Scoping investigation into the cumulative impacts of point source discharge from Low Volume Privately Owned Treatment Works on river health in the eThekwini Metropolitan Municipality

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by

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EXECUTIVE SUMMARY

Domestic wastewater and its treatment is a global problem that threatens human and aquatic ecosystem health. Treated and untreated wastewater negatively impacts the receiving aquatic ecosystems by altering the water quality and water quantity characteristics within these environments.

Domestic wastewater treatment is generally undertaken in large centralised treatment works or in smaller low volume privately owned treatment works (LVPOTW). The impacts of larger centralised treatment works on river health are relatively understood. However, the impacts (direct, indirect and cumulative) of LVPOTW are not that well understood. This is a result of a lack of available information on smaller systems and poorly monitored rivers up- and downstream of these facilities. This lack of information poses a problem for decision makers and authorities regarding the number and size of LVPOTW that can sustainably be accommodated in a given catchment. Therefore, this report is a scoping investigation into the cumulative impacts of point source discharges from LVPOTW on river health in eThekwini Metropolitan Municipality.

The objectives of the report are to provide a better understanding of:

- the cumulative impacts of LVPOTW on river health within the eThekwini Metropolitan Municipality;
- the assimilative capacity of receiving aquatic ecosystems;
- the preliminary guidance needed for management of small treatment plants within a catchment; and
- the further studies required to develop a comprehensive guideline for managing LVPOTW in all municipalities.

Essentially, this report aims at answering the following question for any proposed/current LVPOTW in the eThekwini Metropolitan Municipality: from a freshwater ecosystem perspective, is the proposed/current LVPOTW in the catchment ecologically feasible and sustainable?

In order to answer this question, this study needed to:

a) improve understanding regarding the cumulative impacts that LVPOTW have on the receiving environment; and

b) develop a robust method that can model the associated impacts/risks and be applied in a variety of scenarios and geographies.

In order to achieve the abovementioned objectives and aims, the report is divided into two parts. The first part is an investigation into the cumulative impacts of LVPOTWs on river health, particularly in the eThekwini Metropolitan Municipality. This section looks at the latest research, trends, available methods and limitations to understanding LVPOTW-river health driver-response relationships in South Africa.

Results from the literature review of the report revealed that it is extremely difficult to determine the cumulative impacts of LVPOTW on river health as available tools are:

(i) too narrow in their scope (e.g. only examining water quality impacts);

(ii) too data-intensive to be reliable and/or practical in a South African (i.e. diverse and data deficient) context; and/or

(iii) do not take catchment-scale impacts and the type, state, importance and sensitivity of the receiving aquatic ecosystem into account.

These shortcomings limit policy and decision makers regarding the number of LVPOTW that a catchment can have.

For these reasons, a new tool was required for this study that:

- incorporated international best practice;
- considered both water quality and water quantity impacts;
- considered catchment-scale processes; and
- considered the type, state, importance and sensitivity of the receiving systems.

The new tool was developed as a Bayesian Network as these networks (a) were seen as the most appropriate method to incorporate the abovementioned criteria, and (b) are based on a robust statistical foundation.

The results of the literature and data review were used to inform the Bayesian Network to address the limitations in understanding and predicting LVPOTW-river health driver-response relationships in South Africa. The tool was then tested in various field-based case studies in the eThekwini Metropolitan Municipality.

The second section of the report is informed by the findings of the first section. The understanding gained from the first section was used to refine and test the tool created to better determine and predict LVPOTW-river health driver-response relationships. This refined model was then tested in two catchments in the eThekwini Metropolitan Municipality to determine the potential for the tool to be used at a national scale.

The result of comparing modelled and field-based assessment were positive: with the model able to accurately determine the probable cumulative impacts of the LVPOTW on river health in the catchments. These assessments allowed for a more coherent understanding of the impacts of LVPOTW on river health, and the natural assimilative capacity of rivers receiving treated effluent from these plants.

Moreover, the Bayesian Network provided valuable information not attainable through conventional assessment methods as their results are presented as risk distribution profiles, and not a single category result as with conventional methods. In other words, the network was able to not only report on the likely river health category of the system and potential future states of these systems under different development scenarios, but also the probability that the system could be in any other health category.

For these reasons, Bayesian Networks:

a) can be useful tools to provide preliminary guidance on management of LVPOTW within a catchment;

b) could provide decision makers and authorities with a powerful and relatively low-cost tool to predict impacts of proposed LVPOTW on river health; and

c) be used as a tool for spatial planning at a municipal, regional or national level to illustrate which catchments/systems can accommodate more LVPOTW and which are saturated.

However, despite these promising results, more assessments are needed to validate/verify the model parameters and nodes. In addition, in order to potentially use the tool at a national/international scale, one would have to do more comprehensive tests in different locations to validate the model in different ecoregions.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

PART I:

A PRELIMINARY REPORT ON THE CUMULATIVE IMPACTS OF LOW VOLUME PRIVATELY OWNED TREATMENT WORKS ON RIVER HEALTH IN ETHEKWINI METROPOLITAN MUNICIPALITY

1. Project contextualisation

1.1 Domestic wastewater and its treatment: a global problem

1.1.1 Domestic wastewater is a threat to human and ecosystem health

Domestic wastewater (synonymous with "urban/municipal wastewater" or sewage) is a primary source of global water contamination (WHO/UNEP, 1997; Moe and Rheingans, 2006; Corcoran et al., 2010) and is comprised of wastewater from residential sources (e.g. toilets, washing machines, sinks and baths) and stormwater runoff from roads and other catchment surfaces (UNEP et al., 2004). This wastewater pollutes freshwater ecosystems and poses risks to both human and ecosystem health (Schilling et al., 1997; Dickens and Graham, 1998; Morrison et al., 2001; Castillo, 2002; DEFRA, 2002; UNEO/MAP/NED POL/WHO, 2004; USEPA, 2004; Momba et al., 2006; Corcoran et al., 2010; Muller, 2013; UN, 2015).

Untreated domestic wastewater contains a cocktail of organic (e.g. carbohydrates, proteins and fats) and inorganic substances (domestic chemicals and pharmaceuticals) and bacteria. Pollutants from domestic wastewater include pathogens, pharmaceuticals, oxygen demanding substances, nutrients (including nitrogen, phosphorous and carbon), inorganic salts, synthetic chemical compounds and other chemicals found in stormwater (DEFRA, 2002; UNEP et al., 2004; USEPA, 2004; Corcoran et al., 2010). Bacteria naturally occurring in freshwater ecosystems can typically break down pollutants from domestic wastewater. However, the process that depletes oxygen in the water column (ultimately resulting in certain organisms dying), is not instantaneous (and therefore aquatic organisms are subject to unnaturally high/toxic concentrations of some substances) and under certain conditions is not possible (e.g. if the bacteria are not able to process a certain chemical or substance) (DEFRA, 2002; UNEP et al., 2004; Corcoran et al., 2010).

Humans often unwittingly use water from aquatic ecosystems receiving untreated effluent for raw drinking water, livestock drinking water, irrigation, catching fish and recreation (WHO/UNEP, 1997; Corcoran et al., 2010). Aquatic ecosystems receiving pollutants from domestic wastewater are often unable to improve water quality sufficiently as they themselves are impacted and degraded by the wastewater (Dickens and Graham, 1998; DEFRA, 2002; Corcoran et al., 2010).

This phenomenon is particularly concerning given that the world's population is increasing (UNDESA: PD, 2015) and, therefore, the amount of effluent that we produce is also increasing (Corcoran et al., 2010). The increase in domestic wastewater is a global concern that is exacerbated by the global trend of rapid urbanisation: essentially concentrating effluent and its associated problems geographically (Schilling et al., 1997; WHO/UNEP, 1997; Singh et al., 2004; Castillo, 2002; Moe and Rheingans, 2006; Corcoran et al., 2010).

This trend of increasing domestic wastewater production can jeopardise national and international development goals. For example, the United Nations Sustainable Development Goals: Goal 6 is to "*ensure availability and suitable management of water and sanitation for all*", with their target being to "*protect and restore water-related ecosystems, including* *mountains, forests, wetlands, rivers, aquifers and lakes…* [and] *support and strengthen the participation of local communities in improving water and sanitation management*" by 2020 (UNDESA: PD, 2015). It is therefore clear that domestic wastewater needs to be treated before it enters receiving freshwater ecosystems to protect both the receiving ecosystems and human health and wellbeing (WHO/UNEP, 1997; USEPA, 2004; Corcoran et al., 2010).

1.1.2 The role of wastewater treatment works

Society has developed a number of solutions to manage or mitigate the problem of increasing effluent and its associated human and environmental health risks (UNEP et al., 2004; Corcoran et al., 2010). The basic functions of wastewater treatment works are to simulate and accelerate processes that purify water quality in natural systems (e.g. settling of solids, aeration and biological metabolic breakdown of complex substances into simple substance; USEPA, 2004; UN, 2015).

The primary management tools are based around constructing wastewater treatment works (WWTW. plural WWTWs) that receive domestic wastewater, treat the wastewater to varying degrees, and generally discharge the treated wastewater into surrounding watercourses (e.g. WHO/UNEP, 1997; USEPA, 2004; DEFRA, 2002; Environmental Alliance, 2006; Corcoran et al., 2010; UN, 2015). Basic treatment involves physical (e.g. removing solids), biological (e.g. natural bacterial breakdown of wastewater substances accelerated by aerating the wastewater) and chemical processing (e.g. adding lime, salts or polymers to the wastewater) treatment (USEPA, 2004; UN; 2015). The process can be crude (i.e. primary treatment) in which much of the solid matter is settled out of the water column; more advanced, i.e. using bacteria to process and assimilate the remaining organic substances (i.e. secondary treatment); and/or disinfecting the treated effluent and/or removing additional nutrients (nitrates and phosphorous) from the treated effluent (i.e. tertiary treatment) (USEPA, 2004).

Therefore, domestic wastewater treatment and management requires treating untreated domestic wastewater to acceptable levels to prevent deterioration in the receiving aquatic ecosystem, minimise risk of human disease and protect ecosystem services provided by the surrounding environment (Dickens and Graham, 1998; Corcoran et al., 2010; UN, 2015). Conversely, improper management of domestic wastewater can result in significant risks and damage to human and aquatic ecosystem health (DEFRA, 2002).

1.1.3 Impacts of treated effluent on river health

Healthy rivers are important to humans as they provide a number of valuable services to humanity (UNEP et al., 2004; Corcoran et al., 2010). For instance, in the context of domestic wastewater treatment and reuse of water: rivers dilute, disperse, breakdown and assimilate waste to improve water quality for downstream users (UNEP et al., 2004; Corcoran et al., 2010). This is a regulatory service, whereby water quality is processed and regulated by the river (Corcoran et al., 2010). Other services include provisioning services (e.g. providing water to communities, fish for food, etc.), other regulatory services (e.g. flood attenuation), supporting services (e.g. biodiversity support, nutrient cycling, etc.) and cultural services (e.g. recreation, rituals taking place in or near rivers, etc.). Rivers that are in good health are able to provide a wider range of these services, whereas degraded rivers lose these abilities (Corcoran et al., 2010).

Unfortunately, river health is negatively impacted by receiving treated effluent (Schilling et al., 1997; Castillo, 2002; DEFRA, 2002; USEPA, 2004; UNEP et al., 2004; Corcoran et al., 2010; UN, 2015). The main impacts on river health are briefly described below and are a summary from reports from the USEPA (2004), UNEP et al. (2004), Corcoran (et al., 2010) and UN (2015):

- **Suspended, dissolved and/or settleable solids**

  Increased suspended and settleable solids decrease water clarity, with concomitant decreases in primary production and may smother benthic habitats once settled. This has multiple effects at different levels of the food chain: impacting primary and then secondary productivity, available habitats, modified feeding behaviour disease burdens, etc.

- **Nutrients**

  Increased nutrients can result in over-fertilisation of aquatic plants (including algae), resulting in potential eutrophication and concomitant decreases in water clarity and dissolved oxygen concentrations. These nutrients, particularly nitrogen and phosphorus, can also stimulate growth in undesirable/problematic aquatic plants (e.g. water hyacinth). Under certain conditions, cyanobacteria species producing bio-toxins can proliferate, killing aquatic organisms and terrestrial animals drinking the water. The increased organic matter from eutrophication and associated decomposing organic material further lowers dissolved oxygen in the water column, with associated negative implications to aquatic life.

- **Endocrine disruptors**

  Pharmaceuticals and other similar compounds affect aquatic biota by impacting on their regulatory and reproductive hormones. These impacts can affect the organism's ability to reproduce, alters its physiology and/or ecological resilience.

- **Pathogens**

  Pathogens entering the system increase stress and disease in aquatic organisms and decrease their resilience to other stressors. Impacts can be acute or chronic. These pathogens include viruses, bacteria, fungi and protozoans associated with human and animal faecal waste. Increases in pathogens pose a risk for both human and ecosystem health.

- **Oxygen-demanding substances**

  Increases in oxygen-demanding substances increase the biological and chemical oxygen demand necessary to break down these substances in the system. This demand on available dissolved oxygen decreases oxygen availability to native aquatic life.

- **Energy**

  Altering energy flux and availability in the system changes can shift population and community compositions, e.g. shifting macroinvertebrate community guilds from scrapers to filter-feeders. Energy flux modifications can be the result of nutrient, chemical and/or light energy changes in the system.

- **Pesticides and herbicides**

  Increases in pesticides and herbicides in wastewater can be toxic to aquatic life. The effects can be acute or chronic, depending on the types of chemicals concerned and their concentrations.

- **Other organic and inorganic toxicants**

  Other organic and inorganic toxicants (e.g. ammonia) and leading to chronic or acute toxicity to aquatic life. These toxicants can include heavy metals and/or persistent organic substances (e.g. PCBs). These substances are problematic given their persistence in the aquatic environment and may bio-concentrate in the food chain.
- **Salinity**

  Increased salts concentrations in the receiving aquatic ecosystem increases salinity in the water column and influences chemical reactions in the water.
- **Flows**

  Increased flows in the river, particularly baseflows in the low flow season, can have a negative impact on the receiving aquatic ecosystem. Modified stable base flows can encourage the pest species to proliferate. These modified flows can also alter the geomorphology of the system: changing substrate composition, sediment fluxes, the erosion potential in the system and riparian vegetation population dynamics and composition.

Other notable changes may include temperature fluctuations, pH, oils and grease. These parameters all have negative impacts on the receiving aquatic ecosystems if their levels are modified significantly compared to the background and existing levels in the receiving systems (DWAF, 1996; Schilling et al., 1997; Corcoran et al., 2010).

The abovementioned impacts are compounded when cumulative impacts are considered (i.e. impacts experienced by the river from upstream impacts). Cumulative impacts are the effects experienced by a receptor (e.g. Hilden and Rapport, 1993; Halpern et al., 2008; Smith et al., 2009; Schindler, 2011). These impacts consider point and diffuse pollution sources that are modified by the environment's assimilative capacity (Stakhiv, 1988; Contant and Wiggins, 1991). The receptor's response (e.g. river) is dependent on its state and sensitivity to the experienced impact. For example, in an aquatic ecosystem, the cumulative impacts on the benthic macroinvertebrate community will be all the impacts that the community experiences: the combination of water flow, geomorphological, nutrient, species composition and/or water quality modifications in the system that will cause a change/response in the community (Stakhiv, 1988; Contant and Wiggins, 1991; Kleynhans and Louw, 2008; Smith et al., 2009).

In summary and in terms of the impact of treated WWTW on an aquatic resource, the cumulative impacts experienced by the receiving riparian ecosystem depend on (a) the systems present state, (b) its sensitivity and (c) the quality and quantity of treated effluent entering the system (Stakhiv, 1988; Contant and Wiggins, 1991). The effects can vary and be expressed over time (Schilling et al., 1997). For example:

- Acute impacts can be from increased flows and shear stress, toxic substances, increased suspended solids, oxygen depletion and/or pathogens entering the system

- Delayed impacts can be altering the sediment carrying capacity of the water column, nitrogen-based toxic substances, oxygen depletion in the sediments, changes to feeding and breeding behaviour of aquatic organisms, etc.
- Accumulative impacts can be a permanently altered flow regime (with increased base flows in the low flow season), persistent organic compounds entering the system and/or oxygen depletion under eutrophic conditions.

These impacts are more pronounced in smaller rivers, than larger rivers because of the reduced potential for dilution (Schilling et al., 1997; Dickens and Graham, 1998).

1.2 eThekwini Metropolitan Municipality domestic wastewater and treated effluent problems

1.2.1 eThekwini Metropolitan Municipality's problems mirror global trends

The eThekwini Metropolitan Municipality is probably not unique in this respect and in KwaZulu-Natal, South Africa, experiences many of the same challenges as described above, and as these impact upon aquatic resources, i.e.:

- an increasing urban population;
- treated and untreated domestic wastewater entering these freshwater ecosystems (eThekwini treats >440ML/day (DWS, 2015)); and
- deteriorating river health.

The municipality is fully aware of these challenges (www.durban.gov.za; accessed October 2015). For this reason, the eThekwini Metropolitan Municipality Domestic Wastewater Disposal By-law (2015) "*recognises that effective and sustainable sanitation and domestic wastewater services are essential to community life, business and the environment*".

Therefore, there is a tension between:

- development in the municipality as a result of an increasing population;
- servicing these areas of growth; and
- the use and protection of rivers and other freshwater resources in the region.

This tension is intensified with a number of existing WWTW under pressure from current demands and infrastructure deterioration (DWS, 2015).

1.2.2 Domestic wastewater treatment in eThekwini Metropolitan Municipality

Domestic wastewater treatment in the eThekwini Metropolitan Municipality has largely followed the approach adopted by the rest of the country. South Africa has made great strides in its water resource management legislation (e.g. the seminal National Water Act, 1998). However, the implementation of the law has been hampered by a lack of institutional capacity, enforcement and tools for implementation.

In the WWTW-river health context, the water quantity and quality in the receiving river are governed by the ecological Reserve and Resource Quality Objectives (Muller, 2013). This Reserve needs to be met before the resource can be used (i.e. discharged into; NWA, 1998). These are set as gazetted Resource Quality Objectives (RQOs) for the flow (quantity, pattern, timing, water level and assurance of instream flow), the water quality (chemistry, physical and biological characteristics of the water), the instream and riparian habitat (character and condition) and the aquatic biota (characteristics, condition and distribution) of a water resource (Muller, 2013), with set specifications and thresholds of potential concern for indicator parameters.

However, the Reserve and/or RQOs have not been determined for many significant water resources in the country, let alone for smaller systems that are generally used by low volume privately owned treatment works (LVPOTWs; i.e. small wastewater treatment works: <2Ml/day). Therefore, water quality discharge limits in these systems are generally set to General Limit Values (DWAF, 2004), i.e. a set of water quality parameters. Unfortunately, these limits do not necessarily provide adequate protection for the receiving aquatic ecosystems, as for example has already been illustrated rivers within the eThekwini region (e.g. Dickens and Graham, 1998).

In catchments where the Reserve and RQOs have been set, riparian systems are subject to a critical limitation in the current process, i.e. the Reserve defines the lower threshold for water quantity in the system, but not always the upper thresholds. The latter is typically difficult to determine (when they are assessed). Therefore, though the water quality limits may offer some protection, the water quantity limits do not always necessarily protect river health. This is particularly important in smaller and highly degraded rivers that are more sensitive to the impact of increased flows.

This potential under-protection of water resources is exacerbated by the trend in which LVPOTWs are seen as feasible alternatives to relying on centralised municipal sewage treatment infrastructure (see Figure 1 for the distribution of LVPOTWs in the eThekwini Metropolitan Municipality). The eThekwini Water and Sanitation Unit (eThekwini Municipality, 2005) provides a policy for installing LVPOTWs in the eThekwini Municipality. That said, the municipality has a number of concerns around these systems. For example, the eThekwini Municipality (2012):

> *"Although a place for these plants* [LVPOTW] *is recognised, there are the following concerns:*
>
> *a) private plants must not be permitted to escalate in an uncontrolled manner to become the ready solution for every developer whose plans are frustrated by the IDP "urban edge " and associated absence of water borne reticulation.*
>
> *b) the monitoring and controls necessary are onerous in terms of staff time and the limited staff resources.*
>
> *c) in areas where there are several plants, and notwithstanding that each has a limited capacity, several plants may discharge to the same watercourse.*
>
> *Planning controls will thus be exercised by the Development Planning and Management Unit."*

Indeed, low volume wastewater treatment works (LVTWs; <2ML/day) account for 47% of municipal WWTW in South Africa (DWS, 2015). In KZN, this figure is 62%. Despite their relatively small operational flow contribution when compared to larger WWTW in the country (e.g. only 2% operational flows), these LVTWs are far more wide-spread and therefore potentially impact more freshwater ecosystems in our country than the larger WWTWs. This is particularly true for their impact in terms of proportion of flows comprising of treated effluent: a key factor impacting river health according to Dickens and Graham (1998).

It is therefore difficult to prescribe set discharge caps and limits for developers or authorities who want to place a LVPOTW in a catchment based on current available tools in South Africa. It is this problem of potential under-protection of water resources in the country, when it comes to the impact of LVPOTWs which this project investigates further, with a particular focus on the eThekwini area.

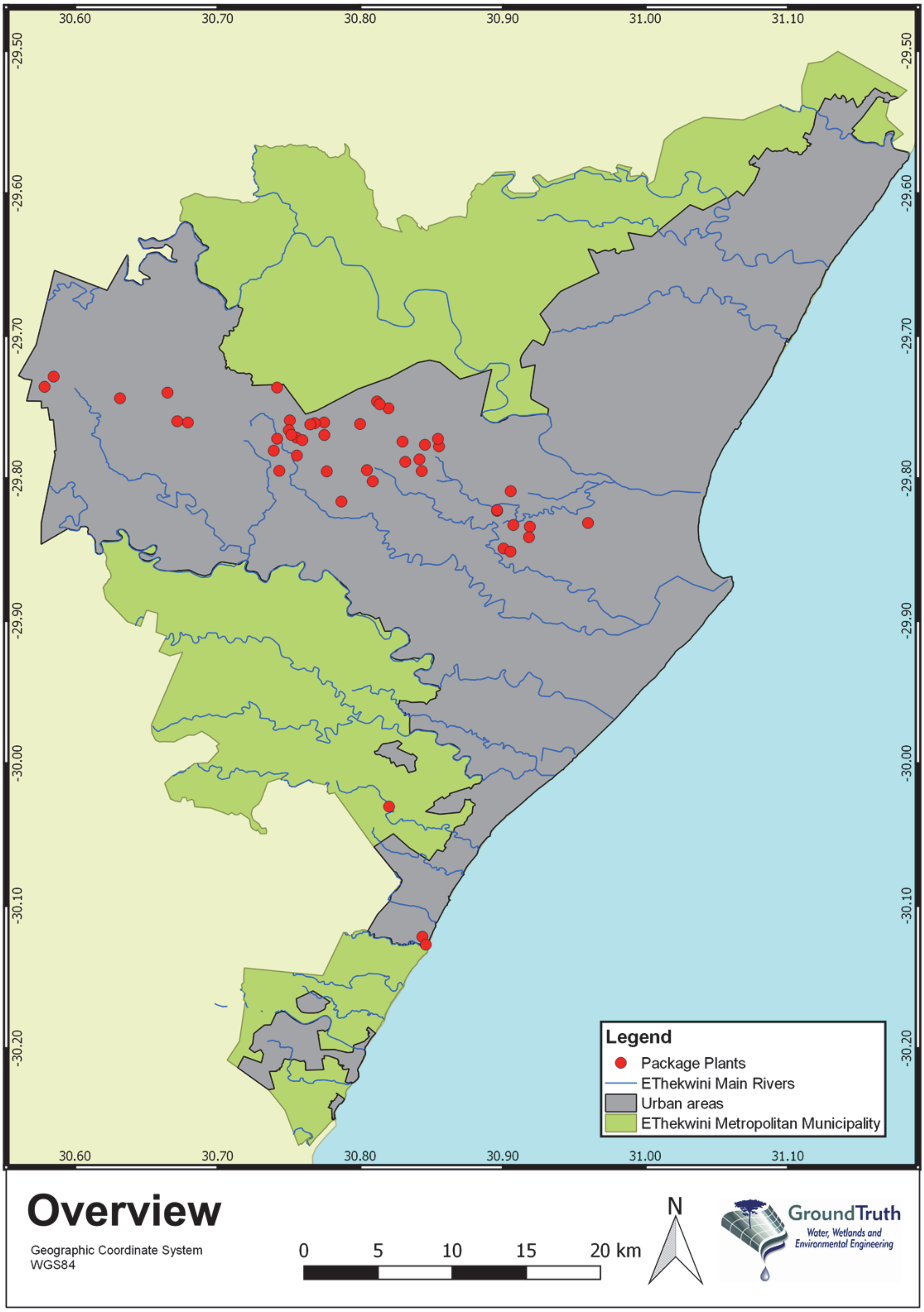


Figure 1: Map of package plants in the eThekwini Metropolitan Municipality

1.2.3 Policy and information gaps leading to under protection of river health in the municipality

The following information is required to make informed decisions regarding LVPOTWs and their relationship with river health:

- What are the cumulative impacts of LVPOTWs on river health?
- What is the broader assimilative capacity of aquatic ecosystems receiving treated effluent from LVPOTWs?
- How many LVPOTWs can be placed in a given catchment?

Currently, the eThekwini Municipality has no guidelines regarding the sustainable number and size of LVPOTWs in a given catchment. The problem is further complicated with only one LVPOTW in the municipality being monitored from a river health point of view. Though others do monitor water quality discharges, this does not provide a realistic view of the impact of these systems on river health. This issue was noted as far back as the 1990s, as for example by Dickens and Graham (1998). Furthermore, given the complex land uses in the municipality and various catchments, results from other river health monitoring sites (regular or ad hoc) cannot be easily extrapolated to link river health in the municipality to WWTW impacts, i.e. little aquatic biomonitoring data is typically available directly up and downstream of the point-source discharge points. Therefore, it is difficult to comment on the cumulative impact of LVPOTW on river health in any given area.

This research project attempts to investigate the cumulative impacts of LVPOTW on river health in the eThekwini Metropolitan Municipality using all relevant and available information. This investigation will consider high level desktop assessments (including literature reviews and GIS analyses), relative risk modelling (using Bayesian Networks (BNs)) and field-based assessments/verification of the BN models developed.

Given the paucity of monitoring data available for the area and in the absence of any other long term river health data linked to LVPOTWs in South Africa, the cumulative impacts of LVPOTWs in the eThekwini Municipality are investigated by looking at a case study of the Fischer Road LVPOTW in Hillcrest (a rare instance in which some long term river health data is available that can be linked to LVPOTWs impacts).

It is hoped that through this preliminary investigation it will be possible to provide further guidance on the management of LVPOTWs and transfer the knowledge of using BNs to the municipality. The study will also provide recommendations on future research needs and potential application of this approach to a national level.

It is noteworthy that the problem addressed in this project has provincial and national relevance (e.g. only 37% of WWTW in KZN are considered as “low risk” in 2012 (DWA, 2012)). Therefore, attempts at solving this complex problem in the eThekwini Metropolitan Municipality may have far-reaching positive implications for the rest of the country and the way in which effluent is treated and river health protected into the future.

2. *Objectives, approach, assumptions and limitations of the project*

2.1 Objectives

In the light of the context provided in the preceding sections, the objective of this study is to provide a better understanding of:

- The cumulative impacts of LVPOTWs on river health in eThekwini Metropolitan Municipality;
- The assimilative capacity of receiving aquatic ecosystems;
- The preliminary guidance on management of small treatment plants within a catchment; and
- The recommendations for further studies to develop a comprehensive guideline for all municipalities in South Africa.

This report aims to partly address the issues raised above, i.e.:

- What are the cumulative impacts of LVPOTWs on river health in eThekwini Metropolitan Municipality; and
- What influences the assimilative capacity of receiving aquatic ecosystems?

Essentially, answering the following question for any proposed/current LVPOTW in the eThekwini Metropolitan Municipality: *from a freshwater ecosystem perspective, is the proposed/current WWTW in the catchment ecologically feasible and sustainable?* In order to answer this question, this study needs to (i) improve understanding regarding the cumulative impacts that LVPOTWs have on the receiving environment; and (ii) development of a robust method that can model the associated impacts/risks and be applied in a variety of scenarios and geographies. These will be addressed in this report.

2.2 Approach

In order to achieve the abovementioned objectives, this study includes the following approach:

a) Review the cumulative impacts of WWTW on river health
b) Reconcile international best practice principles and protocols to measure and manage WWTW effluent discharge-river health relationships in a South African context
c) Develop a model and present results from the only long-term LVPOTW-river health monitoring project in the eThekwini Metropolitan Municipality as a case study

d) Present a framework to guide the development of a tool to help eThekwini Metropolitan Municipality assess the risks of a proposed/current LVPOTWs on the receiving river

This approach will address the objectives of this report and allow for a more coherent understanding of the impacts of LVPOTWs on river health. Results will inform potential mitigation measures and policies regarding planning and operation of LVPOTWs in the eThekwini Metropolitan Municipality.

2.3 Assumptions

- LVPOTWs are minimally designed according to Department of Public Works guidelines (2012); and
- LVPOTWs are considered to be <2ML/day (eThekwini Municipality, 2005; eThekwini Municipality; 2015)

2.4 Limitations

The objective of this study is to describe the cumulative impacts of LVPOTWs on river health within the eThekwini Metropolitan Municipal area and is therefore not a comprehensive literature review or assessment of the impacts of WWTWs on river health both locally and globally.

3. Investigating the cumulative impacts of low volume privately owned treatment works on river health in the eThekwini Metropolitan Municipality

3.1 Long-term biomonitoring linked to the potential impacts of a low volume privately owned wastewater treatment works on river health in eThekwini

The cumulative impacts, i.e. the sum of all impacts in a system as experienced by a receptor, e.g. ecosystem, population, organism, etc. (Stakhiv, 1988; Contant and Wiggins, 1991) of LVPOTWs in eThekwini Municipality were investigated on the Nkutu River (see Figure 2). This was used as a case study to build the understanding and potential models that could be used to both better understand and model these relationships of LVPOTWs on river health, but also allow testing of these models to broader areas.

Long-term river health monitoring has taken place downstream of the Cotswold Downs Estate in Hillcrest, KZN. This biomonitoring has produced a decade's worth of results regarding the impacts of changes in land use, specifically the introduction of a LVPOTW, on river health in the catchment.

Given the size and nature of the system, river health was determined using the SASSv5 macroinvertebrate community health assessment method (Dickens and Graham, 2002) and benthic diatom community health (Taylor et al., 2007a, 2007b; Harding and Taylor, 2011). Results were plotted over time and interpreted in the context of land use changes in the system.

Results indicate that river health in the Nkutu River has varied over time (GroundTruth, 2015). This variability is likely to be the result of changes in land use in the catchment between 2004 and 2015. Initially the system was dominated by sugar cane farming (until August 2006). Thereafter, sugar cane was removed and the Cotswold Downs Estate was established. No discharge was received by the catchment from the LVPOTW until March 2010 (via diffuse runoff from the fertigated golf course). This change in land use in the catchment had three chief implications for the aquatic ecosystem:

1. Water quality impacts shifted from agricultural runoff to diffuse and largely non-point flows of treated effluent entering the system (see above);
2. Riparian habitat was improved as buffer zone sizes were increased and indigenous vegetation was re-introduced to the system; and
3. The system's flow regime was further modified by the introduction of instream impoundments and diffuse return flows from the Fischer Road LVPOTW via the golf course.

Results indicate that water quality appears to have improved once sugar cane was removed from the system (GroundTruth, 2015). Interestingly, no changes were observed before and after treated effluent was released into the system – largely due to the still very small volumes of effluent making their way into this system, primarily by diffuse flow through well-developed riparian buffer zones, but also potentially due the in-channel dams created between the LVPOTW discharge point and the downstream monitoring site. Therefore, it is likely that the dams are playing an important role in polishing water quality before it enters the Nkutu River downstream of the Cotswold Downs Estate.

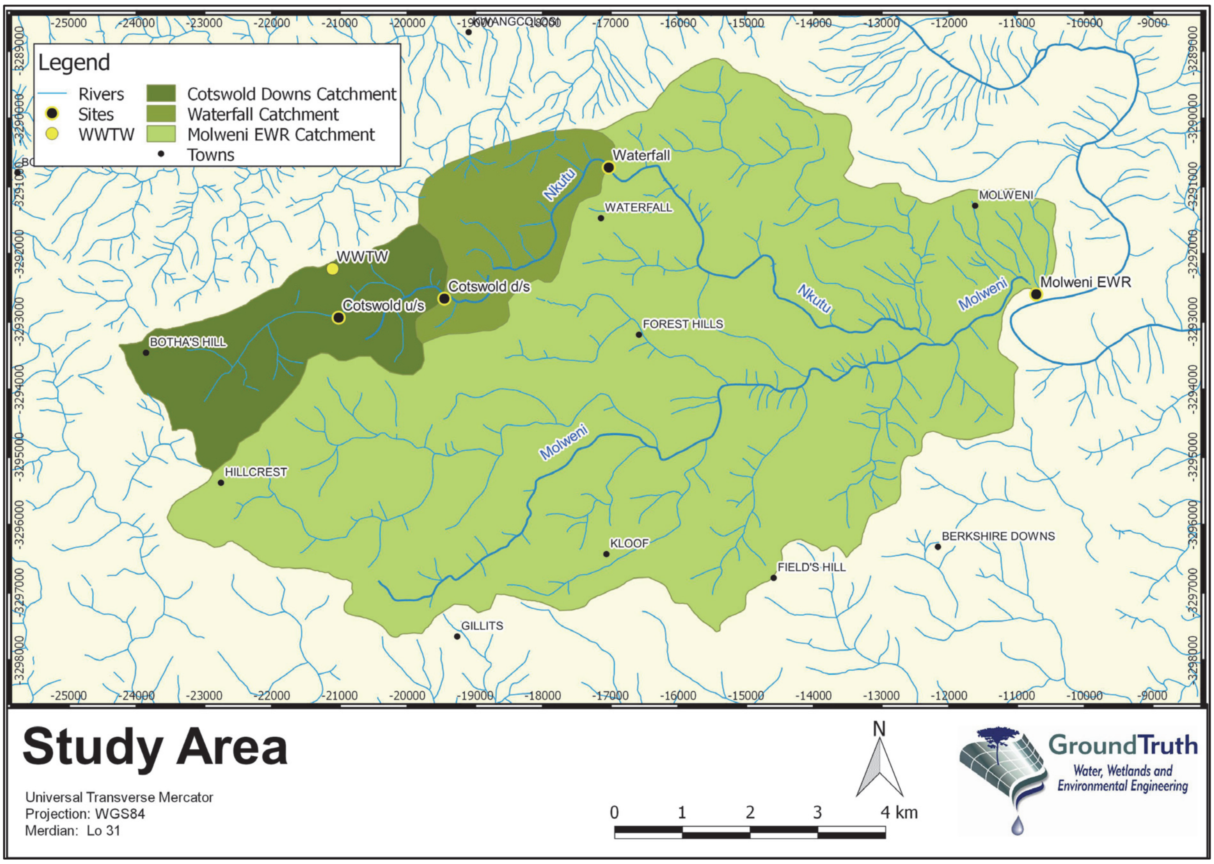


Figure 2: Map of study area

The riparian habitat has also improved significantly since the conversion of the area from sugar cane to low density urban settlement, by removing alien invasive vegetation from the riparian zone, re-introducing indigenous vegetation and increasing the riparian buffer zone size. These changes are likely to have resulted in improved bank stability, reduced sedimentation in the instream habitat and improved vegetation biotope availability for macroinvertebrates and overall river health in the system (GroundTruth, 2015).

Therefore, despite the small scale of the study area and sample sites up- and downstream of the discharge point, the abovementioned factors made it difficult to untangle the cause-response relationship between the LVPOTW and river health in the system. These complex interactions influencing river health make it difficult to determine what the potential cumulative impacts of potential increased discharges from the LVPOTW into the Nkutu River will be in terms of impacting river health.

Therefore, despite a good biomonitoring record in the system, additional studies were required to tease out the potential cumulative impacts from the LVPOTWs on river health in the system. This is needed to determine and predict changes in the system should treated effluent volumes increase in the future, or to determine the impacts of any additional LVPOTWs on river health in the catchment.

3.2 Initial assessment to determine the cumulative impacts on river health

3.2.1 Cumulative impacts of increased water quantity on river health

Results from a Reserve determination study on this system (Stassen, 2014), and hydraulic cross section modelling, indicated that the proposed discharges would significantly impact river health in the Nkutu River directly below the discharge point in the low flow season, should discharges from the LVPOTWs increase to 1.6ML/day. Despite proposed discharges being a relatively small amount of water being added to the system (i.e. 10L/s at 1.6ML/day), the small size of the system results in a 200% increase in flows in the river during the low flow season. This is significant if the flows are released constantly and given the river's size and associated sensitive nature. However, these results did not take into account attenuating structures (i.e. dams) upstream of the assessment site.

3.2.2 Cumulative impacts of modified water quality on river health

The water quality assessment considered over a decade's worth of river health data for the reach of river. Trends in both aquatic ecosystem health, derived from macroinvertebrate community health using the SASS5 protocol (Dickens and Graham, 2002) and interpreted according to Dallas's (2007) bands, and physicochemical water quality parameters were used to determine spatial and temporal driver-response dynamics in the Nkutu system at the Cotswold Downs Estate. This information was supplemented by results from Stassen (2014) and GroundTruth (2014) to provide an indication of the state of the Nkutu-Molweni system as a whole. Furthermore, water quality reference conditions for the catchment were derived from the Department of Water and Sanitation's measuring stations: U2H030Q01, U2H034Q01, U2H033Q01, U2H032Q01 with data from between 1980 and 1981 (n=77). No reliable data was available for the ecoregion II before this time period.

Results were tested and modelled at a desktop level using regression analyses from Dickens and Graham (1998) to determine the impacts of increased flows comprising of treated effluent on aquatic biota in the Nkutu River. This test used aquatic macroinvertebrates as indicators of aquatic health. The relationship between increased flows comprising of treated effluent and the response observed in aquatic biota (using the SASSv5 indices; Dickens and Graham, 2002) is illustrated in Figure 3 and Figure 4. It was assumed that effluent from the LVPOTW would at a minimum be treated to General Limit Values (GLVs; DWA, 2004). The model was run for a maintenance low flow scenario in the low flow months, i.e. the critical time in the year where dilution would be lowest and where the minimum amount of water is available in the system. Three sites along the length of the river were considered for this component of the study.

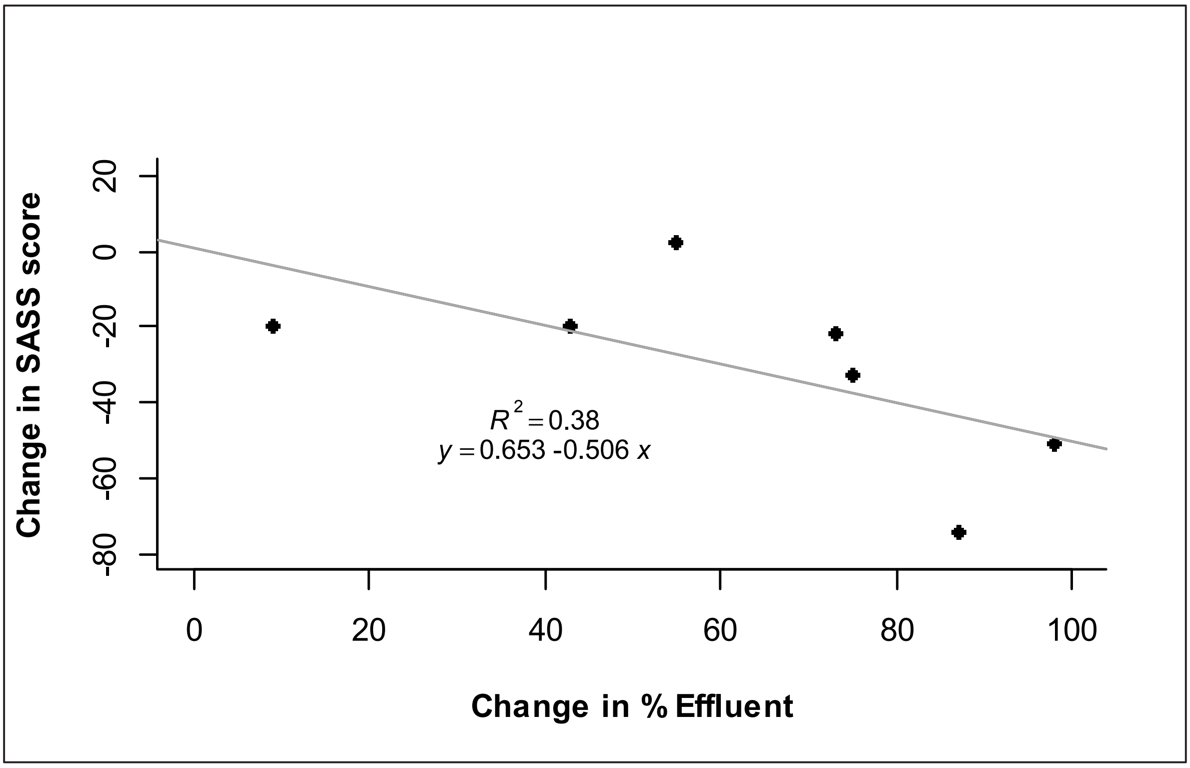


Figure 3: Change in SASS Score in response to the proportion of total flows in the river comprising of treated effluent (from Dickens and Graham, 1998)

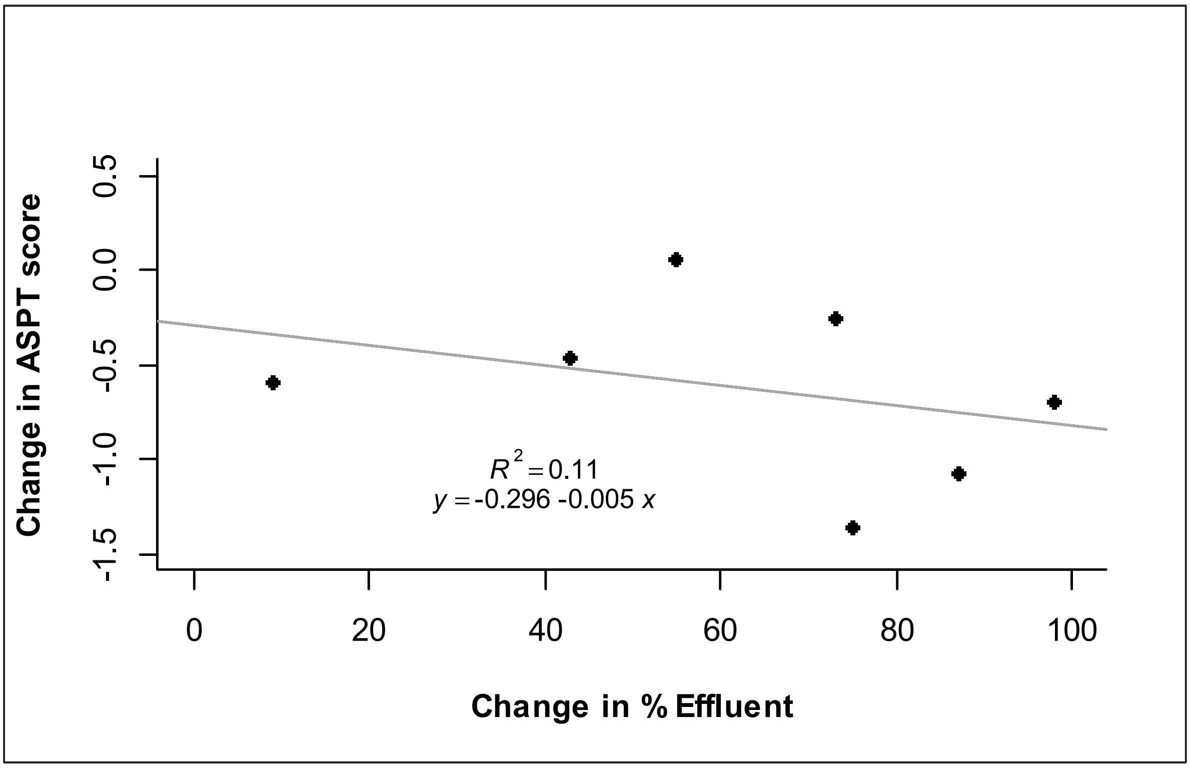


Figure 4: Change in Average Score per Taxon in response to the proportion of total flows in the river comprising of treated effluent (from Dickens and Graham, 1998)

Results from the water quality assessments were similar to those of the Reserve determination study: suggesting an unacceptable deterioration in river health of the system should discharges be increased to 1.6ML/day (GroundTruth, 2014 and 2015). Results suggested that increased flows, as little as 0.45ML/day, would seriously impact river health in the system at the discharge point. The cumulative impacts were less pronounced in the high flow season (summer, and greater dilution potential) and with progression down the river catchment. At the confluence of the Nkutu and Molweni Rivers, the impact was negligible, with no change in river health. Therefore, the system's sensitivity to the proposed increased flows varied both temporally and spatially: becoming less sensitive downstream as the proportion of flows comprising of treated effluent decreased.

3.3 Limitations of the initial approach

The abovementioned studies were limited for a number of reasons:

- The model in Dickens and Graham (1998) did not cater for volumes of treated effluent exceeding 120% of the proportion of flows in the river;
- The model in Dickens and Graham (1998) may be too simplistic and not accurately represent ecological driver-response relationships (e.g. it is a linear regression model and responses are likely to have a reverse sigmoidal pattern);
- The sample site was directly below the Cotswold Downs Estate and is therefore relatively high up in the catchment, thereby reducing confidence in the hydrology results;
- Models assumed that river health would be negatively impacted by the LVPOTW being introduced into the catchment. However; pre- and post-operation results indicated no significant change in the system, and in certain cases, an improvement in river health was observed; It is acknowledged though, that only a small portion of the treated effluent from the Fischer Rd WWTW is currently entering the Nkutu River, and even then via runoff from the Cotzwold Downs golf course.
- The reasons for this was that models used (the best currently available in South Africa) did not adequately address spatial and temporal land use changes in the catchment (e.g. improved riparian habitat over time as a result of rehabilitation in the catchment);
- Nor did the models adequately account for the assimilative capacity of the receiving environment (e.g. a wetland and dams present between the discharge point and monitoring sites);
- The models were therefore too restricted to deal with complex interrelationships and not robust enough to consider multiple impacts (both positive and negative) over time and link these to the assimilative capacity in the system and the resultant cumulative impact on the river health.

For these reasons, a more robust model was required to understand the cumulative impacts that potential increased flows from LVPOTWs in the catchment would have on the river health of the receiving system.

3.4 Modelling of systems using Bayesian Networks

A potential solution to the abovementioned limitations was to use Bayesian Network (BN) modelling. These models are relatively new to the field of water science (e.g. Reckhow, 1999; Marcot et al., 2001; 2006; Woolridge, 2003; McCann et al., 2006; Stevenson et al., 2006), but are the result of the convergence of artificial intelligence with statistics (Woolridge, 2003; Kokkenen et al., 2005). Their versatility and modelling power is now employed across a variety of fields for the purposes of analysis, simulation, prediction and diagnosis (Woolridge, 2003). Essentially the tools are probabilistic graphical models and are proving to be useful in understanding complex problems and predicting the outcomes of multiple driver-response interactions (Reckhow, 1999; Marcot et al., 2006; McCann et al., 2006; Nyberg et al., 2006; Stevenson et al., 2006; Walton and Meidinger, 2006).

Bayesian Networks are probabilistic graphical models that encode relationships between a set of variables in a database (McCann et al., 2006). These models calculate the probability of an event occurring given a set of conditions in a system.

These models are particularly powerful in the context of this project because they:

- learn from past data;
- support empirical data (parameters) and expert knowledge (model structure);
- form a bridge between the technical and managerial information required by decision making in complex problem sets;
- display outputs in a user friendly manner;
- cater for and describe uncertainty;
- are transparent to stakeholders;
- can handle very complex, high dimensional problem domains;
- accommodate incomplete databases;
- have a strong probabilistic foundation;
- explain sensitivities; and
- allow for predictive and historical scenario modelling.

For these reasons, Bayesian Networks are useful for modelling ecological predictions and informing decision-making in water resource management (Reckhow, 1999; Marcot et al., 2001; Borsuk et al., 2004; Marcot et al., 2006; Nyberg et al., 2006; Steventon et al., 2006; Walton & Meidinger, 2006; Stewart-Koster et al., 2010). As a result, Bayesian Networks can be a powerful tool for understanding the cumulative impacts of LVPOTWs on receiving aquatic environments. These Bayesian Networks include impacts from both point and non-point pollution sources (where information on these impacts is available); thereby accounting for direct (from point-source LVPOTWs), and indirect and cumulative (catchment-scale contributions) impacts in a system.

The BN modelling approach considers all known and relevant factors within the system of interest and considers the “risk” of impacts to various receptors in the system (Woolridge, 2003; Stevenson et al., 2006). Therefore, in the context of this case study, BNs could provide insights into the risk to river health in the Nkutu River if additional volumes of treated effluent are discharged from LVPOTWs into the river system?

In order to achieve this, the following steps were undertaken:
(i) Undertake a literature review to inform the structure of the Bayesian Network;
(ii) Develop a conceptual model of the system's drivers, modifiers and responses;
(iii) Set parameters for the model;
(iv) Compile equations to determine the Conditional Probability Tables (CPT, i.e. rules) for the network;
(v) Run the model for three sites along the length of the river system for the *status quo* scenario using field-based data; and
(vi) Run the model for various discharge water quality standards scenarios to determine their likely impacts, if any, on the receiving environment (rivers).

Step (i) and (ii)
Results from the literature review are discussed in Section 1 of this report. In the context of the case study, it is important to remember that river health is not a function of individual drivers or responses, but rather an integrated view of the ecosystem's (a) absence of distress (defined by measured indicators); (b) resilience; and (c) risk factors in its catchment (e.g. domestic wastewater effluents or changes in land use; Norris and Thoms, 1999). Therefore, assessing the impacts of treated domestic wastewater on river health involves understanding source-stressor-response linkages in the WWTW-receiving ecosystem relationship (e.g. Dickens and Graham, 1998; Norris and Thoms, 1999; Callisto, 2002; Momba et al., 2006). In this instance, the source of the threat is increased water quantity and changes in water quality from LVPOTWs in the river's catchment. The stressor is the way or conduit by which the source impacts the receiving aquatic environment (e.g. increased nutrient concentrations and dissolved oxygen depletion in the water column). The response is the reaction of the receptor (e.g. aquatic macroinvertebrate community) to the cumulative impact of the stressor (Norris and Thoms, 1999; Momba et al., 2006; UN, 2015).

Therefore, it is important to understand all components of the linkages to predict or assess the potential or current impacts that discharged treated effluent may have on river health. Once these are known, limits and standards can be imposed regarding the allowable quantity and quality of treated effluent discharged from a LVPOTW (e.g. UNEP/GPA, 2000; DWAF, 2004). Essentially, the process involves (a) knowing the reference condition for the river, (b) determining the present state of the system, (c) predicting the potential impacts of various developments or supply/demand scenarios and (d) determining the best/most practical achievable state, i.e. a compromise between the reference condition and unavoidable human impact (Schilling et al., 1997).

However, given the complexity of treated effluent-river health linkages and interactions, methods of assessment can either be too simplistic, e.g. only focusing on the quality of treated effluent discharged (Barjoveanu et al., 2010) or too complicated and resource intensive, e.g. continual long term monitoring of a comprehensive suite of variables requiring detailed analyses (e.g. UNEP et al., 2004; OECD/Eurostat Joint Questionnaire on Inland Waters, 2008; UN, 2015) – a requirement often too onerous for developing countries to adopt. That said, however, Norris and Thoms (1999) point out that a number of studies suggest that river health and stress can be derived from certain course biotic and abiotic indicator groups. Therefore, it is important to determine a compromise between the number and level of indicators to assess and the political/legal/financial practicalities and realities to provide a suitable idea of the current and/or potential impacts of a WWTW on river health. One solution is to describe these relationships and interactions in a robust ecological risk assessment framework. In this instance, endpoints such as "river health" can be quantified in terms of biological indicators (Hart et al., 1999).

This was the approach taken for this case study: a BN that describes, illustrates and analyses the source-stressor-response linkages in the LVPOTW-river health relationship. The conceptual framework to model the potential cumulative impacts from LVPOTWs on river health, and relationships between the interacting variables (Walton and Meidinger, 2006) in the model are illustrated in Figure 5 to Figure 9. The rationale and rules governing these interactions are presented in Table B in the Appendices.

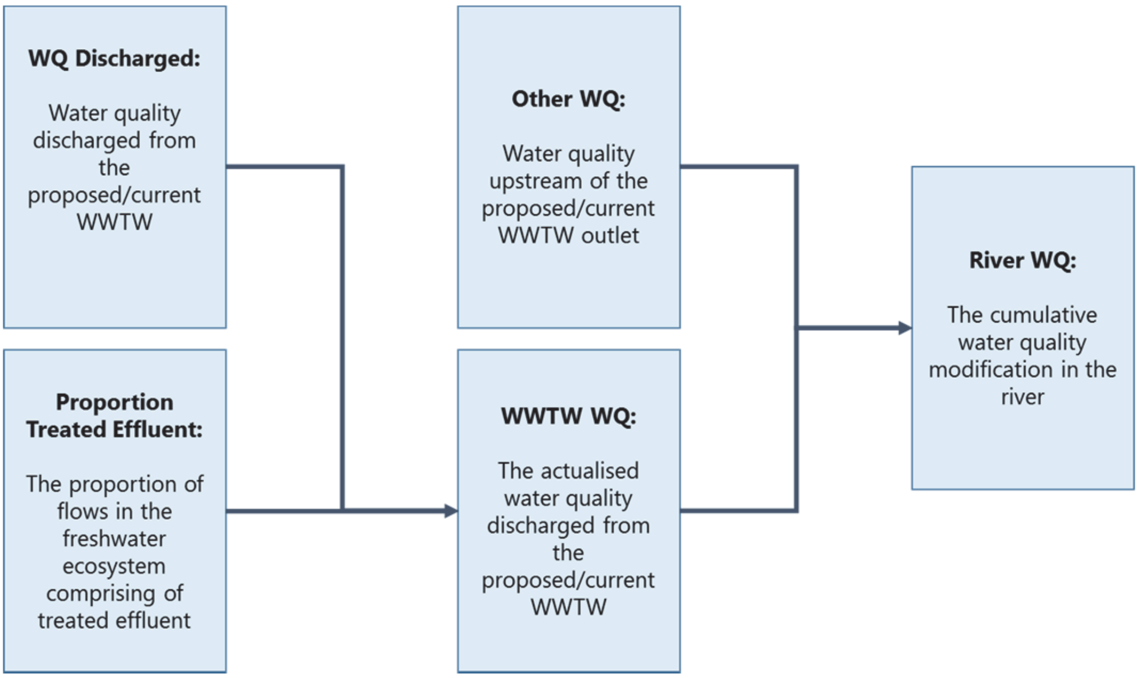


Figure 5: Rationale and linkages affecting the cumulative water quality modification in the river

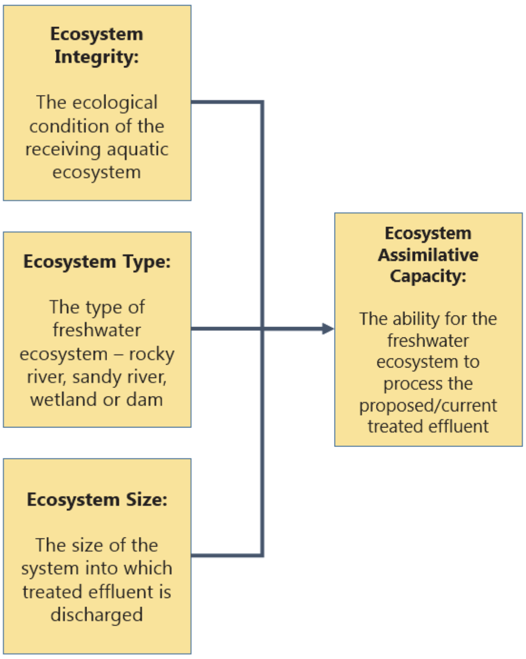


Figure 6: Rationale and linkages affecting the ability of the freshwater ecosystem to process the proposed/current treated effluent discharges

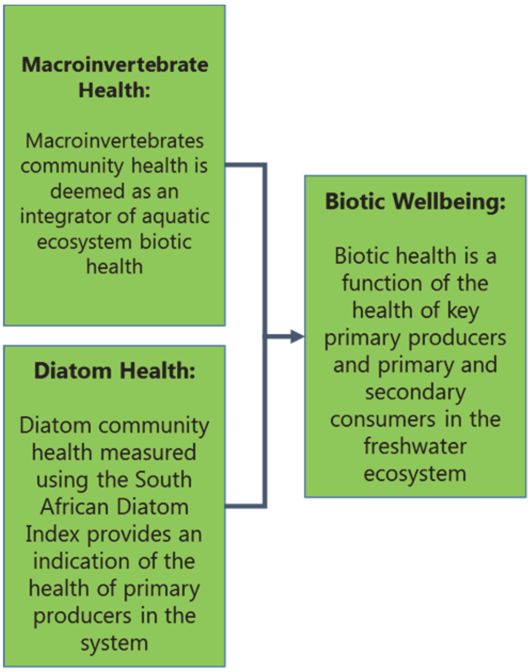


Figure 7: Rationale and linkages used to determine biotic wellbeing in the system

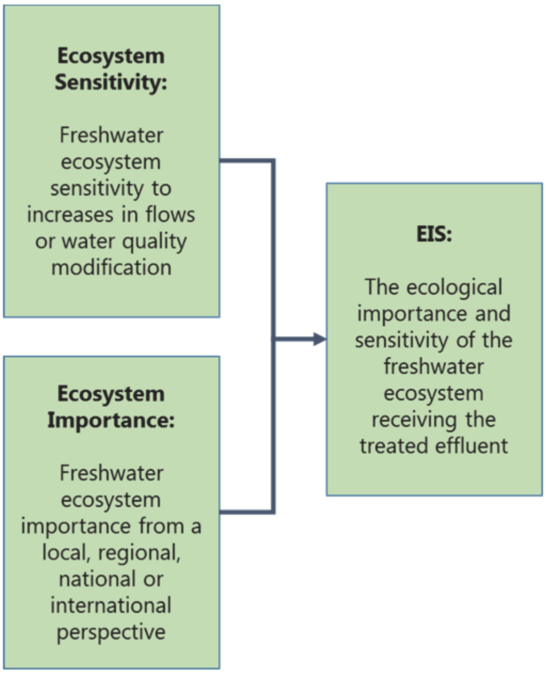


Figure 8: Rationale and linkages determining ecological importance and sensitivity in the system

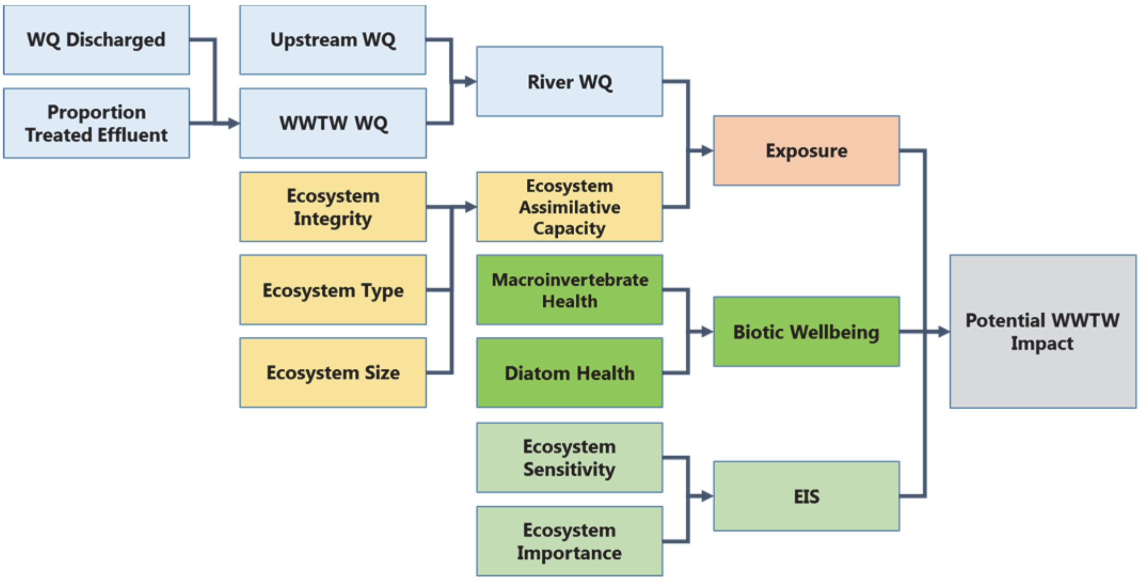


Figure 9: Integrated framework of the rationale and linkages determining the final cumulative potential impacts of the proposed LVPOTW on river health

Step (iii)
Model parametrisation for the abovementioned framework are presented in Table A in the Appendices.

Step (iv)
The following formulae (for simple and nested nodes) show the relationships used to derive the Conditional Probability Tables (CPTs; Kokkonen et al., 2005):

a) Simple:

$$p(Daughter|\ Parent_1, \dots, Parent_n) = NormalDist(Daughter, ((Parent_1 \times Ratio_1) + \dots + (Parent_n \times Ratio_n)) \div n, SD)$$

b) Nested:

$$p(Daughter|\ Parent_1, \dots, Parent_n) = \left(Parent_a Threshold_{a)}\right)?\ NormalDist(Daughter, \left((Parent_a \times Ratio_a) + \dots + (Parent_n \times Ratio_a)\right) \dots (Parent_\partial Threshold_{\partial)})?\ NormalDist(Daughter, ((Parent_1 \times Ratio_\partial) + \dots + (Parent_n \times Ratio_\partial)) \div n, SD$$

Where: $a = Most\ important\ variable\ threshold\ and\ associated\ ratios,$ and
$\partial = Least\ important\ variable\ threshold\ and\ associated\ ratios.$

Equations are presented in Table B in the Appendices.

The result of steps i-iv are illustrated in Figure 10. Throughout the model, risk components of the nodes were defined as follows:

- "Zero" = natural/unimpacted and/or "ideal" state;
- "Low" = "acceptable" state;
- "Moderate" = "concerning" state; and
- "High" = "unacceptable" state.

Parameter classes were set to define input node categories (step iii). The BN endpoint profile were cross-referenced and linked to the Department of Water and Sanitation's EcoStatus outputs (Kleynhans and Louw, 2008) to allow for more accessible interpretation of the results for users that are unfamiliar with the model (see Figure 11).

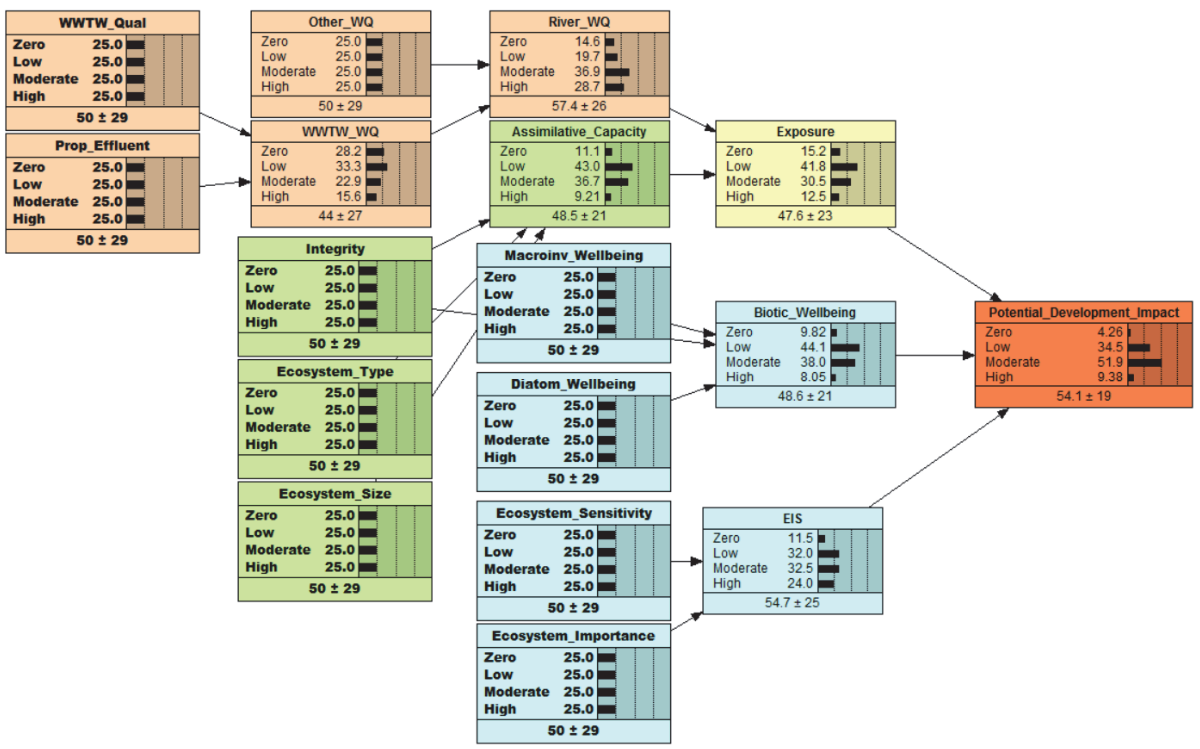


Figure 10: Bayesian Network structure for the Nkutu System

Figure 11: Link between Bayesian Network endpoint ranking with Department of Water and Sanitation's EcoStatus model outputs

Step (v)

Field-based data was used to populate the model for the status quo (step v) based on the parameters set up in step iii. Despite the model's seeming complexity, it is relatively simple to run, with input data simply tabulated in MS Excel and exported as text files.

The results from the BN model suggested that, in contrast to the previous (initial) assessments and models based on a linear regression model from Dickens and Graham (1998), the proposed discharges will only have a moderate impact on the system (see Figure 12). Nonetheless, there was still a significant concern that a proposed upgrade to the LVPOTW would have a moderate impact (55% probability) on the river health, which could result in the system's Recommend Ecological Category not being met (61% probability). The model indicated that the most important factor attenuating potential impacts of the proposed discharges comprising of treated effluent meeting GLVs was the wetland and dam ecosystems upstream of the sampling site.

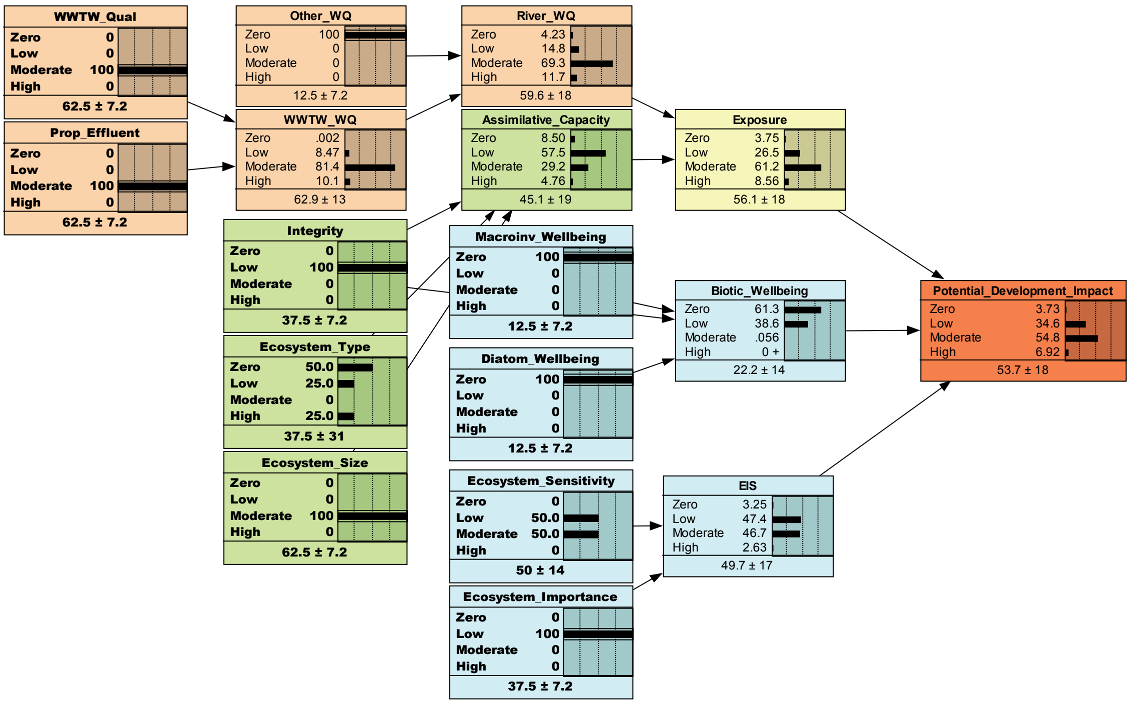


Figure 12: Bayesian Network illustrating the results of the proposed discharges under present conditions at the Cotswold Downs Site

Step (vi) involves running the model for various discharge water quality standards scenarios to determine their likely impacts, if any, on the receiving environment (rivers). In the following scenario; the discharge WQ meeting the SLVs and GLV standards (with effluent discharging at or meeting Special Limit Values (SLVs), the system improved and there was a high probability (75%) that the proposed discharges will have a zero to low impact on the system at the Cotswold Downs Site (see Figure 13). Therefore, under these conditions, the proposed discharge (at SLV standards) into this system will be ecologically acceptable.

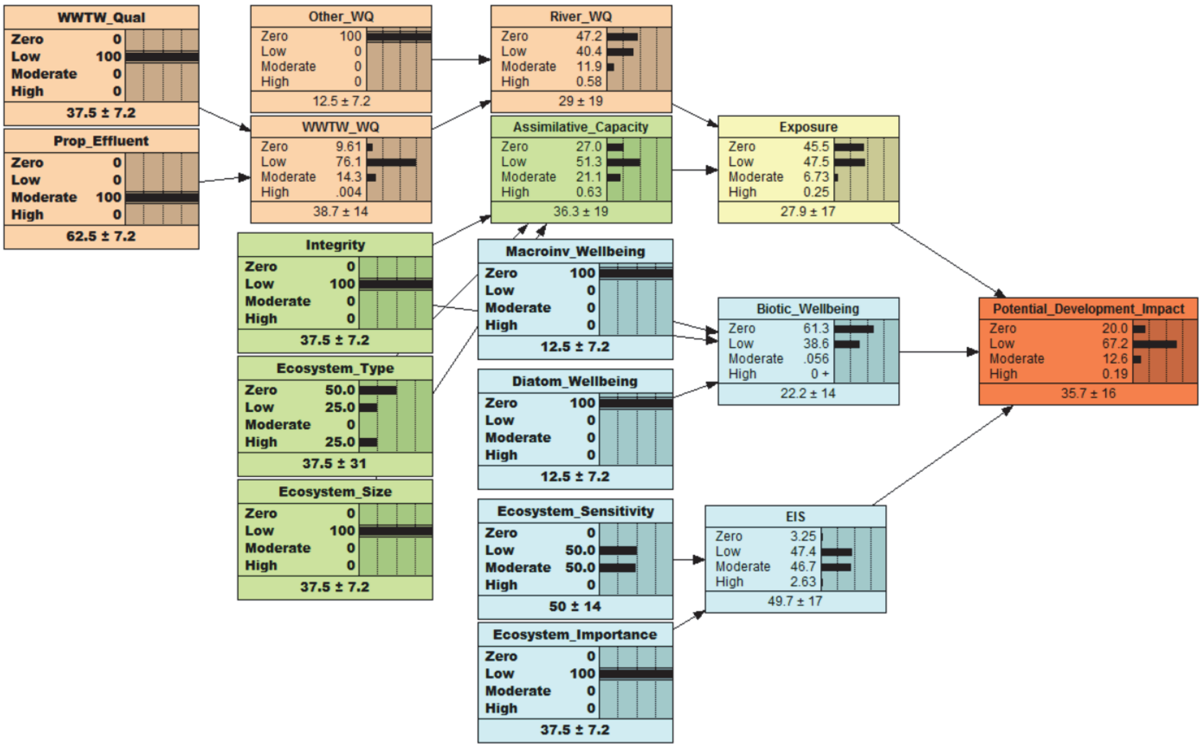


Figure 13: Bayesian Network illustrating the results of the proposed discharges meeting Special Limit Values under present conditions at the Cotswold Downs site

4. Preliminary conclusions and recommendations based on the development of a pilot model of impacts of a LVPOTW on river health

Treated effluent discharge from LVPOTWs impacts water quantity and water quality dynamics in rivers. These impacts generally cause the river health in the receiving system to deteriorate. This is particularly concerning given the number of LVPOTWs used in South Africa. These smaller domestic wastewater treatment systems are generally placed in smaller, more sensitive and often poorly understood catchments. The discharge limits imposed on the discharge water quality of the treated effluent is also then often inadequate and fails to protect the receiving environment.

Current assessment and management tools in South Africa do not adequately address the problem of protecting water ecosystems from treated domestic effluent discharges from LVPOTWs. Therefore, authorities struggle to make informed and ecologically sound decisions regarding proposed future and current LVPOTWs, both in terms of their placement and the ability of receiving catchments to continue to “soak up” this treated effluent. For this reason, there is a clear need for more robust models to assess and predict the cumulative impacts of LVPOTWs on river health.

The initial results from this work have highlighted that current tools and models are too limited (e.g. merely focusing on water quality limits) or too complicated and data intensive (e.g. requiring decades’ worth of river health data up- and downstream of a point source LVPOTW discharges). Investigations into the scope and severity of these impacts in the eThekwini Metropolitan Municipality are hampered by a paucity of biomonitoring data linked to the cumulative impacts of LVPOTWs on river health. Therefore, investigations were concentrated on one system that had sufficient biomonitoring data up- and downstream of LVPOTWs and results were presented as a case study and then used as the basis of building a model which is planned to be tested more widely in the broader eThekwini area as part of the next phase of this project.

The case study indicated that even in systems with a decades’ worth of up- and downstream biomonitoring, the complex nature of catchment land use practices and their impacts on river health make it difficult to untangle the direct cumulative impacts of treated effluent from LVPOTWs on river health. Furthermore, current assessment tools and models have too many inherent limitations to derive coherent and realistic answers to the questions asked.

For this reason, BNs were used to better model and investigate the cumulative impacts of treated effluent from LVPOTWs on river health. These models allowed for understanding and depicting multiple source-stressor-response interactions and modifiers in the system and provided promising results that seemed to mirror and account for the variability in the system. These assessments provided meaningful and realistic results that could be used by decision makers and authorities regarding the cumulative impacts of LVPOTWs on river health. The models also highlight the key areas that buffer and/or mitigate the impacts of effluent discharge on the receiving aquatic environment. This has practical management applications in terms of identifying the key areas to manage for future expansion of LVPOTW discharges to the environment.

The second section of this project will build on the model used in the case study to create a robust model that can potentially be used to more accurately model the cumulative impacts of LVPOTWs on river health in the eThekwini Metropolitan Municipality. This model will then be tested using real data to assess its appropriateness as a tool to inform decision making regarding the use of LVPOTWs in different catchments. Given that this is a national problem; it is hoped that outputs will be nationally relevant.

In summary, in the absence of sufficient long term monitoring data on the cumulative impacts of LVPOTWs on river health available in South Africa, this section of the report:

- highlighted the inadequacies of current models to properly assess potential impacts of LVPOTW discharge on the receiving system's river health;
- examined a case study in which long term monitoring was available to investigate the impacts of a LVPOTWs on river health; and
- suggests using Bayesian Network modelling to address these inadequacies.

The latter will be addressed in part II of this report.

PART II:

PILOT BAYESIAN NETWORK MODEL OF LOW VOLUME PRIVATELY OWNED TREATMENT WORKS-RIVER HEALTH DRIVER-RESPONSE RELATIONSHIPS

5. Introduction

5.1 Problem statement

5.1.1 Lessons learnt from Part 1 and the way forward

Part 1 of this report investigated the following two questions:
1. What are the cumulative impacts of Low Volume Privately Owned Treatment Works (LVPOTW) on river health in eThekwini Metropolitan Municipality?
2. What is the assimilative capacity of receiving aquatic ecosystems?

Results from the initial investigation undertaken in Part 1 of this report revealed the following:
- Cumulative impacts of LVPOTWs on river health are difficult to determine because current assessment tools are too limited in terms of predicting cause-effect relationships between treated effluent discharge impacts and river health responses.
- Conventional freshwater ecosystem assessment tools are either too focused (e.g. merely examining water quality limits; Brooks et al., 2006) or too complicated and data intensive (e.g. requiring decades' worth of river health data up- and downstream of a point source LVPOTW discharges) to be reliable and/or practical in an eThekwini Metropolitan Municipality (or South African) context.
- The complex nature of catchment land use practices and their impacts on river health make it difficult to untangle the cumulative impacts of treated effluent from LVPOTWs on river health, even in systems with a decades' worth of available up- and downstream biomonitoring data (this is confirmed by other researchers, e.g. Kennen, 1998; Brooks et al., 2006; Gücker et al., 2006; Canobbio et al., 2009).
- The assimilative capacity of the receiving aquatic ecosystem is a function of the systems type (e.g. dam, wetland, river-type, etc.), size (a larger system has a greater assimilative capacity than a smaller system) and its integrity (i.e. its present ecological state) and assessments need to consider these in relation to the potential water quality and water quantity modifications from LVPOTWs discharges.

These shortcomings in current assessment methods limit decision makers regarding the management of small treatment plants (LVPOTWs) within catchments and leave authorities with no real guidance on the issue. Furthermore, matters in the eThekwini Metropolitan Municipality are complicated by a paucity of biomonitoring data linked to the cumulative impacts of LVPOTWs on river health (many LVPOTWs are not on major systems and have no biomonitoring done up- and downstream of them; and data potentially linking river health with potential impacts of LVPOTWs is limited to one case study in Municipality).

For the abovementioned reasons, a new model to understand the potential impacts of LVPOTWs on river health was proposed in Part 1 of this report: A Bayesian Network.

The Bayesian Network model used international best practice protocols and allowed for understanding and depicting multiple source-stressor-response interactions and modifiers in the study. The model produced promising results that reflected some of what was observed in the study area reality and accounted for the variability observed in the system. Furthermore, the model provided meaningful and realistic results that could be used by decision makers and authorities regarding the cumulative impacts of a potential upgrade of a LVPOTW on river health.

However, despite the promising results and potential of using Bayesian Networks to model LVPOTW-river health driver-response relationships in the eThekwini Metropolitan Municipality (and potentially throughout South Africa), further testing of the model was required. This testing was conducted and the results and model refinements are presented and discussed in this report.

5.2 Objectives

The objectives of this part II of the report are to:

1) Refine the Bayesian Network developed in Part 1;
2) Provide preliminary guidance on management of small treatment plants within a catchment; and
3) Provide recommendations for further studies to develop a comprehensive guideline for managing LVPOTWs in all municipalities.

Given the positive outcomes of Part 1 of this report, the further testing of the Bayesian Network allows for achieving the abovementioned objectives, i.e. if these models prove accurate in predicting the potential impacts of LVPOTWs on river health, then they can be used to provide preliminary guidance on management of small treatment plants within a catchment (Objective 2). Furthermore, the models will then be able to provide recommendations for further studies to develop a comprehensive guideline for other municipalities in the country (Objective 3).

Therefore, this next section aims at refining the Bayesian Network model created in Part 1 (Objective 1) to produce realistic results that can provide guidance to authorities regarding the use of LVPOTWs in the eThekwini Metropolitan Municipality. Therefore, the model developed in Part 1 of this report is hence improved and tested with further field-based data to determine its value in addressing the Objectives 2 and 3.

6. The modelling approach to determine the potential development impacts of LVPOTWs on river health

The modelling approach to determine potential development impacts of LVPOTWs of river health was informed by Part 1 of this report. Therefore, achieve the abovementioned objectives, the following approach was used:

a) Refine the Bayesian Network created in Part 1 of this report
b) Collect field-based data to test the model's utility by running the Bayesian Network and then comparing the modelled results with standard field-based assessment results
c) Report on the findings in the context of providing:
    - preliminary guidance on management of small treatment plants within a catchment; and
    - recommendations for further studies to develop a comprehensive guideline for managing LVPOTWs in all municipalities in South Africa.

6.1 Part 1 Bayesian Network refinement

Steps taken to refine the Bayesian Network created in Part 1 of this report included:

- Undertaking additional desktop assessments to improve the conditional probability tables in the model (i.e. the rules that operate the model);
- Further interrogation of national, regional and municipal databases (historical water quality and aquatic ecosystem results), geographic information system (GIS) coverages, land use information and literature relating to impacts of wastewater treatment works (particularly LVPOTWs) on receiving aquatic ecosystems;
- Collating and analysing results to determine whether any key abiotic drivers and biotic responses in catchments containing LVPOTWs were overlooked in Part 1 of this report; and
- Using the abovementioned information to inform the final design and structure of the Bayesian Network model from Part 1.

The Bayesian Network model was designed using international best practice principles (Marcot et al., 2006) and protocols (O'Brien & Wepener, 2012). This entailed:

- Developing an understanding for driver-response relationships in the system concerned (Part 1 of this report; McCann et al., 2006; Nyberg et al., 2006)
- Constructing a conceptual model of the various sources, stressors receptors and endpoints in the system (Marcot et al., 2006; O'Brien & Wepener, 2012)
- Formalising a ranking scheme to measure threats in input nodes (O'Brien & Wepener, 2012)

- Calculating outputs for conditional probability tables to govern the Bayesian Network calculations (Marcot et al., 2006)
- Testing the network, i.e. comparing the modelled results with those from the in-field assessments (Marcot et al., 2006; Nyberg et al., 2006)
- Refining the network (Marcot et al., 2006; Nyberg et al., 2006)
- Communicate results to the end users, i.e. this report (Marcot et al., 2006; McCann et al., 2006; Nyberg et al., 2006; O'Brien & Wepener, 2012)

The network was designed so that it is transparent for all stakeholders, i.e. all information in the Bayesian Network can be observed by examining 3 things:

1. The network structure (i.e. the nodes and links that form the Bayesian Network, e.g. see Figure 15 and Figure 18).
2. The properties of each node (e.g. what constitutes zero, low, moderate and high risk for each node, e.g. see Table 5 and the Appendices)
3. The relationships between each node (i.e. the conditional probability tables: the rules that govern the relationships between each node, e.g. see the Appendices)

Furthermore, the Bayesian Network was designed in such a way that it can potentially be upscaled to a national level, i.e. input variables are available throughout the country, though some may need local calculations. This will allow for testing the Bayesian Network in different climatic and geographical conditions and make the results of this study of potential national relevance.

6.2 Collection of field-based data to test the Bayesian Network

6.2.1 Field-based assessments

Field-based assessments up- and downstream of two small (<2ML/day) wastewater treatment plants were undertaken after the desktop phase of the study (i.e. Part I; see Figure 14). Results from these assessments were used to:

1) Provide input data for the model (i.e. upstream data for the "pre-development" scenario)
2) Determine the health of the systems downstream of the LVPOTWs using conventional river health assessment methods; and
3) Determine whether the Bayesian Network was able to "predict" the river health of the downstream site (i.e. after the development/upgrade of a WWTW).

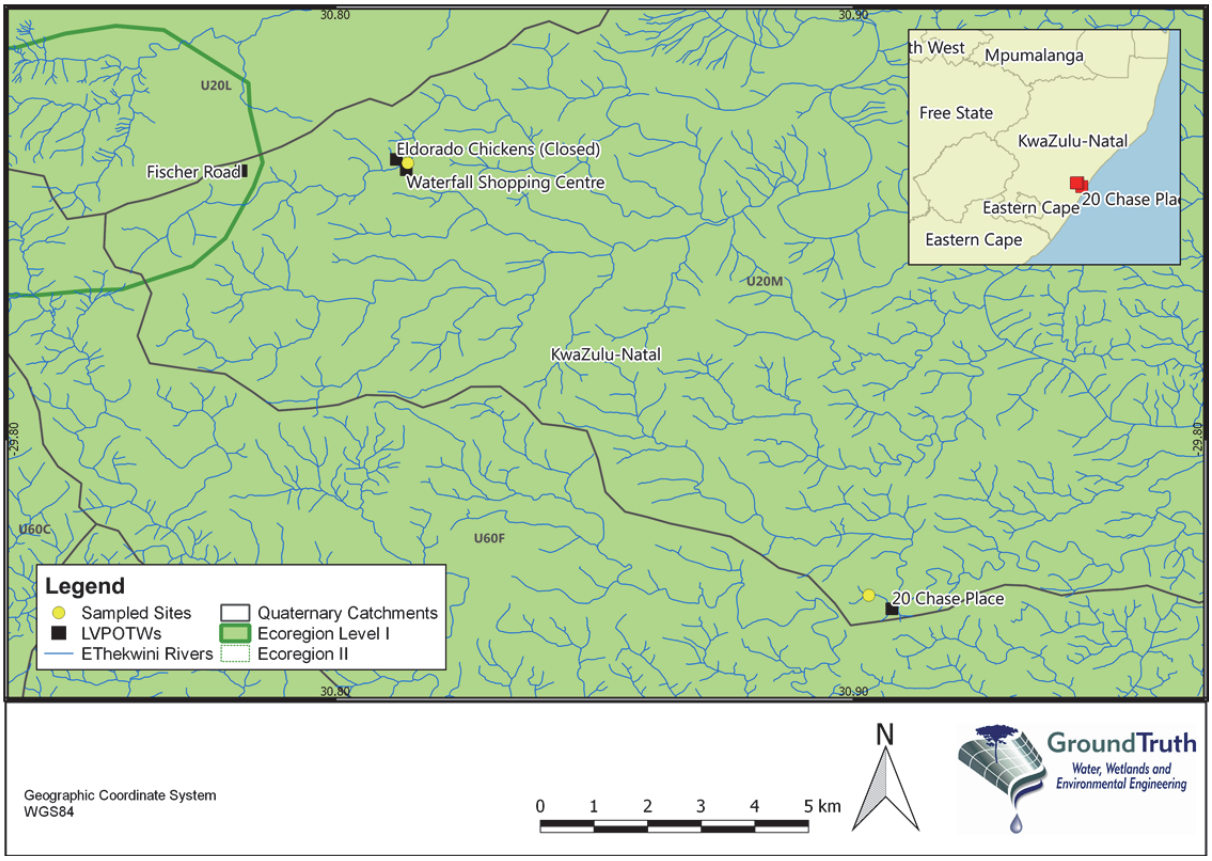


Figure 14: Overview map of the two study areas

The LVPOTWs selected were:

- Fischer Road WWTW on the Nkutu River system: the discharging LVPOTW for the Waterfall Shopping Centre and other effluent pumped to Fischer Road (it must be noted that the Fischer Road WWTW does not discharge treated effluent directly into the Nkutu River, but rather via golf course irrigation); and
- 20 Chase Place WWTW on an unnamed tributary of the Piesangs River)

The LVPOTWs and the rivers were selected to test the Bayesian Network under relatively contrasting scenarios:

- A data rich and relatively high confidence environment (Nkutu River); and
- A data deficient and relatively low confidence environment (Piesangs River tributary).

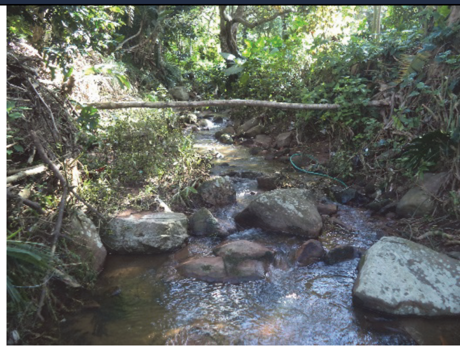
Upstream conditions for the Nkutu River system were based on over a decade's worth of biomonitoring data that provided higher confidence results than a once-off assessment. Therefore, this background information was used to populate the Bayesian Network.

The LVPOTWs were in the same Ecoregion Level 1 and Level 2 (see Figure 14, Table 1 and Table 2; Kleynhans et al., 2005). The sites sampled also had similar geomorphic templates (see Table 1 and Table 2). Therefore, it is assumed that the biotic communities and their responses to disturbance (e.g. water quality and water quantity modifications from LVPOTWs) are likely to be the same. For the purpose of this study, the rivers were also of a similar size. The site characteristics for the sites up- and downstream of the Fischer Road-Waterfall Shopping Centre and 20 Chase Place LVPOTWs are summarised in Table 1 and Table 2 below, respectively.

Table 1: Nkutu River system site characteristics

	Downstream site
View upstream	
View downstream	
Quaternary Catchment	U20M
River	Nkutu
Latitude (dd)	-29.74668
Longitude (dd)	30.81396
Altitude (m)	522
Geomorphic zone	C (Transitional)
Ecoregion I	North Eastern Coastal Belt (17.01)
Ecoregion II	124
Vegetation Type	KwaZulu-Natal Sandstone Sourveld

Table 2: Piesangs River Tributary site characteristics

	Upstream site	Downstream site
View upstream		
View downstream		
Quaternary Catchment	U20M	U20M
River	Tributary of the Piesangs	Tributary of the Piesangs
Latitude (dd)	-29.83012	-29.830753
Longitude (dd)	30.90293	30.91009
Altitude (m)	280	229
Geomorphic zone	B (Mountain Stream)	C (Transitional)
Ecoregion I	North Eastern Coastal Belt (17.01)	North Eastern Coastal Belt (17.01)
Ecoregion II	124	124
Vegetation Type	KwaZulu-Natal Coastal Belt	KwaZulu-Natal Coastal Belt

Field-based assessments included:

- Macroinvertebrate assessments using the South African Scoring System version 5 (Dickens & Graham, 2002) by a DWS accredited SASS5 practitioner. Results were interpreted according to national guidelines (Dallas, 2007).
- Benthic diatom assessments using the prescribed protocols in (Taylor et al., 2007) and interpreted using the Specific Pollution Index and South African Diatom Index (Harding & Taylor, 2011).
- Physicochemical parameters recorded at each site included:
    - Temperature
    - pH
    - Dissolved oxygen
    - Conductivity
    - Water clarity

- Total dissolved solids
- Suspended solids
- Nitrates
- Soluble reactive phosphate
- Ammonia
- Free chlorine

Water quality parameters were interpreted according to DWS water quality guidelines for aquatic ecosystems (Department of Water Affairs and Forestry, 1996).

Aquatic ecosystem integrity was measured using the Index of Habitat Integrity (Kleynhans, 1996; Kleynhans et al., 2008) and the Department of Water and Sanitation's latest Present Ecological State, Ecological Importance and Ecological Sensitivity database (DWS, 2014).

6.2.2 Running the Bayesian Network using field-based data

The Bayesian Network used field-based data to model the impact of the existing LVPOTWs on the respective river systems. To do so, upstream data (i.e. before the impacts of the LVPOTW) were used as input data for the model. The endpoint risk profile (i.e. the risk distribution of the potential impact of the proposed development) was then the modelled impact that the LVPOTWs would have on river health in the system.

6.2.3 Comparison of the Bayesian Network with conventional tools used to assess river health in South Africa

The validity of the Bayesian Network was tested by comparing it to the actual downstream results (i.e. from the field-based assessments). The premise was that if the Bayesian Network was able to “predict” the present state accurately by only using upstream data, discharge information and site conditions; then it is also able to predict future states under different scenarios (similar to Part 1 of this report). In other words, the field-based results were used to see if the Bayesian Network could reliably predict the impact of the LVPOTWs on the downstream system.

Moreover, if the Bayesian Network is indeed able to predict the impact of a LVPOTW on the river health downstream of it, then the model potentially provides decision makers and authorities with a powerful and relatively low-cost tool to predict impacts of proposed LVPOTWs on river health in other systems too; and provide defensible guidance on management of LVPOTWs within catchments throughout eThekwini.

6.3 Assumptions and limitations of Part 2

The following assumptions and limitation are relevant to this study:

- As far as possible, the network structure had to be applicable to all river ecosystems in South Africa;
- Therefore, input data had to be readily available or attainable using established sampling techniques or databases;
- The paucity of information on the various driver-response relationships in the LVPOTW-river health relationship required conditional probability tables (i.e. the probability rules that govern the relationships in the network) to rely on equations using best available information and/or data;
- The confidence of the results was limited by the available input data (i.e. one field-based assessment, the time of year the assessment was undertaken, etc.);
- No hydrological data for were available for the Piesangs River Tributary;
- Assessments were only carried out in one EcoRegion and require further testing and
- Discharge quantities and quality for the Chase Road LVPOTWs were not available from eThekwini Metropolitan Municipality. This data was derived from the field-based assessments and previous work done on similar systems.

7. Results

7.1 Overview of expected results

This section provides reports on the following:

1. Results on the construction and refinement of the Bayesian Network developed in Part 1 of this report;
2. Results from the field-based assessments used to test the Bayesian Network;
3. Results from the refined Bayesian Network using upstream data, discharge information and site conditions; and
4. Results from the comparison between the Bayesian Network results and conventional river health assessment tools.

7.2 Refined Bayesian Network

7.2.1 Network framework and rationale

Figure 15 depicts various interactions that determine the potential impact of a proposed/current LVPOTW on river health. The main variables influencing the potential impact of a proposed/current LVPOTW on river health include:

a) the exposure that the system has to water quality modifications;
b) the exposure that the system has to flow modifications;
c) the biotic condition of the receiving river ecosystem; and
d) the ecological importance and ecological sensitivity of the receiving river ecosystem.

The main changes between the initial Bayesian Network in Part 1 and the refined network described below were (a) the rules governing the relationships in the model were refined; (b) diatom health was used as a surrogate for upstream river water quality; (c) expose was divided into water quantity exposure and water quality exposure; and (d) ecosystem integrity was included to determine biotic wellbeing in the refined model. An explanation for the new framework is expanded upon in the section below. This explanation provides a justification for the refinements to the model based on various studies undertaken throughout the world.

The water quality and water quantity modification exposure experienced by the river ecosystem include (see Figure 15):

- Cumulative water quality modifications in the river (Kennen, 1998; Canobbio et al., 2009; Drury et al., 2013);
- The quantity of water discharged into the system, i.e. a function of the size of the system and proposed discharges (Dickens & Graham, 1998; Gücker et al., 2006; Canobbio et al., 2009); and
- The river ecosystem's assimilative capacity (Kennen, 1998; Gücker et al., 2006; Canobbio et al., 2009).

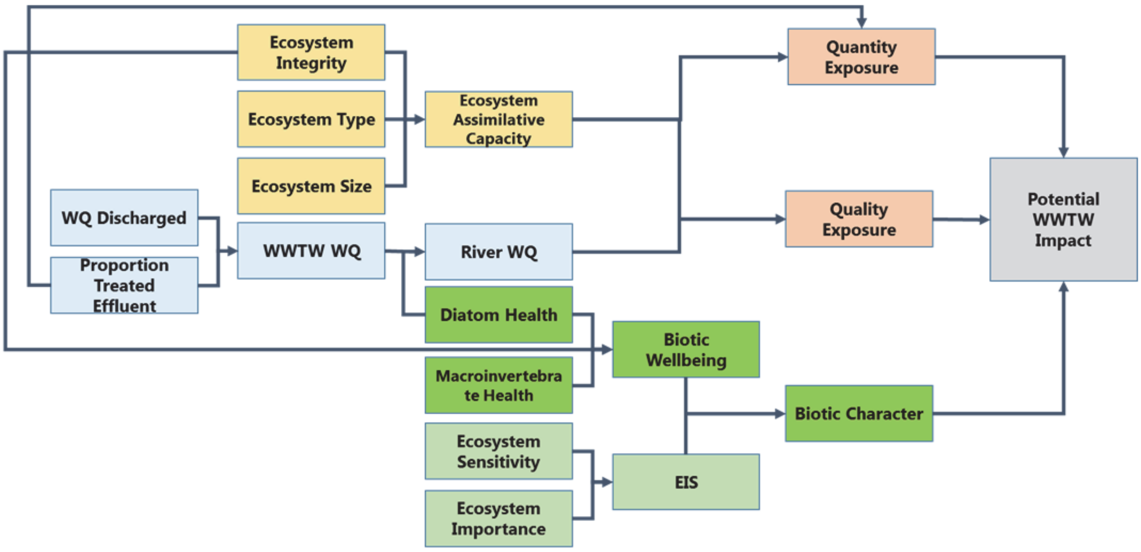


Figure 15: Integrated framework of the rationale and linkages determining the final potential cumulative impacts of a LVPOTW on river health

Cumulative water quality modification in the river is seen as a function of the water quality upstream of the proposed/current LVPOTW discharge point and the water quality modification from the LVPOTW discharge itself. Water quality discharged from the LVPOTW is a function of the water quality discharged from the LVPOTW (e.g. General Limit Values, Special Limit Values or Aquatic Ecosystem Guideline limits; Department of Water Affairs and Forestry, 1996; Department of Water Affairs. 2013) and the proportion of flows in the river comprising of treated effluent (Dickens & Graham, 1998; Gücker et al.. 2006; Canobbio et al.. 2009). This relationship is depicted in Figure 16.

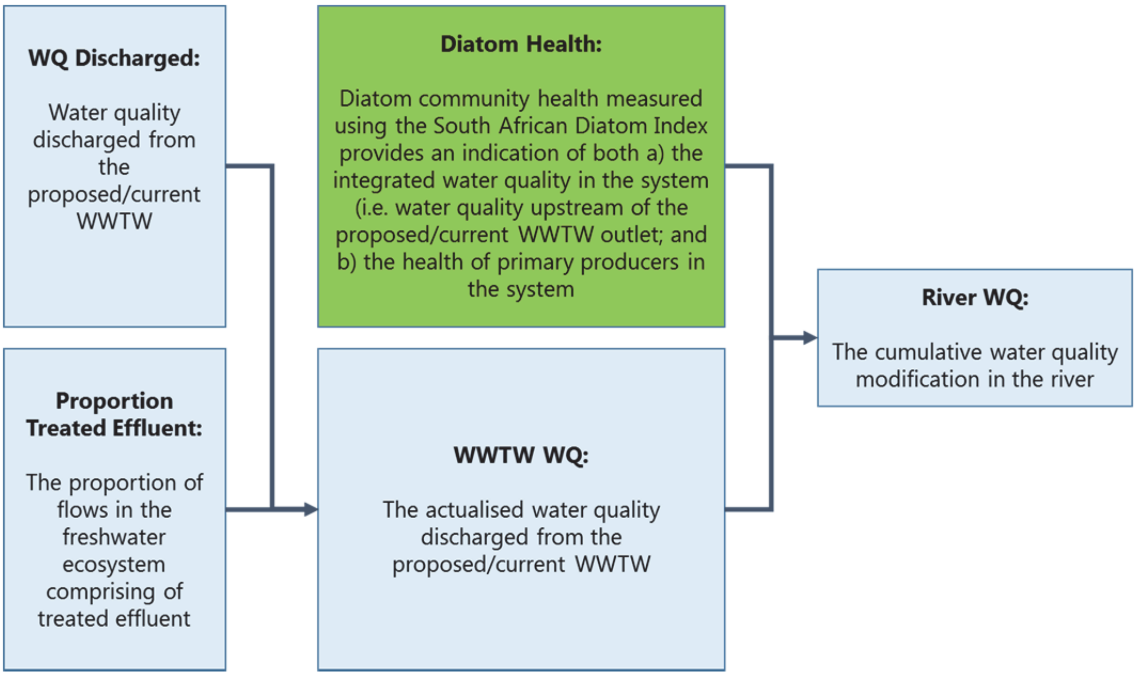


Figure 16: Rationale and linkages affecting the cumulative water quality modification in the river water quality

The aquatic ecosystem's assimilative capacity is seen as the system's ability to buffer water quality and water quantity modifications from proposed/current treated effluent volumes. This is seen as a function of the aquatic ecosystem's integrity/condition (Kennen, 1998), its type (Gücker et al., 2006) and its size (Gücker et al., 2006; Canobbio et al., 2009). The aquatic ecosystem integrity is the present ecological state of the freshwater ecosystem between the discharge and the sample point considered. The ecosystem type is the type of aquatic system/s present between the discharge and the sample point considered. The types of aquatic ecosystems include rocky and sandy rivers, wetlands and/or dams/lakes that occur between the discharge and the sample point considered (Rowntree et al., 2000; Gücker et al., 2006; Ollis et al., 2006; Ollis et al., 2013). The aquatic ecosystem size is the area and/or length of the receiving environment between the discharge point and the sample point considered (Gücker et al., 2006). The relationships between linkages affecting aquatic ecosystem assimilative capacity are depicted in Figure 6

Biotic wellbeing in the receiving aquatic ecosystem is a function of the health of key primary producers and primary and secondary consumers in the system. Key primary producers include benthic diatoms (Blinn & Herbst, 2003; Hering et al., 2006; Winter & Duthie, 2000; Hill et al., 2011; Biggs, 2000; Chetelat et al., 1999; Murdock et al., 2004) and key primary and secondary consumers include aquatic macroinvertebrates (Holomuzki et al., 2006; Holomuzki et al., 2010; Lewis & McCutchan, 2010; Chessman et al., 2009). The relationships between linkages affecting biotic wellbeing are depicted in Figure 17.

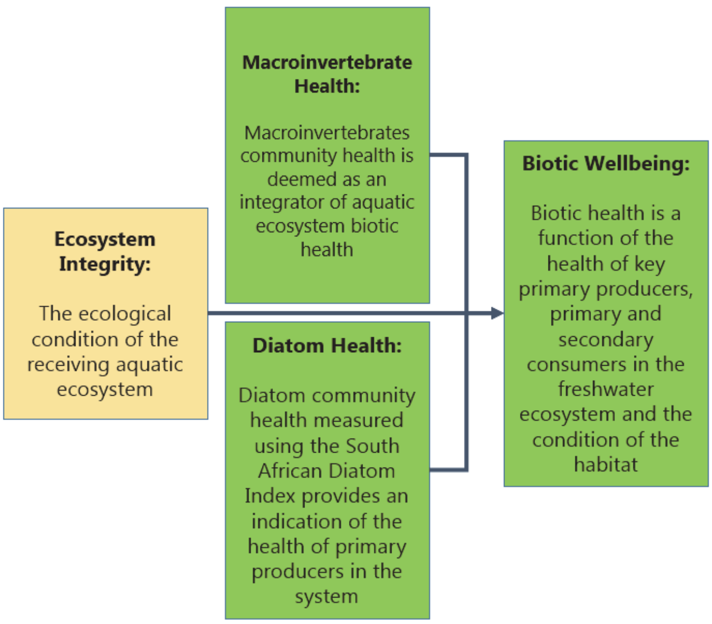


Figure 17: Rationale and linkages used to determine biotic wellbeing in the system

The ecological importance and ecological sensitivity of the received aquatic ecosystem is the function of the system's importance (from a local, regional, national and/or international perspective in terms of providing ecosystem goods and services and/or maintaining important biota in their various life stages) and sensitivity (to increased flows and/or water quality modifications). This relationship is depicted in Figure 8.

The relationship profiles (i.e. the way in which input variable affect the outcome), equations (i.e. relationships that govern interacting variables) and justifications (i.e. for the weightings for the various interactions in the abovementioned section) are summarised in the Appendices of this report.

7.2.2 Variables required to populate the model

The abovementioned framework was used to develop a Bayesian Network to predict the potential impacts of a proposed LVPOTWs on river health in the eThekwini Municipality (see Figure 18). In order to do this, the Bayesian Network had to be comprised of nodes that would capture variables influencing river health in the LVPOTWs-river health relationship.

Variables required to populate the model had to satisfy three conditions:

a) They had to encompass the key drivers and responses in the LVPOTW-River Health relationship;
b) Their information had to be available throughout the country using well-known techniques and/or databases; and
c) They had to conform to international best practice for Bayesian Network construction: most notably the principle of requisite simplicity (i.e. the network has to be as simple as possible with the least amount of nodes required to adequately capture interactions in the system).

Taking the abovementioned factors into account, the resultant Bayesian Network used in this study has nine input nodes. These nodes cover key source-modifier-receptor variables in the LVPOTW-River Health relationship (i.e. they capture the various sources potentially impacting river health, modifiers in the system that either mitigate or amplify these impacts, and receptors in the river ecosystem that experience the resultant impact). As a result, the nodes used are:

1. Water quality discharged into the system;
2. Proportion of flow comprising of treated effluent;
3. Type of receiving aquatic ecosystem;
4. Size of receiving aquatic ecosystem;
5. State of receiving aquatic ecosystem;
6. Aquatic ecosystem importance;
7. Aquatic ecosystem sensitivity;
8. Macroinvertebrate community health; and
9. Diatom community health.

The ranking scheme and justification for each of these input nodes are presented in the Appendices of this report. The resultant Bayesian Network used to model the potential impacts of LVPOTWs on river health in the eThekwini Metropolitan Municipality is displayed in Figure 18.

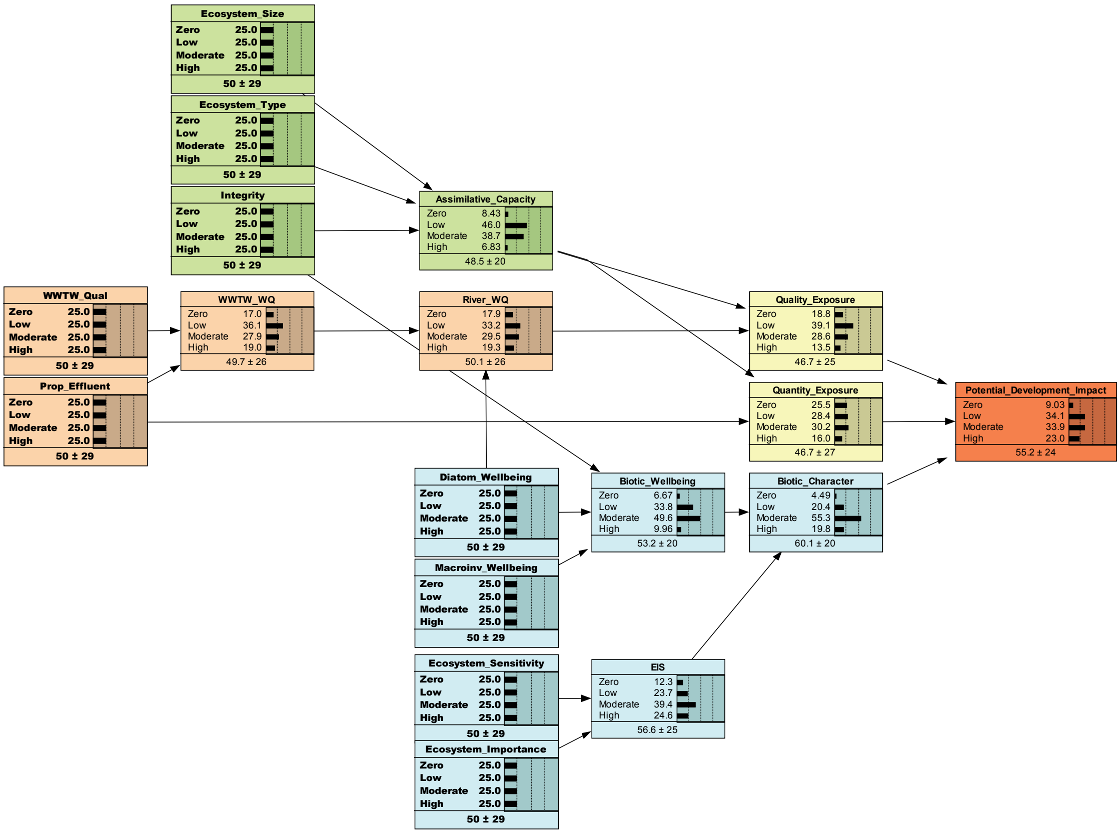


Figure 18: Bayesian Network used to model the potential impacts of LVPOTWs on river health

7.3 Field-based data to test the Bayesian Network

Results from field-based and laboratory assessments for each site up- and downstream sites of the various LVPOTWs are summarised in Table 3 and Table 4 below. Table 3 summarises results for the Nkutu River up- and downstream of the Fischer Road LVPOTW. Table 4 summarises results for the Piesangs River Tributary up- and downstream of 20 Chase Place LVPOTW.

Table 3: Summary of field-based results for the Nkutu River

	Upstream site	Downstream site
SASS Score	N/A	77
ASPT	N/A	5.5
Macroinvertebrate Ecological Condition	B/C	D
SPI	*	9.9
Diatom Ecological Condition	B	C
Habitat Integrity	C	C
River Health	B/C	C
Temperature (°C)	Data derived from biomonitoring database for the site and included in the Bayesian Network	21.3
pH		6.2
Dissolved Oxygen (%)		74.4
Dissolved Oxygen mg/L		6.58
Conductivity		19.7
Water Clarity (cm)		65
Free Chlorine (mg/L)		<0.05
Fluoride (µg/L)		<100
Ammonia (soluble; mg/L)		<0.10
Nitrate (soluble; mg/L)		<0.10
Soluble Reactive Phosphate (µg/L)		19.1
Suspended Solids (mg/L)		12.8
Total Dissolved Solids (mg/L)		126
Comments		Low flows. Only small stones present, mixed with gravel. Downstream of run off from Waterfall Mall and a chicken farm.

* Data derived from biomonitoring database for the site and included in the Bayesian Network

Table 4: Summary of field-based results for the Piesangs River Tributary

	Upstream site	Downstream site
SASS Score	81	87
ASPT	5.4	5.4
Macroinvertebrate Ecological Condition	D	D
SPI	9.5	9.0
Diatom Ecological Condition	C	C/D
Habitat Integrity	C	D
River Health	C/D	D
Temperature (°C)	23.1	23.6
pH	6.7	7.1
Dissolved Oxygen (%)	72.2	88.0
Dissolved Oxygen mg/L	6.2	7.5
Conductivity	61.3	63.6
Water Clarity (cm)	54	79
Free Chlorine (mg/L)	<0.05	<0.05
Fluoride (µg/L)	<100	<100
Ammonia (soluble; mg/L)	0.16	<0.10
Nitrate (soluble; mg/L)	4.30	4.23
Soluble Reactive Phosphate (µg/L)	60.6	82.7
Suspended Solids (mg/L)	13.2	6.40
Total Dissolved Solids (mg/L)	409	423
Comments	Low flows. Habitats limited, site restricted by dual carriage road and private residences.	Recent flooding evident at site. Moderate habitat availability, site predominantly sand substrate, some bedrock and stones, ecological condition likely to be impacted by recent flood.

Water quality results in Table 3 and Table 4 suggest that water quality discharged from the LVPOTWs are within GLVs (NWA, 1998). According to information from eThekwini, the Fischer Road LVPOTWs discharges treated effluent within SLVs; and furthermore, are used to irrigate the golf course prior to entering the freshwater ecosystem. No data on WQ of discharge effluent was available for the Chase Road LVPOTWs.

7.4 Modelled response of river health to treated effluent discharges

The Bayesian Network used upstream data, discharge information and site conditions to predict the potential impacts of the LVPOTWs on river health in the Nkutu and Piesangs River systems. This information was fed into the Bayesian Network though input nodes. Table 5 summarises the information used and the resultant rankings that were used in the model.

Table 5: Input data for the Nkutu River and Piesangs River Tributary Bayesian Networks

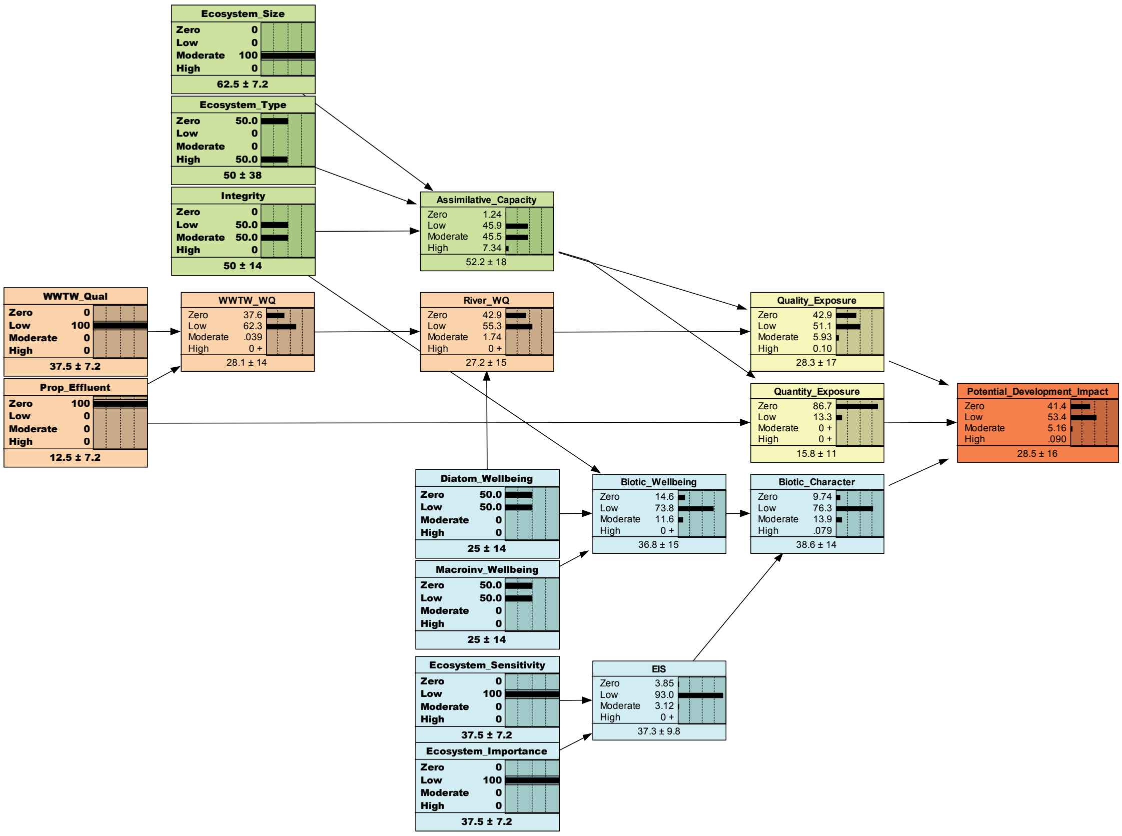
Water Quality Input: WWTW_Qual
Data from eThekwini Municipality suggests that the Nkutu system LVPOTWs is being treated to within SLVs. Therefore, this system has a rating of "Low". It was assumed that the Chase Road LVPOTW is discharging treated effluent that meet GLVs (see Table 4). However, it is uncertain whether they are within SLVs or Aquatic Ecosystem Guidelines. Therefore, using the Precautionary Principle, the rating for the Chase Road system was "Moderate".
Water Quantity Input: Prop_Effluent
Data from eThekwini Municipality suggests that the Nkutu system LVPOTWs is releasing 400kl-500kl/day. This is not the experienced added flows in the system as all of the flows are currently used to irrigate the golf course, and therefore enter the river indirectly. Therefore, the rating for this system was "Zero". No flow records are available for the Chase Road system. Results could be interpolated for the Nkutu River based on work done in Part 1 of this report and other assessments in the system. Based on (1) the size of the systems concerned, (2) the quantities of treated effluent expected from each LVPOTW, (3) previous results from similar sized rivers and LVPOTW, (4) the flows levels observed field-based and (5) incorporating the Precautionary Principle, the rating for the Chase Road system was "Low".
Ecosystem Size Input: Ecosystem_Size
The Nkutu system had 1-5km of river between the discharge point and the sample point, with a small dam in between. Therefore, the rating was "Moderate". The Chase Road model verification site assessed (i.e. the downstream sites) was <1km away from the treated effluent discharge point and therefore had a rating of "High".
Ecosystem Size Input: Ecosystem_Type
The Nkutu system has a small dam between the verification site and the discharge point, as well as a stretch of river in the Transitional/Upper Foothill geozones. Therefore, the dam resulted in a "Zero" rating proportioned at 50% and the river a rating of "High" and proportioned at 50%. The stretch of river from the treated effluent discharge points to the Chase Road model verification sites (i.e. the downstream sites) was assessed as being in Transitional/Upper Foothill geozones (Rowntree et al., 2000). Therefore, its' rating was "High".
Ecosystem Integrity Input: Integrity
Desktop *and* field-based verification revealed that the stretch of river from the treated effluent discharge points to the model verification sites (i.e. the downstream sites) were in a C and C/D condition for the Nkutu and Tributary to the Piesangs River, respectively. Therefore, their ratings were "Low" and "Moderate", respectively.
Diatom Health in the River: Diatom_Wellbeing
Field-based assessments of diatom wellbeing indicated that water quality and diatom community health upstream of the treated effluent discharge points (i.e. before impacts from the LVPOTWs) in the Nkutu system was in a largely natural state, i.e. a "Zero-Low" rating. The water quality and diatom community health upstream of the Chase Road site was in a moderately modified condition, i.e. a "Low" rating.

Macroinvertebrate Health in the River: Macroinvertebrate_Wellbeing
Field-based assessments of macroinvertebrate health indicated that macroinvertebrate community health upstream of the treated effluent discharge points (i.e. before impacts from the LVPOTWs) in the Nkutu system was in a largely natural state, i.e. a "Zero-Low" rating. The macroinvertebrate community health upstream of the Chase Road site was in a poor condition, i.e. a "Moderate" rating.
Aquatic Ecosystem Sensitivity: Ecosystem_Sensitivity
The latest Present Ecological State, Ecological Importance and Ecological Sensitivity assessment by the Department of Water and Sanitation (Department of Water and Sanitation, 2014) and field-based verification revealed that the ecosystem sensitivity of the Nkutu River and Tributary of the Piesangs were both "Low".
Aquatic Ecosystem Importance: Ecosystem_Importance
The latest Present Ecological State, Ecological Importance and Ecological Sensitivity assessment by the Department of Water and Sanitation (Department of Water and Sanitation, 2014) and field-based verification revealed that the ecosystem importance of the Nkutu River and Tributary of the Piesangs were both "Low".

The input data (per Table 5) was used by the Bayesian Network to model the various relationships in the LVPOTWs-river health relationship to produce a risk profile of the potential impact of the LVPOTW on river health in the respective systems. The Bayesian Network results for the Nkutu River system and Piesangs River Tributary are illustrated in Figure 19 and Figure 20, respectively.

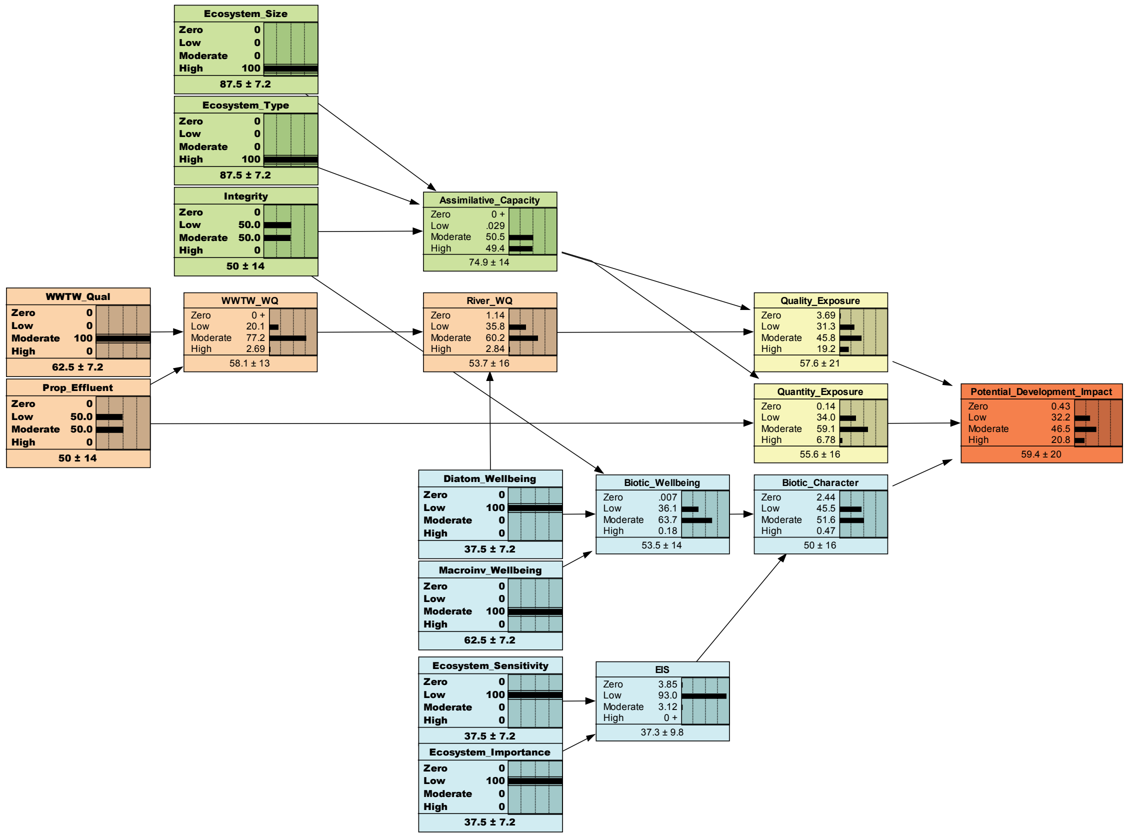
Results suggest that the potential impact of the wastewater treatment works in the Nkutu system is Low (53.4% probability). According to Figure 21, this equates to a resultant "B/C" river health category. There is also a 41.4% chance that the potential LVPOTW risk to river health is "Zero".

Results suggest that the potential impact of the wastewater treatment works in the Piesangs system is predominantly within the Moderate risk class (46.5% probability). According to Figure 21, this equates to a resultant "D" river health category. There is a 32.2% chance that the potential LVPOTW risk to river health is "Low", and a 20.8% chance that the potential LVPOTW risk to river health is "High".



Potential LVPOTW Risk to River Health Distribution	Rating	%
	Zero	41.4
	Low	53.4
	Moderate	5.2
	High	0.1

Figure 19: Bayesian Network results for the Nkutu River system modelling present conditions



Potential LVPOTW Risk to River Health Distribution	Rating	%
	Zero	0.4
	Low	32.2
	Moderate	46.5
	High	20.8

Figure 20: Bayesian Network results for the Piesangs River Tributary system modelling present conditions

7.5 Field-based river health assessment results

Table 3 and Table 4 summarise the results of the standard methods used to determine river health in South Africa (habitat conditions precluded fish community health assessments). Table 3 highlights that the river health of the Nkutu system deteriorates from a B condition upstream of the Fischer Road treatment works to a C category downstream of the works, whilst Table 4 shows that the river health of the Piesangs River Tributary system deteriorates from a C/D condition upstream of the Chase Road treatment works to a D category downstream of the works.

7.6 Comparison between the modelled network and in-field assessment tools used to measure impact of LVPOTW on river health

The potential impacts of the LVPOTWs on the Nkutu River and Piesangs River Tributary systems were modelled using Bayesian Networks (see Figure 19 and Figure 20). These results were compared with results from field-based assessments of the same sites (see Table 1 and Table 2). The comparisons of the results are summarised in Table 6 below.

Table 6: Summary comparing results of field based assessments and the modelled Bayesian Network results for the sites downstream of the LVPOTWs on the Nkutu River and Piesangs River Tributary systems

	Bayesian Network	Field-based assessment
Nkutu River	Low risk (53% chance of a B/C)	C
Piesangs River Tributary	Moderate risk (47% chance of a D)	D

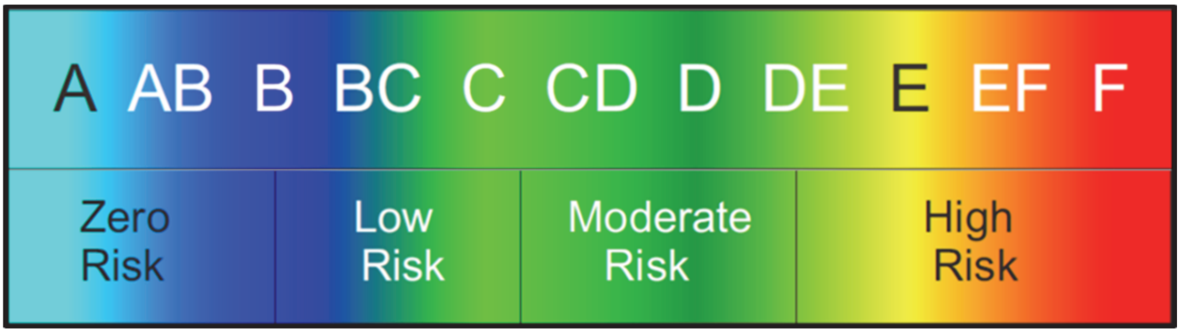


Figure 21: Comparison between standard freshwater ecosystem health categories in South Africa (A-F) and Bayesian Network endpoint risk profile distributions

The modelled approach predicted that the health of the Nkutu River would be in a “Low” risk category (i.e. a B/C category; see Figure 21). Field based assessments revealed that the site was in a C condition (i.e. the lowest portion of the “Low” risk profile; see Figure 21). The Bayesian Network was therefore successful at predicting the current river health of the Nkutu River downstream of the LVPOTWs.

Arguably, the Bayesian Network was able to better predict the real health of the system than the single downstream field-based sample. The actual reason for this supposition is that the field-based assessment of river health results were relatively low compared to background and historical river health conditions on this system. Historical results suggest that the prevailing river health of the system is in a B category, particularly for the instream environment, i.e. the environment that is likely to be impacted by the current discharge water quality and water quantity (Stassen, 2014). Therefore, it appears that the Bayesian Network was able to more accurately predict the impact of the LVPOTW than the once off field assessment.

The relatively low / poor ecological condition experienced in the field-based assessment may be attributed to a high flow rainfall event that occurred just prior to the sampling was undertaken at the site. This again illustrates the value of the risk profile distribution that the Bayesian Network provides. A once off assessment only states that it is in a C-condition, with no variability considered or reported on; whereas the Bayesian Network provided the following results: the condition is most likely to be in a “Low” risk category (53.4%), but can also be in a “Zero” risk condition 41.4% of the time (therefore having an overall “B” category).

This is significant from a management perspective in that it is important to not only know the state in which the system is in, but also the range of states that it can find itself in at any one time, and the probability that the system will be in a given state. For example, a stable system can be in a “C” category for the whole year; whereas an unstable system with frequent disturbances can be in “C” category for the majority of the year, but can also be in an “E” category (i.e. an unacceptable category; DWAF, 1999) for certain periods of the year and therefore needs to be managed to prevent the “E” category conditions. In the current assessment methodologies, this variability is often neglected due to the inherent limitations/inability of current assessment tools to comment on this. However, Bayesian Networks are able to provide this distribution of states in the endpoint risk profile.

Similarly, the Bayesian Network predicted that the health of the Piesangs River Tributary would be in a “Moderate” risk category (i.e. a “D” category; see Figure 21). Field-based assessments confirmed the Bayesian Network results by revealing that the site was in a D condition. The Bayesian Network was therefore able to predict the current river health of the Piesangs River Tributary downstream of the LVPOTW, i.e. accurately predict the cumulative impacts and the potential impacts of LVPOTWs on river health.

Accordingly, these results suggest that if only upstream, or pre-development of a LVPOTW data is available, and a LVPOTW is planned for a catchment, it appears that this modelling approach holds promise in terms of being able to accurately predict the potential risk to river health using BNs.

8. Conclusions and recommendations

8.1 Preliminary guidance on planning and management of small treatment plants within a catchment

Part 1 of this report noted that current freshwater ecosystem assessment tools in South Africa are limited in their ability to predict the potential impacts of LVPOTWs on river health. It was recommended that Bayesian Network be used to provide guidance on planning and management of small treatment plants within catchments in the eThekwini Metropolitan Municipality.

This report expanded on this concept by refining the Bayesian Network used in Part 1 of this report and testing the model by using it to "predict" the impacts of operational LVPOTWs in two river systems in The eThekwini Metropolitan Municipality and comparing the results to field-based assessments.

The result of comparing the modelled and field-based assessment were positive. The model was able to accurately "predict" the probable cumulative impacts of the LVPOTWs on river health in the two systems. These assessments allowed for a more coherent understanding of the impacts of LVPOTWs on river health, and the natural assimilative capacity of rivers receiving treated effluent from these plants.

Moreover, the Bayesian Network provided valuable information not attainable through conventional assessment methods. Bayesian Network results were presented as risk distribution profiles and not a single category result. In other words, the network was able to not only report on the predominant river health category of the system, but also the probability that the system could be in any other category.

For instance, in the Nkutu River, the Bayesian Network predicted that the river health downstream of the LVPOTWs' discharge point had a 53.4% chance of being in a "Low" risk category (i.e. a B/C-C category), but also that there was a relatively high chance (40.3%) that the system would be in a "Zero" risk condition (i.e. an A-B category). Therefore, the model predicted that the prevailing river health would be in a B-B/C condition. This result is supported by a decade's worth of biomonitoring data on the system.

This result was contrasted by the once off field-based assessment that determined that the system was in a C category (with no indication of variability of the system potentially being in a better or worse condition). This once off assessment delivered a result that was one category lower that the prevailing historical condition for the system (i.e. a B category; likely the result of high flow conditions prior to the assessment).

For these reasons, Bayesian Networks prove useful tools to provide preliminary guidance on management of small treatment plants within a catchment. Given the results of this study, Bayesian Networks could provide decision makers and authorities with an incredibly powerful and relatively low-cost tool to predict impacts of proposed LVPOTWs on river health. These models can also provide defensible guidance to decision makers and authorities regarding the management of LVPOTWs within catchments throughout eThekwini. For instance, decision makers can determine which river systems can accommodate additional LVPOTWs and which systems are too stressed to do so.

Figure 22 provides a hypothetical stylistic example of the cumulative impacts of LVPOTWs on river health. What the Bayesian Network model developed in this report can do is help authorities and decision makers know:

a) whether a catchment or system is in a zero, low, moderate or high risk state;
b) what the distribution of this risk is; and
c) where stressed or unstressed systems are situated within the landscape.

This can help them make informed decisions regarding the amount of LVPOTWs in a catchment based on:

i. the current water quality and water quantity discharge in the system;
ii. the proposed LVPOTWs water quality and water quantity discharge;
iii. the assimilative capacity of the receiving system; and
iv. the present risk state of the system.

Furthermore, the Bayesian Network model can also inform authorities regarding the risk distribution at a site, i.e. the chance that the potential impact could have a higher or lower risk to river health.

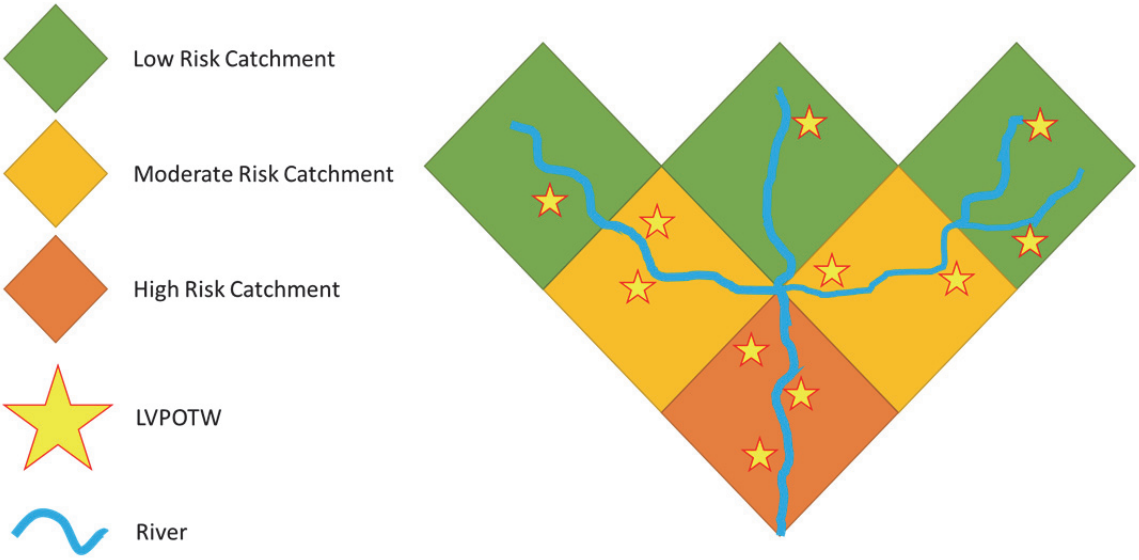


Figure 22: Hypothetical stylistic diagram indicating increasing risk to river health as a result of cumulative impacts from low volume privately owned treatment works in catchments

For these reasons, the model can be used as a tool for spatial planning at a municipal, regional or national level to illustrate which catchments/systems can handle more LVPOTWs, and which are saturated. That said, the model developed in this report used the best information available at the time in a relatively small geographic area (i.e. eThekwini Metropolitan Municipality) and would require further tests at a wider scale (e.g. regional or national) to validate these outcomes.

The pros and cons of using these Bayesian Network models in the context of this study and recommendations for future studies to develop a comprehensive guideline for all municipalities are reported on below.

Pros of using the Bayesian Network developed in this project

- Bayesian Networks are able to predict potential impacts of LVPOTWs on river health
- Results from Bayesian Networks are displayed as probability distribution curves
- Results are comparable between sites and over time
- Once setup, the Bayesian Network can be run for multiple scenarios on multiple systems
- The majority of input data is available on national databases
- The models address gaps/limitations in current South African freshwater ecosystem assessment tools
- Bayesian Networks can provide input and guidance for management of small treatment plants within a catchment

Cons of using the Bayesian Network developed in this project

- The Bayesian Network is designed for rivers and will need to be customised for wetlands and other water resources (though this can be done)
- Some input nodes need refinement (e.g. better defining categories for ecosystem size)
- Simpler methods of determining the proportion of flows comprising of treated effluent are required
- The model requires further testing at a national scale and under different conditions (spatial and temporal)

8.2 Recommendations for further studies to develop a comprehensive guideline for all municipalities

The Bayesian Network developed in this study positively predicted the potential impacts of LVPOTWs on two river systems in eThekwini Metropolitan Municipality. However, despite these promising results, more assessments are needed to validate/verify the model parameters and certain nodes. For this reason, the recommendations below address the relevant "cons" described in the preceding section and provide guidance on future work required to address these and upscale the project nationally:

- Simpler methods of determining the proportion of flows comprising of treated effluent are required
    - Recommendation:
      Create broad flow categories based on stream cross sectional area (width x depth) and flow (measured using the transparent head velocity meter), calculate the proportion of proposed discharge quantities from the LVPOTWs and link this

to the Dickens and Graham (1998) regression graph as a standardised model for the country.

- Some input nodes need refinement
    - Recommendation:

      This will require further research and testing to inform the most appropriate ways of determining, e.g. categories for ecosystem size and how to proportion the influences of various ecosystem types between the discharge point and sample site should be apportioned. A solution to this may be to add another layer to the model that distinguishes between rivers, wetlands and dams and the influence on their size on assimilative capacity in the system. However, this may be problematic in terms of the structure of the Network and potential dilution impacts in the model. For this reason, more research is required to determine the best compromise to this modifier.
- The model requires further testing at a national scale and under different conditions (spatial and temporal)
    - Recommendation:

      Create and test a robust Bayesian Network model at a national scale in different climatic conditions.

Answers to these research points are achievable and can be incorporated into the existing Bayesian Network. This will provide authorities and water resource managers with a powerful tool that can be used throughout the country to assess the potential impacts of proposed LVPOTWs on river health and provide them with guidance and defensibility to their decisions.

9. References

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10. Appendices

Table 7: Input node parametrisation, ranking scheme and justification

DESCRIPTIONS	RANKS	DATA	MEASURE RANGES FOR RANKS	JUSTIFICATION	REFERENCES
WWTW_Qual			**Water Quality Discharge Limits**		
This is the water quality being discharged into the river and does not consider dilution potential. Treated effluent discharged from WWTW can have a wide range of concentrations of various water quality determinands. Limits have been set by DWS to govern the quality of treated effluent discharged into the receiving aquatic environment. These limits vary in terms of what level of water quality is acceptable; with not all limits beneficial for the receiving systems.	Zero	0-25	< Aquatic ecosystem guidelines	Dickens and Graham noted that WQ complying with GLVs still had a negative impact on the receiving aquatic ecosystem. Water quality levels highly harmful to the receiving system. Their work was done on WWTW's that complied with GLVs.	DWAF (1996) NWA (1998) GA (2004)
	Low	25-50	<SLV		
	Moderate	50-75	>SLV		
	High	75-100	> GLV		
Prop_Effluent			%		
	Zero	0-25	0-34	Based on SASS bands for the North Eastern	Dickens and Graham (1998);
	Low	25-50	35-69		

	Moderate	50-75	103-137	Uplands (Dallas, 2007), a change in the SASS score and ASPT by 95 and 1.5 would drop each metric into a different health category, respectively. Based on results from Dickens and Graham (1998), the SASS and ASPT scores drop by a category (i.e. 19 for the SASS score; and 0.3 for the ASPT) for every 34% and 2% increase in flows comprising of treated effluent, respectively. Because the health score is based on the highest of the SASS Score and ASPT, the most resilient (i.e. the SASS Score in this case) should be used as an indication in the risk rating of the proportion of flows comprising of treated effluent. Ratings are therefore based on the assumption that the receiving environment is in a pristine (i.e. threshold of an A-category) condition. This may not be the	Data from the catchment
	High	75-100	>137		

				case, but the PES will be accommodated in the biotic wellbeing component of the network.	
Other_WQ			**System water quality**		
A measure of water quality prior to discharge.	Zero	0-25	Good	This should be measured upstream of the discharge point or before discharge, i.e. the baseline/status quo water quality. Diatoms are used as integrators of water quality impacts in the system.	SPI (CEMAGREF, 1982) SADI (Harding and Taylor, 2011) PES EI ES (DWS, 2014)
	Low	25-50	Fair		
	Moderate	50-75	Poor		
	High	75-100	Seriously modified		
Ecosystem_Type			**Ecosystem Type**		
Impoundments (i.e. lakes and dams) and wetlands, depending on their size, increase the residence time of water passing through the aquatic system. This slows nutrient transport and increases biotic processing (e.g. algal uptake, sedimentation, denitrification), resulting in enhanced retention and uptake of nutrients. Dams therefore act as sinks, and wetlands polishers of water quality.	Zero	0-25	Dam	Impoundments (i.e. lakes and dams) and wetlands, depending on their size, increase the residence time of water passing through the aquatic system. This slows nutrient transport and increases biotic processing (e.g. algal uptake, sedimentation, denitrification), resulting in enhanced retention and uptake of nutrients. Dams therefore act as sinks, and wetlands polishers of water quality.	Harrison (1965) Noble and Hemens (1978) Newbold et al. (1981) Rowntree et al. (2000) Ensign & Doyle (2006) Findlay et al. (2011)
	Low	25-50	Wetland		
	Moderate	50-75	Sandy River - Geozone Lowland river (0.0001-0.0009) / Lower foothills (0.001-0.005)		
	High	75-100	Rocky River - Geozone Transitional/Upper Foothills (0.005-0.039) / Mountain head water stream/Mountain stream (>0.04)		

Within streams sandy substrates and accumulations of fine benthic organic matter (such as algal mats) contributed to water quality processing in rivers.				Within streams sandy substrates and accumulations of fine benthic organic matter (such as algal mats) contributed to water quality processing in rivers. These systems are better processors of water quality than rocky rivers with limited biologically active surface areas. Geozones (Rowntree et al., 2000) using reach slope provide an indicator of dominant substrate composition and instream geomorphological templates.	
Ecosystem_Size			**Size**		
Ecosystem size, relative to discharge quantities and distance between the discharge point and sampling point, is an important consideration in modifying the water quality processing/assimilative potential of the aquatic ecosystem.	Zero	0-25	Large / >10km River	Dam or wetland size, relative to the WWTW discharge and distance of between the discharge point and sampling point (see river justification below) play key roles in the lentic system's ability process water quality impacts. Similarly, the length of river between the	Newbold et al., 1981; Ensign & Doyle, 2006; Data from the catchment
	Low	25-50	Moderate / 5-10km River		
	Moderate	50-75	Small / 1-5km River		
	High	75-100	Weir / <1km River		

				discharge point and monitoring site plays an important role in the river's ability to assimilate water quality impacts, though this is modified by the substrate type.	
Integrity			**Habitat Integrity**		
Ecosystem habitat integrity is linked to the aquatic ecosystem's potential to support biological processors of water quality and maintaining and supporting ecosystem service potential (including water quality maintenance). This is the rationale behind the DWS EcoStatus models, e.g. Index of Habitat Integrity	Zero	0-25	0-5	The modification is limited to very few localities and the impact on habitat quality, diversity, size and variability is also very small.	Kleynhans (1996) Kleynhans et al. (2009) PES EI ES (DWS, 2014) GIS bank modification 100m around rivers
	Low	25-50	6-10	The modifications are present at a small number of localities and the impact on habitat quality, diversity, size and variability is also limited.	
	Moderate	50-75	11-15	The modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	
	High	75-100	16-25	The modification is frequently present and the habitat quality, diversity, size and	

				variability in almost the whole of the defined area is affected.	
Ecosystem_Sensitivity			**Ecological Sensitivity**		
Ecosystem sensitivity is a modifier or habitat integrity and the systems potential to assimilate and accommodate water quality changes. For instance, an ecologically intact system that is very sensitive is more at risk to changes in water quality impacts than an ecologically modified system that is insensitive to changes in water quality.	Zero	0-25	Low	Insensitive ecosystems are more resilient to water quality impacts than sensitive systems.	PES EI ES (DWS, 2014)
	Low	25-50	Moderate		
	Moderate	50-75	High		
	High	75-100	Very High		
Ecosystem_Importance			**Ecological Importance**		
The ecological importance is a further modifier of the potential water quality impact on the system. An important system needs to be handled with more care than an unimportant system (i.e. a system that is not important to regional water	Zero	0-25	Low	Ecologically important systems require more protection from potential water quality impacts than ecologically unimportant systems. See the DWS (2014) PES EI ES assessment for definitions.	PES EI ES (DWS, 2014)
	Low	25-50	Moderate		
	Moderate	50-75	High		
	High	75-100	Very High		

resource integrity, is not home to vulnerable or important biota and has no national significance).					
Macroinv_Wellbeing			**Macroinvertebrate community health**		
These primary and secondary consumers provide an indication of the health of these critical trophic status in freshwater systems. Their cosmopolitan distribution allows for them to be reliably sampled in most systems.	Zero	0-25	Good		Dickens and Graham (2002) Dallas (2007) Thirion (2008)
	Low	25-50	Fair		
	Moderate	50-75	Poor		
	High	75-100	Seriously modified		
Diatom_Wellbeing			**Diatom community health**		
These primary producers provide an indication of the health of this critical trophic status in freshwater systems. Their cosmopolitan distribution allows for them to be reliably sampled in most systems.	Zero	0-25	Good		SPI (CEMAGREF, 1982) SADI (Harding and Taylor, 2011)
	Low	25-50	Fair		
	Moderate	50-75	Poor		
	High	75-100	Seriously modified		

Table 8: Equation inputs and rationale for the conditional probability tables

WWTW_WQ:
Changes in water quality in aquatic ecosystems receiving treated effluent are a function of: (i) the quality of water being discharged from the WWTW; (ii) and the proportion of flows in the system that comprise of treated effluent. In this relationship, the quality of the water being discharged is the most important variable. The proportion of flows comprising of treated effluent is standardised so that small and large systems can be compared. In other words, a high proportion of flows comprising of treated effluent of a certain quality will have the same effects in small and large systems. The quality of water entering the system is therefore the modifier. For these reasons, the following ratios are provided for each interaction: 1.9:0.1 (if WWTW_Qual<50), 0.5:1.5 (if Prop_Effluent<25), 1.5:0.5 (if Prop_Effluent>75) and 1.5:0.5 (if WWTW_Qual>50) are given to WWTW_Qual:Prop_Effluent, respectively.
River_WQ:
Water quality in the river is a product of water quality upstream of the discharge point and the quality of the water being discharged from the WWTW. Therefore, from a receiving aquatic ecosystem perspective, these are weighted equally and given ratios of: 0.1:1.9 (if WWTW_WQ>50), 1.9:0.1 (if Other_WQ>50), 1:1 (if WWTW_WQ<50) and 1:1 (if Other_WQ<50) are given to Other_WQ:WWTW_WQ, respectively.
Assimilative_Capacity:
The assimilative capacity of the receiving aquatic ecosystem is largely dependent on the type, size and integrity of the system. The size and type of system is modified by its integrity: with more intact systems being more resilient and able to process changes in water quality more that those that are in a poor condition. Therefore the following ratios are given for these relationships: 1.5:1:0.5 (if Ecosystem_Type<50), 1.2:1.3:0.5 (if Ecosystem_Size<50), 1.2:1.2:0.6 (if Ecosystem_Type>50), 1.2:1.2:0.6 (if Ecosystem_Size>50), 1:1:1 (if Integrity<50) and 1.2:1.2:0.6 (if Integrity>50) are given to Ecosystem_Type:Ecosystem_Size:Integrity, respectively."
Exposure:
The exposure to changes in water quality experienced by the receiving aquatic ecosystem is a function of the resultant water quality changes and the system's ability to assimilate these changes/impacts. For this reason, the following ratios are given for these relationships: 1.8:0.2 (if River_WQ<50), 0.6:1.4 (if Assimilative_Capacity<50), 1.7:0.3 (if River_WQ>50) and 1.7:0.3 (if Assimilative_Capacity>50) are given to River_WQ:Assimilative_Capacity, respectively.
Biotic_Wellbeing:
Biotic wellbeing is a product of the type and health of organisms present in the system and the system's intactness. Macroinvertebrate wellbeing is weighted slightly higher than diatom wellbeing because macroinvertebrate wellbeing incorporates changes in flow, water quality and habitat modification and are therefore a better indicator of the

biotic wellbeing of the system. The following ratios are provided for these relationships: 0.9:1.2:0.9 (if Integrity<50), 1.2:0.9:0.9 (if Macroinv_Wellbeing<50), 1:1:1 (if Diatom_Wellbeing<50), 1.2:1.2:0.6 (if Integrity>50), 1.2:1.2:0.6 (if Macroinv_Wellbeing>50) and 1.2:1.2:0.6 (if Diatom_Wellbeing>50) are given to Macroinv_Wellbeing:Integrity:Diatom_Wellbeing, respectively.
EIS: EIS is a product of the ecosystem's importance and its sensitivity. These are both modifiers of whether and how a potential development will impact the system. The following ratio is given to these two modifiers in the context of the EIS as a modifier of a development's impact: 1.9:0.1 (if Ecosystem_Sensitivity>25), 0.8:1.2 (if Ecosystem_Importance>50), 1.2:0.8 (if Ecosystem_Sensitivity<25) and 1.2:0.8 (if Ecosystem_Importance<50) are given to Ecosystem_Sensitivity:Ecosystem_Importance, respectively.
Potential_Development_Impact: The potential impact of the proposed WWTW is a product of the exposure to changes in water quality experienced by the receiving aquatic ecosystem, the state of the biota present in the system and the ecosystem's sensitivity and importance. The relationship between these variables is expressed by the following ratios: 0.8:1.8:0.4 (if Exposure>50), 1.2:0.8:1 (if EIS>50), 0.4:1:1.6 (if Biotic_Wellbeing>50), 1.2:1.2:0.6 (if Exposure<50), 1.2:1.2:0.6 (if EIS<50) and 1.2:1.2:0.6 (if Biotic_Wellbeing<50) are given to EIS:Exposure:Biotic_Wellbeing, respectively.

Table B: Equations used to compile conditional probability tables

<table>
<tr><td>p(Assimilative_Capacity|Ecosystem_Type,Ecosystem_Size,Integrity)=
(Ecosystem_Type<50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.5)+(Ecosystem_Size*1)+(Integrity*0.5))/3,7.5):
(Ecosystem_Size<50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.2)+(Ecosystem_Size*1.3)+(Integrity*0.5))/3,7.5):
(Ecosystem_Type>50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.2)+(Ecosystem_Size*1.2)+(Integrity*0.6))/3,7.5):
(Ecosystem_Size>50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.2)+(Ecosystem_Size*1.2)+(Integrity*0.6))/3,7.5):
(Integrity<50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1)+(Ecosystem_Size*1)+(Integrity*1))/3,7.5):
NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.2)+(Ecosystem_Size*1.2)+(Integrity*0.6))/3,7.5)</td></tr>
<tr><td>p(Biotic_Wellbeing|Macroinv_Wellbeing,Integrity,Diatom_Wellbeing)=
(Integrity<50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*0.9)+(Integrity*1.2)+(Diatom_Wellbeing*0.9))/3,7.5):
(Macroinv_Wellbeing<50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1.2)+(Integrity*0.9)+(Diatom_Wellbeing*0.9))/3,7.5):
(Diatom_Wellbeing<50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1)+(Integrity*1)+(Diatom_Wellbeing*1))/3,7.5):
(Integrity>50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1.2)+(Integrity*1.2)+(Diatom_Wellbeing*0.6))/3,7.5):
(Macroinv_Wellbeing>50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1.2)+(Integrity*1.2)+(Diatom_Wellbeing*0.6))/3,7.5):
NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1.2)+(Integrity*1.2)+(Diatom_Wellbeing*0.6))/3,7.5)</td></tr>
<tr><td>p(EIS|Ecosystem_Sensitivity,Ecosystem_Importance)=
(Ecosystem_Sensitivity>25)?NormalDist(EIS,((Ecosystem_Sensitivity*1.9)+(Ecosystem_Importance*0.1))/2,5):
(Ecosystem_Importance>50)?NormalDist(EIS,((Ecosystem_Sensitivity*0.8)+(Ecosystem_Importance*1.2))/2,5):
(Ecosystem_Sensitivity<25)?NormalDist(EIS,((Ecosystem_Sensitivity*1.2)+(Ecosystem_Importance*0.8))/2,5):
NormalDist(EIS,((Ecosystem_Sensitivity*1.2)+(Ecosystem_Importance*0.8))/2,5)</td></tr>
<tr><td>p(Exposure|River_WQ,Assimilative_Capacity)=
(River_WQ<50)?NormalDist(Exposure,((River_WQ*1.8)+(Assimilative_Capacity*0.2))/2,5):
(Assimilative_Capacity<50)?NormalDist(Exposure,((River_WQ*0.6)+(Assimilative_Capacity*1.4))/2,5):
(River_WQ>50)?NormalDist(Exposure,((River_WQ*1.7)+(Assimilative_Capacity*0.3))/2,5):
NormalDist(Exposure,((River_WQ*1.7)+(Assimilative_Capacity*0.3))/2,5)</td></tr>
<tr><td>p(Potential_Development_Impact|EIS,Exposure,Biotic_Wellbeing)=
(Exposure>50)?NormalDist(Potential_Development_Impact,((EIS*0.8)+(Exposure*1.8)+(Biotic_Wellbeing*0.4))/3,7.5):
(EIS>50)?NormalDist(Potential_Development_Impact,((EIS*1.2)+(Exposure*0.8)+(Biotic_Wellbeing*1))/3,7.5):
(Biotic_Wellbeing>50)?NormalDist(Potential_Development_Impact,((EIS*0.4)+(Exposure*1)+(Biotic_Wellbeing*1.6))/3,7.5):
(Exposure<50)?NormalDist(Potential_Development_Impact,((EIS*1.2)+(Exposure*1.2)+(Biotic_Wellbeing*0.6))/3,7.5):</td></tr>
</table>

(EIS<50)?NormalDist(Potential_Development_Impact,((EIS*1.2)+(Exposure*1.2)+(Biotic_Wellbeing*0.6))/3,7.5): NormalDist(Potential_Development_Impact,((EIS*1.2)+(Exposure*1.2)+(Biotic_Wellbeing*0.6))/3,7.5)
p(River_WQ|Other_WQ,WWTW_WQ)= (WWTW_WQ>50)?NormalDist(River_WQ,((Other_WQ*0.1)+(WWTW_WQ*1.9))/2,5): (Other_WQ>50)?NormalDist(River_WQ,((Other_WQ*1.9)+(WWTW_WQ*0.1))/2,5): (WWTW_WQ<50)?NormalDist(River_WQ,((Other_WQ*1)+(WWTW_WQ*1))/2,5): NormalDist(River_WQ,((Other_WQ*1)+(WWTW_WQ*1))/2,5)
p(WWTW_WQ|WWTW_Qual,Prop_Effluent)= (WWTW_Qual<50)?NormalDist(WWTW_WQ,((WWTW_Qual*1.9)+(Prop_Effluent*0.1))/2,7.5): (Prop_Effluent<25)?NormalDist(WWTW_WQ,((WWTW_Qual*0.5)+(Prop_Effluent*1.5))/2,7.5): (Prop_Effluent>75)?NormalDist(WWTW_WQ,((WWTW_Qual*1.5)+(Prop_Effluent*0.5))/2,7.5): NormalDist(WWTW_WQ,((WWTW_Qual*1.5)+(Prop_Effluent*0.5))/2,7.5)

Table 9: Input node structure

DESCRIPTIONS	RANKS	Data	MEASURE RANGES FOR RANKS	JUSTIFICATION	REFERENCES
WWTW_Qual			**Water Quality Discharge Limits**	**Nationally standardised**	
This is the water quality being discharged into the river and does not consider dilution potential. Treated effluent discharged from WWTW can have a wide range of concentrations of various water quality determinands. Limits have been set by DWS to govern the quality of treated effluent discharged into the receiving environment. These limits vary in terms of what level of water quality is acceptable; with not all limits beneficial for the receiving systems.	Zero	0-25	< Aquatic ecosystem guidelines		DWAF (1996) NWA (1998) GA (2004)
	Low	25-50	<SLV		
	Moderate	50-75	>SLV	Dickens and Graham noted that WQ complying with GLVs still had a negative impact on the receiving aquatic ecosystem.	
	High	75-100	> GLV	Water quality levels highly harmful to the receiving system	
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Prop_Effluent			**% in low flow**	**Nationally standardised (need local calculations to determine risk %)**	
	Zero	0-25	0-34 (0-25%)	Based on SASS bands for the North Eastern Uplands (Dallas, 2007), a change in the SASS score and ASPT by 95 and 1.5 would drop each metric into a different health category, respectively. Based on results from Dickens and Graham (1998), the SASS and ASPT scores drop by a category (i.e. 19 for the	Dickens and Graham (1998); Data from the catchment
	Low	25-50	35-69 (25%-50%)		
	Moderate	50-75	103-137 (50%-75%)		
	High	75-100	>137 (>75%)		

				SASS score; and 0.3 for the ASPT) for every 34% and 2% increase in flows comprising of treated effluent, respectively. Because the health score is based on the highest of the SASS Score and ASPT, the most resilient (i.e. the SASS Score in this case) should be used as an indication in the risk rating of the proportion of flows comprising of treated effluent. Ratings are therefore based on the assumption that the receiving environment is in a pristine (i.e. threshold of an A-category) condition. This may not be the case, but the PES will be accommodated in the biotic wellbeing component of the network.	
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Ecosystem_Type			**Ecosystem Type**	**Nationally standardised**	
Impoundments (i.e. lakes and dams) and wetlands, depending on their size, increase the residence time of water passing through the aquatic system. This slows nutrient transport and increases	Zero	0-25	Dam	Impoundments (i.e. lakes and dams) and wetlands, depending on their size, increase the residence time of water passing	Harrison (1965) Noble and Hemens (1978) Newbold et al. (1981)
	Low	25-50	Wetland		
	Moderate	50-75	Sandy River - Geozone Lowland river (0.0001-0.0009) / Lower foothills (0.001-0.005)		

biotic processing (e.g. algal uptake, sedimentation, denitrification), resulting in enhanced retention and uptake of nutrients. Dams therefore act as sinks, and wetlands polishers of water quality. Within streams sandy substrates and accumulations of fine benthic organic matter (such as algal mats) contributed to water quality processing in rivers.	High	75-100	Rocky River - Geozone Transitional/Upper Foothills (0.005-0.039) / Mountain head water stream/Mountain stream (>0.04); Ephemeral system	through the aquatic system. This slows nutrient transport and increases biotic processing (e.g. algal uptake, sedimentation, denitrification), resulting in enhanced retention and uptake of nutrients. Dams therefore act as sinks, and wetlands polishers of water quality. Within streams sandy substrates and accumulations of fine benthic organic matter (such as algal mats) contributed to water quality processing in rivers. These systems are better processors of water quality than rocky rivers with limited biologically active surface areas. Geozones (Rowntree et al., 2000) using reach slope provide an indicator of dominant substrate composition and instream geomorphological templates.	Rowntree et al. (2000) Brooks et al. (2006) Ensign & Doyle (2006) Findlay et al. (2011)

DESCRIPTIONS	RANKS	Data	MEASURE RANGES FOR RANKS	JUSTIFICATION	REFERENCES
Ecosystem_Size			**Size**	**Nationally standardised**	
Ecosystem size, relative to discharge quantities and distance between the discharge point and sampling point, is an important consideration in modifying the water quality processing/assimilative potential of the aquatic ecosystem.	Zero	0-25	Large / >10km River	Dam or wetland size, relative to the WWTW discharge and distance of between the discharge point and sampling point (see river justification below) play key roles in the lentic system's ability process water quality impacts. Similarly, the length of river between the discharge point and monitoring site plays an important role in the river's ability to assimilate water quality impacts, though this is modified by the substrate type.	Newbold et al., 1981; Ensign & Doyle, 2006; Data from the catchment
	Low	25-50	Moderate / 5-10km River		
	Moderate	50-75	Small / 1-5km River		
	High	75-100	Weir / <1km River		
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Integrity			**Habitat Integrity; % Transformed Habitat within 100m**	**Nationally standardised**	
Ecosystem habitat integrity is linked to the aquatic ecosystem's potential to support biological processors of water quality and maintaining and supporting ecosystem service potential (including water quality maintenance). This is the rationale behind the DWS EcoStatus models, e.g. Index of	Zero	0-25	0-5; 0-25%	The modification is limited to very few localities and the impact on habitat quality, diversity, size and variability is also very small.	Kleynhans (1996) Kleynhans et al. (2009) PES EI ES (DWS, 2014) GIS bank modification
	Low	25-50	6-10; 25%-50%	The modifications are	

Habitat Integrity				present at a small number of localities and the impact on habitat quality, diversity, size and variability is also limited.	100m around rivers
	Moderate	50-75	11-15; 50%-75%	The modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced.	
	High	75-100	16-25; 75%-100%	The modification is frequently present and the habitat quality, diversity, size and variability in almost the whole of the defined area is affected.	
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Ecosystem_Sensitivity			**Ecological Sensitivity**	**Nationally standardised**	
Ecosystem sensitivity is a modifier or habitat integrity and the systems potential to assimilate and accommodate water quality changes. For instance, an ecologically intact system that is very sensitive is more at risk to changes in water quality impacts than an ecologically modified system that is insensitive to changes in water quality.	Zero	0-25	Low	Insensitive ecosystems are more resilient to water quality impacts than sensitive systems.	PES EI ES (DWS, 2014)
	Low	25-50	Moderate		
	Moderate	50-75	High		
	High	75-100	Very High		

DESCRIPTIONS	RANKS	Data	MEASURE RANGES FOR RANKS	JUSTIFICATION	REFERENCES
Ecosystem_Importance			**Ecological Importance**	**Nationally standardised**	
The ecological importance is a further modifier of the potential water quality impact on the system. An important system needs to be handled with more care than an unimportant system (i.e. a system that is not important to regional water resource integrity, is not home to vulnerable or important biota and has no national significance).	Zero	0-25	Low	Ecologically important systems require more protection from potential water quality impacts than ecologically unimportant systems. See the DWS (2014) PES EI ES assessment for definitions.	PES EI ES (DWS, 2014)
	Low	25-50	Moderate		
	Moderate	50-75	High		
	High	75-100	Very High		
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Macroinv_Wellbeing			**Macroinvertebrate community health**	**Nationally standardised (needs EcoRegional calculations)**	
These primary and secondary consumers provide an indication of the health of these critical trophic status in freshwater systems. Their cosmopolitan distribution allows for them to be reliably sampled in most systems.	Zero	0-25	Good		Dickens and Graham (2002) Dallas (2007) Thirion (2008)
	Low	25-50	Fair		
	Moderate	50-75	Poor		
	High	75-100	Seriously modified		
DESCRIPTIONS	**RANKS**	**Data**	**MEASURE RANGES FOR RANKS**	**JUSTIFICATION**	**REFERENCES**
Diatom_Wellbeing			**Diatom community health**	**Nationally standardised**	
These primary producers provide an indication of the health of this critical trophic status in freshwater systems. Their cosmopolitan distribution allows for them to be reliably sampled in most systems.	Zero	0-25	Good (0-1)		SPI (CEMAGREF, 1982) SADI (Harding and Taylor, 2011) If unavailable, PES EI ES WQ metric (2014)
	Low	25-50	Fair (2)		
	Moderate	50-75	Poor (3-4)		
	High	75-100	Seriously modified (5)		

Table 10: Summary of input data ranking schemes and justifications

Ranks	Data	Justification
Water quality discharged		
Ranks	**Data**	**Justification**
Zero (0-25)	< Aquatic ecosystem guidelines	This is the water quality being discharged into the river and does not consider dilution potential. Treated effluent discharged from WWTW can have a wide range of concentrations of various water quality determinands. Water Quality Limits have been set by the Department of Water and Sanitation to govern the quality of treated effluent discharged into the receiving aquatic environment (Department of Water Affairs and Forestry 1996; Department of Water Affairs 2013). These limits vary in terms of what level of water quality is acceptable; with not all limits beneficial for the receiving systems (Dickens & Graham 1998). Water quality complying with Department of Water and Sanitation General Limit Values (Department of Water Affairs 2013) have a negative impact on the receiving aquatic ecosystem (Dickens & Graham 1998). Therefore, water quality discharged at higher levels than GLVs are likely to have a high risk to the receiving system. Those complying with Department of Water and Sanitations' Aquatic Ecosystem Water Quality Guidelines will have a low risk to the receiving environment (Department of Water Affairs and Forestry 1996).
Low (25-50)	<SLV	
Moderate (50-75)	>SLV	
High (75-100)	>GLV	
Proportion of flow comprising of treated effluent		
Ranks	**Data**	**Justification**
Zero (0-25)	0-25%	Literature indicates that an important consideration in determining the potential impact of WWTW discharge on the receiving river health is the proportion of flows comprising of treated effluent (Dickens & Graham, 1998; Brooks et al., 2006; Canobbio et al., 2009). Ranking categories for each system is based on EcoRegion (Kleynhans et al., 2005) bands and their corresponding macroinvertebrate health classes (Dallas 2007), and the regression line based on SASS/ASPT scores in relation to the proportion of flows comprising of treated effluent (Dickens & Graham 1998). Because the health score is based on the highest of the SASS Score and ASPT, the most resilient should be used as an indication in the risk rating of the proportion of flows comprising of treated effluent. Therefore, ratings are based on the assumption that the receiving environment is in a pristine (i.e. threshold of an A-category) condition. This may not be the case, but the PES will be accommodated in the biotic wellbeing component of the network.
Low (25-50)	25%-50%	
Moderate (50-75)	50%-75%	
High (75-100)	>75%	
Type of receiving ecosystem		

Ranks	Data	Justification
Zero (0-25)	Dam	Impoundments (i.e. lakes and dams) and wetlands, depending on their size, increase the residence time of water passing through the aquatic system. This slows nutrient transport and increases biotic processing (e.g. algal uptake, sedimentation, denitrification), resulting in enhanced retention and uptake of nutrients (Noble & Hemens, 1978; Newbold et al., 1981; Newbold et al., 1982; Ensign & Doyle, 2006). Dams can therefore act as sinks, and wetlands polishers of water quality. Within streams: sandy substrates and accumulations of fine benthic organic matter (such as algal mats) contributed to water quality processing in rivers (Francoeur et al., 1999; Biggs et al., 2000; Larned et al., 2004). These systems are better processors of water quality than rocky rivers with limited biologically active surface areas. Geozones (Rowntree et al., 2000) using reach slope provide an indicator of dominant substrate composition and instream geomorphological templates.
Low (25-50)	Wetland	
Moderate (50-75)	Sandy River - Geozone Lowland river (0.0001-0.0009) / Lower foothills (0.001-0.005)	
High (75-100)	Rocky River - Geozone Transitional/Upper Foothills (0.005-0.039) / Mountain head water stream/Mountain stream (>0.04); Ephemeral system	
Size of receiving ecosystem		
Ranks	**Data**	**Justification**
Zero (0-25)	Large / >10km River	Ecosystem size, relative to discharge quantities and distance between the discharge point and sampling point, is an important consideration in modifying the water quality processing/assimilative potential of the aquatic ecosystem (Noble & Hemens, 1978; Newbold et al., 1981; Ensign & Doyle, 2006). Therefore, the length of river between the discharge point and monitoring site plays an important role in the river's ability to assimilate water quality impacts, though this is modified by the substrate type (Newbold et al., 1982). Similarly, dam or wetland size, relative to the WWTW discharge and distance of between the discharge point and sampling point play key roles in the lentic system's ability process water quality impacts.
Low (25-50)	Moderate / 5-10km River	
Moderate (50-75)	Small / 1-5km River	
High (75-100)	Weir / <1km River	
State of receiving ecosystem		
Ranks	**Data**	**Justification**
Zero (0-25)	0-5; 0-25%	Ecosystem habitat integrity is linked to the aquatic ecosystems potential to support biological processors of water quality and maintaining and supporting ecosystem service potential (including water quality maintenance) (Corcoran et al., 2010). This is the rationale behind the DWS EcoStatus models, e.g. Index of Habitat Integrity (Kleynhans et al., 2008).
Low (25-50)	6-10; 25%-50%	

Moderate (50-75)	11-15; 50%-75%	The input data can either be attained through using the Index of Habitat Integrity (Kleynhans et al., 2008) or the percentage of transformed land cover in the upstream catchment (Kennen 1998). Data can also be derived from the latest Department of Water and Sanitation's Present Ecological State, Ecological Importance and Ecological Sensitivity assessment (Department of Water and Sanitation 2014). Therefore, a 'zero' category would constitute modifications being limited to very few localities and the impact on habitat quality, diversity, size and variability is also very small (Kleynhans et al., 2008). The 'low' category would constitute modifications that are present at a small number of localities and the impact on habitat quality, diversity, size and variability is also limited (Kleynhans et al., 2008). The 'moderate' category means that the modification is generally present with a clearly detrimental impact on habitat quality, diversity, size and variability. Large areas are, however, not influenced (Kleynhans et al., 2008). The 'high' category means that the modification is frequently present and the habitat quality, diversity, size and variability in almost the whole of the defined area is affected (Kleynhans et al., 2008). Land cover classes (Kennen 1998) use Jenks natural breaks optimisation.
High (75-100)	16-25; 75%-100%	
Ecosystem importance		
Ranks	**Data**	**Justification**
Zero (0-25)	Low	The ecological importance is a modifier of the potential water quality impact on the receiving freshwater ecosystem. An important river (i.e. a system that is important to regional water resource integrity, is home to vulnerable or important biota and/or has national significance) needs more care than an unimportant system (Department of Water and Sanitation 2014). See the DWS PES EI ES assessment for further definitions (Department of Water and Sanitation 2014).
Low (25-50)	Moderate	
Moderate (50-75)	High	
High (75-100)	Very High	
Ecosystem sensitivity		
Ranks	**Data**	**Justification**
Zero (0-25)	Low	Ecosystem sensitivity is a modifier of habitat integrity and the receiving freshwater ecosystem's potential to assimilate and accommodate water quality changes (Department of Water and Sanitation

Low (25-50)	Moderate	2014). For instance, an ecologically intact system that is very sensitive is more at risk to changes in water quality impacts than an ecologically modified system that is insensitive to changes in water quality. Insensitive ecosystems are more resilient to water quality impacts than sensitive systems. See the DWS PES EI ES assessment for further definitions (Department of Water and Sanitation 2014).
Moderate (50-75)	High	
High (75-100)	Very High	
Macroinvertebrate health		
Ranks	**Data**	**Justification**
Zero (0-25)	Good	Macroinvertebrates are useful indicators of river health and have been used extensively throughout South Africa (Dickens & Graham 2002). Sound measures of community health have been developed for all parts of South Africa (Dallas 2007; Thirion 2008). Ranking categories are based on these tools.
Low (25-50)	Fair	
Moderate (50-75)	Poor	
High (75-100)	Seriously modified	
Diatom health		
Ranks	**Data**	**Justification**
Zero (0-25)	Good (0-1)	Benthic diatoms are reliable indicators of integrated water quality in river systems (Taylor et al., 2007; Harding & Taylor 2011). Furthermore, these plants are key primary producers in freshwater ecosystems (Biggs 2000). For these reasons, benthic diatoms are useful at providing information regarding both: a) integrated water quality in the river (i.e. a measure of water quality prior to discharge).; and b) an indication of the health of a critical trophic status in freshwater systems. If this information is not available for the system, then the DWS PES EI ES water quality metric may be used (Department of Water and Sanitation 2014), i.e. providing an indication of water quality in the system at a desktop level, and inferring the diatom health at the site. This latter approach reduces the confidence of the assessment significantly and adjustments should be made to the associated Conditional Probability Tables accordingly.
Low (25-50)	Fair (2)	
Moderate (50-75)	Poor (3-4)	
High (75-100)	Seriously modified (5)	

Table 11: Conditional Probability Tables used in the Bayesian Network

WWTW_WQ						
WWTW_Qual	**Prop_Effluent**	**Zero**	**Low**	**Moderate**	**High**	**100%?**
Zero	Zero	95.0	5.0	0.0	0.0	Yes
Zero	Low	62.2	37.8	0.0	0.0	Yes
Zero	Moderate	47.6	52.4	0.0	0.0	Yes
Zero	High	24.3	75.2	0.5	0.0	Yes
Low	Zero	37.6	62.3	0.0	0.0	Yes
Low	Low	3.7	91.8	4.5	0.0	Yes
Low	Moderate	0.3	77.2	22.5	0.0	Yes
Low	High	0.0	49.9	50.0	0.0	Yes
Moderate	Zero	0.6	85.4	14.0	0.0	Yes
Moderate	Low	0.0	35.3	64.6	0.1	Yes
Moderate	Moderate	0.0	5.0	89.7	5.3	Yes
Moderate	High	0.0	0.4	78.5	21.1	Yes
High	Zero	0.0	0.1	61.2	38.7	Yes
High	Low	0.0	0.0	37.7	62.3	Yes
High	Moderate	0.0	0.0	19.4	80.6	Yes
High	High	0.0	0.0	4.2	95.8	Yes

"Notes:
Changes in water quality in aquatic ecosystems receiving treated effluent are a function of: (i) the quality of water being discharged from the WWTW; (ii) and the proportion of flows in the system that comprise of treated effluent. In this relationship, the quality of the water being discharged is the most important variable. The proportion of flows comprising of treated effluent is standardised so that small and large systems can be compared. In other words, a high proportion of flows comprising of treated effluent of a certain quality will have the same effects in small and large systems. The quality of water entering the system is therefore the modifier. For these reasons, the following ratios are provided for each interaction: 1.6:0.4 (if WWTW_Qual>75), 1.6:0.4 (if WWTW_Qual<25), 1:1 (if Prop_Effluent>50) and 1:1 (if Prop_Effluent<50) are given to WWTW_Qual:Prop_Effluent, respectively."

Equation:
p(WWTW_WQ|WWTW_Qual,Prop_Effluent)=
(WWTW_Qual>75)?NormalDist(WWTW_WQ,((WWTW_Qual*1.6)+(Prop_Effluent*0.4))/2,5):
(WWTW_Qual<25)?NormalDist(WWTW_WQ,((WWTW_Qual*1.6)+(Prop_Effluent*0.4))/2,5):
(Prop_Effluent>50)?NormalDist(WWTW_WQ,((WWTW_Qual*1)+(Prop_Effluent*1))/2,5):
NormalDist(WWTW_WQ,((WWTW_Qual*1)+(Prop_Effluent*1))/2,5)

River_WQ						
Diatom_Wellbeing	**WWTW_WQ**	**Zero**	**Low**	**Moderate**	**High**	**100%?**
Zero	Zero	91.8	8.2	0.0	0.0	Yes
Zero	Low	91.6	8.4	0.0	0.0	Yes
Zero	Moderate	91.4	8.6	0.0	0.0	Yes
Zero	High	90.1	9.9	0.0	0.0	Yes
Low	Zero	21.4	78.1	0.5	0.0	Yes
Low	Low	5.7	89.4	5.0	0.0	Yes
Low	Moderate	0.3	74.6	25.1	0.0	Yes
Low	High	0.0	49.4	50.6	0.0	Yes

Moderate	Zero	0.0	48.3	51.7	0.0	Yes
Moderate	Low	0.0	23.1	76.5	0.4	Yes
Moderate	Moderate	0.0	5.7	89.5	4.8	Yes
Moderate	High	0.0	0.5	76.7	22.8	Yes
High	Zero	0.0	0.0	9.9	90.1	Yes
High	Low	0.0	0.0	7.2	92.8	Yes
High	Moderate	0.0	0.0	9.0	91.0	Yes
High	High	0.0	0.0	8.8	91.2	Yes

"Notes:
Water quality in the river is a product of water quality upstream of the discharge point and the quality of the water being discharged from the WWTW. Therefore, from a receiving aquatic ecosystem perspective, these are weighted equally and given ratios of: 0.01:1.99 (if WWTW_WQ<25), 0.01:1.99 (if WWTW_WQ>75), 0.5:1.5 (if Diatom_Wellbeing<50) and 0.5:1.5 (if Diatom_Wellbeing>50) are given to Diatom_Wellbeing:WWTW_WQ, respectively."

Equation:
p(River_WQ|Diatom_Wellbeing,WWTW_WQ)=
(WWTW_WQ<25)?NormalDist(River_WQ,((Diatom_Wellbeing*0.01)+(WWTW_WQ*1.99))/2,5):
(WWTW_WQ>75)?NormalDist(River_WQ,((Diatom_Wellbeing*0.01)+(WWTW_WQ*1.99))/2,5):
(Diatom_Wellbeing<50)?NormalDist(River_WQ,((Diatom_Wellbeing*0.5)+(WWTW_WQ*1.5))/2,5):
NormalDist(River_WQ,((Diatom_Wellbeing*0.5)+(WWTW_WQ*1.5))/2,5)

Assimilative_Capacity

Ecosystem_Type	Ecosystem_Size	Integrity	Zero	Low	Moderate	High	100%?
Zero	Zero	Zero	98.1	1.9	0.0	0.0	Yes
Zero	Zero	Low	72.4	27.6	0.0	0.0	Yes
Zero	Zero	Moderate	25.7	74.3	0.1	0.0	Yes
Zero	Zero	High	2.5	94.3	3.2	0.0	Yes
Zero	Low	Zero	79.9	20.1	0.0	0.0	Yes
Zero	Low	Low	38.2	61.8	0.0	0.0	Yes
Zero	Low	Moderate	4.6	94.0	1.3	0.0	Yes
Zero	Low	High	0.2	82.0	17.8	0.0	Yes
Zero	Moderate	Zero	47.4	52.6	0.0	0.0	Yes
Zero	Moderate	Low	7.3	91.8	0.8	0.0	Yes
Zero	Moderate	Moderate	0.3	86.8	12.9	0.0	Yes
Zero	Moderate	High	0.0	44.1	55.8	0.0	Yes
Zero	High	Zero	13.6	86.1	0.2	0.0	Yes
Zero	High	Low	0.6	90.7	8.7	0.0	Yes
Zero	High	Moderate	0.0	54.0	46.0	0.0	Yes
Zero	High	High	0.0	13.0	86.7	0.3	Yes
Low	Zero	Zero	60.8	39.2	0.0	0.0	Yes
Low	Zero	Low	18.3	81.6	0.1	0.0	Yes
Low	Zero	Moderate	1.6	94.4	4.0	0.0	Yes
Low	Zero	High	0.0	64.1	35.9	0.0	Yes
Low	Low	Zero	24.8	75.1	0.1	0.0	Yes
Low	Low	Low	2.5	94.9	2.6	0.0	Yes
Low	Low	Moderate	0.1	74.3	25.7	0.0	Yes

Low	Low	High	0.0	25.9	74.1	0.0	Yes
Low	Moderate	Zero	4.7	94.1	1.2	0.0	Yes
Low	Moderate	Low	0.2	83.1	16.7	0.0	Yes
Low	Moderate	Moderate	0.0	34.2	65.7	0.0	Yes
Low	Moderate	High	0.0	5.1	93.5	1.4	Yes
Low	High	Zero	0.2	88.1	11.7	0.0	Yes
Low	High	Low	0.0	46.6	53.4	0.0	Yes
Low	High	Moderate	0.0	7.5	91.6	0.9	Yes
Low	High	High	0.0	0.4	87.0	12.5	Yes
Moderate	Zero	Zero	12.8	86.8	0.4	0.0	Yes
Moderate	Zero	Low	0.8	91.2	8.0	0.0	Yes
Moderate	Zero	Moderate	0.0	53.8	46.2	0.0	Yes
Moderate	Zero	High	0.0	13.8	85.7	0.5	Yes
Moderate	Low	Zero	1.5	93.7	4.8	0.0	Yes
Moderate	Low	Low	0.0	65.7	34.3	0.0	Yes
Moderate	Low	Moderate	0.0	19.6	80.3	0.1	Yes
Moderate	Low	High	0.0	1.6	94.7	3.8	Yes
Moderate	Moderate	Zero	0.1	72.3	27.7	0.0	Yes
Moderate	Moderate	Low	0.0	26.5	73.5	0.0	Yes
Moderate	Moderate	Moderate	0.0	3.0	94.2	2.8	Yes
Moderate	Moderate	High	0.0	0.1	72.3	27.6	Yes
Moderate	High	Zero	0.0	35.8	64.1	0.0	Yes
Moderate	High	Low	0.0	5.5	92.8	1.7	Yes
Moderate	High	Moderate	0.0	0.1	79.7	20.2	Yes
Moderate	High	High	0.0	0.0	37.9	62.1	Yes
High	Zero	Zero	17.2	82.6	0.2	0.0	Yes
High	Zero	Low	0.2	83.4	16.4	0.0	Yes
High	Zero	Moderate	0.0	24.3	75.7	0.0	Yes
High	Zero	High	0.0	2.4	94.8	2.9	Yes
High	Low	Zero	2.7	94.6	2.8	0.0	Yes
High	Low	Low	0.0	49.4	50.6	0.0	Yes
High	Low	Moderate	0.0	2.9	94.9	2.2	Yes
High	Low	High	0.0	0.1	73.7	26.3	Yes
High	Moderate	Zero	0.2	84.3	15.5	0.0	Yes
High	Moderate	Low	0.0	19.1	80.7	0.2	Yes
High	Moderate	Moderate	0.0	0.0	72.8	27.1	Yes
High	Moderate	High	0.0	0.0	27.4	72.6	Yes
High	High	Zero	0.0	47.6	52.4	0.0	Yes
High	High	Low	0.0	2.6	94.5	2.9	Yes
High	High	Moderate	0.0	0.0	28.9	71.1	Yes
High	High	High	0.0	0.0	2.3	97.7	Yes

"Notes:
The assimilative capacity of the receiving aquatic ecosystem is largely dependent on the type, size and integrity of the system. The size and type of system is modified by its integrity: with more intact

systems being more resilient and able to process changes in water quality more that those that are in a poor condition. Therefore the following ratios are given for these relationships: 1.2:1:0.8 (if Ecosystem_Type<75), 0.75:1.5:0.75 (if Ecosystem_Size<50), 1:1:1 (if Integrity<50), 1:1:1 (if Ecosystem_Type>75), 1:1:1 (if Ecosystem_Size>50) and 1:1:1 (if Integrity>50) are given to Ecosystem_Type:Ecosystem_Size:Integrity, respectively."

Equation:
p(Assimilative_Capacity|Ecosystem_Type,Ecosystem_Size,Integrity)=
(Ecosystem_Type<75)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1.2)+(Ecosystem_Size*1)+(Integrity*0.8))/3,5):
(Ecosystem_Size<50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*0.75)+(Ecosystem_Size*1.5)+(Integrity*0.75))/3,5):
(Integrity<50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1)+(Ecosystem_Size*1)+(Integrity*1))/3,5):
(Ecosystem_Type>75)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1)+(Ecosystem_Size*1)+(Integrity*1))/3,5):
(Ecosystem_Size>50)?NormalDist(Assimilative_Capacity,((Ecosystem_Type*1)+(Ecosystem_Size*1)+(Integrity*1))/3,5):
NormalDist(Assimilative_Capacity,((Ecosystem_Type*1)+(Ecosystem_Size*1)+(Integrity*1))/3,5)

Quality_Exposure						
River_WQ	**Assimilative_Capacity**	**Zero**	**Low**	**Moderate**	**High**	**100%?**
Zero	Zero	90.7	9.3	0.0	0.0	Yes
Zero	Low	90.8	9.2	0.0	0.0	Yes
Zero	Moderate	89.6	10.4	0.0	0.0	Yes
Zero	High	91.8	8.2	0.0	0.0	Yes
Low	Zero	7.6	83.6	8.8	0.0	Yes
Low	Low	7.6	83.4	9.0	0.0	Yes
Low	Moderate	7.3	84.8	7.8	0.0	Yes
Low	High	7.5	82.2	10.3	0.0	Yes
Moderate	Zero	3.0	92.6	4.4	0.0	Yes
Moderate	Low	0.0	49.2	50.7	0.0	Yes
Moderate	Moderate	0.0	4.3	91.2	4.6	Yes
Moderate	High	0.0	0.0	48.3	51.7	Yes
High	Zero	0.0	0.4	80.4	19.2	Yes
High	Low	0.0	0.0	48.6	51.4	Yes
High	Moderate	0.0	0.0	22.1	77.9	Yes
High	High	0.0	0.0	5.0	95.0	Yes

"Notes:
The exposure to changes in water quality experienced by the receiving aquatic ecosystem is a function of the resultant water quality changes and the system's ability to assimilate these changes/impacts. For this reason, the following ratios are given for these relationships: 1.99:0.01 (if River_WQ<50), 1.5:0.5 (if River_WQ>75), 1:1 (if Assimilative_Capacity<50) and 1:1 (if Assimilative_Capacity>50) are given to River_WQ:Assimilative_Capacity, respectively."

Equation:
p(Quality_Exposure|River_WQ,Assimilative_Capacity)=
(River_WQ<50)?NormalDist(Quality_Exposure,((River_WQ*1.99)+(Assimilative_Capacity*0.01))/2,5):
(River_WQ>75)?NormalDist(Quality_Exposure,((River_WQ*1.5)+(Assimilative_Capacity*0.5))/2,5):

(Assimilative_Capacity<50)?NormalDist(Quality_Exposure,((River_WQ*1)+(Assimilative_Capacity*1))/2,5):
NormalDist(Quality_Exposure,((River_WQ*1)+(Assimilative_Capacity*1))/2,5)

Quantity_Exposure

Prop_Effluent	Assimilative_Capacity	Zero	Low	Moderate	High	100%?
Zero	Zero	92.4	7.6	0.0	0.0	Yes
Zero	Low	89.1	10.9	0.0	0.0	Yes
Zero	Moderate	84.6	15.4	0.0	0.0	Yes
Zero	High	83.1	16.9	0.0	0.0	Yes
Low	Zero	78.2	21.8	0.0	0.0	Yes
Low	Low	4.3	91.1	4.5	0.0	Yes
Low	Moderate	0.5	78.8	20.7	0.0	Yes
Low	High	0.0	52.4	47.6	0.0	Yes
Moderate	Zero	49.6	50.4	0.0	0.0	Yes
Moderate	Low	0.0	22.4	77.1	0.5	Yes
Moderate	Moderate	0.0	4.2	90.7	5.1	Yes
Moderate	High	0.0	0.3	77.5	22.2	Yes
High	Zero	21.0	78.4	0.6	0.0	Yes
High	Low	0.0	0.0	50.0	50.0	Yes
High	Moderate	0.0	0.0	20.9	79.1	Yes
High	High	0.0	0.0	4.9	95.1	Yes

"Notes:
The exposure to changes in water quality experienced by the receiving aquatic ecosystem is a function of the resultant water quality changes and the system's ability to assimilate these changes/impacts. For this reason, the following ratios are given for these relationships: 1.9:0.1 (if Prop_Effluent<25), 0.5:1.5 (if Assimilative_Capacity<25), 1.5:0.5 (if Prop_Effluent>25) and 1.5:0.5 (if Assimilative_Capacity>25) are given to Prop_Effluent:Assimilative_Capacity, respectively."

Equation:
p(Quantity_Exposure|Prop_Effluent,Assimilative_Capacity)=
(Prop_Effluent<25)?NormalDist(Quantity_Exposure,((Prop_Effluent*1.9)+(Assimilative_Capacity*0.1))/2,5):
(Assimilative_Capacity<25)?NormalDist(Quantity_Exposure,((Prop_Effluent*0.5)+(Assimilative_Capacity*1.5))/2,5):
(Prop_Effluent>25)?NormalDist(Quantity_Exposure,((Prop_Effluent*1.5)+(Assimilative_Capacity*0.5))/2,5):
NormalDist(Quantity_Exposure,((Prop_Effluent*1.5)+(Assimilative_Capacity*0.5))/2,5)

EIS

Ecosystem_Sensitivity	Ecosystem_Importance	Zero	Low	Moderate	High	100%?
Zero	Zero	96.1	3.9	0.0	0.0	Yes
Zero	Low	61.5	38.5	0.0	0.0	Yes
Zero	Moderate	0.8	86.7	12.5	0.0	Yes
Zero	High	0.0	17.1	82.3	0.6	Yes
Low	Zero	34.7	65.2	0.0	0.0	Yes
Low	Low	3.8	93.0	3.1	0.0	Yes
Low	Moderate	0.0	38.8	61.1	0.1	Yes
Low	High	0.0	1.0	83.9	15.1	Yes

Moderate	Zero	0.0	13.2	83.5	3.2	Yes
Moderate	Low	0.0	11.1	83.5	5.4	Yes
Moderate	Moderate	0.0	6.4	86.3	7.3	Yes
Moderate	High	0.0	4.3	85.3	10.4	Yes
High	Zero	0.0	0.0	16.7	83.3	Yes
High	Low	0.0	0.0	13.2	86.8	Yes
High	Moderate	0.0	0.0	11.2	88.8	Yes
High	High	0.0	0.0	8.0	92.0	Yes

"Notes:
EIS is a product of the ecosystem's importance and its sensitivity. These are both modifiers of whether and how a potential development will impact the system. The following ratio is given to these two modifiers in the context of the EIS as a modifier of a development's impact: 1.9:0.1 (if Ecosystem_Sensitivity>50), 0.8:1.2 (if Ecosystem_Importance>50), 1.2:0.8 (if Ecosystem_Sensitivity<75) and 1.2:0.8 (if Ecosystem_Importance<50) are given to Ecosystem_Sensitivity:Ecosystem_Importance, respectively."

Equation:
p(EIS|Ecosystem_Sensitivity,Ecosystem_Importance)=
(Ecosystem_Sensitivity>50)?NormalDist(EIS,((Ecosystem_Sensitivity*1.9)+(Ecosystem_Importance*0.1))/2,5):
(Ecosystem_Importance>50)?NormalDist(EIS,((Ecosystem_Sensitivity*0.8)+(Ecosystem_Importance*1.2))/2,5):
(Ecosystem_Sensitivity<75)?NormalDist(EIS,((Ecosystem_Sensitivity*1.2)+(Ecosystem_Importance*0.8))/2,5):
NormalDist(EIS,((Ecosystem_Sensitivity*1.2)+(Ecosystem_Importance*0.8))/2,5)

Biotic_Wellbeing

Macroinv_Wellbeing	Integrity	Diatom_Wellbeing	Zero	Low	Moderate	High	100%?
Zero	Zero	Zero	97.1	2.9	0.0	0.0	Yes
Zero	Zero	Low	64.6	35.4	0.0	0.0	Yes
Zero	Zero	Moderate	2.9	94.1	3.0	0.0	Yes
Zero	Zero	High	0.0	51.3	48.7	0.0	Yes
Zero	Low	Zero	81.9	18.1	0.0	0.0	Yes
Zero	Low	Low	27.0	73.0	0.0	0.0	Yes
Zero	Low	Moderate	0.4	86.4	13.3	0.0	Yes
Zero	Low	High	0.0	23.0	76.9	0.1	Yes
Zero	Moderate	Zero	11.1	88.4	0.4	0.0	Yes
Zero	Moderate	Low	0.7	89.9	9.4	0.0	Yes
Zero	Moderate	Moderate	0.0	64.1	35.9	0.0	Yes
Zero	Moderate	High	0.0	7.0	91.9	1.1	Yes
Zero	High	Zero	0.3	84.7	15.0	0.0	Yes
Zero	High	Low	0.0	42.3	57.7	0.0	Yes
Zero	High	Moderate	0.0	35.5	64.5	0.0	Yes
Zero	High	High	0.0	1.2	92.4	6.4	Yes
Low	Zero	Zero	73.4	26.6	0.0	0.0	Yes
Low	Zero	Low	19.1	80.8	0.1	0.0	Yes
Low	Zero	Moderate	0.1	76.9	23.0	0.0	Yes
Low	Zero	High	0.0	13.7	85.9	0.4	Yes

Low	Low	Zero	34.8	65.2	0.0	0.0	Yes
Low	Low	Low	2.6	94.6	2.7	0.0	Yes
Low	Low	Moderate	0.0	49.0	51.0	0.0	Yes
Low	Low	High	0.0	3.2	93.9	2.9	Yes
Low	Moderate	Zero	0.9	91.6	7.4	0.0	Yes
Low	Moderate	Low	0.0	57.4	42.6	0.0	Yes
Low	Moderate	Moderate	0.0	22.8	77.1	0.1	Yes
Low	Moderate	High	0.0	0.4	86.3	13.3	Yes
Low	High	Zero	0.0	47.3	52.7	0.0	Yes
Low	High	Low	0.0	9.6	89.7	0.6	Yes
Low	High	Moderate	0.0	6.9	91.9	1.2	Yes
Low	High	High	0.0	0.0	63.6	36.4	Yes
Moderate	Zero	Zero	8.4	90.9	0.7	0.0	Yes
Moderate	Zero	Low	0.3	87.4	12.3	0.0	Yes
Moderate	Zero	Moderate	0.0	35.0	64.9	0.0	Yes
Moderate	Zero	High	0.0	1.1	92.4	6.5	Yes
Moderate	Low	Zero	1.1	92.7	6.2	0.0	Yes
Moderate	Low	Low	0.0	59.2	40.7	0.0	Yes
Moderate	Low	Moderate	0.0	13.0	86.7	0.4	Yes
Moderate	Low	High	0.0	0.1	76.9	23.0	Yes
Moderate	Moderate	Zero	0.1	73.5	26.5	0.0	Yes
Moderate	Moderate	Low	0.0	26.8	73.2	0.1	Yes
Moderate	Moderate	Moderate	0.0	2.8	94.2	3.0	Yes
Moderate	Moderate	High	0.0	0.0	50.5	49.5	Yes
Moderate	High	Zero	0.0	39.9	60.0	0.0	Yes
Moderate	High	Low	0.0	6.5	92.5	1.0	Yes
Moderate	High	Moderate	0.0	0.4	86.4	13.2	Yes
Moderate	High	High	0.0	0.0	22.8	77.2	Yes
High	Zero	Zero	0.1	77.7	22.2	0.0	Yes
High	Zero	Low	0.0	30.9	69.1	0.0	Yes
High	Zero	Moderate	0.0	6.6	92.0	1.3	Yes
High	Zero	High	0.0	0.0	64.5	35.4	Yes
High	Low	Zero	0.0	44.8	55.2	0.0	Yes
High	Low	Low	0.0	8.2	91.0	0.7	Yes
High	Low	Moderate	0.0	1.2	92.1	6.8	Yes
High	Low	High	0.0	0.0	36.3	63.7	Yes
High	Moderate	Zero	0.0	15.6	84.2	0.2	Yes
High	Moderate	Low	0.0	1.2	92.5	6.4	Yes
High	Moderate	Moderate	0.0	0.1	76.4	23.5	Yes
High	Moderate	High	0.0	0.0	12.7	87.3	Yes
High	High	Zero	0.0	3.0	94.2	2.8	Yes
High	High	Low	0.0	0.1	74.1	25.8	Yes
High	High	Moderate	0.0	0.0	50.1	49.9	Yes
High	High	High	0.0	0.0	3.2	96.8	Yes

"Notes:
Biotic wellbeing is a product of the type and health of organisms present in the system and the system's intactness. Macroinvertebrate wellbeing is weighted slightly higher than diatom wellbeing because macroinvertebrate wellbeing incorporates changes in flow, water quality and habitat modification and are therefore a better indicator of the biotic wellbeing of the system. The following ratios are provided for these relationships: 0.9:1.5:0.6 (if Integrity>50), 1.3:1:0.7 (if Macroinv_Wellbeing>50), 0.9:1:1.2 (if Diatom_Wellbeing>50), 1:1.2:0.8 (if Integrity<50), 1:1.2:0.8 (if Macroinv_Wellbeing<50) and 1:1.2:0.8 (if Diatom_Wellbeing<50) are given to Macroinv_Wellbeing:Integrity:Diatom_Wellbeing, respectively."

Equation:
p(Biotic_Wellbeing|Macroinv_Wellbeing,Integrity,Diatom_Wellbeing)=
(Integrity>50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*0.9)+(Integrity*1.5)+(Diatom_Wellbeing*0.6))/3,5):
(Macroinv_Wellbeing>50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1.3)+(Integrity*1)+(Diatom_Wellbeing*0.7))/3,5):
(Diatom_Wellbeing>50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*0.9)+(Integrity*1)+(Diatom_Wellbeing*1.2))/3,5):
(Integrity<50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1)+(Integrity*1.2)+(Diatom_Wellbeing*0.8))/3,5):
(Macroinv_Wellbeing<50)?NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1)+(Integrity*1.2)+(Diatom_Wellbeing*0.8))/3,5):
NormalDist(Biotic_Wellbeing,((Macroinv_Wellbeing*1)+(Integrity*1.2)+(Diatom_Wellbeing*0.8))/3,5)

		Biotic_Character				
Biotic_Wellbeing	**EIS**	**Zero**	**Low**	**Moderate**	**High**	**100%?**
Zero	Zero	95.3	4.7	0.0	0.0	Yes
Zero	Low	31.2	68.7	0.1	0.0	Yes
Zero	Moderate	0.0	50.4	49.6	0.0	Yes
Zero	High	0.0	0.4	77.6	21.9	Yes
Low	Zero	68.9	31.1	0.0	0.0	Yes
Low	Low	4.4	91.4	4.2	0.0	Yes
Low	Moderate	0.0	21.1	78.4	0.4	Yes
Low	High	0.0	0.0	50.6	49.4	Yes
Moderate	Zero	0.0	49.1	50.8	0.0	Yes
Moderate	Low	0.0	21.6	77.9	0.5	Yes
Moderate	Moderate	0.0	4.9	89.9	5.2	Yes
Moderate	High	0.0	0.0	21.3	78.7	Yes
High	Zero	0.0	0.4	78.4	21.2	Yes
High	Low	0.0	0.0	49.7	50.3	Yes
High	Moderate	0.0	0.4	78.1	21.5	Yes
High	High	0.0	0.0	5.0	95.0	Yes

"Notes:
EIS is a product of the ecosystem's importance and its sensitivity. These are both modifiers of whether and how a potential development will impact the system. The following ratio is given to these two modifiers in the context of the EIS as a modifier of a development's impact: 0.5:1.5 (if EIS>50), 1.5:0.5 (if Biotic_Wellbeing>50), 0.7:1.3 (if EIS<50) and 0.7:1.3 (if Biotic_Wellbeing<50) are given to Biotic_Wellbeing:EIS, respectively."

Equation:
p(Biotic_Character|Biotic_Wellbeing,EIS)=
(EIS>50)?NormalDist(Biotic_Character,((Biotic_Wellbeing*0.5)+(EIS*1.5))/2,5):
(Biotic_Wellbeing>50)?NormalDist(Biotic_Character,((Biotic_Wellbeing*1.5)+(EIS*0.5))/2,5):
(EIS<50)?NormalDist(Biotic_Character,((Biotic_Wellbeing*0.7)+(EIS*1.3))/2,5):
NormalDist(Biotic_Character,((Biotic_Wellbeing*0.7)+(EIS*1.3))/2,5)

			Potential_Development_Impact				
Quality_Exposure	Quantity_Exposure	Biotic_Character	Zero	Low	Moderate	High	100%?
Zero	Zero	Zero	94.2	5.8	0.0	0.0	Yes
Zero	Zero	Low	14.6	84.2	1.2	0.0	Yes
Zero	Zero	Moderate	0.0	34.1	65.8	0.1	Yes
Zero	Zero	High	0.0	0.0	28.7	71.3	Yes
Zero	Low	Zero	92.8	7.2	0.0	0.0	Yes
Zero	Low	Low	11.7	86.6	1.8	0.0	Yes
Zero	Low	Moderate	0.0	26.5	73.3	0.2	Yes
Zero	Low	High	0.0	0.0	27.2	72.8	Yes
Zero	Moderate	Zero	91.7	8.3	0.0	0.0	Yes
Zero	Moderate	Low	9.8	87.9	2.3	0.0	Yes
Zero	Moderate	Moderate	0.0	23.8	75.7	0.4	Yes
Zero	Moderate	High	0.0	0.0	22.2	77.8	Yes
Zero	High	Zero	90.0	10.0	0.0	0.0	Yes
Zero	High	Low	9.1	87.2	3.8	0.0	Yes
Zero	High	Moderate	0.0	20.7	78.5	0.8	Yes
Zero	High	High	0.0	0.0	20.0	80.0	Yes
Low	Zero	Zero	15.8	83.0	1.2	0.0	Yes
Low	Zero	Low	11.6	87.9	0.4	0.0	Yes
Low	Zero	Moderate	0.4	89.3	10.3	0.0	Yes
Low	Zero	High	0.0	0.0	22.4	77.6	Yes
Low	Low	Zero	13.7	84.7	1.7	0.0	Yes
Low	Low	Low	2.5	94.3	3.2	0.0	Yes
Low	Low	Moderate	0.0	64.3	35.7	0.0	Yes
Low	Low	High	0.0	0.0	18.8	81.2	Yes
Low	Moderate	Zero	10.8	86.5	2.7	0.0	Yes
Low	Moderate	Low	0.3	88.4	11.3	0.0	Yes
Low	Moderate	Moderate	0.0	33.4	66.6	0.0	Yes
Low	Moderate	High	0.0	0.0	15.9	84.1	Yes
Low	High	Zero	9.2	87.5	3.3	0.0	Yes
Low	High	Low	0.0	27.9	72.0	0.1	Yes
Low	High	Moderate	0.0	8.6	90.9	0.6	Yes
Low	High	High	0.0	0.0	15.0	85.0	Yes
Moderate	Zero	Zero	0.0	31.3	68.5	0.2	Yes
Moderate	Zero	Low	0.3	87.5	12.2	0.0	Yes
Moderate	Zero	Moderate	0.0	36.1	63.8	0.0	Yes
Moderate	Zero	High	0.0	0.0	16.5	83.5	Yes
Moderate	Low	Zero	0.0	28.5	71.3	0.2	Yes
Moderate	Low	Low	0.0	66.1	33.9	0.0	Yes

Moderate	Low	Moderate	0.0	12.6	87.3	0.2	Yes
Moderate	Low	High	0.0	0.0	14.0	86.0	Yes
Moderate	Moderate	Zero	0.0	24.8	74.7	0.5	Yes
Moderate	Moderate	Low	0.0	36.8	63.2	0.0	Yes
Moderate	Moderate	Moderate	0.0	2.8	93.9	3.2	Yes
Moderate	Moderate	High	0.0	0.0	12.6	87.4	Yes
Moderate	High	Zero	0.0	20.8	78.6	0.6	Yes
Moderate	High	Low	0.0	0.6	87.8	11.6	Yes
Moderate	High	Moderate	0.0	0.0	71.5	28.4	Yes
Moderate	High	High	0.0	0.0	11.2	88.8	Yes
High	Zero	Zero	0.0	0.0	26.0	74.0	Yes
High	Zero	Low	0.0	0.0	21.7	78.3	Yes
High	Zero	Moderate	0.0	0.0	16.1	83.9	Yes
High	Zero	High	0.0	0.0	12.7	87.3	Yes
High	Low	Zero	0.0	0.0	24.7	75.3	Yes
High	Low	Low	0.0	0.0	21.4	78.6	Yes
High	Low	Moderate	0.0	0.0	16.1	83.9	Yes
High	Low	High	0.0	0.0	11.3	88.7	Yes
High	Moderate	Zero	0.0	0.0	24.9	75.1	Yes
High	Moderate	Low	0.0	0.0	17.8	82.2	Yes
High	Moderate	Moderate	0.0	0.0	11.6	88.4	Yes
High	Moderate	High	0.0	0.0	7.6	92.4	Yes
High	High	Zero	0.0	0.0	21.1	78.9	Yes
High	High	Low	0.0	0.0	15.1	84.9	Yes
High	High	Moderate	0.0	0.0	11.7	88.3	Yes
High	High	High	0.0	0.0	7.8	92.2	Yes

"Notes:
The potential impact of the proposed WWTW is a product of the exposure to changes in water quality experienced by the receiving aquatic ecosystem, the state of the biota present in the system and the ecosystem's sensitivity and importance. The relationship between these variables is expressed by the following ratios: 2.7:0.2:0.1 (if Quality_Exposure>75), 0.2:2.7:0.1 (if Quantity_Exposure>75), 0.4:2.5:0.1 (if Quality_Exposure<25), 2.5:0.4:0.1 (if Quantity_Exposure<25), 1.2:1.2:0.6 (if Biotic_Character<75) and 1.5:0.5:1 (if Biotic_Character>75) are given to Quality_Exposure:Quantity_Exposure:Biotic_Character, respectively."

Equation:
p(Potential_Development_Impact|Quality_Exposure,Quantity_Exposure,Biotic_Character)=
(Quality_Exposure>75)?NormalDist(Potential_Development_Impact,((Quality_Exposure*2.7)+(Quantity_Exposure*0.2)+(Biotic_Character*0.1))/3,5):
(Quantity_Exposure>75)?NormalDist(Potential_Development_Impact,((Quality_Exposure*0.2)+(Quantity_Exposure*2.7)+(Biotic_Character*0.1))/3,5):
(Quality_Exposure<25)?NormalDist(Potential_Development_Impact,((Quality_Exposure*0.4)+(Quantity_Exposure*2.5)+(Biotic_Character*0.1))/3,5):
(Quantity_Exposure<25)?NormalDist(Potential_Development_Impact,((Quality_Exposure*2.5)+(Quantity_Exposure*0.4)+(Biotic_Character*0.1))/3,5):
(Biotic_Character<75)?NormalDist(Potential_Development_Impact,((Quality_Exposure*1.2)+(Quantity_Exposure*1.2)+(Biotic_Character*0.6))/3,5):
NormalDist(Potential_Development_Impact,((Quality_Exposure*1.5)+(Quantity_Exposure*0.5)+(Biotic_Character*1))/3,5)

Table 12: Bayesian Network Sensitivity Analysis

Sensitivity of 'Potential_Development_Impact' to a finding at another node:

Node ----	Variance Reduction	Percent	Mutual Info	Percent	Variance of Beliefs
Potential_Development_Im	467.9	100	1.72748	100	0.4569174
Quality_Exposure	247.1	52.8	0.70319	40.7	0.1411025
River_WQ	158	33.8	0.36221	21	0.0348914
Quantity_Exposure	76.32	16.3	0.16630	9.63	0.0286820
Diatom_Wellbeing	61.1	13.1	0.14550	8.42	0.0114887
WWTW_WQ	46.9	10	0.10438	6.04	0.0079324
Assimilative_Capacity	42.04	8.98	0.11074	6.41	0.0106748
Prop_Effluent	33.49	7.16	0.06291	3.64	0.0048849
Biotic_Wellbeing	32.36	6.92	0.05987	3.47	0.0048884
Biotic_Character	31.97	6.83	0.07265	4.21	0.0070035
WWTW_Qual	23.51	5.02	0.05390	3.12	0.0041453
Ecosystem_Size	11.46	2.45	0.03049	1.76	0.0021362
Integrity	11.39	2.43	0.02241	1.3	0.0015504
Ecosystem_Type	9.145	1.95	0.02414	1.4	0.0016231
EIS	7.557	1.61	0.02008	1.16	0.0024070
Ecosystem_Sensitivity	5.406	1.16	0.01434	0.83	0.0017550
Macroinv_Wellbeing	0.5693	0.122	0.00143	0.083	0.0001690
Ecosystem_Importance	0.4811	0.103	0.00126	0.0731	0.0001273

Table 13: Diatom species data sampled in the field-based assessment

Site	Count	No. spec.	SPI	%incl. SPI	%PTV	% Deformed
Sunrae Upstream	100	18	14.9	100	16.8	1
Sunrae Downstream	100	34	9.9	94	27.2	3
Whittcut	100	36	9.5	89	11.3	6
Rosebank	100	23	9	100	31.7	4

Taxon	Site			
	Sunrae valley us	Sunrae valley ds	Whittcut Road	Rosebank Road
Abnormal diatom valve or sum of deformities	2	2	6	4
Achnanthes rupestris Krasske	0	1	1	0
Achnanthidium catenatum (Bily & Marvan) Lange-Bertalot	1	0	0	0
Achnanthidium exiguum (Grunow) Czarnecki	1	2	4	0
Achnanthidium sp.	12	3	0	1
Achnanthidium standeri (Cholnoky) Taylor, Ector & Morales	0	0	0	0
Amphora montana Krasske	0	2	1	0
Amphora pediculus (Kützing) Grunow	0	0	0	3
Amphora sp.	0	0	1	0
Bacillaria paradoxa Gmelin	0	1	0	0
Capartogramma crucicula (Grunow) Ross	1	0	0	0
Cocconeis neothumensis Krammer	0	0	0	6
Cocconeis placentula Ehrenberg	2	2	0	0
Cocconeis placentula var. euglypta (Ehrenberg) Grunow	0	0	0	13
Diadesmis confervacea Kützing	0	2	1	0
Diadesmis contenta (Grunow) Mann	0	0	3	1
Encyonema minutum (Hilse) D.G. Mann	3	2	0	0
Encyonema silesiacum (Bleisch in Rabh.) D.G. Mann	0	0	0	0
Eolimna comperei Ector, Coste & Iserentant	0	0	0	1
Eolimna minima (Grunow) Lange-Bertalot	0	0	1	0
Eolimna subminuscula (Manguin) Moser, Lange-Bertalot & Metzeltin	1	0	0	0
Eunotia sp.	12	1	0	0
Fragilaria biceps (Kützing) Lange-Bertalot	3	0	0	0
Fragilaria ulna (Nitzsch) Lange-Bertalot	0	0	0	1
Gomphonema parvulum (Kützing) Kützing	11	4	0	0
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot	7	10	0	0
Gomphonema turris Ehrenberg	2	0	0	0
Gomphonema venusta Passy, Kociolek & Lowe	0	0	1	0
Lemnicola hungarica (Grunow) Round & Basson	0	0	0	1
Luticola mutica (Kützing) D.G. Mann	1	0	0	0
Mayamaea atomus var. permitis (Hustedt) Lange-Bertalot	0	1	0	0
Navicula cryptocephala Kützing	0	1	0	0
Navicula erifuga Lange-Bertalot	0	0	5	2
Navicula gregaria Donkin	0	0	0	8

Navicula riediana Lange-Bertalot & Rumrich	0	2	1	0
Navicula rostellata Kützing	0	0	1	4
Navicula schroeteri Meister	0	1	0	0
Navicula small species	0	8	4	0
Navicula sp.	0	0	0	4
Navicula symmetrica Patrick	0	5	0	4
Navicula veneta Kützing	0	5	3	3
Nitzschia amphibia Grunow	0	0	4	0
Nitzschia filiformis (W.M. Smith) Van Heurck	0	3	0	0
Nitzschia frustulum (Kützing) Grunow	0	2	2	16
Nitzschia linearis (Agardh) W.M. Smith	1	0	0	0
Nitzschia palea (Kützing) W. Smith	0	0	0	8
Nitzschia sp.	0	5	6	0
Nupela sp.	0	0	0	1
Pinnularia gibba Ehrenberg	0	1	0	0
Planothidium engelbrechtii (Cholnoky) Round & Bukhtiyarova	0	0	1	1
Planothidium frequentissimum (Lange-Bertalot) Lange-Bertalot	0	0	0	1
Planothidium lanceolatum (Brébisson) Lange-Bertalot	1	0	0	0
Psammothidium oblongellum (Oestrup) Van de Vijver	36	28	53	2
Reimeria uniseriata Sala, Guerrero & Ferrario	0	0	0	16
Rhoicosphenia abbreviata (C. Agardh) Lange-Bertalot	0	0	0	3
Sellaphora pupula (Kützing) Mereschkowksy	0	1	5	0
Sellaphora seminulum (Grunow) D.G. Mann	4	8	1	0