dam by more than seven fold since the 1970s. The most serious impacts related to mining activities are often only manifested after mining activity has been completed, when, due to lack of appropriate management or rehabilitation, mining activity results in poor quality acidic water as a result of acid mine drainage (AMD). Several reports have documented AMD from both active and abandoned coal mines in this area (e.g. Bell et al., 2002; Hobbs et al., 2008). Aluminium, iron and manganese are common elements in the Earth's crust but are relatively insoluble and seldom reach high concentrations in un-impacted aquatic systems. When these elements do reach elevated concentrations in surface and ground water systems, this is most commonly the result of their solubilisation and mobilisation through acidic seepage from active and/or abandoned mines (Driscoll, 1985; Winterbourne, 2000) and industrial effluent. In the case of the upper Olifants River catchment, a number of studies have documented high metal concentrations associated with AMD (e.g. Bell et al. 2002).

The potential impacts of pollutants associated with AMD are well known. Heavy metals can cause direct toxicity to aquatic organisms or accumulate in the aquatic food chain, ultimately posing a health risk to the aquatic ecosystem and to people that consume fish from the system. Evidence of accumulation of metals in fish has been observed in the upper Olifants catchment (Coetzee, et al. 2004). Aluminium in particular is a highly toxic metal at low pH and is commonly liberated via processes such as acid mine drainage and acid precipitation (Driscoll, 1985; Winterbourne et al. 2000). A number of other trace metals such as zinc and copper are also relatively toxic at certain concentrations and are often mobilised in low pH waters (Gray, 1998; Schenck et al., 1998).

These studies emphasise the importance of planning and managing mine operations appropriately to minimize the occurrence of AMD in the future. This issue will become increasingly important because of the large number of new coal exploration and mining permits that have been granted in the upper Olifants catchment (DME, 2009).

5.3.3.2 *Acid Rain*

Another potential impact with regards to water quality in the upper Olifants River catchment is the contribution of acidic rain to adverse water quality in the upper Olifants catchment. Mobilisation of metals from soil as a result of acid rain has been well documented. Additionally, acid rain can contribute low pH water and airborne pollutants (e.g. sulphate and trace metals) directly into surface waters (Gorham, 1976). There are several important industrial activities (e.g. power generation, chemical industries and metal smelters) in the upper Olifants catchment and the air quality of the area is generally poor, with high levels of SO₂ present in the atmosphere (Zunckel et al., 2000). As a result, the region is regarded as a “hotspot” in terms of global acid rain deposition (Rodhe, 2002).

5.3.3.3 *Nutrients*

Excessive nutrient inputs results in enrichment of the system, leading to eutrophication and the potential development of toxic cyanobacterial blooms. The effects of eutrophication are well known and include oxygen depletion, a general decrease in species diversity and the formation of nuisance algal blooms. These blooms can occasionally be toxic and have been recorded from Lake Loskop (Oberholster et al., 2010).

Nutrients (particularly phosphate – the limiting nutrient for eutrophication in freshwater systems) most likely originate from agriculture (i.e. phosphate based fertilizers and manure originating from livestock, both free-range and feedlots) and excessive sewage discharge from waste water treatment works. A number of feedlots are located within the catchment and crop production (especially maize) takes place across the catchment. WWTWs are likely resulting in a large input of nutrients into the system. This is supported by findings captured by the Green Drop Report compiled by the Department of Water Affairs (DWA, 2010), which gave scores of 15% and 11% to the eMalahleni (which covers Witbank) and Steve Tshwete (which covers Middelburg) local municipalities, respectively. These scores indicate clearly that the waste water treatment works in these municipalities do not comply with specific criteria including, amongst others, adequate process controls; maintenance and management skills; the establishment of an efficient waste water quality monitoring programme; compliance of waste water to effluent discharge license conditions; and the capacity of the waste water treatment works to properly treat the volumes of effluent that they receive.

5.3.4 Ecological and water use effects

With respect to the upper Olifants catchment, the presence of a 'cocktail' of pollutants has been recently manifested in a number of critical ecological and human health concerns further downstream in the catchment, most notably in Loskop Dam in recent years. These include:

- **Cyanobacterial blooms:** The occurrence of massive toxic cyanobacterial blooms in Loskop Dam since 2008 indicates that the system is hypertrophic. The ingestion of cyanobacterial biotoxin released upon cell lysis, can cause sickness or death of animals and pose serious health problems for human drinking water supplies. In China, long-term studies showed that biotoxin concentrations within the range of 0.09-0.46 µg/l – much lower concentrations than those (11000 µg/l) detected by Oberholster and co-workers in Loskop Dam during 2008 and 2009 – was positively associated with high incidence of colorectal and liver cancer.
- **Irrigation:** Because water supply reservoirs in the upper Olifants catchment contain cyanobacterial blooms and their associated toxins, the exposure of edible crop plants to cyanobacterial toxins via spray irrigation or other forms of watering may cause these toxins to accumulate in plant tissues. The introduction of these toxins into the human food chain is therefore a strong possibility, and one which may pose great concern for human health. Spray irrigation practices in first world countries have shown that the aerial parts of plants can be exposed to cyanobacterial toxins.
- **Fish and crocodile mortalities:** Over the past fifteen years, Loskop Dam has had a number of incidents of fish mortality at different times of the year and with different durations. These incidents have become more frequent during the past five years (2003-2008) and have coincided with crocodile mortalities and a dramatic population decline from ± 80 individuals to 4 in 2010. Fish sampling in July 2009 conducted by Oberholster in collaboration with researchers from Onderstepoort indicated tumour formation and severe liver necrosis in certain fish species of Loskop Dam. The precise cause of these mortalities is currently unknown.
- **Bioaccumulation of metals in food crops:** In a recent study in 2009 conducted by Oberholster in collaboration with the UP, high levels of aluminium were detected in irrigation crops and fruit downstream of Loskop Dam.

5.3.5 Future prospects

The extreme nature of pollution events as well as the complexity of water quality issues faced in this catchment requires improved management of land use activities that impact on water quality, which has the support of multiple stakeholders. This is especially important considering future development in the catchment.

In the upper Olifants River catchment, several new coal mining leases have been granted and, if unchecked, the already high levels of AMD will probably increase in future. The progressive urbanisation, industrialisation and changes in habitat along the length of the Olifants River, combined with the adverse effects of water pollution, have already placed enormous strains on the aquatic ecosystems. Anticipated future growth in demands for water and electricity together with the generation of increased quantities of effluents from towns, farms and industries suggest that the Olifants River and its reservoirs will receive even larger volumes of waste in the future.

5.3.6 Catchment stakeholders

Considering the number of activities taking place in the upper Olifants catchment and the economic importance of those activities, there are a number of high profile stakeholders potentially affected by water resource management decisions in the catchment (Table 5.2). As in the uMngeni catchment, the national custodian of our water resources (namely, DWA) is also represented.

Table 5.2. The Olifants catchment stakeholders, their sectors and their national affiliations.

Stakeholder	Sector	National affiliation
Department of Mineral Resources	Mining	Department of Mineral Resources
Department of Agriculture, Forestry and Fisheries		Department of Agriculture, Forestry and Fisheries
Local municipalities	Local Government	SA Local Government Association (SALGA)
Irrigation boards and water user associations	Water	
Farmers (commercial and emerging)	Agriculture	Department of Agriculture, Forestry and Fisheries
Mining	Mining	Department of Mineral Resources
Industry	Trade & Industry	Various National Business Organisations; Department of Trade & Industry
Power generation (ESKOM)	Energy	Department of Energy

An important forum, where many of these stakeholders interact, is the Olifants River Forum, the vision of which is to promote and coordinate voluntary cooperation between all relevant stakeholders to help with the improvement, conservation and sustainable existence of the Olifants River to the benefit of man and the environment. The forum has six main objectives:

1. Encourage and promote the conservation, improvement and sustainable utilisation of the Olifants River and its catchment basin;
2. Create awareness of the importance of the river as a resource and the impact of various activities on it;
3. To encourage voluntary co-operation between interested and affected parties, and to harness expertise, experience and resources to ensure the responsible utilisation of the Olifants River and its catchment basin;
4. Facilitate consultation and interaction between interested and affected parties, and enable identification and communication of their needs and perspectives;
5. Actively promote the involvement of communities in the catchment management activities of the Association; and
6. Develop community leadership capacity so that they can play a meaningful part in the management of the Association.

5.4 INVESTIGATION OF WATER QUALITY DRIVERS AND TRENDS – SUB-CATCHMENT WATER QUALITY IN THE UPPER UMNGENI

5.4.1 Introduction

In meeting the requirement for stakeholder engagement, capacity building, and refining and testing of the developed tools, alternative approaches in the investigation of links between land use and water quality were included under the research project. One such investigation was undertaken in partnership with the development of the Upper uMngeni Integrated Catchment Management Plan (GroundTruth, 2012a). This section details two analyses of water quality and the links to land use within the uMngeni River case study catchment (Figure 5.6). The first involves the analysis of historical water quality records to distinguish sub-catchment water quality trends, with the second involving the simple mapping of water quality drivers (land use activities) within the sub-catchments. In this way the water quality status of each sub-catchment in relation to the land use activities within the catchment, could then be easily interpreted visually by stakeholders.

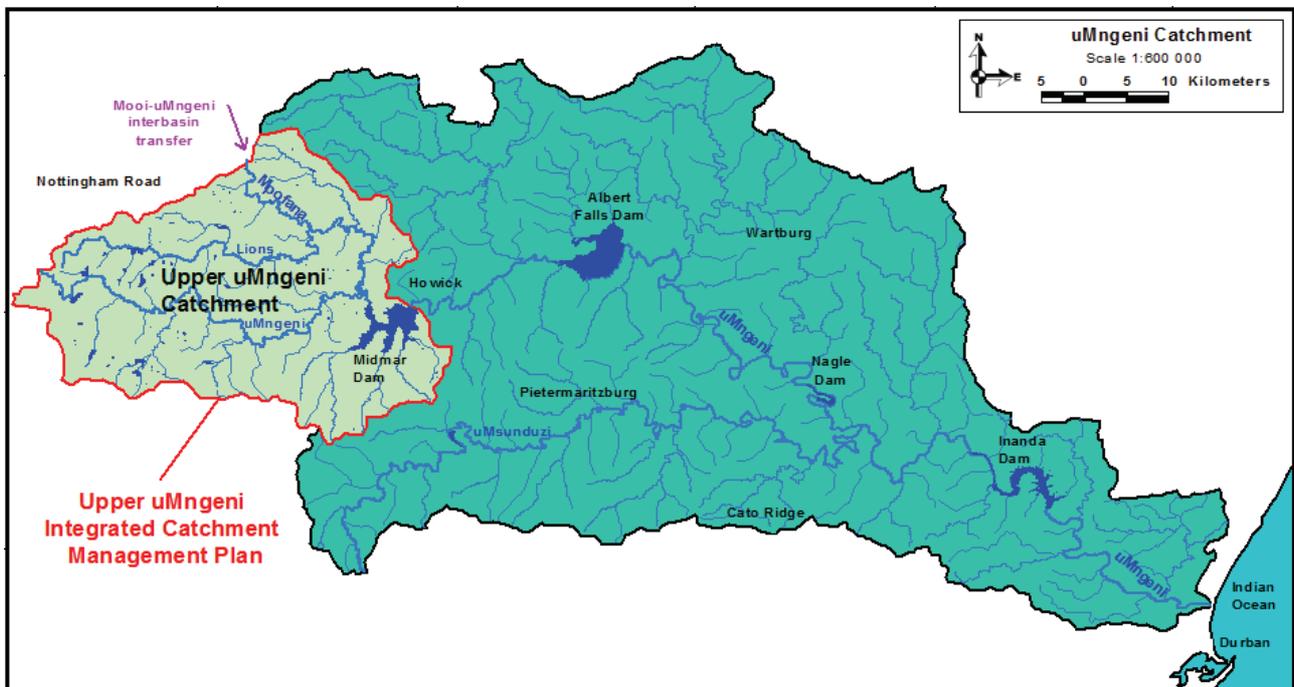


Figure 5.6: uMngeni River catchment and the upper uMngeni case study catchment

Umgeni Water established a network of water quality monitoring sites within the catchment, with water quality records at these sites extending from the early nineties to the present day. Within these assessments the catchment was divided into sub-catchments based on the location of the Umgeni Water monitoring sites, to investigate the water quality history and drivers within each of the upstream land use areas.

5.4.2 Trends of water quality loads and concentrations across the sub-catchments of the upper uMngeni river case study catchment

Investigation of land use types and activities within the upper uMngeni River catchment illustrates that the water quality of the Midmar Dam catchment is driven by a limited range of point and nonpoint pollution source types. The land use of the catchment is currently dominated by

agriculture, with forestry covering the second largest area. Beyond scattered rural dwellings and farm infrastructure nodes, urban land use areas are predominantly restricted to Mpophomeni, housing settlements at Lidgetton and Lions River, and the expansion of residential and hospitality developments within the Balgowan to Nottingham Road area. Industrial type land use activities within the catchment are limited predominantly to on-farm processing of produce and light semi-industrial activity within urban nodes. Future development of the catchment, both in terms of low cost housing such as Khayalisha, and higher end residential and hospitality developments around Nottingham Road, stand to threaten water quality if incorrectly sited, planned and managed.

5.4.3 Methodology of the sub-catchment water quality comparison

Seven sub-catchments of the upper uMngeni River catchment as well as the Mearns abstraction point on the Mooi River were considered for the comparison of water quality. The sub-catchments were aligned with water quality monitoring sites selected as having the longest record of routine water quality monitoring by Umgeni Water. The sites are detailed within Table 5.3.

Table 5.3: Water quality monitoring sites within the upper uMngeni River catchment.

Abbreviation	Description	Latitude	Longitude
Lions River	Lions River at Weltevreden	-29.44292	30.14847
Um. Inflow	uMngeni River at Midmar inflow	-29.48814	30.15600
Um. Petrus Stroom	uMngeni River at Petrus Stroom	-29.51272	30.09444
Mpofana	Mpofana River at the outlet of the Mooi-uMngeni inter catchment transfer	-29.38722	30.06361
Umthinzima	Umthinzima River at Midmar inflow	-29.53972	30.19333
Nguklu	Nguklu River at Midmar inflow	-29.54694	30.17250
Gqishi	Gqishi River at Midmar inflow	-29.54167	30.13500
Mooi	Mooi River at Mearns Weir	-29.24778	29.97083

Time series data for determinant concentrations and water flows were collected for the analyses. Determinant concentrations were available from Umgeni Water for all monitoring points; however the length of the time series available differed between the various points. The following adjustments were made to prepare the data for analysis:

- <'value' was replaced with half of the original value (e.g. <0.05 replaced with 0.025).
- >'value' was replaced with the original value.
- Where an 'R' was attached to a determinant value, it was replaced with just the value.
- MNS and MNR were considered as missing results.

Flow data was obtained from the Department of Water Affairs and where flow data was missing, modelled flow data generated during a WRC research project was incorporated (Warburton *et.al.*, 2010). Modelled flow data was used entirely for the uMngeni Midmar Inflow and Mpofana monitoring points and partially for the Nguklu and Gqishi Midmar Inflow points. A limitation of the modelled flow data, was that it was only modelled to the end of 1999 due to the non-availability of cleaned rainfall records post 2000. This placed a limitation on the full use of the limited water quality records available.

Water quality determinant concentrations were compared over time by calculating average monthly concentrations for the years of data available from 1990 to 2011. The following determinants were considered:

- *E. coli* (*E. coli* counts per 100 ml)
- Soluble reactive phosphorus – SRP ($\mu\text{g P/l}$)
- Total phosphorus – TP ($\mu\text{g P/l}$)
- Nitrate – NO_3 (mg N/l)
- Ammonia – NH_3 (mg N/l)

Water quality determinant loads (kg/month) were calculated from determinant concentrations and monthly water flows (m^3/month) at each point. Daily flows (m^3/day) were estimated from the daily average flows (m^3/s). Monthly flows (m^3/month) were calculated by summing the estimated daily flows. The pollutant loads for the Mooi River at the Mearns abstraction point were calculated using flow data and determinant concentrations for the Mooi River near the Mooi-uMngeni Transfer Scheme (MMTS) abstraction point at the Mearns Weir. Unfortunately pollutant loads for the actual Mooi to uMngeni transfer waters could not be accurately calculated due to the limited water quality data collected during the period that the Mooi-uMngeni Transfer Scheme has been operating. Collected water quality data available from Umgeni Water covering the Mooi River at Mearns Weir covers the period 1990 to 2003, with MMTS-1 beginning operation in 1999. As a result of this limitation, in accounting for the impact of the MMTS on water quality within the uMngeni River, the following comparison of pollutant concentrations between the Mooi and uMngeni Rivers is of more relevance than the comparison of loads.

5.4.4 Results and discussion covering the sub-catchment water quality comparison

Log box-plots were used to graphically represent and compare the determinant concentrations and loads between sub-catchments. Scatter plots and line graphs were used to observe trends in determinant concentrations and loads over time.

5.4.4.1 Comparison of pollutant concentrations across sub-catchments

For all the determinants across all eight sub-catchments, concentration was consistently highest for the Mthinzima catchment. The log box-plots for TP, NO_3 and *E. coli* concentration are shown below within the following three figures.

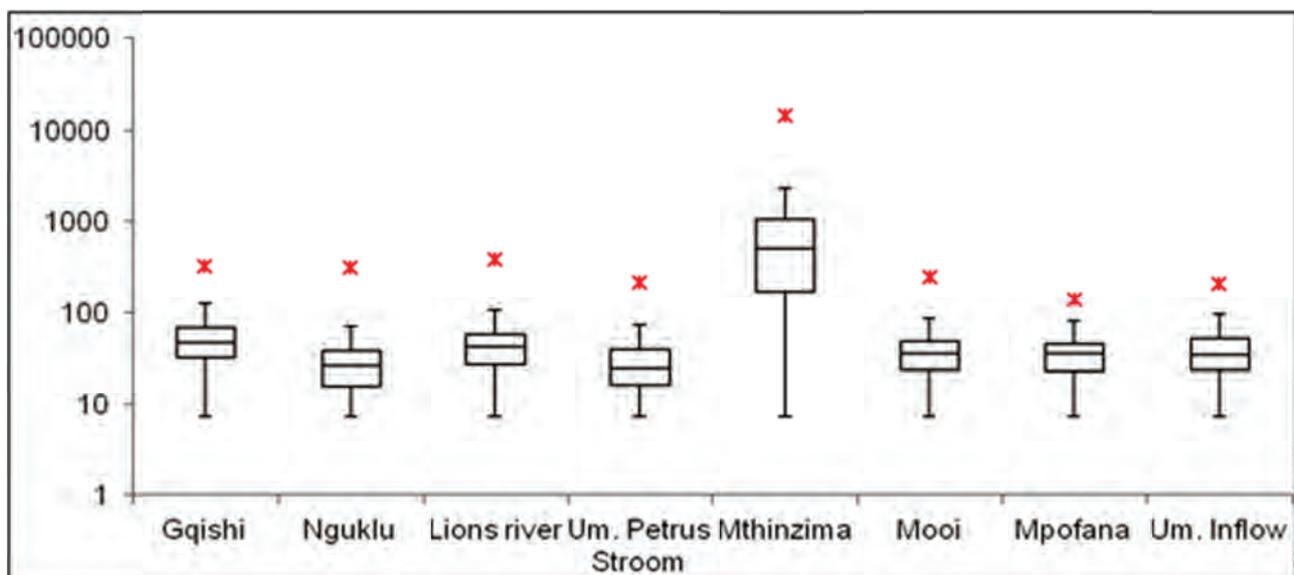


Figure 5.7: Log scale box plot of monthly averages in total phosphate concentrations (μg)

P/I)

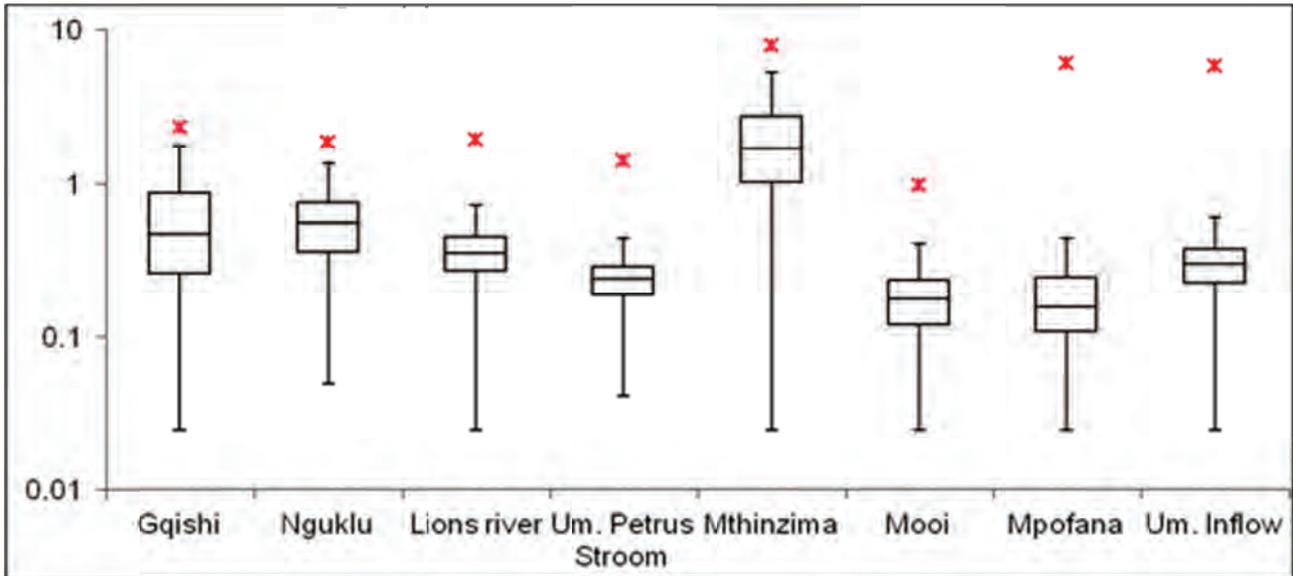


Figure 5.8: Log scale box plot of monthly averages in nitrate concentrations (mg N/l)

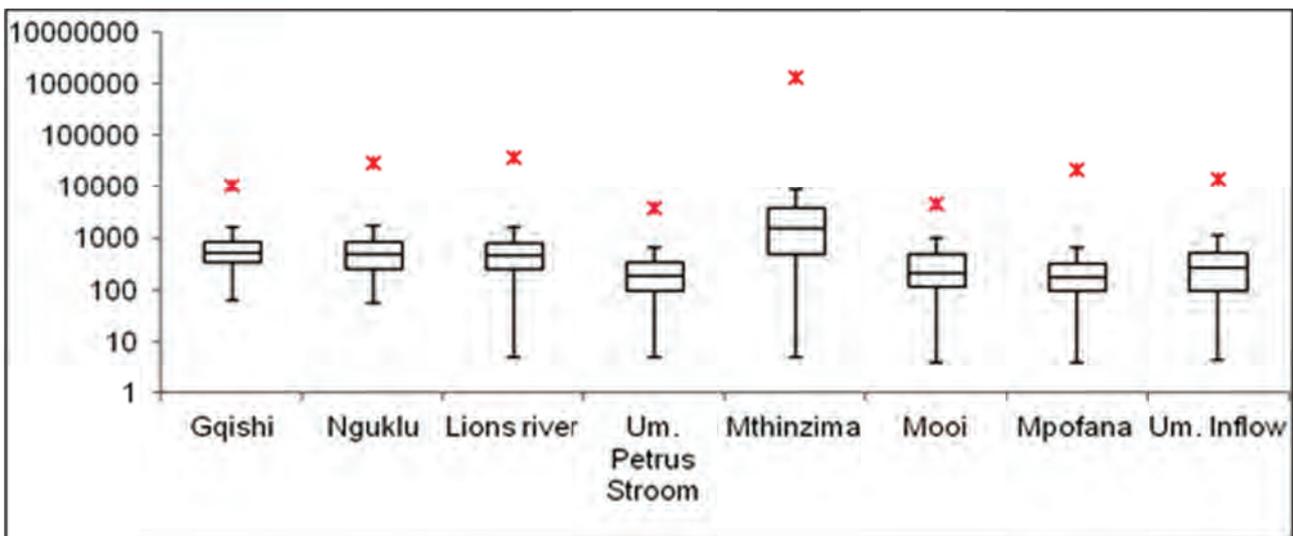
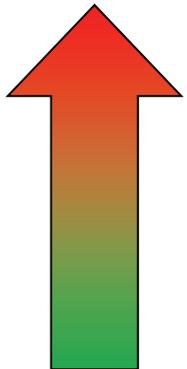


Figure 5.9: Log scale box plot of monthly averages in *E. coli* counts (*E. coli*/100 ml)

Table 5.4 lists the sub-catchments in order of decreasing median value for determinant concentration. The Mthinzima sub-catchment consistently has the highest median concentration for all the determinants considered. The Gqishi and Nguklu Rivers are shown to contain high concentrations of *E. coli* and nitrate in particular, with SRP and TP also high. However, it must be remembered that the Gqishi and Nguklu Rivers flow at low volumes, with the result that the assessment of pollutant load is of more relevance. Of interest is a comparison of the pollutant concentrations between the Mooi River (Mooi) and the uMngeni River inflow to Midmar Dam (uMngeni Inflow). The Mooi River transfer waters contribute higher concentrations of soluble reactive and total phosphorous, but lower concentrations of nitrate, ammonia and *E. coli*.

Table 5.4: Catchment ranks based on the median value of determinant concentration (in order of decreasing median concentration)

<i>E. coli</i>	SRP	TP	NO ₃	NH ₃	
Mthinzima (1%)	 <p>Highest pollutant concentration</p> <p>Lowest pollutant concentration</p>				
Gqishi (4%)	Gqishi (4%)	Gqishi (4%)	Nguklu (2%)	uMngeni Inflow (88%)	
Nguklu (2%)	Lions River (61%)	Lions River (61%)	Gqishi (4%)	Mpofana (5%)	
Lions River (61%)	Mooi (34%)	Mooi (34%)	Lions River (61%)	Lions River (61%)	
uMngeni Inflow (88%)	Nguklu (2%)	Mpofana (5%)	uMngeni Inflow (88%)	Mooi (34%)	
Mooi (34%)	uMngeni Inflow (88%)	uMngeni Inflow (88%)	Petrus Stroom (27%)	Gqishi (4%)	
Petrus Stroom (27%)	Mpofana (5%)	Nguklu (2%)	Mooi (34%)	Petrus Stroom (27%)	
Mpofana (5%)	Petrus Stroom (27%)	Petrus Stroom (27%)	Mpofana (5%)	Nguklu (2%)	

(% of the cumulative land area feeding Midmar Dam upstream of that point, including Mooi River upstream of Mearns Weir)

Figure 5.10 shows the average annual concentration levels of the various determinants over time for the Mthinzima River catchment. The Mpophomeni waste water treatment works (WWTW) was in operation from the beginning of 1991 to the end of 1999, shown by the arrows in the figure. *E. coli* concentrations increase following closure of the WWTW, possibly as a result of the loss of chlorine discharged to the Mthinzima River from the WWTW effluent. Phosphates and nitrate concentrations drop following closure of the WWTW, with ammonia concentrations increasing.

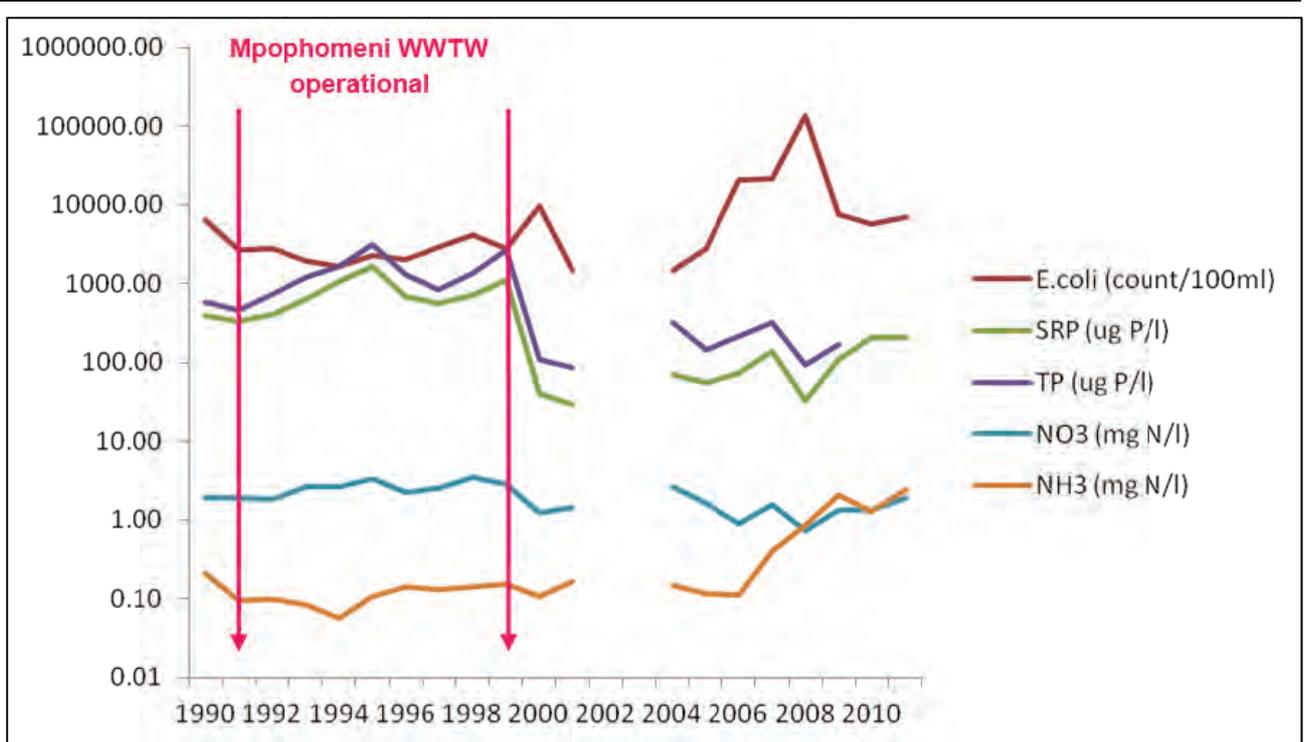


Figure 5.10: A log plot of determinant concentrations (annual monthly averages) over time for the Mthinzima River sub-catchment

5.4.4.2 Comparison of pollutant loads across sub-catchments

For all the determinants across all eight sub-catchments, load was consistently highest for the Mooi River. The Lions River at Weltevreden and the uMngeni Midmar Inflow also showed relatively high loads of all the determinants considered. The Nguklu River had the lowest load across all determinants as a result of the relatively lower flow at this point. The log box-plots for TP, NO₃ and *E. coli* load are shown in the following three figures.

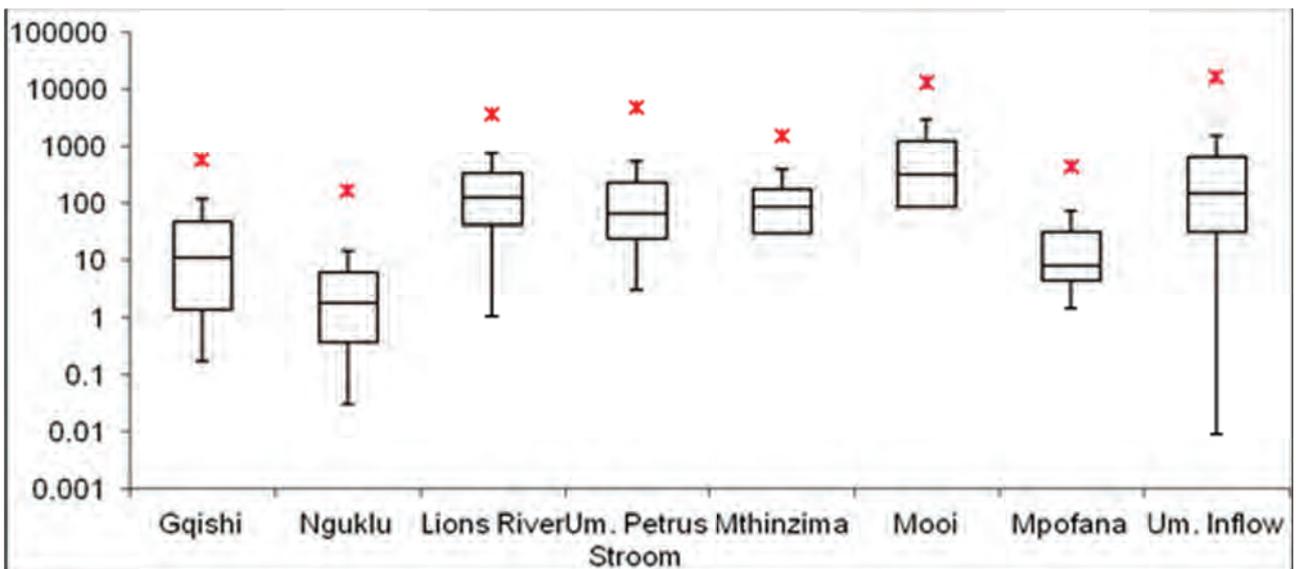


Figure 5.11: Log scale box plot of total phosphate loads (kg/month)

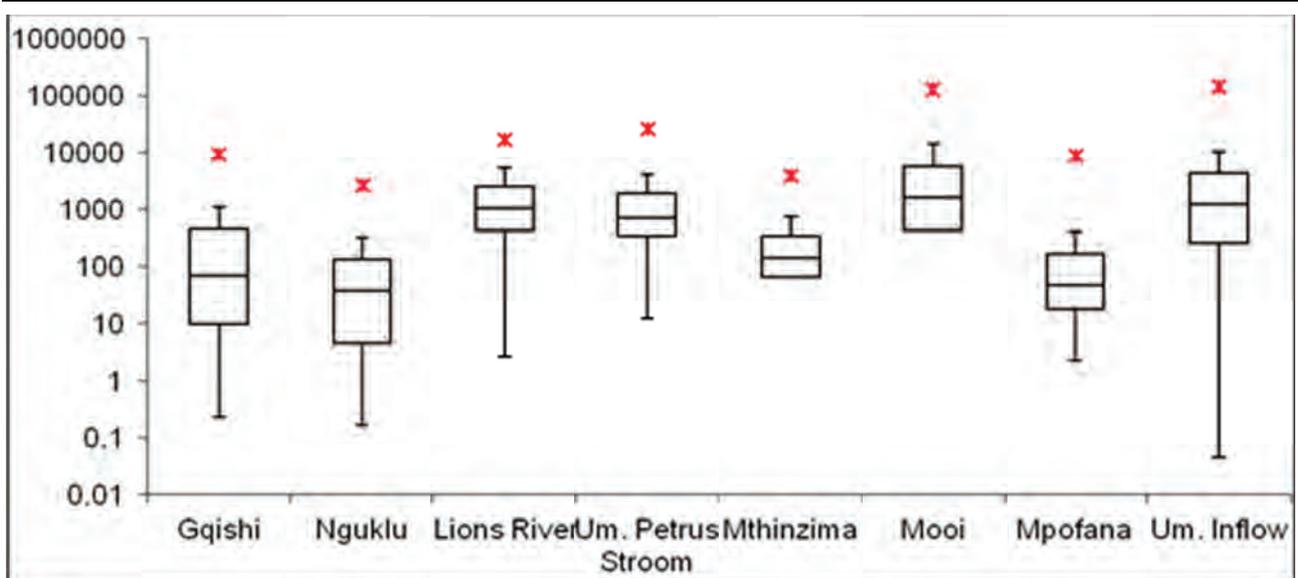


Figure 5.12: Log scale box plot of nitrate loads (kg/month)

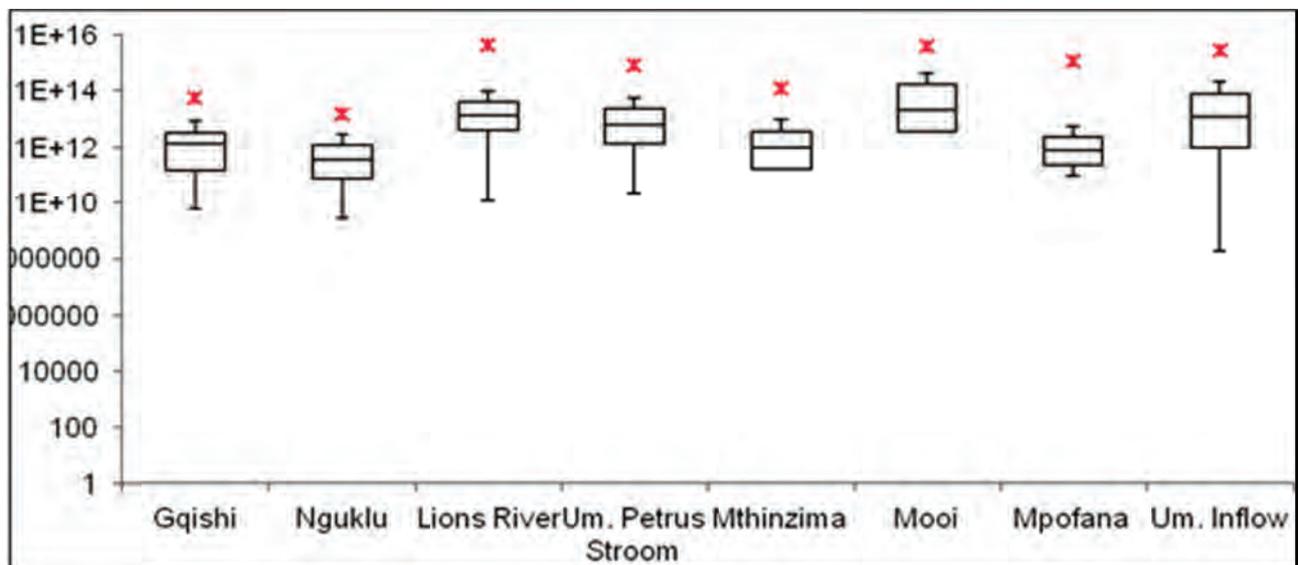
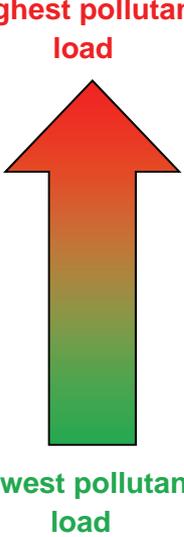


Figure 5.13: Log scale box plot of *E. coli* loads (count/month)

Table 5.5 is a list of the sub-catchments in order of decreasing median load value. The Mooi River has the highest median load for all determinants and the Nguklu sub-catchment has the lowest. Of interest is that despite its relatively small size, the Gqishi River catchment has historically contributed higher loads of certain pollutants than the Mpfana and Mthinzima catchments, illustrating the impact of dairy, piggeries and intensive agriculture. The high pollutant loads of the Mooi River are of less consequence than the actual concentration of pollutants within the waters transferred, given that a relatively small portion of the Mooi River flow volumes are transferred to the uMngeni.

Table 5.5: Catchment ranks based on the median value for determinant load (in order of decreasing median load)

<i>E. coli</i>	SRP	TP	NO ₃	NH ₃	
Mooi (34%)	 <p>Highest pollutant load</p> <p>Lowest pollutant load</p>				
Lions River (61%)	Mthinzima (1%)	uMngeni Inflow (88%)	uMngeni Inflow (88%)	uMngeni Inflow (88%)	
uMngeni Inflow (88%)	uMngeni Inflow (88%)	Lions River (61%)	Lions River (61%)	Lions River (61%)	
Petrus Stroom (27%)	Lions River (61%)	Mthinzima (1%)	Petrus Stroom (27%)	Petrus Stroom (27%)	
Gqishi (4%)	Petrus Stroom (27%)	Petrus Stroom (27%)	Mthinzima (1%)	Mpofana (64 km ²)	
Mthinzima (1%)	Gqishi (4%)	Gqishi (4%)	Gqishi (4%)	Gqishi (4%)	
Mpofana (5%)	Mpofana (5%)	Mpofana (5%)	Mpofana (5%)	Mthinzima (1%)	
Nguklu (2%)					

The following three figures compare the determinant concentrations over time at the uMngeni Midmar Inflow (downstream of the Mooi-uMngeni inter basin transfer outflow) to the average monthly flow of water abstracted from the Mooi River at Mearns Weir. Water was first abstracted from the Mooi River for inter basin transfer to the uMngeni River catchment (MMTS-1) at the start of 1999. Figure 5.14 illustrates that following the start of the MMTS-1 water transfers to the uMngeni River, soluble reactive phosphorous, and total phosphorus concentrations in particular, responded with increases. Within this analysis Figure 5.15 and Figure 5.16 illustrate less convincing changes in nitrate, ammonia and *E. coli* levels in response to initiation of the water transfers.

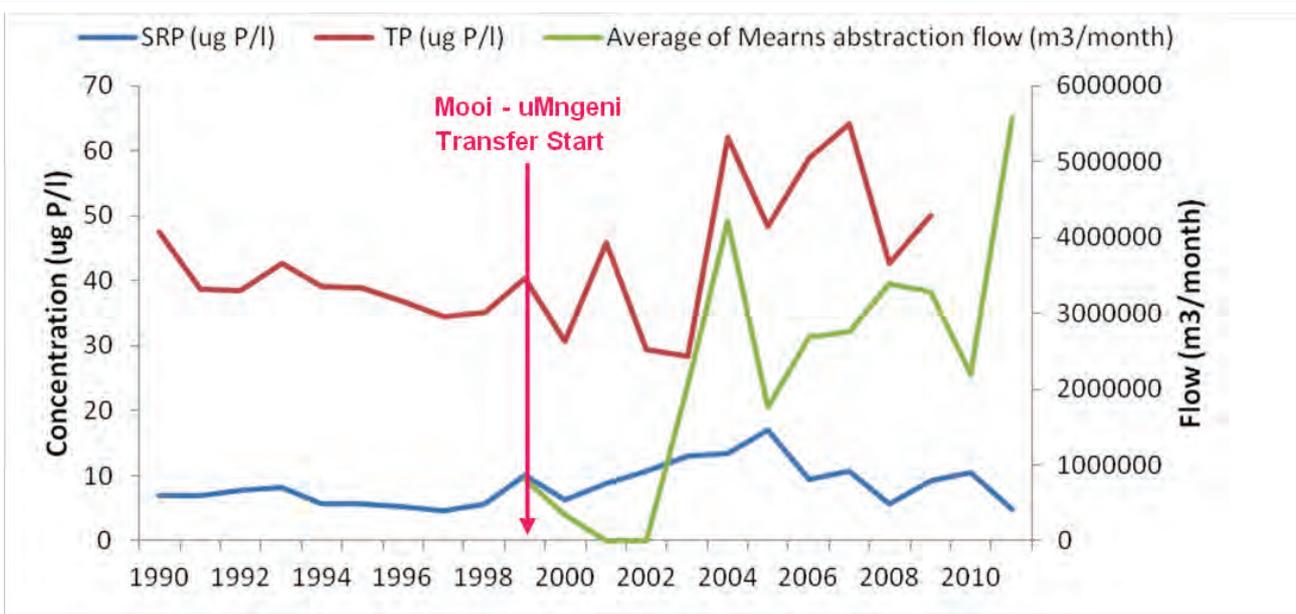


Figure 5.14: SRP and TP concentrations (annual monthly averages) for the uMngeni River Inflow to Midmar Dam monitoring point and the average monthly flow of water abstracted from the Mooi River at Mearns Weir

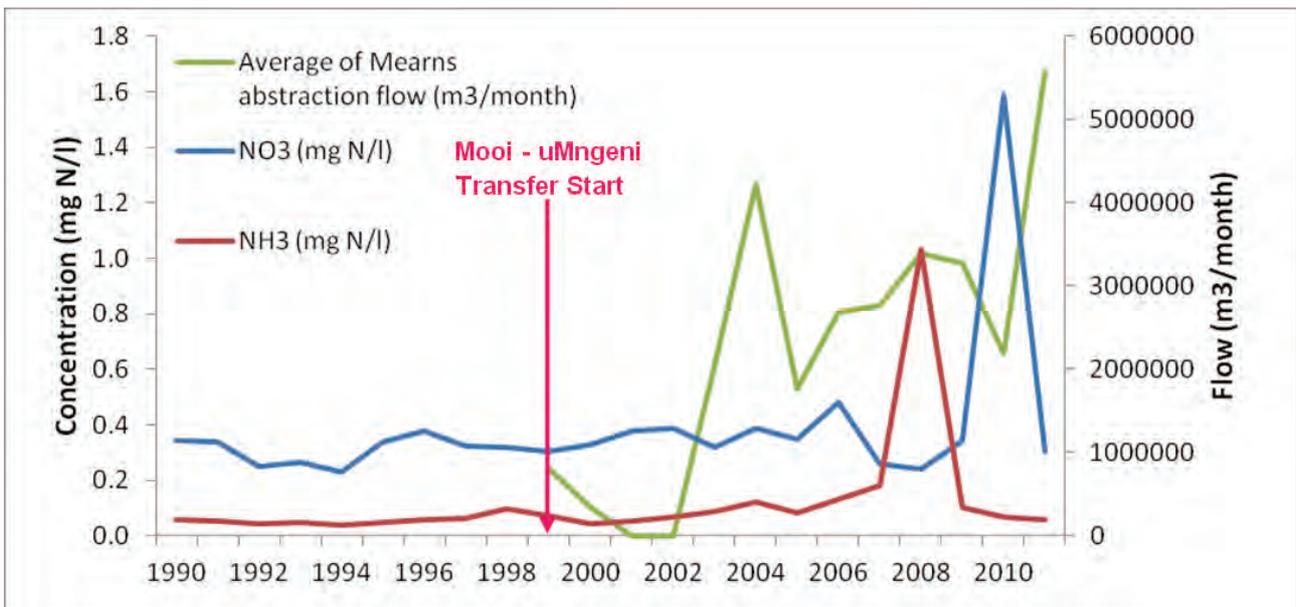


Figure 5.15: NO_3 and NH_3 concentrations (annual monthly averages) for the uMngeni River Inflow to Midmar Dam monitoring point and the average monthly flow of water abstracted from the Mooi River at Mearns Weir

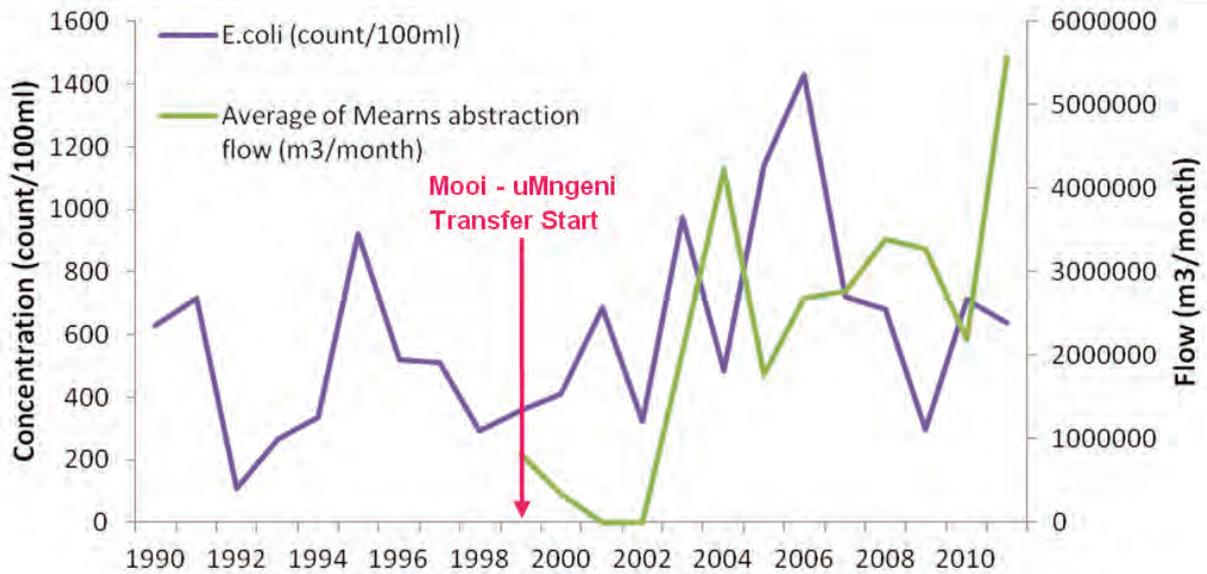


Figure 5.16: *E. coli* concentration (annual monthly averages) for the uMngeni River Inflow to Midmar Dam monitoring point and the average monthly flow of water abstracted from the Mooi River at Mearns Weir

5.4.5 Mapping of water quality drivers within the upper uMngeni River catchment

Mapping of key land use activities which have the potential to negatively impact water quality within the upper uMngeni /Midmar Dam catchment was performed through the assistance of key stakeholders intimately familiar with the land use activities and features of the catchment. The stakeholder group included staff involved in the day to day sampling, analysis and management of water quality within the catchment, as well as representatives of the dominant land owner association active within the area. The first step was a virtual fly through of the entire catchment in Google Earth, to locate and mark key activities and features within the catchment. These features were captured within a Geographic Information System, with a large format map presented to the land owner association chairman for verification and ratification. Figure 5.17 illustrates the upper uMngeni/Midmar Dam catchment, and the key land use activities potentially driving water quality, in relation to the sub-catchment water quality status undertaken within the following section. The subcatchment water quality status was aggregated from the results of the pollutant load and concentration results per subcatchment, detailed within the following section. The water quality status colour coding (Figure 5.17) ranges from green (best water quality) through to red (poorest water quality).

It is immediately apparent that the Midmar surrounds (predominantly a protected area), the kwaGqishi and Nguklu River catchments, and the uMngeni River catchment upstream of Petrus stroom display the lightest density of activities which typically impact water quality, and also display a better water quality status. The sub-catchments at the poor end of the water quality spectrum include the Lions River and Mthinzima River. The Lions River sub-catchment reveals a high density of dairy operations, as well as a few piggery and poultry operations. The Mthinzima River catchment shows the biggest area of low cost and informal housing within the Midmar Dam catchment, with sewer reticulation infrastructure displaying a history of regular and severe leakage and surcharge (Natal Witness, 2009 and Carte Blanche, 2011). However, it must be noted in the interpretation of the water quality records, that the water quality at the Lions River site is impacted

by the water quality of the Mooi River, as a result of the Mooi-uMngeni transfer waters from the Mearns Weir.

5.5 LOAD MODELLING – PHOSPHATE IN THE UPPER UMNGENI

5.5.1 Introduction

This section reports on the results of one of the modelling exercises undertaken within the uMngeni River catchment in KwaZulu-Natal, one of two case study catchments adopted under the research project. Investigations of suitable water quality models and their application within the case study catchments forms one component under the investigation of available tools within the following project aims: “Develop tools and guidelines to guide and improve decision making by relevant management stakeholders with regards to the potential impacts of different land uses on water quality”, and “Test and refine the developed tools through two case study catchments to improve the decision making of management stakeholders”.

It was provisionally decided to use the BASINS 4.0 framework and particular models within this shell for this project. BASINS 4.0 (Better Assessment Science Integrating Point and Nonpoint Sources, version 4.0) is defined by (US EPA, 2010) as: “...a multipurpose environmental analysis system for use by regional, state, and local agencies in performing watershed- and water-quality-based studies”. The model used for this analysis, which was the most appropriate rapid method for estimating pollutant amounts from various land cover types, was the Pollutant Loading Estimator (or PLOAD), which is “...a simplified, GIS-based model to calculate pollutant loads for watersheds. PLOAD estimates nonpoint sources (NPS) of pollution on an annual average basis, for any user-specified pollutant”. The output generated from the PLOAD (Pollutant Loading Estimator) model could be used to identify the priority areas (sub-catchments) that stakeholders would need to investigate in more detailed ground level. Estimating the amount of phosphate typically emitted from these nonpoint sources could assist stakeholders, managers and planners in prioritising actions to address land use and management activities within the sub-catchments, which are contributing high phosphate loads.

The BASINS model framework provides default export coefficient values as a starting point for phosphate simulations with the PLOAD model. The BASINS 4.0 user manual notes the following: “The Export Coefficient ... tables provided with BASINS contain “representative” values as presented in the PLOAD v3 User’s Manual distributed with BASINS 3.1. These values represent a starting point and are based on data from a number of published sources, however they are specific to particular geographic regions. It is important that the user obtain appropriate values from studies in the corresponding geographic region”. With this in mind, the aim of this investigation was to compare the Total Phosphate (TP) values provided as default within the PLOAD model, with those export coefficient values obtained from the literature (Dickens et al., 2010), when running the model within the uMngeni River case study catchment in South Africa.

5.5.2 Phosphate export coefficient comparisons

First, the raster land cover grid (obtained from Geoterraimage, 2010, using 2008 imagery) had to be converted into vector format (the PLOAD model will only recognise vector format). One of the steps in the procedures required before calculating the Total Phosphate (TP) values is to perform a land cover reclassification. From the detailed land cover grid of KZN (Geoterraimage, 2010, using 2008 imagery), the classes were reclassified according to the level 2 categories along the principles of SANS 1877 (SSA, 2004). Table 5.6 illustrates this reclassification. Once this process was completed for the land cover GIS layer, the PLOAD model could then be set up. Initially, the intention was to perform PLOAD simulations on multiple, fine scale sub-catchments of the uMngeni River catchment created by an automatic watershed delineation tool. However, the tool produced 245 sub-catchments, which proved too time-consuming to model within this study, particularly because of the high resolution land cover layer. Hence, a single quaternary catchment was identified for simulation to establish proof of concept.

A PLOAD simulation was performed for the whole uMngeni River catchment (Figure 5.18) using the TP export values collated by Dickens et al. (2010), to identify the priority quaternary catchments. The output from this simulation calculated that the U20M quaternary catchment draining the Durban area had the highest phosphate pollutant load (3.35 kg/ha/year), with U20J (draining Pietermaritzburg) having the second highest (1.55 kg/ha/year). Due to a large proportion of the project team being based in the Pietermaritzburg region, and with stakeholders from the area already engaged within the project (e.g. Umgeni Water, Msunduzi Municipality, and the local CMA), it was decided that the U20J catchment would be a suitable focus catchment for further modelling investigation.

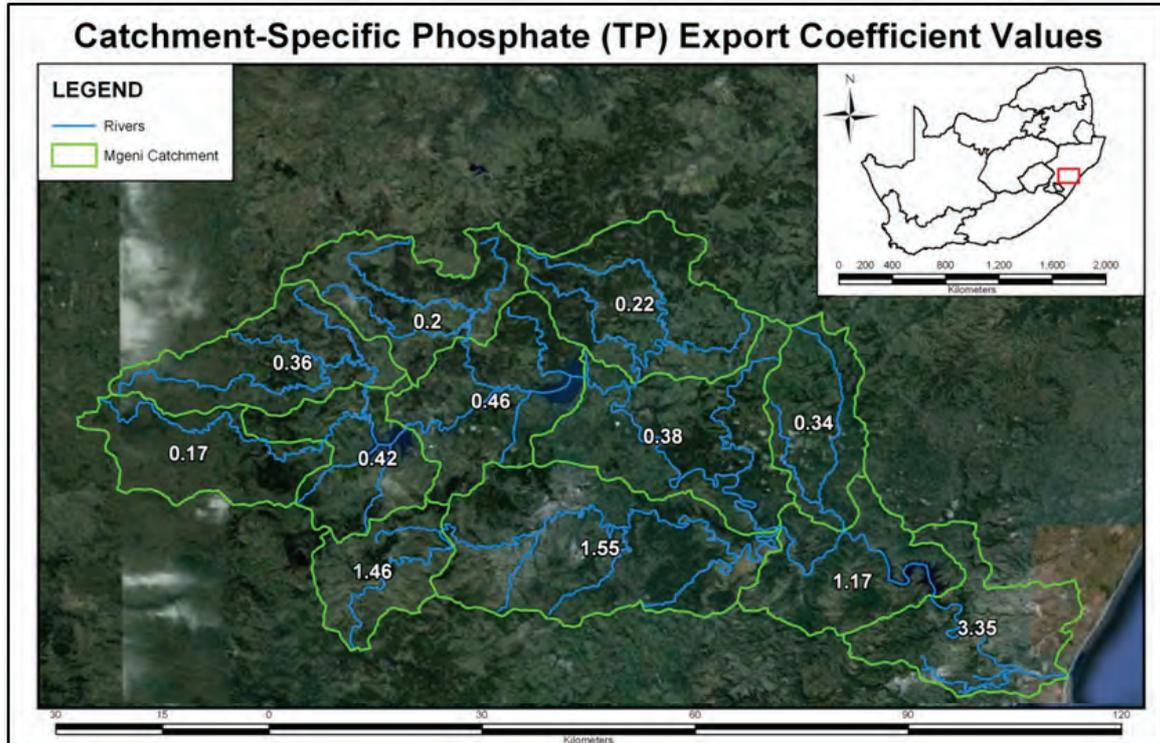


Figure 5.18: PLOAD simulation for quaternary catchments of the uMngeni catchment, using Dickens et al. (2010) TP export coefficient values (sub-catchment TP export values in kg/ha/yr).

The uMngeni River case study catchment is the quaternary catchment in which the City of Pietermaritzburg is situated, namely U20J. Automatic watershed delineation was performed on the U20J catchment, creating 43 sub-catchments. The land cover distribution in this study catchment is presented in Figure 5.19, along with the various land cover contributions (Figure 5.20).

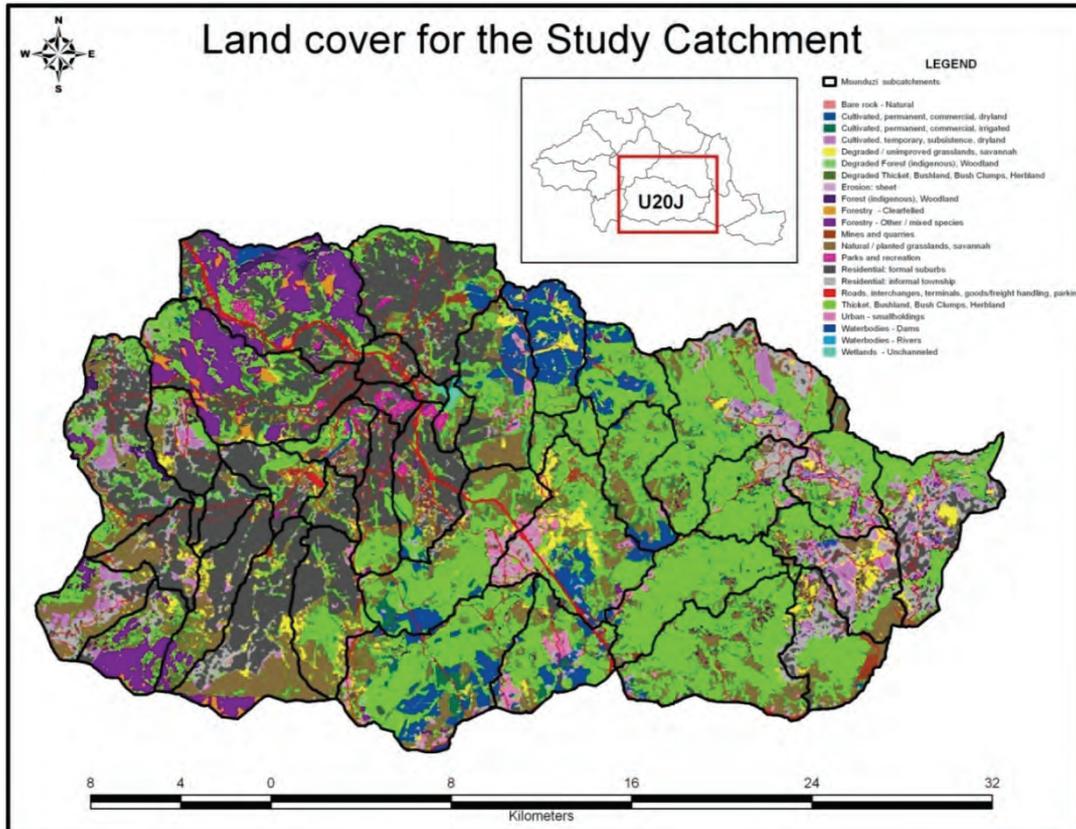


Figure 5.19: Land cover for the various sub-catchments from with the PLOAD model was simulated (Geoterraimage, 2010, using 2008 imagery).

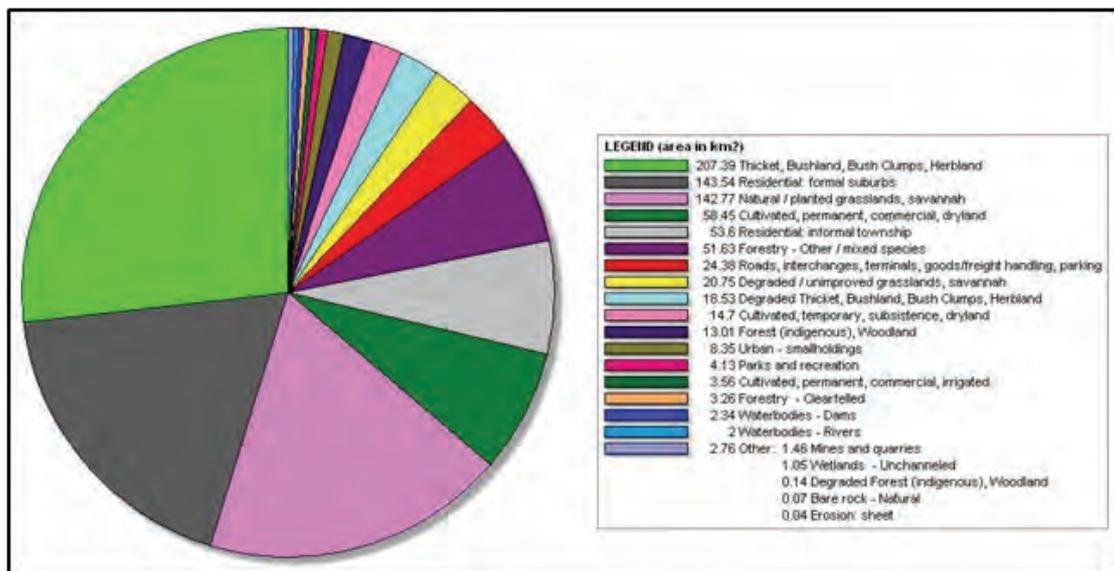


Figure 5.20: Land cover contributions for the catchment (i.e. U20J) used for the PLOAD simulations(Geoterraimage, 2010, using 2008 imagery).

Table 5.6: Land cover reclassification with comparison of default and uMngeni total phosphate export coefficients.

KZN Land Cover 2008 classification	Reclassified naming (along principles of SANS 1877)		PLOAD default TP (kg/ha/yr)	uMngeni TP (kg/ha/yr)	PLOA D ID
	Level 2	Level 1			
Bare rock	Bare rock – Natural				1
Bare sand	Bare sand – Natural	Bare rock and soil	0.22	0	2
Bare sand coastal (NEW)	Bare sand – Natural				
Annual commercial crops dryland	Cultivated, permanent, commercial, dryland				
Permanent orchards (banana, citrus)	Cultivated, permanent, commercial, dryland				
Sugarcane – commercial	Cultivated, permanent, commercial, dryland	Agriculture	1.12	0.1	3
Sugarcane – emerging farmer	Cultivated, permanent, commercial, dryland				
Annual commercial crops irrigated	Cultivated, permanent, commercial, irrigated				4
Subsistence (rural)	Cultivated, temporary, subsistence, dryland				5
Degraded grassland	Degraded/unimproved grasslands, savannah		1.12	0.1	6
Degraded forest	Degraded Forest (indigenous), Woodland	Natural vegetation			7
Degraded bushland (all types)	Degraded Thicket, Bushland, Bush Clumps, Herbland		0.22	0.02	8
Erosion	Erosion: sheet	Bare rock and soil	0.22	0	9
Forest	Forest (indigenous), Woodland				
Woodland	Forest (indigenous), Woodland	Natural vegetation	0.22	0.02	10
Plantation clearfelled	Forestry – Clearfelled				11
Plantation	Forestry – Other/mixed species	Forestry	0.22	0.02	12

Table 5.6 (cont): Land cover reclassification with comparison of default and uMngeni total phosphate export coefficients.

Mines and quarries	Mines and quarries	Mining	0.11	0.8	13
Smallholdings – grassland	Urban-smallholdings	Built-up land/Urban	2.24	1.00	20
forest glade	Natural/planted grasslands, savannah				
old cultivated fields – grassland	Natural/planted grasslands, savannah	Natural vegetation	0.11	0.1	14
grassland	Natural/planted grasslands, savannah				
grassland/bush clumps mix	Natural/planted grasslands, savannah				
Golf courses	Parks and recreation			0.1	15
Built up dense settlement	Residential: formal suburbs	Built-up land/Urban	2.24	5	16
Low density settlement	Residential: informal township			3	17
Airfields	Roads, interchanges, terminals, goods/freight handling, parking				
KZN main & district roads	Roads, interchanges, terminals, goods/freight handling, parking	Transport and infrastructure	2.24	2.70	18
KZN national roads	Roads, interchanges, terminals, goods/freight handling, parking				
KZN railways	Roads, interchanges, terminals, goods/freight handling, parking				
Old cultivated fields – bushland	Thicket, Bushland, Bush Clumps, Hermland	Natural vegetation	0.22	0.02	19
Bushland (< 70cc)	Thicket, Bushland, Bush Clumps, Hermland				

Table 5.6 (cont): Land cover reclassification with comparison of default and uMngeni total phosphate export coefficients.

Dense bush (70-100 cc)	Thicket, Bushland, Bush Clumps, Herbland			
Water dams (NEW)	Waterbodies – Dam			21
Water estuarine (NEW)	Waterbodies – River	Waterbodies	0.22	0
Water natural (NEW)	Waterbodies – River			22
Wetlands	Wetland – Un-channelled	Wetlands	0.22	0
				23

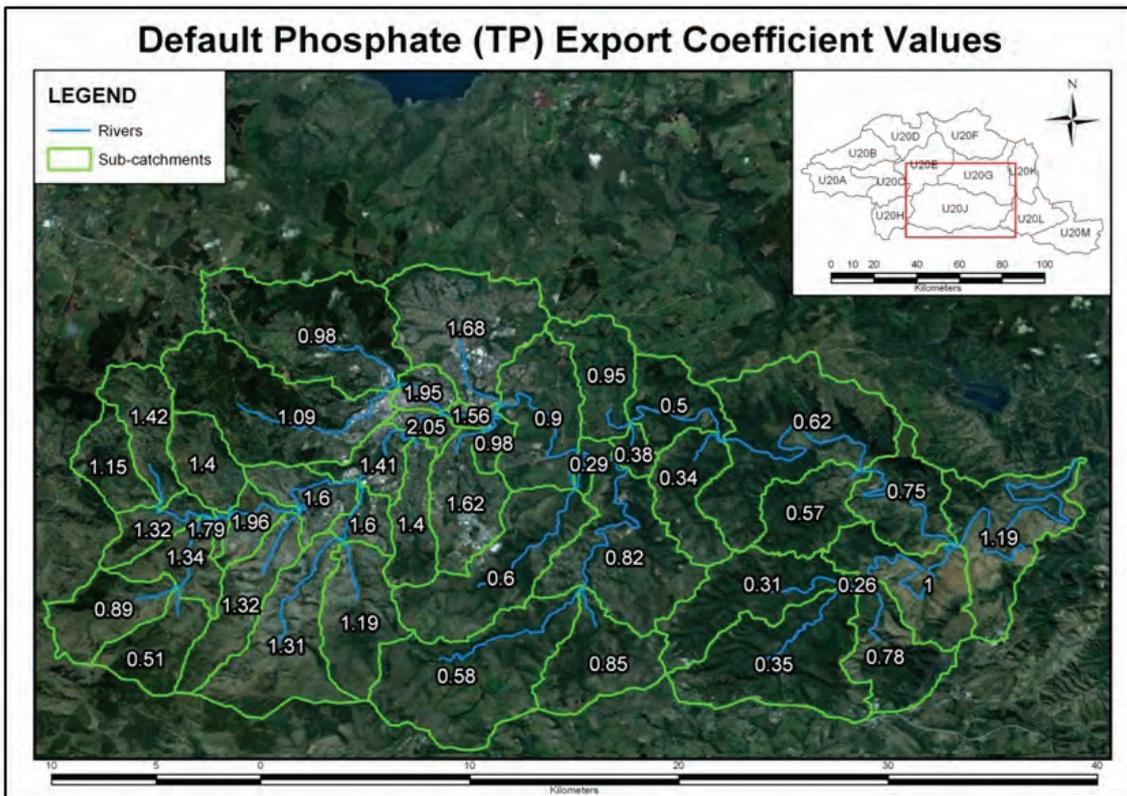


Figure 5.21: PLOAD simulation for the U20J quaternary catchment using the PLOAD default TP export coefficient values (sub-catchment TP export values in kg/ha/yr).

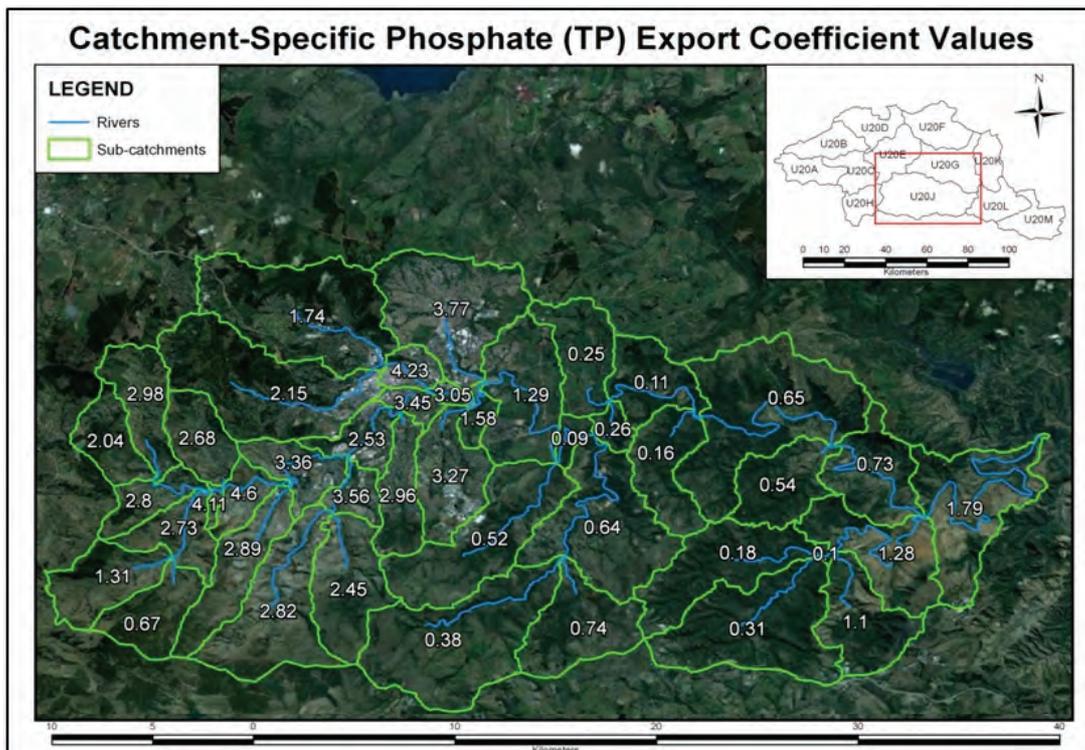


Figure 5.22: PLOAD simulation for the U20J quaternary catchment using Dickens et al. (2010) export coefficient values (sub-catchment TP export values in kg/ha/yr).

A PLOAD simulation using the export coefficient method was performed using the default values for TP (Table 5.15) for the 43 sub-catchments situated within the U20J quaternary catchment

(Figure 5.21). A PLOAD run was then executed for the U20J sub-catchments (Figure 5.22) using the values collated by Dickens et al. (2010) illustrated in Table 5.4. Before generating outputs from PLOAD, the export coefficient values were converted from the typical metric units in kg/ha/y to the imperial units of lbs/acre/yr. Once the simulations were complete, the units were then converted back to metric kg/ha/yr (PLOAD requires input in lbs per acre per year, and calculates output in the same units). Conversions before and after PLOAD were effected to enable both the South African reader and PLOAD to operate in their familiar “unit” environments.

A comparison between the PLOAD modelling scenarios using the default phosphate export values and the values obtained predominantly from South African literature (Table 5.4) are shown in Figure 5.23. It is evident that most of the TP loads generated from the various sub-catchments using the local values (higher than about 0.5 kg/ha/yr) produce higher phosphate loads than the PLOAD default values sourced from international publications. As a result, preliminary modelled outputs indicate that phosphate loads exported from the local case study catchment would tend to be higher than those land areas typically modelled by PLOAD in the USA. However the PLOAD modelling simulations performed for South African conditions with local data would require further calibration and testing.

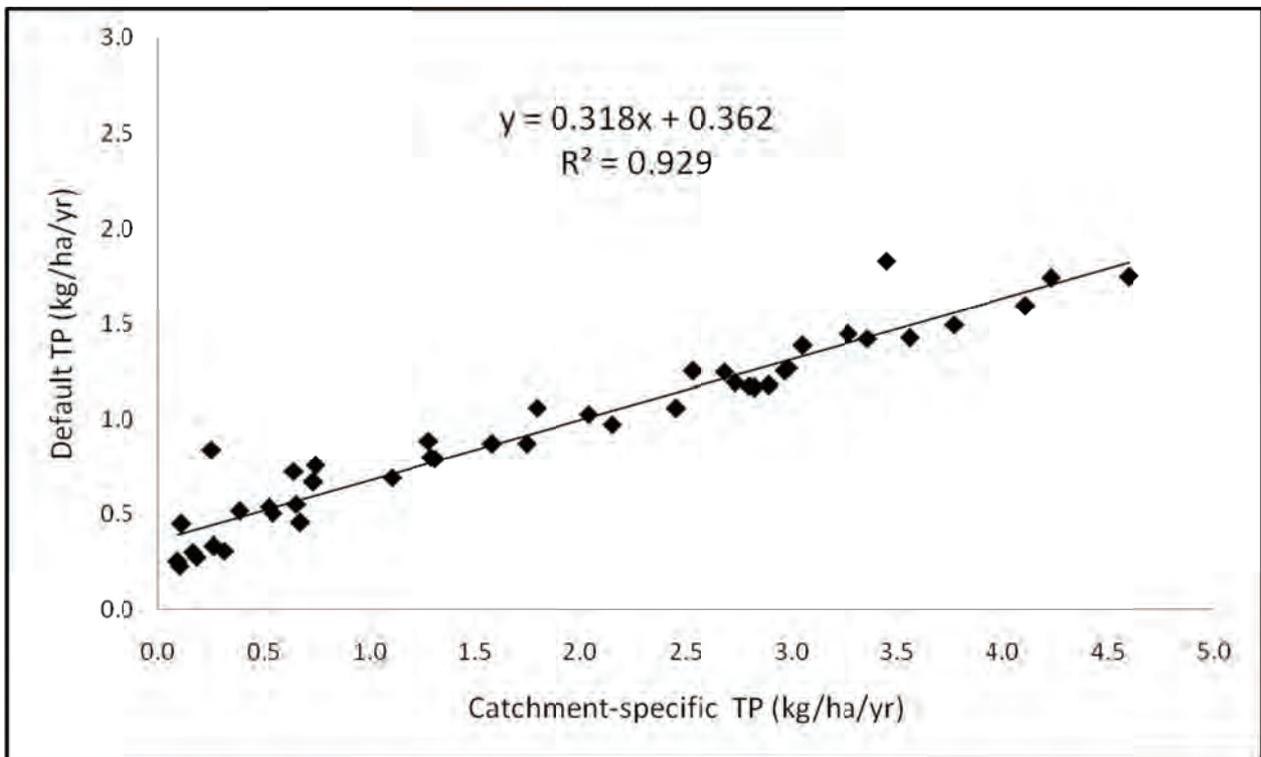


Figure 5.23: PLOAD default phosphate values (Default TP) versus phosphate export coefficients obtained mainly from South African literature (catchment-specific TP).

5.6 METHOD FOR CALCULATION OF PHOSPHATE EXPORT COEFFICIENTS IN THE UPPER OLIFANTS CATCHMENT

5.6.1 Introduction

Export coefficients are typically developed by calculating loads (i.e. combination of flow and water quality measurements) downstream of a specific land use activity and expressing these loads as a function of the surface area of the land use in the catchment (i.e. kg/(ha.yr)). Thus detailed flow and water quality monitoring data and geographical analysis tools (i.e. Geographical Information Systems) are essential for developing export coefficients. Due to the cost of rigorous monitoring exercises export coefficients are typically calculated for one catchment and then applied to other catchments. There is therefore a high degree of uncertainty associated with export coefficients due to the variety of factors that influence nonpoint source pollution, which typically vary within a catchment and from one catchment to another. Regionally specific export coefficients are recommended, because variations in precipitation, soils, and management practices associated with specific land uses between regions often limit the transferability of export coefficients (Clesceri et al., 1986). A further challenge associated with calculating accurate export coefficients in this manner is that monitoring stations where water quality data are routinely collected and therefore abundant, are typically downstream of catchments that comprise a number of different land use activities. This problem was highlighted by Enongene and Rossouw (2007), who, in the process of developing export coefficients for South Africa, suggested:

“that gauging stations be identified or established in both point and nonpoint sources dominated catchments that should be monitored with the main purpose of obtaining long term monitoring records of pollutant fluxes; and that, in the selection of the appropriate gauging stations, due consideration should be given to how representative the gauged catchments of the drainage basins are in terms of land use and land form.”

These recommendations highlight the problems related to heterogeneous land use activities in catchments and highlight more rigorous and refined monitoring as the solution to deriving more accurate export coefficients. Considering the pros and cons illustrated above, and the need for incorporating tools of varying data input and output uncertainty into decision making choices, the objective of this chapter was to use a multiple regression approach (McFarland and Hauck, 2001) to determine phosphate export coefficients and to provide a measure of their uncertainty for major land use activities in the upper Olifants River catchment. While point source pollution from WWTWs has been identified as a major problem in the catchment, implementing appropriate and cost-effective management strategies needs to take all potential sources into account and also prioritise hotspot areas responsible for high levels of pollutant loading. The development and use of phosphate export coefficients can therefore be highly beneficial in terms of understanding the main land use activities responsible for high pollution as well as identifying catchment areas responsible for high pollutant loading.

5.6.2 Methods

The Department of Water Affairs routinely collects water quality data from a number of flow and water quality monitoring stations sites located across the upper catchment of the Olifants River. The following steps were initiated to calculate the export coefficients:

- 1) Identify appropriate monitoring stations where reliable water quality and flow data are available.
- 2) Delineate the catchment area of each of the selected monitoring stations using Geographical Information Systems (GIS).
- 3) Quantify land categories within each delineated sub-catchment.
- 4) Calculate phosphate export coefficients by linking calculated loads with the proportion of land use categories in each of the sub-catchments.
- 5) Calculate the uncertainty associated with export coefficients.

5.6.2.1 Site selection

Monitoring stations where both flow and water quality data are available were identified in the catchment. This allows for the calculation of the total quantity of a pollutant (i.e. kg) exiting a sub-catchment over a specific time period (i.e. a year). Based on these criteria eighteen monitoring stations were selected using the Department of Water Affairs Google Earth water quality exploration tool (DWA, 2011a). The location of these monitoring stations is indicated in Figure 5.24 while the details of each monitoring station are recorded in Table 5. Flow data for these stations was obtained from the DWA Hydrology web page (DWA, 2011b).

Table 5.7: Location and description of DWA monitoring points in the upper Olifants River catchment.

DWA Flow Gauge Station ID	DWA Water Quality Monitoring ID	River	Latitude	Longitude	Start of monitoring	Latest monitoring record	Total number of WQ records
B1H002	B11_90407	Klipspruit	-25.82	29.34	19/02/1970	18/06/2008	1261
B1H004	B11_90408	Spookspruit	-25.67	29.17	18/04/1966	16/06/2008	1375
B1H005	B11_90410	Olifants	-26.01	29.25	20/11/1979	06/05/2008	902
B1H010	B11_90412	Olifants	-25.89	29.30	23/02/1983	20/05/2008	617
B1H012	B12_90413	Klein-Olifants	-25.81	29.59	03/01/1986	02/05/2008	1138
B1H015	B12_90414	Klein-Olifants	-25.77	29.54	01/02/1983	02/05/2005	1166
B1H017	B11_90415	Steenkoolspruit	-26.31	29.27	02/01/1990	17/06/2008	846
B1H018	B11_90416	Olifants	-26.22	29.46	27/05/1991	17/06/2008	634
B1H019	B11_90417	Noupoort	-25.94	29.26	09/05/1990	20/05/2008	803
B1H021	B11_90419	Steenkoolspruit	-26.14	29.27	02/07/1990	17/06/2008	750
B2H003	B20_90433	Bronkhorstspruit	-25.80	28.74	03/05/1983	21/05/2008	589
B2H004	B20_90434	Osspruit	-25.92	28.59	27/10/1984	21/05/2008	862
B2H007	B20_90437	Koffiespruit	-25.99	28.66	26/08/1985	21/05/2008	867
B2H008	B20_90438	Koffiespruit	-26.08	28.56	26/08/1985	18/06/2008	536
B2H014	B20_90441	Kromdraaispruit	-25.83	28.88	30/01/1991	18/06/2008	578
B2H015	B20_90422	Wilge	-25.62	29.02	05/01/1994	10/12/2008	769
B2H016	B20_188223	Wilge	-25.58	29.13	18/05/2005	10/12/2008	129
B3H017	B32_90455	Olifants	-25.42	29.36	01/09/1993	22/05/2008	532

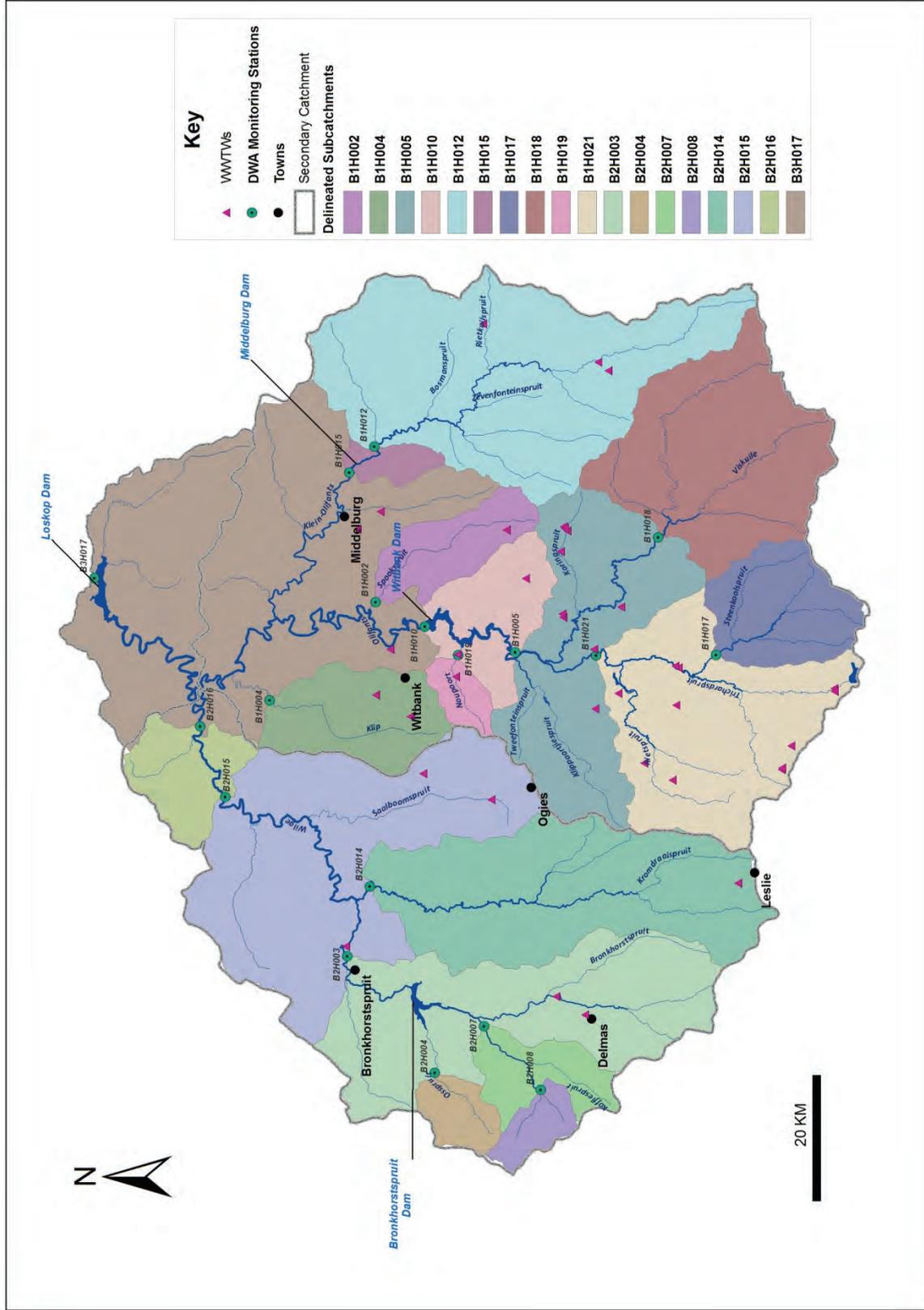


Figure 5.24: Location of DWA monitoring stations and their respective catchment area in the upper Olifants River catchment. The location of waste water treatment works is also indicated.

5.6.2.2 *Land use*

For each monitoring station, the catchment area contributing to the station was delineated using Geographical Information Systems (GIS) and a 30 m Digital Elevation Model (DEM). The purpose of this exercise is to identify the extent of the catchment area that drains into each of the selected monitoring points and identify major land use activities taking place in the sub-catchment. The catchment extent of each of the monitoring stations is indicated in Figure 5.249. Using the delineated sub-catchment map and GIS, it was possible to quantify the relative proportion of each of the major land cover categories falling within each sub-catchment. A map of the land cover categories per catchment is provided in Figure 5.25. The entire catchment is dominated by agriculture and natural land cover (Table 5.8). Mining covers just over 2% of the total surface land cover. Within each of the sub-catchments, there is variation within the different land cover categories. The Noupoot and Klipspruit catchments have relatively high urban land coverage, while the Spookspruit, Klipspruit and Steenkoolspruit catchments show the highest percentage mine coverage. Plantations are clearly a minor contributor to the total land coverage of the upper Olifants catchment.

5.6.2.3 *Calculation of loads*

Annual phosphate loads were calculated for each monitoring station using the FLUX32 (Walker, 1996) programme. FLUX was designed for estimating constituent loads from intermittent water quality (DWA, 2011a) and continuous flow data (DWA, 2011b) using a multiple regression modelling approach. An average annual load was calculated for reach station for the period 2004 to 2008. Only recent data was used so as to reflect the most recent land management patterns in the catchment. At the time of analysis complete data was only available up until the end of 2008.

5.6.2.4 *Total export coefficients*

Mean annual total phosphate export coefficients (kg/ha) for each catchment were calculated by dividing the load (kg) by total catchment area upstream of the monitoring point. As forest plantations, bushveld, bare rock and degraded land form a small proportion of the overall land use (particularly for catchments that were included in the regression analysis) and are therefore not expected to contribute significantly to phosphate loads, they were excluded from the analysis of land use specific coefficients. Thus phosphate coefficients were determined for grassland, agriculture, urban and mine land cover categories only. To isolate the loading contribution of different sources from these heterogeneous catchment areas, multiple regression techniques were used to develop the phosphate export coefficients for the major land cover categories (McFarland and Hauck, 2001). The independent variables were the fraction of the drainage area above each site represented by each land cover category (Table 5.8), while the dependent variable was the

average annual ortho-phosphate coefficient at each site (Table 5.9). The coefficients from the resulting multiple regression models define optimized export coefficients across all sites for each land cover category for the time period evaluated. All multiple regression models were developed using a forced zero intercept, thus, giving a loading of zero when all independent variables equal zero. Not all monitoring points were included in the calculation of land use specific coefficients. Sites B1H005, B1H012 and B1H021 were excluded from the regression analysis as these sites are likely to be heavily impacted by point source phosphate discharges from STWs in their respective catchments (Figure 1). Sites B1H010, B1H015, B2H003 and B3H017 were also excluded as these sites are directly below large dams which are all flow regulated and also act as sinks for nutrients. Finally B2H015 was also excluded as flow data from this station was found to be incomplete and inaccurate. For each catchment, total phosphate loads were calculated using the total area of each land cover category (ha) and the calculated ortho-phosphate export coefficients for the land cover category (kg/ha). These were compared to mean annual measured phosphate loads for each site.

A number of sites were not included in the regression analysis and were used in an attempt to test predicted loads against measured loads for validation purposes. These sites were B1H017, B1H018, B2H007 and B2H008. Furthermore, as mentioned above, other sub-catchments not included in the model regression included those below dams and those which contained a relatively high number of STWs. Considering that export coefficients predict nonpoint source pollution it would be expected that catchments containing a high number of STWs would be under predicted by export coefficients and sites downstream of dams would be over predicted by export coefficients (due to retention of nutrients in the dam). These broad patterns were also used to determine whether application of the derived export coefficients provided realistic results in predicting phosphate loads.

5.6.2.5 Uncertainty

The standard error associated with the calculated phosphate export coefficients for the land uses represent a range of potential values. These ranges per land use were used in a Monte Carlo analysis so as to determine the uncertainty associated with phosphate loadings per land use category. The export coefficients were allowed to vary randomly within a range defined by the standard error for each land use. The ranges were not allowed to go below 0 as it was assumed that no land use would result in a negative loading of phosphates. Ten thousand simulations were performed using export coefficients that were generated using a random number generator (Excel). For each simulation the load contribution by each land use by kilogram and percentage was calculated. The outputs of the simulations were used to calculate the mean and standard deviation of phosphate loads in kilograms and as a percentage. This analysis was performed for the catchment outlet (B3H017) as well as the lowest monitored points for main contributing catchments (i.e. the Klein-Olifants [B1H012], the Olifants [B1H005] and the Wilge [B2H015] catchments). This enabled a relative comparison of major contributing land uses to ortho-phosphate loading per main sub-catchment.

5.6.3 Results

5.6.3.1 Land Use

Analysis of land use area revealed variation within the different land cover categories across sub-catchments. Sub-catchments located high up in the catchment are comprised predominantly of

grassland and agriculture (i.e. B1H017, B1H018, B2H007, B2H008). Mining and urban land use becomes more prominent in the middle reaches of the catchment. B1H019 and B1H004 catchments have relatively high urban land coverage and, together with B1H002 and B1H021, also have relatively higher area under mining in comparison to other catchments. Plantations are clearly a minor contributor to the total land coverage of the upper Olifants catchment. STWs are located throughout the catchment, with B1H005, B1H010, B1H021 and B2H003 having particularly high numbers in relation to the catchment area (Figure 1). B1H002, B1H017, B1H018, B1H019, B2H004, B2H007 and B2H008 contain no STWs and B2H014 contains only one STW in relation to a large catchment area.

Table 5.8: Catchment area and proportion of land coverage category draining into DWA monitoring stations in the upper Olifants River catchment.

DWA Flow Gauge Station ID	Area (km ²)	% Land Coverage					
		Grassland	Bushveld	Plantations	Agriculture	Urban	Mines
B1H002	224	55.8	0.2	0.8	34.4	0.4	8.4
B1H004	341	53.4	5.2	4.4	19.8	8.9	8.4
B1H005	2964	49.5	0.2	0.1	45.9	0.6	3.6
B1H010	3244	49.9	0.2	0.1	43.9	0.7	5.1
B1H012	1437	48.5	0.1	1.0	46.8	0.7	2.9
B1H015	1507	48.9	0.1	1.0	46.6	0.7	2.8
B1H017	361	56.0	0.0	0.0	44.0	0.0	0.0
B1H018	905	52.0	0.0	0.1	47.6	0.0	0.2
B1H019	72	45.7	0.1	2.5	24.5	13.2	13.9
B1H021	878	50.5	0.1	0.0	44.0	1.4	3.9
B2H003	1425	50.9	4.7	2.3	39.1	2.6	0.5
B2H004	115	55.6	8.7	7.5	26.9	0.1	1.2
B2H007	201	47.0	4.7	2.4	41.0	4.8	0.0
B2H008	97	44.2	4.3	0.9	48.7	1.9	0.0
B2H014	1055	46.3	4.8	0.8	47.1	0.7	0.4
B2H015	3810	48.9	4.7	1.7	42.5	1.8	0.5
B3H017	11497	49.5	8.3	1.2	36.6	1.6	2.8

5.6.3.2 Ortho-phosphate Loads

There is clearly a large amount of annual variation in ortho-phosphate loads at monitoring sites (as indicated by the standard deviation values), which is almost certainly as a result of variation in rainfall and flow conditions experienced from year to year (Table 5.9). In terms of mean annual load contributions from the tributaries, the Steenkoolspruit (B1H021) is the largest contributor of ortho-phosphate to the Olifants River. This translates into a very high total ortho-phosphate export coefficient for this catchment. B1H019 and B1H004 catchments, both of which have a relatively high proportion of urban land use, also have relatively high ortho-phosphate export coefficients (0.023 and 0.021 kg/ha, respectively).

Table 5.9: Total mean annual phosphate loads of major tributaries flowing into the mainstem Olifants River upstream of Loskop Dam.

DWA Flow Gauge Station ID	Flow (m ³ x 10 ⁶)	kg/yr	kg/ha/yr
B1H002	17 (± 5)	256 (± 188)	0.012 (± 0.008)
B1H004	44 (± 9)	622 (± 282)	0.0219 (± 0.009)
B1H005	187 (± 60)	6212 (± 8898)	0.021 (± 0.03)
B1H010	176 (± 63)	7853 (± 6135)	0.024 (± 0.019)
B1H012	77 (± 26)	2287 (± 1773)	0.016 (± 0.012)
B1H015	69 (± 27)	1482 (± 1700)	0.01 (± 0.011)
B1H017	37 (± 11)	1861 (± 1716)	0.052 (± 0.047)
B1H018	56 (± 19)	328 (± 285)	0.004 (± 0.002)
B1H019	7 (± 1)	159 (± 47)	0.023 (± 0.007)
B1H021	64 (± 17)	6825 (± 3410)	0.055 (± 0.028)
B2H003	49 (± 23)	817 (± 1004)	0.006 (± 0.007)
B2H004	5 (± 1)	148 (± 82)	0.013 (± 0.007)
B2H007	14 (± 5)	226 (± 150)	0.008 (± 0.005)
B2H008	3 (± 1)	35 (± 28)	0.004 (± 0.003)
B2H014	52 (± 17)	1422 (± 1231)	0.014 (± 0.012)
B2H015	72 (± 14)	2060 (± 729)	0.005 (± 0.002)
B3H017	530 (± 206)	7767 (± 10396)	0.007 (± 0.009)

The results of the multiple regression analysis are summarized in Table 5.10. The multiple regression models for each constituent were highly significant ($p = 0.003$ and $R^2 = 0.87$). In addition coefficient values for each of the individual land use variables were highly significant. This indicates that the land categories used as independent variables explain a large proportion of the variability in phosphate loadings and that the specific contribution from each land cover category was statistically defined as significantly different from zero.

Table 5.10: Phosphate export coefficient (kg/ha/yr) estimates for land cover categories using a zero-intercept multiple regression model for the period 2000-2008 in the upper Olifants River catchment.

Land Cover	Export Coefficient	
	(kg/ha/yr)	p-Value
Agriculture	0.015 (± 0.0004)	0.0173
Grassland	0.011 (± 0.0003)	0.0171
Urban	0.053 (± 0.001)	0.0170
Mining	0.044 (± 0.002)	0.0217

In general there was a very good correlation between measured and predicted values for the DWA stations included in the model regression ($R^2 = 0.79$), indicating that the applied export coefficients

were capable of estimating relative differences in phosphate loading between sub-catchments Table 5.11.

Table 5.11: Predicted and measured annual phosphate loads (and estimated percentage contribution from important land cover categories) for monitoring stations in the upper Olifants River catchment.

Monitoring Station	Measured (kg)	Predicted (kg)		% Contribution per Land Use			
				Grassland	Mining	Agriculture	Urban
Stations used in regression							
B1H002	256	362	79	5.9	26.0	66.1	2.0
B1H004	622	631	5	5.1	23.3	34.1	37.5
B1H019	159	179	40	3.1	27.4	30.0	39.5
B2H004	148	125	1	9.6	6.1	83.3	1.0
B2H014	1422	1347	-2	5.0	1.1	90.8	3.2
Test Stations							
B1H017	1861	478	-74	6.6	0	93.4	0
B1H018	328	1188	262	5.7	0.7	93.4	0.2
B2H007	226	416	84	4.7	0.1	73.9	21.3
B2H008	35	127	263	6.6	0	93.4	0
B2H015*		3224		25.3	0.7	65.9	8.2
Stations downstream of STWs							
B1H005	6212	4444	-28	4.9	10.5	81.8	2.8
B1H012	2288	2050	-10	23.8	4.1	69.0	3.0
B1H021	6825	1376	-80	5.0	11.2	77.8	6.1
Stations below dams							
B1H010	7853	5033	-36	4.9	14.6	77.4	3.1
B1H015	1482	2144	45	4.9	8.2	83.9	3.0
B2H003	817	1877	130	5.8	1.8	79.7	12.8
B3H017	7767	15431	99	5.8	9.3	76.5	8.4

Very good predictions were estimated for B1H004, B2H004 and B2H014. Measured loads were over predicted by export coefficients at other sites included in the regression analysis. Stations that were not included in the model regression were generally not well predicted by the derived export coefficients. Stations downstream of STWs were all under estimated by predicted values. In contrast, all sites located below the large dams (with the exception of B1H010) all showed predicted values considerably higher than mean annual measured values. Apart from highly urbanised and mined catchments (e.g. B1H002, B1H004 and B1H019), agricultural land use was the largest contributor to phosphate loading in all catchments.

This trend was confirmed with respect to total orthophosphate loading at the catchment outlet (B3H017), which showed agriculture to be the largest source of ortho-phosphate (44%). Grassland (comprising 50% of the total land area) is responsible for approximately 39% of total ortho-phosphate loading. Urban land use, while comprising only 1.6% of the total catchment area is responsible for 7% of the total loading. Mining contributes relatively high proportions of total loading in the Olifants catchment upstream of Witbank Dam. In the Klein-Olifants and Olifants catchments, (upstream of Middelberg and Witbank dams, respectively) mining resulted in ortho-phosphate loading comparable to that derived from grassland. The Wilge River received

comparably lower loads from mining, while urban land use comprised 8% of total loading. Uncertainty in relation to loading predictions for all land uses was relatively low (as reflected by the low standard deviation).

Table 5.12: Simulated phosphate loads by land use for the Klipspruit (B1H004) and upper Klein-Olifants (B1H012) catchments using Monte Carlo techniques.

Land Use	Contribution (kg/yr)		Contribution (%)	
	Mean	Stdev	Mean	Stdev
B1H005 – Olifants				
Grassland	1486	146	35	2.25
Mining	499	13	17	0.44
Agriculture	2144	33	51	1.79
Urban	107	1	3	0.09
B1H012 – Klein-Olifants				
Grassland	685	68	35	2.29
Mining	189	5	10	0.41
Agriculture	1027	15.8	52.6	1.88
Urban	53	0.58	3	0.1
B2H015 – Wilge				
Grassland	1181	117	39	2.39
Mining	51	1	2	0.08
Agriculture	1594	24	52	2.04
Urban	234	3	8	0.31
B3H017 – Olifants				
Grassland	5666	559	39	2.36
Mining	1441	38	10	0.44
Agriculture	6504	101	44	1.75
Urban	1032	11	7	0.28

5.6.4 Discussion

There is a large amount of inherent variability in environmental and land management factors that influence the movement of phosphate into surface waters. Crop type, fertilizer management practices and stocking density of livestock are all examples of land management decisions that influence the amount of phosphorous added to different land use types (Sharpley et al. 2000), while slope, soil and rainfall characteristics and the integrity of riparian buffer zones (Borin et al. 2005) all influence the extent to which added phosphorus is able to move off of the land into adjacent water resources. All these factors vary considerably across a catchment as large as the upper Olifants and there is therefore a high amount of uncertainty associated with the use of export coefficients, as highlighted by the large differences between measured and predicted loads for some of the catchments (Table 4). Due to the high uncertainty associated with export coefficient calculations, regionally specific estimation of export coefficients is recommended due to the limited transferability of export coefficients across large geographical areas encompassing a high degree of variation in environmental conditions and land management practices (Clesceri et al., 1986, Wickham, 2006). It is for this reason that export coefficients should always be used as a relative, spatial indicator of land use activities and catchments responsible for high loading as opposed to an absolute quantitative predictor of phosphate loading. One of the major advantages of the

approach adopted in this study is that it can be relatively easily applied in multiple catchments so as to gain catchment specific coefficients that take local climate, soil conditions and agricultural practices into account. For example the export coefficients derived for an agricultural land use activity (dominated by maize in the Highveld) is likely to be quite different from an export coefficient derived in a similar land cover category (dominated by sugar cane) in KwaZulu-Natal. Given the multiple number of factors that influence nonpoint source pollution, the uncertainty analysis is useful in that it takes the variability of the export coefficients within land uses into account, without the expense and time of collecting additional data (McFarland and Hauck, 2001).

The catchment specific total export coefficients compare well with those calculated for other catchments in South Africa (Engonge and Rossouw, 2007). It is more difficult to determine the reliability of the land use specific coefficients as most studies locally and internationally report values for total phosphate and not for ortho-phosphate (or soluble reactive phosphate). However, the relative difference in export coefficients presented in this study is in agreement with those reported locally (Dickens et al., 2010) and internationally (Hilton et al., 2002). The analysis identified urban areas as having the highest export coefficients followed by mining and agriculture. Studies generally find urban land use to have amongst the highest export coefficients, due to the high level of imperviousness, facilitating rapid runoff of nonpoint soil bound phosphorus as well as due to point source effluent discharges (Dickens, et al., 2010, Easton Zachary and Petrovic, 2008). Agricultural land use activities are well known for their input of phosphates due to application of organic and inorganic fertilizers to improve crop yields (Kronvang et al., 2005). The upper Olifants catchment is an important coal mining area and studies have linked nonpoint source phosphate pollution with coal mining (Trew et al., 1990). Phosphate occurs naturally in the soil and open cast mining and associated rock piles in particular leads to the exposure of this phosphate to weathering and erosion processes leading to increased input into water resources (Carpenter et al., 1998). The high export coefficients observed in this study may also be linked to high concentrations of sulphate that occur in surface waters of the catchment. Sulphate concentrations are elevated as a result of the intensive coal mining in the catchment (De Villiers and Mkwelo, 2009). Sulphate has been shown to stimulate the release of sediment bound ortho-phosphate into surface waters (Zak et al., 2006). Grasslands in the upper Olifants catchment are typically used for grazing, which is generally associated with lower phosphate inputs in comparison to other land uses considered here (Dickens et al., 2010).

In general, the export coefficients and the comparison of predicted to measured loads provided realistic indications of phosphate sources and catchment processes. Poor comparisons between measured and predicted loads could largely be explained by factors other than nonpoint source pollution. For example, the fact that measured loads were always lower than predicted loads at the outlets of dams is a realistic representation of nutrient entrapment in the dams. The export coefficient model does not take this process into account and it would be expected that measured values would be lower than predicted values at dam outlets. The fact that B1H010 showed higher loads than predicted may be indicative of the fact that the Naauwpoort STW discharges almost directly into the Witbank Dam.

The discrepancy between measured and predicted loads at other catchments (i.e. B1H021 and B1H005) is useful in terms of highlighting catchments for more intensive scrutiny or identifying the existence of a point source or land use activity that may be contributing higher than expected loads. This is clearly illustrated at B1H021, where predicted values were considerably lower than measured values. Measured values clearly indicate that this catchment is responsible for very high phosphate loading. This is not predicted by export coefficients alone and the difference is most

likely attributable to the large number of point source STWs in the catchment, all of which are not operating to acceptable standards (DWA, 2011a). A similar case can be made for B1H005. This discrepancy further emphasises the application of export coefficients which is to identify nonpoint sources of pollution. A good understanding of the contribution of point sources is therefore important with respect to interpreting outputs from export coefficient modelling exercises. This example also serves to illustrate the value of utilising measured data in combination with modelled data. The measured loads provide an accurate assessment of total load contributions (therefore prioritising high loading catchments, such as B1H021) and application of the export coefficients provides an added level of detail in terms of likely sources of the pollutant (e.g. discriminating between point and nonpoint sources of pollution and/or identifying land uses of concern). However, the main intention of export coefficients is to provide an indication of loading without having to rely on measured data. In this respect measured annual loads across all monitoring points correlated well with predicted loads calculated from the derived export coefficients. This indicates that the derived export coefficients and associated phosphate loading at each site provided a good relative indication of phosphate loading amongst the catchments. This indicates that the coefficients can be used to identify both land uses as well as catchments responsible for high loading.

Apart from B2H014, most sites used in the regression model were over predicted. This is to be expected as the model will not take in-stream processes that naturally attenuate phosphate loads over large distances into account. In smaller catchments (B1H019 and B1H004) the difference between measured and predicted values was much less. The high variation between measured and predicted loads at B1H018 and B2H008 may indicate the presence of a point source that was not detected in this study or the presence of a land use activity (i.e. feedlots) that was not identified by the land cover data used in this study. In this context it is important to note that a land cover (i.e. agriculture) does not accurately reflect land use (i.e. land management practices that may be occurring on a land cover type) and also highlights the importance of having a good understanding of the location of point sources or land use activities that may not be 'interpreted' by the land cover maps.

5.6.5 Conclusion

The multiple regression approach used for determining nutrient export coefficients maximizes the use of in-stream flow and water quality data from stream sites with heterogeneous land-use drainage areas within a monitoring network without the need for isolating individual land uses (McFarland and Hauck, 2001). In doing so the method integrates variation in catchment and land management characteristics (e.g. weather conditions, soil types, planting and harvest dates, fertilizer management, slopes, tillage practices, and proximity to streams) to provide export coefficients representative of average conditions at the scale of the entire catchment. Developing coefficients at a smaller scale single land use catchment areas will not necessarily account for this variation, potentially resulting in greater uncertainty when scaling up to larger catchment areas. Export coefficients are indicative of the climatic conditions under which the monitoring data were collected (McFarland and Hauck, 2001). The fact that monitoring data collected over a five year period was used is likely to result in export coefficients that are representative of a range of weather conditions (e.g. seasonal rainfall and annual wet and dry years), and are typical of average nutrient contributions, and are not skewed towards extreme dry or wet periods. An added advantage of the approach adopted here is that uncertainty related to the use of export coefficients can be quantified (Table 5) which enables users to define a range of loading estimates (thereby

accounting for uncertainty) as opposed to single estimates of loading. While export coefficients do not indicate the specific geographical drivers or land management practices causing surface runoff and pollutant transport, they can be used to identify dominant land uses and/or catchments that result in a proportionally high contribution of nutrient loading to the system. This information can further serve to identify appropriate management practices that could potentially reduce nonpoint source pollution in problem areas.

5.7 BAYESIAN DECISION NETWORKS – DECISION MAKING IN THE UPPER UMNGENI

5.7.1 Introduction

“Sherlock Holmes closed his eyes and placed his elbows upon the arms of his chair, with his fingertips together. ‘The ideal reasoner,’ he remarked, ‘would, when he had once been shown a single fact in all its bearings, deduce from it not only all the chain of events which led up to it but also all the results which would follow from it. As Cuvier could correctly describe a whole animal by the contemplation of a single bone, so the observer who has thoroughly understood one link in a series of incidents should be able to accurately state all the other ones, both before and after.’”

Sir Arthur Conan Doyle – Adventures of Sherlock Holmes: The Five Orange Pips

Water resource management is complex, involving multiple stakeholders and numerous cause-and-effect variables. Typically, stakeholders seeking maximum allocation of a limited resource in a multi-stakeholder environment resort to competitive behaviour in securing their portion of this resource, which is typically less than equitable for downstream users. These are often reactive, crisis-driven approaches, when what is ideally required is a co-operative, creative process where all stakeholders are given the opportunity to jointly define a vision and participate in a problem-solving process (Senge, 2009).

Even assuming problem solving occurs in a co-operative environment, solving such puzzles in the absence of suitable conceptual tools is sub-optimal because typically human short-term memory can only consider up to seven points (Bacon et al., 2002). Additionally, management plans often fail as they are developed without participation of local individuals (Cain et al., 2000). It is becoming increasingly obvious that stakeholder participation is critically important in successful water resources management (Zorilla et al., 2010). Even with these pitfalls catered for, scientific knowledge forms only a small component of available knowledge from stakeholder groups (Smith and Bosch, 2004), with decisions based on perceptions rather than absolute reality (Zorilla et al., 2010).

Increasingly, looking at alternatives to deterministic models to inform decisions is enabling a more creative approach to solving complex problems in connected systems. For example, graph theory has been applied to solve riverscape conservation issues (Erős et al., 2011). Suitable tools which involve stakeholders in a creative discussion process, and which enhance capacity to consider complexity are required (Cain et al., 2000; Zorilla et al., 2010), which graph theory on its own does not cater for.

Key when choosing such tools is their capacity to capture perceptions, and utilise non-scientific information in a structured, logical form. One approach which has been used extensively in solving complex IWRM problems is the use of probabilistic networks and belief systems. “Probabilistic networks are graphical models of (causal) interactions among a set of variables, where the

variables are represented as vertices (nodes) of a graph and the interactions (direct dependences) as directed edges (links or arcs) between the vertices” (Kjaerulff and Madsen, 2008). Probabilistic networks are a compact representation of inter-causal relationships, and a “clever graphical representation of dependence and independence relations between random variables. A domain of random variables can, for instance, form the basis of a decision support system to help decision makers identify the most beneficial decision in a given situation” (Kjaerulff and Madsen, 2008).

Belief systems allow users to estimate the probability of a management intervention having a particular effect and a level of confidence associated with this. One type of belief system which has gained prominence in environments of taking decisions under uncertainty has grown out of a clergyman’s published theorem which remained obscure for over a century

5.7.2 Bayesian Decision Networks

Thomas Bayes (ca. 1702-1761) was an English clergyman from Tunbridge Wells in Kent, England, who derived a formula for finding inverse probabilities (the probability of “the other way around”), which formed the basis for conditional probability theory (Crilly, 2007, Bryson, 2010). Baye’s Theorem provides a tool for working out complex problems using observations and partial information, from which reliable statistical distributions can be derived. This theorem largely came of age in recent decades with the development of computers, and has been used in modelling climate change, predicting the behaviour of stock markets, business analyses, fraud detection management, and medical diagnoses (Kjaerulff and Madsen, 2008; Bryson, 2010).

Bayesian theory is sometimes at odds with traditional statistic theory (“frequentists”), where probability is based on hard numerical data. Frequentists define probability using confidence intervals (typically $p < 0.1$) and based on frequencies of an event occurring after an experiment has been repeated many times. Conversely, Bayesians link probability to a subjective statement about how likely an event is to occur. The advantage of the Bayesian approach is that degrees of belief can be assigned to causes based on observations of effects. The higher the number of observations, and the more that is known about the causes, the greater becomes the confidence in the belief.

Bayesian networks (BNs) and inference diagrams are ideal knowledge representations for use in many situations involving reasoning and decision-making under uncertainty (Kjaerulff and Madsen, 2008). BNs provide a method of representing relationships between variables, even if the relationships involve uncertainty, unpredictability or imprecision (Batchelor and Cain, 1999). They are also viewed as a strong tool for visualising complexity and engaging stakeholders (Zorilla et al., 2010), being useful in many levels, including the following:

- Coherent and mathematically sound handling of uncertainty;
- Intuitive and compact representation of cause-and-effect relationships (i.e. inter-causal inference);
- Efficient solution of queries given evidence.

5.7.2.1 *Links between land use and water quality*

The complexities of resolving water quality issues in South Africa’s rivers, in spite of relatively good knowledge on the science and data of water quality, continue to hamper solving the problems. This is in spite of a growing urgency to do so. Indeed, theuMngeni River has been identified as a

system whose water quality poses potentially serious health risks to people and agriculture (CSIR, 2010). In a recent report-back to South Africa's parliament on water quality, the uMngeni River was singled out as a system with high phosphate levels due to "poultry farms, effluent from cattle feedlots and informal settlements without sanitation facilities" (Anon., 2011). Implicit in such statements are ingredients for considerable finger-pointing, denials, and ultimately, inaction and complacency, followed by reactive management in response to a crisis.

The upper uMngeni catchment has been subject to human activity since at least the 15th century, when black pastoralists lived in the area. From 1850, white farmers settled the area (Moll, 1965). Since the most extensive natural climax community in the catchment is *Themeda triandra* grassland, which is noted for its good grazing (Moll, 1976, van Oudtshoorn, 1992), agriculture became the dominant land use. By 1970 dairy dominated as the key agricultural activity (Scotney, 1970). While wetlands were historically a notable feature, together with considerable freshwater resources, there has been a slow attrition of wetlands over time, due to increased land use pressures. Accompanying the loss of wetlands has been a decrease in grassland area, and a concomitant increase in crop land and a remarkable 388% increase in afforestation area between 1944 and 1996 (Rivers-Moore, 2007). In many grasslands, *T. triandra* has been replaced by the secondary grass *Aristida junciformis* due to poor management in areas of the catchment (Moll, 1965). This grass is an indicator of overgrazed veld with very low grazing value (van Oudtshoorn, 1992).

Between 1944 and current, other notable transformations have included construction of a golf course and quarry. Mpophomeni township and Midmar Dam were both active from 1963, and the catchment has undergone increasing fragmentation (Rivers-Moore, 2007). Accelerated land use change, with concomitant water quality impacts, is inevitable. These trends are borne out by the number of applications for development in the area in the past decade. Between 1999 and 2010, a total of 337 Environmental Impact Assessment Applications were received by the uMngeni Municipality alone (Kallicharan, 2010). In assessing these, applications which considered a change in land use were assessed, and the biggest change was from agricultural to residential land (49%), with agriculture to tourism accounting for 18% of EIAs assessed. Linked to this is a burgeoning tourism industry (ca. 2500 recorded visitors to the Howick falls each month, and up to 25% being foreign – Haynes, 2011) which feeds into a growing bed-and-breakfast market, and a growing demand for residential land. Many of the proposed developments were centred along road networks and adjacent to the main water reservoir in the upper catchment (Midmar Dam). A gradual attrition of agriculture and dairy farms to other types of land use has culminated in a situation of cumulative housing developments (low-income and luxury) whose waste-water contributions far exceed the existing capacity of the current WWTW infrastructure.

5.7.2.2 Research context and aim

The aims of this research were twofold, viz. firstly to develop a Bayesian decision network for key variables affecting water quality in the upper uMngeni catchment, and focussing on the area around the Mpophomeni township. Secondly, to demonstrate the use of a BDN as a management tool, which could be adopted for facilitating negotiations between various stakeholders represented by a Catchment Management Forum (CMF); as such, the "client" would be the CMF.

5.7.3 Methods

5.7.3.1 Study Area

The general study area fell within primary catchment U, and covered the upper three quaternary catchments (U20A-C) (Figure 5.26) of the uMngeni River. This largely corresponded with the area represented by the upper uMngeni Catchment Management Forum. Moll (1965) described the catchment topography as “open with rolling, grass-covered dolerite-capped hills, occasional steep valleys and broad, flat plains”. The nature of the landscape limits intensive agriculture (Scotney, 1970), but favours extensive agriculture. The area is drained by the uMngeni River, with its main tributaries the Lions River and Dargle Stream. Catchment U20C is dominated by Midmar Dam, which is largely fed by the uMngeni River, although smaller tributaries in the south-east (Gqishi, Nguklu and Mthinzima Rivers) fall within smaller subcatchments and drain into Midmar Dam. Land use generally consists of a mix of forestry and agriculture (mixed crop cultivation and stock farming – poultry, dairy and piggeries), with extensive areas of grassland and natural vegetation (non-grassland Mistbelt mixed *Podocarpus* forest, bushland and woodland). Derivation and calculation of land use categories and areas is described in a subsequent section. The abundance of dolerite in the catchment, and associated dykes, together with a high rainfall (Scotney, 1970), explains the large number of wetlands in the catchment.

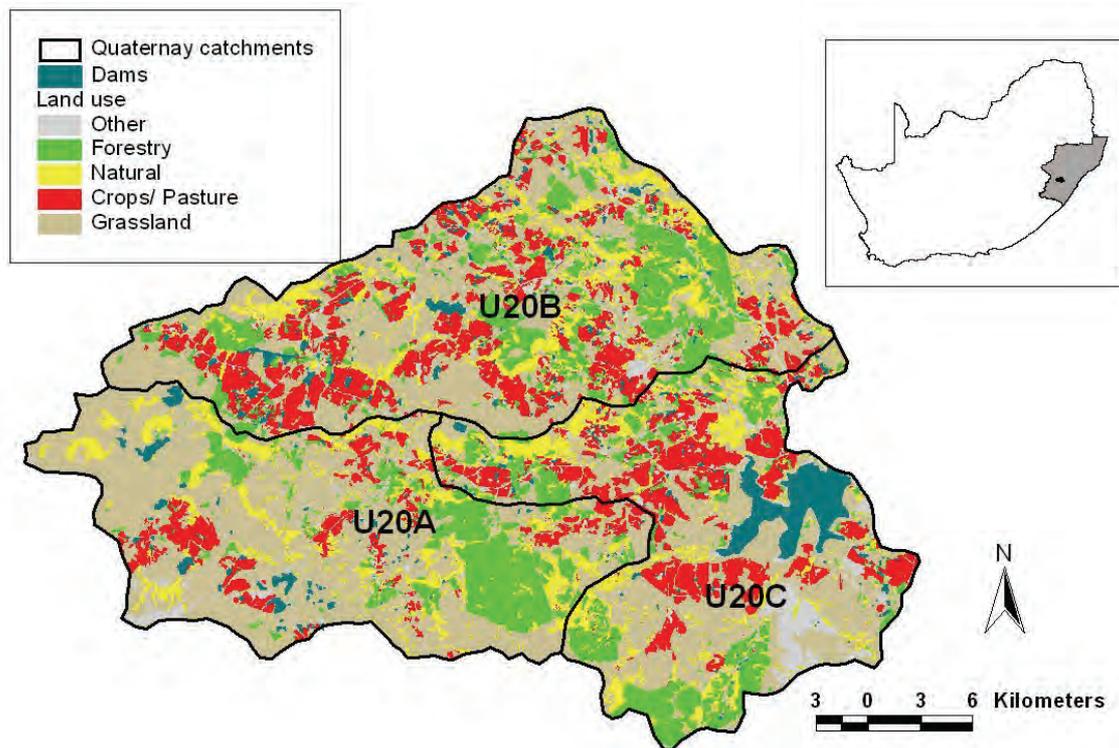


Figure 5.26: General study area, showing the three upper quaternary catchments of the uMngeni River.

After considerable discussions with various stakeholders (see subsequent section) it was decided to focus on catchment U20C to test the development and applicability of a Bayesian decision network (Figure 5.27). This catchment represents, albeit more intensely, many of the same water quality issues occurring in the rest of the upper uMngeni catchment area. Of the various input

points going into Midmar Dam, the Mthinzima River has the highest concentration of pollution loads (nitrates, phosphates and *E. coli*). Calculated as a pollution load (i.e. taking into account catchment area and flow volume), the relative contribution of the Mthinzima stream is reduced, but remains high (GroundTruth, 2012b). Present in the study area are rural and urban settlements (current and proposed), agriculture (dairy, piggeries and poultry), and a large number of wetlands. Issues and stakeholders are described in more detail in the next section, and in the results.

5.7.3.2 Issues and Stakeholders

Engagement with stakeholders and identification of key water quality issues began with, and focussed considerably on, building a relationship with members of the Upper uMngeni Catchment Management Forum. CMFs are facilitated by the Department of Water Affairs, through provision by the 1998 SA National Water Act. These forums are in place to facilitate information and feedback to community and stakeholders, and provide a platform to discuss catchment-related issues. Members of the upper uMngeni CMF include, inter alia, individuals from NGOs (Dusi-Mngeni Conservation Trust DUCT; Crane Foundation), community members from urban and rural areas, Umgeni Water, various conservancies, residents associations, and farmers.

Thus far three meetings have been attended (February, 26th May and 24th November 2011), where presentations and an interactive exercise have been undertaken as part of the Agenda of the February and November meetings, under the heading “Changing the thinking in how collective decisions about integrated water resource management are made”. The results of the first presentation and interactive workshop have been described in an earlier deliverable. Many of the key issues were gathered through a process of attending the meetings, and listening to discussions.

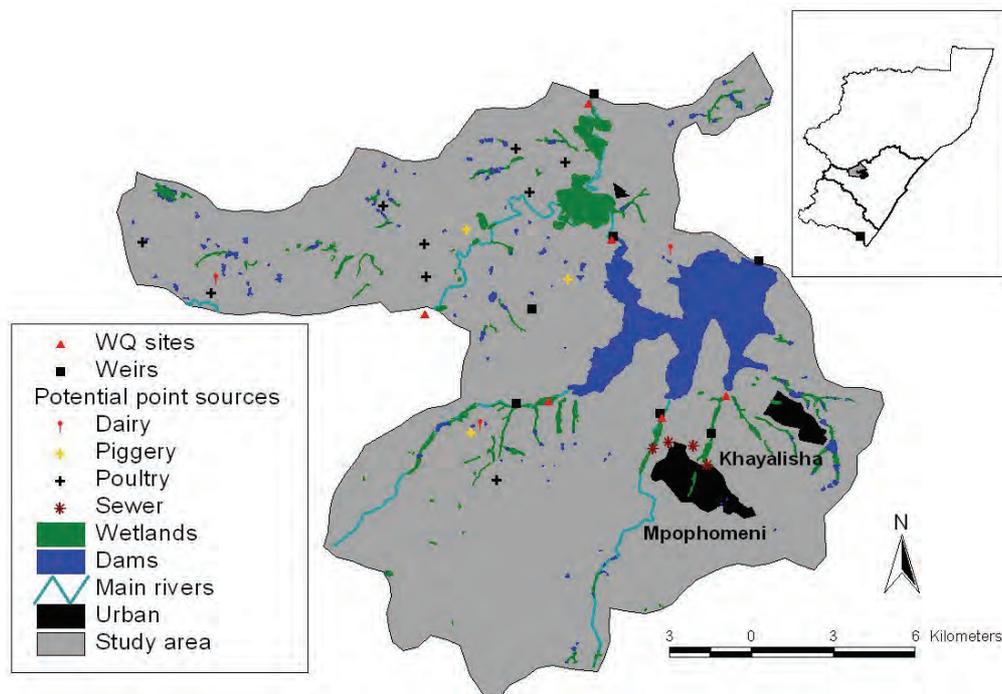


Figure 5.27: Schematic of quaternary catchment U20C, the focal study area, showing salient features used in the development of the Bayesian networks to facilitate water quality decision making.

Further insights on more complex issues were gained from talking to key members of DUCT (Haynes, 2011, 2012; Rees, 2012). A large amount of qualitative information was gathered, recognising that much expert information is available as tacit knowledge. Further information was gathered from popular articles (for example, Coan, 2010) and e-mail transcripts circulated to stakeholders informed by DUCT members (Appendix C).

A deeper understanding on assessment of water quality was provided through discussions with key staff at Umgeni Water (Terry, 2012). Further qualitative assessments were undertaken through a field visit to catchment U20C on 31st January 2012, which included a meeting with a key agricultural sector stakeholder (Crookes, 2012).

5.7.4 Construction of Bayesian Decision Network

5.7.4.1 Definition of variables and states, and critical season

Since Bayesian networks do not have explicit spatial or temporal components, an initial step in constructing a functional network is to understand the critical reason for which it is being developed (Cain, 2001). Flow data for the nearest gauging weir (U2H001) with extensive flow data was used for analyses using the IHA software (TNC, 2006). The baseflow index of the flow data was also calculated using suitable software (Nathan et al., 2007) to provide an indication of the possible relative inputs of surface flows versus groundwater inputs to assess final water quality.

Next, the qualitative component of the Bayesian networks was developed by defining variables and states using an iterative process. Based on the current understanding of the issues in the catchment, variables were defined to represent cause-and-effect issues. Variables were categorised into chance (background, problem, mediating and symptom), decision and utility categories, and states were assigned to each variable. All variables used discrete states, arranged from most positive to most negative. Generally two, but sometimes three, states were assigned to each variable. Nodes were linked in cause-and-effect sequences using appropriate Bayesian software (Norsys, 2010). Development of a Bayesian network was also an iterative process of testing the logic of relationships and keeping the network as simple as possible. In this study, no more than four parent nodes were linked to any child node. This was because the elements of a conditional probability table increase exponentially according to i^n based on number of states (i) and the number of parent nodes (n).

5.7.4.2 Data sources and population of diagram

To quantify the main land uses per quaternary catchment, a 20 m 2005 land cover image was used as the basis for calculating % land cover per category at quaternary catchment scales (EKZMW 2010). This land coverage had 43 categories, some of which were aggregated into broader categories according to Appendix C.

The “quantitative” aspect of building the Bayesian networks, i.e. defining probabilities and populating conditional probability tables, was achieved using a combination of expert knowledge and opinions (qualitative input data) and probabilities calculated from time series (quantitative input

data). For the former approach, probabilities were elicited after discussions with key stakeholders, and numbers assigned based on numbers of belief as illustrated in Figure 5.28.

Probabilities for certain variables (for example, spills, cable theft) were calculated from DUCT reports on water quality from January to November 2011. These were circulated by DUCT as a spreadsheet with the date of a water quality related issue, and the description of the issue. From this information, issues were refined as to whether an “event” occurred, and events were categorised (spill, manhole leak, etc.). From this, return intervals (and hence probabilities) were calculated using the number of events per category, and the number of sites an event occurred at.

Time series data on water quality parameters were obtained for rainfall (Lynch, 2004), and water quality (Terry, 2012). Daily rainfall data were available for the Mpophomeni area (SAWB station no. 239102) for an eight year period from 1 August 1991 to 15 October 1999, for which a return interval for “high” rainfall events (> 3 times the average for overall record length) was calculated. Water quality data (temporal resolution ranged from weekly to monthly to less frequent, and generally for the period 1990-1999/2011) was extracted for six monitoring sites which were selected based on the catchment land uses they represented. Since no single metric on its own provides a reliable estimate of whether water quality is good or bad (Terry, 2012), three metrics were used, viz. *E. coli* count, conductivity and nitrates. Nitrates enter both surface and groundwater as a result of, inter alia, agricultural activities and wastewater disposal. An excess of nitrates in drinking water may cause methaemoglobinaemia in infants (blue baby syndrome) (WHO 2011). Return intervals of exceedances of “reasonable” thresholds for each metric were calculated. (*E. coli* = 1000/100 ml, conductivity = 30 mS/m and nitrates (NO₃) = 6 mg N/l – all as extrapolations of DWAF, 2005 and WHO, 2011). Final probabilities of whether water quality was good or bad per land use was calculated as the average of all three individual probabilities of threshold exceedance.

More complex conditional probabilities were calculated using a CPT calculator in software developed by Cain (2001).

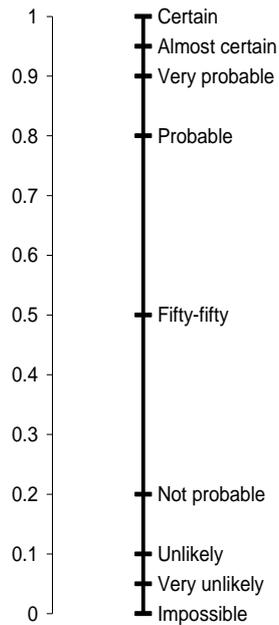


Figure 5.28: Scale bar based on expert opinion and qualitative data for eliciting probabilities (from Kjaerulff and Madsen, 2008 p. 165).

A Bayesian network only becomes a reasoning support system (i.e. a Bayesian decision network) with the addition of decision and utility nodes. In this study, a single decision node was added to include nine possible management actions (from a “Do nothing” to various interventions along a cost gradient). Management categories were defined to capture the value of environmental resilience, role of community organisations and research, as well as management accountability. The relative value of each option was assessed based on arbitrary utility values of 0, 500 and 1000 units for poor, medium and good water quality.

Limited scenarios were assessed based on combinations of states for selected variables and the resultant management scores based on the utility values.

5.7.5 Results

5.7.5.1 Definition of variables and states

All three quaternary catchments generally had similar percentages of land uses, with grassland plus other natural vegetation making up over 50% of each. In U20C as the focal catchment of this study, agriculture made up the most significant secondary land use.

Identification of the critical flow period for the Bayesian network was considered to be when runoff from the catchment was highest, rather than when flows were lowest and dilution capacity was smallest. This decision was made because high runoff was also likely to coincide with high flows having to be processed by the Waste Water Treatment works (WWTW). Forty years of mean daily flow data were assessed for the gauging weir U2H001 (2 December 1948 to 1 December 1988). The time series was split into two unequal parts (1949-1962 and 1963-1989) to compare mean daily flow rates for each month before and after impoundment due to completion of Midmar Dam in 1963. Analyses indicated that the period of highest flows has been delayed by one month, from February until March (Figure 5.29). In this study, the critical season was consequently identified as

February-March. The annual baseflow index (ratio of mean annual baseflow to mean annual flow) of U2H001 = 0.783, which indicates a relatively high dependence on groundwater for the uMngeni River.

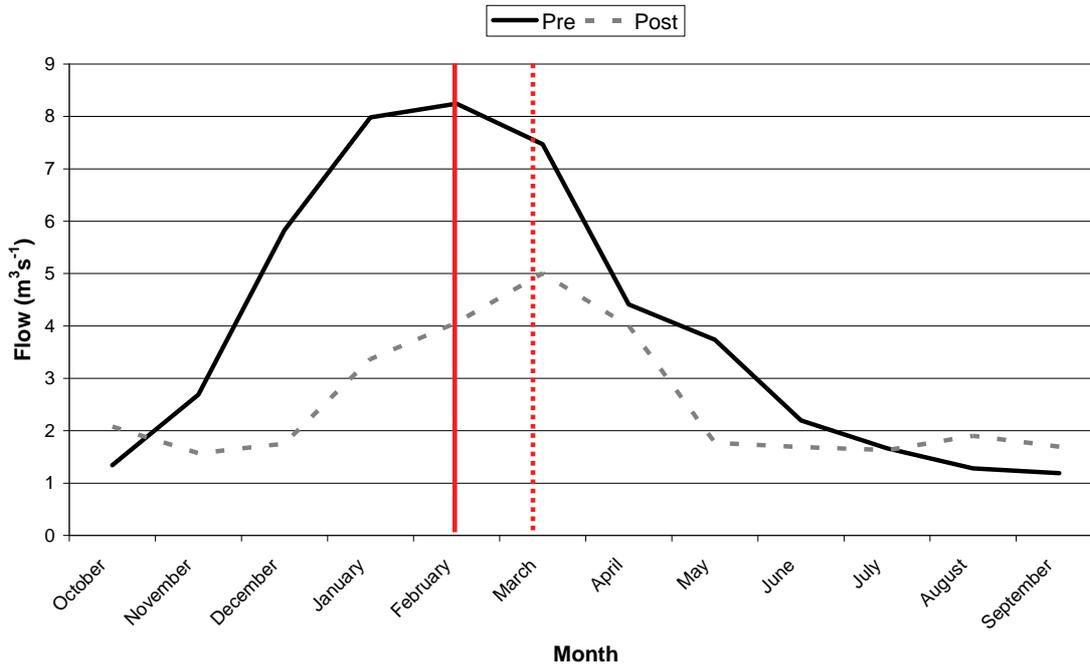


Figure 5.29: Critical flow season for the Mpophomeni Bayesian network, based on analyses of mean daily flows per month for pre- (1949-1962) and post-impoundment (1963-1988) flows for gauging weir U2H001.

Based on discussions with various stakeholders, repeated concerns raised at the Catchment Management forum, themes emerging from DUCT e-mails, etc., the following narratives could be described. They have been grouped into the broad themes below:

Agriculture: Members of the CMF voiced concerns over nitrates and phosphates from agriculture going into rivers. A number of farms with intensive dairy, piggery and broilers (poultry) occur in the catchment. However, excrement waste from these land uses is typically centrifuged, and solid waste is redistributed as fertiliser and liquid waste is transferred to settling ponds before being applied as irrigated fertiliser to crops. Leaking effluent dams represent a loss of income to a farmer, as fertiliser then needs to be bought. Essentially, it is bad farming practice and uneconomical not to see value in feedlot effluent, and desirable to prevent loss of this into water courses. Impacts of forestry on water quality have not been considered in this study.

Current urban areas: The township of Mpophomeni was built on the dairy farm “Rietvallei” (Reed Valley), which was expropriated by the National government in 1963. The original farmhouse “Montrose” remains and is currently where the municipal offices are based. Black people who were forcibly removed from kwaMevana (near Howick) were settled here (Coan, 2010). This township has grown organically, with more formal houses towards the lower part of the catchment, and poorer, less formal houses located in an economic gradient up the catchment. The WWTW was operational from 1991-1999, and effluent is currently pumped via a problematic reticulation system to the Howick WWTW.

Cumulative developments: A large number of individual developments are planned or currently being built in the catchment. It is estimated that a low-income household will discharge 200 ℓ/day of effluent, while a more upmarket household will discharge 700 ℓ/day (Rees, 2012). The general consensus of stakeholders is not so much concern about the impact of each development, but rather the collective impact of all developments taken cumulatively. Of significance to this study are the phased developments of the high-density Khayalisha township, with Phase 1 set to have 500 houses built (estimated 200 ℓ per day per house), and Phase 2 having 1073 units + 43 upmarket houses (200 ℓ and 700 ℓ per day assumed). Another proposed development is the Midmar Cove complex of 45 luxury units at 700 ℓ per day. Concerns relate to the capacity of sewerage plants to handle effluent relative to rates of increase of housing developments. The Mpophomeni WWTW, which is currently de-commissioned and effluent is instead pumped to the over-allocated Howick WWTW, has a capacity of 3.8 Mℓ per day. Assuming that Mpophomeni currently has 6000 registered houses, phased developments conservatively amount to at least ca. 10 and 20% increases from the current situation, and which alone already account for 20% of the non-functional Mpophomeni WWTW capacity.

Waste water treatment works: The aim of this study was not to unpack or describe the complexities of how a WWTW functions. Instead, issues have been identified based on where failure occurs, resulting in water quality problems. Explicitly identified were the danger of power cuts and resultant impacts on sewerage plants. Vandalism and theft of power cables has occurred, leading to failure of pump stations and overflows of sewerage. What occurs more frequently than power failures in causing pump station problems has been inconsistent cleaning of screens which intercept non-liquid matter. Regular problems also encountered with the WWTW are blockages and leaks in the sewer reticulation system due to WWTW functioning beyond capacity or blocked/broken sewer lines as a consequence of vandalism or illegal dumping of unsuitable material into reticulation systems. In many instances overflowing manholes discharge sewage into streams. Households which are not part of the formal reticulation system rely on pit latrines and septic tanks, which cumulatively could lead to groundwater problems. Exacerbating the reticulation and WWTW problems are periods of high rainfall (Müller-Nedebock, 2011).

Miscellaneous environmental issues: Concerns have been voiced over groundwater contamination due to inappropriately placed cemeteries, and leaching from landfill sites (formal and informal). Stormwater pipes which are fed by runoff can also leach into groundwater, or enter sewer reticulation systems. Cumulative developments exacerbate these problems. Random events of spills add to surface water pollution.

Community involvement: Not quantifiable but discussed at the CMF has been the role of “sense of place” in the stewardship of an area. This manifests through local residents participating in community gardens and wetland clean-ups, church groups, and a sense of community. In the absence of municipal management self-regulation and accountability, the chances of outright management failure are reduced through the influence of pressure groups, such as NGOs (DUCT, CMFs). Public awareness and alerting relevant individuals to water quality issues all play some role in reducing the likelihood of reduced water quality.

Management options: Nine management options were identified in this study, ranging from the “do nothing” option, to infrastructural changes, and less quantifiable actions such as the role of community awareness and research in improving water quality. Research at various levels (Kallicharan, 2010; Müller-Nedebock, 2011; Weston, 2010) helps to inform management decisions. Infrastructural changes focussed specifically on the WWTW – build new ones/upgrade/rehabilitate

old plants. It has been estimated that the Mphophomeni WWTW upgrade would cost in excess of R100 million. Management accountability is difficult to measure, but can be facilitated through forums and better communication, audits, prosecution, vision, and co-operation to avoid duplication of effort. Valuing environmental services in improving water quality is achieved through wetland rehabilitation, which builds environmental resilience.

Table 5.13: Land Use categories for three upper quaternaries of the uMngeni River.

	U20A	U20B	U20C
Other	4.03	6.31	13.97
Forestry	13.85	15.33	13.70
Natural	12.85	13.99	13.35
Agric	8.24	20.96	18.37
Grassland	61.03	43.42	40.61

Based on an understanding of the key catchment issues, and desirable versus non-desirable conditions, the qualitative part of developing a Bayesian network was achieved by defining 17 variables with 2-3 states (Table 5.14).

Table 5.14: Categorised variables and states, where all categories excluding Decision and Utility nodes are chance variables.

Variable	States	Category
Cable theft	No, Yes	Background
Cemeteries, location of	Good, Poor	Problem
Dairy/Pig farms	Sealed, Leaks	Background
Environmental resilience	High, Low	Mediating
Groundwater	Good, Poor	Problem
Housing developments	Current, Up 33%, Up 100%	Problem
Management effectiveness	Effective, Not effective	Mediating
Management options	See text	Decision
Rainfall	Low, High	Background
Screens	Cleaned, Not cleaned	Background
Sewer reticulation	Contained, Overflow	Problem
Spill	No, Yes	Background
Stormwater	Contained, Leaches	Problem
Surface water	Good, Poor	Problem
Utility (Benefits)	N/A	Utility
Water quality	Good, Medium, Poor	Symptom
WWTW	Compliant, Non-compliant	Problem

Where:

- **Cable theft:** WWTW pumps cannot function when electricity cables are stolen.
- **Cemeteries:** Badly located cemeteries can result in water quality problems due to leaching into groundwater and/or runoff into streams.

- **Dairy/Pig farms:** This relates specifically to effluent storage dams from dairy or pig feedlots.
- **Environmental resilience:** Defined as the ability of the environment to clean itself, i.e. improved water quality as a result of environmental services provided by ecosystems such as wetlands.
- **Management options:** Nine management options were identified, with the aim of trying to show relevance of direct management interventions, and also to show the value of less measurable but equally important qualitative options. Options were:
 - Do nothing
 - Wetland rehabilitation, to reflect environmental services
 - Increase farm profit, where a less profitable farm will be losing water from a seepage dam, and be having to resort to purchasing fertiliser
 - Community awareness, which has value and creates a channel to put pressure on Municipal managers and to alert people to water quality problems. This is the value NGOs such as DUCT add
 - Research, where applied research can feed into improved management decisions
 - Community awareness + Research, where the combination of the abovementioned variables is synergistic
 - Management accountability, where consequences for good or bad management decisions are reflected in the quality of water
 - Upgrade WWTW, as the most expensive option
 - Management accountability + upgrade WWTW, as recognising that upgrading the WWTW is not optimal without management accountability
- **Rainfall:** A higher-than-average rainfall event will result in increased inflows to WWTW and into the stormwater drainage system.
- **Sewer reticulation:** Includes full system of sewerage pipes and overflows of manholes.
- **Spill:** A random event resulting from a spill of contaminants ending up in a river.
- **Stormwater:** In this study, includes storm water drains and water, landfill and septic tanks lumped into one category.

5.7.5.2 *Calculation of probabilities and derivation of conditional probability tables*

Prior probabilities for eight parent nodes were estimated from a combination of “expert” opinion, return intervals of events based on reported incidents by DUCT, and use of elicited probabilities (Table 5.15). The probability of a leak in the sewer reticulation system was difficult to assess. Based on the reports of manhole leakage events, there were 10 events reported at nine sites over a period of 11 months, which gave a 91% probability of a manhole leaking somewhere in the catchment each month. For the Mpophomeni catchment, it was assumed that there are a minimum of 50 manhole covers, such that the probability of a particular manhole leaking was 0.91/50 or 2%. This figure does need to be refined.

Table 5.15: Parent node prior probabilities.

Variable	States	Probabilities (%)
Housing developments	Current, up 33%, up 100%	(5, 55, 40)
Location of cemeteries	Good, Poor	(50, 50)
Spill	No, Yes	(55, 45)
Dairy/Pig farms	Dam sealed, Dam leaks	(99.5, 0.5)*
Screens	Cleaned, not cleaned	(55, 45)
Stormwater	Contained, Leaches	(44, 56)
Sewer reticulation	Contained, Overflows	(98, 2)
Cable Theft	No, Yes	(91, 9)

*Under low rainfall conditions

Calculation of return intervals was a more quantitative approach to determining probabilities. Since high rainfall events are more likely to lead to effluent dam leaks and overflows at the WWTW, it was necessary to define and then estimate the probability of a high rainfall event. The return interval for rainfall was set at roughly three times the mean daily rainfall of 7.82 mm (for days when a rainfall event occurred for the period assessed), or ca. 24 mm. This resulted in a return period of 58.7 days, so that any “high” rainfall event had a probability of 1.7% (Figure 5.30).

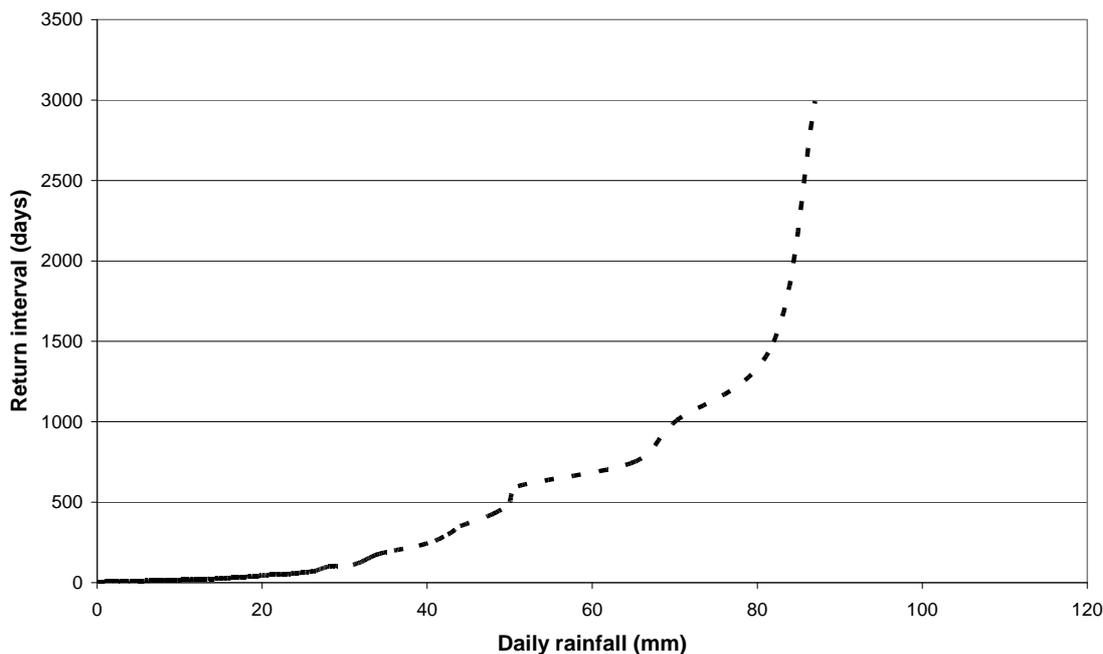


Figure 5.30: Return intervals for daily rainfall over an eight year period (1991-1999) for the rainfall station at Mpophomeni.

In the initial engagement process with the upper uMngeni CMF in February 2011, the stakeholders set the objective of wanting “good” water quality. This needed to be defined in a measurable way in order to set probabilities for this. Additionally, it was desirable in this study to be able to measure the improvement in water quality in response to identified management interventions. Since these data were not directly available, it was necessary to measure this indirectly. This was achieved using water quality time series data from six water quality monitoring points located in catchments covering a range of land uses. Return intervals for exceedances of reasonable thresholds for *E. coli* (Figure 5.31), conductivity (Figure 5.32) and nitrates (Figure 5.33) were

calculated, with the final probability of “bad” water quality as an average of the probability of exceedance for each of the three metrics (as derived from return intervals). At all six sites return interval curves showed a successive increase in exceedances as land use intensity increased. Thus, the two “natural” sites (RMG001 and RMR 001) had a 5.06 and 8.60% chance of any of their readings showing poor water quality. The site downstream of agriculture had a 19.06% chance of indicating poor water quality, while the site just downstream of Mpophomeni (RMT005) had an 82.6% probability of any reading reflecting poor water quality. The probability of poor water quality dropped by almost 15% in the same stream downstream of a poorly functioning wetland (Table 5.16). Site RMT001 was in the upper Mpophomeni catchment and potentially reflects the probability of poor water quality as a result of pit latrines. These probabilities do not explicitly factor in cumulative upstream impacts, and were simply based on land use in the immediate vicinity. The odds of poor water quality were calculated against RMG001 (5.06%), such that, for example, a rural site with septic tanks was five times more likely to have poor water quality than a “natural” site.

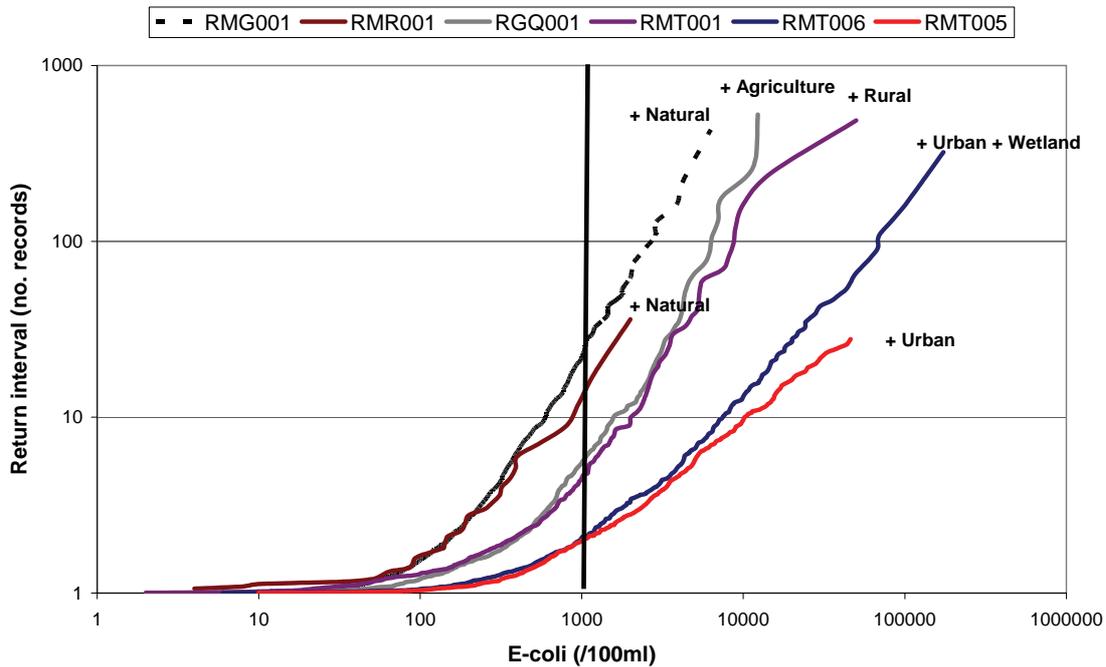


Figure 5.31: Return intervals for *E. coli* at six water quality monitoring points in the upper uMngeni catchment, covering five different land uses.

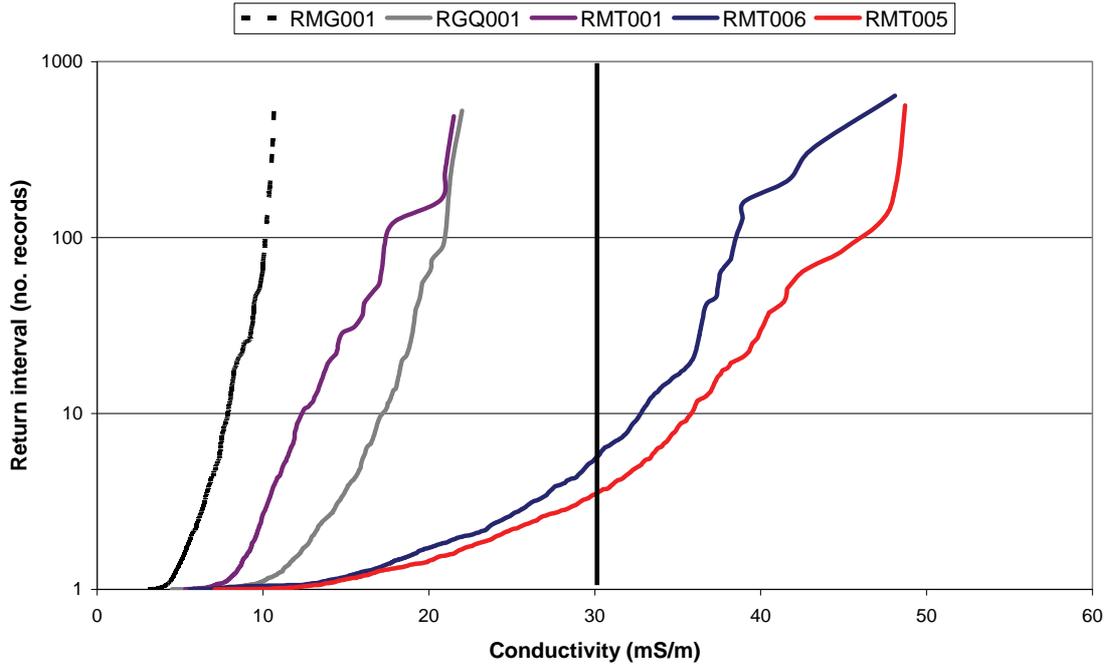


Figure 5.32: Return Intervals for conductivity at five water quality monitoring points in the upper uMngeni catchment, covering five different land uses.

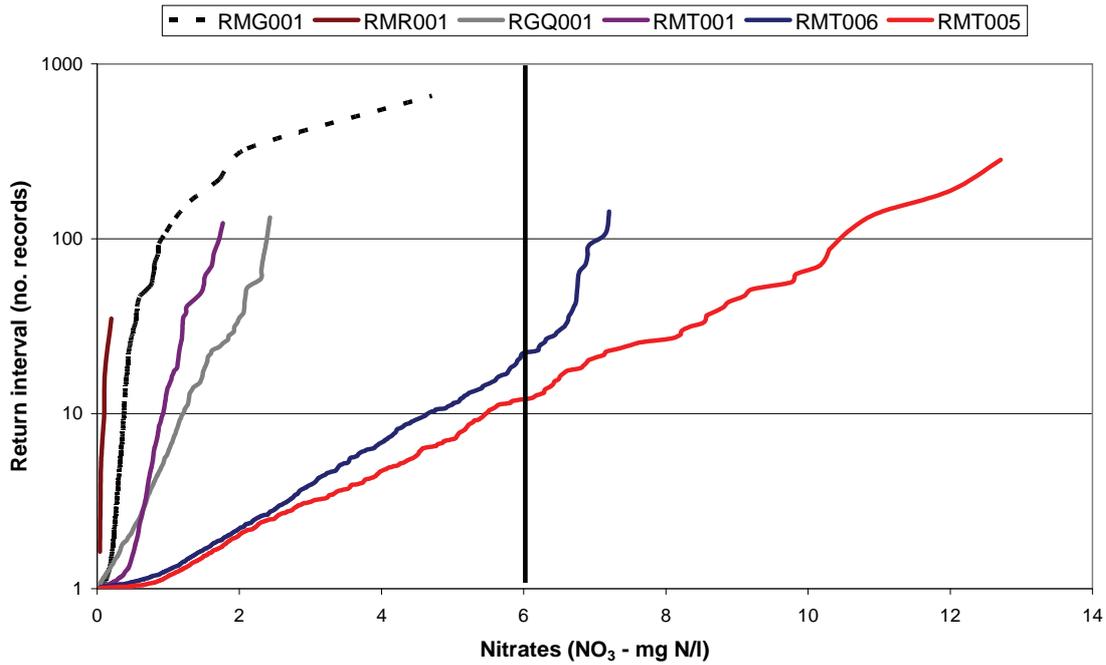


Figure 5.33: Return intervals for Nitrates at six water quality monitoring points in the upper uMngeni catchment, covering five different land uses.

Table 5.16: Calculation of probabilities of bad water quality (i.e. return intervals of exceedance of thresholds) at six monitoring sites under different land uses (i.e. different management interventions as listed in the decision node).

Threshold	E. coli	Conductivity	Nitrate	Probability – Bad WQ	Odds	Land use
	1000	30	6			
Return intervals						
RGQ001	5.32	500	500	19.06	4	+Agric
RMT001	4.39	490	490	23.05	5	+Rural
RMT005	1.97	3.44	12.02	82.60	16	+Urban
RMT006	2.03	5.38	22.21	69.35	14	+Urban+Wetland
RMG001	20.87	500	500	5.06	N/A	Natural
RMR001	12	500	500	8.60	N/A	Natural

5.7.5.3 Simple Bayesian Network

A simple Bayesian network was developed to illustrate the Bayesian approach as applied to water quality issues. In this example (Figure 5.34), there are two parent nodes and one child node, with water quality being a simple function of a WWTW and an effluent dam from a dairy (or pig) farm. Each parent node was defined with two states. Probabilities for the farm dam were as per Table 5.15. Compliance probabilities for the WWTW were not available for the Mpophomeni WWTW, and the closest functional WWTW was used, viz. at Howick, which had a reported compliance of 83.1% for 2011 (The Witness, 23 December 2011).

In this simple Bayesian network, the probability of good/medium/poor water quality is represented as a dial, which may have more significance for stakeholders than the use of numbers. Under current prior parent probabilities, water quality is fairly good, based on conditional probabilities as derived from both parent nodes.

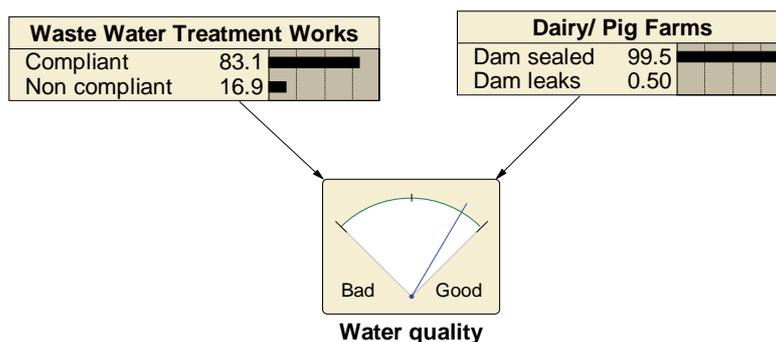


Figure 5.34: Simple Bayesian network for U20C based on two inputs which affect water quality.

5.7.5.4 Complex Bayesian Decision Network

Based in listening to concerns from stakeholders at the first upper uMngeni CMF attended in February 2011, a preliminary Bayesian network consisting of 9 variables was constructed, and populated with reasonable (but not defensible) probabilities (Figure 5.35). Under these prior probabilities, there is almost even odds of water being “drinkable” versus “non-drinkable”. In this,

and subsequent BNs, water quality was informed by inputs from surface water and groundwater inputs.

The revised Bayesian network had 13 nodes (Figure 5.36), with probabilities more rigorously defined, as described above. A simple table of conditional probabilities for the sewer reticulation node, which has parent nodes “cumulative housing developments” and “stormwater”, is included for illustrative purposes (Table 5.17). In this example of the BN, under existing prior probabilities (based on best available data), the likelihood is that water quality will be poor (probability = 69.8%), based on the current set of prior probabilities.

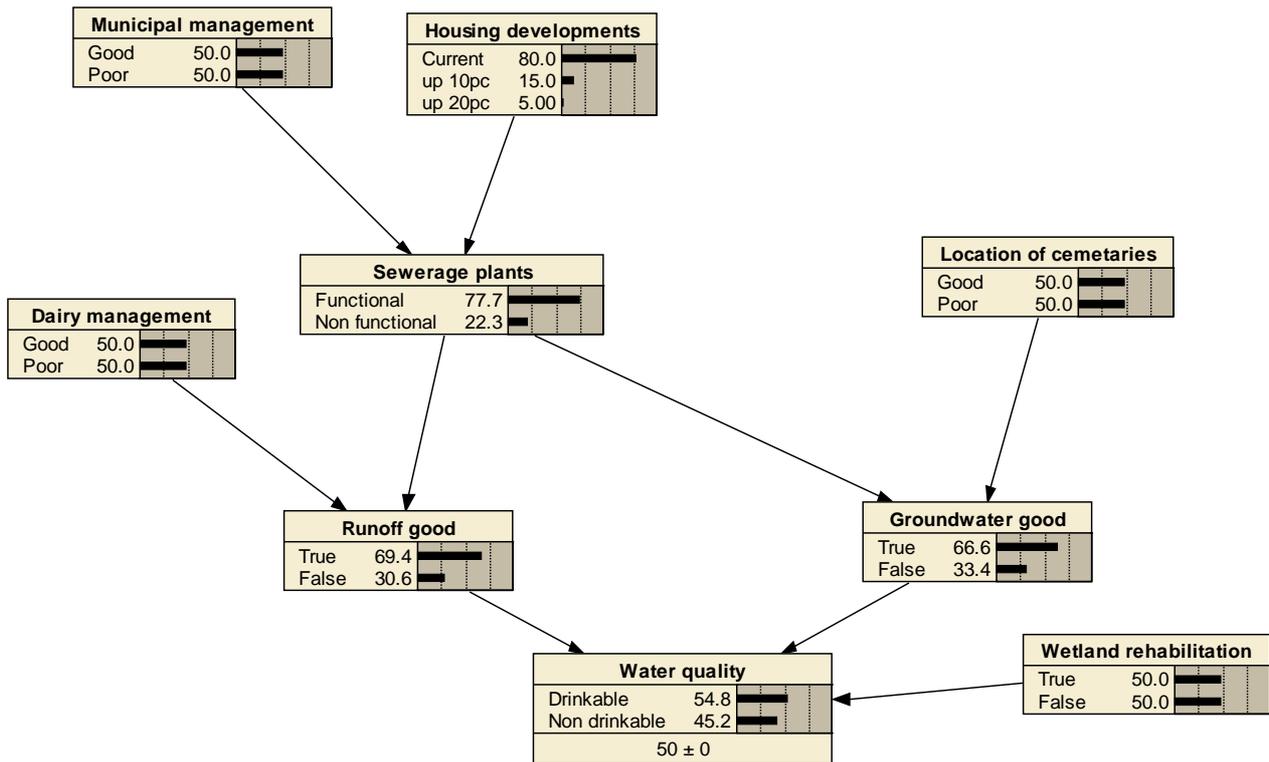


Figure 5.35: Original Bayesian Network developed from discussions at the upper uMngeni CMF in February 2011.

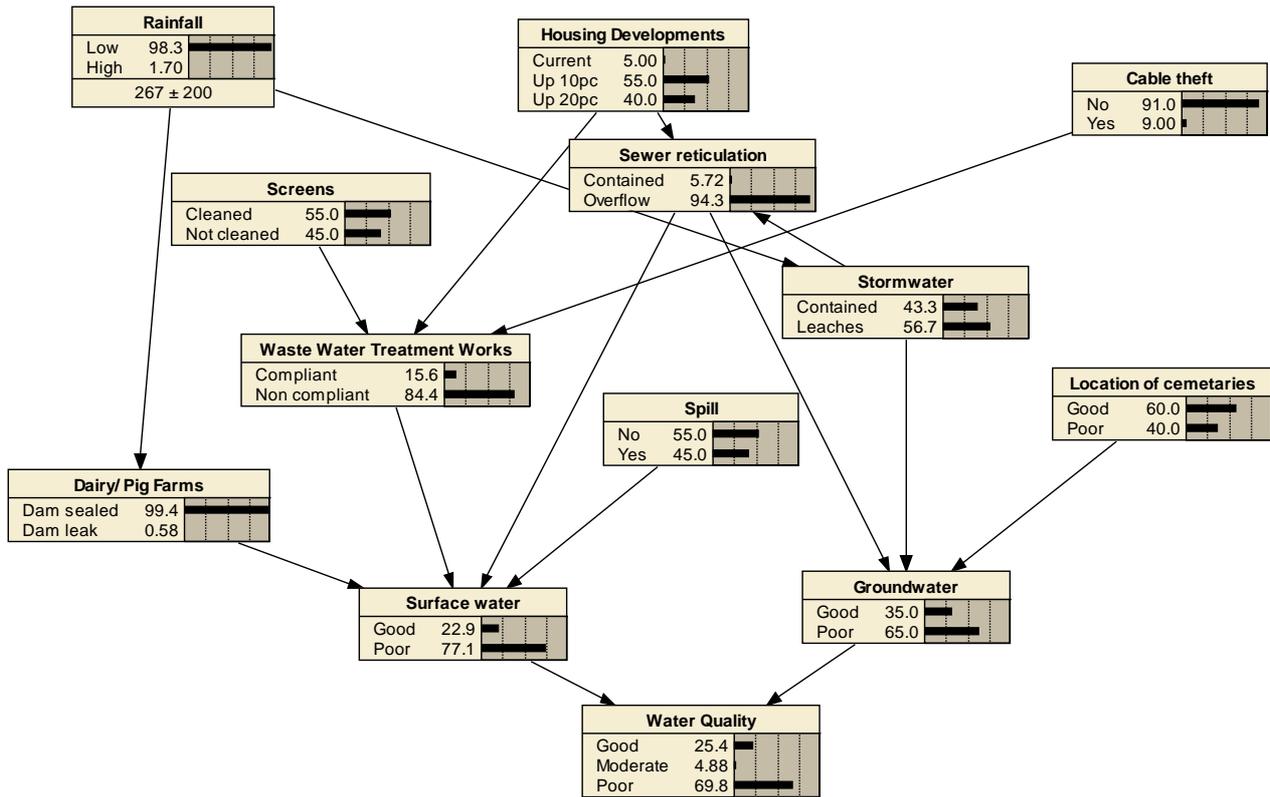


Figure 5.36: Refined Bayesian Network after three engagements with the upper uMngeni CMF, and additional research and interaction with individual stakeholders.

Table 5.17: Conditional probabilities for sewer reticulation being contained or overflowing, based on parent nodes of cumulative housing developments (three states) and stormwater being contained or leaching.

Parent nodes		Sewer reticulation	
Housing	Stormwater	Contained	Overflow
Current	Contained	0.98	0.02
Current	Leaches	0.70	0.30
33pc	Contained	0.60	0.40
33pc	Leaches	0.43	0.57
100pc	Contained	0.40	0.60
100pc	Leaches	0.02	0.98

5.7.5.5 Bayesian Influence Diagrams: Selecting the best management options given the evidence

A decision node, with actions “Do Nothing”, “Upgrade WWTW” and “Fix Dam”, and a utility node with benefits of good/bad water quality (values 1, -1) were added to the earlier example of Figure 5.34. The addition of decision and utility nodes transformed the earlier example from a Bayesian network into a Bayesian influence diagram (Figure 5.37). Through this action, it became possible to choose the optimal management decision under different probability scenarios. In this example, the highest utility was achieved by upgrading the WWTW.

The BN from Figure 5.36 was converted into an influence diagram with 15 nodes through the addition of a management node with nine management options, and a utility node linked to water quality, with utility values assigned for good, medium and poor water quality. Because the freeware version of Netica only allowed for the development of BNs with ≤ 15 nodes, two nodes (rainfall and spills) were dropped from Figure 5.36, to allow for the inclusion of the management and utility nodes. Additionally, two further mediating nodes were added to simplify the conditional probability tables for WWTW, groundwater and surface water (Figure 5.38).

The first mediating node, Management effectiveness, had probabilities of effectiveness which change as a result of community awareness, research, management accountability and upgrading the WWTW, while the remaining management options had a 50/50 probability effect. In the second mediating node, the impact of upgrading the wetland, however, was incorporated into the Environmental Resilience node, where the action of upgrading the wetland increased the probability of high environmental resilience. The “simplified” conditional probability tables for WWTW, surface water and groundwater, each with four parent nodes, are provided in Table 5.18 to Table 5.20. In this example, with default prior probabilities reflected (i.e. no node states have been actively selected), the likelihood is that water quality will be “medium”, and the most appropriate management intervention, based on utility scores, is to rehabilitate the wetland.

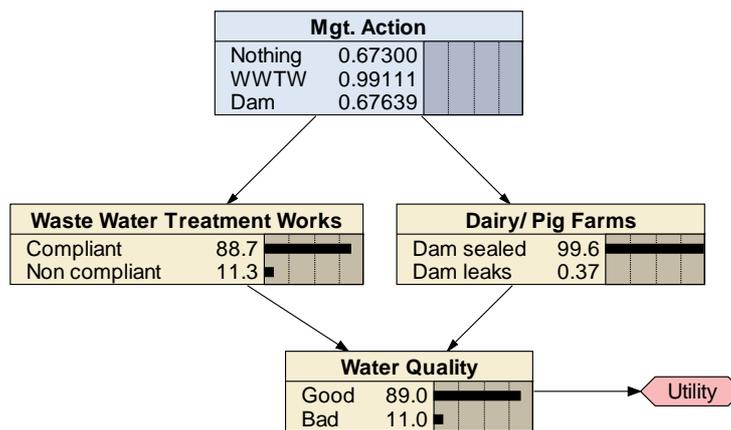


Figure 5.37: Simple Bayesian Influence Diagram for U20C based on two inputs which affect water quality.

Linking Land Use to Water Quality

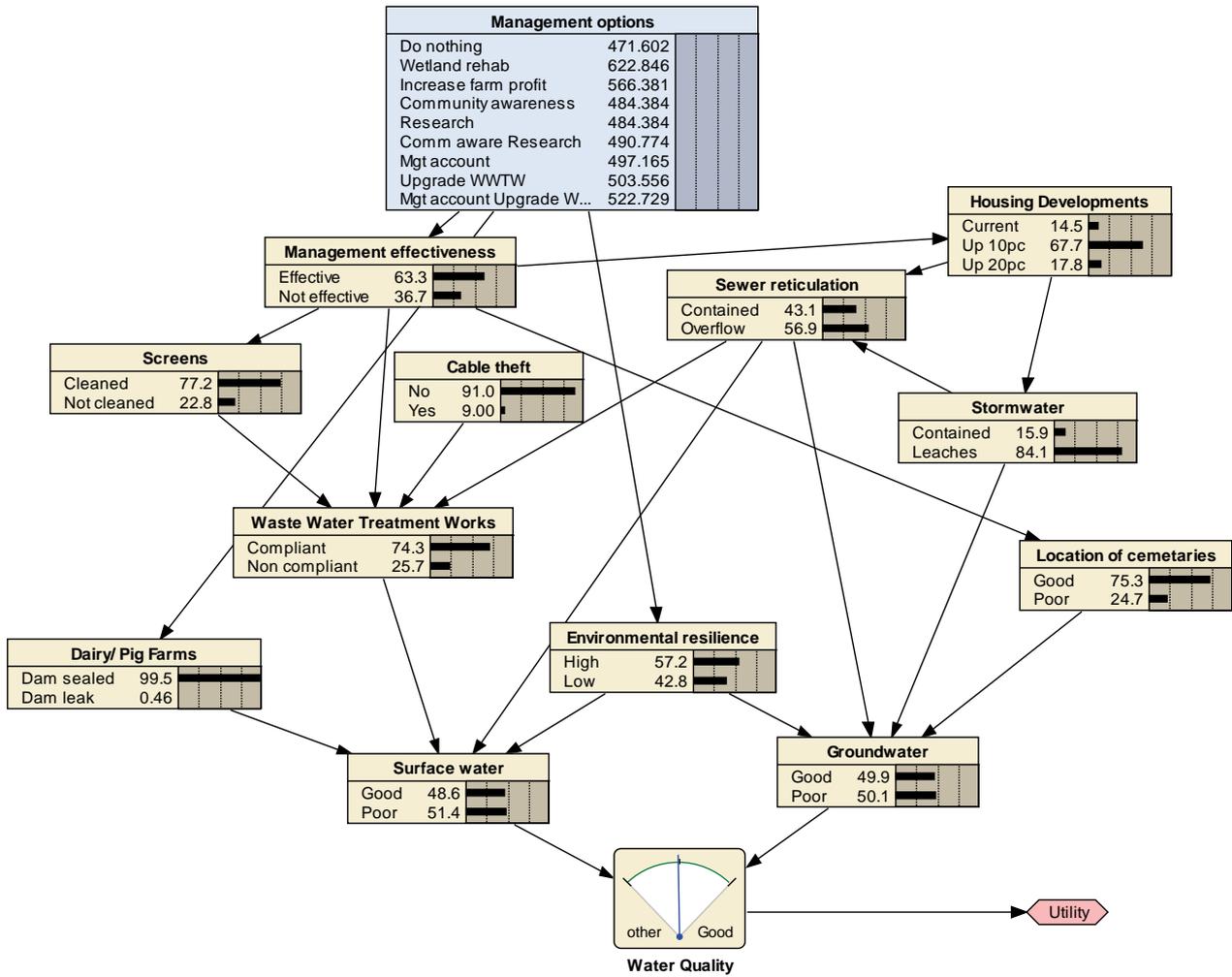


Figure 5.38: Complex Bayesian Influence Diagram based on Figure 5.36

Table 5.18: Conditional probabilities for WWTW node, based on combinations of states from four parent nodes.

Parent nodes				WWTW	
Cable	Screens	Sewer_reti	Mgt_eff	Compliant	Non-compliant
No	Cleaned	Contain	Effect	0.99	0.01
No	Cleaned	Contain	Not	0.83	0.17
No	Cleaned	Overflow	Effect	0.8	0.2
No	Cleaned	Overflow	Not	0.67	0.33
No	Not_clean	Contain	Effect	0.6	0.4
No	Not_clean	Contain	Not	0.5	0.5
No	Not_clean	Overflow	Effect	0.49	0.51
No	Not_clean	Overflow	Not	0.41	0.59
Yes	Cleaned	Contain	Effect	0.75	0.25
Yes	Cleaned	Contain	Not	0.63	0.37
Yes	Cleaned	Overflow	Effect	0.61	0.39
Yes	Cleaned	Overflow	Not	0.51	0.49
Yes	Not_clean	Contain	Effect	0.46	0.54
Yes	Not_clean	Contain	Not	0.38	0.62
Yes	Not_clean	Overflow	Effect	0.37	0.63
Yes	Not_clean	Overflow	Not	0.01	0.99

Table 5.19: Conditional probabilities for surface water node, based on combinations of states from four parent nodes.

Parent nodes				Surface water	
Dairy	WWTW	Sewer	Resilience	Good	Poor
Sealed	Compliant	Contained	High	0.95	0.05
Sealed	Compliant	Contained	Low	0.31	0.69
Sealed	Compliant	Overflow	High	0.77	0.23
Sealed	Compliant	Overflow	Low	0.26	0.74
Sealed	Non-comp	Contained	High	0.17	0.83
Sealed	Non-comp	Contained	Low	0.08	0.92
Sealed	Non-comp	Overflow	High	0.15	0.85
Sealed	Non-comp	Overflow	Low	0.08	0.92
Leaks	Compliant	Contained	High	0.81	0.19
Leaks	Compliant	Contained	Low	0.27	0.73
Leaks	Compliant	Overflow	High	0.66	0.34
Leaks	Compliant	Overflow	Low	0.23	0.77
Leaks	Non-comp	Contained	High	0.15	0.85
Leaks	Non-comp	Contained	Low	0.08	0.92
Leaks	Non-comp	Overflow	High	0.13	0.87
Leaks	Non-comp	Overflow	Low	0.05	0.95

Table 5.20: Conditional probabilities for groundwater, based on combinations of states from four parent nodes.

Cemetery	Parent nodes			Groundwater	
	Sewer	Stormwater	Env_res	Good	Poor
Good	Contain	Contain	High	0.99	0.01
Good	Contain	Contain	Low	0.8	0.2
Good	Contain	Leach	High	0.6	0.4
Good	Contain	Leach	Low	0.49	0.51
Good	Overflow	Contain	High	0.75	0.25
Good	Overflow	Contain	Low	0.61	0.39
Good	Overflow	Leach	High	0.46	0.54
Good	Overflow	Leach	Low	0.37	0.63
Poor	Contain	Contain	High	0.9	0.1
Poor	Contain	Contain	Low	0.73	0.27
Poor	Contain	Leach	High	0.55	0.45
Poor	Contain	Leach	Low	0.44	0.56
Poor	Overflow	Contain	High	0.68	0.32
Poor	Overflow	Contain	Low	0.55	0.45
Poor	Overflow	Leach	High	0.41	0.59
Poor	Overflow	Leach	Low	0.01	0.99

5.7.6 Discussion

5.7.6.1 Categorisation of the problem

Solutions to problems in aquatic systems often embody conflicting societal interests (Kingsford et al., 2011). Complex problems are increasingly emerging in society. These require collaborative learning and interacting, self-reflection, and embracing of complexity (Woodhill, 2010). Mental models facilitate co-learning and joint decision making, while scenarios allow assessment of a range of potential management interactions (Kingsford et al., 2011). Simple models are good because they can be readily adapted to suit needs (less buy-in). BNs are useful to examine conceptualisations on knowledge representation (Lynam et al., 2010).

Water quality issues in South Africa are a typical illustration of complex and conflicting societal interests. The upper uMngeni catchment is no exception, and almost twenty years ago, it was already recognised that provision of high quality water to the Pietermaritzburg/Durban axis could only be achieved through holistic catchment management (Little 1996). As has been illustrated by this study, there are many interacting variables driving water quality issues, and the stakes are particularly high as the likelihood of Midmar Dam passing the tipping point and becoming a eutrophic system increase with growing land use change. Climate change will only exacerbate these problems, through impacts on rainfall, leading to knock-on effects on changes in runoff, groundwater mineral composition and thus changes in water treatment needs (WHO, 2011). Rather than watching this happen in a state of paralysis and in an environment of conflict and finger-pointing, there is the opportunity to collectively learn how to solve the problem.

5.7.6.2 Assessment of Bayesian Decision Networks as a DSS

Bayesian networks have been used successfully as a participatory tool in representing complex issues in tropical forest communities (Evans et al., 2006), water quality management (Lynam et al., 2010), ecological responses to flow variation (Webb et al., 2010). They have also been extended as a decision support tool to evaluate different management options, and have been applied successfully in environmental flow decision making (Hart et al., 2009), catchment management decisions (Ames et al., 2005; Shenton et al., 2010), land use decision behaviour (Aalders, 2008) and assessment of management options in river ecosystem restoration planning (Stewart-Koster et al., 2010).

BNs are a versatile tool for participatory problem solving, and are being increasingly used in the arena of environmental management. The Bayesian networks developed so far in this study represent only the first step in what could become a more complex and iterative process. What has been achieved so far has integrated a considerable amount of quantitative and qualitative data into an interactive conceptual model of the problem. Developing such a network has been a successful process, and shows promise in integrating issues and stakeholders. What has emerged from this process as simple lessons is the importance of listening and observing, engaging, and keeping the approach simple. As highlighted by the report of Coan (2010) on Mpophomeni, community buy-in is key to the success of any problem-solving process, and what is important is taking the time to tap into the resource of often untapped community wisdom (tacit knowledge). Linking back to the general comment from the above introduction that water quality problems in the uMngeni are due to “poultry farms, effluent from cattle feedlots and informal settlements without sanitation facilities” (Anon., 2011) – the BNs have illustrated that all of these issues contribute to the problem, but not equally. It has been demonstrated that certain water quality variables are more likely to be the cause of problems than others, and that these should be addressed as the greater priority.

5.8 SWAT (SOIL WATER ASSESSMENT MODEL) – PHOSPHATE IN THE OLIFANTS

5.8.1 Introduction

Nutrient pollution and resulting eutrophication is one of the main impacts on water quality in the upper Olifants catchment. This has resulted in the proliferation of dense algal blooms in Loskop Dam as well as significant growth of filamentous algae in the main stem of the Olifants River and its tributaries. The main nutrients responsible for eutrophication are phosphorus and nitrogen (Carpenter et al., 1998), with phosphorus commonly regarded as the limiting nutrient (Mainstone and Parr, 2002) (i.e. the nutrient that is generally in shortest or lowest supply and thus limits algal growth). Nonpoint source agricultural runoff containing nutrients derived from fertiliser and manure and point source effluent from waste water treatment works (WWTWs) are typically the most important sources of phosphorus pollution in freshwater systems (Hart et al., 2004; Jarvie et al., 2006). It is well known that the majority of WWTWs in the catchment are not functioning optimally, with most facilities scoring very poorly in the DWA annual Green Drop Report (DWA, 2010). This implies that these point sources may be contributing significant loads of phosphate to the upper Olifants system. The catchment is also agriculturally intensive, with cattle (both free range and feedlot) and crop (predominantly maize) production being the most common agricultural activities in the catchment (STATSSA, 2002). Furthermore, mining and the concurrent removal of vegetation and exposure of bare soil and rock also results in the potential for relatively high losses of naturally

occurring phosphorus in the soil, similar to what would be expected at large construction sites (Carpenter et al., 1998).

The overall objective of this section is to implement the SWAT model in the test catchment (i.e. the upper Olifants catchment) with a view to assessing its applicability and ease of use (particularly with respect to data input requirements). This case study focuses on the implementation of the model in the catchment and interpretation of the model output results and addresses the following aims:

- **Phosphate load modelling:** Modelling of point (sewage and industrial discharges) and nonpoint (agricultural runoff) source nutrient load inputs to the Olifants River upstream of Loskop Dam.
- **Identification of spatial trends:** Identification of the location of important sources of phosphate loading in the catchment (i.e. phosphate loading attributable to point and nonpoint source pollution and identification of 'hotspot' areas responsible for high nutrient inputs).
- **Identification of temporal trends:** Identification of temporal trends in phosphate loading and the potential link to eutrophication and algal blooms in the Olifants River and Loskop Dam.
- **Scenario development:** Modelling of point source reduction scenarios and the implications for phosphate loading and eutrophication.

Modelling outputs were compared to DWA monitoring data so as to calibrate the model input parameters and validate the model output results.

5.8.2 Methods

5.8.2.1 Model Description

The eco-hydrological model, SWAT (Arnold et al., 1998, version 2009), has been widely used for catchment scale studies dealing with water quantity and quality. SWAT is a semi-distributed, process-oriented hydrological model. It is a continuous time model, which simulates water and nutrient cycles with a daily time-step. The SWAT model represents the large-scale spatial heterogeneity of the study area by dividing the watershed into sub-catchments. The sub-catchments are then further subdivided into hydrologic response units (HRUs) that are assumed to consist of homogeneous land use and soils. The climatic variables required by SWAT include daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. Major components of the model include hydrology, weather, and agricultural management. The details of all components can be found in Arnold et al. (1998) and Neitsch et al. (2005).

In the SWAT model, soil water content, surface runoff, nutrient cycles, crop growth and management practices are simulated for each HRU and then aggregated for the sub-catchment by a weighted average. The model's hydrological components are comprised of surface runoff, percolation, lateral flow, groundwater, and evapotranspiration and channel transmission loss. Simulation of the hydrology of a watershed is split into two major divisions. The first division is the land phase of the hydrologic cycle, which controls the amount of water, sediment, nutrient and pesticide loading into the main channel in each sub-catchment. The second division is the water or routing phase of the hydrologic cycle that can be defined as the movement of water, sediment,

nutrient, etc. through the channel network of the watershed to the outlet (Neitsch et al., 2005). The SWAT model simulates surface runoff volumes and peak runoff rate for each HRU using daily rainfall or sub-daily rainfall amounts. Surface runoff is calculated using a modification of the Soil Conservation Service (SCS, 1972) curve number method, which is a function of the soil's permeability, land use and antecedent soil water conditions. The soil profile is subdivided into multiple layers including infiltration, evaporation, plant uptake, lateral flow, and percolation.

SWAT offers various methods to estimate the potential evapotranspiration (PET), such as Hargreaves, Penman-Monteith, and Priestley-Taylor. The Penman-Monteith (Monteith, 1965) method was chosen to be employed in this study because the PET evaluation is based on the basic data such as solar radiation, wind speed, air temperature and relative humidity, while wind speed is not considered by the Hargreaves and Priestley-Taylor methods. The model computes evaporation from soils and transpiration from plants separately. Potential soil water evaporation is predicted as a function of potential evapotranspiration and leaf area index, whereas actual soil water evaporation is predicted by using exponential functions of water content and soil depth. Plant transpiration is predicted as a linear function of potential evapotranspiration and leaf area index.

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (Williams, 1975). The sediment transport in the channel is controlled by the simultaneous operation of deposition and degradation processes. The channel sediment routing equation uses a modification of the equation of Bagnold (1977) that defined stream power as the production of water density, flow velocity and water surface slope. The maximum amount of sediment that can be transported from a reach segment is a function of the peak channel velocity. The SWAT model either deposits excess sediment or re-entrains sediment via channel erosion depending on the sediment load entering the channel.

SWAT simulates the nitrogen cycles in the soil profile and in the shallow aquifer (Neitsch et al., 2005). In soil and water, nitrogen is extremely reactive and exists in a number of dynamic forms. It may be added to the soil in the form of fertiliser, manure or residue application, bacteriological fixation, and rain. It can be removed from the soil through plant uptake, soil erosion, leaching, volatilisation and denitrification. Plant use of nitrogen is estimated using the supplying and demand approach (William et al., 1984). In the SWAT model, there are five different pools of nitrogen in the soil. Two of the pools are inorganic forms of nitrogen, while the other three pools are organic forms of nitrogen. Nitrate may be transported with surface runoff, lateral flow or percolation. Nitrate entering the shallow aquifer in recharge from the soil profile through the percolation may be retained in the aquifer, moved with groundwater flow into the main channel, or be transported out of the shallow aquifer with water moving into the soil zone in response to water deficiencies, and moved with recharge to the deep aquifer. For the lowland catchment, the groundwater component is a dominant pathway and plays an important role in transporting nitrate from the shallow aquifer to the main channel or to the soil zone through the upwelling of groundwater processes. The amount of nitrate moved with the water is calculated by multiplying the nitrate concentration in the mobile water by the volume of water moving in each pathway. Organic N transport with sediment is calculated with a loading function developed by McElroy et al. (1976) and modified by Williams and Hann (1978) for application to separate runoff events. Estimation of the daily organic N runoff loss is based on the concentration of organic N in the topsoil layer, the sediment yield, and the enrichment ratio: that of organic N in sediment to organic N in soil (Neitsch et al., 2005).

The different phosphorus processes modelled by SWAT in the HRUs and the various pools of phosphorus in the soil are described in Neitsch et al. (2005). Plant use of phosphorus is estimated

using the supply and demand approach similar to nitrogen. Three major forms of phosphorus in mineral soils are organic P associated with humus, insoluble forms of mineral P, and plant-available P in soil solution. Due to the low mobility of phosphorus, surface runoff will only partially interact with the solution P stored in the top 10 mm of soil. Sediment transport of organic and mineral P to the stream is calculated with a loading function as described in organic N transport. The SWAT in-stream water quality algorithms incorporate constituent interactions and relationships used in the QUAL2E model (Brown and Barnwell, 1987), which contains the major interactive factors such as the nutrient cycles, algae production, and benthic oxygen demand.

5.8.2.2 *Input Data*

The study area for the modelling exercise was confined to the catchment of the upper Olifants, upstream of Loskop Dam. The impact of land use and point source pollution from WWTWs on ortho-phosphate loads and concentrations in Middelburg, Witbank and Loskop dams were investigated using SWAT. The land use in the catchment is dominated by agricultural crop production, grassland vegetation (used primarily for grazing) and mining. Middelburg and Witbank are the largest urban areas in the catchment and there is a number of coal mines located in the catchment, most of which fall in the Olifants and Klein-Olifants catchment areas, upstream of Middelburg and Witbank. There are a number of WWTWs located throughout the catchment. The WWTWs are mainly municipal but are also associated with large mines and industries (e.g. ESKOM power plants). The location of WWTWs was identified using the South African Department of Water Affairs GoogleEarth-enabled water quality data exploration tool (DWA, 2011a). This system was also used to identify a number of DWA monitoring stations for which both water quality and flow data were available (Figure 5.39). Flow data for these stations was downloaded from the DWA Hydrology website (DWA, 2011b) and water quality data (including ortho-phosphate concentrations) was downloaded using the DWA water quality data exploration tool (DWA, 2011a). These data were used to calibrate and validate the model outputs.

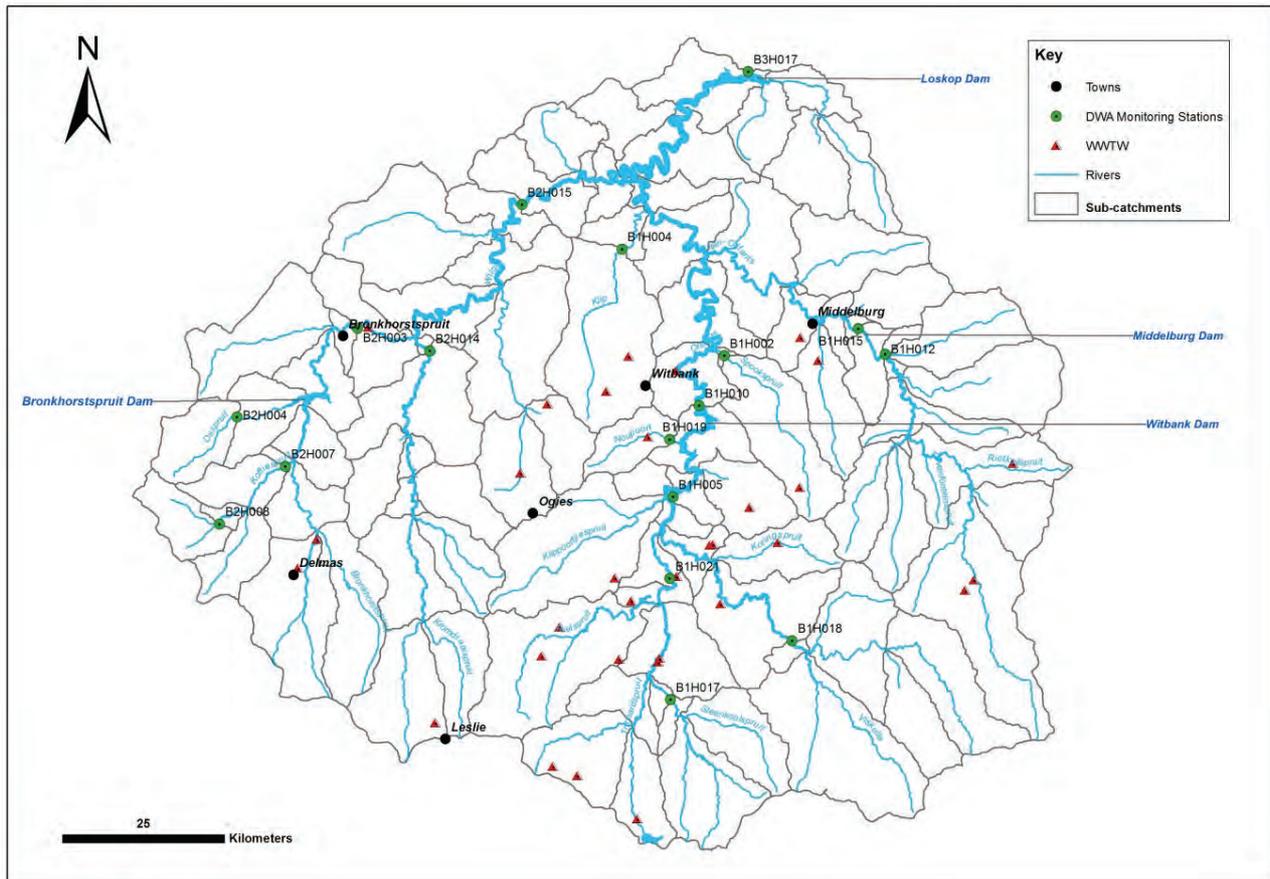
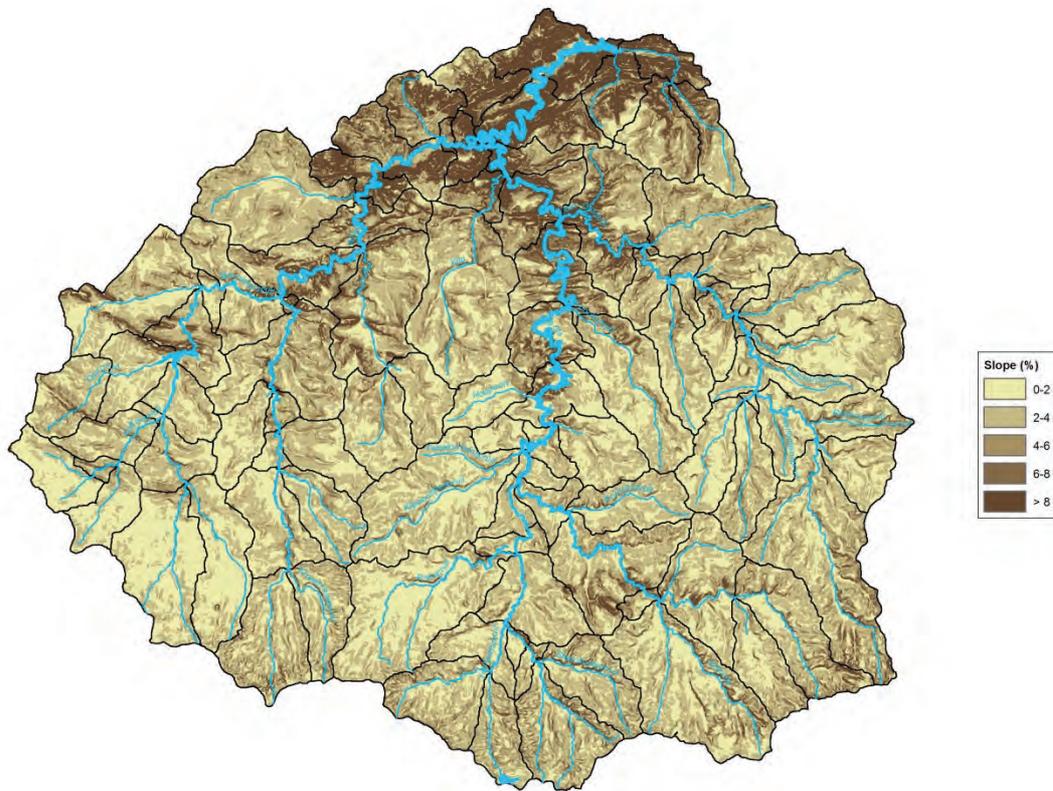
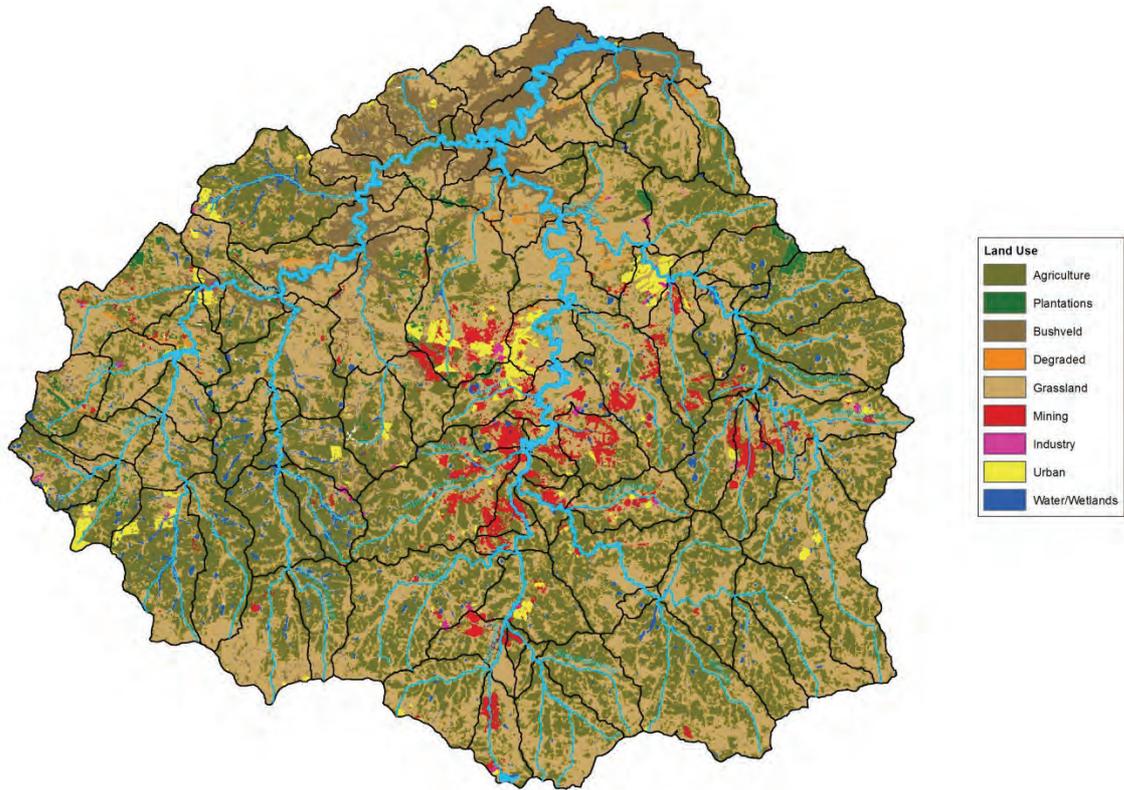


Figure 5.39: Sub-catchments (delineated by the SWAT programme) and location of waste water treatment works and DWA flow and water quality monitoring stations.

The ArcSWAT interface for SWAT version 2009 was used to compile the SWAT input files. The basic data sets required to set up the model inputs are: topography (in the form of a Digital Elevation Model – DEM), soil, land use and climatic data. These data source are listed in Table 5.21. The topographic information was used for automatic delineation of the main catchment into 96 sub-catchments (Figure 5.39). The land use, soil and slope maps (Figure 5.40) were superimposed to identify 985 HRUs. Weather data for a station located close to Witbank were obtained from the South African Weather Service. The data from this station were used to simulate weather conditions for the entire upper catchment. There were significant gaps in the data record and the simulation was performed for the most recent complete data record, which was from January 2005 to December 2010.

Approximately 90% of agricultural crop production in the catchment was assumed to be maize production, with planting taking place in the beginning of October after a tillage operation. Fertiliser application was based on data from the FAO (2005), with an annual N and P application of 70 and 55 kg/ha, respectively. Grasslands were assumed to be predominantly grazed by cattle. Average livestock density was assumed to be 0.1 head of cattle per hectare (for the entire catchment) according to estimated grazing capacity values for South Africa (AGIS, 2011). Limited data on ortho-phosphate effluent concentrations were available for WWTWs located within the catchment. An average effluent concentration of 4 mg/l was calculated and applied to all WWTWs within the catchment.

Linking Land Use to Water Quality



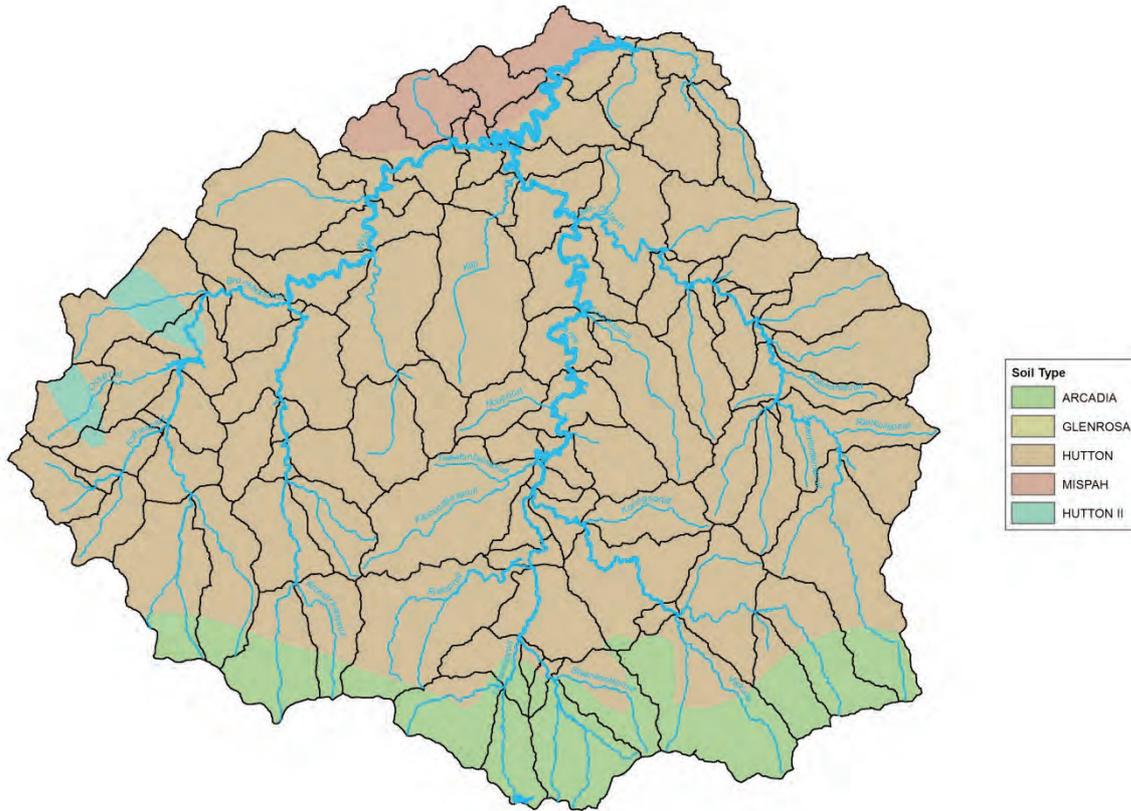


Figure 5.40: Spatial data sets used as input for estimation of phosphate loading by the SWAT programme.

Table 5.21: SWAT model data input sources for the upper Olifants catchment.

Data Type	Source	Description
Topography	DRDLR-NGI	Digital Elevation Model 50 x 50 m
Soil	WRC (2008)	Soil data for South Africa from the WR2005 project
Land Use	ARC-ISCW	Land Cover Classifications
Climate	South African Service	Weather Rainfall, humidity, solar, wind and temperature data.

5.8.2.3 Model Calibration

Detailed calibration procedures for the SWAT model and the definitions and sensitivity of various calibration parameters are presented in Neitsch et al. (2002). These parameters were adjusted manually so as to calibrate the model outputs. The calibration for flow and phosphate simulations was performed for the continuous time period 2005-2010. Calibration of flow and phosphate loads was performed for a monthly time step using measured data from the DWA monitoring stations located in the catchment. The first step involved calibrating flow output. Surface runoff and base

flow were calibrated simultaneously. Parameters adjusted for surface runoff were curve number (CN2) and available water capacity (SOL_AWC). The main parameters adjusted for base flow were the groundwater revap coefficient (GW_REVAP), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), and threshold depth of water in shallow aquifer (REVAPMN). For instance, GW_REVAP and GWQMN were adjusted from the default values of 1 and 0 to the simulated values of 250 and 1000, respectively. The different pathways modelled by the SWAT model are separated into the transport through surface and subsurface runoff, upwelling of groundwater, groundwater and transport to the river, and deep aquifer recharge.

Sediment calibration in the SWAT model was implemented by changing parameters in relation to the loading from sub-catchments and channel degradation/deposition. While surface runoff is the primary factor controlling sediment load to the stream, some important parameters affecting sediment movement from sub-catchments into the stream were changed. These include cover or management factor (C FACTOR) used for agricultural crops and pasture, support practice factor (USLE_P) for contour farming terraced fields. Phosphate calibration was performed based on ortho-phosphate loads. For the purposes of validation, the model outputs were compared to calculated monthly ortho-phosphate loads at each of the DWA monitoring stations. Loads (in kg) were obtained by calculating an average ortho-phosphate concentration (kg/ℓ) for the month (from DWA water quality monitoring records) and multiplying the concentration by the monthly flow (ℓ). Phosphate calibration was performed and simulated into two steps, calibration of phosphate load and calibration of in-stream water quality processes. Default model values were used for initial concentrations of organic and mineral phosphorus in the upper soil layer (SOL_ORGP, and SOL_SOL P). Main parameters adjusted for phosphorus load simulation, were phosphorus percolation (PPERCO), phosphorus soil partitioning coefficient (PHOSKD), residue mineralisation (RSDCO), and biological mixing efficiency (BIOMIX). These parameters were verified within their allowable ranges. In addition, some parameters affecting in-stream water quality processes such as the fraction of algal biomass that is phosphorus (AL2) and rate constant for mineralisation of organic phosphorus to dissolved phosphorus (BC4) were also considered.

Predicted values were compared to measured values using the square of the Pearson's product – moment correlation coefficient (R²), which is an indicator of the strength of the relationship between measured and simulated values. The values of R² range from 0 to 1. If the R² values are less than or close to 0, the model simulation is taken as an indication of poor or unacceptable performance. The closer the values get to 1, the more perfect the model simulation. Santhi et al. (2001) found that a value greater than 0.5 for these variables constitutes an acceptable simulation model.

5.8.2.4 Phosphate Reduction Scenarios

Two point source load reduction scenarios were simulated by reducing ortho-phosphate concentrations (and derived loads) at each WWTW from 4 mg/ℓ to 1 (current national phosphate effluent standard) and 0.1 (international phosphate effluent standard) mg/ℓ, respectively. The effect of these reductions on ortho-phosphate loads and concentrations at Middelburg, Witbank and Loskop Dams were simulated.

5.8.3 Results

5.8.3.1 Flow

The 2005/2006 and 2006/2007 hydrological years (October to September of the following year) experienced relatively low rainfall (Figure 5.41), with total rainfall for these periods being 591 and 389 mm, respectively. In contrast the 2007/2008 hydrological year experienced very high rainfall (total of 892.4 mm), and was characterised by a number of high daily rainfall events in excess of 50 mm. The total rainfall for 2008/2009 and 2009/2010 was also relatively high, with annual totals of 737.2 and 879.6 mm, respectively.

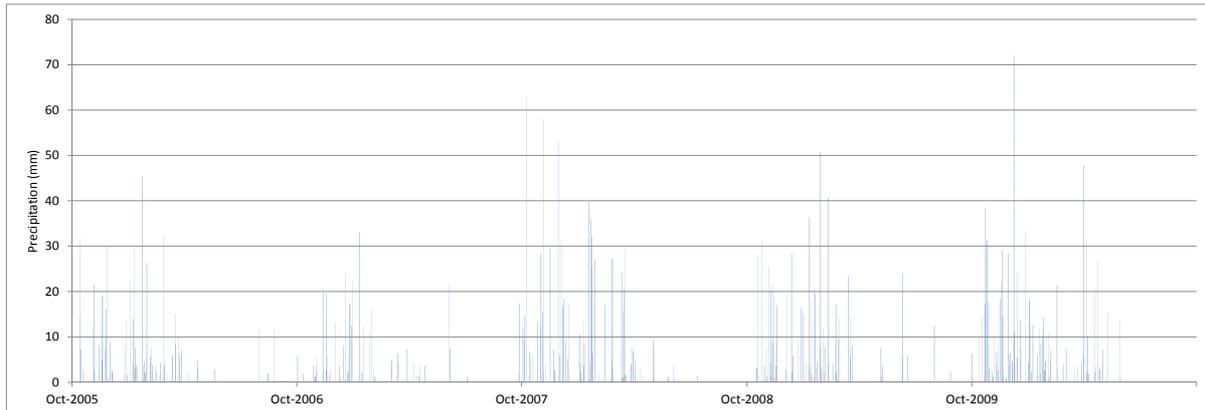


Figure 5.41: Daily rainfall measured at the Witbank meteorological station from October 2005 to October 2010.

Simulated flow outputs were compared to flow records measured at each of the selected DWA monitoring stations (Figure 5.42). In general, the flow simulation compared well to measured flow records and peak flow events were within maximum peaks measured at flow gauging stations across the catchment. Very good correlations were observed for the Naauwpoort and Klipspruit catchments. These flow gauging stations were in closest proximity to the weather station and had no other catchment inlets. Stations located further away from the location of the weather station showed comparatively poorer correlations between measured and predicted values, in particular those located in the upper most part of the catchment – base-flow for these catchments was generally under-predicted (i.e. B2H004, B2H007 and B2H008). Measured flow at B2H015 lacked distinct peaks associated with peak summer rainfall events (apparent at other flow gauging stations further upstream), indicating that the station is not functioning correctly and is not measuring flows accurately.

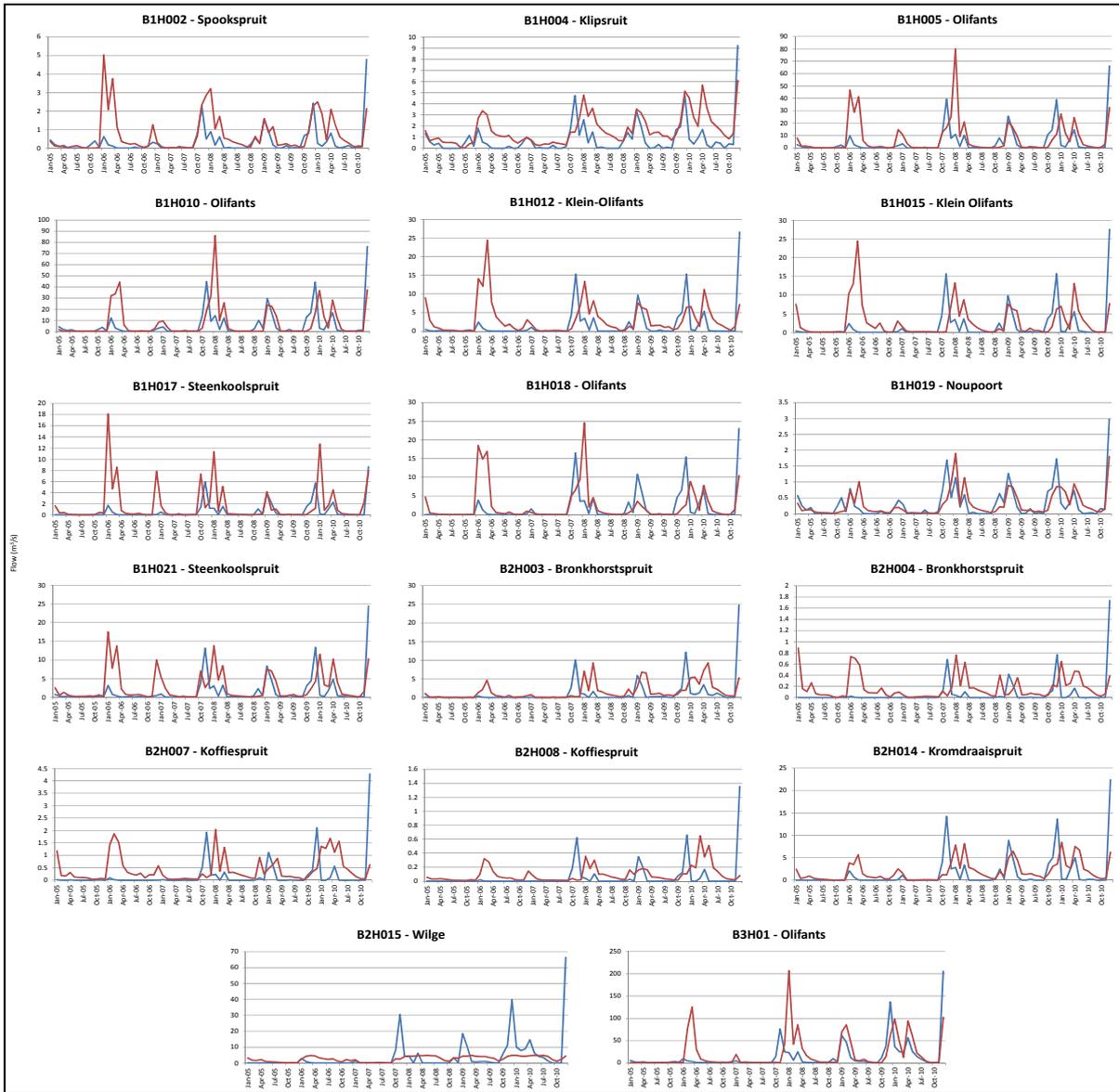


Figure 5.42: Predicted (blue) versus measured (red) mean monthly flow (m^3/s) at DWA flow gauging stations in the upper Olifants River catchment, upstream of Loskop Dam.

5.8.3.2 Phosphate Loads

The SWAT model expresses ortho-phosphate input in the form of loads (kg) transported out each sub-catchment river reach (Figure 5.43). The model predicted high peak phosphate loads during October and November 2007 that were higher than calculated/measured loads at most DWA water quality stations. The correlation between measured and predicted average annual loads was relatively poor with all R^2 values at all monitoring stations being below 0.5 (Table 5.22). In particular, the model significantly under predicted loads at sub-catchments situated high up the catchment (e.g. B2H004, B2H007 and B2H008). The model over-predicted phosphate loads at the catchment outlet (B3H01) by 51% of the calculated measured load. Mean annual phosphate loads per sub-catchment reach are presented in **Error! Reference source not found**. These loads are as a result of both point and nonpoint sources. In general there is an expected increase in loads from upstream to downstream in both the Wilge and Olifants rivers. Figure 5.44 clearly shows that the Steenkoolspruit has a significant contribution to the Olifants River, resulting in high phosphate

input high up in the catchment. This tributary of the Olifants River also had the highest calculated measured average annual loads (Table 5.22). Loads predicted in the lower reaches of the Wilge River, which drains a far larger catchment, are comparable to loads simulated in the Steenkoolspruit. The high phosphate loading in the upper catchment results in high phosphate loading along the length of the main stem of the Olifants River.

Table 5.22: Mean annual measured and predicted flow and phosphate loads (and % difference between measured and predicted values) for DWA monitoring stations in the upper Olifants River catchment, upstream of Loskop Dam for 2005 to 2010 (2008 for phosphates).

DWA Monitoring Station	Flow (m ³ x 10 ⁶)				Phosphate Loads (kg)			
	Measured	Predicted	% Difference	R ²	Measured	Predicted	% Difference	R ²
B1H002	22	10	-117	0.45	331	640	48	0.38
B1H004	50	24	-112	0.64	644	1275	49	0.27
B1H005	231	141	-64	0.42	9622	8462	-14	0.34
B1H010	230	166	-39	0.46	5470	10416	47	0.33
B1H012	96	49	-95	0.26	2400	2455	2	0.14
B1H015	85	50	-69	0.25	1777	2482	28	0.02
B1H017	49	19	-163	0.32	1908	309	-517	0.19
B1H018	74	53	-39	0.35	3062	1180	-160	0.36
B1H019	9	9	-1	0.73	246	491	50	0.31
B1H021	82	47	-74	0.40	6563	9560	31	0.41
B2H003	48	34	-43	0.28	952	2538	63	0.13
B2H004	5	2	-163	0.11	144	3	-4878	-0.04
B2H007	13	6	-135	0.08	364	84	-332	0.09
B2H008	3	2	-69	0.03	44	10	-343	-0.11
B2H014	60	44	-36	0.41	1327	1541	14	0.15
B2H015	84	119	30	0.33	3116	4359	29	-0.05
B3H017	652	415	-57	0.48	9649	19812	51	0.26

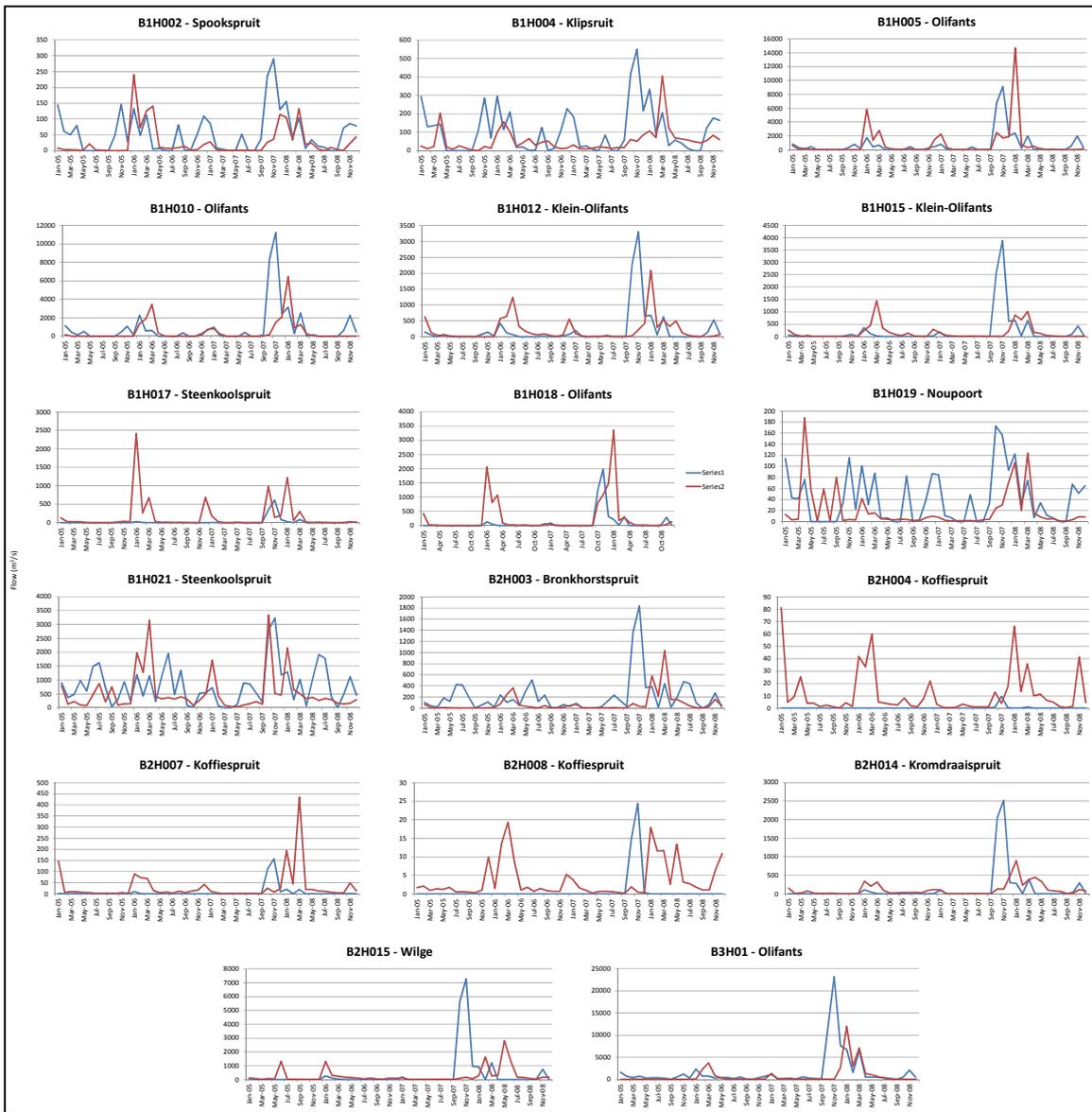


Figure 5.43: Predicted (blue) versus measured (red) mean monthly ortho-phosphate loads (kg) at DWA flow gauging stations in the upper Olifants River catchment, upstream of Loskop Dam from 2005 to 2008.

5.8.3.3 Nonpoint source phosphate export coefficients

Export coefficients are a measure of the amount of phosphate lost per hectare and provide a relative comparison of the influence of different land uses on phosphate loading. Average annual phosphate export coefficients per land use category are presented in Table 2. For the Olifants catchment, urban and mining land use areas were identified as having the highest phosphate export coefficients. Based on this information the model was able to identify sub-catchments with high and low total mean annual phosphate export coefficients (i.e. loss per hectare per sub-catchment and not per land use) (Figure 5.45). These represent nonpoint source losses only. Highest losses per hectare are obviously associated with those sub-catchments containing a relatively high percentage of urban (i.e. Witbank and Middelburg) or mining (i.e. upstream of Witbank Dam) land use. The upper sub-catchments of the Klein-Olifants, Olifants and Kromdraaispruit show relatively high export coefficients. These catchments are all dominated by agricultural activities and grassland.

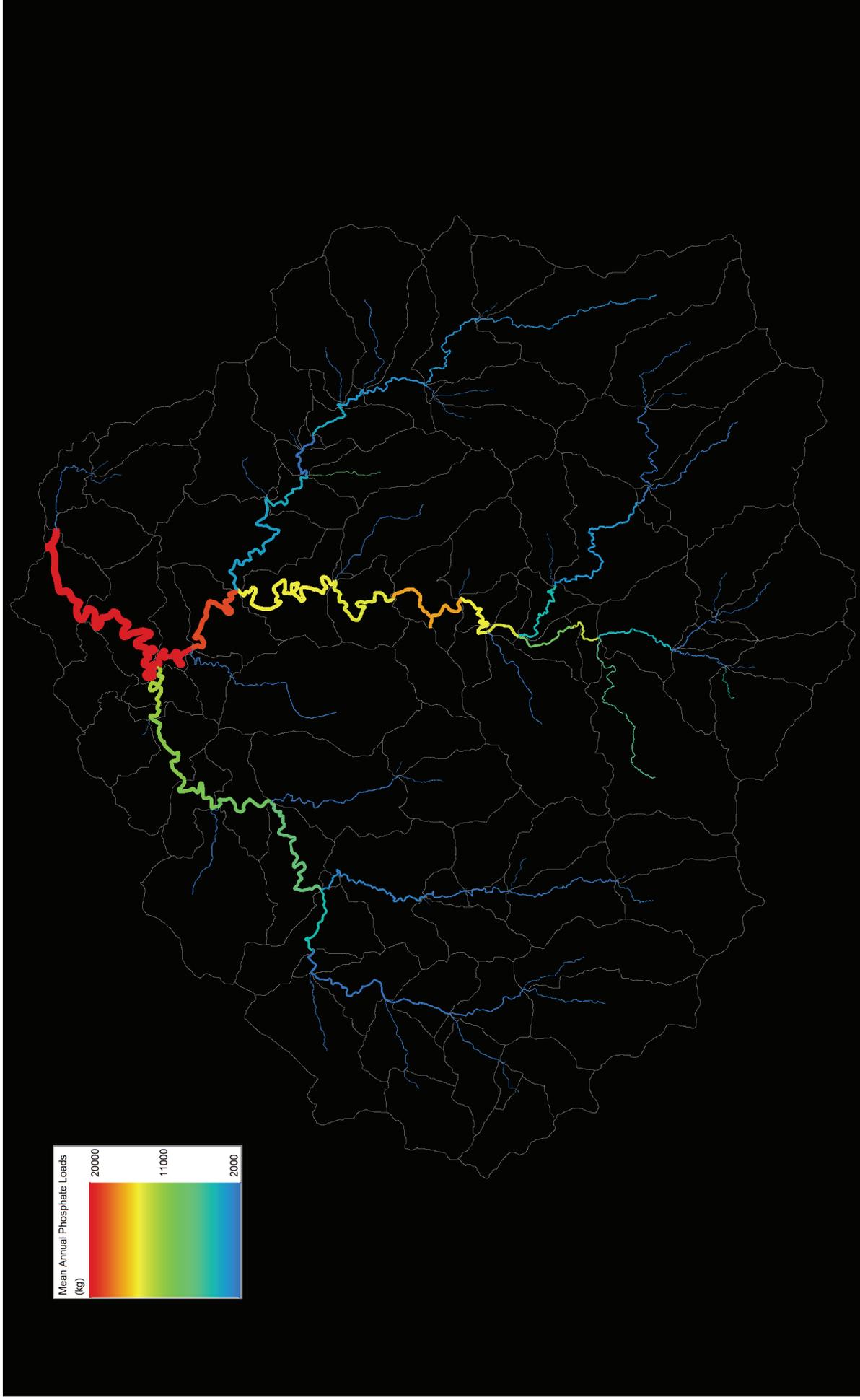


Figure 5.44: Mean annual phosphate loads exiting sub-catchments of the upper Olifants River catchment from 2005 to 2010.

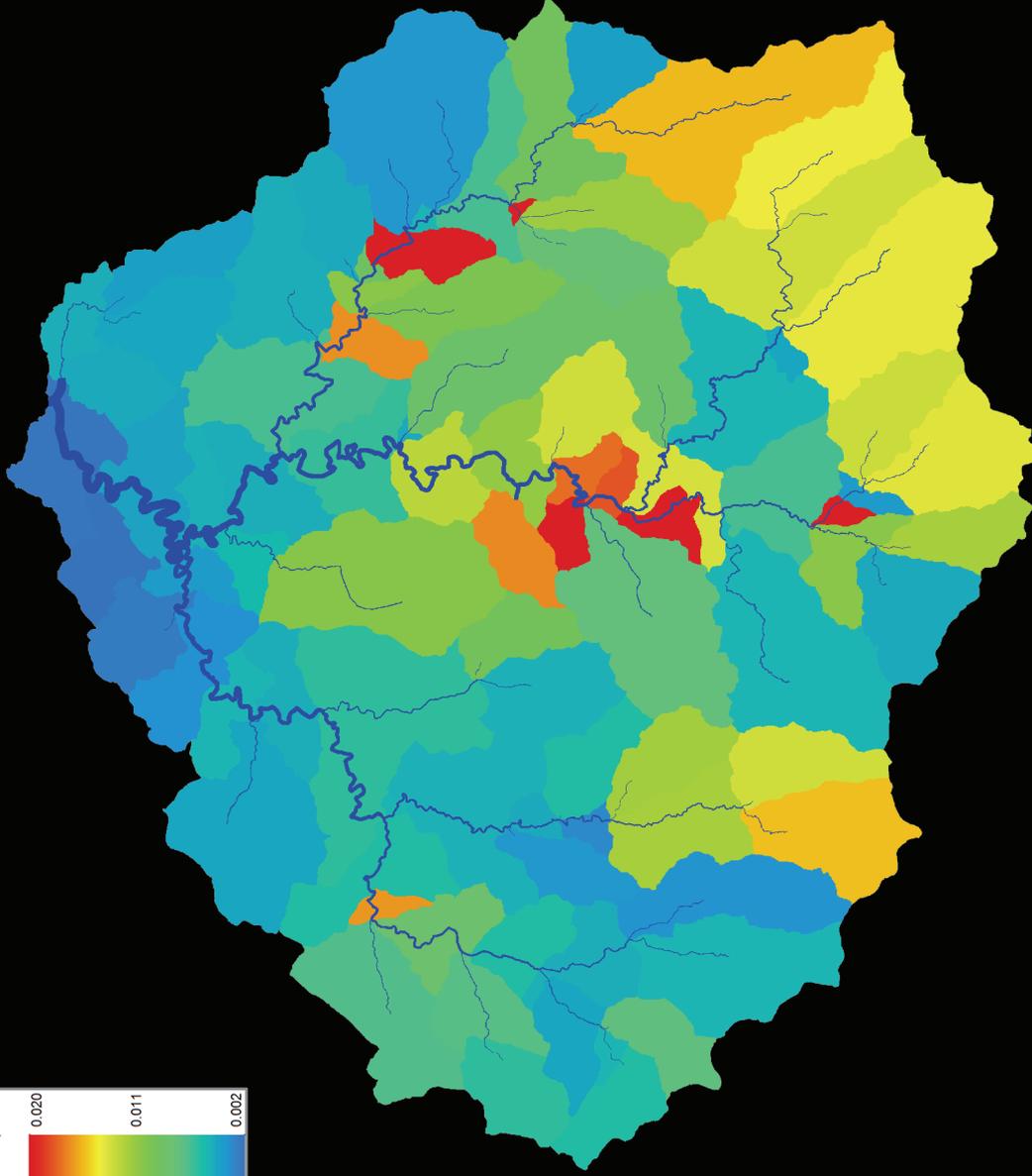
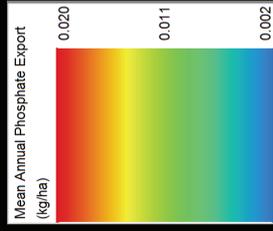


Figure 5.45: Mean annual ortho-phosphate export coefficients for sub-catchments of the upper Olifants River catchment from 2005 to 2010.

5.8.3.4 Dam simulations: measured versus predicted.

The model was used to estimate ortho-phosphate concentrations in the three major dams in the Olifants catchment (Figure 5.46). Simulated concentrations compared favourably to measured values for all three dams from January 2005 to September 2007. For all dams there is a simulated distinctive peak in ortho-phosphate concentrations (associated with increased phosphate loads towards the end of 2007). This coincided with large rainfall events that followed a prolonged period of relatively low rainfall. The effect can be seen for Loskop Dam, where the low rainfall experienced during the 2005/2006 and 2006/2007 hydrological years resulted in a significant drop in dam levels (to less than 40% – Figure 5.47). The heavy rainfall experienced in October 2007 resulted in a large input of nonpoint source derived phosphate loads. This high load input in combination with initially low dam volumes most likely resulted in a significant peak in phosphate concentrations, together with the onset of algal blooms (as indicated by the increased chlorophyll-a concentrations – Figure 5.47). This peak is relatively well represented by measured data, with all three dams showing elevated ortho-phosphate concentrations post October/November 2007. Measured concentrations post the peak period do not correspond well with predicted values, with measured concentrations being lower than predicted values.

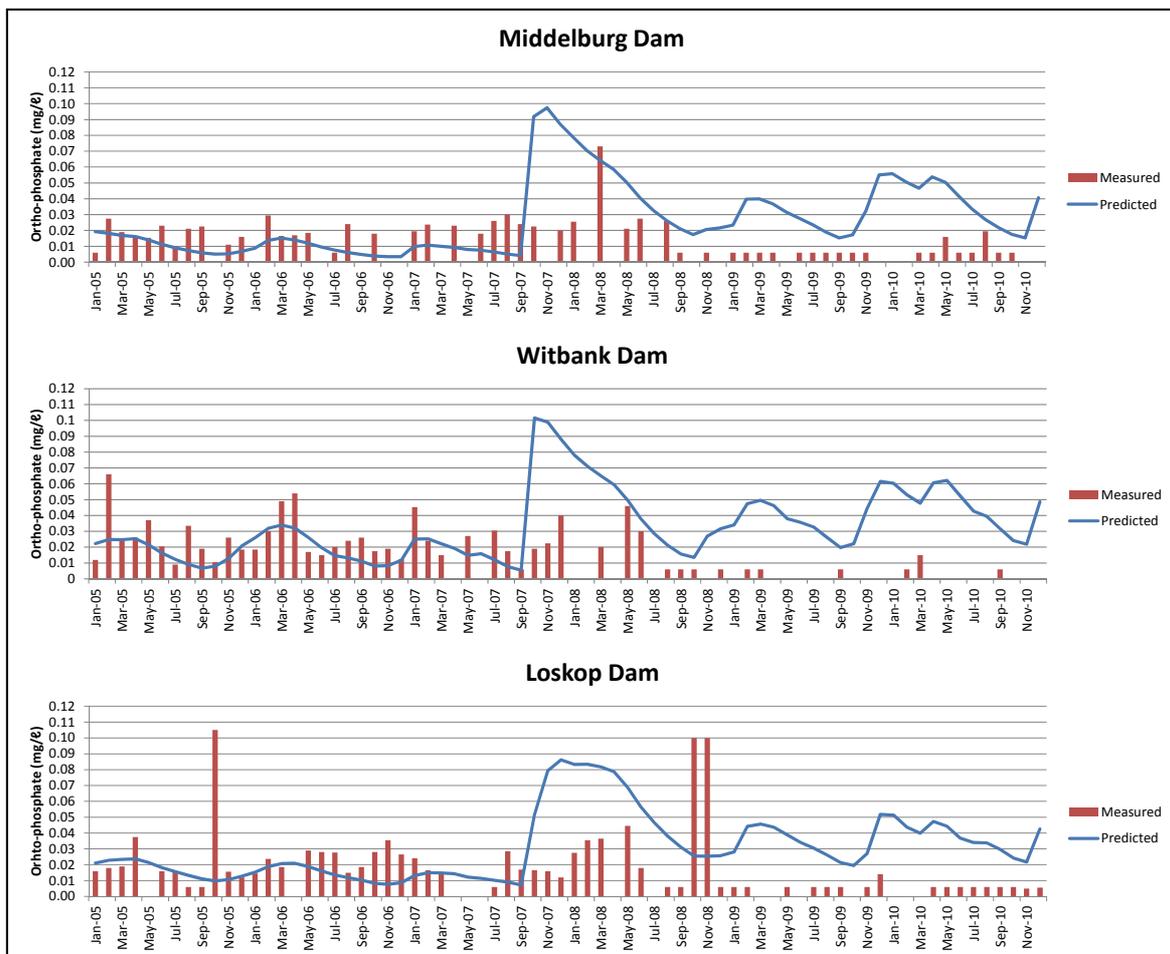


Figure 5.46: Predicted (blue line) versus measured (red bars) mean monthly ortho-phosphate concentrations in three dams in the upper Olifants River catchment.

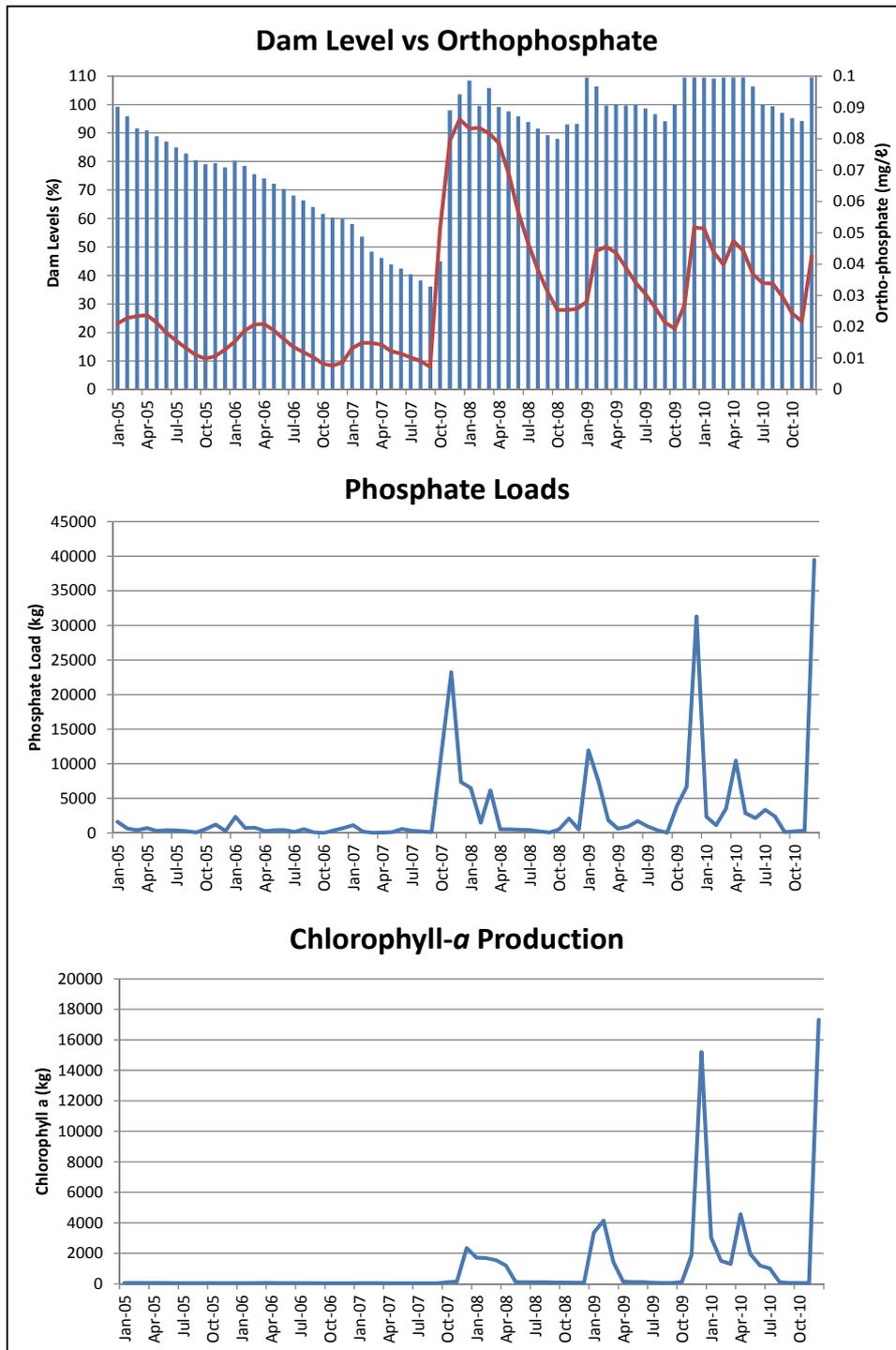


Figure 5.47: SWAT output of predicted dam levels versus ortho-phosphate concentrations, phosphate loads and chlorophyll production in Loskop Dam from January 2005 to December 2010.

5.8.3.5 Point source versus nonpoint source contributions

Simulations excluding the influence of point source WWTWs allowed for the quantification of the contribution of these point sources to mean annual ortho-phosphate loads at each of the dams included in the analysis (Table 5.23) Point sources contribute very little to total ortho-phosphate loads at Middelburg Dam with nonpoint-sources contributing an annual mean of 97%. There was

also little variation in terms of the contribution of point or nonpoint sources to loads at Middelburg Dam across different years, with point source contribution being less than 5% for most years. The exception was 2010, when point sources contributed approximately 10% to the average annual load. In contrast to Middelburg Dam, Loskop and Witbank dams are more heavily influenced by point sources, which contribute approximately 30 and 24% to average mean annual loads, respectively. For both of these dams there was a large annual variation in the contribution of point sources to total orthophosphate loads, ranging between 16 and 49% for Witbank Dam and 7 and 47% for Loskop Dam. For both dams high point source contributions were associated with low rainfall years (i.e. 2005/2006 and 2006/2007 – Table 5.23)

Table 5.23: Mean annual point (PS) and nonpoint source (NPS) contributions to total orthophosphate loading (in kg and %) at three dams in the upper Olifants River catchment.

	2005	2006	2007	2008	2009	2010	Average
Middelburg							
PS (kg)	14	0	124	0	67	791	166
NPS (kg)	244	528	7150	1867	8869	6888	4258
Total (kg)	258	528	7274	1867	8936	7680	4424
%PS	5	0	2	0	1	10	3
%NPS	95	100	98	100	99	90	97
Witbank							
PS	1882	1819	3688	2604	5036	8474	3917
NPS	1978	2964	19913	6818	23526	18200	12233
Total	3861	4783	23600	9422	28562	26674	16150
%PS	49	38	16	28	18	32	30
%NPS	51	62	84	72	82	68	70
Loskop							
PS	3268	2766	3134	3583	5911	16962	5938
NPS	3650	4159	41991	16696	62873	52749	30353
Total	6918	6926	45125	20279	68785	69711	36291
%PS	47	40	7	18	9	24	24
%NPS	53	60	93	82	91	76	76

5.8.3.6 Point source reduction scenarios

Point source reduction scenarios are predicted to have minimal impact on ortho-phosphate loads and concentrations in Middelburg Dam (Figure 5.48), with mean annual load reductions being between 13.9 and 12.5% of current loads (Table 5.24). In contrast, point source reduction scenarios can potentially have a significant influence on phosphate load reduction and concentrations into Witbank and Loskop dams. For these dams, the difference between a 1 and 0.1 mg/l phosphate effluent standard appears to be minimal – 4.1 and 4.7% difference between reductions associated with 1 and 0.1 mg/l effluent standards for Witbank and Loskop dams, respectively. Highest percentage reductions for these two dams are associated with years 2005 and 2006, where rainfall and resulting flow were relatively low in comparison to latter years.

Table 5.24: Mean annual phosphate load reductions (in %) associated with a 1 and 0.1 mg/l phosphate effluent standard at WWTWs in the upper Olifants River catchment.

	2005	2006	2007	2008	2009	2010	Average
Middelburg							
1 mg/l	30.3	11.6	6.9	16.0	7.6	10.8	13.9
0.1 mg/l	33.5	2.6	5.9	15.8	5.5	12.0	12.5
Witbank							
1 mg/l	41.9	35.5	15.8	28.6	18.0	27.9	28.0
0.1 mg/l	48.2	40.1	18.0	32.4	20.5	33.3	32.1
Loskopop							
1 mg/l	37.9	33.9	11.0	21.3	13.4	22.7	23.3
0.1 mg/l	46.2	40.7	12.6	25.5	15.2	27.7	28.0

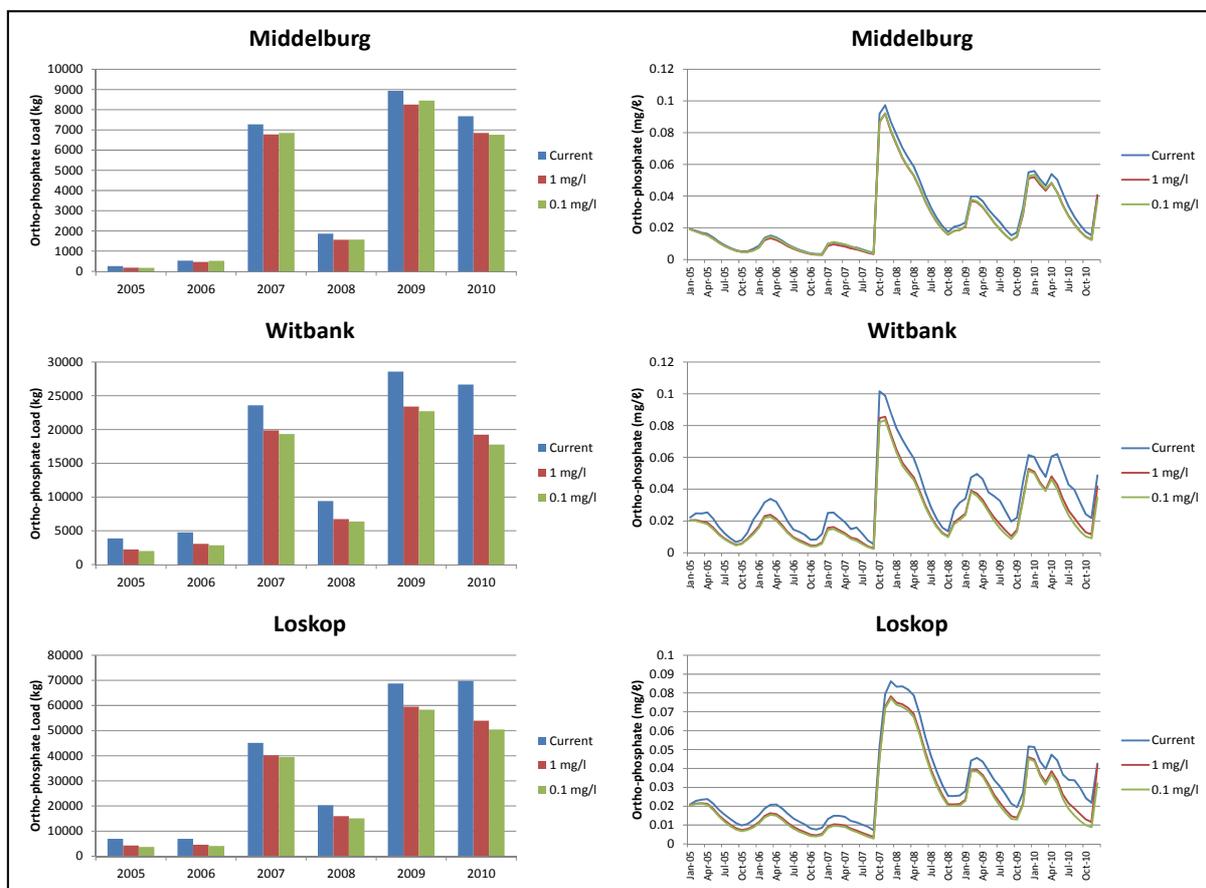


Figure 5.48: Mean annual ortho-phosphate load and mean monthly ortho-phosphate concentration reductions associated with a 1 and 0.1 mg/l effluent standard at WWTWs for three dams in the upper Olifants River catchment.

5.8.4 Discussion

5.8.4.1 Calibration and uncertainty

Before discussing results it is important to discuss the limitations and uncertainty associated with large-scale catchment based modelling. The objective of the study was to test the influence of

point source reduction strategies on loads and ortho-phosphate concentrations in the Olifants River and its tributaries and into three large dams in the upper catchment. In order to increase the amount of certainty associated with the model output it is important to calibrate the model and ensure that the model output (prediction) approximates as closely as possible measured field values. Calibrating a catchment model over such a large area is an extremely challenging process, particularly in highly managed watersheds, where natural processes may in many instances play a secondary role. Without the knowledge of detailed management data, calibration of the model may not be possible. Management of dams and releases and use of water from these dams, irrigation and water transfers will all significantly impact on the natural flow of water. Particularly in a large catchment such as the upper Olifants, it is difficult to obtain all this detailed information and only expert opinion or assumptions can be used. Over such a large area there is bound to be a high degree of uncertainty associated with model outputs. These uncertainties stem from conceptual, input and parameter uncertainty (Abbaspour, 2011).

Conceptual model uncertainty could be as a result of: a) simplifications in the conceptual model (e.g. assumptions in the universal soil loss equation for estimating sediment loss), b) processes occurring in the catchment that are not included in the model (e.g. wind erosion effecting mobilisation of particulates from the soil surface), c) processes that are included in the model but are unknown to the modeller (e.g. the magnitude of dam releases, water transfers and irrigation), and d) processes unknown to the modeller that are also not included in the model (e.g. dumping of waste material and chemicals into the river and sewage or chemical spills). Input uncertainty is as a result of errors in input data (i.e. rainfall) and/or the extension of this point data over a large catchment area. Considering the size of the upper Olifants catchment, the number of individual farms (each with their own management regimes) and the inherent variability in input parameters it is thus inevitable that there is a large amount of uncertainty associated with the input parameters and the resulting model output. For the objectives of this study, the model was calibrated as best as possible using a manual procedure. Thus the main aim of the exercise was to achieve realistic model outputs that gave a fair reflection of measured observations in the field that could be used to understand the dynamics of phosphate loading and eutrophication in the upper Olifants catchment.

5.8.4.2 Flow

Predicted flow outputs at the various gauging stations approximated the natural variation observed at these sites. Model predictions ranged from good ($R^2 = 0.73$) to poor ($R^2 = 0.03$) across the catchment. The fact that good flow correlations were observed at flow gauging stations in close proximity to the weather station (i.e. B1H002, B1H004 and B1H019) indicates that the model is able to approximate realistic and accurate flow conditions. The poor correlation observed at gauging stations further away from the weather stations is most likely as a result of input uncertainty associated with rainfall data. Given that only one weather station was used to simulate rainfall and other weather parameters over a large catchment area, it is expected that there would be variation with respect to the accuracy of output results. The upper Olifants catchment falls within a summer rainfall region which is characterised by isolated, scattered thunder showers. This results in highly variable rainfall patterns across the catchment. Additional weather stations used in the simulation would therefore significantly improve the flow correlation. In the case of catchments high up in the main catchment, base-flow predictions often under-predicted observed data, indicating that further refinement of the model parameters would most likely improve model simulations. Finally it is important to note that models are calibrated based on comparison to observed data, which is assumed to be accurate. However, there are often inaccuracies

associated with measured data. For example the flow readings collected from the Wilge River (B2H015) lack distinct peaks associated with summer rainfall conditions (Figure 5.42) and are clearly not an accurate measurement of real-time flow conditions. In this respect catchment-based hydrological models can also be useful for interrogating and questioning the reliability of measured data.

5.8.4.3 Phosphate loads

Whilst flow is measured daily, water quality samples are collected far less frequently (from once a week to once a month). Given the large time periods between water quality sampling there is thus a large degree of uncertainty associated with the calculation of measured phosphate loads. This could partly explain the overall poor correlations between measured and predicted loads observed at all the monitoring stations.

However for this preliminary modelling exercise, the primary objective was to simulate realistic phosphate loads as opposed to temporally accurate loads. In this context, the difference between measured and predicted average loads was acceptable for many of the catchments. Those that showed very large differences between measured and predicted loads were concentrated in the higher end of the catchment – the poor flow correlation for these catchments would undoubtedly contribute to the poor phosphate load correlation. These sub-catchments however contribute relatively low phosphate loads to the overall system. Further calibration of the model could potentially yield more accurate results for these sub-catchments.

In spite of the lower predictions for these sub-catchments, in general the model seemed to over predict phosphate losses, particularly during high rainfall events, which is characterised by the high peaks associated with phosphate loads (i.e. October and November 2007). This consistently over-predicted peak during this period would suggest that further calibration of the model would result in improved simulations. However, improved knowledge of the catchment, particularly with respect to dam releases could reduce uncertainty in model inputs and improve the overall simulation. For example B1H010 and B3H01 are monitoring stations located below Witbank and Loskop dams, respectively. The simulated flow at these stations for November 2007 was under predicted (Figure 5.42). The phosphate loads however were over predicted (Figure 5.43). Similarly, for gauging stations located along the main stem of the Olifants River (i.e. B1H005 and B1H018), peak flows during October and November 2007 were under predicted, while phosphate loads at the same locations were well over predicted.

This strongly suggests that nonpoint source phosphate loads associated with high rainfall events are being heavily over predicted by the model. Furthermore, apart from sub-catchments at the head of the catchment (which were under predicted) all other catchments resulted in an over-prediction of average annual loads. Further calibration of processes associated with nonpoint source phosphate input could therefore improve model simulations. In particular the influence of sediment input on phosphate loading is something that may also contribute to inaccurate results. A major route of entry of organic and inorganic phosphates into river reaches is via attachment to sediment (Sharpley et al., 2001). Because no routine monitoring of sediment concentrations takes place in the catchment it was not possible to calibrate the sediment model outputs against measured data. This could have a significant bearing on the accuracy of phosphate loads. A manual calibration approach was used to adjust model output parameters. Further investigation of the SWAT auto-calibration feature could potentially also yield more accurate results.

In spite of the poor correlations between measured and predicted phosphate loads, the model was able to distinguish between sub-catchments responsible for high or low phosphate loading (i.e. qualitative indication of phosphate loads). There was a very good correlation between different sites ($R^2 = 0.8$) and mean annual phosphate loads (as opposed to time-series within a site as reported in Table), indicating that the model is able to provide a good qualitative indication of which sub-catchments are responsible for high phosphate loads entering the Olifants system. Apart from stations located along the main stem of the Olifants River, the Steenkoolspruit (B1H021) tributary, draining an area of 1342 km² showed the highest predicted and measured phosphate load input of all the monitored tributaries. These loads were even higher than those predicted for the Wilge River, a significantly larger river in terms of discharge, draining an area of 4007 km². The Steenkoolspruit sub-catchment is therefore clearly a major source of phosphate pollution, already impacting the Olifants River relatively high up in the system. In comparison to other catchments with similar land use (i.e. upstream of B1H012) this catchment contains a large number of WWTWs (Figure 5.39) which undoubtedly contribute to the very high phosphate loads observed at this site.

Export coefficients associated with the different land uses in the catchment are well within the range of reported values and also reflect the relative contribution of different land uses (McFarland and Hauck, 2001). Organic phosphate coefficients were also provided as the literature general provides export coefficients for total phosphate (i.e. the sum of inorganic and organic phosphate). Agriculture is commonly associated with nonpoint source phosphate pollution from the use of fertilisers and production of manure by livestock (Sharpley et al., 2001). An improved understanding of the localities of intensive livestock production areas (i.e. feedlots) could help to provide a more spatially accurate picture of nonpoint sources. In the case of the upper Olifants, the sub-catchments located further up in the main catchment are also associated with a higher frequency of steeper slopes. Highest export coefficients were associated with mining and urban land use. The SWAT model does not differentiate between these two land uses. High loads are generally associated with urban land use due to the hardened surfaces, high use of fertilisers and detergents, septic tanks (not identified as point sources) and in particular lack of sewage and sanitation in informal settlement areas. In the context of mining, high export coefficients are as a result of exposure of rock and soil to increased weathering and runoff of naturally occurring phosphates (Carpenter et al., 1998).

5.8.4.4 Dam simulations

Comparison of predicted with measured ortho-phosphate concentrations in the three dams analysed in this study further suggests that the model is over predicting nonpoint source phosphate loads associated with heavy rainfall events. While all dams showed a general increase in ortho-phosphate concentrations during the summer rainfall period of 2007/2008, the peak predicted concentrations were significantly higher than measured concentrations (Figure 5.46). Again, caution should be exercised in relying only on measured monitoring data. It is clear that the monitoring record for all three dams is not rigorous and many months do not have recorded data. The reliability of the measured data is thus questionable. Furthermore, ortho-phosphate concentrations are highly dependent on dam volumes, which in turn are dependent on releases and water extraction. In general though the predictions made by the model support the observations found in this and other studies. Ortho-phosphate concentrations recorded in Loskop Dam during 2010 and 2011 are well within the range of predicted values after the October 2007 peak. Monitoring data prior to 2008 indicate that Loskop Dam was mesotrophic (1990-2000; Van

Ginkel, 2002) and even oligotrophic (2002-2003; DWA, 2011c). Oberholster et al. (2010) state that the first major algal bloom in Loskop Dam was recorded in 2008 and suggested that the dam had switched to a hypertrophic state. This observation supports the results of the simulation for Loskop Dam, which clearly shows increased chlorophyll-a loads from 2008 (Figure 5.47). This suggests the possibility that the heavy rainfall and associated high phosphate loads may have pushed Loskop Dam into an alternate trophic state. The main driver behind the onset of algal blooms in Loskop Dam may thus have been the low dam levels (as a result of a prolonged period of low rainfall) in combination with a sudden high input of phosphate loads resulting in high ortho-phosphate concentrations, which pushed the dam into an alternative stable state.

In ecology, the theory of alternative stable states (sometimes termed alternate stable states or alternative stable equilibria) predicts that ecosystems can exist under multiple “states” (sets of unique biotic and abiotic conditions) (Beisner et al., 2003). These alternative states are non-transitory and therefore considered stable over ecologically-relevant time-scales. Ecosystems may transition from one stable state to another, in what is known as a state shift (sometimes termed a phase shift or regime shift), when perturbed. Due to ecological feedbacks, ecosystems display resistance to state shifts and therefore tend to remain in one state unless perturbations are large enough. While the initial onset of the algal bloom would have been caused by the combination of low dam levels and high phosphate input, feedbacks maintain the eutrophic state of the dam over time. Inorganic phosphate is bound to iron under oxic conditions and is released to the water when the hypolimnion becomes deoxygenated. One of the main causes of oxygen depletion in the hypolimnion is decomposition of sinking phytoplankton, which is related to lake trophic status (Genkai-Kato and Carpenter, 2005). Elevated phytoplankton concentrations as a result of eutrophication lead to additional sedimentation that promotes bacterial respiration and anoxia. Thus once eutrophication starts, this feedback mechanism maintains nutrient cycling within the dam resulting in the maintenance of the alternative stable state.

The model suggests that point sources play a relatively large role in ortho-phosphate loads in Witbank and Loskop dams. Minimising phosphate loads into aquatic ecosystems is key to combating eutrophication (Carpenter, 2008). In this respect, adherence to the 1 mg/l ortho-phosphate standard at WWTWs located in the catchment can have a significant impact on ortho-phosphate load reduction in the Olifants River and Witbank and Loskop Dams (Figure 5.48). While eutrophication in large water bodies can be reversed by decreasing inputs of phosphorus, rates of recovery are highly variable among water bodies and often the eutrophic state persists and recovery is slow (Carpenter et al., 1998). This is largely because of the effective recycling of phosphates within the water body.

Interestingly, the model does not predict a significantly greater reduction in loads associated with a 0.1 mg/l standard over a 1 mg/l standard. In 1980, an ortho-phosphate standard of 1.0 mg/l was introduced in South Africa, with the specific aim of controlling eutrophication in sensitive catchments. This standard has apparently had little effect on eutrophication problems (Walmsley, 2000) and a number of publications have emphasised the importance of reducing the current phosphate effluent standard of 1 mg/l to a stricter standard of 0.1 mg/l (Rossouw, 1990; Dickens et al., 2010). The fact that the model did not predict significantly greater load reductions may be because the very high nonpoint source loads predicted by the model make any reductions below 1 mg/l relatively insignificant with respect to total loading. The fact that nonpoint sources appeared to be over predicted by the model indicates that point source loads may be even more important to total phosphate loading than currently predicted, and that a 0.1 mg/l phosphate effluent standard may therefore have more of a significant influence on phosphate load reductions than currently

predicted. In this respect, reduction of point source phosphate effluent loads is crucial to reversing eutrophication in Loskop Dam.

5.8.4.5 Conclusions

While an improved calibration of the model can produce results with a higher degree of certainty, the SWAT model was able to provide good simulations of flow (particularly in catchments located in close proximity to the weather stations) and nutrient loading processes. The Steenkoolspruit catchment was identified as a significant contributor to phosphate loads in the Olifants River, even exceeding that of the Wilge River (a significantly larger catchment). Catchments responsible for high nonpoint source ortho-phosphate loading were identified and were dominated by urban and mining land uses in particular. Other more agricultural catchments in the upper reaches of the Olifants and Klein-Olifants rivers also showed relatively high nonpoint source loads, mainly due to the steeper slopes in these areas.

Eutrophication in Loskop Dam most likely occurred as a result of relatively high nonpoint source loads of ortho-phosphate (following a prolonged relatively low rainfall period) and very low dam levels, which resulted in high ortho-phosphate concentrations and the proliferation of algal blooms that have been apparent since 2008. Modelled reduction scenarios indicate that catchment-wide implementation of the 1 mg/l ortho-phosphate standard at WWTWs in the catchment can reduce loads into Witbank and Loskop Dams between 16 and 42% and 11 and 38%, respectively. These values could potentially be higher because it appeared as if the model over-predicted nonpoint source loading in the catchment. Compliance of WWTWs to phosphate effluent standards is therefore essential to manage the extent of eutrophication in Witbank and Loskop dams. Middelburg Dam is far less impacted by point sources. Effective management of nonpoint source phosphate input associated with agricultural and mining activities is required to minimise phosphate loading in this dam.

The model could be improved in various ways. Incorporation of additional weather stations as model input could provide a far more accurate representation of spatial weather conditions which will undoubtedly improve flow simulations in sub-catchments across the main catchment. Improved knowledge of sediment loads and concentrations could help improve calibration of phosphate loading. Automated calibration as opposed to manual calibrations (which are extremely time-consuming) may also help to refine model input parameters. Improved knowledge of dam releases (and daily extraction from each dam) could provide more accurate simulations of phosphate concentrations in the dams. Finally, a sensitivity analysis of input parameters would allow for further improved calibration by identifying those parameters that have the greatest influence on model outputs and ensuring that the information used for these parameters is as accurate as possible.

While the model could estimate load reductions and ortho-phosphate concentrations associated with compliance to phosphate effluent standards at WWTWs, these figures do not provide a clear indication of whether or not these reductions are sufficient to reduce eutrophication in Loskop Dam. Further work should therefore focus on calibrating the model (so as to have increased certainty associated with model simulations) and then estimating the load reductions that would be required to bring ortho-phosphate concentrations below a specific guideline value that is indicative of mesotrophic or oligotrophic conditions. Based on these predictions, it would be possible to

determine the maximum allowable phosphate load for Loskop Dam and to better identify sub-catchments or WWTWs that require remediation/management so as to achieve this load limit.

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Developing tools and guidelines to guide and improve decision making by relevant management stakeholders with regards to the potential impacts of different land uses on water quality is a complex challenge. Through this project a number of independent researchers have used a variety of tools we considered suitable at the outset of the project. The application of these models has been demonstrated through a series of case studies which are presented, predominantly in chapter five but also under chapter three and four. These approaches need to be developed and utilised in what we consider as a collaborative space since no single person, discipline or organisation is able to fully understand the whole system. The OpenMI developments are key to achieving the synergies, as are economies of scale, technical completeness and integration.

Data and information for the pursuit of modelling land use impacts on water quality are often not complete and, in many cases, are sparse, however, societal actors need to utilise modelling to enhance their scientific conversations. A major conclusion from this study is that post-normal science paradigms are crucial to adopt if we are going to utilise the available technologies in a manner that leads to socially robust (*aka actionable*) knowledge. Monitoring systems by various stakeholders need to be harnessed in concert with one another for ongoing model use and implementation of agreed courses of remedial and preventative action by the stakeholders.

Affordability in terms of time and resources is key and in this regard, commonly agreed, installed systems are imperative. In this respect the further development of a national business model that promotes the use of common software and common databases across multiple sectors and stakeholders is essential. The necessary concepts that underpin this business model are discussed in detail in Chapter 2 of this report. This recommendation is actually not new. As far back as 2004 the Department of Water Affairs and Forestry published Internal Strategic Perspectives which diagrammed the role of such systems in ongoing interactive development of options. In this respect the BASINS 4.0 software shell provides an excellent example of a modelling platform that supports the key principles of a proposed business model. Additional advantages of the BASINS 4.0 software shell are discussed in Chapter 3 and are repeated here for added emphasis. Briefly these are:

- **Avoidance of duplication.** The whole catchment modelling community focusses their efforts on creating datasets and information sets and developing models that potentially everyone else can use. This avoids the duplication ('wheel re-invention') that would occur if different modelling shells were in use.
- **Accommodation of "no size fits all".** Even though the same software shell is in use throughout the country, the BASINS 4.0 shell allows individual users to include datasets and models that are specific to the needs of their water management area.
- **Open-source.** BASINS 4.0 is based on open-source GIS software making it independent of any proprietary GIS platform. It uses the free public domain MAPWindows GIS although

also accommodates other GIS software platforms (e.g. ArcGIS and GRASS). The BASINS 4.0 stewards (i.e. the US EPA and USGS) are committed to migrating it to the OpenMI Standard interface for integrating time-dependent models. The US EPA and USGS have publically and strongly stated their commitment to embracing Open MI.

- **Modularity.** Modularity is a fundamentally sound principle in any software development. BASINS 4.0 is a highly modular shell with four main parts:
 - **Data.** These can include political boundaries, monitoring data, hydrography, land use, elevation data, soils data, meteorological data, etc.
 - **Tool and utilities.** These can include catchment reports, catchment delineation, parameter estimation, etc.
 - **Modelling.** There is a variety of models (a) linking land use and water quality, (b) estimating loads, and (c) for instream water quality.
 - **Decision making and analysis.** Post-processing (presentation of results), catchment management, sensitivity analysis, climate analysis tool, nutrient management, source water protection, total maximum daily loads (TMDLs), etc.
- **Multi-functional modelling.** The BASINS 4.0 shell contains a variety of models, ranging from simple (e.g. export coefficient) that provide estimates of load estimation (e.g. PLOAD) to complex (e.g. hydrological and instream water quality models) that are capable of predicting detailed land use and land management effects on water quality at multiple time-steps (e.g. HSPF, SWAT) and ecotoxicological effects of pollutants on aquatic ecosystems (e.g. AQUATOX).
- **Online data availability.** When installing BASINS 4.0 and building a project, data is pulled in from freely available, centralised data sets.
- **Integrative.** The BASINS 4.0 shell allows a wide variety of datasets to be used in an integrated way. It can also specifically integrate point and nonpoint source data.
- **Broad international experience base.** BASINS 4.0 has been extremely widely used and tested in a wide variety of contexts. This means that there can be high level of trust in the system. The following website illustrates the enormous emphasis given by the USA to TMDLs and hence the BASINS 4.0 shell.

The purpose of illustrating these key attributes of the BASINS 4.0 model is not to advocate or recommend the use of BASINS 4.0 in South Africa – this would require a far more detailed needs assessment that would need to take a fully developed business model into account. Rather it is to highlight key attributes that would facilitate greater use and application of these types of tools in making more informed, stakeholder driven related to land use impacts on water quality.

The team was successful in implementing a variety of modelling approaches in the case study catchments. All models varied in their application context and had strengths and weaknesses. The assessment of these models (Chapter 3) provides a guideline on their suitability for making decisions related to water quality impacts on land use. Ultimately, the choice of model is generally dependent on the nature of the problem and the level of detail required to make a decision.

Through use of these different modelling approaches, the project team concludes that it is not necessary to develop new models. There are a number of freely (open source) and commercially available options that have undergone intensive research and development and have been proven to be effective in making decisions related to land use impacts on water quality throughout the world (for example the BASINS 4.0 modelling shell is used extensively to develop TDMLs for catchments in the USA).

Rather, the challenge lies in advancing the use of models for water resource management in South Africa. This implies a deeper understanding of the use of 'models', 'modellers' and 'modelling' in helping make better decisions related to managing the impacts of land use on water quality. This was addressed in detail in Chapter 2. In addition, as mentioned above, the development and implementation of a national business model would also significantly enhance the application of models in water resource management.

The models investigated in this study varied according their data requirements. Within the context of this study, the application of the SWAT model in the upper Olifants catchment was the most data intensive modelling application. In general geospatial, water quality, flow, point source, weather, etc. data was available for populating and executing the model. However the data was often spread across multiple domains and was often difficult to source and obtain. While an entire project could focus on populating the SWAT databases for easier use in South African conditions, in general, it is recommended that a central point be established to serve as a portal for users to link to relevant institutions or online data to ease access. This feature is one of the main advantages of the BASINS 4.0 modelling shell which is able to pull all relevant data required to populate models from freely available, centralised datasets.

While local, national data was often available, in some instances it was necessary to use international data. The review of the South African land cover classification system found that levels 1 and 2 of SANS1877 in line with international classification systems used in water quality modelling software. Pollutant load export coefficients were mostly available for level 1 for phosphates, nitrates and suspended solids, however to a lesser degree for level 2 of SANS1877. However mass of pollutant exported can vary greatly based on local variables, such as climate, soils and land management, such that universal application has limitations. Thus, a method to calculate export coefficients is presented as a case study, with data requirements also listed. Further development of locally relevant export coefficients should be considered against the context of whether the export coefficient approach is seen as playing an important contribution in managing land use impacts on water quality.

The completeness and sufficiency of the available geospatial datasets for water quality modelling in South Africa remains to be evaluated. It is recommended that this evaluation be conducted within the context of the development of a national business plan that promotes the use of common software and common databases across multiple sectors and stakeholders.

A strong recommendation from this project is that South Africa can gain by developing synergies between this project and another recently completed WRC project that mapped National Freshwater Ecosystem Priority Areas (NFEPAs). The partners in the NFEPAs multi-sector, public private partnership project were:- CSIR; SANBI; WRC; DEA; DWA; WWF; SANParks and SAIAB. If one combines the work of this WRC K5-1984 project on "*Linking land use to water quality for effective water resource and ecosystem management*" to the NFEPAs project they could together

create significant momentum into the Nexus, Stewardship, CMA stakeholder and SA Water Partnership Network engagements which are beginning to take place.

At the public launch of the “*Atlas of Freshwater Ecosystems Priority Areas in South Africa :- maps to support sustainable development of water resources*”, (November, 2011) the Deputy Minister of Water & Environmental Affairs said, “*Let us continue to build on the momentum of this excellent collaboration all around the country, working together across agencies & sectors to secure these strategic areas that enhance our ability to grow and develop as a nation*”, CSIR/WRC/SANBI (2011). If we are serious about “*working together across agencies & sectors*” as the Deputy Minister said then we need to look no further than the CMA engagement space for a good place to start.

There are some unseen and unheralded organizational behaviour lessons, inherent which illustrate why this collaborative work in this WRC Project K5-1984 has an importance, way beyond the information products it contains. These are outlined below as ‘key lessons’ from our collective experiences.

1. **The value of in-kind contributions.** The building blocks of this work were essentially in-kind contributions by the partners and others. It is evident in reading and hearing about this project that were it not for in-kind contributions the project would have taken far longer, been much more expensive, much less accepted and of a lower quality. In-kind contributions are the basis of speed, affordability, credibility and implementability and sustainability in common resources management. We recommend that in-kind contributions be promoted as a major part of taking the products and processes of this WRC Project K5-1984 forward.
2. **Creation of socially robust knowledge is possible.** It is evident from talking to many people regarding this project that what has emerged is socially robust knowledge. According to Nowotny, Scott & Gibbons (2001: 258), “socially robust knowledge is the product of intensive (and continuous) interaction between results and interpretation, people and environments, applications and implications.” For knowledge regarding land use impacts on water quality to be translated into wise actions, the knowledge will have to first become socially robust. The models and socio-scientific processes assessed in this WRC project K5-1984 lend themselves to be strongly suited to generating socially robust knowledge. We recommend that the SA Water Partnership Network role-players be approached with the message that the results of this study are imperative for their systemic risk management strategy.
3. **Relational responsibility is possible to foster**, i.e. the stakeholders take their relational responsibilities as seriously as their functional responsibilities. This underlines the importance of relationship building work in the pursuit of capabilities to collectively and continuously co-reasoning using models as a key element of the process. The NFEPA atlas mentioned above is undoubtedly a key product for our future, however, the trusting and respectful relationships that have been built between the actors in this project are arguably by far the most importance result.
4. **Public-Private Partnerships can work if the context is right.** In her speech at the launch of the NFEPA report the Deputy Minister of Water & Environment Affairs said, “*We need to step up our efforts to empower communities and the private Sector to engage in water problems*”.

Hopefully the Deputy Minister will put an end to thoughts to scrap CMAs as they are potentially the biggest ongoing Public-Private Partnership to be launched in the RSA and as institutions they would place the sectors in a good position, in terms of absorptive capacity, to tackle water quality modelling at the required intellectual level. We recommend that the results of this WRC K5-1984 project be promoted as a core element of the sort of informal Public-Private Partnership that needs to form in the CMA inter-sectoral role-player engagement space.

5. **National to local connections are through people.** At national level, inter-sector engagement has yielded affordable products for local level action. Furthermore the actors who engaged at national level also engage at local level on particular projects. This goes to show the importance of people and conversations as connectors between levels of governance. In this regard we recommend that the product of this research be promoted as valuable to enhance national to local connections as a pre-condition to successful water quality management. In this regard we recommend that the WRC K5-1984 project connects closely with the Schools and Citizens River Health Programme (Dent et al., 2012), which emerged initially to assist the capacity building efforts of, *inter-alia*, post-graduate students on this project
6. **Team learning is possible amongst South African water related role-players.** Undoubtedly the team members in this project learned some key lessons about working in teams across sectors and organizations both public and private. It is these lessons which are valuable as the myriad of organizations strive to work together in managing our shared natural resources.
7. **It is possible to generate considerable momentum/motivation/co-innovation/co-creativity/spirit of generosity around water related issues.** Clearly these are all key phenomena in our quest for integration and sustainability and the actors in the NFEPA project learned that it is possible to develop such phenomena and enjoy them as the productivity flows. The same is possible from this WRC Project K5-1984.
8. **Installed systems are possible.** The systems legacy of NFEPA project is twofold. First, an installed system of free and accessible maps in GIS form, but more importantly a *de facto* installed system of relationships, trust and respect between the actors that undoubtedly augers well for the future. It is recommended that this WRC Project K5-1984 can capitalise on the NFEPA project success and can together create significant momentum into the Nexus, Stewardship, CMA stakeholder and SA Water Partnership Network engagements which are beginning to take place.

6.2 RECOMMENDATIONS

- The data paucity and the value laden nature of the issues make it imperative to work according to the paradigms present in post-normal science and those which seek to generate socially robust knowledge in a context of 'wicked' problems. The priority areas for future research are therefore in using these technologies in participatory agent-based social simulation modelling within the world class policy, legal and institutional frameworks which South African's have created since 1994.

- In this respect the development and implementation of a national business model that promotes the use of common software and common databases across multiple sectors and stakeholders is essential with regards to generating socially robust knowledge.
- While data was available for running more complex hydrological models with high data requirements, it was often spread across multiple domains and was often difficult to source and obtain. While an entire project could focus on populating the SWAT databases for easier use in South African conditions, in general, it is recommended that a central point (e.g. database) be established to serve as a portal for users to link to relevant institutions or online data to ease access for water quality modelling initiatives.
- The completeness and sufficiency of the available geospatial datasets for water quality modelling in South Africa remains to be evaluated. It is recommended that this evaluation be conducted within the context of the development of a national business plan that promotes the use of common software and common databases across multiple sectors and stakeholders.
- Export coefficients were identified as a useful first tier assessment of identifying land use impacts on water quality. However modelling applications in the case study areas relied on international values. Mass of pollutant exported can vary greatly based on local variables, such as climate, soils and land management, such that universal application has limitations. A method to export coefficients was successfully implemented in the upper Olifants catchment and consideration should be given to applying this method more widely to develop local, catchment specific export coefficients for South Africa.
- In the interests of promoting continuous multi-sector stakeholder modelling engagement that generates socially robust (i.e. actionable) knowledge to take us forward, it is recommended that a workshop involving top level executives and their water advisors needs to be held. The participants should be the calibre of people who are involved in water/food/energy Nexus conversations and those who are involved in Systemic Risk conversation. The messages to stimulate discussion in this workshop need to be those contained in this report.

6.3 REFERENCES

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CHAPTER 7: APPENDICES

APPENDIX A

TABLE A1: Water quality and land use tool evaluation matrix.

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Objective/s underlying the model's use							
Expert/participatory combination	Y	Y	Y	Y	Y	Y	
Used to Identify stakeholders	Y	Y	Y	Y	Y	Y	
Elicit knowledge about landscapes and resources	Y	Y	Y	Y	Y	Y	
Elicits stakeholder perceived values relating to landscapes and resources	Y	N	N	N	N	N	
Elicit values about social interactions	Y	N	N	N	N	N	
Encourage communication between stakeholders	Y	Y	Y	Y	Y	Y	At the appropriate level YES
Motivate long-term thinking	Y	Y	Y	Y	Y	Y	YES insofar as their proper use promotes the "WHAT IF" question
Build Consensus	Y	Y	Y	Y	Y	Y	
Institutional memory building & retention	Y	Y	Y	Y	Y	Y	
Develop plans	Y	Y	Y	Y	Y	Y	YES in the sense that participants can see where their contribution fits. Consequences of inclusion of their idea in the plans is revealed.
Motivate participation	Y	Y	Y	Y	Y	Y	YES in the sense that participants can see where their contribution fits. The high number of variables in the model is key to the inclusivity
Manage conflict	Y	Y	Y	Y	Y	Y	YES insofar as their appropriate use promotes the surfacing of assumptions, maintains transparency and indicates consequences

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Objective/s underlying the model's use (cont)							
Explore uncertainty	Y	Y	Y	Y	Y	Y	YES insofar as their proper use promotes the "WHAT IF" question
Explore complexity	Y	Y	Y	Y	Y	Y	YES proper participative modeling promotes emergence and indicate feedbacks & linkages and will reveal trigger thresholds
Identify cause and effect	Y	Y	Y	Y	Y	Y	YES if used in appropriate manner it can greatly assist
Identify potential issues or problems	Y	Y	Y	Y	Y	Y	
Facilitation of organisational co-operation	Y	Y	Y	Y	Y	Y	YES if appropriately used for social learning & generation of socially robust knowledge & inter-institutional memory
Transparency	Y	Y	Y	Y	Y	Y	YES if used appropriately
Absorptive capacity exists for its use	Y	Y	Y	Y	Y	Y	YES see major Sectors have top class intellectual capability to engage through their Govt; Business & Civil Society elements, e.g. see Table Section
Socially robust knowledge is generated through its multi-stakeholder use	Y	Y	Y	Y	Y	Y	YES if absorptive capacity is used wisely
Part of Universities, CSIR, WRC network of MoUs with DHI	N	N	N	N	Y	N	This MoU enables all these entities to use the DHI suite for capacity building.
Information elicited							
Stakeholder identification	Y	Y	Y	Y	Y	Y	
Stakeholder relationship building	Y	Y	Y	Y	Y	Y	YES if used appropriately
Plans or strategies for the future	Y	Y	Y	Y	Y	Y	YES these are probed by "what if" questions fed into the modeling systems if wisely used
Maps (Spatial component)	N	Y	Y	Y	Y	N	

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Information elicited (cont)							
Time series (continuous Temporal component)	N	Y	Y	N	Y	Y	
Perceptions of landscapes	Y	Y	Y	Y	Y	N	YES if outputs are mapped spatially
Quantitative variable values	Y	Y	Y	Y	Y	Y	
Qualitative variable values	Y	Y	Y	Y	Y	Y	Yes if translated into a default number, e.g. high; medium; low. Qualitative aspects are entrained in the model use discourse.
Group vision	Y	Y	Y	Y	Y	Y	All of the Objectives listed in these table contribute to group vision building
Possible future outcomes	Y	Y	Y	Y	Y	Y	YES through the "what if" questions translated into the model/s
Plans or strategies	Y	Y	Y	Y	Y	Y	YES through the "what if" questions translated into the model/s
Numerical projections	Y	Y	Y	Y	Y	Y	YES these are dependent on the assumptions imbedded in the models. The projection trigger mental feedbacks by participants to check assumptions. If this healthy, wisely facilitated process continues then socially robust (aka actionable knowledge) emerges. This is key for implementation.
Operational considerations							
Commercial	Y	Y	Y	Y	Y	Y	
Open source	Y	Y	Y	Y	N	Y	DHI are however leaders in OpenMI & are progressing towards OpenGIS and Open DataBase software

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Low time investment to develop standalone expertise	Y	N	N	Y	N	N	YES if one already has expertise in related areas, e.g. GIS or systems thinking or probabilities or facilitation
Operational considerations							
High time investment to develop standalone expertise							Yes if one wants to master all the functionality of the model oneself.
User Support availability in RSA or internet	M	L	M	L	H	L	High; Medium ; Low
High skills requirement	*						YES but none of these should be implemented in isolation if genuine change in stakeholder behaviour is the Objective
Low skills requirement	*						YES means that if desired then only low skills are needed but then low functionality is a consequence
Inter-operability (OpenMI compliant)	n/a	N	Y	n/a	Y	N	
Guiding Principals							
Accessibility	Y	Y	Y	Y	Y	Y	
Communicability	Y	Y	Y	Y	Y	Y	
Ongoing maintenance and development of the models and shell system at no direct cost to stakeholders	Y	Y	Y	Y	Y	Y	
Practicality	Y	Y	Y	Y	Y	Y	YES given the appropriate multi-stakeholder context we have sketched continually in this project
Requisite simplicity	Y	Y	Y	Y	Y	Y	
Scientific defensibility	Y	Y	Y	Y	Y	Y	
Scenario specificity	Y	Y	Y	Y	Y	Y	

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Transparency	Y	Y	Y	Y	Y	Y	
Guiding Principals							
Updatability	Y	Y	Y	Y	Y	Y	
Contributes to socially robust knowledge generation (co-generation; co-creation; co-consideration of consequences.	Y	Y	Y	Y	Y	Y	
Absorptive capacity available	Y	Y	Y	Y	Y	Y	
Simultaneously serve the water/energy/food Nexus engagement space	Y	Y	Y	Y	Y	Y	YES given the appropriate multi-stakeholder context we have sketched continually in this project
Institutionally sound	Y	Y	Y	Y	Y	Y	
Is compatible with OpenMI needs	Y	Y	Y	Y	Y	Y	
Affordable	Y	Y	Y	Y	Y	Y	
Global Water Partnership – Guiding Principles for Effective IRWM							
Openness	Y	Y	Y	Y	Y	Y	
Transparency	Y	Y	Y	Y	Y	Y	
Participative	Y	Y	Y	Y	Y	Y	
Accountability	Y	Y	Y	Y	Y	Y	
Effectiveness	Y	Y	Y	Y	Y	Y	
Coherence	Y	Y	Y	Y	Y	Y	
Efficiency	Y	Y	Y	Y	Y	Y	YES given the appropriate multi-stakeholder context we have sketched continually in this project
Communication	Y	Y	Y	Y	Y	Y	
Equitability	Y	Y	Y	Y	Y	Y	
Integration	Y	Y	Y	Y	Y	Y	

	Bayesian Belief Networks	HSPF	SWAT	PLOAD	MIKE-SHE (& related DHI suite)	AQUATOX	General comment on why Y or N
Sustainability	Y	Y	Y	Y	Y	Y	
Ethical behaviours	Y	Y	Y	Y	Y	Y	

APPENDIX B: GEOSPATIAL DATA GUIDELINE AND LIST OF DATASETS

Categories of geospatial data required for water quality modelling

This section provides information to sources of geospatial data in South Africa at a national level for use in water quality modelling and prediction. The section is structured according to the geospatial data categories used by water quality models in the United States Environmental Protection Agency (US EPA), namely:

- Base cartographic data
- Environmental background data
- Environmental monitoring data
- Point sources/loading data

Using Geospatial data

Geospatial data is available in different formats ranging from text files to shapefiles (vector) and grids (raster format) and in various coordinate systems. If required, format changes can be done using a Geographical Information System. The most common format is shapefiles (vector) or georeferenced GRID/TIFF/JPGs formats (raster) associated with the Environmental System Research Institute's (ESRI) ArcGIS software.

Data are captured and stored in either an unprojected or projected coordinate system.

- Unprojected coordinate systems use locational information to refer to the position of features in geospace. Examples include latitude and longitude references such as degrees, minutes and seconds, or decimal degrees. Unprojected systems are used for small areas to indicate location. This is usually referred to as a "Geographic" coordinate system.
- Projected coordinate systems use metric space to refer to the position of features in geospace. Examples include metres from the equator or a central meridian. Projected coordinate systems are used in geospatial analyses and measurements.

Each country develops computational models to represent the irregular shape of the earth which will best represent the topography of their country. Geodetic datums are then defined as official standard coordinate systems and consist of a defined ellipsoid and its location in space.

From 1999 South Africa has used the Hartebeesthoek94 Datum as its official geodetic datum (<http://www.ngi.gov.za/index.php/Geodesy-GPS/datums-and-coordinate-systems.html>). This datum is based on the World Geodetic System of 1984, which was modelled on the Global Positioning System (GPS) revolving the earth. GPSs allowed improvements on previous surveying methods. Previously the Clark1880 ellipsoid was used with the Cape Datum, which was located near Port Elizabeth. The two datums differ quite significantly in location with a difference of approximately 134 m in longitude, 110 m in latitude and 292 m in height. It is therefore of utmost importance to verify the coordinate system of a shapefile before any modelling. Many people use the WGS84 Datum as a substitute for the Hartbeesthoek94 Datum.

Always check which coordinate system the water quality modelling software requires before converting all your shapefiles to the same coordinate system (whether projected or not). The metadata file of a shapefile is usually an .xml file which will indicate the coordinate system information. If no coordinate system or metadata is provided, it is best to contact the data custodian to verify the coordinate system information before using the data, or assuming that it is geographic.

Current GIS software reads the projection file information (*.prj) and project data visually to the same coordinate system. This is however insufficient when undertaking geospatial analysis, where all shapefiles need to be in the same projected coordinate system. In older GIS software such as ArcView 2.x or 3.x the differences were quite visible as the software did not create projection files or “project on the fly”. Please do not assume that geospatial data published after 1999 would be in the Hartbeesthoek1994 datum. Always verify and transform or project your data before use. The projected coordinate system needs to be defined when starting up a new project. In South Africa users can choose between a variety of projected coordinate systems, of which the Transverse Mercator and Albers Equal Area projections are mostly used. Some properties of geospatial features are preserved and others distorted when data are projected. Investigate these properties of a projected system before you choose one. Preservation of surface area often uses Albers Equal Area projections, however in network analysis this may not preserve distance and direction. Other projected coordinate systems are then preferred.

Lists of geospatial data per category:

POLITICAL BOUNDARIES

The Municipal demarcation board is the data custodian of provincial boundaries, district and local municipality boundaries and ward boundaries. Data can be downloaded directly from their website at district and local municipal level per province. To obtain the full extent of South African political boundaries contact them directly.

Metadata for political boundaries are listed in the following tables:

- Table A1 – province boundaries
- Table A2 – district/local municipality boundaries
- Table A3 – ward boundaries

Table B1: Metadata for geospatial data of provincial boundaries of South Africa

Data custodian	Municipal Demarcation Board (MDB)
URL	http://www.demarcation.org.za/pages/default_new.html
Contact details	See website
File Format	ArcGIS shapefile or Google Earth kmz file
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Not indicated
Product date/Source date	2011 (previous ones available for 2007, 2005 and prior 1992)
Source of capturing	Not indicated
Temporal frequencies of updates	When required
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ OBJECTSID – unique polygon identifier ○ PROVNAME – name of the provinces ○ AREA – surface area but not indicated in which projected coordinate system it was calculated ○ Shape_Length – unclear what this is ○ Shape_Area – surface area but not indicated in which projected coordinate system it was calculated 	
<u>Description:</u> The provincial boundaries and names of South Africa	
<u>Citation to be used:</u> Not indicated	

Table B2: Metadata for geospatial data of district/local municipality boundaries of South Africa

Data custodian	Municipal Demarcation Board (MDB)
URL	http://www.demarcation.org.za/pages/default_new.html
Contact details	See website
File Format	ArcGIS shapefile or Google Earth kmz file
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Not indicated
Product date/Source date	2011 (previous ones available for 2007, 2005 and prior 1992)
Source of capturing	Not indicated
Temporal frequencies of updates	When required
Cost	Free
<p><u>Attribute field descriptions for district municipalities:</u></p> <ul style="list-style-type: none"> ○ OBJECTID – unique polygon identifier ○ DISTRICT – district code that can be used for mapping and labelling ○ DCNAME – name of the municipality ○ PROVINCE – province code within which the municipality falls ○ Shape_Length – meaning not clear ○ Shape_Area – surface area calculated but not sure in which projection. <p><u>Attribute field descriptions for local municipalities:</u></p> <ul style="list-style-type: none"> ○ OBJECTID – unique polygon identifier ○ CATEGORY – category A or B of local municipality (metropolitan or not) ○ CAT_B – code that can be used to map and label the municipality ○ MUNICNAME – name of the municipality ○ NAMECODE – name of the municipality with the code in brackets ○ MAP_TITLE – name of the municipality with type of municipality and code in brackets ○ DISTRICT – District code within which the municipality is located ○ PROVINCE – province code within which the municipality is located ○ Shape_Length – meaning not clear ○ Shape_Area – surface area calculated but not sure in which projection. 	
<u>Description:</u> Boundaries of local and district municipalities of South Africa	
<u>Citation to be used:</u> Not indicated	

Table B3: Metadata for geospatial data of ward boundaries of South Africa

Data custodian	Municipal Demarcation Board (MDB)
URL	http://www.demarcation.org.za/pages/default_new.html
Contact details	See website
File Format	ArcGIS shapefile or Google Earth kmz file
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Not indicated
Product date/Source date	2011 (previous ones available)
Source of capturing	Not indicated
Temporal frequencies of updates	When required
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ PROVINCE – province code within which the ward is located ○ CAT_B – local municipal code in which the ward is located ○ WARDNO – unique two digit ward number ○ WARD_ID – unique eight digit ward code ○ SUM_WARD_P – meaning unclear ○ Shape_Length – meaning unclear ○ Shape_Area – surface area calculated but not sure in which projection. ○ Density – meaning unclear 	
<u>Description:</u> Boundaries and codes of wards in South Africa	
<u>Citation to be used:</u> Not indicated	

INFRASTRUCTURE

There are two suppliers of transport infrastructure in South Africa:

- The Department of Rural Development & Land Reform's National Geo-Spatial Information Directorate (DRDLR-NGI) who has cartographic responsibilities to map basic features and produce topographical maps;
- The Department of Transport (<http://www.transport.gov.za/Default.aspx>). This website is however still under construction and no links to data download or contacts were visible. Links to departments managing rail, road, bus and taxi transport is listed but inactive.

Metadata for transport infrastructure is therefore listed only for DRDLR-NGI:

- Roads, railway lines and railway stations – Table A4.

Geospatial data cannot be downloaded from the DRDLR-NGI website, but can be acquired from their Mowbray office in Cape Town. Other NGI branches in other cities, for example, provide only hardcopy maps. Shapefiles can be requested at the counter in Mowbray and received on a CD or DVD, or one can send an external hard drive down with the request to copy all the data, though this will take some time. Data is for free however media provided will be charged (CD/DVD). One can also contact the vendors listed on their website to obtain the data, though not all vendors hold the latest versions.

Maps and data were originally captured and generated from stereo-pair aerial photography. More recent updates are created from both aerial photography and satellite imagery.

The geospatial data is provided as shapefiles per group of sixteen 1:50 000 topographical maps. This extends over a latitude-longitude degree block of South Africa. Various shapefiles are sorted under a folder for each degree-blocks, e.g. 2528 (i.e. latitude 25°S and longitude 28°E) including *i.a.* air transport areas, rivers, road lines, railway lines, railway stations, inland water bodies, relief lines and spot heights (Figure 4.3.2). The road file is listed as, e.g. "2528_ROAD_LINE_2006_04.shp". The first 4 digits are indicative of the latitude and longitude block, followed by the descriptive name, then the year and month.

Some of the other files may look useful (e.g. artificial surface area, land use and vegetation), though is not always complete, or consistently captured throughout South Africa.

To cover a whole study area these files needs to be merged, the lines connected on the borders and topology created. A merged national dataset is not available from the DRDLR-NGI, but the CSIR (Pretoria) has merged the roads, railways and airports and other features as was issued in 2006. They are a registered vendor of the DRDLR-NGI and data can be obtained through CallCentre@csir.co.za.

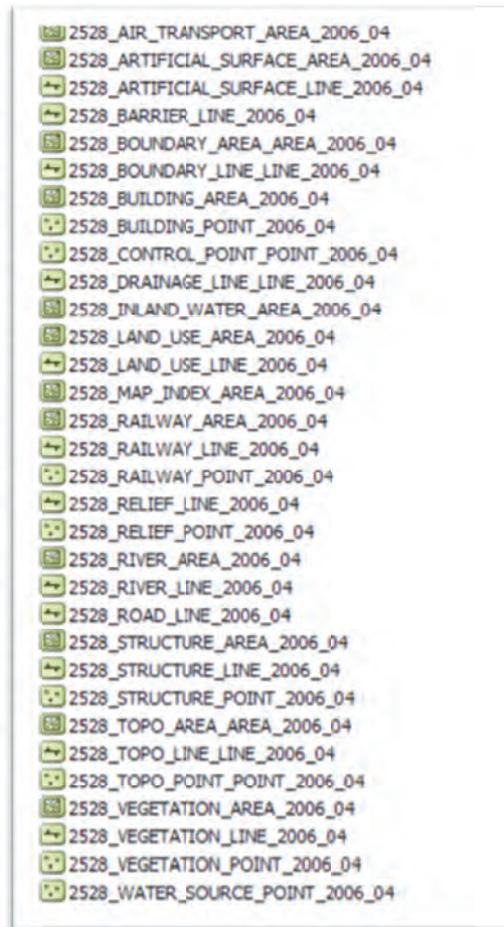


Figure B1: Example of geospatial data available from DRDLR-NGI for each degree block in South Africa

Table B4: Metadata for geospatial data of the road infrastructure of South Africa (road, railway lines and railway stations)

Data custodian	Department of Rural Development & Land Reform's National Geo-Spatial Information Directorate
URL	http://www.ngi.gov.za/
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	No metadata was provided with the 2009 shapefile updates and no coordinate system is indicated. Assumed to be geographic.
Scale of data capturing	1:50 000
Product date/Source date	Vary per degree block, most recent 2011
Source of capturing	Aerial photographs/satellite imagery
Temporal frequencies of updates	Continuous updates are done for some areas
Cost	Free; media are charged (CD/DVD) unless you provide your own

Attribute field descriptions:

- GDO_GID – unique id
- TAG – contains the road or railway station name in some instances, or a tag code starting with “#”. These should be removed or excluded for labelling purposes
- FEAT_TYPE – road classes or railway line types:

Road types:	Railway line types:
<i>National freeway</i>	<i>Abandoned</i>
<i>National route</i>	<i>Large Station</i>
<i>Interchange</i>	<i>Marshalling line</i>
<i>On-off ramp</i>	<i>Narrow gauge</i>
<i>Arterial road</i>	<i>Standard</i>
<i>Main road</i>	<i>Station</i>
<i>Secondary road</i>	<i>Under construction</i>
<i>Other access</i>	
<i>Street</i>	
<i>Under construction</i>	
<i>Track footpath</i>	
<i>Hiking trail</i>	
<i>Fence</i>	

- GEOM_TYPE – all line features
- MAPSHEET – the 1:50 000 ¼-degree grid block representing the extent of the dataset
- ROW_STATUS – meaning unclear
- LOCK_DATE – meaning unclear
- SELECTION_ – meaning unclear
- VERSION_NU – meaning unclear
- VERSION_DA – meaning unclear; not sure how this differ from CREATE_DAT field
- VERSION_ST – meaning unclear
- MODIFIED_B – person who captured or modified the feature
- RETIRED_DA – meaning unclear

- ORIGINAL_G – meaning unclear
- CREATE_DAT – meaning unclear; not sure how this differ from VERION_DA field
- DATA_SOURC – meaning unclear
- EST_REVISI – meaning unclear
- SOURCE_VER – meaning unclear
- SOURCE_PRO – meaning unclear
- SOURCE_P_1 – meaning unclear
- SOURCE_CON – meaning unclear
- CAPTURE_IN – meaning unclear
- DESCRIPTIO – meaning unclear

Description: Road lines per degree block of South Africa. Unmerged. Once merged, topology needs to be created.

Citation to be used: Not indicated.

URBAN AREAS

There are three national datasets that could be considered for urban or built-up areas:

- A polygon extent of the urban areas of South Africa, produced by MapIT
- A polygon extent of the communities, village and urban areas of South Africa produced by the Department of Water Affairs (DWA) in 2006
- A point and polygon file of the dwelling units captured from the SPOT satellite imagery from 2006-8

The ESKOM Dwelling inventory (Breytenbach, 2008) consists of a combined set of point and polygons for each province which should be used in combination with one another (Table A6).

Table B6: Metadata for geospatial data of urban areas in South Africa

Data custodian	MapIT (Pty) Ltd
URL	http://www.mapit.co.za
Contact details	Trevor Morgan Operations Manager MapIT (Pty) Ltd Office: +27 (0) 12 003 0753 Fax: +27 (0) 86 606 2748 Skype: t.morgan_mapit.co.za www.mapit.co.za
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Most information is captured from 0.2 or 0.4 metre resolution aerial photography.
Product date/Source date	Various dates but imagery is sourced from Geospace and captured in house.
Source of capturing	Aerial photography is the primary source with some use of SPOT but this is very limited.
Temporal frequencies of updates	Not indicated
Cost	Not free
<u>Attribute field descriptions:</u> Names – not indicate whether this name is a suburb or town area name.	
<u>Description:</u> Built up areas of South Africa	
<u>Citation to be used:</u> Not indicated.	

Table B6: Metadata for geospatial data of community villages in South Africa

Data custodian	Department of Water Affairs (DWA) Water Services Planning & Information
URL	
Contact details	Stephen Marais MaraisS@dwa.gov.za 012 336 8276
File Format	ArcGIS shapefile
Coordinate system	Not available at the time of publication
Scale of data capturing	Not available at the time of publication
Product date/Source date	2011
Source of capturing	Not available at the time of publication
Temporal frequencies of updates	Not available at the time of publication
Cost	Not available at the time of publication
Attribute fields descriptions: Not available at the time of publication	
Description: Not available at the time of publication	
Citation to be used: Not indicated.	

Table B7: Metadata for geospatial data of dwellings in South Africa

Data custodian	ESKOM and CSIR Satellite Application Centre (SAC) ¹
URL	http://www.eskom.co.za/
Contact details	Sajidha Hoosen GIS Advisor Corporate Services IARC ESI-GIS, Komati House Eskom Academy of Learning, Midrand Tel 011 690-4082 (8139-4082) Fax 011 690-4271 (086 661-7843) Sajidha.Hoosen@eskom.co.za
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	1:5 000
Product date/Source date	2009
Source of capturing	SPOT-5 2.5 panchromatic satellite imagery
Temporal frequencies of updates	Not identified
Cost	Free, though a Legal Confidentiality and Non-Disclosure agreement needs to be signed.
Attribute field descriptions: please refer to Table 2 in Breytenbach 2008:6 for more information on each attribute field. Dwellings are classified according to the following 7 types:	
<ul style="list-style-type: none"> • School • Complex/Hostel 	

¹ The CSIR Satellite Application Centre has stemmed of from the CSIR in 2011 to become the South African National Space Agency (SANSA)

- Mine/Quarry
- Resort
- Dwelling
- Other Built-up
- Dense Informal

Description: SPOT building count per province. Point shapefile of individual dwellings with associated polygons of adjacent areas with high density buildings.

Citation to be used: Not indicated.

CENSUS INFORMATION

Statistics South Africa (StatsSA) is the main data custodian of census surveys in South Africa.

- Previous census data can be obtained from StatsSA, but should be used with the previous political boundaries.
- Population census survey statistics of 1996 and 2001, and the Community Survey of 2007 and information on the planning for the 2011 census is accessible from <http://www.statssa.gov.za/publications/populationstats.asp>. Follow the link to “Interactive & electronic products” to obtain tables at provincial, district or municipal level. A GIS CD can also be requested and obtained from their User Information Services.
- Data needs to be linked to an Enumerate Areas (Table A8).

Table B8: Metadata for geospatial data of census information and Enumerate Areas of South Africa

Data custodian	Statistics South Africa
URL	http://www.statssa.gov.za
Contact details	User Information Services Tel. +27 12 310 8600 E-mail: info@statssa.gov.za
File Format	Not available at the time of publication
Coordinate system:	Not available at the time of publication
Scale of data capturing	Not available at the time of publication
Product date/Source date:	2001
Source of capturing	Not available at the time of publication
Temporal frequencies of updates	Not available at the time of publication
Cost	Not available at the time of publication
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ Not available at the time of publication 	
<u>Description:</u> Enumerate Areas	
<u>Citation to be used:</u> Not available at the time of publication	

HYDROLOGICAL UNITS (CATCHMENT BOUNDARIES)

Catchment boundaries in South Africa are available at primary, secondary, tertiary and quaternary level. Originally data were captured manually using hardcopy topographical maps and rainfall run-off information (Midgley et al., 1994). The Water Research Commission (WRC) in association with the Department of Water Affairs (DWA) completed an updated set of catchment boundaries for hydrological purposes. The hydrological flow and river network was calculated from the Shuttle Radar Topography Mission's 90 m Digital Elevation Model (DEM), and known pour point positions are included in the product (Weepener, 2012).

Table B9: Metadata for geospatial data of the hydrological units of South Africa (primary – quaternary catchments)

Data custodian	Department of Water Affairs (DWA): Directorate Spatial and Land Information Management
Vendor	Data: Department of Water Affairs (DWA): Directorate Spatial and Land Information Management Report: Water Research Commission (WRC)
URL	
Contact details	Lynton Twyman Department of Water Affairs (DWA) Directorate: Spatial & Land Information Management Tel: 012 336-7220 TwymanL@dwa.gov.za
File Format	ArcGIS grid and TIFF files
Coordinate system	Geographic, Spheroid and datum WGS84
Scale of data capturing	90 m
Product date/Source date	DEM 90 m
Source of capturing	Hydrological modelling in ArcGIS
Temporal frequencies of updates	Updated 2012
Cost	Free of cost
<u>Attribute field descriptions</u> (refer to the individual data sets for more information)	
<ul style="list-style-type: none"> ○ Catchments codes for primary, secondary, tertiary and quaternary catchments provided. 	
<p><u>Description:</u> All remaining sinks in the flow path improved DEM were filled before the quaternary catchments were calculated.</p> <p>Pour points were defined for each of the quaternary catchments by hydrologists from the Department of Water Affairs (Danie van der Spuy and Pieter Rademeyer). Mostly geographic recognisable points such as the intersection of tributaries with the main stream or dam walls were used as pour points. Furthermore the pour points were selected in such a way that they did not deviate too much from the previous catchments. The quaternary catchments include urban areas where drainage is artificially manipulated.</p> <p>At the coast small rivers were often grouped together. Where possible a pour point was selected for at least every second catchment along the coastline, which then defined the left or right catchment boundary of the grouped catchment.</p>	

The international boundary follows river lines and /or watersheds where applicable. The boundary was digitised from SPOT 5 imagery by hydrologists from the Department of Water Affairs (Danie van der Spuy and Pieter Rademeyer).

The coastline follows an hydrological boundary that excludes areas where dunes forms a drainage boundary near the coastline, causing the water to flow directly towards the see and not into the catchment.

The names of catchments outside South Africa include the original name with the words cross_border at the end.

Citation to be used: Weepener H.L., Van den Berg H.M., Metz M. and Hamandawana H., 2012: The development of a hydrologically improved Digital Elevation Model and derived products for South Africa based on the SRTM DEM Water Research Commission (WRC) Report No.1908/1/11.

Environmental Background Data

WATER MANAGEMENT AREAS

The data custodian of the Water Management Areas (WMA) is the Department of Water Affairs (DWA) and the file is downloadable from their website (Table B10).

Table B10: Metadata for geospatial data of the Water Management Areas (WMAs) of South Africa

Data custodian	Department of Water Affairs (DWA) Resource Quality Services (RQS)
URL	http://www.dwa.gov.za/geomatics/
Contact details	See metadata
File Format	ArcGIS shapefile
Coordinate system:	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	1:50 000
Product date/Source date:	2004
Source of capturing	Manual digitizing
Temporal frequencies of updates	Unknown
Cost	Free
Attribute field descriptions:	
<ul style="list-style-type: none"> ○ AREA – Surface area (not calculated) ○ PERIMETER – Meaning unclear ○ WMA_DWAF_ – Unique polygon identifier ○ WMA_DWAF_I – WMA code ○ WATERMAN_N – WMA name ○ MAJOR_RIVS – Major river within WMA ○ SHAPE_AREA – Surface area, not indicated in which coordinate system this was calculated ○ SHAPE_LEN – Meaning unclear 	
<p>Description: The National Water Resources Strategy provides the framework within which water will be managed at regional and catchment level, within defined Water Management Areas. Supplemental Information: The boundaries are based on the drainage region boundaries.</p> <p>The water management areas are the areas whereby regional or catchment levels will be managed. The National Water Act (Act 36 of 1998) requires the progressive development of a National Water Resource Strategy (NWRS), which provides a framework for the protection, use, development, conservation, management and control of water resources for the country as a whole.</p>	
Citation to be used: Not indicated.	

ECOREGIONS

The Ecoregions of South Africa was developed to Level I and II by the Department of Water Affairs (DWA).

Table B11: Metadata for geospatial data of the ecoregions of South Africa

Data custodian	Department of Water Affairs (DWA) Resource Quality Services (RQS)
URL	http://www.dwaf.gov.za/iwqs/gis_data/ecoregions/get-ecoregions.asp
Contact details	(use website information)
File Format	ArcGIS shapefile
Coordinate system:	Geographic, Spheroid Clarke 1880, Cape Datum
Scale of data capturing	1:2 000 000 and 1:10 000 000
Product date/Source date:	2005
Source of capturing	Various – please refer to metadata associated with file
Temporal frequencies of updates	Unknown
Cost	Free
<u>Attribute field descriptions:</u>	
Level I shapefile:	
<ul style="list-style-type: none"> ○ ID: unique identifier of the ecoregion ○ LEV1: unique identifier of the ecoregion ○ ECOREGION: name of the ecoregion ○ ID_ECOREGI: unique identifier and name of the ecoregion 	
Level II shapefile:	
<ul style="list-style-type: none"> ○ LEVEL: numerical code indicating the first and second level ecoregion separated by a full stop, e.g. Level I #19 and Level II #03 will be coded as 19.03 ○ LEV1: numerical codes for Level I ecoregions ○ LEV2: numerical codes for Level II ecoregions 	
<u>Description:</u> Ecoregions (Level I, version 2005) for South Africa derived from terrain and vegetation, with some consideration of altitude, rainfall, runoff variability, air temperature, geology, soil. Level I typing is based on the premise that ecosystems and their components display regional patterns that are reflected in spatially variable combinations of causal factors such as climate, mineral availability (soils and geology), vegetation and physiography (Omernik, 1987). In South Africa, physiography, climate, geology, soils and potential natural vegetation, have been used as the delineators of Level I. Level II typing will produce regional or sub-catchment scale ecotypes. Level II will be a suitable stage to link to stream classification. Due to the amount of detail required to progress beyond Level II (i.e. Levels III & IV), such delineations will probably not be done in the near future.	
<u>Citation to be used:</u> Kleynhans, CJ, Thirion, C and Moolman, J (2005). A Level I River Ecoregion classification System for South Africa, Lesotho and Swaziland. Report No. N/0000/00/REQ0104. Resource Quality Services, Department of Water Affairs and Forestry, Pretoria, South Africa.	

SOIL DATABASE

The data custodian for soil information in South Africa is the Agricultural Research Council's Institute for Soil Climate and Water (ISCW). A number of soil-related datasets are available from the Agricultural GIS website (AGIS) at <http://www.agis.agric.za/agisweb/agis.html>. Follow the Metadata link and type in "soils", for example. These datasets can be previewed in a number of online atlases and then either downloaded or requested. License agreements pertain to those which need to be requested.

The Food and Agricultural Organisation (FAO), World Soil Information (ISRIC) and the United Nations Environment Programme (UNEP) compiled a soil and terrain database for Southern Africa in 2003 at a scale of 1:1 200 000 (FAO, ISRIC & UNEP, 2003). This dataset is available from the ISRIC website, now associated with a report on soil and landform properties for LADA countries (Dijkshoor, Van Engelen & Hunting, 2008) (Table 4A12). The soil data included in this dataset originated from the ARC-ISCW, however in the references it is not clear which dataset was obtained from AGIS.

Table B12: Metadata for geospatial data of the soil associations of Southern Africa

Data custodian	Food and Agricultural Organisation (FAO)
URL	http://www.isric.org/projects/soter-southern-africa-sotersaf
Contact details	See website
File Format	The geospatial data is in Arc/Info export format (*.e00) and the soil and terrain attributes in a database (MS Office 2004 Access format – *.mdb).
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	1:1 200 000
Product date/Source date	Prior to 2008
Source of capturing	Not indicated
Temporal frequencies of updates	Not indicated
Cost	Free
Attribute field descriptions (please refer to the report for explanations of unlisted fields):	
<ul style="list-style-type: none"> ○ AREA – Surface area, not indicated in which projection this was calculated ○ PERIMETER – meaning not clear ○ SOTERSAF# – unique polygon identifier ○ SOTERSAF-ID ○ ISOCSUID ○ SUID ○ OTHER ○ LANDFORM – Landform code ○ LITHOLOGY ○ SOILS – Soil code ○ WRB ○ DOMSOILS ○ CODE_WRB 	

Description: Soil and terrain data of South Africa and other adjacent countries
Citation to be used: Dijkshoorn JA, van Engelen VWP and Huting JRM 2008. Soil and landform properties for LADA partner countries (Argentina, China, Cuba, Senegal and The Gambia, South Africa and Tunisia). ISRIC report 2008/06 and GLADA report 2008/03, ISRIC – World Soil Information and FAO, Wageningen (23 pp with dataset). http://www.isric.org/isric/Webdocs/Docs/ISRIC_Report_2008_06.pdf

HYDROGRAPHY DATASET

A number of hydrography datasets exists for South Africa:

- 1:500 000 river network from DWA-RQS (Table A13)
- 1:50 000 river network from DWA (Table A14)
- 1:50 000 river network from DRDLR-NGI (Table A15)
- 1:500 000 large dams from DWA-RQS (Table A16)
- 1:50 000 water bodies from DRDLR-NGI (Table A17)
- National Wetland Map v.4 – South African National Biodiversity Institute (SANBI) (Table A18)

For data generated by the DRDLR-NGI please refer to Section 4.3.2 on how the data is generated.

Table B13: Metadata for geospatial data of the 1:500 000 rivers of South Africa

Data custodian	Department of Water Affairs (DWA) Resource Quality Services (RQS)
URL	http://www.dwaf.gov.za/iwqs/gis_data/river/rivs500k.html Also download xml separately
Contact details	See website
File Format	ArcInfo coverages or shapefile
Coordinate system	Geographic, Spheroid Clarke 1880, Cape Datum
Scale of data capturing	1:500 000
Product date/Source date	2010
Source of capturing	Topographical maps as produced by the Department of Rural Development and Land Reform (DRDLR) in Mowbray, Cape Town.
Temporal frequencies of updates	Infrequent, as required
Cost	Free
Attribute field descriptions (as indicated in metadata.xml file):	
<ul style="list-style-type: none"> ○ NAME: generally, the name assigned to the reach on a topographical map <ul style="list-style-type: none"> ▪ sometimes the correctness is uncertain. ▪ ALIAS: alternate name or names for the reach, separated by \. ▪ RIVN_ROOT: For multilingual annotation purposes (prototype): the root of the river name. ▪ RIVN_SUFEX: The qualifier of the river name, e.g. river, spruit, loop. ○ CLASS: unreliable indicator of seasonality of river flow. The classes and allocation require review: <ul style="list-style-type: none"> ▪ Dry=dry river, Perennial=perennial river, Non=non-perennial river, ▪ Unknown=not present in original coverage or not transferred from source map. ○ PRIMARY: primary drainage region where the reach occurs. <ul style="list-style-type: none"> ▪ a lower-case letter indicates a pseudo drainage region outside South Africa. ○ ORDER: Strahler order, starting from source=1. ○ END: S=Source, N=iNtermediate, M=Mouth, E=Endorheic. ○ REACHCODE: 10-character reach code made up as follows: <ul style="list-style-type: none"> ▪ 1 to 4: quaternary drainage region in which MOST of the river falls. (Note that some USA programs like BASINS expect eight numerical digits. 	

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- o The qat4qat8.txt lookup table contains the correct DWA to USA conversions.)
 - 5 to 6: arbitrary sequence number of the reaches within a quaternary drainage region.
 - 7 to 10: four zeroes (0000) in the 1:500 000 coverage, intended for later use at more detailed scale.
- o SORTER: sorting field — always increases downstream in a river network
- o LENGTH_KM: length of reach in kilometres (not to be confused with the meaningless LENGTH field).
- o RivEX fields: (see <http://www.rivex.co.uk/>)
 - SHREVE: Shreve order.
 - US_ACCUM: Accumulated upstream metres at the lower node of each arc.
 - CATCHID: Automatically generated ID for each end node (i.e. when END='E' or 'M').
 - DIST2MTH : Distance to the mouth in metres from the upper node of each arc.
 - LINK_TYPE : same idea as the "END" field, above. E=Exterior, I=Interior, O=Outlet.
 - SEGMENT : Channel identifier.
 - CATCHID : drainage region identifier.

Description: A 1:500 000 medium scale drainage network of main stem rivers and tributaries of South Africa and parts of neighbouring countries. Characteristics:

- o Rivers lines are within 50 m of the 1:50 000 river network as shown on topographical maps
- o Topologically correct
- o Streams are ordered (Strahler method)
- o Reach codes calculated using quaternary drainage regions

Processing done on file:

“Cape datum 1994 – Digital data supplied to Department of Water Affairs

1995 – Rivers selected to match national monitoring network by GisLAB – Gaps in rivers at dams closed – Rivers made to point downstream – Strahler ordering applied – Some river names checked – still 50% unlabelled arcs – perennial/non-perennial classification inconsistent – WARNING – Digitising at 1:500 000 with 1 mm accuracy implies errors of up to 500 metres. Each original map sheet may have its own offset...

1996 to 2003 – Rivers adjusted to match arcs on 1:50 000 maps – Obvious drainage errors corrected – River orders re-calculated with Lamphear and Lewis' STREAM_ORDER.AML – REACHCODE allocated to each inter-node stretch (based on main quaternary drainage) – SORTER code allocated (increases downstream) – Names corrected where possible, ALIAS field added for alternatives – LENGTH_KM field added to retain arc lengths in geographic projection – Rivers added to "empty" quaternary drainage regions: A62E, A62F, A91A, A91E, G40H, M20A, U70F, W60M, X32E, Y10H, Y60A. – Quaternary drainage regions confirmed as "dry": D62H, H80F, Z10D – First public beta release of rivers 2003-06-20.

2004 – Limpopo rivers in Mozambique updated with the Atlas for Disaster Preparedness and Response in the Limpopo Basin, INGC, University of Eduardo Mondlane Department of Geography and USAID/FEWS NET MIND 2003.

2005 – Michael Silberbauer used Shuttle Radar Topography 90-metre DEM data to improve river alignments in Lesotho (no 1:50_000 data available for most of Lesotho). – Lungile Gaulana checked through the naming of river arcs, making about 5000 changes to names and alignments. – Michael Silberbauer used the South African Geographical Names System web site (<http://sagns.dac.gov.za>) to update the official naming and orthography. – Accuracy in comparison with the 1:50_000 data, for the area of South Africa, Lesotho and Swaziland, based on a random 1% sample of arcs: Spatial: 94.6% OK, 4.3% no 1:50_000 data, 1.1% > 50 metre error. Attributes: Names: 97.8% OK, 2.2% wrong Alias: 95.7% OK, 4.3% wrong Class: 83.9% OK, 10.8% non-perennial wrong, 5.4% perennial wrong.

2006 – Michael Silberbauer used RivEX (<http://www.rivex.co.uk/>) to verify the topology. Found and corrected about 100 previously undetectable errors (microloops and double vertices). – JOINITEMed these fields generated by RivEX: SHREVE: Shreve order US_ACCUM: Accumulated upstream metres at the downstream node of each arc CATCHID : Automatically generated ID for

each end node (END=E or M) DIST2MTH : Distance to the mouth in metres at the upstream node of each arc August release: Minor changes to the river arcs in B, V, W & X regions. Inclusion of many "trace" .txt files that were previously missing from the web site. December release: Minor changes to the river arcs in B. Major change in L: closure of gap in the Sout River (L11A) near the Skilpadkop River, Gamtoos catchment.

2009 4 new headwater streams in A31A. Naming of streams in E: Oudste, Noordhoeks, Agterste, Voorste, Boskloof and Krom. In T: Nenga River. 2010 Fixed errors in D61F07, F30F05, S10B05; E region Ratel given alias Ratels; Fixed uncertain river directions and quaternary drainage edges in D55F, J1, 7 and D54A5, 6."

Citation to be used: Not indicated

Table B14: Metadata for geospatial data of the 1:50 000 rivers from DWA of South Africa

Data custodian	Department of Water Affairs (DWA)
URL	None – data must be requested
Contact details	SoulsB@dwa.gov.za
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	1:50 000
Product date/Source date	2010 for parts of the country. A full dataset will be available in 2012.
Source of capturing	DRDLR-NGI data, flow direction and topology fixed
Temporal frequencies of updates	None
Cost	Free
Attribute field descriptions: This will be made available with the full publication of the dataset in 2012.	
Description: This is the 1:50 000 mapjoined river data, per Primary Drainage Region, based on the 1:50 000 topographic series of DRDLR-NGI. These, as part of the DWA Sub-Directorate: Geomatics project, were 'cleaned' to have 'calculated' flow directions and stream ordered, to meet the requirements of the DWA uses.	
Citation to be used: DWA, 2010.	

Table B15: Metadata for geospatial data of the 1:50 000 rivers from DRDLR-NGI of South Africa

Data custodian	Department of Rural Development & Land Reform's National Geo-Spatial Information Directorate (DRDLR-NGI)
URL	http://www.ngi.gov.za/
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	No metadata was provided with the 2009 shapefile updates and no coordinate system is indicated. Assumed to be geographic.
Scale of data capturing	1:50 000
Product date/Source date	Vary per degree block
Source of capturing	Aerial photographs/satellite imagery
Temporal frequencies of updates	Continuous updates are done for some areas
Cost	Free; media is charged (CD/DVD) unless you provide your own
Attribute field descriptions:	
<ul style="list-style-type: none"> ○ GDO_GID – unique id ○ TAG – contains the river names in some instances, or a tag code starting with “#”. These should be removed or excluded for labelling purposes ○ FEAT_TYPE – river line types includes i.a. “Non-perennial center line”, “perennial center line” and “Waterfall” ○ GEOM_TYPE – all line features ○ MAPSHEET – the 1:50 000 ¼-degree grid block representing the extent of the dataset ○ ROW_STATUS – meaning unclear ○ LOCK_DATE – meaning unclear 	

- SELECTION_ – meaning unclear
- VERSION_NU – meaning unclear
- VERSION_DA – meaning unclear; not sure how this differ from CREATE_DAT field
- VERSION_ST – meaning unclear
- MODIFIED_B – person who captured or modified the feature
- RETIRED_DA – meaning unclear
- ORIGINAL_G – meaning unclear
- CREATE_DAT – meaning unclear; not sure how this differ from VERION_DA field
- DATA_SOURC – meaning unclear
- EST_REVISI – meaning unclear
- SOURCE_VER – meaning unclear
- SOURCE_PRO – meaning unclear
- SOURCE_P_1 – meaning unclear
- SOURCE_CON – meaning unclear
- CAPTURE_IN – meaning unclear
- DESCRIPTIO – meaning unclear

Description: River lines per degree block of South Africa. Unmerged. Once merged, topology needs to be created.

Citation to be used: Not indicated.

Table B16: Metadata for geospatial data of the 1:500 000 large dams of South Africa

Data custodian	Department of Water Affairs (DWA) Resource Quality Services (RQS)
URL	http://www.dwaf.gov.za/iwqs/gis_data/river/rivs500k.html See “Download unofficial shapefile of dams (i.e. artificial lakes)... “
Contact details	See metadata
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid Clarke 1880, Cape Datum
Scale of data capturing	1:500 000
Product date/Source date	2006
Source of capturing	Various – see metadata
Temporal frequencies of updates	Infrequent, as required
Cost	Free

Attribute field descriptions:

- AREA – surface area, not calculated
- PERIMETER – meaning unclear
- DAMS500G_ – unique polygon identifier
- DAMS500G_I – meaning unclear
- STATION – meaning unclear
- NAME – name of the dam
- X-COORD – meaning unclear, possible centre point of dam
- Y-COORD – meaning unclear, possible centre point of dam
- TYPE – reservoir, island, natural (*sic.*)
- ALIAS – alternative name of dam
- FEAT_ID – meaning unclear, field empty
- AREA_K – surface area calculated but coordinate system in which it was done not indicated
- SHAPE_AREA – surface area calculated but coordinate system in which it was done not

<p>indicated</p> <ul style="list-style-type: none"> ○ SHAPE_LEN – meaning unclear
<p>Description: Processing done on file as listed in metadata by Dr Silberbauer: “1994 – Digital data supplied to Department of Water Affairs 1995 – Dam polygons closed by GisLAB 1995 – Dams cleaned and named by IWQS (over-cleaned?) 1996 – Dams fixed and stations added by IWQS (Michael Silberbauer) 1996 – Extra dams & lakes added from satellite images 1999 – Extra dams added from 1:50 000 blue plate coverage – Some 1:500 000 arcs replaced by 1:50 000 arcs – Errors in station numbers fixed – TYPE field added – Z field used for metadata 2001 – November – 27 added Vaal Barrage from 1:50_000 coverage 2002 – September – 16 added Spitskop Dam from 1:50_000 coverage 2002 – October – 23 added Grassridge, Katriver, Kommandodrift Dams and Lake Arthur from 1:50_000 coverage 2002 – November – 28 improved Theewaterskloof Dam outline using 1:50_000 coverage 2003 – May – 21 improved Inanda Dam outline using 1:50_000 coverage 2003 – June – 2 added Katse outline from Rural Communities Drinking Water CD 2002 2003 – Magda Smidt checked many dams against scanned 1:50_000 maps 2004 – Michael Silberbauer checked many dams against scanned 1:50_000 maps 2005 – Michael Silberbauer added name to Corumana Dam (Mozambique) 2006 – Michael Silberbauer added name to Pequenos Libombos Dam (Mozambique) Polygons: TYPE – ISLAND, RESERVOIR, NATURAL NAME – Most current name, with best possible spelling STATION — Department of Water Affairs & Forestry hydrological code – the presence of a station number does not imply that flow or quality data exists. Arcs: Z – 500 = from 1:500 000 scanned blue plates – 255 = from 1992 wla_tv1 "farm dams" Landsat TM project (DWAFF HRI) – 250 = Rural Communities Drinking Water CD – 59 = rough estimate where no polygon available – 52 = rough estimate based on 1:50 000 map contours where no polygon available – 51 = heads-up trace from scanned 1:50 000 map – 50 = from 1:50 000 scanned blue plates”</p>
<p>Citation to be used: Not indicated</p>

Table B17: Metadata for geospatial data of the 1:50 000 inland water bodies of South Africa

Data custodian	Department of Rural Development & Land Reform’s National Geo-Spatial Information Directorate (DRDLR-NGI)
URL	http://www.ngi.gov.za/
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	No metadata was provided with the 2009 shapefile updates and no coordinate system is indicated. Assumed to be geographic.
Scale of data capturing	1:50 000
Product date/Source date	Vary per degree block, most recent 2011
Source of capturing	Aerial photographs/satellite imagery
Temporal frequencies of updates	Continuous updates are done for some areas
Cost	Free; media is charged (CD/DVD) unless you provide your own
Attribute field descriptions:	
<ul style="list-style-type: none"> ○ GDO_GID – unique id ○ TAG – contains the inland water areas name in some instances, or a tag code starting with “#”. These should be removed or excluded for labelling purposes 	

- FEAT_TYPE – inland area (polygon) types (possibly incomplete list):

Type categories:	Type categories (continued):
<i>Dam</i>	<i>Perennial pan</i>
<i>Lake</i>	<i>Pool</i>
<i>Large reservoir</i>	<i>Purification plant</i>
<i>Marsh vlei</i>	<i>Sewerage works</i>
<i>Non-perennial pan</i>	<i>Water Tank</i>

- GEOM_TYPE – all polygon/area features
- MAPSHEET – the 1:50 000 ¼-degree grid block representing the extent of the dataset
- ROW_STATUS – meaning unclear
- LOCK_DATE – meaning unclear
- SELECTION_ – meaning unclear
- VERSION_NU – meaning unclear
- VERSION_DA – meaning unclear; not sure how this differ from CREATE_DAT field
- VERSION_ST – meaning unclear
- MODIFIED_B – person who captured or modified the feature
- RETIRED_DA – meaning unclear
- ORIGINAL_G – meaning unclear
- CREATE_DAT – meaning unclear; not sure how this differ from VERION_DA field
- DATA_SOURC – meaning unclear
- EST_REVISI – meaning unclear
- SOURCE_VER – meaning unclear
- SOURCE_PRO – meaning unclear
- SOURCE_P_1 – meaning unclear
- SOURCE_CON – meaning unclear
- CAPTURE_IN – meaning unclear
- DESCRIPTIO – meaning unclear

Description: Inland water areas (polygons) per degree block of South Africa. Unmerged. Once merged, topology needs to be verified.

Citation to be used: Not indicated.

Table B18: Metadata for geospatial data of the National Wetland Map v.4 of South Africa

Data custodian	South African National Biodiversity Institute (SANBI) as part of the National Freshwater Ecosystems Priority Areas (NFEP) Atlas
URL	http://bgis.sanbi.org/nfepa/NFEPAmapping.asp see information on the National Wetland Map 4
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Various, apply at 1:50 000
Product date/Source date	2011
Source of capturing	Various, please refer to the lineage description on the website
Temporal frequencies of updates	Continuous
Cost	Free

Attribute field descriptions (only six of the 31 field is listed here. For a complete list, please see [the metadata of the file](#)):

- AREA - Surface area calculated in Albers Equal Area for South Africa
- PERIMETER – Polygon perimeter
- NATART – distinguishes between “natural”, “artificial” and “estuaries”. Data from DRDLR-NGI were used to distinguish between natural and artificial (see above flow diagram for details of what is considered artificial).
 - Note: estuaries may have artificial parts to them, but this is not coded here as the entire estuarine functional zone was coded as “estuaries”.
- NWCS_L3 – Level 3 of the National Wetland Classification System, which describes the landscape setting of the wetland.
- NWCS_L4 – Level 4 of the National Wetland Classification System, which describes the landform of the wetland. This was combined with the wetland vegetation group (level 2 of the National Wetland Classification System which describes the regional context) to produce the wetland ecosystem types used by NFEPA.
- WETUNITID – each wetland system may consist of many different contiguous polygons (e.g. due to having different wetland vegetation groups or occurring in different sub-quaternary catchments). The wetunitid is an identifier that can be used to tell which polygons belong to the same wetland system.
- ...

Description: Wetland (polygons) for South Africa combined from various data sources.

Citation to be used: SANBI, 2011. National Wetland Map 4. Pretoria: SANBI.

DIGITAL ELEVATION MODELS (DEMs)

Various Digital Elevation Models (DEMs) exist for South Africa, generated at various scales and for multiple purposes. Those that were derived from satellite sensors are discussed in this section, while those that can be generated from spot height surveying, are discussed below. Satellite-derived DEMs are provided in tiles of image extents and need to be mosaicked to a national coverage. A number of errors are generated during the acquisition phase which would require quality checking and modification to improve the DEM before it can be used in applications. DEMs can be used to derive slopes in degrees or percentage using GIS software. The characteristics of each should be investigated to determine the most appropriate one for the extent of your study area and purpose of the study.

The following datasets have been described in this sub-section:

- The 90 m Shuttle Radar Topographic Mapper (SRTM) DEM for South Africa (Table B19)
- The 30 m Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) data for South Africa (Table B20)

The SRTM 90 m DEM v4 has been used internationally following a number of cleaning-up processes (Jarvis et al., 2008). In South Africa a number of versions of the SRTM DEM are available, however methods used for improvements are not always indicated. It is therefore recommended that only the one listed in Table B19 be used until the improved version of this product becomes available for South Africa in 2012. The ARC-ISCW has been contracted by the WRC to improve the SRTM DEM for hydrological applications in South Africa. Extensive work has been done thus far to ensure that flow direction and pour points are corrected, in associate with experts from DWA. This hydrologically-improved DEM is expected to be available to users in 2012.

The ASTER GDEM (2008) is only available as tiles to date, so extensive improvements would be required before it can be used in hydrological applications. In comparing the SRTM 90 m DEM and the 30 m ASTER GDEM, the ARC-ISCW found islands in water bodies on the ASTER GDEM which were artificial artefacts. Regardless of the higher spatial resolution of the ASTER GDEM data, this data set was still found less preferable for the hydrological applications required in comparison to the SRTM 90 m data (Weepener et al., in print). It is therefore advisable to thoroughly check and correct the data before using it.

Table B19: Metadata for geospatial data of the SRTM 90 m DEM of South Africa

Data custodian	Consultive Group on International Agricultural Research's Consortium for Spatial Information (CGIAR-CSI)
URL	http://srtm.csi.cgiar.org
Contact details	See website
File Format	ArcInfo ASCII and GeoTiff format
Coordinate system:	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Remote sensing
Product date/Source date:	2008
Source of capturing	Radar
Temporal frequencies of updates	Unknown
Cost	Can be freely downloaded. "Users are prohibited from any commercial, non-free resale, or redistribution without explicit written permission from CIAT. Users should acknowledge CIAT as the source used in the creation of any reports, publications, new datasets, derived products, or services resulting from the use of this dataset. CIAT also request reprints of any publications and notification of any redistributing efforts. For commercial access to the data, send requests to Andy Jarvis."
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ Height above mean sea level (metres) 	
<u>Description:</u> Radar-derived DEM for the world available at 90 m resolution tiles.	
<u>Citation to be used:</u> Jarvis A, Reuter HI, Nelson A and Guevara E (2008) Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90 m Database (http://srtm.csi.cgiar.org).	

Table B20: Metadata for geospatial data of the ASTER GDEM 30 m DEM for South Africa

Data custodian	Ministry of Economy, Trade, and Industry (METI) of Japan & the United States National Aeronautics and Space Administration (NASA)
URL	http://www.gdem.aster.ersdac.or.jp/index.jsp
Contact details	See website
File Format	GeoTiff format
Coordinate system:	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Remote sensing
Product date/Source date:	v.1 2009 v.2 2011
Source of capturing	Radar
Temporal frequencies of updates	Unknown
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> o Height above mean sea level (metres) 	
<u>Description:</u> Radar-derived DEM for the world available at 30 m spatial resolution as 1 degree tiles.	
<u>Citation to be used:</u> Advanced Spaceborne Thermal Emission And Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) (2009) Courtesy of the Ministry of Economy, Trade, and Industry (METI) of Japan & the United States National Aeronautics and Space Administration (NASA). Available online at: [http://www.gdem.aster.ersdac.or.jp/index.jsp]. Last date accessed 17 February 2011.	

NATIONAL ELEVATION DATASET

National elevation data is available per 1-degree blocks (sixteen combined 1:50 000 grid tiles) from the DRDLR-NGI as relief lines and spot heights (Table B21). Please refer to Section 2.2 for more information on how these datasets are generated by the DRDLR-NGI. Data would have to be verified, merged and converted to DEMs using interpolation tools in GIS software. Hydrologically correct DEMs can be generated through the Topo-to-Raster command in ArcGIS using river networks, water bodies and other features.

Table B21: Metadata for geospatial data of the national elevation datasets of South Africa

Data custodian	Department of Rural Development & Land Reform's National Geo-Spatial Information Directorate (DRDLR-NGI)
URL	http://www.ngi.gov.za/
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	No metadata was provided with the 2009 shapefile updates and no coordinate system is indicated. Assumed to be geographic.
Scale of data capturing	1:50 000
Product date/Source date	Vary per degree block
Source of capturing	Surveying and aerial photographs/satellite imagery
Temporal frequencies of updates	Continuous updates are done for some areas
Cost	Free; media is charged (CD/DVD) unless you provide your own

Attribute field descriptions:

- GDO_GID – unique id
- TAG – numbers, meaning unclear
- FEAT_TYPE – “CONTOUR”/“DEPRESSION CONTOUR”/“SPOT HEIGHT”
- GEOM_TYPE – all line/point features
- MAPSHEET – the 1:50 000 ¼-degree grid block representing the extent of the dataset
- **HEIGHT – contains the height value**
- ROW_STATUS – meaning unclear
- LOCK_DATE – meaning unclear
- SELECTION_ – meaning unclear
- VERSION_NU – meaning unclear
- VERSION_DA – meaning unclear; not sure how this differ from CREATE_DAT field
- VERSION_ST – meaning unclear
- MODIFIED_B – person who captured or modified the feature
- RETIRED_DA – meaning unclear
- ORIGINAL_G – meaning unclear
- CREATE_DAT – meaning unclear; not sure how this differ from VERION_DA field
- DATA_SOURC – meaning unclear
- EST_REVISI – meaning unclear
- SOURCE_VER – meaning unclear
- SOURCE_PRO – meaning unclear
- SOURCE_P_1 – meaning unclear
- SOURCE_CON – meaning unclear
- CAPTURE_IN – meaning unclear

- DESCRIPTIO – meaning unclear

Description: Spot heights as surveyed and captured for the 1:50 000 topographical maps. Relief lines with 20 m contour intervals.

Citation to be used: Not indicated.

LAND USE AND LAND COVER (LULC)

A South African National Standard (SANS), SANS1877 (SSA, 2004) for land cover mapping was developed following the first national land cover dataset in 1996 (Thompson, 1996; Fairbanks, 2000). SANS1877 defines land cover classes and nested groupings thereof at four levels. The standard was used in the classification of NLC2000 (Van den Berg et al., 2010). The National Land Cover 2005 (NLC2005) project has been allocated to CSIR's Satellite Application Centre (SAC), who became the South African National Space Agency (SANSA), in 2011 (GTI, 2008). DRDLR-NGI is the formal data custodian of the NLC datasets.

In a comparison with the LULC datasets used in BASINS 4 shell, Level I of SANS1877 compared quite well and is recommended for use in water quality models.

The following National Land Cover datasets are available:

- NLC1996 (Table B22)
- NLC2000 (Table B23)
- NLC2009 (Table B24)

Provincial land cover datasets have been generated for many of the South African provinces using the SPOT05 imagery. More information on these can be obtained from GeoTerraimage (GTI) (Pty) Ltd at <http://www.geoterraimage.com/>. These provincial datasets have been combined with NLC2000 by SANBI, into a NLC2009 dataset. A land cover dataset for KwaZulu-Natal is also available from Ezemvelo KZN Wildlife.

Table B22: Metadata for geospatial data of the NLC1996 of South Africa

Data custodian	CSIR Satellite Application Centre (SAC), now SANSA
URL	http://www.sansa.org.za
Contact details	See website
File Format	ArcGIS shapefile per province
Coordinate system	Not indicated
Scale of data capturing	1:50 000
Product date/Source date	1996
Source of capturing	Manual capturing from imagery
Temporal frequencies of updates	Regular, see following versions
Cost	Free
Attribute field descriptions:	
<ul style="list-style-type: none"> ○ AREA ○ PERIMETER ○ XX_PROV_ – the XX refers to a two-letter code for each province ○ XX_PROV_ID – the XX refers to a two-letter code for each province ○ CODE ○ SYMBOL_COL 	

<ul style="list-style-type: none"> ○ SYMBOL_HAT ○ Descriptio – Level 2 descriptions of land cover. ○ LAND_CODE ○ PROVINCE – South African province in which it falls
Description: Land cover dataset of South Africa per province
Citation to be used: Not indicated

Table B23: Metadata for geospatial data of the NLC2000 of South Africa

Data custodian	Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW)
URL	Data should be requested through contact given below:
Contact details	Mrs. Elna van den Berg Agricultural Research Council – Institute for Soil, Climate and Water Geoinformatics Division Private Bag X1251, Potchefstroom, 2520 Tel.: (018) 299-6206 Fax: (018) 299-6290 VDBergEC@arc.agric.za vdbergec@arc.agric.za
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Please refer to the report for more information
Product date/Source date	2000
Source of capturing	Please refer to the report for more information
Temporal frequencies of updates	Planned, refer to NLC2005
Cost	Free, DVD set should be requested.
Attribute field descriptions:	
<ul style="list-style-type: none"> ○ ID – unique polygon ID ○ DESCR – Level 2 land cover description 	
Description: Land cover dataset of South Africa.	
Citation to be used: Van den Berg EC, Plarre C, Van den Berg HM and Thompson MW (2008) The South African National Land Cover 2000. Agricultural Research Council Institute for Soil, Climate and Water. Pretoria. (Report No. GW/A/2008/86).	

Table B24: Metadata for geospatial data of the NLC2009 of South Africa

Data custodian	South African National Biodiversity Institute (SANBI)
URL	http://bgis.sanbi.org/mapsearch.asp
Contact details	See website
File Format	ArcGIS shapefile
Coordinate system	Albers Equal Area for RSA, Spheroid WGS84, Datum WGS84
Scale of data capturing	Please refer to the associated metadata and report
Product date/Source date	2009
Source of capturing	Please refer to the associated metadata and report. Data was derived from a variety of sources, including i.a. land cover datasets at various scales, ARC cultivation filed boundaries and ESKOM Spot 5 building count data.
Temporal frequencies of updates	Please refer to the associated metadata and report
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ Rowid – unique ID ○ VALUE* – meaning unclear ○ COUNT – possibly surface area calculated in Albers Equal Area for South Africa ○ DESCRIPTION – seven classes listed: Natural, Waterbodies, Cultivation, Degraded, Urban Built-up, Plantations and Mines. ○ RECLASS – two classes listed, namely: Natural or Transformed 	
<u>Description:</u> This product should not be used as a new version of land cover but rather be used as an indicator of major land use changes in the country. It have seven classes which represents major land uses, and this is not on the finer details as the previous land cover products	
<u>Citation to be used:</u> SANBI, 2009.	

Protected areas are not listed as a category of land cover or land use in the above-mentioned products, but remain useful when considering land use practices and water quality. The South African National Biodiversity Institute (SANBI) hosts a number of files, including National Protected Areas (NPAs) which are formally protected (Table A25) as well as conservancies which are not formally protected (see their website for more information). A number of provincial or municipal nature reserves may be managed locally and it is always to verify with other relevant authorities on the completion of a dataset for use in water quality modelling.

Table B25: Metadata for geospatial data of the National Protected Areas of South Africa

Data custodian	South African National Biodiversity Institute (SANBI)
URL	http://bgis.sanbi.org/mapsearch.asp
Contact details	See website, you need to register (Free)
File Format	ArcGIS shapefile
Coordinate system	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Please refer to the associated metadata
Product date/Source date	2010
Source of capturing	Please refer to the associated metadata
Temporal frequencies of updates	Please refer to the associated metadata
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ Name Description Alias ○ FID Feature Identification ○ SHAPE Polygon ○ RESERVENAM Reserve Name, name of the protected area ○ SPEC_TYPE Specific Type of Protected Area (see Table 1) ○ PA_CATEG Protected area category PA Category ○ MGMT_AGENT Management agency of the respective protected area 	
<u>Description:</u> National Protected Areas boundaries and classification	
<u>Citation to be used:</u> SANBI, 2010.	

Environmental Monitoring Data

WATER QUALITY MONITORING STATIONS AND DATA SUMMARIES

The Department of Water Affairs (DWA) is the main data custodian of water quality (observation) monitoring stations and data summaries in South Africa. Three datasets are relevant:

- The National Chemical Monitoring Programme (NCMP) provides data and information on the surface inorganic chemical water quality of South Africa's water resources (Table B26).
 - More information on this national programme is available on: http://www.dwa.gov.za/iwqs/water_quality/NCMP/default.asp.
 - Data summaries can be viewed and downloaded from: <http://www.dwa.gov.za/iwqs/wms/data/>
- The National Groundwater Quality Monitoring Project (NGwQMP) includes observation of both groundwater and boreholes (Table B27).
 - More information available from <http://www.dwa.gov.za/Groundwater/NGQMP.aspx>.
 - Data summaries can be downloaded from: <http://www.dwa.gov.za/Groundwater/data.aspx>.

Table B26: Metadata for geospatial data for surface water quality observation points of South Africa

Data custodian	Department of Water Affairs (DWA) Hydrological Services
URL	http://www.dwa.gov.za/iwqs/wms/
Contact details	The Director, Resource Quality Services +27 12 808 9500 (the switchboard number at RQS) General E-mail address for resource quality database enquiries: wms@dwa.gov.za
File Format	ArcGIS shapefile/coverage/txt/Google Earth kml/kmz format
Coordinate system	Unknown
Scale of data capturing	Unknown
Product date/Source date	Unknown
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Free
Attribute field descriptions (refer to the Water Quality guidelines for relevant information):	
<ul style="list-style-type: none"> ○ PointID – Unique identifier for item ○ Date – Calendar date and time ○ DMS_Tot_Water ○ EC_Phys_Water ○ pH_Diss_Water pH ○ Na_Diss_Water ○ K_Diss_Water ○ Ca_Diss_Water ○ Mg_Diss_Water ○ Cl_Diss_Water ○ SO4_Diss_Water ○ TAL_Diss_Water ○ F_Diss_Water ○ PO4_P_Diss_Water 	<ul style="list-style-type: none"> ○ P_Tot_Water ○ NO3_NO2_N_Diss_Water ○ NH4_N_Diss_Water ○ KJEL_N_Tot_Water ○ Si_Diss_Water ○ B_Diss_Water ○ SAR_Diss_Water ○ Time ○ BeginDepth ○ EndDepth ○ Preserve ○ Year ○ Station

○ Qat
Description: Observations and location of surface water monitoring points.
Citation to be used: Not indicated

Table B27: Metadata for geospatial data for groundwater quality observation points of South Africa

Data custodian	Department of Water Affairs (DWA) Hydrological Services
URL	http://www.dwa.gov.za/geohydrology/ The National Groundwater Archive is available at http://www3.dwa.gov.za/NGANet/ – register as a user.
Contact details	geo-requests@dwa.gov.za for requests re groundwater and borehole information and observations Ernst Bertram (BertramE@dwa.gov.za) for the National Groundwater Archive
File Format	ArcGIS shapefile/coverage/txt/Google Earth kml/kmz format
Coordinate system	Unknown
Scale of data capturing	Unknown
Product date/Source date	Unknown
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Free
Attribute field descriptions (refer to the Water Quality guidelines for relevant information):	
<ul style="list-style-type: none"> ○ PointID – Unique identifier for item ○ Date – Calendar date and time ○ DMS_Tot_Water ○ EC_Phys_Water ○ pH_Diss_Water pH ○ Na_Diss_Water ○ K_Diss_Water ○ Ca_Diss_Water ○ Mg_Diss_Water ○ Cl_Diss_Water ○ SO4_Diss_Water ○ TAL_Diss_Water ○ F_Diss_Water ○ PO4_P_Diss_Water 	<ul style="list-style-type: none"> ○ P_Tot_Water ○ NO3_NO2_N_Diss_Water ○ NH4_N_Diss_Water ○ KJEL_N_Tot_Water ○ Si_Diss_Water ○ B_Diss_Water ○ SAR_Diss_Water ○ Time ○ BeginDepth ○ EndDepth ○ Preserve ○ Year ○ Station ○ Qat
Description: Observations and location of surface water monitoring points.	
Citation to be used: Not indicated	

Weather Stations

Weather stations in South Africa are managed by both the South African Weather Services (SAWS) and the Agricultural Research Council (ARC). The locations of the stations from these organisations are free, however weather observations made would need to be purchased:

- Various stations types and observations from the SAWS (Table B28)
- Mechanical and automatic stations with observations from the ARC (Table B29)

Table B28: Metadata for geospatial data for weather stations from the SAWS in South Africa

Data custodian	South African Weather Services (SAWS)
URL	http://www.weathersa.co.za/web/
Contact details	Dawn.Mahlobo@weathersa.co.za
File Format	Excel, needs to be converted
Coordinate system	Assumed to be Geographic
Scale of data capturing	Unknown
Product date/Source date	Unknown
Source of capturing	Unknown
Temporal frequencies of updates	Various
Cost	The data is not Free
Attribute field descriptions (refer to the for relevant information):	
<ul style="list-style-type: none"> ○ ClimNo – unique number of the stations ○ StasName – name of the stations ○ Latitude – in decimal degrees ○ Longitude – in decimal degrees ○ Height – in metres ○ Name – province name ○ Current_Or 	
Description:	
<p>The SAWS has 1 700 different station types which monitor observations. These are detailed on (http://www.weathersa.co.za/web/Content.asp?contentID=116):</p> <p><u>Automatic Weather Stations (ELEC TEMP)</u> Report the following weather variables: Temperature Humidity Rainfall Wind Speed Wind Direction Pressure Some of these stations report sunshine hours as well.</p> <p><u>Weather Offices (WEATHER OF)</u> Report the same information as automatic weather stations as well as all hourly visible climate variables such as cloud, visibility and present and past weather at 08:00, 14:00 and 20:00 SAST</p> <p><u>Semi-Automatic Weather Stations (ELEC MANUAL)</u> Report the same information as automatic weather stations as well as visible climate variables such as cloud, present weather and visibility at 08:00, 14:00 and 20:00 SAST. These stations differ from Weather Offices in that they are manned by volunteer observers who used to be responsible for</p>	

observations at “FIRST ORDER” stations. In time all FIRST order stations will be converted to ELEC_MANUAL stations

First Order Stations (FIRST)

Report all climate variables and visible weather at 08:00, 14:00 and 20:00 SAST

Second Order Stations (SECOND)

Report maximum and minimum temperatures and rainfall at 08:00 and various other climate variables at 08:00 and 14:00 SAST – the other climate variables depend on the needs of the specific station.

Third Order Stations (THIRD)

Report only maximum and minimum temperatures and rainfall at 08:00 SAST.

Rainfall Stations (RAINFALL)

Report only rainfall once a day at 08:00 SAST.

Processing time

The Data from ELEC_TEMP, ELEC_MANUAL and WEATHER_OF stations is usually available from the database within 7 days of it being recorded. The data from FIRST, SECOND and THIRD_ORDER as well as from RAINFALL stations is reported by volunteer observers and is available for distribution to clients 45 days after the end of the month in which it is recorded. The exception to this is the maximum and minimum temperature and rainfall data for FIRST_ORDER stations and the rainfall data for selected RAINFALL stations. This data is available the day after it has been recorded via the Climate Monitoring System (CLIMOS) and is displayed on our web site for 24 hours after it has been recorded. The latter data can be viewed Free.

The SAWS endeavours to provide the most complete and accurate data possible. Due to the fact that the SAWS relies very heavily on the dedication of volunteer observers, it is not always practical or reasonable to expect these observers to never take a day off from their normal activities and so it is possible that there may be data periods that are not complete.

All users are thus urged to check the availability of the data for the Weather Station and Weather Variable that they wish to request prior to initiating the order process and making payment for the information. This information is contained in the downloadable files on this page.

The following list of parameters and frequency of updates is listed as available from the SAWS on their website (<http://www.weathersa.co.za/web/Content.asp?contentID=117>):

“The various weather parameters are recorded in various time frames depending on the usefulness of that measurement for the specific variable. The table below shows that available time frame available for each weather parameter.

- **Minimum and maximum temperature:** Daily & Monthly
- **Temperature:** 5 minute, Hourly, Daily, Monthly
- **Wind speed and direction:** 5 minute, Hourly, Daily (wind gust data and average daily wind speeds), Monthly (wind speed only)
- **Minimum and maximum humidity:** Daily, Monthly
- **Humidity:** 5 minute, Hourly, Daily, Monthly
- **Rainfall and precipitation:** 5 minute, Hourly, Daily, Monthly

- **Barometric pressure:** 5 minute, Hourly, Daily, Monthly

Citation to be used: Not indicated.

Table B29: Metadata for geospatial data for weather stations from the ARC in South Africa

Data custodian	Agricultural Research Council (ARC)		
URL	http://www.arc.agric.za/home.asp?pid=6372		
Contact details	<p><u>Stations Western and Eastern Cape:</u> Ritha Wentzel Agro Climatology, ARC-ISCW, Stellenbosch Tel: 021 809 3349 Fax: 021 809 3477 Email: wentzel@arc.agric.za</p> <p><u>Stations Other provinces:</u> Gert de Nyschhen gert@arc.agric.za</p> <p><u>Prices for data is available from the:</u> Climate Network Manager: Mr. Chris Kaempffer E-mail: ChrisK@arc.agric.za Tel: +27 (0)12 310 2560</p>		
File Format	The stations are in MS Excel and need to be converted		
Coordinate system	Assumed to be Geographic		
Scale of data capturing	Unknown		
Product date/Source date	Unknown		
Source of capturing	Unknown		
Temporal frequencies of updates	Daily?		
Cost	The data is not Free		
<u>Attribute field descriptions of the weather stations (only stations, no climate information):</u>			
<table style="width: 100%; border: none;"> <tr> <td style="width: 50%; vertical-align: top;"> <p><u>Western/Eastern Cape:</u></p> <ul style="list-style-type: none"> ○ COMP NO. ○ STATION NAME ○ AREA ○ START ○ END ○ LATITUDE ○ LONGITUDE ○ ALTITUDE ○ CALIBRATIONS ○ TYPE AWS </td> <td style="width: 50%; vertical-align: top;"> <p><u>Other provinces:</u></p> <ul style="list-style-type: none"> ○ Compno ○ Latitude ○ Longitude ○ Altitude ○ Station_Name ○ Country ○ Province ○ MagDist ○ Abbreviation ○ Description ○ Unit ○ sDate ○ eDate </td> </tr> </table>		<p><u>Western/Eastern Cape:</u></p> <ul style="list-style-type: none"> ○ COMP NO. ○ STATION NAME ○ AREA ○ START ○ END ○ LATITUDE ○ LONGITUDE ○ ALTITUDE ○ CALIBRATIONS ○ TYPE AWS 	<p><u>Other provinces:</u></p> <ul style="list-style-type: none"> ○ Compno ○ Latitude ○ Longitude ○ Altitude ○ Station_Name ○ Country ○ Province ○ MagDist ○ Abbreviation ○ Description ○ Unit ○ sDate ○ eDate
<p><u>Western/Eastern Cape:</u></p> <ul style="list-style-type: none"> ○ COMP NO. ○ STATION NAME ○ AREA ○ START ○ END ○ LATITUDE ○ LONGITUDE ○ ALTITUDE ○ CALIBRATIONS ○ TYPE AWS 	<p><u>Other provinces:</u></p> <ul style="list-style-type: none"> ○ Compno ○ Latitude ○ Longitude ○ Altitude ○ Station_Name ○ Country ○ Province ○ MagDist ○ Abbreviation ○ Description ○ Unit ○ sDate ○ eDate 		
<p><u>Description:</u> The ARC-ISCW AgroClimatology Programme maintains an operational national agro-climate network of weather stations (approximately 500) and a climate databank. Hourly, daily, monthly, yearly or long-term average data is available for the following parameters:</p> <p>Temperature Rainfall</p>			

Humidity

Radiation

Wind speed and direction, including wind gust and wind rose information

Certain value-added information, e.g. evapotranspiration and cold/heat units, is also available.

For more information or to request a price list contact the Climate Network Manager:

Mr. Chris Kaempffer

E-mail: ChrisK@arc.agric.za

Tel: +27 (0)12 310 2560

Citation to be used: Not indicated.

POINT SOURCE/LOADING DATA

Wastewater Treatment Works (WWTW)

The Department of Water Affairs is the data custodian of point locations of the Wastewater Treatment Works (WWTW). The reticulation of sewage pipes is kept at local municipality level.

Table B30: Metadata for geospatial data of the Wastewater Treatment Works (WWTW) of South Africa

Data custodian	Department of Water Affairs (DWA)
URL	
Contact details	Karlien de Villiers DeVilliK111@dwaf.gov.za
File Format	Text file
Coordinate system:	Assumed geographic
Scale of data capturing	Unknown
Product date/Source date:	Unknown
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Free
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ Monitoring Point ID – unique monitoring point ID ○ Monitoring Point Name – name of monitoring point ○ WATER USE SITE NAME – Name of site ○ WU SITE ID – unique site ID ○ Located on Feature Name – description of area on which WWTW is located ○ Located on Type – Description of land use ○ Latitude – Southern coordinate point (latitude) ○ Longitude – Eastern coordinate point (longitude) ○ Drainage Region Name – Four-digit quaternary catchment code ○ Number of Samples – ○ First Sample Date – ○ Last Sample Date – 	
<u>Description:</u> Sewerage works inventory.	
<u>Citation to be used:</u> Not indicated.	

- Compliance monitoring and reporting:
 - Greendrop status => waste water service regulation monitoring http://www.dwa.gov.za/Dir_WS/GDS/Default.aspx
 - Bluedrop status => municipal drinking water quality compliance system monitoring and reporting http://www.dwaf.gov.za/dir_ws/DWQR/Default.asp?Pageid=40&PageHeading=Compliance%20Overview&Prov=0&wsa=0

POWER STATIONS

ESKOM is the data custodian of power stations in South Africa, particularly the ones linking transmission and distribution lines.

Table B31: Metadata for geospatial data of the power stations of South Africa

Data custodian	ESKOM
URL	http://www.eskom.co.za
Contact details	<p><u>Transmission lines and power stations:</u> Joan Hartman HartmaSJ@eskom.co.za</p> <p><u>Distribution lines and substations:</u> Ansunette van der Walt Ansunette.vdWalt@eskom.co.za</p>
File Format	ArcGIS shapefile
Coordinate system:	Geographic, Spheroid WGS84, Datum WGS84
Scale of data capturing	Unknown
Product date/Source date:	2008, perhaps a more recent update is available
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Free, license agreement needs to be signed
<u>Attribute field descriptions:</u>	
<ul style="list-style-type: none"> ○ DESCRIPTION – ○ TYPE – Distributed Power Station, Generation Power Station, Mini Substation, MTS Substation, Pole Mount Switching Bay, Pole Mounted Trfr Bay, Power Station, Power Station HV Yard, Substation, Switching station, Traction Substation ○ SLOT_ID – ○ END_DATE – ○ LABEL – ○ VOLTAGE – voltage in kV ○ COMMENTS – ○ STATUS – (commissioned) ○ DATE – ○ OWNER – ESKOM Distribution/Transmission ○ LABEL0 – ○ LABEL1 – ○ DESCRIPT0 – ○ TYPE0 – 	
<u>Description:</u> ESKOM power stations (high and medium volt)	
<u>Citation to be used:</u> Not indicated.	

MINES

The South African MINeral Deposits DATAbase (SAMINDABA) which indicate the locations of mines (Table B32) as well as the Ownerless & Derelict Mines Database (Table B33) is hosted by the Council for Geoscience (CGS).

Table B32: Metadata for geospatial data of the point locations of mines in South Africa

Data custodian	Council for Geoscience (CGS)
URL	http://www.geoscience.org.za/ – see SAMINDABA
Contact details	<p><u>Spatial Data Management Unit:</u> Molefe Letsoalo letsoalom@geoscience.org.za Tel: 012 841 1041 or 012 841 1036</p> <p><u>SAMINDABA:</u> Contact person: Cornelis Vorster Council for Geoscience Private Bag X112, Pretoria, 0001, SOUTH AFRICA Tel: +27 12 841 1131 Fax: +27 12 841 1148</p>
File Format	Database with coordinates
Coordinate system:	Assumed Geographic, possible in Cape Datum
Scale of data capturing	1:1 000 000
Product date/Source date:	Captured since 1980s
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Pricing structure listed on http://www.geoscience.org.za/ > Spatial Data Management > More on SDM > Spatially Referenced Attribute Data > SAMINDABA Also see the CD-ROM product available for R500 on http://www.geoscience.org.za/index.php?option=com_content&task=view&id=453&Itemid=144 Called the “Metallogenic Map of South Africa – available on CD-ROM”.
Attribute field descriptions: (Data was not obtained; metadata not available, therefore attributes not listed.)	
Description: South African Mineral Deposits Database, which stores a large variety of data on mines, mineral deposits and occurrences within the borders of South Africa	
Citation to be used: Not indicated.	

Table B33: Metadata for geospatial data of the Ownerless & Derelict mines database of South Africa

Data custodian	Council for Geoscience (CGS)
URL	http://www.geoscience.org.za
Contact details	Magda Roos mroos@geoscience.org.za
File Format	Database with coordinates
Coordinate system:	Assumed Geographic, possible in Cape Datum
Scale of data capturing	Unknown
Product date/Source date:	Unknown
Source of capturing	Unknown
Temporal frequencies of updates	Unknown
Cost	Unknown
Attribute field descriptions: (Data was not obtained; metadata not available, therefore attributes not listed.)	
Description: Ownerless & Derelict Mines database.	
Citation to be used: Not indicated.	

FEED LOTS

An old dataset (shp, Geographic) of Feedlots is available from the Agricultural GIS website (AGIS) <http://www.agis.agric.za/>. The data was compiled for Department of Agriculture (DoA) Marketing Information System project at a scale of 1:20 000. No date or spheroid and datum information is provided.

The Department of Agriculture, Forestry and Fisheries (DAFF) is in the process of liaising with SA Feedlot Association to update the dataset.

DAIRY

The DAFF is in the process of liaising with Milk South Africa (<http://www.milk.co.za/>) to generate a geospatial dataset of dairies for South Africa.

LANDFILLS/REFUSE DISPOSAL

The Department of Environmental Affairs (DEA) is currently the data custodian of the Hazardous Landfill Sites in RSA.

Other landfill sites have been delegated to provincial level.

More information on the metadata was not received at the time of publication of this report.

Mr Deon Marais or Mrs Nicolene Fourie from the GIS unit of DEA will be able to provide more information in future: dmarais@environment.gov.za or NFourie@environment.gov.za.

An old map of the landfill sites was found on the internet: <http://www.sawic.org.za/documents/357.PNG>

APPENDIX C

Chronology of DUCT mails

Chronology of duct mails for Bayesian modelling.

Date	Node	Notes	Issue Identified
23-Aug-11	Public awareness	Community clean up day 12-17 September	> 500 volunteers + 1000 bags. How many sites?
26-30 Aug-11	Community awareness/Action by authorities	Blue dye spill in Nguklu R (tributary of uMngeni) near Mpophomeni	Lack of accountability by private individuals. Highlighted need for who to contact when. Highlights usefulness of a network like CMF/DUCT in blowing the whistle. Monitoring and reporting by community; legal action by authorities
31-Aug-11	Sewerage failure	Holding dam at Howick West pump station spilled – raw sewerage ending up in uMngeni. Photos available	Alerted by DUCT. Not sure who to contact. Spill detected after 3 days
01-Sep-11	Sewerage failure	Holding dam at Howick West pump station spilled – raw sewerage ending up in uMngeni. Photos available	Spill ongoing – no action by authorities
15-Sep-11	Sewerage infrastructure	Notification from Green Door consultants of proposed EIA revision to upgrade WWTW from 3 to 6 million cubic metres per day	Project to refurbish Mpophomeni WWTW
16-Sep-09	Community awareness	DUCT Howick spillage report Jan-Sep 2011	Need to recode information from sheet and calculate probabilities
17-18 Sep-11	Sewerage failure	Sewerage spill near entrance to Mpophomeni – photos	Use of wetlands to help. Contact authority identified. Problem spotted by DUCT (Pia)
20-Sep-11	Sewerage failure	Sewerage spill at uMngeni River Bridge reported by community member (source =uMngeni River Bridge Pump station near Howick)	Authorities reported to are Ken Philips (municipality), Ravin Gunirajh (Umgeni Water) and Simphiwe (DBSA?)
27-Sep-11	Sewerage failure	Njaloba Pump station failure on 1 September failed	<i>E. coli</i> > 1 000 000 from sample

Linking Land Use to Water Quality

Date	Node	Notes	Issue Identified
24-Oct-11	Community awareness/Action by authorities	Umgeni Municipal Disaster Management advisory Forum held on 25 October	Lack of communication between different groups and authorities?
26-Oct-11	Community awareness	<i>E. coli</i> sample results from 21 September which refer to mail on 20 September	<i>E. coli</i> > 1 000 000 from sample; Ian Bailey at Umgeni Water as contact
01-Nov-11	Research	Honours project from UKZN Geography on sewage spills at Siphumelele	
04-Nov-11	Ecological problems/Community awareness	Water Hyacinth spotted in section of Midmar Dam near Mpophomeni (Mtinzima Stream inlet) & downstream of wetland!	Intervention by Umgeni Water by 7 November. Lots of panic based on hearsay and failure of ongoing monitoring by authorities. Lack of contingency plan = key issue
07-Nov-11	Ecological problems/Community awareness	Pete Thomson asks for calm, calls for a pilot study to get facts, and the development of a structured action plan	
09-Nov-11	Community awareness/failure of authorities	Howick Waste Water Work compliance report. 13% drop in compliance in one month (August = 97.8; September = 84.8)	Issues of reporting, transparency and accountability. Lack of capacity for sludge
11-Nov-11	Community awareness	Alien infestations and alien invasives in riparian zone	Lack of community ownership. Business not good stewards (broken pallisade fence behind Spar)
14-Nov-11	Community awareness	Beach Clean-up awards	Actions have consequences – systems are connected
14-Nov-11	Community awareness	Letter from member of community thanking DUCT for actions at Symmonds Lane stream	Tacit knowledge from local community on reference condition and goings-on over the years (what has worked and what hasn't)

Table C1: Land use codes for the 2005 land cover image in KwaZulu-Natal.

Code	Land cover	Model class
1	water natural (NEW)	Other
2	plantation	Forestry
3	plantation clearfelled	Forestry
4	wetlands	Natural
5	wetlands-mangrove	Natural
6	permanent orchards (banana, citrus)	Other
7	permanent orchards (cashew) dryland	Other
8	permanent pineapples dryland	Other
9	sugarcane – commercial	Other
10	sugarcane – emerging farmer	Other
11	mines and quarries	Other
12	built up dense settlement	Other
13	golf courses	Other
14	low density settlement	Other
15	subsistence (rural)	Other
16	annual commercial crops dryland	Pasture/Agriculture
17	annual commercial crops irrigated	Pasture/Agriculture
18	forest	Natural
19	dense bush (70-100 cc)	Natural
20	bushland (< 70cc)	Natural
21	woodland	Natural
22	grassland/bush clumps mix	Natural
23	grassland	Grassland
24	bare sand	Other
25	degraded forest	Other
26	degraded bushland (all types)	Other
27	degraded grassland	Other
28	old cultivated fields – grassland	Other
29	old cultivated fields – bushland	Other
30	smallholdings – grassland	Other
31	erosion	Other
32	bare rock	Other
33	alpine grass-heath	Other
34	KZN national roads	Other
35	KZN main & district roads	Other
36	water dams (NEW)	Other

Linking Land Use to Water Quality

Code	Land cover	Model class
37	water estuarine (NEW)	Other
38	water sea (NEW)	Other
39	bare sand coastal (NEW)	Other
40	forest glade	Other
41	Outside KZN boundary	Other
42	KZN railways	Other
43	Airfields	Other

APPENDIX D

GENERAL ASSESSMENT OF BASINS 4.0

In an effort to begin capturing the team's experience with the BASINS 4.0 software shell, the following section outlines some positive and negative aspects. The responses were recorded to a series of general questions that probed the applicability and user-friendliness of the package.

Q: What was the single most irritating aspect of the work?

UNITS

A: Coming to grips with the different units (US English/Imperial units versus RSA Metric units) was initially one of the most irritating and time-consuming aspects with models associated with BASINS 4.0, particularly the HSPF and PLOAD models. However, unit differences were not perceived as a 'show-stopper'. Within the WinHSPF model, the user has the option to specify the input and output units as English or Metric. For PLOAD, output units are automatically generated in pounds and acres. The addition of a new field in the shapefile's attribute table, along with a calculation to convert, for example, from pounds to kilograms, does not take long to perform.

FILENAME LENGTH

Another irritating aspect of BASINS 4.0 is file paths. At times, the software is quite particular about where it searches for files, and if a file is located at a different file path, it will not find it. Also, for certain aspects of BASINS 4.0 (i.e. WDMUtil and WinHSPF), file paths cannot be read if there are more than, roughly, 70 characters. When a project is opened from a file path with more than 70 characters (for example, C:\BASINS\BASINS Lessons (2011)\3 – WDMUtil and HSPF\WDMUtil\Mgeni Catchment\Mgeni.wdm), an error appears on the screen. If the user is not aware of this problem in BASINS 4.0, they could have a very frustrating task trying to open a project if it is located under a long directory.

PROJECTIONS

Having spatial data that is not projected properly was another issue. Initially, models were run (PLOAD) or tools were used (automatic and manual watershed delineation) where the output did not make logical sense. The problem arose that the shapefiles or DEMs were not in a projected format (i.e. using meters rather than decimal degrees to determine areas, etc.). However, once this problem was solved, meaningful outputs were generated.

Q: What was the most positively surprising thing you came across? (The kind of thing you might perhaps use as a selling point.)

AQUATOX

A: AQUATOX was one of the more exciting models that was used during this work. AQUATOX is "...a simulation model for aquatic systems that predicts the fate of various pollutants, such as nutrients and organic chemicals, and their effects on the ecosystem, including fish, invertebrates,

and aquatic plants". It focuses on how different aquatic ecosystems (streams, ponds, lakes, reservoirs, estuaries and enclosures) may respond to their surroundings for various 'what if' scenarios. For example, how are particular invertebrates affected by the addition of phosphorus loadings to their surroundings?

INSTITUTIONAL MEMORY

The documented institutional "memory" within this model is something to behold, where each pre-loaded animal and plant within the model has a variety of attribute data (with references), for example, data included for invertebrates are optimum temperature, mean net weight, excretion: respiration ratio, mean life span, low oxygen effects, N and P tolerances, abundance percentages in various biotopes, to name a few. The user has also has the option of adding their own data to the model.

SCENARIOS

A great feature about AQUATOX is that it models the ecosystem under 2 different conditions: Control – has all organic toxicants zeroed out or omitted; Perturbed – includes toxicants and chemicals. The impressive feature is that these two separate simulations can be run concurrently.

The output from the simulations is incredibly user friendly, where graphs are generated for both Control and Perturbed simulations, enabling immediate comparisons to be made between a pristine and disturbed ecosystem. This has great potential to stimulate in depth conversations based on the AQUATOX output, where likely decision-making and management measures may be enforced. Reasoning can be explored, leading to more innovative options and hence, better decisions.

Q: What was the most time-consuming?

A: There were several tedious steps that took time to overcome, particularly steps that are not described in detail in the BASINS 4.0 manual. As a user not having immediate personal assistance with BASINS 4.0, gaining experience while 'playing around' with the model was one of the most tedious steps, particularly reading the manual to obtain step-by-step procedures (as with any new model). Many obstacles were overcome by trial and error. However, once several steps were achieved, these were documented (i.e. BASINS 4.0 lesson format), making it easier for other users to undertake similar steps with their own data, avoiding the tedious task of reading the manual. For example, with the HSPF model, the manual does not explicitly specify the minimal meteorological data required to run the model, which was eventually discovered. Another step for the WinHSPF model which took a while to overcome was obtaining the required data for the stream shapefile. Initially, it was thought that several measurements had to be determined in the field to populate the stream shapefile being used. However, using a DEM (the higher the resolution, i.e. 20 m, the more accurate the output), the automatic and manual watershed delineation tools create the required fields for HSPF in a new shapefile, enabling the user to later edit any of the fields (if there is measured data available, including depth, width, length, slope). When the HSPF model is now opened, the stream fields are automatically populated under the streams tab.

A further time consuming task could potentially involve populating various fields accurately within the Input Data Editor in the WinHSPF model. This depends on the size of the catchment, the number of sub-catchments, the number of different land cover units present and what the modeller

wishes to accurately simulate. The more constituents there are to be simulated, the more fields there are requiring input data. It is time-consuming populating these fields initially, however, once they have been edited, various scenarios may be run many times over without having to re-edit these fields.

Q: How demanding is site-specific data acquisition generally?

SITE-SPECIFIC DATA ACQUISITION

A: Obtaining site-specific data for a model is always an advantage, as, with every model, the more accurate the input, the more accurate the output. However, this is often a time consuming and expensive exercise. In my opinion, the export coefficient (or event mean concentration) values necessary to run the PLOAD model could be one of the most important site-specific data to obtain, as every river catchment is different in one way or another. Obtaining data from stakeholders may be beneficial, as this helps with the buy-in into the BASINS framework.

METEOROLOGICAL DATA

Meteorological data is also important data to the running of models in BASINS 4.0, particularly the WinHSPF and SWAT models. Observed daily (or hourly) data has not been actively sought after at this stage, as the proof of concept involving the successful running of the models has thus far been the focus. When wanting to use the BASINS 4.0 models for scientific purposes or for decision-making, meteorological data will be required. This may (or may not) be quite tedious to obtain from relevant people or companies, i.e. Umgeni Water, particularly recent and accurate data, which may or may not have to be later converted into the correct units to be read by the models.

Q: How far can one get away with default values?

A: The default values are relatively meaningful within the models used, particularly PLOAD and WinHSPF. The default values give the user an idea of rough 'ball-park' figures, where the user can later make edits. The default values are the same for all types of land uses in WinHSPF, and broadly grouped in PLOAD. However, field work should not necessarily be needed to obtain values, as there should be sufficient literature available to populate fields (i.e. soil types, bulk densities, soil layer depths, infiltration rates, etc.), within HSPF particularly. However, catchment- and land cover-specific data would be more useful for accuracy, but is often not feasible in terms of time and money constraints.

Default values are a useful starting point for conversation. For example, one comes up with a figure and the conversation is simulated around that figure until everyone is in agreement on the final figure. This process can be repeated several times, until the relevant figures are obtained for a particular model.

Q: What else do you feel will help others understand the sustainability of the use of such packages?

A: BASINS 4.0 is continuously progressing, with more recent versions becoming available to the public every three years or so, along with more models being included. This becomes available to

the user in a plug-in format. BASINS 4.0 has a huge working force, continuously making improvements to the overarching framework. In this way, the software will never become outdated.

Based upon the experiences attained with using BASINS 4.0, the transition and preparation for the DHI software will be swifter than without having obtained this experience, particularly when learning the MIKE BASINS and ECO Lab components thereof.