CHALMERS
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# Hydrological and microbial modelling using Soil and Water Assessment Tool

## Lake Vomb and uMgeni catchment

*Master of Science Thesis in the Master's programme Infrastructure and Environmental Engineering at the Chalmers University of Technology*

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Cover:
Cover photos taken in uMgeni Municipality, by Charles V. Löwenström: Top: Agricultural soy field, Bottom left: Grazing horses and Bottom right: the uMgeni river.

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# ABSTRACT

In line with the Water Safety Plans and Sanitation Safety Plans by the World Health Organisation, understanding the impact of human and animal faecal sources on water quality is essential for safe drinking water supply and other water uses. Protozoan parasites, e.g. *Cryptosporidium*, have caused diarrhoeal outbreaks in both developed and developing countries. Diarrheal disease is a leading cause of child mortality in low-income settings, and *Cryptosporidium* was shown to be one of the most important pathogens in a large study in sub-Saharan Africa. Hydrological modelling can be used to simulate the fate and transport of faecal pollution within the catchment and to estimate the impact of diffuse and point faecal sources on the water source. In this project, Lake Vomb catchment in Sweden and the uMgeni catchment in South Africa were modelled using the Soil and Water Assessment Tool (SWAT). The aim was to quantify the loads of *Cryptosporidium* and faecal indicator *E. coli* from human wastewater and animal husbandry to the water sources. For Lake Vomb catchment, the hydrological model was successfully calibrated and showed a good performance in terms of simulating the water flow. The main source of microbial loads into Lake Vomb, which is used as a drinking water source, was manure application on agricultural land. For the uMgeni catchment, calibration of the hydrological model was unsuccessful, mainly due to the lack of suitable precipitation data and uncertainties regarding hydraulic properties of the soil. The main pollution source was the failed wastewater treatment plant releasing untreated sewage into the Midmar dam, which is a major drinking water source in the area. For the Lake Vomb catchment, the model can be improved by acquiring better data on locations and performance of on-site wastewater treatment systems, pathogen prevalence in livestock, and amount of manure applied on agricultural land. For the uMgeni catchment, simulation of the water flow needs to be improved by in-situ testing of soil properties and adding more precipitation monitoring stations in the area. After improvement, water quality modelling can be used together with microbial source tracking to inform quantitative microbial risk assessment.

**Key words**: *Cryptosporidium*, drinking water, *E. coli*, microbial risk, SWAT

Hydrologisk och mikrobiell modellering med Soil and Water Assessment Tool
-Vombsjön och uMgeni avrinningsområde

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# SAMMANFATTNING

I linje med Världshälsoorganisationens säkerhetsplaner för vattenskydd och sanitet är det viktigt att man förstår effekterna av mänskliga och animaliska fekalkällor på vattenkvaliteten för att kunna försäkra säker dricksvattenförsörjning och annan vattenanvändning. Protozoa parasiter, t.ex. *Cryptosporidium*, har orsakat diarréutbrott i både utvecklade och utvecklingsländer. En studie om sub-sahariska Afrika visade att diarrésjukdomar är en ledande orsak till barndödlighet i utvecklingsländer och att *Cryptosporidium* är en av de främsta smittorsakerna. Hydrologisk modellering kan användas för att simulera transporten av fekalförorening och för att uppskatta effekterna av diffusa och punktutsläpp från fekala källor på vattentäckter. I detta projekt modellerades Vombsjöns avrinningsområde i Sverige och uMgenis avrinningsområde i Sydafrika med hjälp av Soil and Water Assessment Tool (SWAT). Syftet var att kvantifiera belastning av *Cryptosporidium* och fekalindikatorn *E. coli* från avloppsvatten och djurhållning till vattentäkterna. För Vombsjön var den hydrologiska modellen framgångsrikt kalibrerad och visade en bra prestanda när det gällde att simulera vattenflödet. Den huvudsakliga källan till mikrobiell belastning i Vombsjön, som används som dricksvattentäkt, var gödselanvändning på jordbruksmark. För uMgenis avrinningsområde misslyckades kalibrering av den hydrologiska modellen, främst på grund av bristen på nederbörds och osäkerheter avseende jordens hydrauliska egenskaper. Den huvudsakliga källan till mikrobiell belastning kommer ifrån det ej fungerande avloppsreningsverket i Mpophomeni, vilket släpper ut obehandlat avloppsvatten till Midmar dammen - en viktig dricksvattentäkt i området. För Vombsjön kan modellen förbättras genom att utöka data angående lokalisering och avskiljning av enskilda avlopp, förekomst av patogener i boskap och gödselmängder för jordbruket. För uMgenis avrinningsområde kan simuleringen av vattenflödet förbättras genom in-situ undersökning av markegenskaper och installation av fler nederbördsstationer i området. Efter förbättring kan vattenkvalitetsmodelleringen användas tillsammans med mikrobiell källspårning för att utföra kvantitativ mikrobiologisk riskanalys.

**Nyckelord**: *Cryptosporidium*, dricksvatten, *E. coli*, mikrobiologisk risk, SWAT

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We are also very thankful to Professor Thor-Axel Stenström at the Durban University of Technology, Institute of Water and Wastewater technology, for the opportunity to visit South Africa as exchange students and for all his help with everything from managing our research process to ensuring our well-being. We are also grateful to all his Master and PhD students for their kindness and help.

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# 1. Introduction

## 1.1 Background

Safe and easily available water is one of the fundamental requirements for life and good health for all humankind. Available freshwater on the planet is limited and its quality is under pressure. In general, the waterborne diseases are a public health issue worldwide, causing death of several millions of people each year (WHO, 2016). Faecal contamination sources have a significant impact on the microbial water quality, which determines the suitability of water bodies for drinking water production and bathing. The microbial contamination of surface water is more common than groundwater contamination due to the natural filtration by soil layers (Rosen, et al., 2012).

Faecal contamination sources are often unknown and identification of the sources and their impact on the water quality is necessary to estimate the risks for human health (Krentz, et al., 2013). Urban wastewater discharges into water bodies are considered as point faecal sources, while land use activities, such as manure application, wildlife and livestock grazing, are considered as non-point faecal sources (Bougeard, et al., 2010). Water runoff increases the probability of pathogens reaching the water source especially during the heavy rainfall events (Parajuli, 2007). Management of these faecal sources is essential to ensure safe drinking water. Many of the zoonotic pathogens transmitted into the water directly are the reason of almost 75% of infectious diseases in humans (Coffey, 2012). For this reason, the loads and concentration of *Cryptosporidium* and *E. coli* to/in surface water have been studied.

Manure application on agricultural land and livestock grazing on grassland deposit a large quantity of faecal matter, which might enter the surface water system. The applied manure volume, land topography, hydrology and proximity to surface water are the factors which might increase the risk of water contaminated by manure.

On-site wastewater treatment systems (OWTS) are commonly used to treat wastewater produced by private households that are not connected to centralized wastewater treatment plant. The wastewater is treated and dissipated into the soil. The physical, chemical and biological treatment processes remove pathogens. Failing treatment systems release untreated wastewater into the soil or nearby water bodies; this can lead to unexpected increases of microbial concentrations.

*Cryptosporidium* is an intracellular protozoan parasite commonly identified as intestinal pathogen in humans and animals. The life cycle of *Cryptosporidium* is complicated and contains different life stages. It does not require dual or multiple hosts for completion. The thick-walled *Cryptosporidium* oocysts pose a critical challenge to drinking water treatment as they are resistant to chlorine disinfection (Yates, et al., 2013). *Cryptosporidium* infections are common in humans and animals, causing diarrheal disease, with symptoms of stomach cramps, vomiting and fever in humans. Many *Cryptosporidium* species have been confirmed by genetic analysis in the recent decades and it is clear now that not all species are infectious to humans. *C. hominis* and *C. parvum* are the main cause of human disease. Other species, such as *C. felis* and *C. canis*, are occasionally associated with human disease in specific environments, while some other species were identified to be human pathogens such as *C. meleagridis* and *C. cuniculus* (Yates, et al., 2013). The infection of *Cryptosporidium* occurs generally through the faecal oral route, through contaminated drinking water and recreational activities.

*Escherichia coli (E. coli)* is a bacterium member of the family *Enterobacteriaceae. E. coli*. exists in the human and animal gastrointestinal tract in different strains. Many of the *E. coli* strains are harmless and provide health benefits to the host, such as preventing colonization of the gut by harmful pathogens. At the same time, there are a small groups of *E. coli* that form and develop a harmful strain that cause a broad spectrum of diseases including severe diarrheal and serious health issues such as *E. coil* O157:H7 (Rivas, et al., 2015).A study was made by (Avery, et al., 2004) to determine the fate of *E. coli* loads onto grazing areas via faeces from cattle, pigs and sheep. It showed that *E. coli* could survive on grass for 5 to 6 months resulting in pathogenic biotypes which infect animals and contaminate plants and water. The *E. coli* survival rate in lakes and puddle waters were found to be higher than in rivers and it has a general survival range between 2 and 12 weeks in water (Avery, et al., 2007). Faecal indicators were used to estimate the microbiological water quality for many years, due to the difficult, time-consuming and expensive methods of measuring the concentration of specific pathogens. *E. coli*, is one of the most common microbiological indicators of faecal contamination in raw water sources (Coffey, 2012). *E. coli* as an indicator is used in a high number of tools for assessing the risk of microbial/ pathogenic contamination and to study the presence of faecal contamination (Yates, 2007).

There is a modern approach for determining water quality in catchment areas affected by non-point and point contamination sources. It consists of hydrological and microbial models, which serve as a tool to connect the contamination sources to receiving streams. The models save time and money due to their ability to perform long term simulations of the impact of catchment processes and management activities on water quality and quantity (Moriasi, et al., 2007). Identification and elimination of non-point contamination sources are a challenging task, due to their heterogeneity and frequency. Hydrological and microbial models could be helpful to solve this issue and could play significance role in the decision-making process in water management projects (Bougeard, et al., 2010).

Several modelling tools have been developed to simulate the hydrological conditions and impacts of different management scenarios on water quality in catchment areas. Borah & Bera (2003) reviewed in their study eleven hydrological and non-point contamination source models such as the European Hydrological System Model MIKE-SHE, Hydrological Simulation Program- Fortran (HSPF) and the Soil and Water Assessment Tool (SWAT). The study concluded that the models could simulate all major (hydrology, microbial, sediment and chemical) components relevant to the water catchments. Many continuous simulation models are based on the Geographic Information System (GIS) software, which is considered as a useful tool for spatially-distributed physical processes on catchment scale. The suitable input data for such simulations are often GIS-based (Borah, et al., 2007).

The Soil and Water Assessment Tool, SWAT, was created in the early 1990s by Dr. Jeff Arnold for the U.S. department of agriculture (USDA). The software is an add on to the Geographic Information System. SWAT showed reliable performance as a continuous simulation model in a predominantly agricultural catchment (Borah, et al., 2007). A study made by Shi, et al. (2011), showed that the SWAT model was capable of simulating streamflow with a coefficient determination value ($R^2$) >0.72 and Nash- Sutcliffe efficiency (NSE) > 0.69. The SWAT has a microbial sub- model to address the fate and transport of both persistent and less persistent faecal pathogens (Arnold & Moriasi, 2012). Coffey, et al.(2009) used the SWAT microbial sub-model to estimate the impacts of land use practices on the water quality by quantifying the loads of faecal pathogens in an Irish catchment. The results of both the hydrological and microbial model were reasonable and satisfactory with $R^2$=0.83 and NSE=0.78 for the hydrological model and $R^2$=0.68 and NSE= 0.59 for the microbial sub-model.

This project included two catchments areas, Lake Vomb catchment in the south part of Scania in Sweden and uMgeni catchment upstream Albert falls Dam in the north part of Kwazulu-Natal in South Africa. Both catchments include drinking water sources, and the microbial water quality is influenced by the land use practices and the wastewater discharges in the catchment. The faecal contamination that reaches Lake Vomb derives from agriculture practices, livestock grazing, and OWTS within the catchment. The faecal contamination sources in the uMgeni catchment are livestock grazing, OWTS and the untreated wastewater discharge from the Mpophomeni township due to the failing in the Mpophomeni wastewater treatment plant. To help manage and protect the water quality of these two drinking water sources, the Soil and Water Assessment Tool, SWAT, was used to model pathogen fate and transport, simulate the impacts of land use practices on water quality and assess the pathogen loads to the drinking water sources.

## 1.2 Aim and Objectives

The aim of the project was to study the impact of different contamination sources on the microbial water quality using hydrological modelling. The study areas were: Kävlinegeåns catchment upstream Lake Vomb in Sjöbo municipality, Scania, Sweden and uMgeni catchment upstream the Albert falls dam in uMgeni municipality, Kwa-Zulu Natal, South Africa. The objectives were:

- to set-up the hydrological models using the modelling software ArcSWAT for the two study areas;
- to quantify the peak loads of *Cryptosporidium* and *E. coli* and their frequency using the hydrological models;
- to assess the contribution from human wastewater and animal husbandry to the contamination of the water sources.

## 1.3 Limitations

The study was conducted using available data and literature values, no on-site measurements were made. Furthermore, the model river flow validations are limited to the number of flow measuring stations in the two areas.

method

# 2. Methodology

The study focused on two catchment areas. Lake Vomb, located in the southern part of Sweden and uMgeni catchment, located in the eastern part of South Africa. To study microbial water quality in the two study areas, hydrological models was created using the Arc GIS based software Soil and Water Assessment Tool, SWAT. The two areas were studied and modelled separately and later compared focusing on *E. coli* and *Cryptosporidium* concentrations in three scenarios.

## 2.1 General description of the SWAT model

The information about the Soil and Water Assessment tool described in this chapter is based on the SWAT manual Soil & Water Assessment Tool Theoretical Documentation, Version 2012 (Arnold, et al., 2013) if not another reference is mentioned.

The Soil and Water Assessment Tool, SWAT, was created in the early 1990s by Dr. Jeff Arnold for the U.S. department of agriculture (USDA). The software is an add on to the Geographic Information System GIS, Arc GIS. There are two main types of map files used for spatial data in SWAT, raster files and vector files. Arc SWAT is used to predict water quality and sediment content from land usage and wastewater. The tool incorporates physical data such as geographic data, land use maps, hydrological data, meteorological data and animal activity. With the given input, it simulates water movement, nutrient cycling, spread of microbial organism, sediment movement, etc. The simulations are driven by the water balance in the area, which incorporates water, sediment, nutrient and pesticide loadings into the river as well as their movement in the channel network.

Arc SWAT divides the catchment area into sub-basins based on topography and water course. This makes it possible to study results of each sub-basin independently, which aids in locating problematic areas. The data which defines a sub-basin are climate, wetlands/ponds, groundwater, rivers and hydrologic response units, HRUs. The HRUs are a combination of land use, soil and slope data, which together determines the water flow through an area.

The SWAT model input values are inserted in four steps before the simulation can be run. These steps are Watershed Delineator, HRU Analysis, Write Input Tables and Edit SWAT Input.

The first step is to define the Watershed Delineation. The purpose of this step is to define the outline of the hydrological system in the study area, this include inlets, outlets, sub-basins, catchment area outline and water course. The configuration starts with the addition of a Digital Elevation Modell (DEM), which contains topographic data in raster format. On this layer, a map of the studied catchment area and a water course map are added, using the two options mask and burn. With these three layers in place, the river stream is defined by DEM-based flow direction and accumulation. This means that the flows directions in the river, defined in the water course map, are calculated based on elevation data from the DEM. Also, sinks that are detected in the DEM that are under the water level and connected to the river stream gets filled with water. Finally, when the Watershed Delineation is defined a topographic report, containing elevation data, longest path and watershed elevations for all the sub-basins is created.

The second step is to define the HRU Analysis. The purpose of this step is to combine a soil map, a land use map and slope data from the DEM to create HRU units. The three layers can be reclassified in this stage by adding look up tables, which contains information about how the map areas are labelled. When all three layers has been added the HRU threshold values can be defined. The threshold values refer to which minimum area as percentage of a sub-basin will be classified as an HRU. If the percentage is set to 5% all areas with a smaller area will be neglected and the area will be divided and included to the adjacent HRUs. After the HRU definition is finalised an HRU analysis report is created, which contain descriptions of land use, soil and slope class distribution in all sub-basins.

The third stage is to define the Input weather data. In this stage, relative humidity, solar radiation, rainfall, temperature and wind data are added. The data are added by attaching data tables including time observations from weather stations or simulated from the built-in US databases.

The final stage is Edit SWAT input. This is where microbial organisms and other contaminant are defined and where management practices can be added. For example, it is possible to add wastewater treatment plants, animal grazing activity, manure application, fertilizers, reservoirs etc.

## 2.2 Study area Lake Vomb

Lake Vomb (Figure 1) is located 20 km to the east of the city of Lund, Sweden in the county of Scania and lies inside Kävlingeåns catchment area (Vombsjön, 2017). Lake Vomb has a surface area of 12 km$^2$ and a catchment area of 447 km$^2$ (SMHI, 2017). The lake has an average depth of 6.6 m, a maximum depth of 16 m and is located about 20 m above sea level. In the catchment area, there are three main water bodies that have their outlet point in Lake Vomb: Brostbäcken, Björkaån and Torpbäcken (Lörmyr, 2010).

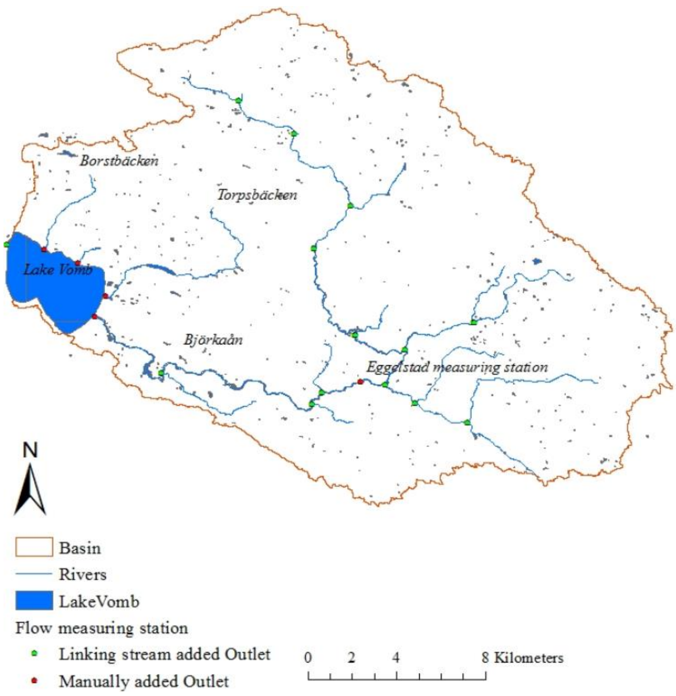



*Figure 1: Map of the Lake Vomb catchment area of (447 km$^2$).*

Sjöbo is the main municipality in the catchment area. It has an area of 500 $km^2$ and a population of around 19 000 people (Dedering, 2011). About 60% of the population,10 000 people, live in rural areas with no connection to a wastewater treatment plant (Sjöbo, 2017). The unconnected population treat their wastewater by using different on-site wastewater treatment systems (OWTS). Around 3000 OWTS exist in the municipality (Ejhed, et al., 2004).

Lake Vomb catchment includes small parts of three neighboring municipalities, Lund, Eslöv and Hörby and the southern part of Sjöbo municipality lies outside the catchment. The excluded part of Sjöbo has approximately the same area as the added parts of the three neighboring municipalities. To simplify the model, the amounts of OWTS in Sjöbo municipality was assumed to represent the entire catchment.

Lake Vomb is used as the drinking water source for 350 000 persons. The water is treated in Vombverket drinking water treatment plant (DWTP), which withdraws approximately 1 $m^3/s$ using two intake pipes in the south-western parts of the lake (Ejhed, et al., 2004).

The average local precipitation in the catchment is 736 mm/year, with average local air temperature of 9.2 C°. The total average lake outflow per year is 3.74 $m^3/s$ after drinking water extraction, the evapotranspiration is averaged to 451 mm/year and the total catchment runoff is 285 mm/year (SMHI, 2016).

The watershed has its lowest and highest points at 18 and 185-meter elevation above sea level and the main land uses in the catchment area are agriculture, livestock grazing areas and forest. Land use activity is divided with a high concentration of animal husbandry in the north and crop farming in the south (Dedering, 2011).The bedrock in the catchment is identified to consists of shale, marble and sandstone in the most parts of the area. In the north, there are some parts with gneiss bedrock (Geological Survey of Sweden, 2016).

The ecological and chemical status of the lake is unsatisfactory. because of the high nutrient concentration in the water, which are a result of the human and animal activities in the area (Ekologgruppen, 2012). There are several livestock farms and diary production industries in the area which house different kind of livestock: swine, cattle, sheep and poultry (SEPA, 2016).

## 2.3 Study area uMgeni Catchment

The South African study area was decided as the upper parts of the uMgeni catchment area upstream the Alberts fall dam (Figure 2). The decision made in collaboration with professor Thor Axel Stenström at the Institution of Water and Wastewater technology, Durban University of Technology and Professor Graham Jewitt at the University of KwaZulu-Natal.

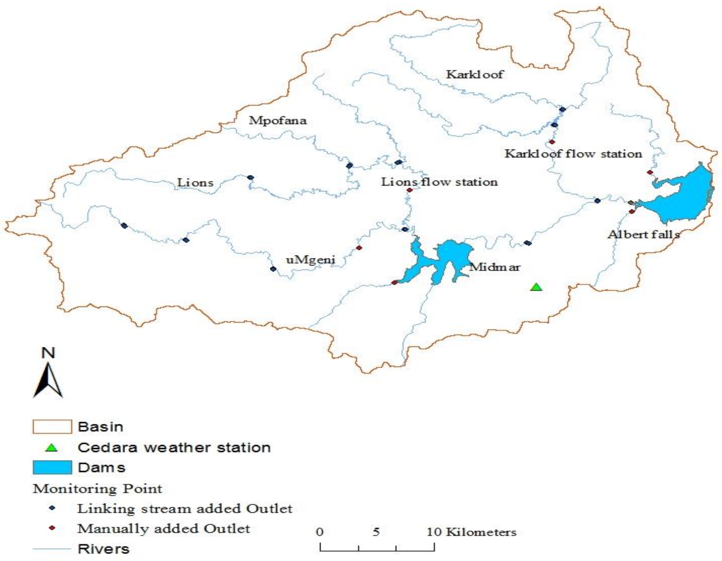



*Figure 2:Map of the uMgeni catchment area of (1567 km$^2$)*

The catchment is located in the uMgungundlovu district, KwaZulu-Natal (KZN) and include several municipalities. Most parts lie within uMgeni municipality, which has an area of 1567 km$^2$. Moreover, the catchment includes some part of the Mpofana municipality in the north, Impendle municipality in the west and uMshwathi municipality in east of the catchment (uMgeni Water, 2016)

The uMgeni river is the main water source of the KZN Midlands, providing high quality water to the major urban centres of Durban and Pietermaritzburg. It also supplies several other urban and peri-urban areas within the KZN region such as Howick, Wartburg, Nottingham Road and Mpophomeni. The uMgeni river has a total length of 225 km from source to mouth. From its source, the river flows eastward and is joined by the Lions river before flowing into the Midmar and Albert falls dam. The river can be considered as a narrow channel overhung by grassed banks, fine-leaved shrubs and occasional trees. The river habitats here are predominantly riffles and pools and cascades are common due to hard dolerite rock (uMgeni Water, 2016).

There are two large dams in the catchment area: Midmar and Albert falls. Three main rivers flow into Midmar dam: Lions, Mpofana and uMgeni river. The Midmar dam catchment area is considered as closed, as the outflow from Midmar dam is controlled and no longer open to streamflow. Also, other flow reducing activities such as afforestation and expansion of irrigation has been prohibited due to issues with draught in the area. Two rivers flow into Albert falls dam: Karkloof and uMgeni river (uMgeni Water, 2016).

The upper uMgeni Catchment area falls principally within the inland margin zone, which have some of the highest rates of wetland loss in South Africa. Wetlands in the uMgeni catchment area are most abundant upstream of Midmar Dam in the uMgeni Sponge. The KZN Wildlife agency protected some of these wetlands because they are important breeding areas for the threatened Wattled crane. Human activities were the cause of destroying many of the catchment wetlands in form of cultivation, artificial drainage, dams, urbanization, alien plant invasion, overgrazing and frequent burning. Approximately half of the original wetlands in the catchment area have been lost, some of the remaining are in good condition, while the others are degraded and their original functions are impaired (RHP, 2017).

A study of the pollution loads entering Midmar Dam from 1999 to 2009 shows that the Mpophomeni township, which comprised 2.4% of the Midmar catchment area, contributed to 51 % of the *E. coli* loads. The impact is a result of a failing waste water treatment plant, which release untreated waste water directly into the Midmar Dam (Wildlife KZN Ezemvelo, 2014).

The mean annual precipitation within the study area varies between 700 and 1000 mm, where most rainfalls event occur in summer (October to March), also there are occasional winter showers. The prevailing weather patterns are predominantly orographic, where warm, moist air moves in over the continent from the Indian Ocean, rise over the hills, cools down and creates rainfall. The distribution of evaporation has similar pattern to rainfall, where the daily mean peak in February, ranging from 68% in the inland areas to greater than 72 % for the coast. Where the daily mean low in July ranging between 60% and 68% in inlands area to the coast. In general, the potential annual mean gross evaporation ranges between 1600mm and 1800 mm in the west of the catchment to between 1400mm and 1600mm in the coastal areas (uMgeni Water, 2016). The maximum temperatures are in the summer months of December to February and minimum temperatures in the winter for the winter season between June and July. The annual minimum, mean and maximum temperatures are -8, 16 and 40 $^{o}C$ respectively (KZNWildlife, 2017).

## 2.4 SWAT hydrological modelling

In this chapter, the input parameters and maps from the hydrological model creation are presented.

### 2.4.1 Lake Vomb

The SWAT modelling of the hydrological behaviour in the watershed of Lake Vomb required a combination of map layers, look up tables and data series. The input data and their sources are presented showing file type, resolution and reference (Table 1). The shape files do not include any description of resolution. This is due to that the files are made up of polygons and lines which cannot be described with a specific resolution in the same way as the raster files. The coordinate system used for the model was SWEREF99_TM.

*Table 1: Input data, Lake Vomb, hydrological model*

| Input Data | File Type | Resolution | Reference |
|---|---|---|---|
| Digital Elevation Model | Raster | 8 x 8 m | (Lantmäteriet, 2016) |
| Water Course | Shape | - | (Geological Survey of Sweden, 2016) |
| Land Use | Raster | 50x50 | (Lantmäteriet, 2016) |
| Soil Types | Shape | - | (Geological Survey of Sweden, 2016) |
| Meteorological data | Text | Daily Data | (SMHI, 2016) |
| Private Properties | Shape | - | (Lantmäteriet, 2016) |

The watershed delineation was based on the DEM, water course map and study area mask. This defined the river outline and flow directions in the catchment. Eggelstad measuring station was added as a sub basin outlet, for model flow validation. Also, the lake inlets were added to be used as microbial observation points. From the watershed report the total modelled catchment area was 41 544 ha containing 28 sub-basins.

To define model HRUs and to create the HRU analysis report the land use map, soil map and slope classification was combined.

The land use map layer contained land uses classified into seven groups (Figure 3). The land use area distribution was given from the HRU report output (Table 2). The private property class refers to rural homes with an OWTS and each property was given a buffer zone of 1 ha. The reason is that SWAT requires a land use area to distribute the OWTS effluent.

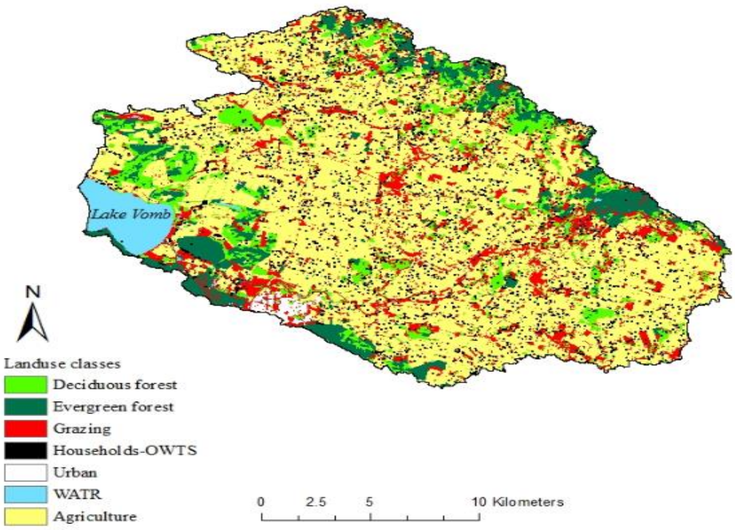



*Figure 3: Land use map, Lake Vomb catchment*

*Table 2: Land use class area, Lake Vomb*

| Land use | Area [ha] | % Total area |
|---|---|---|
| Agriculture | 24 018 | 57.5 |
| Grazing area | 5 580 | 13.4 |
| Forest-deciduous | 4 244 | 10.2 |
| Forest-evergreen | 3 574 | 8.6 |
| Private property | 2 858 | 6.8 |
| Water | 1170 | 2.8 |
| Urban area | 270 | 0.7 |

The soil types in the area were defined from a soil map layer. The map included various clays, sands, peat and glacio-fluvial sediments (Figure 4). However, the studied map had Swedish soil names which was converted into U.S. soils so that they corresponded to the SWAT databases. This was made by comparing the content of clay, silt, sand, rock and organic content of the Swedish soils with the content of the pre-defined SWAT soils (Table 3). The soil reclassification table was received from Viktor Bergion, Phd student at Chalmers University of Technology.

*Table 3: Soil reclassification table, Lake Vomb*

| Swedish soil type | Clay [%] | Silt [%] | Sand [%] | Rock[a] [%] | Organic content [%] | SWAT soil type | Area [ha] | Part of catchment [%] |
|---|---|---|---|---|---|---|---|---|
| Moränlera and/or morän | 14 | 20 | 66 | 6 | 2.65 | Fredon | 16026 | 38.6 |
| Morän | 4 | 16 | 80 | 20 | 0 | Scarboro | 13870 | 33.4 |
| Isälvssediment | 6 | 7 | 87 | 22 | 2.33 | Hinckley | 7920 | 19.1 |
| Vatten | - | - | - | - | - | Water | 1267 | 3.1 |
| Torv | 10 | 45 | 45 | 0 | 9.88 | Bucksport | 1070 | 2.6 |
| Lera-silt | 38 | 54 | 7 | 0 | 3.49 | Kingsbury | 611 | 1.5 |
| Postglacial sand-grus | 7 | 45 | 47 | 40 | 0 | Pillsbury | 570 | 1.4 |
| Lera-silt | 59.5 | 40 | 0.5 | 0 | 5.81 | Panton | 205 | 0.5 |

a) % of total weight.

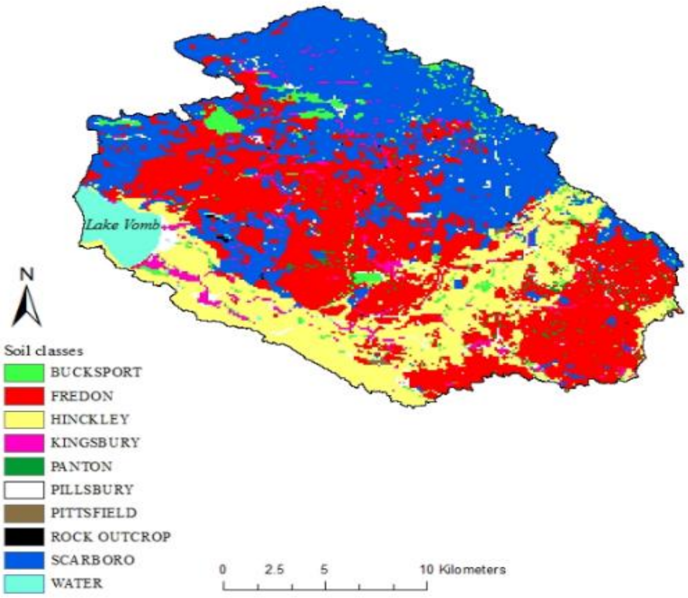



*Figure 4: Soil map, Lake Vomb*

Meteorological daily data was taken from several measuring stations and stretched from 2008-01-01 to 2015-12-31. Precipitation data was taken from Vomb measuring station, humidity, wind and temperature data from Hörby measuring station and Solar radiation data from Lund Measuring station. Three slope classes were used. 0-1 % slope, 1-10% slope and >10%. HRU limits was set to 3% for land use, soil use and slope class.

### 2.4.2 uMgeni Catchment

The input data was collected from various sources and prepared using ArcGIS 10.3.1 to be available to use in Arc SWAT (Table 4). The coordinate system used was Cape_UTM_Zone_35S for all maps used as input data to the model.

*Table 4: Input data, uMgeni catchment, hydrological model*

| Data | File type | Resolution | Reference |
|---|---|---|---|
| DEM | Raster | 90x90 | (Souls, 2017) |
| Water course | Shape | | (WR2012, 2017) |
| Land use | Raster | 30x30 | (GeoTerraImage south Africa, 2015) |
| Soil types | Shape | | (SOTERSAF, 2014) |
| Meteorological data | Text | daily data | (Dlamini, 2017) |
| Population map | Feature | | (WR2012, 2017) |
| Study Area | Shape | | (Namugize,, 2017) |

The watershed delineation was based on the DEM, water course map and study area mask. This defined the river outline and flow directions in the catchment. Karkloof and Lions measuring station was added as a sub basin outlet, for model flow validation. Also, the dam inlet points were added to be used as microbial observation points. From the watershed report the total modelled catchment area was 162 334 ha with 30 sub-basins.

The land cover map was reclassified in ArcGIS into ten land use types to be connected to the SWAT land use database (Figure 5). The classification includes a “township/villages” class, which refer to areas where OWTS discharge is distributed. The other classes were estimated based on area of woods/ trees, grasslands, bare soil, grazing areas and agriculture (Table 5).

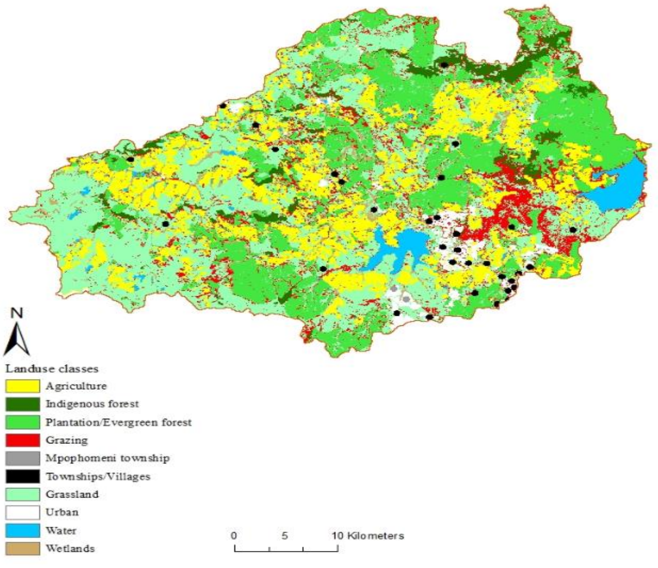



*Figure 5: Land use map, uMgeni catchment*

*Table 5: Land use class area, uMgeni Catchment*

| Land use | Area [ha] | % Total area |
|---|---|---|
| Agriculture | 30409 | 18.7% |
| Grassland | 56095 | 34.6% |
| Plantation/Evergreen Forest | 38440 | 23.7% |
| Grazing area | 15537 | 9.6% |
| Indigenous Forest | 6126 | 3.8% |
| Wetland | 5413 | 3.3% |
| Water | 4792 | 3.0% |
| Urban area | 4184 | 2.6% |
| Townships/villages | 1256 | 0.8% |
| Mpophomeni township | 82 | 0.1% |

One of the main inputs data in the SWAT model was the soil parameters of the catchment area, because they play significant role in estimating the water flow in the model. The soil of the uMgeni Catchment has been characterized by the International Soil Reference and Information Centre, (ISRIC), the Food and Agriculture Organization of the United Nations, (FAO) and Soil and Terrain Database of South Africa (SOTER_SAF). To use the SOTER_SAF soil dataset of the uMgeni catchment area, manually created soil layers had to be added to the SWAT database (Figure 6).

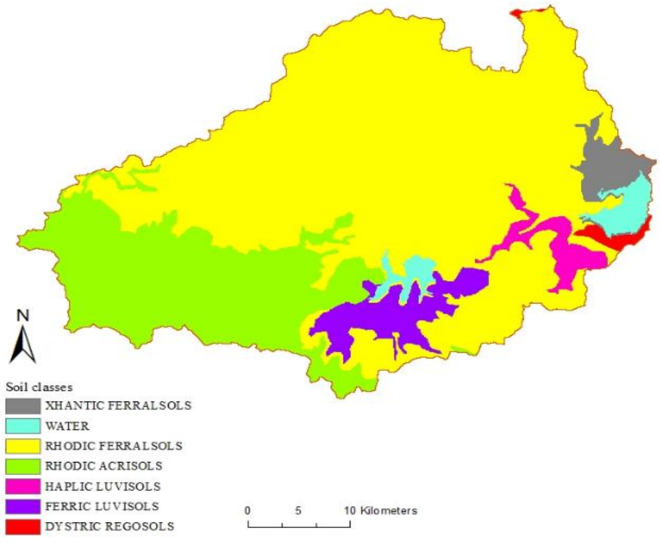



*Figure 6: Soil map, uMgeni catchment*

The SOTER database are combined of two main elements: a geographic and an attribute data component. The geographical database provides information on the location, extent, and topology of each SOTER_SAF defined soil, while the attribute database describes the characteristics of the soil groups. By using the Harmonized World Soil Database (HWSD) Viewer soil layers were defined by soil particle distribution and organic content (Table 6).

*Table 6: Soil reclassification, uMgeni catchment*

| SOTER soil | Texture | Clay [%] | Silt [%] | Sand [%] | Rock[a] [%] | Organic content [%] |
|---|---|---|---|---|---|---|
| Dystric regosols | SL-Sandy Loam | 14 | 21 | 65 | 30 | 0.3 |
| Ferric luvisols | SL-Sandy Loam | 27 | 24 | 49 | 1 | 0.26 |
| Haplic luvisols | SCL- Sandy Clay Loam | 35 | 17 | 48 | 1 | 0.36 |
| Rhodic acrisols | SCL- Sandy Clay Loam | 44 | 9 | 47 | 1 | 0.39 |
| Rhodic ferralsols | SCL- Sandy Clay Loam | 54 | 14 | 32 | 1 | 0.49 |
| Xhantic ferralsols | SC- Sandy Clay | 30 | 14 | 53 | 1 | 0.33 |

a) % of total weight

Using the Soil Plant Atmosphere Water (SPAW) software the required soil hydrological parameters, hydraulic conductivity and soil available water were estimated (Figure 7). The soil hydrologic groups were classified by four categories A, B, C, D, due to the soil infiltration characteristics. Group A soils have a high infiltration rate and low runoff, group B soils have a moderate infiltration rate, group C soils have a slow infiltration rate and group D soils have a very slow infiltration rate (Arnold, et al., 2012). The new soil data were inserted into the SWAT database as new soil types, keeping the same names that presented by SOTER_ SAF.

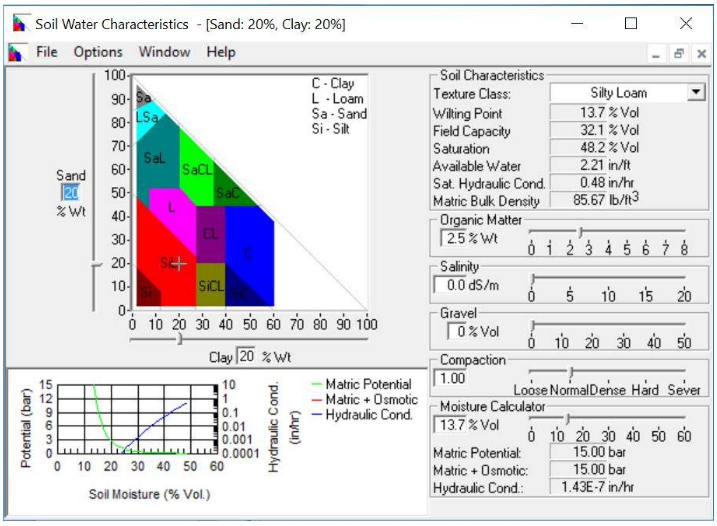



*Figure 7: SPAW software interface*

A more detailed information about the soil input parameters formats that are required for SWAT can be found in Appendix 1 and in the ArcSWAT 2012.10_3.18 User's guide (Arnold, et al., 2013).

Meteorological daily data from Cedara weather station (Figure 4) was used from January 2007 to December 2016. Precipitation, temperature, wind and humidity data were obtained from the South African Weather Service institute. Due to lack of data for solar radiation the US first order weather database provided by SWAT was used.

Three slope classes were defined, slope class 0-1% was assigned 2 % of the catchment area, slope class 1-10 % assigned 49 % and slope 10-99 % assigned to the other 49 %. Threshold for HRU definition were set to 0 % for land use and 3 % for soil and slope. The low land use threshold was set to include the township Mpophomeni in the model, as its area was smaller than 1% of its sub-basin.

## 2.5 Microbial sub-model

The SWAT microbial sub- model considers the fate and net transport of microbial organisms that originate from added contamination sources. The two microbial organisms that was studied in this project are *Cryptosporidium* and *E. coli* (Table 7). The decay rates are calculated by SWAT based on Chick's law for first order decay, see equation 1 (Arnold & Moriasi, 2012).

$$C_t=C_0 \cdot e^{-K_{20} t \Theta^{(T-20)}} \qquad \text{Equation 1}$$

$C_t$ = Microbial concentration at time t, [count/100mL]
$C_0$ = Initial microbial concentration, [count/100mL]
$K_{20}$ = First-order die-off rate at 200°C, [day$^{-1}$]
t = Exposure time, [days]
θ = Temperature adjustment factor
T = Temperature, [°C]

SWAT abbreviation definition:

**BACTKDDB**: Part of the organisms that are in soil solution.
**BACTKDQ**: Coefficient defining ratio between soil solution and runoff organisms:
**FRT_SURFACE**: Fraction of manure applied to the top 10 mm soil layer
**WDPQ:** Die-off, persistent organisms in soil solution
**WDPRCH**: Die-off, persistent organisms during river transport
**WDPS**: Die-off, persistent organisms adsorbed to soil particles
**WDPF**: Die-off, persistent organisms on foliage
**WOF_P**: Fraction persistent organisms washed off in rainfall events

*Table 7: SWAT parameter values, E. coli and Cryptosporidium*

| Microorganism | SWAT abbreviation | Unit | Value |
|---|---|---|---|
| Both | BACTFDDB | Fraction 0≤1 | 0.9[a] |
| Both | BACTKDQ | Constant | 175[b] |
| Both | FRT_SURFACE | Fraction 0≤1 | 0.5[c] |
| *E. coli* | WDLPQ | 1/day | 0.092[d] |
| *E. coli* | WDLPRCH | 1/day | 0.18[d] |
| *E. coli* | WDLPS | 1/day | 0.023[e] |
| *E. coli* | WDLPF | 1/day | 0.016[e] |
| *E. coli* | WOF-LP | Fraction 0≤1 | 0.5[f] |
| *Cryptosporidium* | WDPQ | 1/day | 0.005[d] |
| *Cryptosporidium* | WDPRCH | 1/day | 0.032[d] |
| *Cryptosporidium* | WDPS | 1/day | 0.003[a] |
| *Cryptosporidium* | WDPF | 1/day | 0.03[c] |
| *Cryptosporidium* | WOF_P | Fraction 0≤1 | 0.8[c] |

a) (Coffey, et al., 2010)
b) (Arnold & Kiniry, 2012)
c) (Tang, et al., 2011)
d) (Westrell, 2004)
e) (Bougeard, et al., 2011b)
f) (Bougeard, et al., 2011a)

Three management operation were used as microbial contamination sources. The management operations were: OWTS, faecal droppings from livestock grazing and manure applications on agriculture land. Simulated *E. coli* levels were then compared to guide values from the Swedish ocean and water authorities, which states that values should be lower than 1000 cfu/100 ml for a waterbody to be considered as a safe bathing water (Swedish Agency for Marine and Water Management, 2013).

*E. coli* concentrations from untreated OWTS effluent was $10^{5.6}$ [cfu/100ml], and the *Cryptosporidium* concentrations was [2 oocysts/100ml] (Westrell, 2004).

For the livestock grazing and manure application on agricultural land the average *Cryptosporidium* concentrations in livestock faeces were calculated from the prevalence of infection and the concentration in an infected animal (Table 8). The *E. coli* concentration for different livestock was obtained from literature.

*Table 8: Microbial concentration and prevalence in livestock faecal matter.*

| Livestock | Age | *Cryptosporidium* prevalence[a] | *Cryptosporidium* Concentration infected livestock[a] [oocysts/g] | *Cryptosporidium* concentration total livestock [oocyst/g] | *E. coli* concentration [*E. coli*/g] |
|---|---|---|---|---|---|
| Cattle | Adult | 0.5152 | 3.8E+03 | 2.0E+03 | 2.0E+05[b] |
| Calve | Juvenile | 0.283 | 3.8E+04 | 1.1E+04 | 4.2E+05[c] |
| Pigs | Adult | 0.221 | 2.4E+01 | 5.3E+00 | 3.0E+06[b] |
| Pigs | Juvenile | 0.261 | 4.7E+02 | 1.2E+02 | 3.0E+06[b] |
| Poultry | Adult | 0.2 | 2.1E+03 | 4.2E+02 | 1.0E+06[b] |
| Goats | Adult | 0.187 | 7.8E+02 | 1.5E+02 | 2.0E+07[b] |
| Horses | Adult | 0.1 | 1.0E+03 | 1.0E+02 | 1.0E+04[b] |
| Sheep | Adult | 0.346 | 7.8E+02 | 2.7E+02 | 2.0E+07[b] |
| Sheep | Juvenile | 0.524 | 9.1E+03 | 4.8E+03 | 2.0E+07[b] |

a) (Dufour, et al., 2012)
b) (Stenström, et al., 1980)
c) (Coffey, 2012)

### 2.5.1 Lake Vomb

*On-site wastewater treatment system*

On-site wastewater treatment systems, (OWTS), are used for sewer treatment of individual residences and are widely utilized in rural areas of Sweden. In Lake Vomb catchment, there are almost 3900 OWTS, with an average of 2.56 persons per OWTS. Assuming an average wastewater outflow of 160 l/person/day each household produce 409.6 L sewage (Swedish Agency for Marine & Water Management, 2016). Effluent from each household was distributed evenly over a circular area of 1 ha surrounding each house. The main types of these OWTS are: Sand filter systems, with a microbial reduction factor between 90-99%. Infiltration plants, with a microbial reduction factor between 90-95%. Households using end tank treatment system were neglected in the model as they do not produce any effluent.  (Ejhed, et al., 2004).

The used number of OWTS in the study area where 3375, which was obtained from removing the end tank treatment systems, 13.5% of the total amount (Ejhed, et al., 2004). Each OWTS was assumed to have a microbial reduction of 1 $\log_{10}$ for both *E. coli* and *Cryptosporidium*, the reduction was chosen assuming the worst-case scenario, that both the sand filter systems and infiltration plants operate on 90% reduction.

*Livestock grazing*

Livestock dropping contain different pathogenic microorganisms including bacteria, protozoa and viruses. Cattle and sheep require a minimum of 120 days grazing per year somewhere between 1 April and 31 October (Swedish Board of Agriculture, 2016). The study area lies in the south of Sweden with a warmer than average climate, therefore, the number of grazing days was set to 180 days. All livestock are subsequently housed for the winter and early spring periods.

In the SWAT model for Lake Vomb catchment, the grazing area is obtained to be 5583 ha. This was used to calculate livestock density and the faecal production per ha and day (Table 9). A uniform distribution of livestock over the grazing areas was assumed.

*Table 9: Faecal production, grazing, Lake Vomb*

| Livestock | Age | Amount of livestock[a] | Livestock density grazing area [1/ha] | Faecal production[b] [kg/(animal*day)] | Grazing days | Faecal production [kg/ha/day] |
|---|---|---|---|---|---|---|
| Cattle | Adult | 14654 | 2.62 | 14.4 | 180 | 37.73 |
| Calve | Juvenile | 6750 | 1.21 | 1.65 | 180 | 2.00 |
| Sheep | Adult | 1510 | 0.27 | 0.7 | 180 | 0.19 |
| Sheep | Juvenile | 1638 | 0.29 | 0.7 | 180 | 0.20 |

a) (Jordbruksverket, 2008)
b) (Dufour, et al., 2012)

*Manure application*

During the housed periods for livestock, the produced manure is stored to be used later as fertilisation for agricultural land during the growing season and after harvest of crop.
The agriculture land has a total area of 24032 ha which considered as 57.6 % percent of the total catchment area. The model was set up based on an assumption that the collected manure is distributed uniformly onto agriculture land first on 15 April and then on 15 October. The produced manure was calculated into kg manure per ha of agricultural area and divided by the two application dates to fit the input data requirements in SWAT (Table 10).

*Table 10: Applied manure, Lake Vomb*

| Livestock | Amount of livestock[a] | Age | Manure production[b] [kg/(animal·day)] | Number of housed days | Collected manure [kg] | Applied manure per application [kg/ha] |
|---|---|---|---|---|---|---|
| Cattle | 14654 | Adult | 14.4 | 185 | 3.9E+07 | 8.1E+02 |
| Calve | 6750 | Juvenile | 1.65 | 185 | 2.1E+06 | 4.3E+01 |
| Pigs | 35912 | Adult | 2.7 | 365 | 3.5E+07 | 7.4E+02 |
| Pigs | 11457 | Juvenile | 2.7 | 365 | 1.1E+07 | 2.4E+02 |
| Poultry | 259184 | Adult | 0.12 | 365 | 1.1E+07 | 2.4E+02 |
| Sheep | 1510 | Adult | 0.7 | 185 | 2.0E+05 | 4.1E+00 |
| Sheep | 1638 | Juvenile | 0.7 | 185 | 2.1E+05 | 4.4E+00 |

a) (Jordbruksverket, 2008)
b) (Dufour, et al., 2012)

### 2.5.2 uMgeni Catchment

*On-site wastewater treatment systems*

The uMgeni study area includes two wastewater treatment plants in Howick and Mpophomeni. Howick WWTP provides treatment service for approximately 48% of the uMgeni municipality (STATSSA, 2017). It has a design capacity of treating 6 800 $m^3$/day and is currently treating 5 000 $m^3$/day. The WWTP effluent was not considered in the model as the outlet is outside the study area (uMgeni Water, 2016). From the data of connected households to the WWTP, the number of people using an OWTS or no treatment was determined to be 59 853 persons, which was calculated as 52% of the total population in the study area (STATSSA, 2017). The faecal weight produced per person was set to 150 g/day (Feachem, et al., 1983).

No data were found concerning the distribution of OWTS treatment methods in the area, therefore an assumption was made to use a 1 $\log_{10}$ reduction for both *E. coli* and *Cryptosporidium*. The locations of the OWTS were determined by the location of townships and villages in the area. The wastewater produced by the population in each area was grouped together and distributed over an area of 40 ha.

For the township Mpophomeni, with a population of 25 732, all effluent was modelled to be untreated, 0 $\log_{10}$ reduction. This is due to the failed WWTP, which releases untreated wastewater directly into the Midmar dam.

*Livestock grazing*

In the uMgeni municipality there were three main groups of grazing livestock: cattle, goats/sheep and horses. Due to the warm climate, these animals are grazing 365 days a year. Because of lacking data over the position of each livestock herd the produced faecal matter was evenly distributed over the modelled grazing area of 15 537 ha. This was used to calculate livestock density and faecal production per ha (Table 11). Livestock data for the uMgeni municipality did not cover the distribution of the adult and juvenile population of each herd. Therefore, the distribution was calculated based on the data regarding the livestock in Sjöbo municipality.

*Table 11: Faecal production and grazing, uMgeni catchment*

| Livestock | Age | Amount of livestock[a] | Livestock density grazing area [1/ha] | Faecal production[b] [kg/(animal*day)] | Grazing days | Faecal production [kg/ha/day] |
|---|---|---|---|---|---|---|
| Cattle | Adult | 34935 | 2.25 | 14.4 | 365 | 32.38 |
| Calve | Juvenile | 16065 | 1.03 | 1.65 | 365 | 1.71 |
| Goats | Adult | 1200 | 0.08 | 0.7 | 365 | 0.05 |
| Horses | Adult | 2000 | 0.13 | 18.5 | 365 | 2.38 |
| Sheep | Adult | 4176 | 0.27 | 0.7 | 365 | 0.19 |
| Sheep | Juvenile | 4524 | 0.29 | 0.7 | 365 | 0.20 |

a) (de Lange, 2017)
b) (Dufour, et al., 2012)

In the study area, there are three wildlife game parks: Alberts fall dam natural reserve, Midmar dam natural reserve and uMgeni valley natural reserve. However, due to relatively small wildlife amounts, the influence from the wildlife in these game parks was neglected (KZNWildlife, 2017).

*Manure application*

The livestock in the uMgeni municipality include about 35 221 pigs and 583 641 poultry (de Lange, 2017). These livestock are indoors or in small confinements for the entire year. The produced manure from the livestock was not added as agricultural fertilization in the model, since most farms in the area practice inorganic farming (Ngubane, 2017).

## 2.6 Sensitivity analysis, calibration and validation

The SWAT model performance is based on the input parameters, to improve the model performance and preform a statistical analysis a calibration and validation of the model is required. One method to do this is to compare simulated and measured river flow data in specific points (Arnold & Moriasi, 2012). This comparison can be made manually using Microsoft Excel or with the calibration software SWAT-CUP.

The most used statistics reported for SWAT calibration and validation are $R^2$ and NSE. The $R^2$ values can range from 0 to 1, with 0 indicating no correlation and 1 representing perfect correlation; $R^2$ provides an estimate of how good the variance of observed data is replicated by the model prediction. The NSE values can range between $-\infty$ and 1, with 1 representing a perfect fit between the simulated and the observed data; NSE provides a measure of how good the simulated output matches the observed data. For a more typical application (Arnold & Moriasi, 2012)proposed that NSE value should exceed 0.5 for model results to be judged satisfactory for hydrological and contaminant evaluation performed on monthly time step.

SWAT-CUP includes automated as well as semi-automated procedures for model calibration; the semi-automated program SUFI2 was used to calibrate the model and to determine the most sensitive parameters. Correct parameterisation is a crucial step in the model calibration, and the selection of parameters was based on the knowledge of the hydrologic processes and variability in soil, land use, slope and location, as well as the findings of the previous studies that used SUFI2 (Arnold & Moriasi, 2012).The parameter definition is presented in Appendix 2.

To examine how the models output responds to change in variables, a sensitivity analysis was conducted (Arnold & Moriasi, 2012). The sensitivity analysis was performed by the SWAT-CUP–SUFI2 program, seeking the sensitive parameters that had impact on the streamflow in Lake Vomb catchment. The global sensitivity analysis was used in this study, which shows relative sensitivities in t-stats and p-values for each parameter. The t-stat provides a measure of sensitivity, where the absolute values of the parameters determine which parameters are more sensitive. The p-value ranks the parameters after their significance of the total model sensitivity; a value closer to zero indicates more significance.

The calibration method referred to in the model calibration tables as relative and replace refer to which method used to calibrate the model parameters. “Relate” means that the parameter value is multiplied with a number between the minimum and maximum values. This is suited for parameters which vary in different HRUs and sub basins, e.g. this was used when calibrating soil parameters as they are different for each soil type. “Replace” means that the parameter value is replaced with the simulated number.

### 2.6.1 Lake Vomb

From the SWAT output data, simulated flows from Eggelstad measuring station and three rivers: Björkaån, Borstbäcken and Torpsbäcken which have their outlet in Lake Vomb, were extracted. Simulated and observed flows (SMHI, 2017) at Eggelstad were compared using statistical analysis, which resulted in a $R^2$-value of 0.84 and a NSE-value of 0.71, which is satisfactory (Figure 8). For the three rivers, no observed data were available, instead the simulated flows were compared with SMHI modelled data, Appendix 3.

The four observed points show NSE values over 0.5, which means that the model is satisfactory. However, to further improve the model, the simulated and observed flows from Eggelstad was used in a model improvement calibration using SWAT-CUP. The decision to use Eggelstad was made, as the three river outlets did not have observed data.

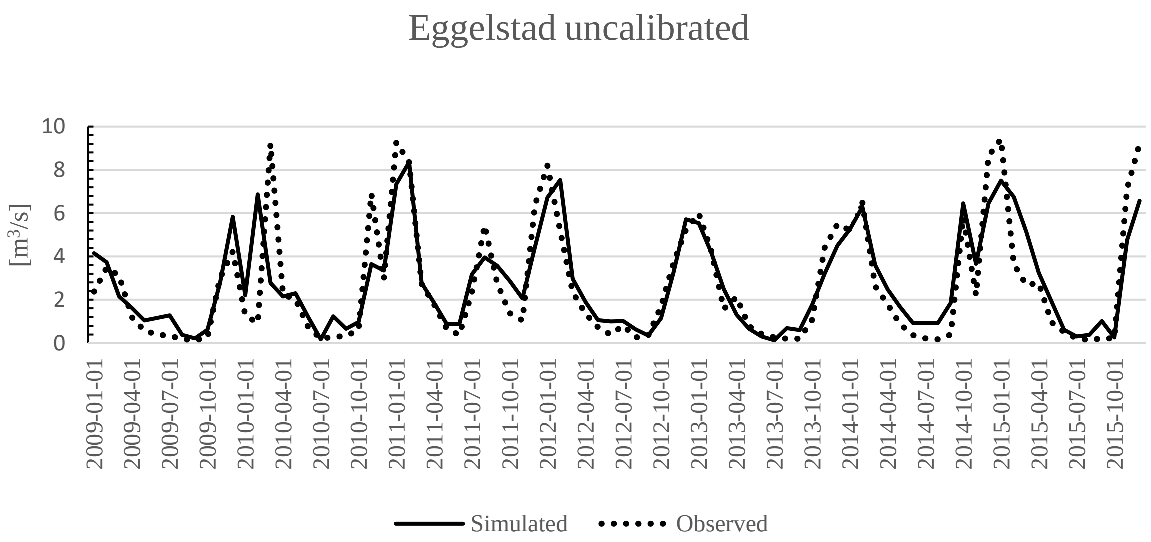



*Figure 8: Water flow comparison: simulated and observed waterflow at Eggelstad measuring station, ($R^2$=0.84, NSE=0.71).*

Sensitivity analysis was made to determine which parameters to use in the model calibration. The sensitivity analysis shows that the three most sensitive parameters are CN2, which affects water runoff. GW_DELAY, which affects groundwater flow and SOL_AWC which affects the water capacity in the soil (Table 12). According to the SWAT-CUP manual these parameters are often the most sensitive when preforming a flow calibration (Arnold & Moriasi, 2012).

*Table 12: Sensitivity analysis results, Lake Vomb*

| Parameter | t-stat | p-value |
|---|---|---|
| CN2 | -7.26 | 0 |
| GW_DELAY | -4.67 | 0.00001 |
| SOL_AWC | 3.57 | 0.0006 |
| ESCO | 1.12 | 0.26 |
| ALPHA_BF | 1.08 | 0.28 |
| SOL_K | -0.95 | 0.34 |
| REVAPMN | -0.79 | 0.43 |
| SMFMX | 0.77 | 0.44 |
| SMFMN | -0.09 | 0.92 |
| GW_REVAP | 0.04 | 0.97 |
| GWQMIN | 0.02 | 0.98 |

The six most sensitive parameters, were used in a model calibration for a four-year period from 2009-2012 (Table 13). The reason is that the calibrated model was afterwards validated by examining the flow correlations for the uncalibrated following three years 2013-2015. The SWAT-CUP calibration was run with 500 iterations.

*Table 13: SWAT-CUP calibrated parameters, Lake Vomb*

| Parameter Name | Method | Min | Max | Cup-values |
|---|---|---|---|---|
| CN2 | Relative | -0.2 | 0.2 | -0.17 |
| ALPHA_BF | Replace | 0 | 1 | 0.735 |
| GW_DELAY | Replace | 30 | 450 | 40.5 |
| ESCO | Replace | 0 | 1 | 0.855 |
| SOL_K | Relative | -0.5 | 0.5 | 0.385 |
| SOL_AWC | Relative | -0.5 | 0.5 | 0.145 |

The four-year calibration 2009-2012 resulted in a $R^2$-value 0.84 and NSE-value 0.71 and the three-year validation 2013-2015 in a $R^2$-value 0.93 and NSE-value 0.87. Since, the validation yielded a satisfactory result, the calibrated parameters were used for the eight-year simulation (Figure 9). The $R^2$-value for the calibrated model was 0.94 and the NSE-value 0.87. The results show that the model performance improved and was deemed to be enough to proceed with the microbial sub-model (Table 14). Calibrated river flow graphs for Björkaån, Borstbäcken and Torpsbäcken can be found in Appendix 3.

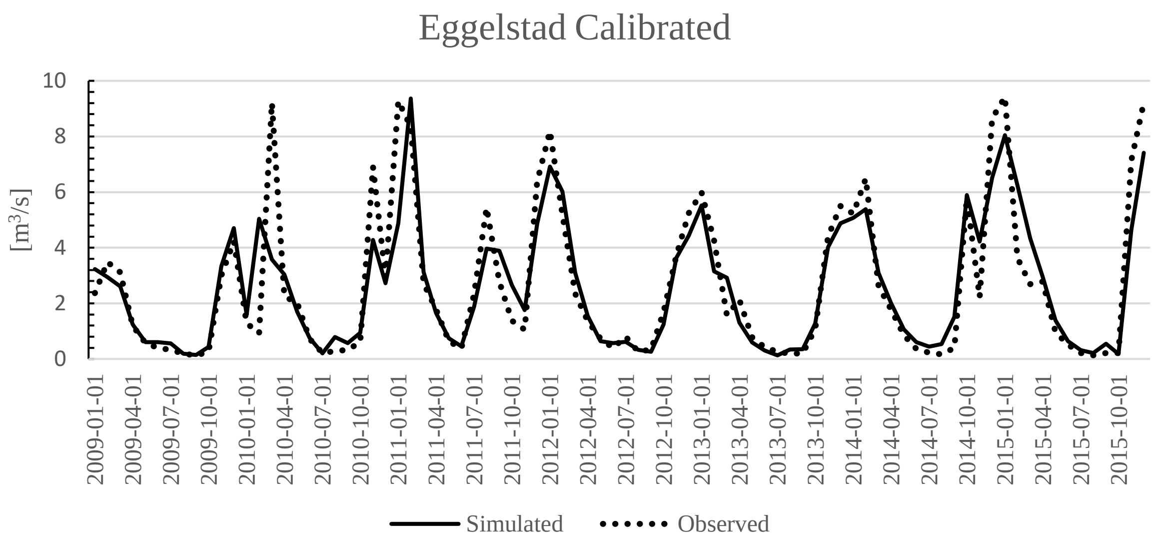


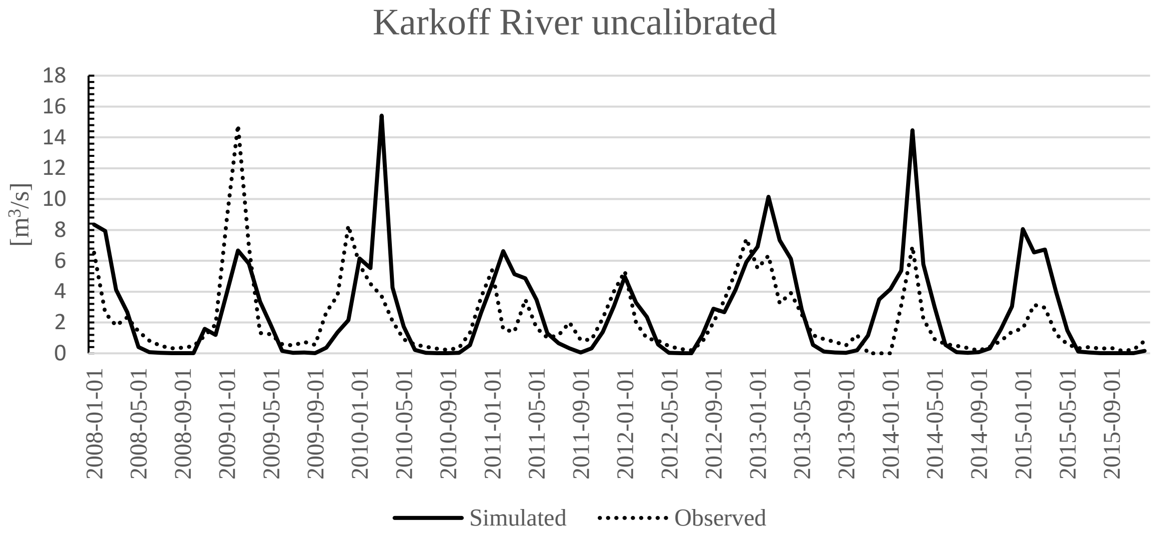

*Figure 9: Water flow comparison: calibrated and observed waterflow at Eggelstad measuring station, ($R^2$=0.94, NSE=0.87).*

*Table 14: $R^2$ and NSE-values for the uncalibrated and calibrated model, Lake Vomb*

| Measuring point | Uncalibrated | Calibrated | Uncalibrated | Calibrated |
|---|---|---|---|---|
| | $R^2$ | $R^2$ | NSE | NSE |
| Eggelstad | 0.84 | 0.94 | 0.71 | 0.87 |
| Björkaån | 0.83 | 0.89 | 0.68 | 0.8 |
| Torpsbäcken | 0.83 | 0.89 | 0.63 | 0.77 |
| Borstbäcken | 0.82 | 0.89 | 0.57 | 0.61 |

### 2.6.2 uMgeni Catchment

From the SWAT output data, simulated flows from Karkloof and Lions River flow stations, were extracted. The simulated flow in both stations was compared to observed flow data received from (Water & Sanitation, 2016) (Figure 10). For Karkloof flow station the $R^2$-value was 0.62 and the NSE-value was -0.1. For Lions River flow station the $R^2$-value was 0.55 and the NSE-value was -1.27. The two observed points show $R^2$-values over 0.5. However, the NSE-values are both negative. This means that the river flows follow the observed patterns, but they do not match in flow magnitude. To improve the model the simulated and observed flows was inserted into SWAT-CUP for calibration. Due to the low NSE-values, the calibration was made on the criteria to focus on improving the NSE-value.



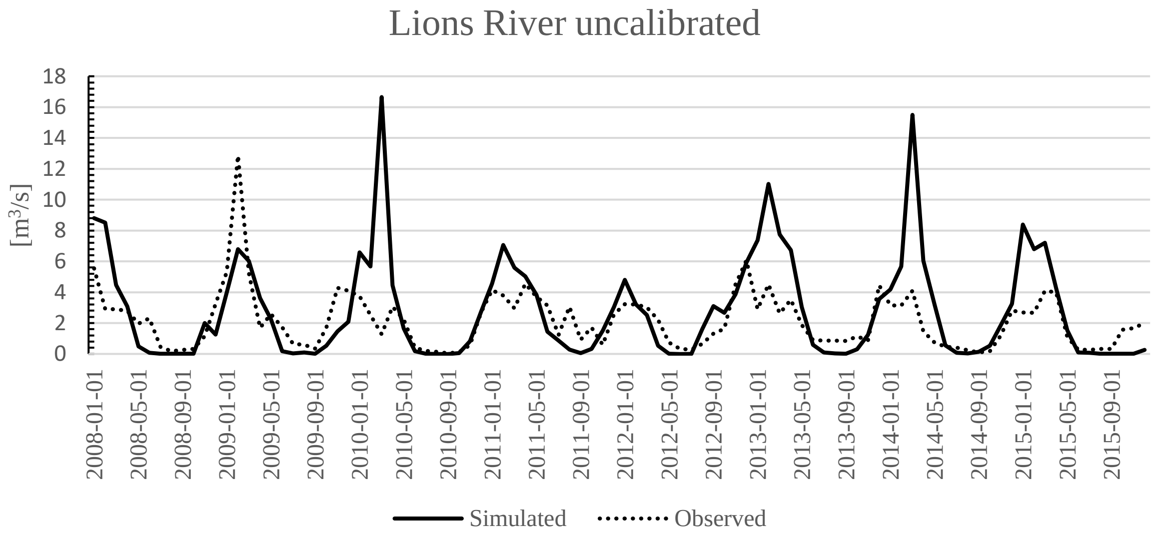




*Figure 10: Water flow comparison: simulated and observed waterflow at Karkloof and Lions River measuring stations, (Karkloof: $R^2$=0.62, NSE -0.1; Lions: $R^2$=0.55, NSE = -1.27).*

A Sensitivity analysis was made to determine which parameters to use in the model calibration (Table 15).

*Table 15: Sensitivity analysis results, uMgeni Catchment*

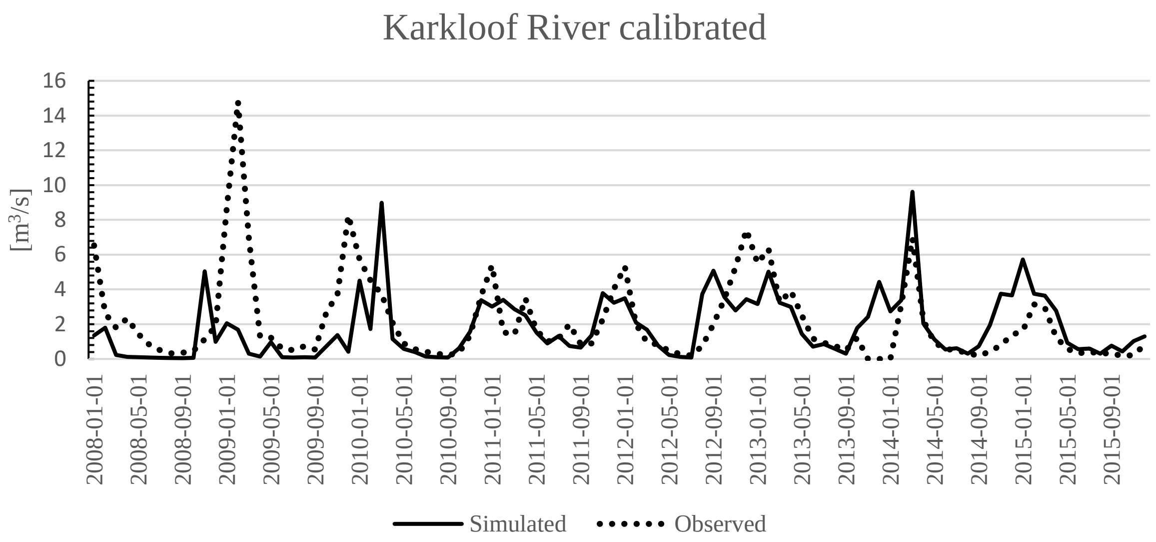
| Parameter | t-stat | p-value |
|---|---|---|
| ESCO | -3.22 | 0.01 |
| GW_DELAY | 2 | 0.07 |
| CN2 | 1.8 | 0.1 |
| SOL_K | 0.89 | 0.39 |
| SOL_AWC | -0.86 | 0.4 |
| ALPHA_BF | -0.73 | 0.48 |
| GW_REVAP | -0.65 | 0.53 |
| GWQMN | 0.27 | 0.78 |
| REVAPMN | -0.2 | 0.84 |

The six most sensitive parameters were used in a model calibration for Karkloof flow station during a four-year period from 2008-2011 (Table 16). The reason is that the calibrated model was afterwards validated by examining the flow correlations for the following four years 2012-2015. The SWAT-CUP calibration was run with 500 iterations.

*Table 16: SWAT-CUP calibrated parameters, uMgeni Catchment*

| Parameter Name | Method | Min | Max | Cup-values |
|---|---|---|---|---|
| ESCO | Relative | 0 | 1 | 0.69 |
| GW_DELAY | Replace | 30 | 450 | 355 |
| CN2 | Replace | -0.2 | 0.2 | 0.02 |
| SOL_K | Relative | -0.5 | 0.5 | -0.11 |
| SOL_AWC | Relative | -0.5 | 0.5 | 0.007 |
| ALPHA_BF | Replace | 0 | 1 | 0.122 |

The four-year calibration resulted in a $R^2$-value 0.34 and NSE-value -0.06 and the three-year validation in a $R^2$-value 0.59 and NSE-value -0.67. Due to the low NSE-value for the validated flow the decision was made to calibrate the model for eight years and validate with the resulting flows from Lions River measuring station (Figure 11). For the eight-year calibration of Karkloof, the $R^2$-value was 0.37 and the NSE value -0.01. For Lions River, the calibrated model gave the $R^2$-value of 0.31 and the NSE-value -0.44. The results show that the NSE-values improved with the model calibration (Table 17). However, the model performance is unsatisfactory, since NSE-values were below 0.5.



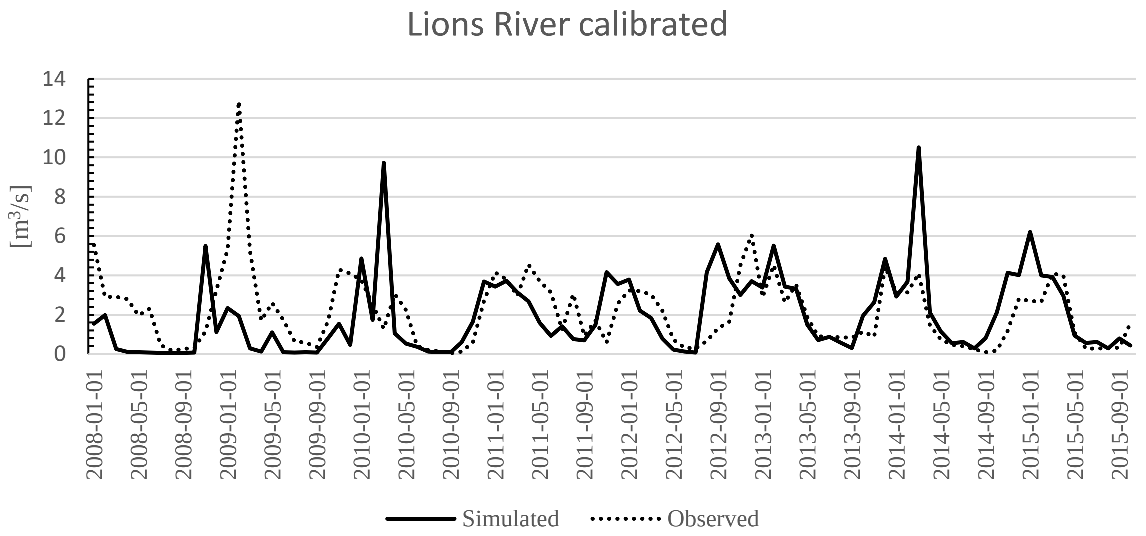




*Figure 11: Water flow comparison: calibrated and observed waterflow at Karkloof and Lions River measuring stations, (Karkloof: $R^2$=0.37, NSE=0.01; Lions: $R^2$=0.31, NSE=-0.44).*

*Table 17: $R^2$ and NSE-values for the uncalibrated and calibrated model, uMgeni Catchment*

| Measuring point | Uncalibrated | Calibrated | Uncalibrated | Calibrated |
|---|---|---|---|---|
| | R2 | R2 | NSE | NSE |
| Karkloof | 0.62 | 0.37 | -0.1 | 0.01 |
| Lions River | 0.55 | 0.31 | -1.27 | -0.44 |

# 3. Results

## 3.1 Lake Vomb

To study the microbial loads into Lake Vomb the three major river inlets were used as observation points. The sources of microbial contamination in Lake Vomb catchment are: OWTS discharge, animal grazing and manure application. The daily loads of *Cryptosporidium* and *E. coli* from Björkaån, Borstbäcken and Torpsbäcken outlets into Lake Vomb show peak values around $2.3 \cdot 10^{10}$, $3.2 \cdot 10^{9}$, $1.5 \cdot 10^{9}$ oocysts/day and $1.1 \cdot 10^{13}$, $1.5 \cdot 10^{12}$, $1.1 \cdot 10^{12}$ cfu/day respectively. The peak loads occur between October and February this is related to the manure application on October 15 and the high river flow, which was observed for the same period (Figure 12).

Björkaån outlet had the most influence on microbial loads entering Lake Vomb. Therefore, it was further investigated to examine the individual influence of livestock grazing, manure application and OWTS discharge. The daily loads of *Cryptosporidium* and *E. coli* from OWTS discharge, was simulated to have peak values of $10^4$ oocysts/day and $1.7 \cdot 10^9$ cfu/day. Moreover, for livestock grazing $9.3 \cdot 10^3$ oocysts/day and $1.4 \cdot 10^9$ cfu/day. In comparison with the total river load, OWTS discharge and livestock grazing contribute with less than 1%. The manure application practises are shown to have the biggest impact on the modelling results, representing over 99% of the microbial loads. The microbial loads are like the values observed in the scenario with all management practises included. The management operation graphs can be found in Appendix 4.

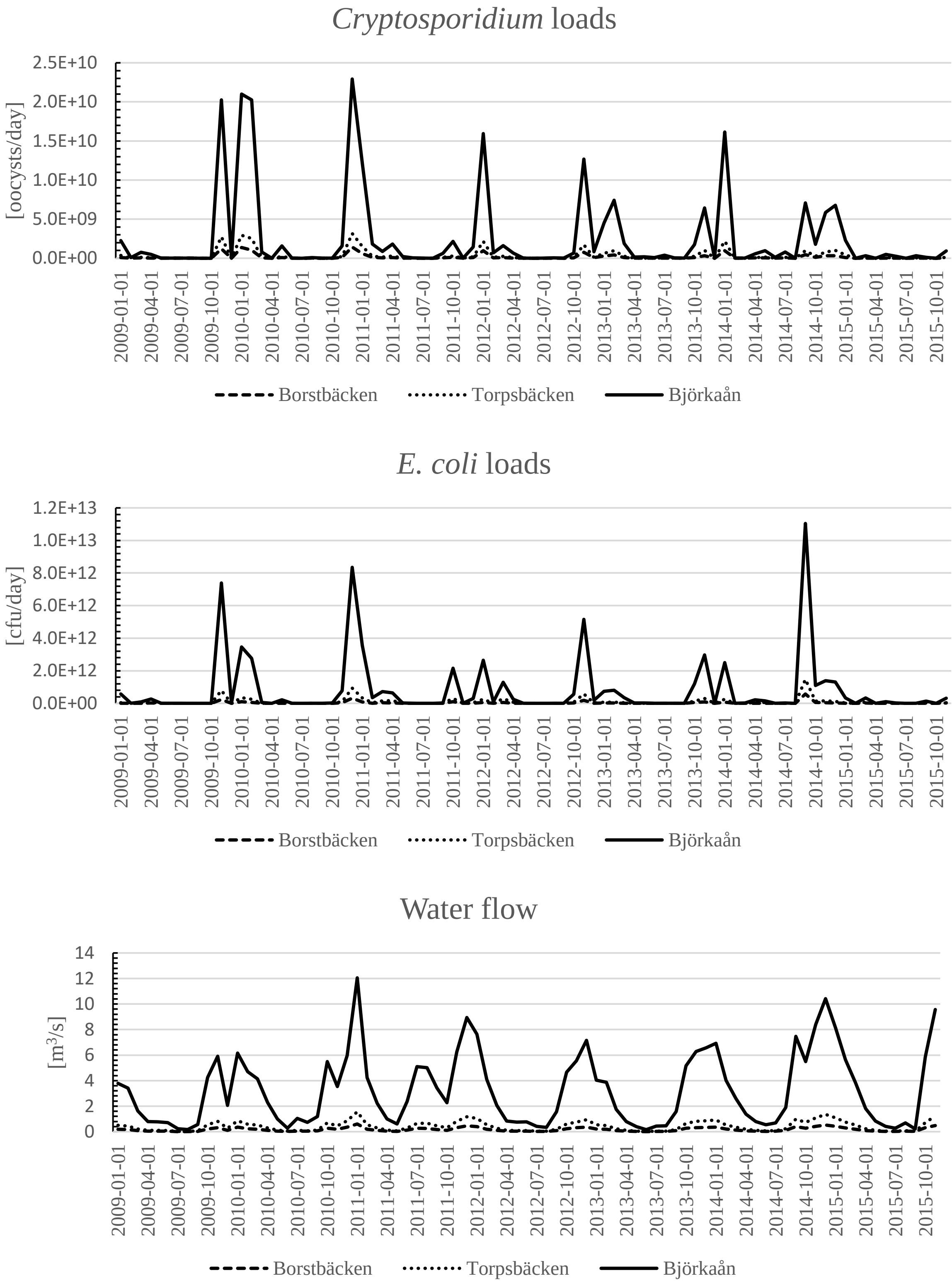



*Figure 12: Cryptosporidium and E. coli loads for Borstbäcken, Torpsbäcken and Björkaån along with their corresponding water flow.*

## 3.2 uMgeni Catchment

The model for the Umgeni catchment was not working well as the model validation yielded unsatisfactory results. Hence, the simulated microbial loads do not accurately represent reality. The choice of observation points had to be carefully selected for the uMgeni catchment scenario. The reason is that flows and contamination loads downstream the Midmar dam were not accurate since the dam was modelled as a river. In reality, the Midmar dam has a controlled outflow, which is currently closed due to draught. Therefore, the three observation points were chosen in areas either upstream the Midmar dam or in areas unaffected by its outlet flows. Two observation points were chosen to study the loads entering the Midmar dam.

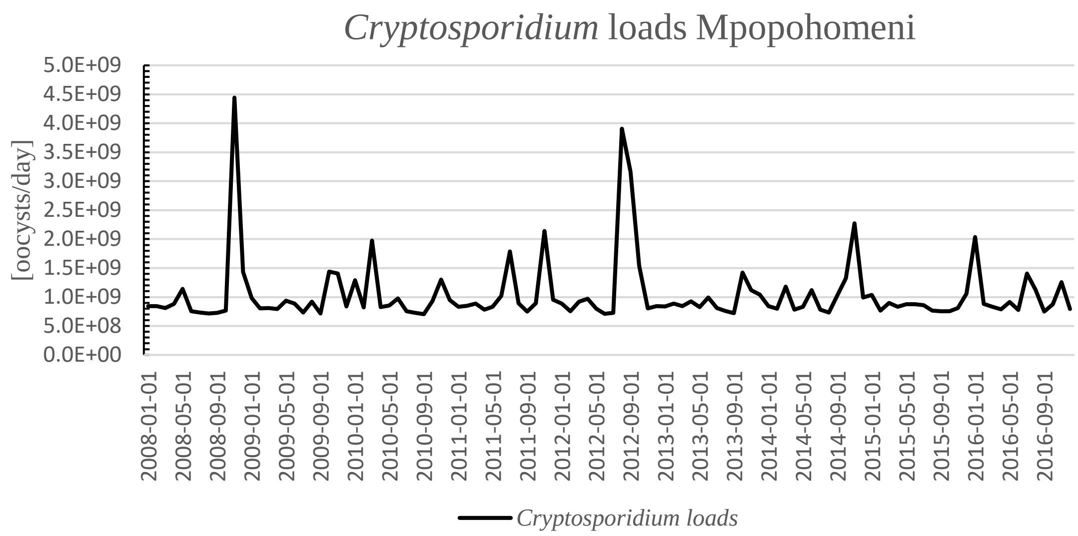
The first observation point was the uMgeni river outlet. The rivers Lions and Mpofana run through the north-western parts of the catchment area and merge with the uMgeni river before flowing into the Midmar dam. Hence, loads from the uMgeni river outlet represent a substantial portion of the catchment.

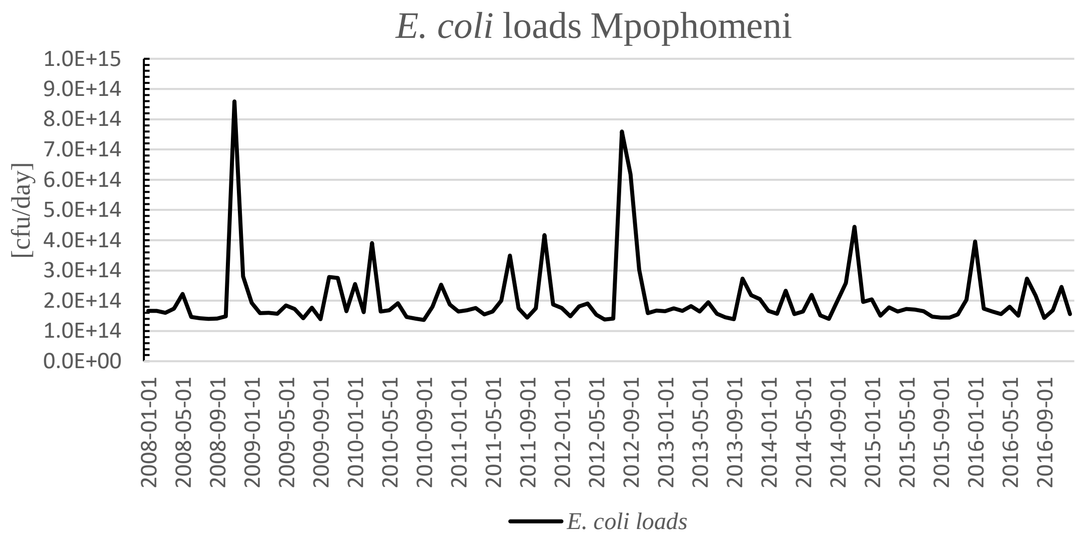
The second observation point was at the wastewater outlet point from Mpophomeni, which was chosen to study the microbial contamination from the failed WWTP.

The third observation point was the southmost point of the Karkloof river, before it merges with the uMgeni river and flows into the Albert falls dam. The Karkloof river starts in the north-eastern part of the catchment and combines with nearby rivers before flowing south; this made it a suitable river to study for the contamination loads from the north-eastern parts of the catchment.

Microbial concentration was studied and compared to observe trends and patterns. However, since the point of interest was to study the impact on water quality in the Midmar and the Alber falls dam results are presented in microbial loads/day as it more accurately indicates the impact on water quality in the two dams.

From Mpophomeni WWTP the daily loads of *Cryptosporidium* showed peak values of $4.5 \cdot 10^{9}$ oocysts/day and *E. coli* loads peak values of $8.5 \cdot 10^{14}$ (Figure 13). Moreover, the loads do not correlate to river flow patterns since, a steady stream of contaminants are released from the WWTP.



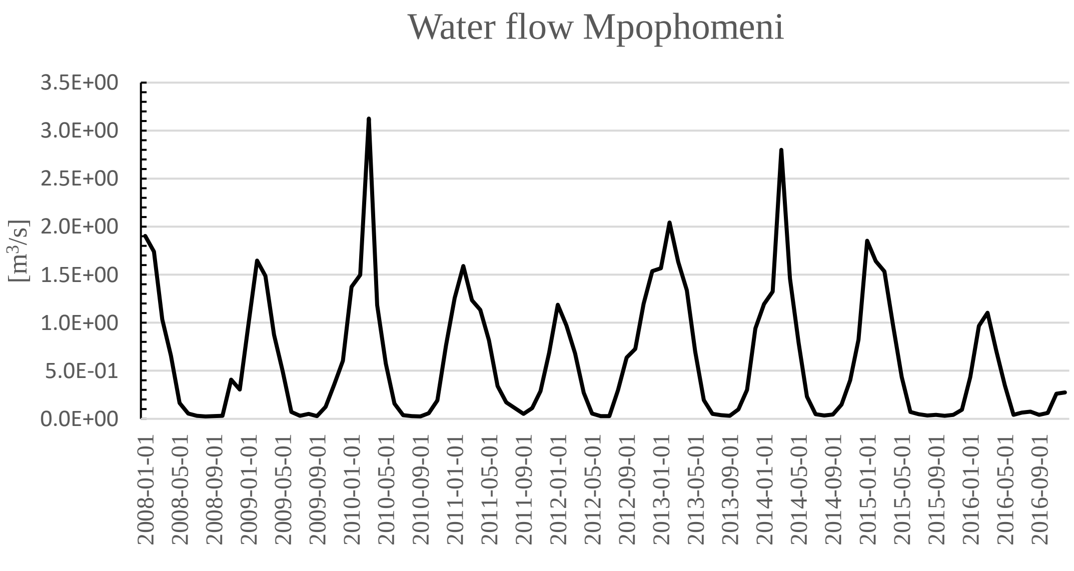




*Figure 13: Cryptosporidium and E. coli loads from the failed WWTP in Mpophomeni along with the water flow in the outlet stream.*

The simulated microbial loads at the Umgeni and Karkloof river observation points were influenced by livestock grazing and OWTS discharge only. The uMgeni river carries contamination from the western part of the catchment and the Karkloof river outlet - from the eastern parts. The daily loads of *Cryptosporidium* from the Umgeni river show peak values of $3.7 \cdot 10^4$ oocysts/day and from the Karkloof river $1.7 \cdot 10^4$ oocysts/day. The daily loads of *E. coli* from the Umgeni river show peak values of $4 \cdot 10^9$ cfu/day and from the Karkloof river $2 \cdot 10^9$ cfu/day. Furthermore, microbial loads in the two rivers correlate to the water flow pattern and since the uMgeni river has a higher water flow it carries a higher load (Figure 14).

Further analysis was conducted to examine the individual influence of livestock grazing and OWTS discharge on the microbial loads from the uMgeni and Karkloof river. The result showed that livestock grazing had no influence on the microbial loads, hence the simulated loads from uMgeni and Karkloof river originates from OWTS discharge.

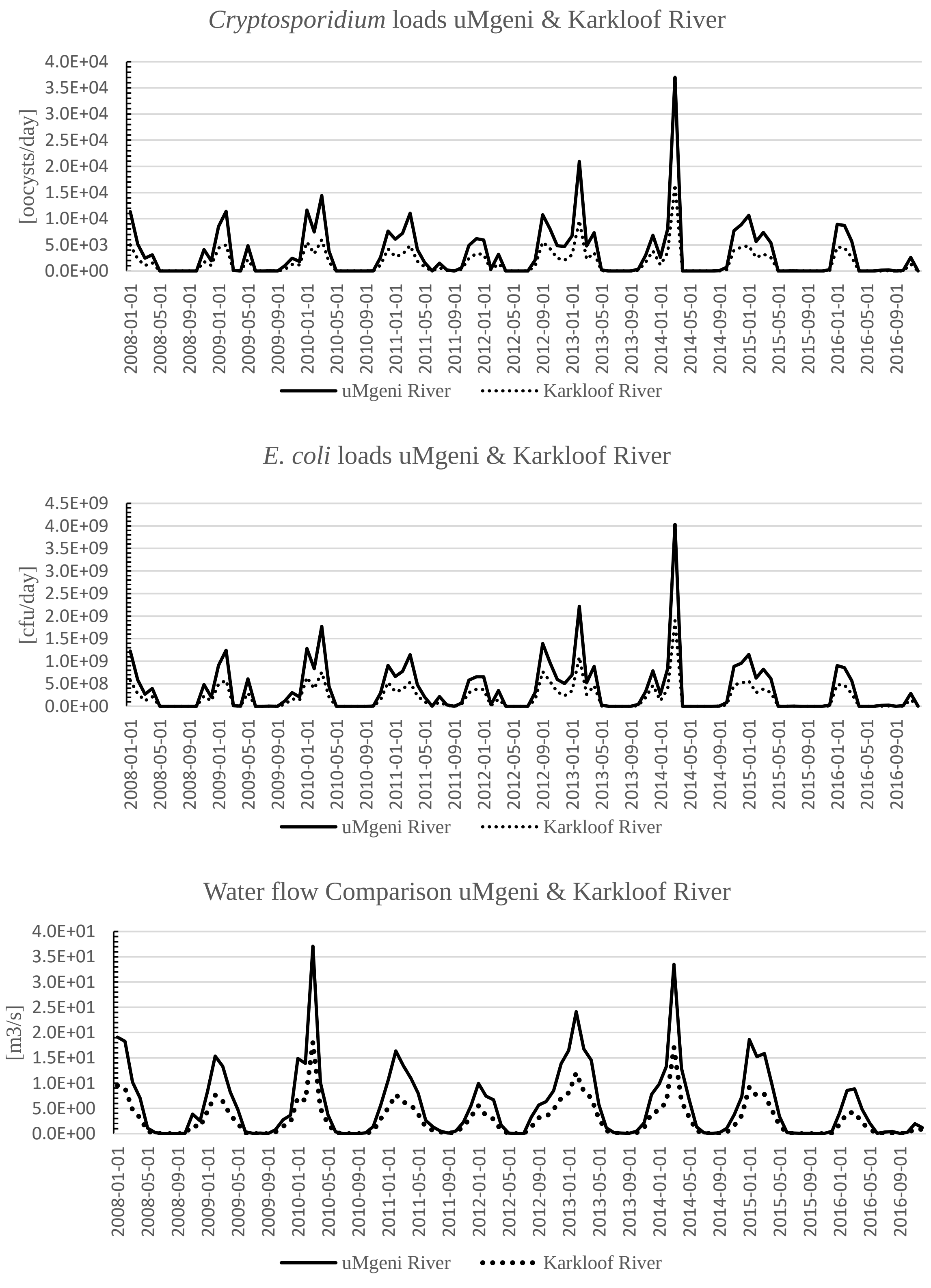



*Figure 13: Cryptosporidium and E. coli loads from uMgeni and Karkool River along with their corresponding water flow.*

# 4. Discussion

Two SWAT models were set up, calibrated, and successfully run with the aim to study the *E. coli* and *Cryptosporidium* loads in selected measuring points. The purpose of the project was to identify and quantify pollution sources so that mitigation measures can be implemented. Also, modelling using SWAT adds to the research concerning the software applicability and limitations in different types of study areas. Many simplifications, generalisations and assumptions had to be made during the model creation as SWAT requires specific input data and data format. Moreover, the project time was limited to five months and no on-site measurements were made, which made it necessary to use data from previous studies and literature.

The map layers used were mostly found on different government websites and were freely available. However, in South Africa much of the data received from government agencies had to be requested using data application forms or received from personal contacts with university and government personnel. Besides knowledge of SWAT, the completion of the project required GIS knowledge, as map layer editing using the geoprocessing and conversation tool box was an essential part. Furthermore, much data preparation and reformatting was made in Microsoft Excel, especially in the creation of meteorological data files.

## 4.1 Model simplifications and uncertainties

The modelling of lakes and dams can be performed in SWAT in one of two ways. It can be done by creating a reservoir with the same area as the modelled water body. Using a reservoir to model a lake is a simplified representation. The reservoir has a constant depth, hence varying lake bathymetry is not included, also the outline, which may include peninsulas or bays that may trap contaminants in the lake are neglected. The other way is to model the lake as a river, which will have a conjunction point for all the lakes inlet rivers. This method saves time and is suited if flow and contaminant loadings into lake are to be studied. However, it will not correctly model the flows downstream the waterbody and neither, will it correctly model the fate and transport of contaminants in the lake. Since both methods misrepresent the hydrodynamic properties of a lake (Åström & Johansson, 2015), the flow and microbial data extracted from the lake inlet points are better suited to be used in a hydrodynamic modelling tool, like MIKE 3, if a lake is to be studied in more detail.

SWAT includes predefined land use and soil classes, which are used when creating HRU definitions. However, since the software is U.S. made the definitions do not always correlate to soil and land use practices used in other parts of the world. Regarding land use, the biggest issue lies in finding the best way to reclassify and group land uses. For example, the downloaded land use map layer used in the uMgeni catchment contained over 100 different land uses, where some categories only have a slight difference. Consequently, to simplify the model and to get a more presentable land use division, similar areas are grouped together. The assigned land use class directly affects run off, furthermore it also affects the distribution area and location of management practices such as manure application, OWTS discharge and livestock grazing.

Defining the OWTS locations was made in different ways for the two study areas. For Lake Vomb a map containing locations of private properties was edited to approximate the locations the OWTSs in the catchment based on municipality data. In the uMgeni catchment, no such map existed, hence the same method could not be applied. Instead, a map containing all villages and towns in the area was used, through assigning one large OWTS for the entire population of each area. This method has its downfalls as it simplifies the spread of contaminants, which lead to misrepresentation of microbial concentrations.

The soil map classification was also created differently in the two study areas. For Lake Vomb study area, similarities between U.S. and Swedish soils made it possible to use the pre-defined SWAT database soil types to represent the different soils in the area. However, for the South African study area, the soil characteristics differed from the pre-defined SWAT soils; this made it necessary to create custom-made soil layers in the SWAT database. Hydrological parameters, such as hydraulic conductivity, wilting point, filed capacity, available water etc., were determined using literature and other soil characterizing software. The predefined SWAT soils include data for four layers of soil, but due to lacking data only a one meter deep layer was defined in the South African soils, which was less than the depth of the pre-defined soils. Furthermore, the used soil map included coarse data and unspecific soil descriptions, this created uncertainties about the soil parameters. This may have influenced the simulated river flows and microbial concentrations, both in the peak values and their date of occurrence. For example, the uMgungundlovu biodiversity sector plan (KZNWildlife, 2017), states that 50 % of the *E. coli* loads into the Midmar dam originates from the failed WWTP in Mpophomeni. However, the simulated results regarding *E. coli* loads into the Midmar dam show that more than 99% originate from Mpophomeni.

The occurrence of wetlands influences flow and die-off of microbial organisms. The stream, which transfers pollutants from Mpophomeni WWTP, passes through a wetland before entering the Midmar dam. This was not accounted in the model, since SWAT requires that point source discharges are entered directly in to a stream. The consequence of this is that both the flow and the microbial concentrations entering the Midmar dam from Mpophomeni WWTP are overestimated. Data over how much the wetland influences flow and microbial concentrations could have been studied if field sampling had been made. However, this was not involved in the scope of the project and no previous studies of the subject had been made in the study area. A study made by the University of California showed that depending on the characteristics and size of a wetland, it can remove up to 90% of the incoming *E. coli* loads (O'geen & Bianchi, 2015).

Two livestock management operations were used in the project: livestock grazing and manure application to agricultural land. The foundation for these two scenarios were defining the microbial content of livestock faeces. No site-specific data were used in any of the two study areas, because there was no information available about local measurements. This is not an ideal approach to modelling, as factors like *Cryptosporidium* prevalence and excretion amounts vary between different livestock herds, hence variations are likely to occur between the two study areas.

There were no land use maps available which included a pre-defined grazing area in the uMgeni catchment study area. This made it necessary to manually reclassify suitable areas. Grassland and shrublands were considered as suitable grazing areas. However, due to a large area defined as grassland, which would lead to a very low livestock density, shrublands were used. They had a smaller area and were situated closer to the rivers. However, if a correct area definition is to be made, it is necessary to do an in-depth study on a local level; this would include communication with farmers to receive more information about livestock grazing.

For both study areas, land use maps included information about agricultural land, which made it simple to define manure application locations. However, there were uncertainties concerning the manure application dates and frequency. No information was found about the exact dates and amounts of manure that was applied. Therefore, the assumptions were made that the manure was applied on two specific dates and evenly distributed over all agricultural land in the model. It is not realistic that all manure is applied instantly in the entire catchment. The effects of this assumption are that peak values that were observed when high river flow coincided with the manure application dates were overestimated.

The main driving force in the hydrological model is the meteorological data, especially precipitation. Observed rain data from one measuring station was used in both study areas. In Lake Vomb catchment, the station was centrally located, hence river flows were accurately simulated; this can be seen by the satisfactory $R^2$ and NSE-values. However, in the uMgeni catchment, the flow calibration resulted in unsatisfactory NSE-values. The most probable reason behind this was the location of the rain measuring station and the size of the catchment. In comparison, the uMgeni catchment had approximately a three times larger area and the rain station was situated on the south-eastern edge of the catchment. Therefore, the used precipitation data do not accurately represent the entire area, which in turn led to an inaccurate hydrological model.

## 4.2 Microbial loads

In general, the highest microbial loads from land use practises occurred during seasons with high river flows which for both study areas occurred during fall to early spring. This scenario agrees with work by Coffey, et al. (2009), which indicated that the late autumn/winter and early spring were the highest risk periods. In the lake Vomb catchment, notable peak values correlating with the manure application dates could also be observed.

For the Lake Vomb catchment the results show that manure application was the main contamination source, contributing with *Cryptosporidium* loads up to $2 \cdot 10^{10}$ oocysts/day and *E. coli* loads up to $10^{13}$ cfu/day from Björkaån; this corresponds to a *Cryptosporidium* concentration of 5 oocysts/100 ml and a *E. coli* concentration of 1600 cfu/100 ml. The Swedish guideline values for bathing quality is 1000 *E. coli*/100 ml (Swedish Agency for Marine and Water Management, 2013), which makes the simulated values high. However, the microbial concentrations in Lake Vomb will probably be lower than that in the studied rivers, since dilution and sedimentation of microbial organisms will occur. Mitigation measures that might improve water quality include: constructed wetlands along the river banks to reduce the impact of run-off and using inorganic fertilisers instead of manure on agricultural land.

For the uMgeni catchment, the results show that the failed WWTP in Mpophomeni was the main contamination source, contributing with *Cryptosporidium* loads up to $4.5 \cdot 10^9$ oocysts/day and *E. coli* loads up to $8 \cdot 10^{14}$ cfu/day; this corresponds to a *Cryptosporidium* concentration of 30 oocyst/100 ml and a *E. coli* concentration of 35 000 cfu/100 ml during low river flows. As discussed above, the microbial concentration from the WWTP will probably be reduced before entering the Midmar dam, since the contaminated stream runs through a wetland. The mitigation measure most suitable for the uMgeni catchment is to improve the failed WWTP. The impact of OWTS discharge and livestock grazing needs further investigation due to model uncertainties such as, hydraulic parameters for soil and OWTS and grazing locations.

## 4.3 Further research

Data quality improvement is essential to increase the model performance. For the Lake Vomb catchment, the focus should be on improving the microbial sub-model. This would include: an in-depth study of *Cryptosporidium* prevalence in livestock, a complete identification of OWTS locations and their reduction of microbial organisms, and a quantification of used manure for agricultural fertilisation along with specific dates of application. For the uMgeni catchment, improvements must be made on the hydrological model. This would include: in-situ testing of soil parameters and adding more precipitation measuring stations in the area. A starting point could be to model a smaller part of the catchment using more detailed data and including field measurements into the project scope. Muirhead, et al. (2006) and Mawdsley, et al. (1995) conclude in their studies that runoff events and the soil saturation in combination with the land use applications may have a significant impact on the microbial transport.

# 5. Conclusions

The aims of this study were to apply the Soil and Water Assessment Tool to set up the hydrological models for the Lake Vomb and uMgeni catchments, in order to quantify the peak loads of *Cryptosporidium* and *E. coli* and their frequency by simulating different land use practices affecting the water quality in these catchments.

Arc SWAT requires a wide range of input data that span over many scientific fields. The model user should have a background in Geographical Information System (GIS), which is needed to adjust, simplify and classify the input data required by SWAT. The user should fully understand the geological properties and their impacts on the hydrological and microbial models. Moreover, the user should have enough knowledge of microorganisms and their behaviour, to be able to understand how the input parameters impact the microbial sub-model simulations. SWAT can be a suitable tool in variety of catchments for many management operations. However, detailed information is necessary to create models with a satisfactory result.

Hydrological modelling of Lake Vomb showed satisfactory $R^2$ and NSE values, which indicated that the model was suitable for further analysis. The simulated microbial loads showed that the manure application had the most impact on the overall water quality; this indicates that proper manure application management is required to reduce microbial contamination. The modelling results regarding the microbial loads produced by livestock grazing in the catchment were uncertain. The microbial simulation showed occurrence of peak load values outside the operations dates, instead the pattern corresponded to the water flow. This indicates that the model does not properly simulate contamination events that are not related to runoff, such as time-based operations. In general, the microbial sub-model results show high level of uncertainty in simulating several management operations, therefore observed microbial data are needed to validate the accuracy of the model performance.

Hydrological modelling of the uMgeni catchment resulted in poor performance, where both $R^2$ and NSE values were unsatisfactory. The microbial sub-model results showed that the failed WWTP in Mpophomeni was the largest microbial contamination source to the Midmar dam, while livestock grazing and OWTS discharge had less impact. However, due to the low model performance of the hydrological model, the impacts of grazing and OWTS discharge are uncertain. The model predictions for the uMgeni catchment could be improved if more input data and information were available. Specifically, precipitation data, the spatial distribution of OWTS, information on grazing areas for livestock and soil hydraulic parameters would enhance the model performance. Also, if more observed data of water flow and microbial concentrations in rivers were available, the model results could be calibrated to a greater degree of accuracy.

The results indicate that SWAT can simulate microbial transport in catchments as well as identify high-risk periods and estimate peak loads of microorganisms such as *E. coli* and *Cryptosporidium.* Output data from an improved SWAT model together with microbial source tracking could be used as input data for hydrodynamic modelling of the two drinking water sources and to conduct Qualitative Microbial Risk Assessment (QMRA). This would make it possible to create water source protection strategies and mitigation measures with the goal to provide safe drinking water and protect human health.

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# 7. Appendix I

## SWAT soil parameter classification

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| OBJECTID | | | | 203 | | | | |
| MUID | | | | VT099 | | | | |
| SEQN | 1 | 2 | 1 | 2 | 3 | 4 | 1 | 2 |
| SNAM | Dystric N | Associated | Dystric W | Asso 1 | Asso 2 | Asso 3 | Dystric E | Associated |
| S5ID | MN0001 | MN0001 | MN0001 | MN0001 | MN0001 | MN0001 | MN0001 | MN0001 |
| CMPPCT | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NLAYERS | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| HYDGRP | A | C | A | D | B | A | A | D |
| SOL_ZMX | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| ANION_EXCL | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| SOL_CRK | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| TEXTURE | Sandy Loam | Sandy Clay Loam | Sandy Loam | Clay Loam | Loam | Sandy Loam | Sandy Loam | Clay Light |
| SOL_Z1 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| SOL_BD1 | 1.46 | 1.41 | 1.46 | 1.33 | 1.42 | 1.46 | 1.46 | 1.27 |
| SOL_AWC1 | | 0.11 | | 0.11 | | 0.11 | | |
| SOL_K1 | | 25 | | 25 | | 25 | | |
| SOL_CBN1 | 0.95 | 0.8 | 0.95 | 1.75 | 0.61 | 0.95 | 0.95 | 1.19 |
| CLAY1 | 17 | 24 | 17 | 31 | 21 | 17 | 17 | 47 |
| SILT1 | 25 | 19 | 25 | 35 | 28 | 25 | 25 | 16 |
| SAND1 | 58 | 57 | 58 | 34 | 51 | 58 | 58 | 37 |
| ROCK1 | 30 | 1 | 30 | 1 | 1 | 30 | 30 | 1 |
| SOL_ALB1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| USLE_K1 | | 0.22 | | 0.25 | | 0.37 | | |
| SOL_EC1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z2 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| TEXTURE2 | Sandy Loam | Sandy Clay | Sandy Loam | Clay Loam | Clay Loam | Sandy Loam | Sandy loam | Clay Light |
| SOL_BD2 | 1.5 | 1.34 | 1.5 | 1.34 | 1.37 | 1.5 | 1.5 | 1.24 |
| SOL_AWC2 | | 0.096 | | 0.096 | | 0.096 | | |
| SOL_K2 | | 36 | | 36 | | 36 | | |
| SOL_CBN2 | 0.3 | 0.36 | 0.3 | 0.66 | 0.26 | 0.3 | 0.3 | 0.49 |
| CLAY2 | 14 | 35 | 14 | 29 | 34 | 14 | 14 | 54 |
| SILT2 | 21 | 17 | 21 | 35 | 23 | 21 | 21 | 14 |
| SAND2 | 65 | 48 | 65 | 36 | 43 | 65 | 65 | 32 |
| ROCK2 | 30 | 1 | 30 | 1 | 1 | 30 | 30 | 1 |
| SOL_ALB2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| USLE_K2 | | 0.22 | | 0.25 | | 0.37 | | |
| SOL_EC2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| OBJECTID | 204 | | | | OBJECTID | 205 | | | |
| MUID | VT099 | | | | MUID | VT099 | | | |
| SEQN | 1 | 2 | 3 | 4 | 5 | SEQN | 1 | 2 | 3 |
| SNAM | Ferric Luvisols | Assoc 1 | Assoc 2 | Assoc 3 | Assoc 4 | SNAM | Haplic Luvisols | Assoc 1 | Assoc 2 |
| S5ID | MN9028 | MN9028 | MN9028 | MN9028 | MN9028 | S5ID | MN0029 | MN0029 | MN0029 |
| CMPPCT | 0 | 0 | 0 | 0 | 0 | CMPPCT | 0 | 0 | 0 |
| NLAYERS | 2 | 2 | 2 | 2 | NLAYERS | 2 | 2 | 2 | |
| HYDGRP | A | A | A | C | B | HYDGRP | C | A | B |
| SOL_ZMX | 100 | 100 | 100 | 100 | 100 | SOL_ZMX | 100 | 100 | 100 |
| ANION_EXCL | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | ANION_EXCL | 0.5 | 0.5 | 0.5 |
| SOL_CRK | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | SOL_CRK | 0.5 | 0.5 | 0.5 |
| TEXTURE | Sandy Loam | Sandy Loam | Sandy Loam | Sandy Clay Loam | Loam | TEXTURE | Sandy Clay Loam | Sandy Loam | Loam |
| SOL_Z1 | 30 | 30 | 30 | 30 | 30 | SOL_Z1 | 30 | 30 | 30 |
| SOL_BD1 | 1.47 | 1.46 | 1.47 | 1.41 | 1.42 | SOL_BD1 | 1.42 | 1.46 | 1.42 |
| SOL_AWC1 | 0.094 | | | | SOL_AWC1 | 0.11 | | | |
| SOL_K1 | 27 | | | | SOL_K1 | 16.5 | | | |
| SOL_CBN1 | 0.6 | 0.95 | 0.56 | 0.8 | 0.61 | SOL_CBN1 | 0.6 | 0.95 | 0.61 |
| CLAY1 | 17 | 17 | 17 | 24 | 21 | CLAY1 | 21 | 17 | 21 |
| SILT1 | 18 | 25 | 18 | 19 | 28 | SILT1 | 25 | 25 | 28 |
| SAND1 | 65 | 58 | 65 | 57 | 51 | SAND1 | 54 | 58 | 51 |
| ROCK1 | 1 | 30 | 1 | 1 | 1 | ROCK1 | 1 | 30 | 1 |
| SOL_ALB1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | SOL_ALB1 | 0.01 | 0.01 | 0.01 |
| USLE_K1 | 0.23 | | | | USLE_K1 | 0.35 | | | |
| SOL_EC1 | 0 | 0 | 0 | 0 | 0 | SOL_EC1 | 0 | 0 | 0 |
| SOL_Z2 | 100 | 100 | 100 | 100 | 100 | SOL_Z2 | 100 | 100 | 100 |
| TEXTURE2 | Sandy Clay Loam | Sandy Loam | Sa ndy Loam | Sandy Clay Loam | ClayLoam | TEXTURE2 | Sandy Clay Loam | Sandy Loam | Caly loam |
| SOL_BD2 | 1.37 | 1.5 | 1.37 | 1.34 | 1.33 | SOL_BD2 | 1.38 | 1.5 | 1.33 |
| SOL_AWC2 | 0.11 | | | | SOL_AWC2 | 0.12 | | | |
| SOL_K2 | 6.1 | | | | SOL_K2 | 8.6 | | | |
| SOL_CBN2 | 0.33 | 0.3 | 0.21 | 0.36 | 0.26 | SOL_CBN2 | 0.26 | 0.3 | 0.26 |
| CLAY2 | 30 | 14 | 29 | 35 | 34 | CLAY2 | 27 | 14 | 34 |
| SILT2 | 17 | 21 | 17 | 17 | 23 | SILT2 | 24 | 21 | 23 |
| SAND2 | 53 | 65 | 54 | 48 | 43 | SAND2 | 49 | 65 | 43 |
| ROCK2 | 1 | 30 | 1 | 1 | 1 | ROCK2 | 1 | 30 | 1 |
| SOL_ALB2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | SOL_ALB2 | 0.01 | 0.01 | 0.01 |
| USLE_K2 | 0.23 | | | | USLE_K2 | 0.35 | | | |
| SOL_EC2 | 0 | 0 | 0 | 0 | 0 | SOL_EC2 | 0 | 0 | 0 |

| OBJECTID | | | | 206 | | | |
|---|---|---|---|---|---|---|---|
| MUID | | | | VT099 | | | |
| SEQN | 1 | 2 | 1 | 2 | 1 | 2 | 4 |
| SNAM | Rhodic A_M | Assoc 1 | Rhodic A_EAST | Assoc 1 | Rhodic A_WEST | Assoc 1 | Assoc 3 |
| S5ID | MN0054 | MN0054 | MN0054 | MN0054 | MN0054 | MN0054 | MN0054 |
| CMPPCT | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NLAYERS | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| HYDGRP | C | A | C | C | C | A | D |
| SOL_ZMX | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| ANION_EXCL | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| SOL_CRK | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| TEXTURE | Sandy Clay Loam | Sandy Loam | Sandy Clay Loam | Sandy Clay Loam | Sandy Clay Loam | Sandy Loam | Clay loam |
| SOL_Z1 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| SOL_BD1 | 1.41 | 1.46 | 1.41 | 1.41 | 1.41 | 1.46 | 1.35 |
| SOL_AWC1 | | 0.1 | | 0.1 | | 0.1 | |
| SOL_K1 | | 12 | | 12 | | 12 | |
| SOL_CBN1 | 0.8 | 0.95 | 0.8 | 0.8 | 0.8 | 0.95 | 0.93 |
| CLAY1 | 24 | 17 | 24 | 24 | 24 | 17 | 29 |
| SILT1 | 19 | 25 | 19 | 19 | 19 | 25 | 31 |
| SAND1 | 57 | 58 | 57 | 57 | 57 | 58 | 40 |
| ROCK1 | 1 | 30 | 1 | 1 | 1 | 30 | 30 |
| SOL_ALB1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| USLE_K1 | | 0.23 | | 0.15 | | 0.23 | |
| SOL_EC1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| SOL_Z2 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| TEXTURE2 | Sandy Clay | Sandy Loam | Sandy Clay | Sandy Clay | Sandy Clay | Sandy Loam | Clay Loam |
| SOL_BD2 | 1.34 | 1.5 | 1.4 | 1.4 | 1.34 | 1.5 | 1.31 |
| SOL_AWC2 | | 0.12 | | 0.12 | | 0.12 | |
| SOL_K2 | | 3.3 | | 3.3 | | 3.3 | |
| SOL_CBN2 | 0.36 | 0.3 | 0.36 | 0.36 | 0.36 | 0.3 | 0.33 |
| CLAY2 | 35 | 14 | 35 | 35 | 35 | 14 | 35 |
| SILT2 | 17 | 21 | 17 | 17 | 17 | 21 | 28 |
| SAND2 | 48 | 65 | 48 | 48 | 48 | 65 | 37 |
| ROCK2 | 1 | 30 | 1 | 1 | 1 | 30 | 1 |
| SOL_ALB2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| USLE_K2 | | 0.23 | | 0.15 | | 0.23 | |
| SOL_EC2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| OBJECTID | | | OBJECTID | | | 208 | | |
| MUID | | VT099 | | MUID | | VT099 | | |
| SEQN | 1 | 2 | 3 | 4 | 1 | SEQN | 1 | 2 |
| SNAM | RhodicF_ ML | Assoc 1 | Assoc 2 | Assoc 3 | RhodicF_ East | SNAM | Xhantic | Assoc 1 |
| S5ID | MN0095 | MN0095 | MN0095 | MN0095 | MN0095 | S5ID | MN0094 | MN0094 |
| CMPPCT | 0 | 0 | 0 | 0 | 0 | CMPPCT | 0 | 0 |
| NLAYERS | 2 | 2 | 2 | 2 | 2 | NLAYERS | | |
| HYDGRP | C | A | D | A | D | HYDGRP | D | A |
| SOL_ZMX | 100 | 100 | 100 | 100 | 100 | SOL_ZMX | 100 | 100 |
| ANION_EXCL | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | ANION_EXCL | 0.5 | 0.5 |
| SOL_CRK | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | SOL_CRK | 0.5 | 0.5 |
| TEXTURE | Sandy Clay loam | Sandy Loam | Clay Light | Sandy Loam | Clay Light | TEXTURE | Sandy Clay | Sandy Loam |
| SOL_Z1 | 30 | 30 | 30 | 30 | 30 | SOL_Z1 | 30 | 30 |
| SOL_BD1 | 1.46 | 1.46 | 1.27 | 1.46 | 1.27 | SOL_BD1 | 1.35 | 1.53 |
| SOL_AWC1 | | 0.1 | | 0.12 | | SOL_AWC1 | 0.1 | |
| SOL_K1 | | 1.8 | | 0.5 | | SOL_K1 | 2.3 | |
| SOL_CBN 1 | 1.36 | 0.95 | 1.19 | 0.95 | 1.19 | SOL_CBN 1 | 0.95 | 0.45 |
| CLAY1 | 21 | 17 | 47 | 17 | 47 | CLAY1 | 35 | 12 |
| SILT1 | 5 | 25 | 16 | 25 | 16 | SILT1 | 11 | 19 |
| SAND1 | 74 | 58 | 37 | 58 | 37 | SAND1 | 54 | 69 |
| ROCK1 | 0 | 30 | 1 | 30 | 1 | ROCK1 | 1 | 30 |
| SOL_ALB 1 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | SOL_ALB 1 | 0.01 | 0.01 |
| USLE_K1 | | 0.19 | | 0.31 | | USLE_K1 | 0.17 | |
| SOL_EC1 | 0 | 0 | 0 | 0 | 0 | SOL_EC1 | 0 | 0 |
| SOL_Z2 | 100 | 100 | 100 | 100 | 100 | SOL_Z2 | 100 | 100 |
| TEXTURE 2 | Caly Light | Sandy Loam | Caly Light | Sandy Loam | Clay Light | TEXTURE 2 | Sandy Clay | Sandy Loam |
| SOL_BD2 | 1.24 | 1.5 | 1.24 | 1.5 | 1.34 | SOL_BD2 | 1.3 | 1.52 |
| SOL_AWC2 | | 12.3 | | 12.3 | | SOL_AWC2 | 0.11 | |
| SOL_K2 | | 0.25 | | 0.25 | | SOL_K2 | 0.5 | |
| SOL_CBN 2 | 0.49 | 0.3 | 0.49 | 0.3 | 0.49 | SOL_CBN 2 | 0.39 | 0.21 |
| CLAY2 | 54 | 14 | 54 | 14 | 54 | CLAY2 | 44 | 13 |
| SILT2 | 14 | 21 | 14 | 21 | 14 | SILT2 | 9 | 17 |
| SAND2 | 32 | 65 | 32 | 65 | 32 | SAND2 | 47 | 70 |
| ROCK2 | 1 | 30 | 1 | 30 | 1 | ROCK2 | 1 | 30 |
| SOL_ALB 2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | SOL_ALB 2 | 0.01 | 0.01 |
| USLE_K2 | | 0.19 | | 0.31 | | USLE_K2 | 0.17 | |
| SOL_EC2 | 0 | 0 | 0 | 0 | 0 | SOL_EC2 | 0 | 0 |

# 8. Appendix II

Hydrological parameter definitions

***CN2***: Curve number
Directly impacts the surface runoff, however as the surface runoff changes, all components of hydrology balance change. Soil erosion and nutrients transport are also directly impacts by surface runoff, as plant growth and nutrient cycling.
This is the reason behind starting with the hydrology balance, then move to sediment and finally calibrate nutrients and pesticides (Arnold & Kiniry, 2012).

***ESCO***: Soil evaporation compensation factor.
Used to allow the user to modify the depth distribution used to meet the soil evaporative demand to account for the effect of capillary action, crusting and cracks. ESCO must be between 0.01 and 1, as the value is reduced, the model can extract more of the evaporation demand for lower levels.

***Alpha_BF:*** Baseflow alpha factor (1/day), the baseflow recession constant $\alpha_{gw,}$ is a direct index of groundwater flow response to changes in recharge. Values vary from (0.1-0.3) for slow land response to recharge TO (0.9-1) for land with rapid response (Arnold & Kiniry, 2012).

***GW_REVAP:*** Groundwater "REVAP" coefficient. Water may move from the shallow aquifer into the overlying unsaturated zone. In periods when the material overlying the aquifer is dry, water in the capillary fringe that separate the saturated and the unsaturated zones will evaporate and diffuse upwards. As GW_REVAP approaches 0, movement of water from the shallow to the root zone is restricted. As the GW_REVAP approaches 1, the rate of transfer from the shallow aquifer to the root zone approaches the rate of potential evapotranspiration. The value for GW_REVAP should be between 0.02 and 0.2 (Arnold & Kiniry, 2012).

***GW_DELAY***: the delay time of the groundwater can't be directly be measured, but it can be estimated by simulating aquifer recharge using different values of GW_DELAY, and comparing the simulated variations in water table level with observed data (Arnold & Kiniry, 2012).

**SOL_AWC**: available water capacity of the soil layer (mmH2O/mm soil), available water capacity is estimated by determining the amount of water released between situ field capacity and the permanent wilting point.

**SOL_K:** saturated hydraulic conductivity (mm/hr), $K_{sat}$ , relates soil water flow rate to the hydraulic gradient and is measure of the ease of water movement through the soil (Arnold & Kiniry, 2012).

**SOL_BD**: Moist bulk density, it expresses the ratio of the mass of solid particles to the total volume of the soil. Bulk density values should be between 1.1 and 1.9 $Mg/m^3$ (Arnold & Kiniry, 2012)

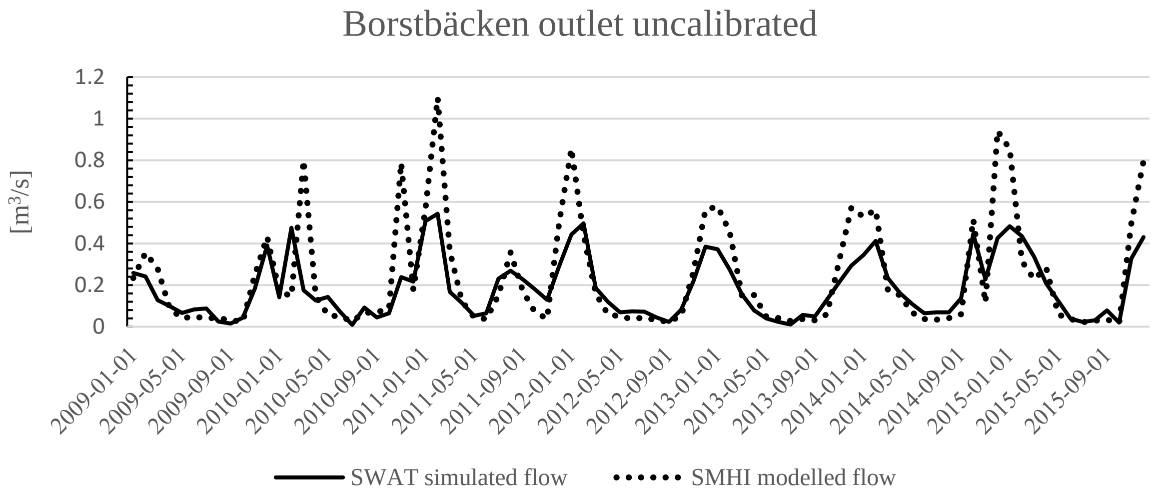
**REVAPMN**: Threshold depth of water in the shallow aquifer for (REVAP) or percolation to the deep to occur (mmH2O), movement of water from the shallow aquifer to the unsaturated zone is allowed only if the volume of water in the shallow aquifer is equal to or greater than REAVPMN (Arnold & Kiniry, 2012).

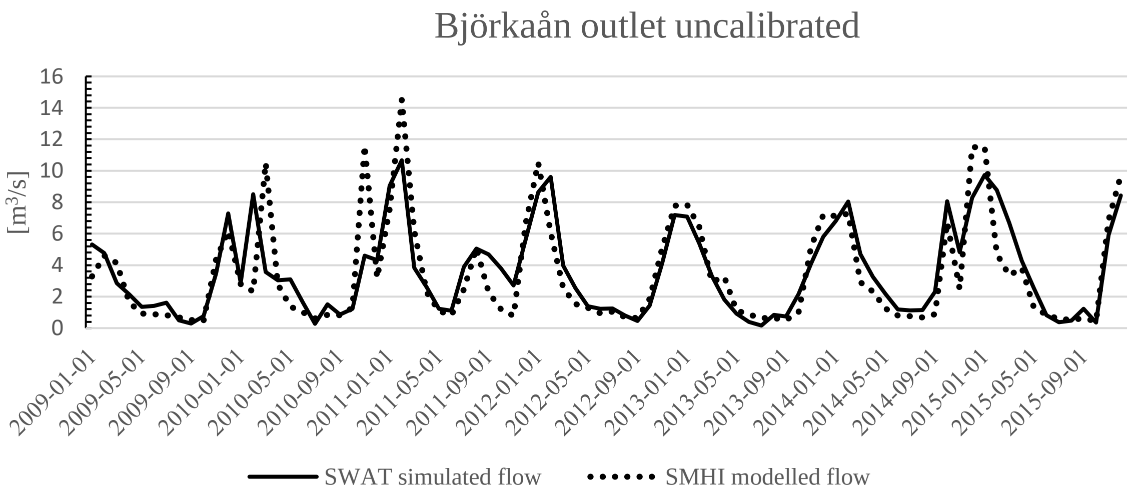
**SMFMN:** melt factor for snow on December 21, if no values was set , the model will set the SMFMN = 4.5, in rural areas is between (1.4 6.9), in urban snow melt in Sweden is between (3-8), asphalt (1.7-6.5) (Arnold & Kiniry, 2012).

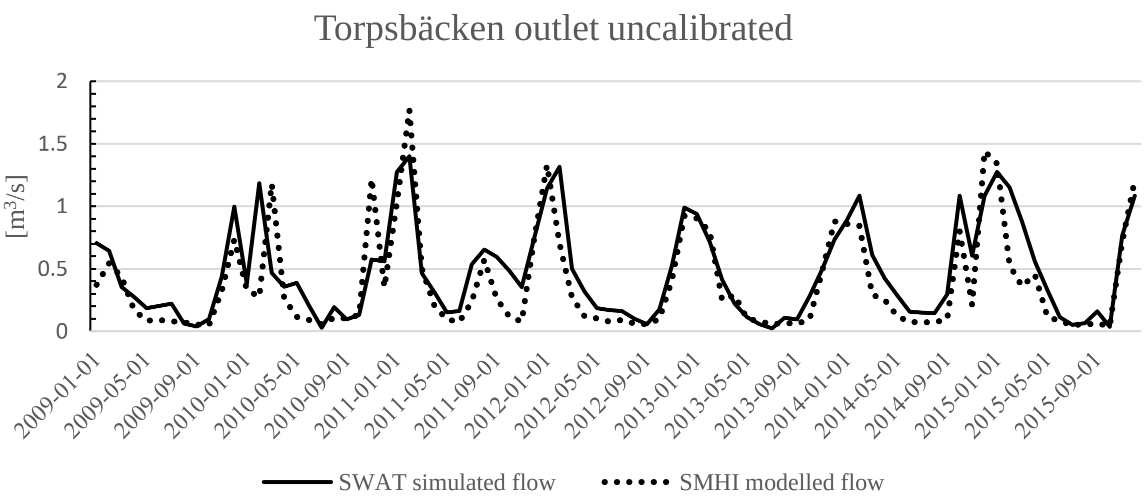
**SMFMX**: melt factor for snow on the June 21, if the watershed located in the northern Hemisphere, SMFMX will be the maximum melt factor, if the watershed located in the southern hemisphere the SMFMX will be the minimum melt factor. It is allowing the rate of snow melt to vary through the year. Has the same values as the SMFMN (Arnold & Kiniry, 2012).

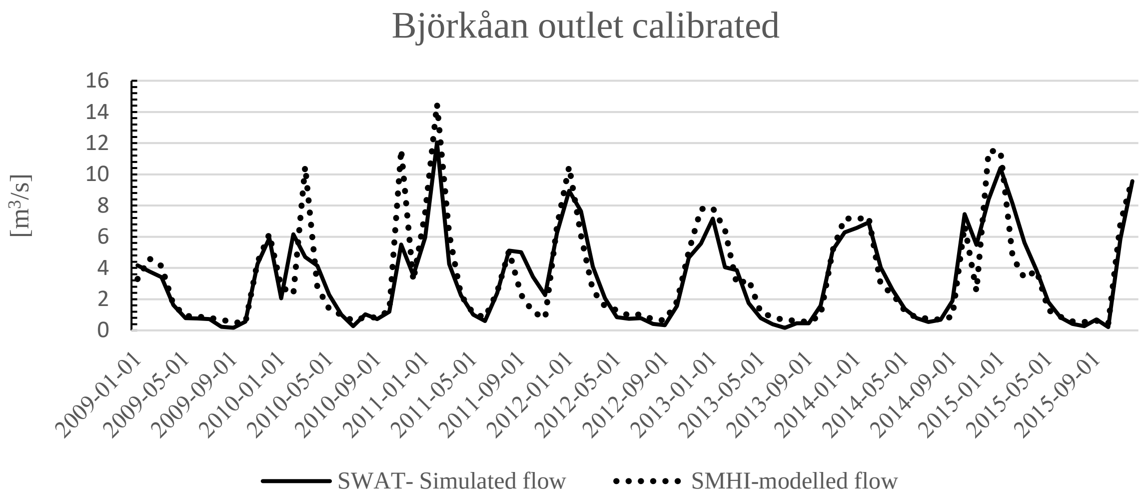
# 9. Appendix III

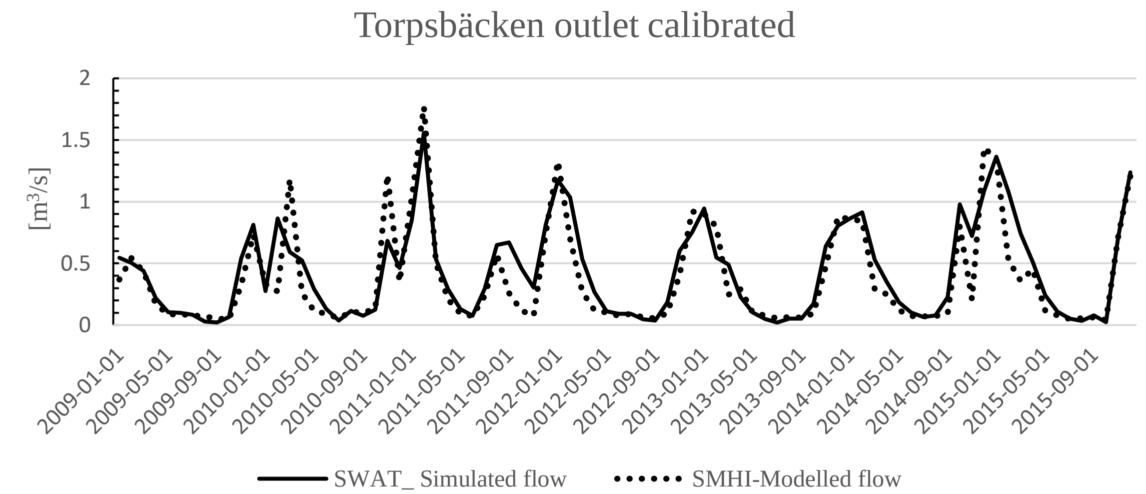
Water flow calibration for Borstbäcken, Torpsbäcken and Björkaån.

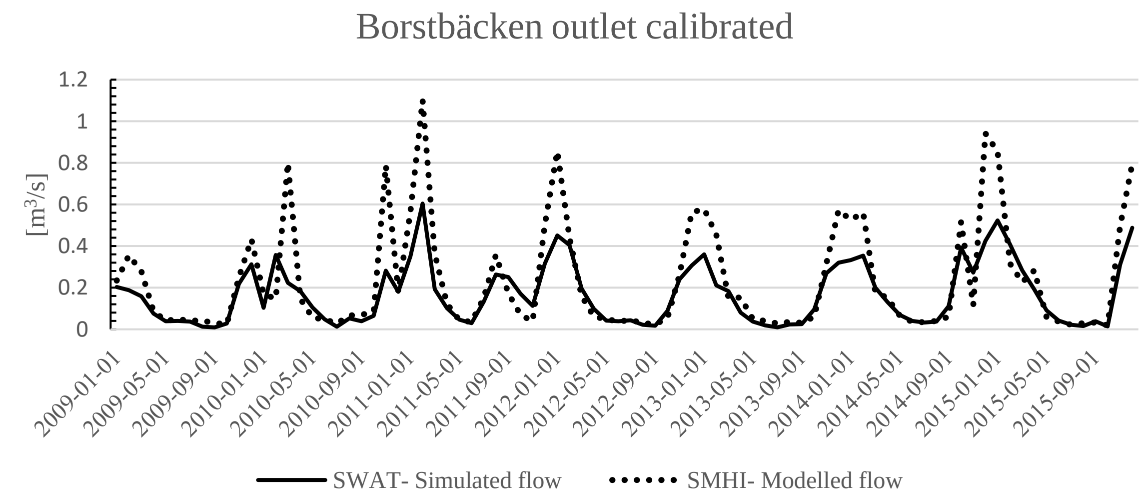



Björkåan outlet calibrated
16
14
12
10
8
6
4
2
0
[m3/s]
2009-01-01
2009-05-01
2009-09-01
2010-01-01
2010-05-01
2010-09-01
2011-01-01
2011-05-01
2011-09-01
2012-01-01
2012-05-01
2012-09-01
2013-01-01
2013-05-01
2013-09-01
2014-01-01
2014-05-01
2014-09-01
2015-01-01
2015-05-01
2015-09-01
SWAT- Simulated flow
SMHI-modelled flow


Torpsbäcken outlet calibrated
2
1.5
1
0.5
0
[m3/s]
2009-01-01
2009-05-01
2009-09-01
2010-01-01
2010-05-01
2010-09-01
2011-01-01
2011-05-01
2011-09-01
2012-01-01
2012-05-01
2012-09-01
2013-01-01
2013-05-01
2013-09-01
2014-01-01
2014-05-01
2014-09-01
2015-01-01
2015-05-01
2015-09-01
SWAT_ Simulated flow
SMHI-Modelled flow


Borstbäcken outlet calibrated
1.2
1
0.8
0.6
0.4
0.2
0
[m3/s]
2009-01-01
2009-05-01
2009-09-01
2010-01-01
2010-05-01
2010-09-01
2011-01-01
2011-05-01
2011-09-01
2012-01-01
2012-05-01
2012-09-01
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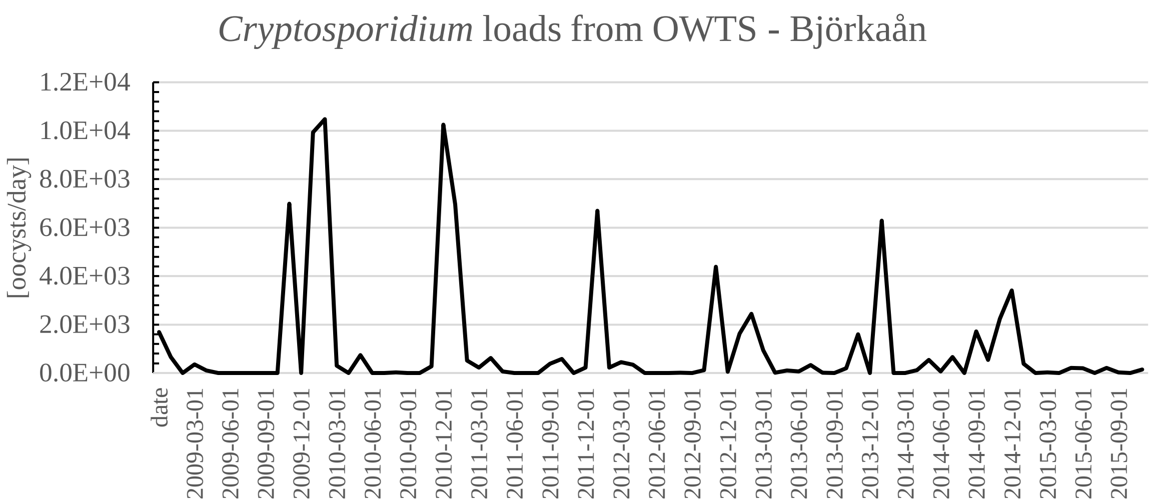
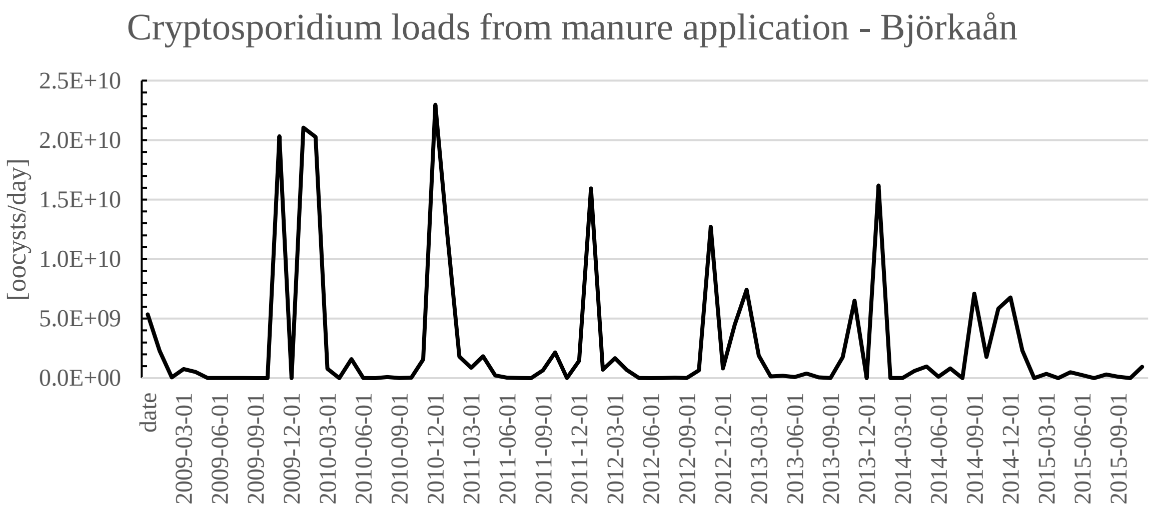
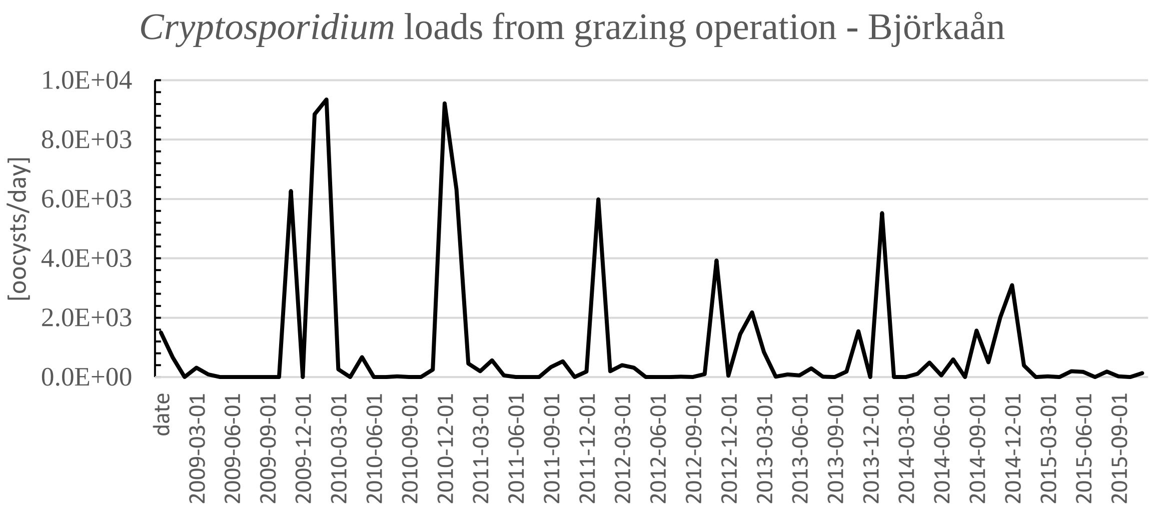
2013-05-01
2013-09-01
2014-01-01
2014-05-01
2014-09-01
2015-01-01
2015-05-01
2015-09-01
SWAT- Simulated flow
SMHI- Modelled flow

# 10. Appendix IV

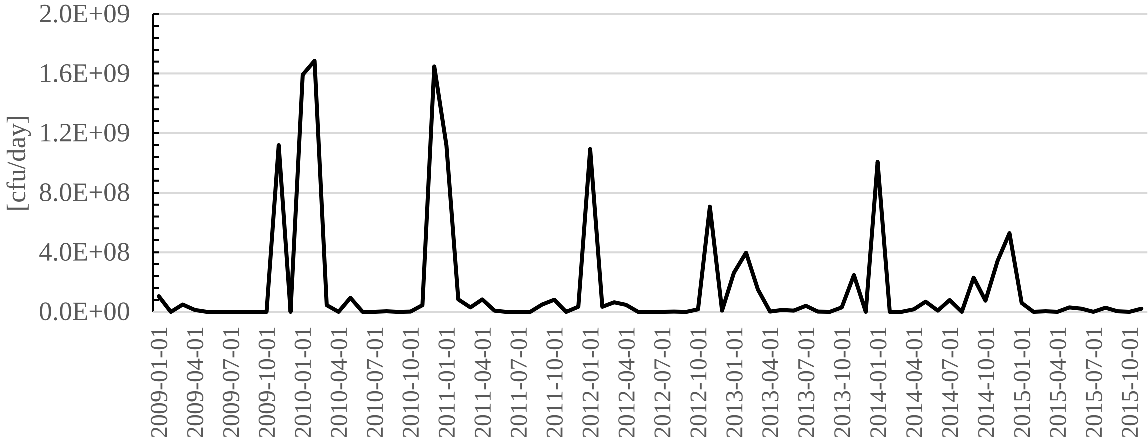
Microbial loads from OWTS discharge, manure application and livestock grazing in Björkaån



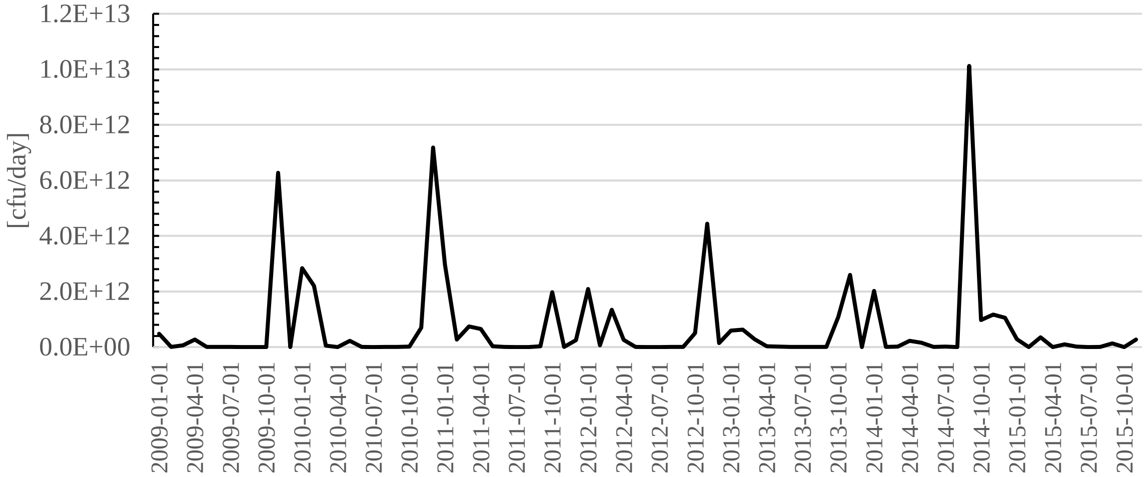



*E. coli* loads from OWTS - Björkaån




*E. coli* loads from manure application - Björkaån




*E. coli* loads from grazing operation - Björkaån