CHALMERS

Modelling fate and transport of *Escherichia coli* and *Cryptosporidium* spp. using Soil and Water Assessment Tool

Within Stäket drainage basin

Master of Science Thesis in the Master's programme Environmental Sciences at the University of Gothenburg

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Cover:
Cover photos taken in Ucklum, by Oskar Johansson: Top: Grazing cows, Bottom left: Lake Hällungen, drinking water source and Bottom right: Agricultural wheat field.

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ABSTRACT

Maintaining good quality of drinking water sources is essential as a part of drinking water management. Important steps are evaluation of drinking water sources quality and identification of contamination sources. Lately microbial organisms originating from faecal contamination have been increasingly identified as health risks and as impediments for providing safe drinking water. Stäket catchment area drains to Lake Mälaren, a drinking water source for two million people. The aim with this study was to set up the Soil and Water Assessment Tool (SWAT) in the Stäket drainage basin in order to model transport and fate of faecal contaminants in the form of *Escherichia coli* and *Cryptosporidium* spp. oocysts. Sources of faecal contamination and microbial attributes were identified through literature studies and contacts with local authorities. During calibration, model performance evaluated on water flow in three different subbasins showed an NSE of 0.44, 0.25, 0.18 and R^2 of 0.53, 0.27 and 0.26 respectively, whereas validation gave an NSE of 0.11, 0.05 and 0.11 and R^2 of 0.16, 0.10 and 0.14 respectively. SWAT results showed that wastewater treatment plants were the dominating source of faecal contamination and that contributions from diffuse sources were generally evenly spread over the area. Concentrations of *E. coli* were higher than acceptable for Swedish bathing water quality and *Cryptosporidium* spp. oocysts concentrations were in the same range as reported in other studies. Should the model be used further it ought to be calibrated on additional parameters.

Key words: Soil and Water Assessment Tool, SWAT, faecal contamination, *Escherichia coli*, *Cryptosporidium*, modelling

Modellering av *Escherichia coli* och *Cryptosporidium* med Soil and Water Assessment Tool
- Inom Stäkets avrinningsområde

Examensarbete i masterprogrammet i miljövetenskap vid Göteborgs universitet

VIKTOR JOHANSSON
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SAMMANFATTNING

Dricksvattentäkter av god kvalitet är en vital del av dricksvattenförsörjningen. Utvärdering av kvaliteten på dessa dricksvattentäkter samt identifiering av föroreningskällor är viktiga steg i arbetet. Den senaste tiden har sjukdomsalstrande organismer som härstammar från fekala föroreningar fått ökad uppmärksamhet som hälsorisker och hinder för en säker dricksvattenförsörjning. Stäkets avrinningsområde mynnar i Mälaren, som är dricksvattentäkt för två miljoner människor. Syftet med denna studie var att skapa en Soil and Water Assessment Tool(SWAT)-modell över Stäkets avrinningsområde, för att modellera transport och avdödning av fekala föroreningar representerade av *Escherichia coli* och *Cryptosporidium* oocystor. Fekala föroreningskällor och mikrobiella parametrar identifierades genom en litteraturstudie samt kontakter med lokala myndigheter. Modellens NSE-värden var på 0.44, 0.25, 0.18 och R^2-värden på 0.53, 0.27 och 0.26 för tre olika delavrinningsområden under kalibreringsperioden. Under valideringsperioden var motsvarande NSE- värden 0.11, 0.05 och 0.11 och R^2-värden 0.16, 0.10 och 0.14. Resultaten från SWAT-modellen visade att avloppsreningsverk stod för störst del av de fekala föroreningarna och att bidrag från diffusa källor var relativt jämnt spridda över området. Halterna *Escherichia coli* var högre än tillåten vattenkvalitet för svenska badvatten och halterna *Cryptosporidium* oocystor var i samma storleksordning som rapporterats i andra studier. Vid fortsatt användning av modellen bör den kalibreras på ytterligare parametrar.

Nyckelord: Soil and Water Assessment Tool, SWAT, fekala föroreningar, *Escherichia coli*, *Cryptosporidium*, modellering

Contents

Preface

Project was conducted at the Chalmers University of Technology during the spring 2014. Research group behind the project was DRICKS at the division of Water Environment Technology at Chalmers. The study was performed as a part of two research projects: “GIS-based dispersion modelling of parasites in surface water sources” (GIS-baserad spridningsmodellering av parasiter i ytvattentäkter) and “Risk-based decision support for safe drinking water”, both funded by the Swedish Water and Wastewater Association (Svenskt Vatten Utveckling, SVU).

Without discussions and tips provided by Johan Åström at Tyréns AB the road travelled for completing my study would have been much more troublesome and exhausting. For this I am greatly thankful. I would also like to acknowledge all master thesis workers I have shared work space with and thank them for welcoming me and for providing a friendly atmosphere capable of encouraging great work.

Finally, I would like to express my gratitude towards my supervisor Ekaterina Sokolova for productive discussions, valuable comments and support throughout the process of conducting this research.

Gothenburg, May 2014

Viktor Johansson

1 Introduction

Lake Mälaren (onwards also addressed as Mälaren) is a drinking water resource for two million people (Sveriges Lantbruksuniversitet 2013). Increasing population, climate change and rising sea level are threats to the area in relation to safe drinking water distribution in the longer time perspective (VAS-rådet 2011). Population growth increases the pressure on water sources and climate change is associated with an increase in precipitation thus enhancing the run-off and transport of pollutants, such as pathogens, affecting drinking water sources. Also the rise of sea level, if not managed, can in the long run turn Mälaren into a salt ocean bay (VAS-rådet 2011). At the time being there are no sustainable alternatives to Mälaren as a drinking water source, making it even more essential to protect it and to improve present water quality (Vattenmyndigheten Norra Östersjön 2014a). Spread of waterborne diseases through one of the three largest drinking water treatment plants (DWTPs) is considered the largest risk for water sources in Stockholm county (VAS-rådet 2011). Therefore, faecal contamination and the associated spread of waterborne diseases is a threat towards the provision of safe drinking water on the shorter time scale. Knowing the water quality of a drinking water source is important due to that the treatment processes in the DWTP can be adjusted to reflect the contamination level of the source and therefore optimising the use of resources (Sokolova 2014). To increase knowledge of the water quality, modelling fate and transport of faecal contaminants within the watershed is of importance.

The kind and the quantity of faecal contamination sources and associated pathogens existing within a drainage basin are dependent on the activities located in the area as well as what kind of land uses that dominate. Faecal contamination originates either from human or animal faeces. Sources can be divided into point and non-point sources. Point source examples are: failing, inadequate or lack of On-site Wastewater Treatment Systems (OWTSs), grazing animal and wild animal defecating directly into the stream and permitted discharges (e.g effluents from wastewater treatment plants (WWTPs)). Examples of non-point sources are: manure application on agricultural land, runoff from manure produced by grazing livestock and wildlife, stormwater runoff (Benham et al. 2006) and release from streambeds (Kim et al. 2010).

Drinking water quality can be evaluated on chemical, microbial and radiological aspects (World Health Organisation 2011). The most essential parameter taking into account regarding microbial water quality is whether there are waterborne pathogens present in the water source or not. This can be done through detecting pathogens or detecting indicators of faecal contamination and by that the possible presence of pathogens. World Health Organisation (2011) emphasizes management practices focusing on preventing pathogens from reaching water sources instead of relying on intense water treatment processes. When ingested, infectious pathogens ultimately affect the human health and are often associated with simultaneous infection of a large number of persons, thus potent of impacting a large proportion of the society (World Health Organisation 2011).

The parasite *Cryptosporidium* spp. has been detected in raw water at Norsborg, Lovö and Görvälns DWTPs (Hansen 2011). *Cryptosporidium* spp. is a parasite within the family *Cryptosporiidae* (Sunnotel et al. 2006) that infect humans causing cryptosporidiosis, a diarrheal disease with symptoms such as stomach cramps, fever, vomiting, nausea, dehydration and weight loss (Centers for Disease Control and Prevention 2014a). *C. hominis* and *C. parvum* are the species most associated with human infections (Centers for Disease Control and Prevention 2014b), although species such as *C. canis*, *C. felis*, *C. meleagridis* and *C. muris* have also been reported to be responsible for human infection (Sunnotel et al. 2006). The lifecycle of *Cryptosporidium* spp. is complicated involving several different life stages, although only the thick walled oocysts are able to persist outside a host long enough to be able to infect other organism (Smith et al. 2005). Infection occurs mainly through the faecal oral route; hence, the exposure to faecal contamination though drinking water and recreational activities (e.g. bathing, swimming) is of importance as well as infection through food intake and inhalation of aerosols (World Health Organisation 2011). The similarities between transport and fate for *Cryptosporidium* spp. and for indicator organisms (e.g. *E. coli*) are limited due to differences in characteristics such as survival, adsorption to soil particles and sediment rates in water (Wilkes et al. 2009). *Cryptosporidium* spp. oocysts can survive in water for longer than one month (World Health Organisation 2011).

Escherichia coli is a bacterium species naturally present in the intestines and faeces of humans and animals (Odonkor & Ampofo 2013). In general, *E. coli* does not cause illness, although some strains, e.g. *E. coli* O157:H7 (Centers for Disease Control and Prevention 2014c), can infect humans causing different diarrhoeal diseases (Folkhälsomyndigheten 2014b) as well as urinary tract infections and respiratory illnesses, such as pneumonia (Centers for Disease Control and Prevention 2014c). *E. coli* can also refer to the faecal indicator (Ashbolt et al. 2001), see next paragraph. *E. coli* deposited by livestock can survive for 5-6 moths on grass (Avery et al. 2004) and the survival in water is reported to be 4-12 weeks (Edberg et al. 2000). Unless other stated, *E. coli* will be referred to as the faecal indicator.

Measuring concentrations of specific pathogens in the environment can be difficult, time-consuming and expensive. Instead, indicators that are less expensive and easier to measure are commonly used. Swedish national food agency describes three different types of indicators: general microbial indicators that indicate microbial activities and possibilities for microbes to grow; faecal indicators that indicate faecal contamination and therefore possible presence of pathogens; and index and modelling organisms that indicate the presence of specific pathogens (Dryselius 2012). With few exceptions, *E. coli* is not found in natural water bodies unless a faecal contamination source is present, hence it is recommend as an indicator of recent faecal contamination of water (Odonkor & Ampofo 2013). Presence of *E. coli* in water samples only indicates a faecal contamination and a possible presence of pathogen organisms. Actual pathogen presence depends on the prevalence of pathogens in the faecal contamination source (Odonkor & Ampofo 2013, World Health Organisation 2011). Likewise, the absence of *E. coli* does not guarantee that the water is free from pathogens (World Health Organisation 2011).

The main factors affecting the transport of faecal indicators and pathogens are adsorption, desorption, mechanical and biological movement processes as well as hydrologic characteristics of a drainage basin. The factors that affect the fate and survival of faecal indicators and pathogens are organic and inorganic nutrients, water availability, temperature, sunlight and pH (Ferguson et al. 2003). To calculate transport and fate of faecal contamination, many different models have been developed; some examples are Soil and Water Assessment Tool (SWAT), Hydrological Simulation Program FORTRAN (HSPF) and a modified version of WATFLOOD. HSPF is a model similar to SWAT simulating water quality within a drainage basin (Benham et al. 2006). WATFLOOD is a model that has been modified to predict transport and inactivation of pathogens using the same mechanisms as for soil transport (Åström 2013). SWAT has received the highest score in several evaluations of different hydrological models and its ability to evaluate microbial risk has been assessed to be very high.

1.1 Aim and objectives

The aim with this study is to calibrate and validate the SWAT model in the "Stäket" catchment area in order to:

- Simulate the fate and transport of *E. coli* and *Cryptosporidium* spp.
- Identify major contamination sources within Stäket drainage basin.
- Estimate how different faecal contamination sources contribute to contaminating the catchment area.

2 Background

2.1 Soil and Water Assessment Tool (SWAT)

The description of Soil and Water Assessment Tool (SWAT) below is based on (Winchell et al. 2013) unless other references are reported. SWAT is a hydrological process-based model for predicting the impact of land management practices on water, sediment and agricultural chemical yields and it is adopted for simulating large watersheds over long time periods (Nietsch et al. 2011). Modelling runoff and rainfall is based on a daily time basis (Chin et al. 2009). Sadeghi & Arnold (2002) developed a sub-model for SWAT, simulating microbial loadings in surface- and groundwater.

Topographic data, the elevation above sea level, are entered into SWAT as a raster layer called “Digital Elevation Model” (DEM). This layer is assigning a height value to each cell in the grid. From the DEM, SWAT calculates the delineation of the catchment and the outline of the rivers. There is also an option in the model to manually burn in a pre-defined river system. By defining a threshold value for the area that is required for a river to start forming, SWAT also divide the drainage basin into different subbasins based on the river outline. Land use and soil type have to be defined according to the types provided by SWAT, reclassified into those types or manually defined by the user. Based on the DEM, SWAT calculates the slope and then categorise the cells into different slope classes defined by the user (Winchell et al. 2013). “Hydrological response units” (HRUs) are the base for the hydrological modelling and are derived from raster data on land use, soil type and slope. Each raster cell, with the same size as the DEM, is assigned an HRU. Each unique combination of land use, soil type and slope gives a setting (i.e. HRU) for the hydrology and transport of both water and microbial organisms (Winchell et al. 2013). HRU threshold values for minimum percentage of area of land use, soil type and slope can be defined. Areas smaller that this will not be accounted for in the HRU definition, but reclassified into land uses, soil types and slopes with areas larger than the threshold value. Reclassification is based on the area percentage of those land uses, soil types and slopes with larger area than the threshold value. Meteorological data can be entered into SWAT as measured records or generated by SWAT using weather databases provided either by SWAT or the user. Generation of meteorological data is based on the latitude of the weather station, whereas longitude is not used (Arnold et al. 2012b).

SWAT incorporates organism transport, which is based on the hydrology, adsorption of organisms and meteorological data, as well as pathogen die-off, which is controlled by pathogen attributes and temperature (Nietsch et al. 2011). Transport can be divided into two phases, one phase including land transport and one phase accounting for movement in the stream of the specific subbasin (Nietsch et al. 2011). Within each transport phase each organism has an adsorption coefficient, a growth rate and a die-off rate, these attributes affect the amount of organisms that is contributing to the total load of the catchment. Organisms can be modelled either as persistent or less persistent organisms. Underlying mechanisms for transport and survival are the same for both types, although variables can be assigned different values depending on the attributes of the organism that is being modelled.

Organisms can be entered into the model through either point sources (directly into the stream) or non-point sources (into the land phase). Two different organism groups can be used, one persistent and one less persistent. Organisms entering the model through non-point sources are divided into two populations, one on foliage and one in the top 10 mm soil layer. Both populations are affected by surface runoff, though only the population in the top 10 mm soil layer is capable of being transported to the river system. Organisms on foliage can enter the soil population by being washed off by rainfall events, which occurs when rainfall exceeds 2.54 mm on any given day (Nietsch et al. 2011). The organism group in the top 10 mm soil layer can be in solution or adsorbed to sediment particles and this is specified by a coefficient between 0 and 1, with 1 meaning that all organisms are in solution.

Organisms can be transported through runoff from land areas to the river either in water solution or adsorbed to sediment. SWAT include both pathways and can also store organisms not reaching the river in one day, adding these to the organism concentration the next day (Nietsch et al. 2011). Organisms adsorbed to particles are transported associated to sediments in surface run-off whereas organisms in solution are transported directly in water run-off. Organisms that are in the soil below 10 mm or transported in water that percolate through the soil are expected not to reach the river and thus are assumed to die off (Nietsch et al. 2011).

Point sources are specified using coordinates and their contributions of organisms are directly discharged into the river. During transport in rivers and water reservoirs organisms growth and die off is modelled using a first order decay function and concentrations of organisms in rivers are also affected by sedimentation and resuspension of sediment associated organisms (Nietsch et al. 2011). SWAT provides a database on different fertilisers, although information on organism concentrations in different types of manures and management practices on fertilizer application is not included but can be manually added (Arnold et al. 2012b).

Entering faecal contamination through OWTS in the SWAT model is limited to the use of faecal coliforms. Faecal coliforms are entered as concentration in sewage effluent. Performance of the OWTS can be either functioning or failing, affecting the hydraulics of the system (Nietsch et al. 2011). Since OWTS only enter the model as faecal coliforms and the model does not treat faecal coliform the same way as the persistent and less persistent organism groups, Coffey et al. (2010b) suggests to use a continuous fertilization operation to account for this input in the form of *E. coli* or *Cryptosporidium* spp.. The continuous fertilisation was also recommended by Åström, J.[1]. Frey et al. (2013) accounts for sewage and wildlife through equally dividing the contributions as a point source to each subbasin.

2.2 SWAT modelling faecal contamination transport and fate literature review

References cited in the literature review are listed in Table 1. Information on catchment location, catchment size and what type of model organisms modelled are also provided.

[1] Johan Åström, Thyréns AB, personal communication on March 5th 2014

Table 1 List of references in the literature review using SWAT for modelling E. coli, Cryptosporidium or faecal coliforms.

Reference	**Site**	**Catchment area (km^2)**	**Indicator/pathogen**
Benham et al. (2006)	USA, Shoal Creek catchment	367	Faecal coliforms
Bougeard et al. (2011a)	France, Saint-Anne catchment	5	*E. coli*
Bougeard et al. (2011b)	France, Mignonne River catchment	113	*E. coli*
Chin et al. (2009)	USA, Little River Experimental Watershed	334	Faecal coliforms
Cho et al. (2012)	USA, Wachusett reservoir catchment	100 (estimated size)	Faecal coliforms
Coffey et al. (2010a)	Ireland, Fergus catchment	29	*E. coli*
Coffey et al. (2010b)	Ireland, Fergus catchment	29	*Cryptosporidium* spp.
Coffey et al. (2010c)	Ireland, Fergus catchment and Kilshanvey catchment	29 and 6	*E. coli*
Coffey et al. (2012)	Ireland, Kilshanvey catchment	6	*E. coli*
Frey et al. (2013)	Canada, Payne River catchment	178	*E. coli* and Faecal coliforms
Jayakody et al. (2013)	USA, Pelahatchie catchment	572	Faecal coliforms
Kim et al. (2010)	USA, Little Cove Creek catchment	68	*E. coli*
Parajuli et al. (2009)	USA, Upper Wakarusa catchment with three sub-catchments	950, 75, 51 and 152 respectively	Faecal coliforms
Tang et al. (2011)	Ireland, North and South Leinster catchment	3,98 and 4,19	*Cryptosporidium* spp.

SWAT and the microbial sub-model have been used to model the transport and fate of faecal indicators in catchments roughly during the last decade both successfully and less successfully. Coffey et al. (2012) used SWAT to model *E. coli* in the Kilshanvey catchment area in Ireland and reported that results estimating *E. coli* were erratic and inconsistent, although with limited input data it could be used for estimating the magnitude of faecal indicators in small catchment areas. Evaluating the Fergus watershed, Coffey et al. (2010a) displays that although it is possible to simulate *E. coli* transport in catchment areas, it is unlikely to be able to account for all factors contributing to degrading water quality. Findings also conclude that it is possible to use SWAT for assessing potential *E. coli* concentrations, although due to limited observations results should be interpreted carefully. Coffey et al. (2010c) also investigated the use of SWAT for *E. coli* source estimation in the Fergus and Kilshanvey catchments and found a satisfactory correlation between observed and predicted *E. coli* concentrations for both catchment areas. Bougeard et al. (2011b) connected a SWAT model of the Mignonne River catchment with a hydrodynamic model simulating *E. coli* concentration in the Daoulas estuary based on input concentrations from the SWAT model. Comparing observed concentrations with modelled concentrations gave poor or none correlation (Bougeard et al. 2011b). Studies of Saint Anne catchment, France showed that 54.3 % of the observed concentration was within the daily variance of the modelled range (Bougeard et al. 2011a). Frey et al. (2013) used SWAT to simulate occurrence of waterborne pathogens in the Payne River watershed, Canada. Findings showed that SWAT could not simulate *E. coli* and faecal coliforms loadings with sufficient accuracy.

In recent years SWAT has been used to model transport and fate of *Cryptosporidium*. A SWAT model set up for the Fergus catchment, Ireland (Coffey et al. 2010b) is claimed to be the first report using SWAT for modelling *Cryptosporidium* transport and fate. Results showed that SWAT can be used to predict *Cryptosporidium* spp. oocyst in water catchments, though no validation was made using observed oocyst concentrations. Tang et al. (2011), modelling two separate agricultural catchments in Ireland, concluded that it is possible to model *Cryptosporidium spp.* oocyst using SWAT to estimate the contamination order of magnitude and results could be useful as aid when estimating source of waterborne outbreaks.

The faecal contamination more successfully modelled with SWAT has been faecal coliforms. Cho et al. (2012) modelled the Wachusett Reservoir catchment area using a modified SWAT-model. Modification made it possible to include solar radiation inactivation of bacteria and to account for animal wildlife contribution. One of their conclusions was that SWAT can be used for achieving a reliable simulation of the faecal coliforms in a catchment area. Results from faecal coliform bacteria transport and fate SWAT modelling in the Pelahatchie sub-catchment, USA (Jayakody et al. 2013) show that the model reached a good performance in simulating the faecal coliform bacteria concentrations. Chin et al. (2009) investigated the transport and fate of faecal coliforms in a small sub-catchment within the Little River Experimental Watershed, USA and SWAT modelling showed a good correlation between simulated and measured concentrations. Faecal coliforms were modelled in the Shoal Creek catchment (Benham et al. 2006) concluding that the model had limitations describing the bacterial life cycle and simulating heavy rainfall events, but can be used for evaluating total maximum daily loads for evaluating bacterial water quality. Using the SWAT-model for predicting total faecal coliform bacteria concentrations in the Upper Wakarusa catchment, USA showed that modelled and measured values corresponded in a range from unsatisfactory to good (Parajuli et al. 2009). A study made in Little Cove Creek catchment, Pennsylvania USA (Kim et al. 2010) also incorporated an addition to the SWAT bacteria model that included *E. coli* contribution from sediment resuspension. The hydrodynamic model coupled with SWAT developed by Bougeard et al. (2011b) has been used further in order to estimate the microbial quality of the bathing water in the Daoulas estuary (Bougeard et al. 2010), as an example of SWAT as a part of practical implementation of several models.

Different parameters have been described to influence SWAT in different ways. Direct stream deposition (defecation directly into streams) and die-off rate were identified as the most sensitive input parameters (Coffey et al. 2010c, Coffey et al. 2012). Inaccurate GIS input data can be a major factor that contributes to errors in modelling outputs (Parajuli et al. 2009). Bacteria partition coefficient parameter (Coffey et al. 2010a, Coffey et al. 2010c), point sources (Coffey et al. 2010c) and bacteria die-off (Coffey et al. 2010a, Coffey et al. 2010c) have been identified as factors most influential to model outputs. Application of manure is an important factor for *E. coli* (Bougeard et al. 2011b) and *Cryptosporidium* spp. oocyst (Coffey et al. 2010b) concentrations. Rainfall is impacting *E. coli* concentrations (Bougeard et al. 2011b) and during autumn and winter *Cryptosporidium* spp. oocysts concentration and amount of rainfall were correlated based on monthly averages (Coffey et al. 2010b). Furthermore rainfall and run-off events in relation to manure application are important for *Cryptosporidium* spp. oocyst transport and the first storm event after manure application is the most important (Tang et al. 2011). Autumn and winter periods are associated with higher risk of oocyst occurrence (Coffey et al. 2010b). During dry weather WWTP has been shown to be a major source of *E. coli* (Bougeard et al. 2011b). Solar intensity, when added to the model, significantly affects the faecal coliform bacteria survival (Cho et al. 2012). Rainfall seasonal patterns have been shown to be reflected in faecal coliform bacteria concentration (Jayakody et al. 2013).

SWAT performance is limited due to a set of factors, such as lack of data (Cho et al. 2012, Coffey et al. 2012), lack of knowledge of faecal contamination sources (Bougeard et al. 2011a) and parameter uncertainties (Cho et al. 2012). To overcome model limitations and to improve the model knowledge of catchment hydrological processes, climate conditions and contamination events including time aspects of contamination concentrations are important factors (Bougeard et al. 2011a). Better knowledge regarding bacteria die-off and the ability to accurately account for extreme weather events are other fields to improve (Benham et al. 2006). Taking into account daily variations based on hourly measurements (Bougeard et al. 2011a) and wildlife contribution (Cho et al. 2012) increases the accuracy of the model. Animal access to stream increases uncertainties modelling *Cryptosporidium* spp. oocysts (Tang et al. 2011). Accounting for streambed contribution of *E. coli* enhanced the model performance on predicting *E. coli* concentrations (Kim et al. 2010). On the contrary, Bougeard et al. (2011a) reports that *E. coli* contribution from river sediments to water contamination was limited.

A multi criteria analysis was made to evaluate the most common models for non-point source water quality models (Booty & Benoy 2009) and SWAT received the highest score amongst the models and it got the highest grade on its suitability to simulate pathogens. Another evaluation (Coffey & Cummins 2008) of thirteen different models for microbial evaluation of agricultural catchments also gave SWAT the highest score and assessed its ability to evaluate microbial risk as very high. SWAT is more commonly used in catchments with high proportion of agricultural land and was more accurate predicting faecal coliform concentrations compared to the HSPF model (Chin et al. 2009).

2.3 Norrström drainage basin

2.3.1 Geography of the Norrström drainage basin

The Norrström drainage basin, displayed in figure 1, part of the administrative department "Norra Östersjön", is 22600 km^2 and its outlet through Norrström is located in the central parts of Stockholm just north of the royal castle (Norra Östersjöns Vattendistrikt 2008). Outflow through Norrström accounts for 98 % of Mälaren water flow, 2 % are discharged through Södertälje canal and a negligible part is discharged through Årstaviken (Sahlberg & Gustavsson 2010). Roughly the drainage basin is located between 59° and 60° North and 14.5° and 18° East. Lake Mälaren is a part of the watershed and is located to the west of the Norrström outlet to the Baltic Sea. Mälaren is the country's third largest Lake with an area of 1120 km^2. It supplies freshwater for two million people (Sveriges Lantbruksuniversitet 2013) and is in the Environmental code (SFS 1999:808) chapter 4 §2 identified by the Swedish parliament as a national interest for its nature and cultural values. Lake Hjälmaren, Sweden's fourth largest lake (Sveriges Hydrologiska och Meteorologiska Institut 2008) is also located within the Norrström drainage basin and its outlet is connected via Eskilstunaån to Mälaren. Dominating land use types are forest (56.5 %) and agricultural land (20.2 %) furthermore a significant part of the area consists of water bodies (10.9 %) (Sveriges Lantbruksuniversitet 2013). About one and a half million people live within the catchment; there are six different counties and sixty municipalities represented of which four counties and twenty-three municipalities are in direct proximity to the lake (Norra Östersjöns Vattendistrikt 2008).

Average yearly temperature for the drainage area is between 4-6 °C (Sveriges Hydrologiska och Meteorologiska Institut 2014a), and temperature varies during the year from an average temperature of between -5°C and -4°C in February to an average temperature of between 15°C and 16°C in July (Sveriges Meteorologiska och Hydrologiska Institut 2014e). Annual rainfall is 600-900 mm (Länsstyrelsen Västmanlands län 2009). Solar radiation ranges from 4-8 kWh/m^2 in February to 170-180 kWh/m^2 in June (Sveriges Hydrologiska och Meteorologiska Institut 2014b).

Main soil types in the drainage basin are moraine, clay-silt and mountainous outcrops (Sveriges geologiska undersökning 2014). Differences in soil types, with moraine dominating in the western parts and clay rich soils in the eastern parts, are reflected in the land use distribution with high proportion of forest areas to the North West and high proportion of agriculture areas in the eastern parts as well as areas close to Mälaren (Sveriges Lantbruksuniversitet 2013). Areas south of Mälaren have a large portion of mountainous outcrops (Sveriges geologiska undersökning 2014).

2.3.2 Lake Mälaren as a drinking water source

In Lake Mälaren there are several drinking water intakes. Five DWTPs, of which two are large (Lovö and Norsborgs DWTPs), are located in the eastern parts of the lake, see Figure 1 (Sveriges Lantbruksuniversitet 2013). Both Norsborg and Lovö DWTP treat the water in three steps, first chemical, then mechanical and last biological. Before distribution the water is pH adjusted and disinfected using chloramine at Norsborg and UV-disinfection at Lovö (Stockholm Vatten 2014). Together they supply 1 240 000 users with drinking water (Länsstyrelsen Stockholms län 2011). Görväln DWTP treats the drinking water first using flocculation and sedimentation followed by filtration, both through sand and carbon filter. Last step of the treatment process is UV-disinfection and before distribution, the water is chlorinated with chloramine to prevent bacterial growth in the distribution system (Norrvatten 2014a). Other DWTPs are listed in Table 2 and shown in Figure 1.

Table 2 Drinking water treatment plants using surface water from Mälaren.

DWTP	Users[a]	Location	Water protection area
Lovö	1 240 000*	Eastern parts	Östra Mälaren[b]
Norsborg		Eastern parts	Östra Mälaren[b]
Görväln	520 000	Eastern parts	Östra Mälaren[b]
Skytteholm	7 400[d]	Eastern parts	Östra Mälaren[b]
Västerås	100 000	North western parts	Hässlö and Fågelbacken[c]
Djupdals	80 000	Eastern parts	Källtorp-Djupdal[c]

a) Länsstyrelsen Stockholms län (2011)
b) Norrvatten (2014b)
c) Länsstyrelsen (2014)
d) Ekerö Kommun (2001)
*Both Lovö and Norsborg together

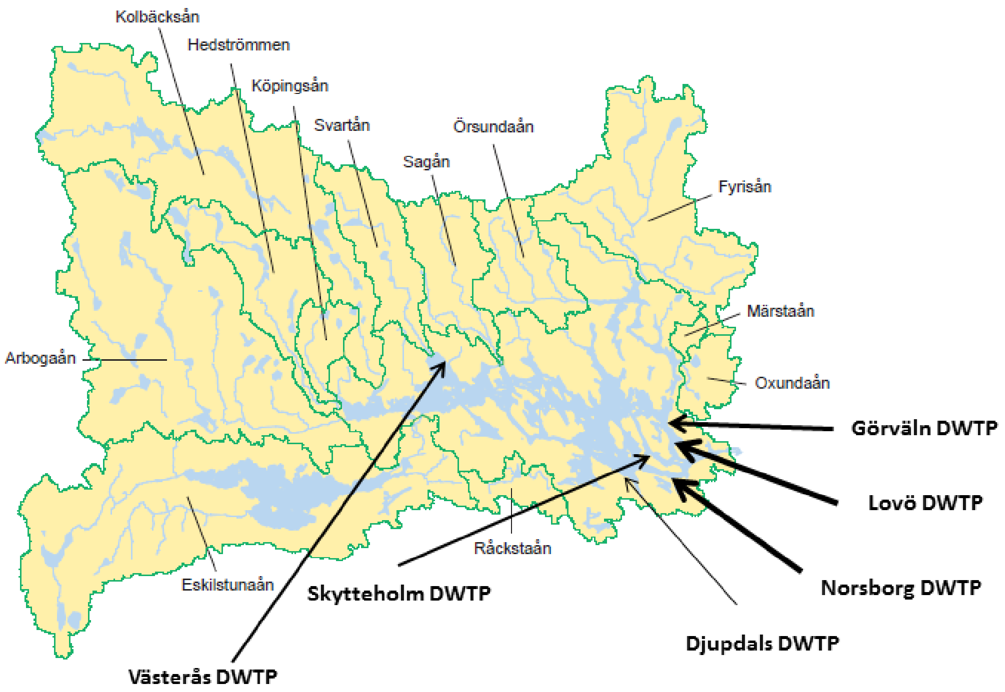


Figure 1 Mälaren drainage basin, including major sub-catchments areas. DWTPs are marked with arrows. Arrow boldness indicates magnitude of number of drinking water users. Adopted from (Sveriges Lantbruksuniversitet 2013).

2.3.3 Sources of faecal contamination within the Norrström drainage basin

Agricultural land is a major non-point source within the catchment area. In general most of the agricultural land is located close to Mälaren (Länsstyrelsen Stockholms län 2013) or close to rivers (Vattenmyndigheten Norra Östersjön 2014a) making it a potent source of faecal contamination in the context of drinking water supply (Norra Östersjöns Vattendistrikt 2008). However, agricultural practices in Stockholm county are dominated by crop production (Länsstyrelsen i Stockholms län 2010), making live-stock contribution of faecal contamination less important than contribution from spreading of manure. WWTP effluents and OWTS are identified as important sources of nutrients (Norra Östersjöns Vattendistrikt 2008) for the area and these sources are also associated with faecal contamination. The Swedish Agency for Marine and Water Management states that half of Sweden's 700 000 OWTS are not in adequate conditions (Havs och Vattenmyndigheten 2014). Until maintained or replaced these will also be a significant contributor of faecal contamination. Wastewater effluents from municipal WWTPs represent five percent of the flow through Norrström outlet (Sveriges Lantbruksuniversitet 2013). Table 3 shows information on numbers of WWTPs, land use and water flow in the different sub-catchments.

Table 3 Land use and information on WWTPs within the area. Adopted from (Sveriges Lantbruksuniversitet 2013).

Subbasin	**Area (km^2)**	**Agricultural land (%)**	**Forest (%)**	**Water surface (%)**	**WWTPs[a] (amount)**	**Average water flow (m^3/s)**
Mälaren[a] *	4605	26	34	25	9	-
Oxundaån	272	26	39	6.2	0[a]	1.6
Märstaån	77	24	-	-	-	-
Knivstaån[a]	121	27	58	2.5	1[a]	-
Fyrisån	2 005	27	59	1.6	5[a]	14.3
Hagaån[a]	123	25	59	0.4	0[a]	0.95
Sävaån[a]	199	29	60	0.9	0[a]	1.6
Örsundaån	736	42[c]	52	1.2	3[a]	6.0
Fiskviks kanal[a]	46	49	40	0	0[a]	-
Ekaån[a]	38	44	45	0	0[a]	-
Enköpingsån[a]	164	49	31	0	1[a]	-
Sagån	857	37	51	1	1[a]	7.2
Svartån	776	22	63	3	1[c]	6.2
Kolbäcksån	3 117	4	78	9	8[a]	28.6
Köpingsån	287	15	71	5	1[a]	2.6
Hedströmmen	1 050	8	77	7	1[a]	11.9
Arbogaån	3 807	12	72	7	39[b]	44.1
Eskilstunaån	4 182	25	46	15	62[b]	24.7
Råckstaån	261	15	68	5.1	2[b]	1.8

a) Norra Östersjöns Vattendistrikt (2008)
b) Vattenmyndigheten Norra Östersjön (2014b)
c) Vattenmyndigheten Norra Östersjön (2014c)
* Areas directly adjacent to Mälaren

Small recreational boats emptying their septic tank and leakage from wastewater drainpipes located in the lake are also considered risks for contamination of drinking water (VAS-rådet 2011). Åström (2013) reports that *Cryptosporidium* spp. has been detected in faeces samples from elk, red deer, roe deer and red fox. Based on number of elks hunted and shot, the elk concentration in Dalarna and Örebro counties are only matched by three and outranked by two of total 21 counties in Sweden (Statens Offentliga Utredningar 2009), hence wildlife contribution to faecal contamination within the area can be of importance.

2.3.4 Hydrodynamic conditions in Lake Mälaren

Mälaren is divided into six distinct hydrodynamic separate compartments of water, although to make environmental classifications more accurate a process of increasing number of compartments to 32 is in progress (Sveriges Lantbruksuniversitet 2013). Average theoretical retention time for water in Mälaren is 2.8 years (Sonesten 2012). Mälarens vattenvårdsförbund (2010) indicates that a large portion of the water in Mälaren takes a northerly route. Ages of Mälaren water after a three year hydrodynamic simulation based on the six hydrodynamic compartments are presented in Figure 2. Water flow from Stäket is considered a separate contributor and water entering is assumed to be new in the context of residence time in the simulation (Mälarens vattenvårdsförbund 2010).

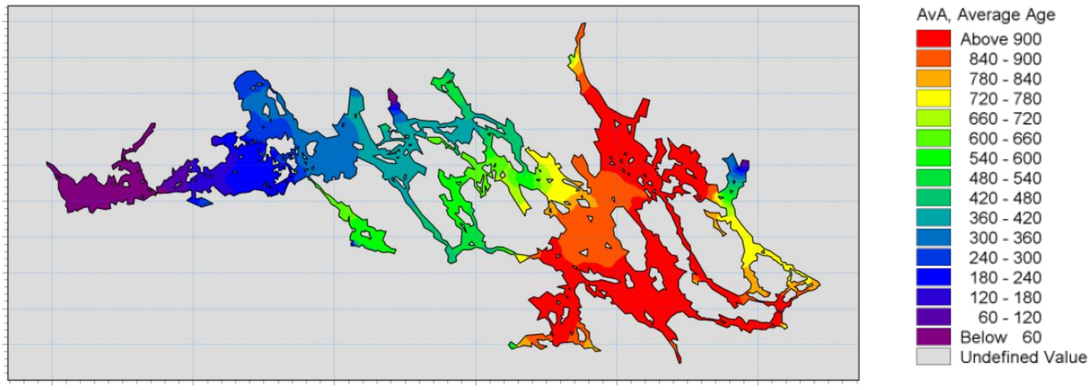


Figure 2 Simulated age of water after a three year period, legend numbers are presenting age in days (Mälarens vattenvårdsförbund 2010).

2.3.5 Selection of study area

To narrow down the investigated area, consideration has been taken to hydrodynamics of Mälaren, land use types and location of the drinking water intakes. The drainage point for the sub-catchment area, called "Rinner till Mälaren-Görväln" by Sveriges Hydrologiska och Meteoroligiska Institut, drains a large catchment area of 4130 km^2 (Sveriges Hydrologiska och Meteorologiska Institut 2014d). This drainage point will be further referred to as "Stäket", and it is located approximately 6 km from the drinking water intake of Görväln DWTP. Stäket catchment area includes large parts of Uppsala county and Västmanlands county, two counties that between 1995 and 2010, unlike the other counties of Sweden, have increased its agricultural land area (Boverket 2012). Land use in that area consists of almost 30 % agricultural land.

3 Methodology

3.1 Study area - Stäket drainage area

The area chosen for the model setup is the catchment area drained at Stäket. It is 4130 km^2 of which 29.7 % is agricultural land (Sveriges Hydrologiska och Meteorologiska Institut 2014d). Legislation for sensitive agricultural land is applied to the whole drainage basin (Jordbruksverket 2013) stating that manure only is allowed to be spread between 1st of March and 31st of July without extended technical demands. Main five rivers are Fyrisån, Örsundaån, Oxundaån, Knivstaån and Märstaån. In Figure 3 the area is marked with a black line, note that the river Knivstaån is incorporated into Fyrisåns catchment area. Stäket drainage point and Görväln DWTP are also marked in Figure 3. Lake Mälaren compartments Ekoln, Gorran, Oxen, Ullfjärden, Skofjärden, Sigtunafjärden and Skarven are located within the area. Sources of faecal contamination in the area that are included in the modelling are agriculture, WWTP and OWTS.

Figure 3 Stäket drainage basin, map edited from (Sveriges Lantbruksuniversitet 2013).

3.2 SWAT modelling

3.2.1 Model setup

ArcSWAT version 2012.10_1.13 was used for modelling faecal contamination in Stäket drainage basin. Topological, geographical, geological and meteorological data are providing the base for the modelling of faecal contamination transport and fate were used according to Table 4. Digital Elevation Model (DEM), a raster data set with the grid size 50x50 m, originating from the Swedish National Land Survey, was obtained from Sokolova (2009). First it was cropped in order to minimize calculation time and to more accurately fit the drainage basin and then loaded into SWAT. In order to accurately reproduce the river network and also to avoid errors due to that SWAT cannot model the presence of lakes within the catchment, the river burn in shape file from Sokolova (2009) was modified to the Stäket drainage area and used as a predefined outline of the rivers.

Table 4 Input data for hydrological setting and location of point sources.

Data type	**Origin**	**File type**	**Resolution**
Digital Elevation Model	Swedish national land survey	Raster	50x50 m
River burn in	Sokolova 2009	Shape	Coarse
Flow gauges location	SMHI	Text	Six stations
Point source location	PLC5[b]	Text	Nine WWTP
Land use	EEA (CORINE) [c]	Shape	95x95 m
Soil	Swedish national land survey[a]	Shape	1:1 000 000, ten different soil types
Slope	SWAT calculates from DEM	Raster	Two classes
Meteorological data	SMHI	Text	Daily recordings

a) Sveriges geologiska undersökning (2014)
b) Svenska miljöemissionsdata (2006)
c) Obtained from Sokolova (2009) but can also be downloaded at http://www.eea.europa.eu/data-and-maps

Based on the DEM, SWAT determined the slope. From the slope and the burn in river file, SWAT derived the delineation of the catchment, its subbasins and the river network. Locations of flow measuring points from SMHI used for flow validation as well as the locations of WWTPs from the PLC5 as point sources were entered into SWAT. The drainage basin according to SWAT is displayed in Figure 4.

SWAT defined 35 different subbasins with areas from 1 to 346 km^2. The total drainage area is calculated to be 3744 km^2. Slope class 0-10 % was assigned 93 % of the drainage area and slope class 10-9999 % to the other 7 %. Nine WWTPs and six monitoring stations were located within the area. The monitoring point located in subbasin 35 represents the discharge point at Stäket and not a water flow gauge station.

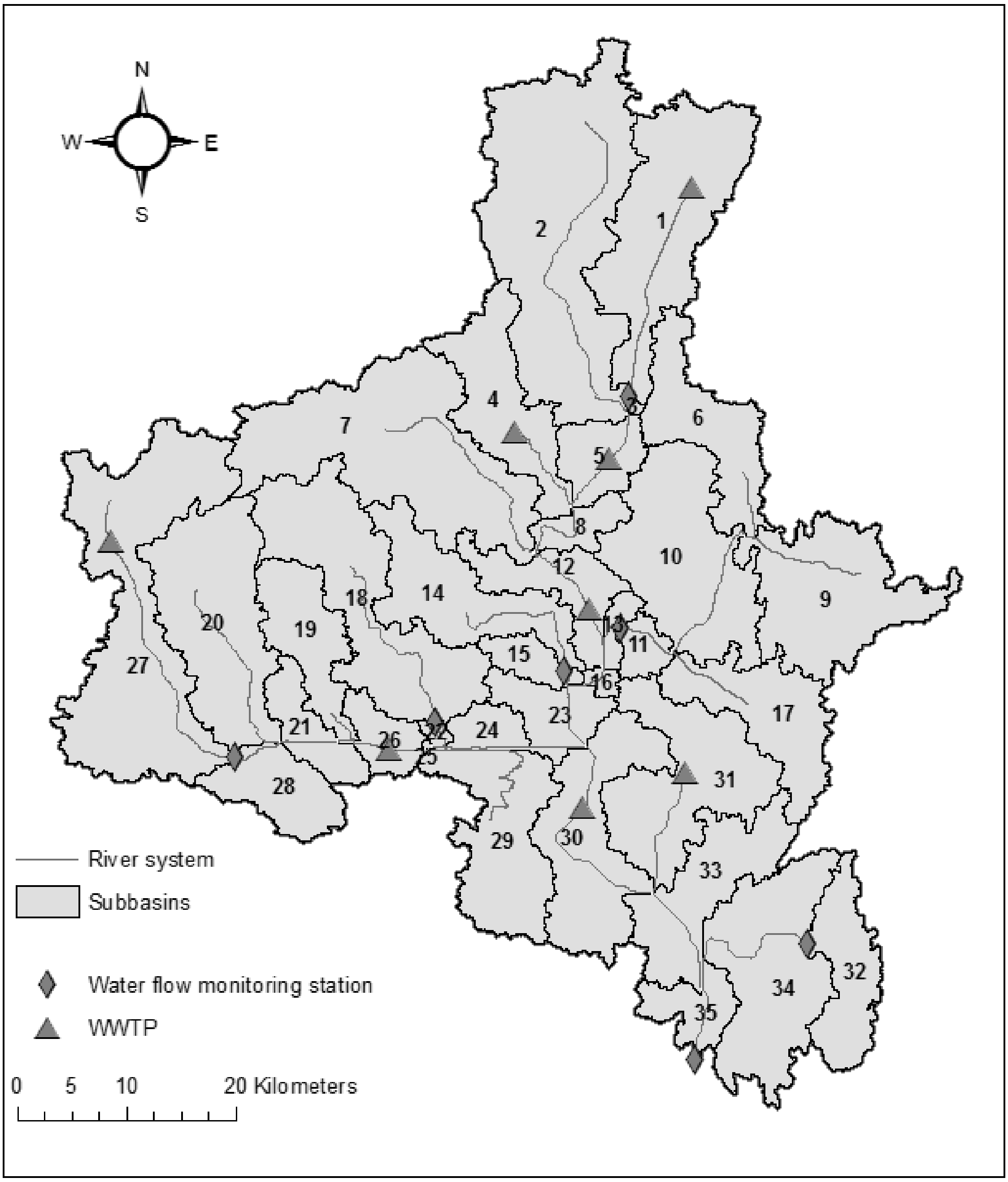


Figure 4 Stäket drainage basin defined by SWAT. Water flow monitoring station in subbasin 35 is symbolising the catchment's draining point.

Land use data (CORINE) from European Environmental Agency were obtained from Sokolova (2009) and were reclassified into land use options provided by SWAT. Land classified as pasture was defined as Tall fescue (FESC) in line with (Arnold et al. 2012b) that states that pasture on latitudes higher than 37° should use settings for Tall fescue instead. Other land use classes within the area were mixed (FRST), deciduous (FRSD) and evergreen (FRSE) forest as well as urban areas (URBN), range land (RNGE), agricultural land (AGRL) water (WATR) and wetland (WETL). A shape file of SGU's soil map "Jordarter" (Sveriges geologiska undersökning 2014) in scale 1:1 000 000 was used. Parameters for Swedish soils were manually interpreted and a match was chosen from the soil types defined by SWAT, as displayed in Table 5.

Table 5 Interpretation of Swedish soil types into SWAT soil types.

Swedish soil type	**SWAT soil type chosen**	**Clay (%)**	**Silt (%)**	**Sand (%)**	**Total rock weight (%)**	**Organic content**
Torv [d]	BUCKSPORT	10	45	45	0	9.88
Lera--silt [a]	KINGSBURY	38	54	7	0	3.49
Postglacial sand-grus [c]	PILLSBURY	7	45	47	40	0
Isälvssediment [b]	HINCKLEY	6	7	87	22	2.33
Moränlera och/eller morän, lerig [b]	FREDON	14	20	66	6	2.65
Morän [b]	SCARBORO	4	16	80	20	0
Berg (även tunt eller osammanhängande jordtäcke på berg)	ROCK OUTCROP	-	-	-	-	0
Morän och/eller vittringsjord, ler--block [b]	PITTSFIELD	6	34	60	40	0
Vatten	WATER	-	-	-	-	0

a) Interpreted through Sveriges geotekniska institut (2014)
b) Interpreted through Sveriges geologiska undersökning (2000)
c) Interpreted through Sveriges geotekniska institut (2003)
d) SWAT soil type with highest organic content was chosen

Two slope classes were defined, one 0-10 % slope class and one class for all slopes steeper than this (10-9999 %). Thresholds for HRU definition were set to 1% for land use and 5 % for soil type and slope. In total SWAT identified 899 different HRUs. Precipitation data were downloaded from SMHI open data set (Sveriges Meteorologiska och Hydrologiska Institut 2014c). Sätra gård, Vallentuna, Vattholma and Vittinge measuring stations were used for the period from 1st of January 2002 and 31st of December 2011. Daily temperature from SMHI open data set were used (Sveriges Meteorologiska och Hydrologiska Institut 2014c). Uppsala and Stockholm measuring points, with measurements for both maximum and minimum temperature of the day were used for the period between 1st of January 2002 and 31st of December 2011. Hourly measurements of wind speed and humidity (Sveriges Meteorologiska och Hydrologiska Institut 2014c) were recalculated into daily averages. Measurements on wind speed between 1st of June 1985 and 30th of November 2013 were used from the stations Uppsala and Stockholm. Measurements on humidity between 1st of June 2000 and 30th of November 2013 from the stations Adelsö and Films Kyrkby were used. To generate data on solar radiation the US first order weather database provided by SWAT was used.

3.2.2 Faecal contamination parameters

In the model, persistent organisms were representing the pathogen *Cryptosporidium* spp. and less persistent organisms were representing the indicator organism *E. coli*. Growth for both *E. coli (Ohlsson et al. 2011)*[2] and *Cryptosporidium* spp. (World Health Organisation 2011) was set to zero. Parameters used for *E. coli* attributes are displayed in Table 6.

Table 6 E. coli parameters.

Parameter	SWAT abbreviation	Unit	*E. coli*	Value used
Part of the organisms that are in soil solution	BACTKDDB	Fraction, 0≤1	0.9 [b] 0.9 [c] 0.9 [d]	0.9
Coefficient defining ratio between soil solution and runoff organisms.	BACTKDQ	Constant	175 [c]	175
Manure fraction applied to the top 10 mm soil layer.	FRT_SURFACE	Fraction, 0≤1	-	0.5
Die-off, less persistent organisms in soil solution	WDLPQ	1/day	2.1 [a] 0.659 [e]	0.659
Die-off, less persistent organisms during river transport	WDLPRCH	1/day	0.35 [f] 0.990 [e]	0.67
Die-off, less persistent organisms adsorbed to soil particles	WDLPS	1/day	0.023 [a]	0.023
Die-off, less persistent organisms on foliage	WDLPF	1/day	0.016 [a]	0.016
Fraction less persistent organisms washed off in rainfall events	WOF_LP	Fraction, 0≤1	0.5 [e]	0.5

a) Bougeard et al. (2011b)
b) Coffey et al. (2010a)
c) Coffey et al. (2012)
d) Coffey et al. (2012)
e) Bougeard et al. (2011a)
f) Kim et al. (2010)
g) Bougeard et al. (2010)

Literature value for FRT_SURFACE was not obtained; therefore the same value was used for *E. coli* as for *Cryptosporidium* spp. For parameters with more than one reference, the mean was used. Regarding WDLPQ, the value of 2.1 was not used due to that SWAT only accepts values between 0 and 1.

Parameters used for attribute data on *Cryptosporidium* spp. are listed in Table 7. Regarding WDPS, the value of 1.4 was not used due to that SWAT only accepts values between 0 and 1. For BACTKDDB the mean was used.

[2] With favourable conditions *E. coli* can grow in nature, although indicator species are in general assumed not to grow.

Table 7 Cryptosporidium parameters.

Parameter	SWAT abbreviation	Unit	*Crypto-sporidium*	Used
Part of the organisms that are in soil solution	BACTKDDB	Fraction, 0≤1	0.9 [a] 0.2 [b]	0.55
Coefficient defining ratio between soil solution and runoff organisms.	BACTKDQ	Constant	4800 [b]	500 [c]
Fraction of manure applied to the top 10 mm soil layer.	FRT_SURFACE	Fraction, 0≤1	0.5 [b]	0.5
Die-off, persistent organisms in soil solution	WDPQ	1/day	0.05 [b]	0.05
Die-off, persistent organisms during river transport	WDPRCH	1/day	0.01 [a]	0.01
Die-off, persistent organisms adsorbed to soil particles	WDPS	1/day	1.4 [b] 0.003 [a]	0.003
Die-off, persistent organisms on foliage	WDPF	1/day	0.02 [b]	0.02
Fraction persistent organisms washed off in rainfall events	WOF_P	Fraction, 0≤1	0.8 [b]	0.8

a) Coffey et al. (2010b)
b) Tang et al. (2011)
c) Maximum number for SWAT input

3.2.3 Faecal contamination sources

3.2.3.1 Wastewater treatment plants

WWTP dimensioned for more than 2000 users are presented in Table 8 and were entered into SWAT as continuous sources of *E. coli* and *Cryptosporidium* spp. oocysts. Water outflow was obtained from WWTPs environmental reports except from Skokloster. This information was received from the municipality Håbo[3].

[3] Personal communication on 16th of April 2014

Table 8 WWTPs in the drainage area. Connected persons and water flow based on environmental reports.

WWTP	Municipality	Connected persons	Subbasin	Average discharge 2013 (m^3/day)
Heby	Heby	2 630	27	776
Morgongåva	Heby	1 810	27	753
Örsundsbro	Enköping	2 000[a]	26	510[b]
Skokloster	Håbo	2 000[c]	30	510
Knivsta	Knivsta	10 000	31	2 464
Uppsala	Uppsala	164 200	12	57 240
Storvreta	Uppsala	3 695	5	2 070
Björklinge	Uppsala	3 690	4	1 020
Österbybruk	Östhammar	2 450	1	1 493

a) Enköping Kommun (2014)
b) No available data, hence same number Skokloster WWTP due to same amount of connected persons
c) Habo Kommun (2014)

Concentration of *Cryptosporidium* spp. oocysts in treated wastewater was set to 0.132 oocysts/100 ml based on Ottoson et al. (2006). *E. coli* concentration in WWTP untreated wastewater has been reported to be 1.5 x 10^6 colony forming units (cfu)/100 ml (Ohlsson et al. 2011). Reduction in Swedish WWTP has been reported to be 2.37 $\log_{10}$ (Ottoson 2006), hence *E. coli* concentration in treated wastewater from WWTPs was set to 10^4 cfu/100 ml.

3.2.3.2 On-site Wastewater Treatment Systems

OWTSs were entered into SWAT using a continuous fertilisation operation, spreading the contribution geographically evenly over the whole subbasin. Based on house properties located outside urban areas (Lantmäteriet 2014) the total numbers of OWTSs in each municipality were recalculated into "OWTS-density". The number of OWTSs in each subbasin was in proportion to the amount of non-urban house properties located within the subbasin. This number was multiplied with the OWTS-density of each municipality. Further information can be found in Appendix I. Numbers of OWTSs in each subbasin are listed in Table 9.

E. coli concentration in untreated wastewater was assumed to be 10^6-10^7 cfu/100 ml (Ottoson 2013). *Cryptosporidium* spp. oocyst concentration in untreated wastewater was reported to be 2 oocysts/100 ml (Ottoson et al. 2006). *E. coli* reduction in OWTS has been reported to be 99 % for infiltration and 95 % for drain fields (Naturvårdsverket 2003). These two types of OWTS constitute the majority of OWTSs in Sweden (Havs och Vattenmyndigheten 2008). Reduction was set to 2 $\log_{10}$ units for both *E. coli* and *Cryptosporidium* spp. oocysts. Hence, *E. coli* concentrations in outlet were set to 10^5 cfu/100 ml and concentrations of *Cryptosporidium* spp. oocyst to be 0.02 oocysts/100 ml. Wastewater was assumed to have the density 1 kg/dm^3 (Coffey et al. 2010b). Based on total numbers of OWTS in each county and number of people living in residences with OWTS (Svenska miljöemissionsdata

2006) each OWTS was assumed to have 2.5 persons in the household and each person assumed to produce 160 l wastewater (Havs och vattenmyndigheten 2013) each day.

Table 9 Numbers of OWTS in each subbasin.

Subbasin	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	194	2 396	1	866	317	447	1 198
Subbasin	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	173	630	1 460	192	299	2	513
Subbasin	**15**	**16**	**17**	**18**	**19**	**20**	**21**
	231	1	876	885	445	715	247
Subbasin	**22**	**23**	**24**	**25**	**26**	**27**	**28**
	60	241	251	3	171	1 129	445
Subbasin	**29**	**30**	**31**	**32**	**33**	**34**	**35**
	306	839	1 168	211	313	37	24

3.2.3.3 Agriculture

Amount of manure applied to agricultural land was based on number of animals in the subbasin. Based on geographical distribution of municipality’s agricultural area, the total numbers of animals in the municipalities were divided into the subbasins. Total agricultural area of each municipality (Lantmäteriet 2014b) was obtained from (Jordbruksverket 2014a). Amount of animals of different types in each municipality, provided by Swedish Department of Agriculture[4], was used to calculate average number of animals per m^2 agricultural land area. All types of agricultural birds (hens, ducks, turkeys etc.) were gathered into one group called poultry, and sheep and goats into one group called sheep. Numbers of animals in each subbasin were calculated using size of the specific municipal agricultural area within the subbasin multiplied with the number of animals per m^2 of each animal for the specific municipality. Contributions from all municipalities within each subbasin were added up to the total numbers of animals of each kind within each subbasin. Further information is provided in Appendix II. Based on manure production per animal type (Jordbruksverket 2013), listed in Table 10, the total amount of manure for each subbasin was calculated. Amounts of manure produced each year per subbasin are shown in Table 11.

Table 10 Amount of manure produced each day by different types of animals. Means from Jordbruksverket (2013).

Species	**Kg/day**
Cattle[a]	17.30
Swine[b]	4.70
Poultry[c]	0.06
Sheep	1.97

a) Mean from dairy cows producing either 6 000, 8 000 or 10 000 kg milk/year
b) Mean from sow in production, sow separated for farrowing during 8 or 16 weeks respectively and sow not separated for farrowing.
c) Mean from hens and pullets

[4] Information from Swedish Department of Agriculture’s record of domestic animals, personal communication on 25th of March 2014

As suggested by Coffey et al. (2012) manure from winter storage was applied to agricultural areas during spring and summer. Fertilising operation was used and the manure was equally distributed over the agricultural areas. Although there can be management and timing differences between farmers regarding manure application, a general praxis was adopted. Based on information regarding manure application time in the counties Uppsala and Stockholm (Statistiska Centralbyrån 2012) 60 % of the winter stored manure was applied in the 15 April and 40 % was applied on the 30th of September. All animals were assumed to be grazing between 1st of June and the 31th of August, based on legal requirements for cattle (Jordbruksverket 2014b). Manure produced during this time was applied using the grazing operation and equally distributing the manure over range (RNGE) and pasture (FESC) areas.

Table 11 Manure produced (kg) during one year for each species within each subbasin.

Subbasin	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cattle	18 554 363	36 508 977	29 469	10 783 056	5 021 286	8 212 691	19 670 046
Sheep	662 677	1 115 800	1 354	494 799	230 781	377 460	904 334
Swine	612 118	1 281 019	1 693	618 391	288 500	471 863	1 131 746
Poultry	171 773	697 066	618	226 065	105 313	172 248	729
Subbasin	**8**	**9**	**10**	**11**	**12**	**13**	**14**
Cattle	3 396 203	7 194 818	14 172 542	2 023 831	5 023 796	1 485 048	8 551 739
Sheep	156 091	340 398	665 440	93 925	230 897	68 253	393 043
Swine	195 130	435 017	831 276	117 377	288 644	85 324	491 343
Poultry	71 230	145 962	288 664	41 892	105 366	31 146	179 359
Subbasin	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Cattle	2 331 588	46 301	3 149 683	14 052 543	3 589 554	8 032 388	3 008 472
Sheep	107 161	2 979	259 533	637 182	139 617	327 694	100 011
Swine	133 962	3 688	533 031	973 983	690 809	1 698 609	903 145
Poultry	48 901	451	68 651	287 003	52 897	91 838	29 390
Subbasin	**22**	**23**	**24**	**25**	**26**	**27**	**28**
Cattle	458 912	3 227 011	3 320 201	35 877	15 93 715	13 517 860	4 904 320
Sheep	18 117	151 656	155 621	1 192	53 224	530 674	163 035
Swine	83 139	189 445	240 115	10 770	473 771	3 103 071	1 472 280
Poultry	7 004	65 642	69 428	350	15 784	149 972	47 912
Subbasin	**29**	**30**	**31**	**32**	**33**	**34**	**35**
Cattle	3 007 520	3 442 766	4 792 140	3 784 236	2 667 847	8 074 914	714 716
Sheep	266 383	298 997	400 184	259 155	221 993	446 855	46 252
Swine	3 115 806	995 352	1 031 339	989 651	664 820	906 187	15 076
Poultry	21 481	38 286	174 035	24 937	134 177	137 029	327

Prevalence was entered as a factor to adjust the manure *Cryptosporidium* spp. oocyst concentrations. Values of *Cryptosporidium* spp. oocyst concentration in manure from different animals were multiplied with the prevalence for that animal type displayed in Table 13. SWAT maximum manure concentrations for both persistent and less persistent bacteria is 110 000 cfu/g, therefore limits for faecal contamination in manure were modified in SWAT and increased to 1 000 000 000 cfu/g.

E. coli concentrations in different types of animal manure are listed in Table 12. Mean was used for cattle and sheep. BACTLPDB is SWAT abbreviation for concentration of less persistent bacteria in manure.

Table 12 E. coli concentrations in different types of manure.

Animal type	*E. coli* (cfu/g)	BACTLPDB used (cfu/g)
Calves	4.2×10^5 [a]	
	4.2×10^5 [a]	
Cattle	8.2×10^4 [b]	
	5.0×10^7 [c]	7.75×10^6 (Used for cattle)
	1.1×10^3 [d]	
Cows	2.9×10^4 [e]	
	4.0×10^7 [e]	
Sheep	6.6×10^4 [a] 3.9×10^7 [c]	1.503×10^7 (Used for sheep)
Swine	3.0×10^7 [c]	3.0×10^7 (Used for swine)
Mix of Pig, Cattle and poultry	8.9×10^5 [f]	8.9×10^5 (Used for poultry)

a) Coffey et al. (2010a)
b) Moriarty et al. (2008)
c) Avery et al. (2004)
d) Donnison et al. (2008)
e) Kim et al. (2010)
f) Bougeard et al. (2011b)

Cryptosporidium spp. oocyst concentrations in different types of animal manure and prevalence are displayed in Table 13. Means were used for cattle and sheep. BACTPDB is SWAT abbreviation for concentration of less persistent bacteria in manure.

Table 13 Cryptosporidium spp. oocyst concentrations in different types of manure.

Animal type	*Cryptosporidium* spp. (oocysts/g)	Prevalence	BACTPDB used (oocysts/g)
Calves	3643 [a]		
Cattle	398 [a]	0.254 [c]	372 (Used for cattle)
Dairy cows	353 [a]		
Lambs	17 976 [a]	0.133 [c]	111 (Used for sheep)
Sheep	837 [a]		
Swine	367 [b]	0.322 [c]	118 (Used for swine)
Poultry	0 [b]	0 [b]	0 (Used for poultry)

a) Coffey et al. (2010b)
b) Cox et al. (2005)
c) Åström (2013), prevalence was based on methodology suggested by Dorner et al. (2004) combining different prevalence for different types and ages of animals into one single value.

3.2.4 Model calculations

3.2.4.1 Land transport

The hydrological cycle is the driving force behind water flow and organism transport in the catchment and it is affected by climate (precipitation, solar radiation, temperature and humidity), type of soil and type of crop grown. For more information on the calculations behind and further information on the different factors in equation (1), I refer to the SWAT theoretical documentation (Nietsch et al. 2011).

The soil water content is based on the general calculation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (1)$$

Where SW_t is the water content, SW_0 is the initial water content of the day, t is the time (day), R_{day} is the amount of precipitation of day *i*, E_a is the amount of evapotranspiration on day *i*, w_{seep} is the amount of water entering the vadose zone on day *i* and Q_{gw} is the amount of water in return flow on day *i*.

3.2.4.2 River transport

SWAT models the mass flow of water in the river channel as well as processes in the water and sediments such as evaporation, transmission through river bed, sedimentation, resuspension and organism die–off. For further information on factors in equation 2 and calculations behind I refer to the SWAT theoretical documentation (Nietsch et al. 2011). Water mass balance is calculated using:

$$V_{stored,2} = V_{stored,1} + V_{in} - V_{out} - tloss - E_{ch} \pm div + V_{bnk} \quad (2)$$

Where $V_{stored,2}$ is the amount of water in the river section at end of the time step, $V_{stored,1}$ is the amount of water at start of time step, V_{in} is the amount of water that flows in to the section, V_{out} is the water flowing out of the section, *tloss* is the water loss from transmission through stream bed, E_{ch} is the amount of water lost due to evaporation in the river section, div is water added or removed through diversion practices and V_{bnk} is the amount of water that enters the section from bank storage.

3.2.4.3 Transport and fate

Below is a presentation of the model calculations that involves organism die-off and transport. Abbreviations in capital letters within [CAPITAL LETTERS] are the one used in Soil and Water Assessment Tool – Theoretical documentation version 2009 (Nietsch et al. 2011) and Soil and Water Assessment Tool – Input/Output documentation version 2012 (Arnold et al. 2012b). Displayed functions below were also attained from these two references.

During transportation from source to the river, die-off is calculated separate for three different pools: on foliage, adsorbed to soil particles and in soil solution (Arnold et al. 2012b) using the formula:

$$org_{\downarrow}(pool_{\downarrow}i) = org_{\downarrow}(pool_{\downarrow}y) * e^{\uparrow}((-((\mu d - \mu g)\theta(T - 20)))) - \min - loss \quad (3)$$

Where org_{pool_i} is the amount of organisms present day, each pool calculated separately, org_{pool_y} is the number of organisms in the specific pool on the day before, µd is the rate constant for die off for the specific pool [WDPQ, WDLPQ, WDPQ, WDPS, WDLPQ, WDPF and WDLPF], µg is the rate constant for growth for the specific pool [WGPQ, WGLPQ, WGPQ, WGPS, WGLPQ, WGPF and WGLPF], θ is the temperature adjustment factor [THBACT], T is the average mean daily temperature and min_{loss} [BACTMINLP and BACTMINP] is the minimum daily loss of the specific organism.

In the case of rainfall events (>2.54 mm rain during one day) organisms in the foliage pool can be washed off entering the soil solution pool according to the function:

$$org_{wsh} = fr_{wsh} * org_{fol} \quad (4)$$

Where org_{wsh} is the amount of organisms washed off, fr_{wsh} is the proportion of organisms on foliage that is dislodgable [WOF_P and WOF_LP] and org_{fol} is the amount of organisms in the foliage pool.

Organism routes can be either through run-off or percolating through the soil. All organisms percolating are assumed to die and calculation is made through:

$$org_{perc} = \frac{org_{sol} * w}{10 * p * d_{surf} * k_{perc}} \quad (5)$$

Where org_{perc} is the amount of organisms percolating through soil, org_{sol} is the amount of organisms in soil solution, w is the amount of water percolating from the top 10 mm soil to the first soil layer, p is the soil bulk density [SOL_BD], d_{surf} is the depth of 10 mm top soil (always 10 mm) and k_{perc} is the percolation coefficient [BACTMIX]. Transport in surface runoff is calculated through:

$$org_{surf} = \frac{org_{sol} * Q_{surf}}{p * d_{surf} * k_{part}} \quad (6)$$

Where org_{surf} is the amount of organisms lost in surface runoff, org_{sol} is the amount of organisms in soil solution, Q_{surf} is the amount of surface runoff the given day, p is the soil bulk density [SOL_BD], d_{surf} is the depth of 10 mm top soil (always 10 mm) and k_{part} is the partitioning coefficient [BACTKDQ].

Transport attached to sediments is calculated through:

$$org_{sed} = 0{,}1\left(\frac{org_{part} * sed}{p * d_{surf} * area_{hru}}\right) * 0{,}78\left(\frac{sed}{10 * area_{hru} * Q_{surf}}\right)^{-0{,}2468} \quad (7)$$

Where org_{sed} is the amount of organisms transported with sediment, org_{part} is the amount of organisms attached to soil particles, *sed* is the sediment yield of the given day, p is the soil bulk density, d_{surf} is the depth of 10 mm top soil (always 10 mm) $area_{hru}$ is the area of the HRU and Q_{surf} is the amount of surface runoff the given day.

Only a part of surface runoff generated in one day reaches the river during that day, other organisms are stored in runoff lags. Runoff associated organisms reaching the river is calculated through:

$$org_{rof} = org'_{rof} + org_{sedstore_i}\left(1 - exp\left(-\frac{surlag}{t_{conc}}\right)\right) \quad (8)$$

Where org_{rof} is the amount of organisms entering the river from surface runoff the given day, org'_{rof} is the amount of organisms generated in the HRU on the given day,

$org_{sedstore\_i}$ is the amount of organisms stored in surface lag from the day before, *surlag* is the surface runoff lag coefficient [SURLAG] and t_{conc} is the time of the concentration for the HRU.

After organisms enter the river either through run-off or as point sources, die-off is calculated using the formula:

$$org_{rch_i} = org_{rch_y} * e^{\left(-\left((\mu d_{rch})\theta(T_{water}-20)\right)\right)} \quad (9)$$

Where org_{rch_i} is amount of organisms present in the river on day I, org_{rch_y} is the amount of organisms present in the river yesterday, μd_{rch} is the rate constant for die off in river [WDPRCH and WDLPRCH], θ is the temperature adjustment factor [THBACT] and T_{water} is the water temperature.

The concentration of organisms in the river is calculated with the formula:

$$conc_{org_{ch}} = 10^{-4} * \frac{org_{ch_i} + org_{deg} - org_{dep}}{V_{ch}} \quad (10)$$

Where $conc_{org\_ch}$ is the concentration of organisms in the river, org_{ch_i} is the initial amount of organisms in the river, org_{deg} is the amount of organisms released from streambed, org_{dep} is the amount of organisms settling to streambed and V_{ch} is the water volume present in the river.

Organisms attached to sediment settles according to

$$org_{dep} = org_{ch_i} * \frac{K_p * sed_{dep}}{V_{ch} + K_p * conc_{sed_{ch_i}} * V_{ch}} \quad (11)$$

Where K_p is the linear partitioning coefficient between organisms in suspended sediment and in water, sed_{dep} is the amount of sediment deposited to streambed, and $conc_{sed\_ch\_i}$ is the initial sediment concentration in the river. Other abbreviations are already explained in previous equations.

sed_{dep} is calculated with:

$$sed_{dep} = \left(conc_{sed_{ch_i}} - conc_{sed_{ch_{mx}}}\right) * V_{ch} \quad (12)$$

Where $conc_{sed\_ch\_mx}$ is the maximum sediment the river can transport and the other abbreviations already are explained.

K_p is calculated through:

$$K_p = 10^{-1,6} * clay^{1,98} \quad (13)$$

Where clay is the percentage of clay in the soil.

Re-suspension from streambed is calculated according to the equation:

$$org_{deg} = sed_{deg} * conc_{org_{sed}} \quad (14)$$

Where sed_{deg} is the amount of sediment re-entering the river water from streambed and $conc_{org\_sed}$ is the concentration of organisms in the streambed sediment.

sed_{deg} is calculated:

$$sed_{deg} = \left(conc_{sed_{ch_{mx}}} - conc_{sed_{ch_i}}\right) * V_{ch} * K_{ch} * C_{ch} \quad (15)$$

Where K_{ch} is the channel erodibility factor for that soil type and C_{ch} is the channel cover factor.

$conc_{org\_sed}$ is calculated:

$$\log\left(conc_{org_{sed}}\right) = bsc_1 * \sin\left(bsc_2 * \frac{day - bsc_3}{366} * \pi\right) + bsc_4 \quad (16)$$

Where day is the day of the year and bsc_1-bsc_4 are regression coefficients. Values during simulations were bsc_1=0.1, bsc_2=0.1, bsc_3=0.02 and bsc_4=0.35.

3.3 Model evaluation

3.3.1 Sensitivity analysis

To estimate the sensitivity of input data, several “trail-models” were set up. Monthly modelled water flow was manually compared to the flow measurements at the stations Sävjaån, Sävaån and Härnevi located in the subbasins 11, 18 and 27 respectively. Other subbasins with water flow gauges were chosen not to be used due to big differences in subbasin area definition between SWAT and SMHI. Results from the sensitivity analysis showed that if a fine resolution river burn in file and over 300 subbasins defined for the drainage basin were used, it was no difference compared to the coarse river burn in file and 35 subbasins defined for the drainage basin. Precipitation data with daily measurements from four measuring stations were more accurate than hourly measurements from two measuring stations. Using solar radiation data either generated from US first weather database or data downloaded from SWAT official global weather data (Texas A&M University 2014) showed no difference in output. Manual interpretation of Swedish soil types into SWAT soil types and a coarse soil map were more accurate than soil type parameters defined by SGU and a fine soil map. Swedish soil type clay make up 45 % of subbasin 11 and 35 % of subbasin 27 and changing the interpretation of this soil type from SWAT soil type KINGSTON to SWAT soil type PANTON gave no change in output.

3.3.2 Performance parameters

SWAT performance was evaluated using the Nash-Sutcliffe Efficiency (NSE) and R^2. Both R^2 and NSE have some bias towards high flows (Arnold et al. 2012a). Outliers, magnitude and time shift biases as well as time step are significant factors affecting the outcome of NSE (McCuen et al. 2006). Although R^2 and NSE were chosen on the basis of that these are recommended and the most commonly used for evaluating SWAT performance (Moriasi et al. 2007). NSE is a statistical method for evaluating the accuracy of a hydrological model. NSE results range from -∞ to 1. If the result is less than zero, accuracy would be higher if observed mean values were used instead of modelled values (Moriasi et al. 2007). Calculations are made according to equation 17 and evaluation was made based on performance categories listed in Table 14.

$$NSE = 1 - \left(\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{P})^2}\right) \quad (17)$$

Where O_i is the observed value at time i, P_i is the simulated value at time i and $\overline{P}$ is the mean for the observed values.

Table 14 Evaluation of model performance suggested by Parajuli (2007) adopted from Moriasi et al. (2007).

Performance	NSE range
Excellent	≥0.90
Very good	0.75-0.89
Good	0.50-0.74
Fair	0.25-0.49
Poor	0-0.24
Unsatisfactory	<0

R^2 is a measurement of the linear relationship between modelled and observed data. Values range from 0-1 and acceptable results are $R^2 \geq 0.50$ (Moriasi et al. 2007). R^2 is calculated using equation 18.

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n} (O_i - \overline{O})^2 * \sum_{i=1}^{n} (P_i - \overline{P})^2}} \right)^2 \quad (18)$$

Where O_i is the observed value at time $_i$, $\overline{O}$ is the mean for observed values, P_i is the simulated value at time $_i$ and $\overline{P}$ is the mean for simulated values.

3.3.3 Calibration

SWAT-CUP version 5.1.6.2 was used for flow calibration. Calibration was performed on a monthly basis for the subbasins 11, 18 and 27 between the years 2003-2006 and this corresponds to 48 data points. The first year of simulation, 2002, was used as a warm up period for the model. Water flow measurements were collected from SMHI "Vattenwebb" open data set (Sveriges Hydrologiska och Meteorologiska Institut 2014d). Water flow gauges locations, river measured as well as names and station numbers are displayed in Table 15.

Table 15 Water flow measurement points.

Station	River name	SMHI Station-number	Sub-basin	Longitude (Decimal degrees)	Latitude (Decimal degrees)
Härnevi	Örsundaån	2248	27	17.069565	59.733069
Ransta	Sävaån	2247	18	17.393286	59.757926
Stabby	Stabbybäcken	1742	14	17.583200	59.795538
Sävja	Sävjaån	2243	11	17.704470	59.829038
Vattholma 2	Vattholmaån	2244	1	17.730636	60.019625
Skällnora	Oxundaån	1843	32	17.978692	59.485022

A total of 1000 simulations were used for calibration. Between each simulation SWAT-CUP used a new set of parameter values that were within parameter value ranges according to Table 16. Ultimately SWAT-CUP creates a parameter set for the best simulation.

Table 16 Parameters calibration ranges. For detailed information on parameters I refer to Arnold et al. (2012b).

SWAT parameter	Description	Min	Max
CN[a]	Initial SCS runoff curve moist conditions II	-0.5	0.5
ALPHA_BF[b]	Base flow alpha factor	0	1
GW_DELAY[b]	Ground water delay	30	450
GWQMN[b]	Threshold depth of water in the shallow aquifer for return flow to occur	0	2
GW_REVA [b]	Groundwater revap coefficient	0	0.2
ESCO[b]	Soil evaporation compensation factor	0	1
CH_N2[b]	Manning's n-value for main channel	0	0.3
CH_K2[b]	Effective hydraulic conductivity - main channel alluvium	5	400
ALPHA_BNK[b]	Baseflow alpha factor for bank storage	0	1
SOL_AWC[a]	Available water capacity of the soil layer	-0.5	0.5
SOL_K[a]	Saturated hydraulic conductivity	-0.5	0.5
SOL_BD[a]	Soil bulk density	-0.5	0.6
SFTMP[b]	Snow fall temperature	-5	5

a) Minimum and maximum refers to the percentage range parameter value is allowed to change from original value between simulations
b) Minimum and maximum refers to the allowed range of absolute parameter values.

3.3.4 Validation

Modelling years 2007-2011 were used for flow validation, which was performed on a monthly basis using ArcSWAT. Based on the results of statistical calculations, best parameter values from calibration simulations were used for the validation.

3.3.5 *E. coli* and *Cryptosporidium* spp. oocyst load

E. coli and *Cryptosporidium* spp. oocyst loads were evaluated for Stäket drainage point. Simulations for 2003-2011 were used for acquiring *E. coli* and *Cryptosporidium* spp. oocyst concentrations. Results for *E. coli* were compared to the values for Swedish bathing water quality displayed in Table 17 and results for *Cryptosporidium* spp. oocyst were compared to other studies using SWAT to model fate and transport of *Cryptosporidium* spp. oocysts. For comparison only, water quality measurements at the closest bathing place, Bonäsbadet located 250 m south from Stäket drainage point, have been also used (Folkhälsomyndigheten 2014a).

Table 17 Swedish bathing water quality, adopted from Ohlsson et al. (2011).

Quality	*E. coli* (cfu/100 ml)
Acceptable	<100
Less acceptable	100–1000
Unacceptable	>1000

4 Results

4.1 Water flow calibration

Observed monthly values and the best estimate from calibration of subbasin 11, 18 and 27 are displayed in Figure 5.

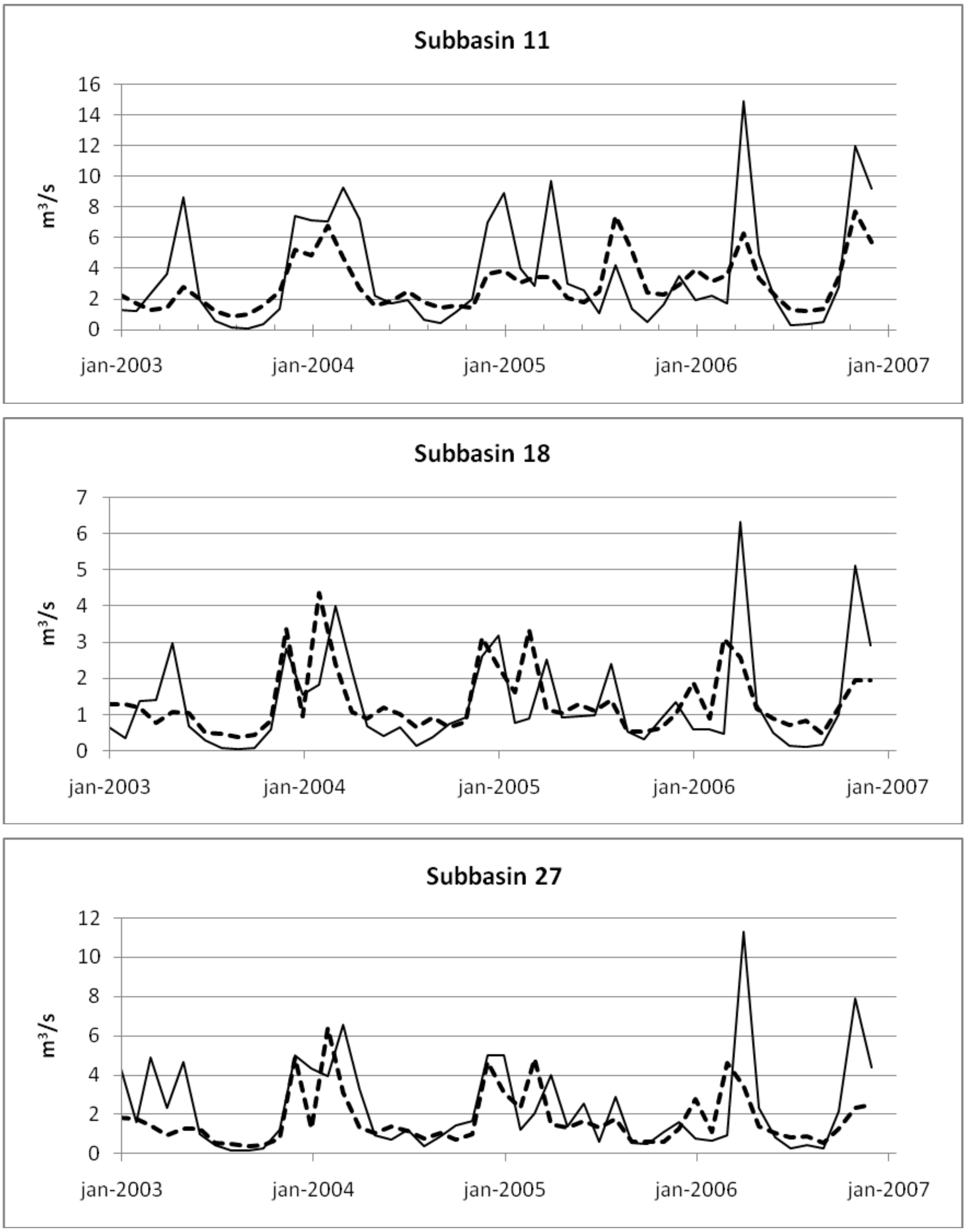


Figure 5 Flow calibrations of subbasins 11, 18 and 27. Dotted line represents simulated values and the full drawn line represents observed values. NSE equals 0.44, 0.25 and 0.18 and R^2 equals 0.53, 0.27 and 0.26 in subbasins 11, 18 and 27 respectively.

Statistical calculations were performed by SWAT-CUP and results of the calibration are shown in Table 18.

Table 18 Statistic performance during calibration period.

Subbasin	NSE	R^2
11	0.44	0.53
18	0.25	0.27
27	0.18	0.26

SWAT-CUP results showed that the best estimated simulation was found using parameter values presented Table 19.

Table 19 Parameter values for best estimation from calibration.

SWAT parameter	Calibrated values
CN2	0.945748[a]
ALPHA_BF	0.234173
GW_DELAY	120.309
GWQMN	0.201319
GW_REVAP	0.085857
ESCO	0.013628
CH_N2	0.165604
CH_K2	215.411
ALPHA_BNK	0.050516
SOL_AWC	1.44245[a]
SOL_K	1.21727[a]
SOL_BD	1.012349[a]
SFTMP	4.65165

a) Original parameter value multiplied by this number

4.2 Water flow validation

Validation showed that the model performance based NSE was ranging from 0.05 to 0.11. Subbasin 11, 18 and 27 showed poor performance based on NSE. R^2 values were all below the accepted level of 0.50 and ranged from 0.10 to 0.16. Calculations were performed manually for NSE and by Microsoft Excel for R^2. Observed values versus simulated values of water flows in subbasins 11, 18 and 27 are displayed in Figure 6, performance and R^2 are displayed in Figure 7 and a summary of statistical performance can be seen in Table 20.

Table 20 Model performance during validation period.

Subbasin	NSE	R^2
11	0.11	0.16
18	0.05	0.10
27	0.11	0.14

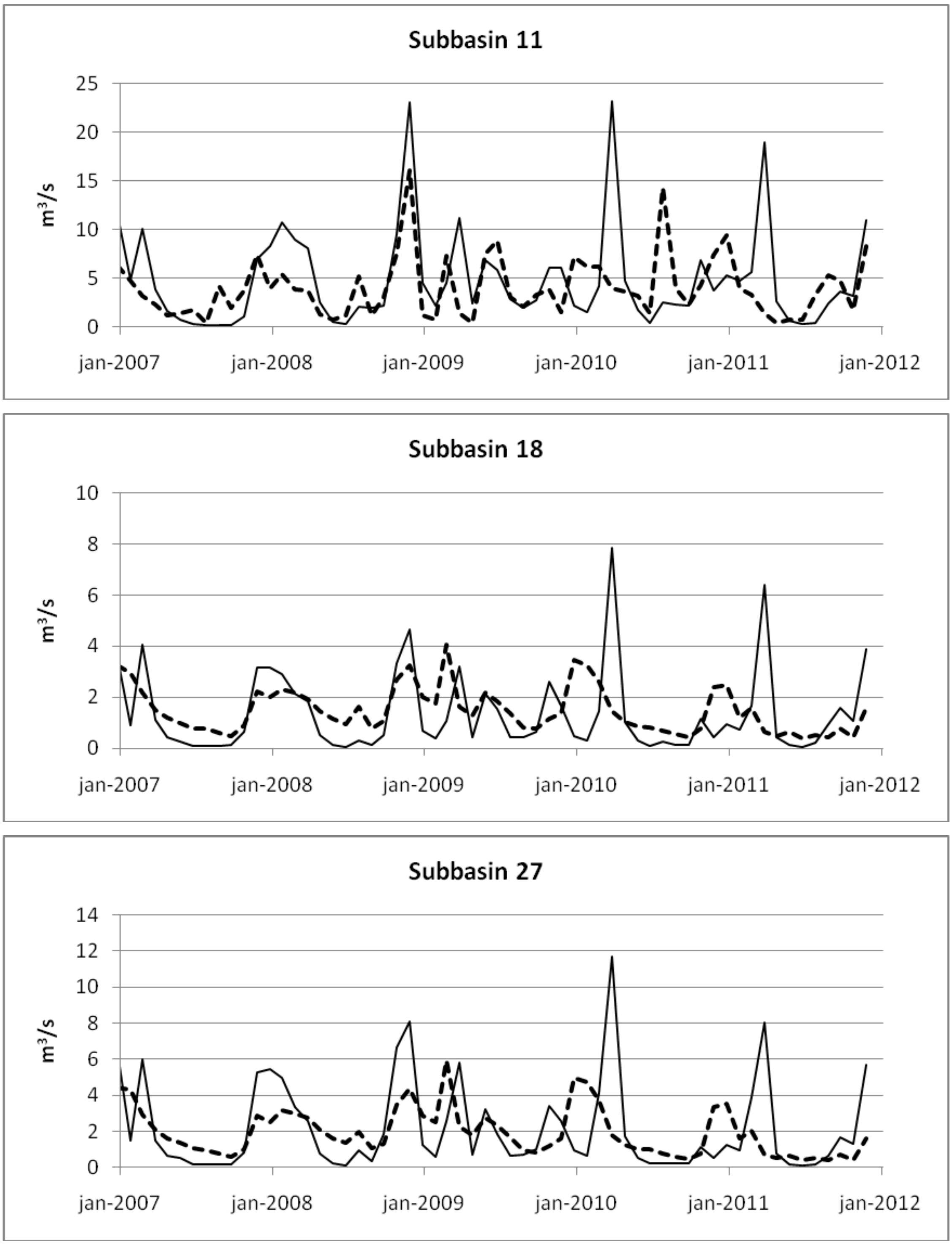


Figure 6 Validation of simulated values versus observed water flow in subbasin 11, 18 and 27. Dotted line represents simulated values and the full drawn line represents observed values. NSE equals 0.11, 0.05 and 0.11 in subbasins 11, 18 and 27 respectively.

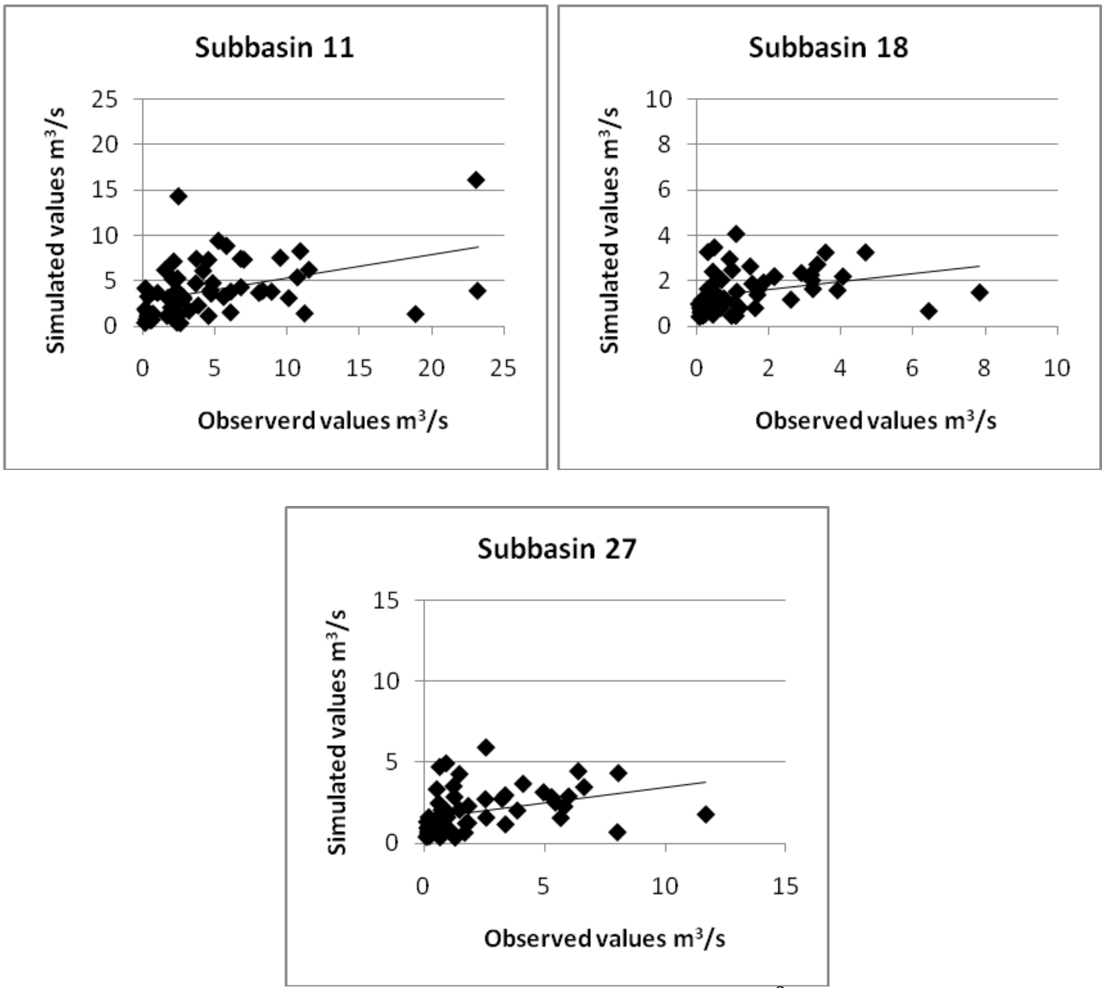
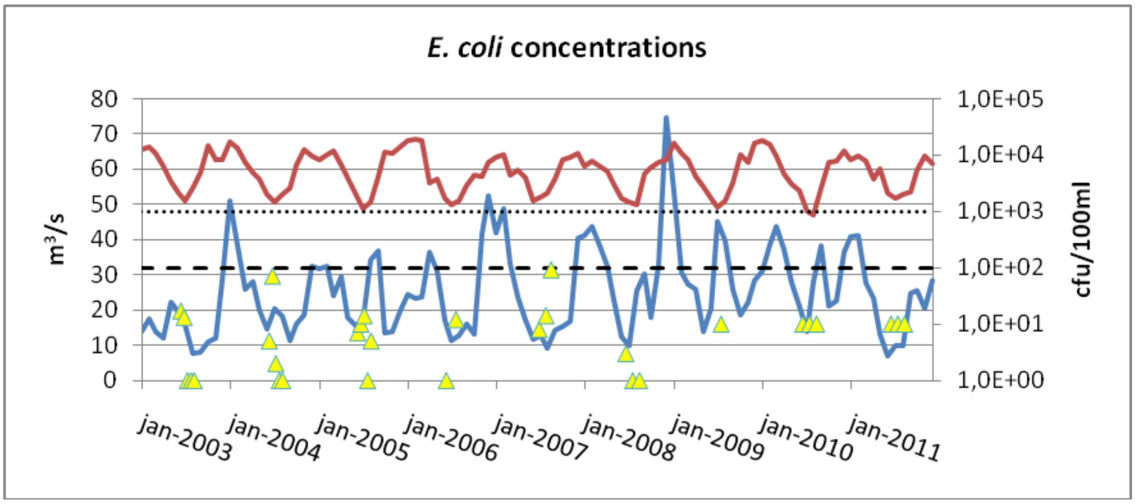


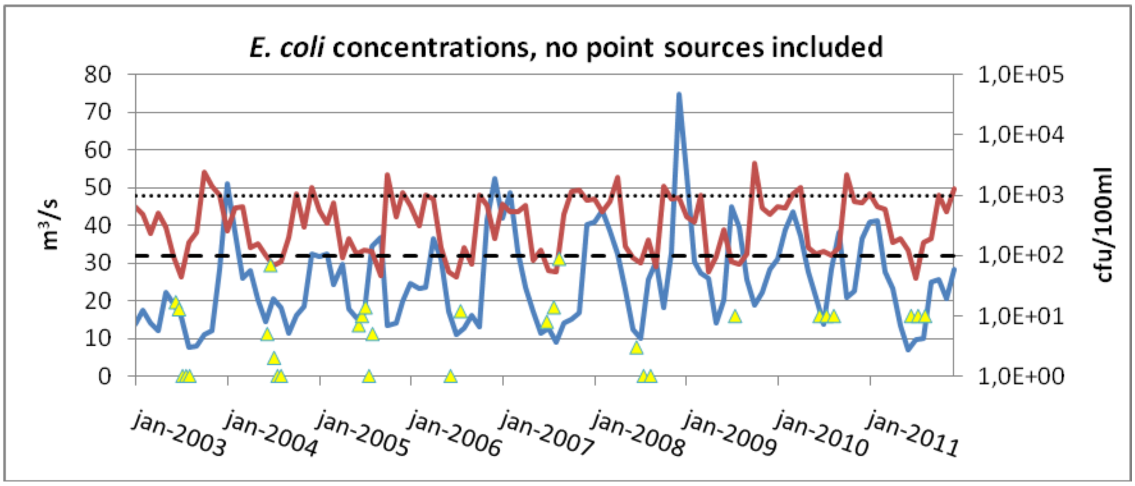
Figure 7 Model performance for subbasins 11, 18 and 27. R^2 equals 0.16, 0.10 and 0.14 in subbasins 11, 18 and 27 respectively.

4.3 *E. coli* and *Cryptosporidium* loads

Monthly simulated *E. coli* concentrations in Stäket outlet and measured *E. coli* concentrations during summer periods in Bonäsbadet are displayed in Figure 8 for a) total *E. coli* and b) for *E. coli* without any contribution from WWTPs. Measured values, yellow triangles, are the same in both a) and b). Mean *E. coli* concentration was 6563 cfu/100 ml, monthly values ranging from 850 to 19480 cfu/100 ml. Without WWTPs, mean *E. coli* concentration was 550, monthly values ranging from 42.1 to 3451 cfu/100 ml.



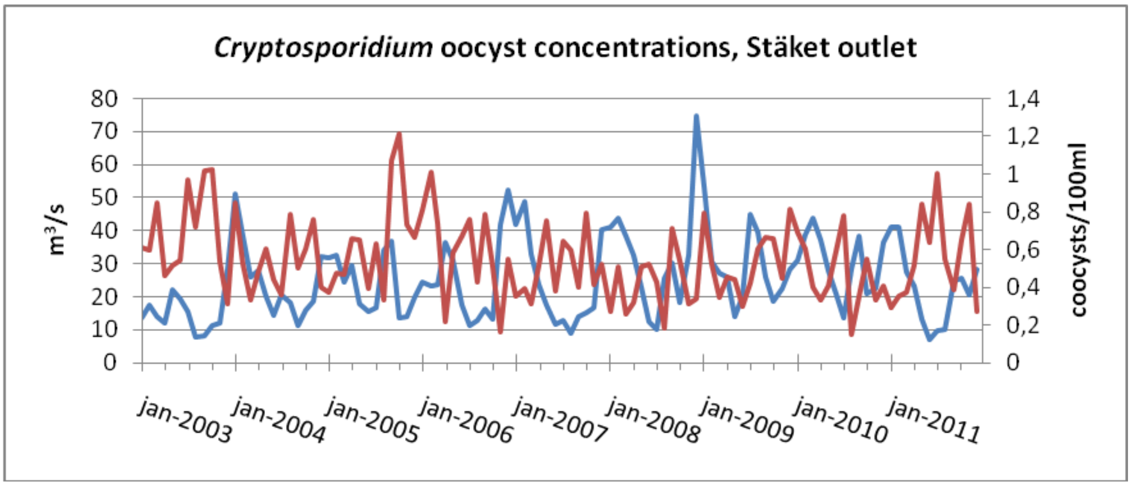
a) WWTP, OWTS and agricultural contamination sources



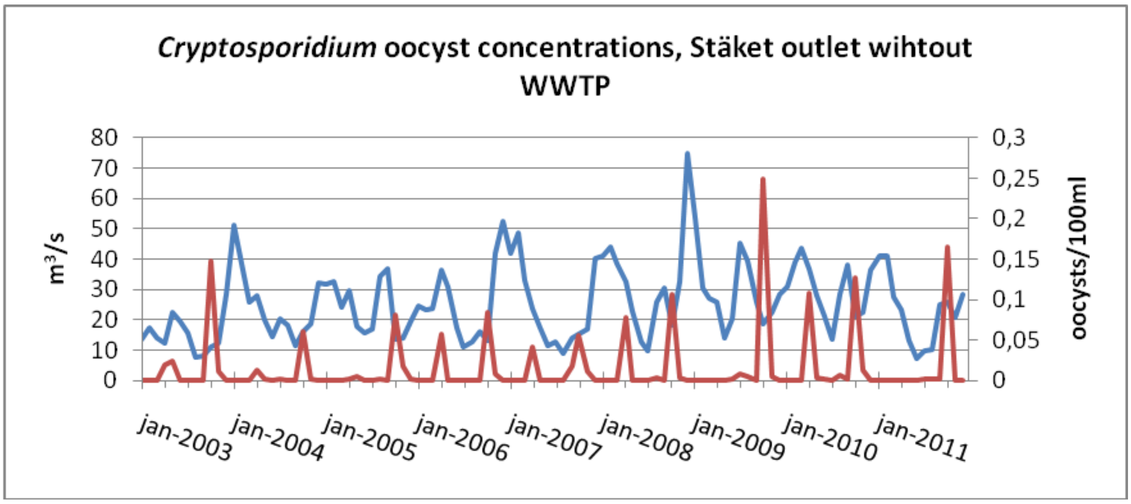
b) OWTS and agricultural contamination sources

Figure 8 Blue lines represent simulated water flow, red lines represent simulated E. coli concentrations at Stäket draining point, yellow triangles are measured values from Bonäsbadet bathing place, coarse dotted line is the level for acceptable bathing water quality and fine dotted line is the level for unacceptable concentrations of E. coli according to Swedish bathing water quality guidelines. a) Includes WWTPs, OWTSs and agricultural contaminations sources, whereas b) only includes OWTSs and agricultural contamination sources.

Monthly simulated *Cryptosporidium* spp. oocyst concentrations in Stäket outlet are shown in Figure 9 for total *Cryptosporidium* spp. oocyst and for *Cryptosporidium* spp. oocysts without any contribution from WWTPs. Mean oocyst concentration were 0.55 oocysts/100 ml, monthly values ranging from 0.15 to 1.2 oocysts/100 ml. Without WWTPs, mean oocyst concentration was 0.015, monthly values ranging from 8.6 x 10^{-6} to 0.25 oocysts/100 ml.



a) WWTP, OWTS and agricultural contamination sources



b) OWTS and agricultural contamination sources

Figure 9 Blue lines represent simulated water flow, red lines represent simulated Cryptosporidium spp. oocyst concentrations at Stäket draining point. a) Includes WWTPs, OWTSs and agricultural contaminations sources, whereas b) only includes OWTSs and agricultural contamination sources.

OWTS, grazing animals and manure application contributions of *E. coli* from each subbasin were categorised and are displayed in Figure 10. Categorisation was based on average daily *E. coli* concentration reaching the river from each subbasin during the validation period 2003-2011. Low corresponds to 0-1628, Medium 1629-3215, 3216-4801 and Very high 4802-6387 cfu/100ml*day*km^2. Subbasins 3, 15, 22 and 25 were categorised as medium, high or very high, and the rest of the subbasins were categorised as low contributors.

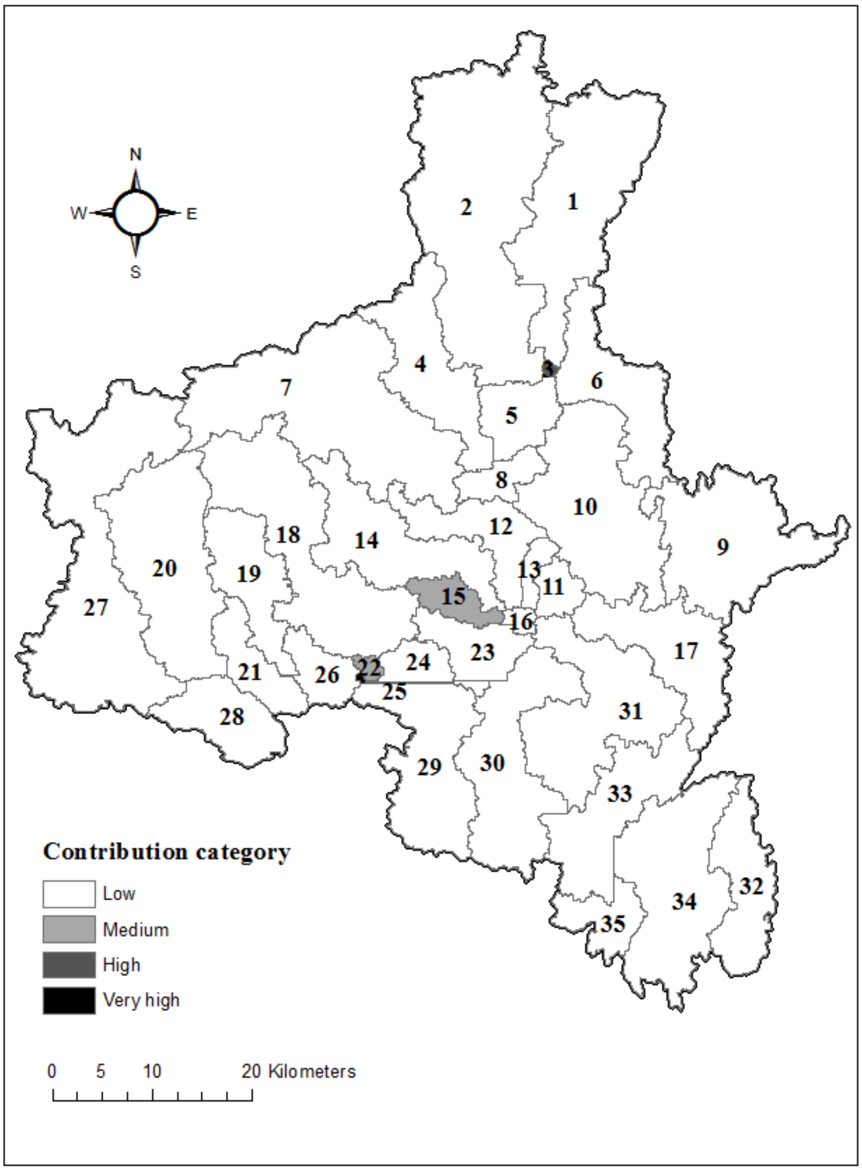


Figure 10 Categorisation of subbasins based on E. coli concentrations entering the river from land areas.

5 Discussion

5.1 Model setup

Setting up the model has to be performed according to the conditions and model frames set up by SWAT. It is also restricted by quality of available information. This makes it necessary to make some simplifications. Definition of the area was made on the basis of hydrology and the possibility to model a whole drainage basin, and not the basis of resolution or knowledge of input parameters. This made it necessary to generalise to a large extent regarding input values. Size of the chosen area was large, roughly ten times larger, compared to other studies modelling faecal contamination using SWAT. Since SWAT is adapted for large scale catchment modelling, the catchment size could have benefited the hydrological part of the model, but on the other hand, information on faecal contamination sources has been generalised to a large extent, and defining a smaller catchment area could have opened for more detailed information on contamination sources. When conducting the sensitivity analysis, no change between the coarse and fine resolution "river burn in” files was observed, the burn in from Sokolova (2009) was chosen, in order to keep the same subbasins that were defined earlier as well as the catchment outline. Mälaren lake compartments were not put in to SWAT, hence the transport and fate within the lakes were not included. This is also a reason why the river burn in file was used, to accurately describe the water pathway, also emphasised by Sokolova (2009).

5.2 Data quality

Given that more accurate input data on contamination sources, soil properties, land use and meteorology are available and that additional SWAT parameters could be calibrated, performance of the model could be enhanced. Bougeard et al. (2011a) also reports that more detailed information on faecal contamination sources and *E. coli* attributes as well as animal shedding quantities would improve the model. Lack of input data and parameter uncertainties are described as major factors for improving modelling performance (Cho et al. 2012).

Land use was based on coarse scale data applying unique conditions for each different land use type. SWAT water balance is influenced by plant growth (Abbaspour 2013) and by defining the type of plant grown on a more detailed level could increase model performance. This could be done by splitting each land use type i.e. agricultural land, urban areas, wetlands, deciduous forest, mixed forest and evergreen forest into several sub groups.

Interpretations of Swedish soil types were made on the basis of percentage of grain size fractions in the soil. These compositions of grain sizes were matched to a SWAT soil type with as similar composition as possible; since matching was made somewhat arbitrary, it may not have been the most accurate definition. Swedish soil types were assigned only one layer, whereas SWAT soil types are assigned several layers. Differences in soil parameters between Swedish soils and SWAT soils in deeper layers can result in reduced model performance.

Sensitivity analysis showed that increased number of rain gauges increased model performance. Both temperature and precipitation are factors with large local variations (Bogren & Gustavsson 2008). Subbasins 18 and 27 have water flow patterns very similar to each other although magnitude differs. Subbasin 11 has a slightly different shape of the flow graph displayed in Figure 6, a phenomena that could be explained by the fact that subbasin 11 has a different precipitation gauge assigned than subbasins 18 and 27. Increasing number of both precipitation and temperature gauges could improve the model performance.

Only the largest WWTPs were entered into SWAT, due to that information of discharge from smaller could not be obtained. OWTSs and information regarding agriculture were only available on municipal resolution, if setting up the model in a smaller drainage basin, this information could be entered on a much more detailed level. If possible each OWTSs and each agricultural activity could be geographically defined. Agricultural management of manure and its application on 15th of April and 30th of September each year were highly generalized. All manure stored during winter is probably not applied during only two occasions and definitely not at the same time by all agricultural activities. Although lack of detailed information and the fact that applying manure on different times for each of the ten years modelled and individually for each farm would be too time consuming. Local distribution of agriculture inputs or failure of OWTSs can give temporary peaks in measured data that are not included in the model (Coffey et al. 2010a). Wildlife contribution of faecal contamination was not accounted for. Since Uppsala County has high densities of elks (Statens Offentliga Utredningar 2009), this is a possible source of faecal contamination and accounting for wildlife contributions has been shown to increase the model accuracy (Cho et al. 2012). Stream availability is higher for wildlife than domesticated animals, thus enhancing the contribution from direct stream deposits. Direct stream deposits is a parameter described to have high influence on contamination concentrations (Coffey et al. 2012).

SWAT parameters chosen for *E. coli* and *Cryptosporidium* spp. oocysts were based on values from literature. Many of these studies were executed in other countries, not reflecting the local Swedish conditions. Since SWAT has not yet been used for modelling transport and fate of faecal contamination and pathogens in Sweden, these values were used as best estimates. Prevalence of *Cryptosporidium* spp. oocysts in animal has been entered into the model, although waterborne outbreaks can create local hotspots of *Cryptosporidium* spp. oocyst contribution. Using the model for risk assessment of drinking water resources, ignoring the fact that there can be infected individuals shedding large amount of pathogens close to drinking water intakes, could underestimate the risks.

Calibration and validation are recommended to be performed not only on water flow but also sediment transport and water quality parameters such as faecal contamination (Arnold et al. 2012a, Moriasi et al. 2007). Given the fact that *E. coli* and *Cryptosporidium* spp. oocysts can be transported attached to sediment, enhancing model performance on simulating sediment transport would enhance model performance simulating transport and fate of faecal contamination.

5.3 SWAT limitations

Conceptual uncertainties are described as simplifications incorporated into the model or processes that take place in the drainage basin but are not accounted for. Either the processes are ignored by the model or accounted for by the model but ignored by the user. Processes can also be ignored by both the model and the user (Abbaspour 2013). Inactivation due to solar radiation is not accounted for in SWAT, a factor that is influential on the survival of *E. coli* (Cho et al. 2012) and *Cryptosporidium* (World Health Organisation 2011). Bacteria originating from streambed is not accounted for in SWAT and can contribute to the inaccuracy of model *E. coli* concentration predictions (Kim et al. 2010). OWTSs contamination contributions were entered using the continuous fertilising operation. These contributions are treated as if transported in the same way manure is, not entering the surface waters or infiltrated as OWTS effluents usually are. No account has been taken to die-off during winter storage of manure.

5.4 Model performance

Statistical performances of the model water flow validation are in the range of reported values of NSE and just outside the range of R^2. Gassman et al. (2007) has reported on SWAT performance and monthly stream flow validation for NSE and R^2 ranging between -1.1 to 0.99 and 0.34 to 0.97 respectively. Although performance is within the range of reported NSE, most studies report an NSE >0.50. Model calibration and validation were performed on water flow. Results are relying on the model performance in terms of water flow. Since the performance of the model is classified as poor, modelled concentrations have to be interpreted carefully.

5.5 Modelled concentrations

Cryptosporidium spp. oocyst concentrations are high when the water flow is low. This corresponds to the fact that there are large numbers of *Cryptosporidium* spp. oocyst in a small amount of water and this can especially be seen in Figure 9a although pattern is not consistent throughout all years. This pattern was also reported for faecal coliforms by Jayakody et al. (2013). Figures 8 and 9 show that WWTPs are a much larger *E. coli* and *Cryptosporidium* spp. oocyst contributor than OWTS and agricultural practices. This may be true for this drainage basin, but in other cases, source contribution has shown to be the opposite, for example with 75 % from manure application and 24 % from WWTPs for a catchment in Ireland (Coffey et al. 2010b). Application of manure during spring and autumn influences the *E. coli* and *Cryptosporidium* spp. oocyst concentrations. This is expressed clearly each autumn in Figures 8b and 9b, whereas spring is less pronounced but can be indicated in Figure 8b and in Figure 9b during the years 2007, 2008, and 2010. Similar findings were also reported by Coffey et al. (2010b).

E. coli concentrations are higher during winter than summer, see Figure 8a, also reported for faecal coliforms by Jayakody et al. (2013). This can be due to that bacterium in general are surviving longer in colder temperatures. *Cryptosporidium* oocysts concentrations are high both during winter and summer, see Figure 9a. One reason for this can be the fact that *Cryptosporidium* prevalence in animals as well as concentrations in faeces are higher in animal faeces than human faeces and that the contribution from grazing animals is applied during the summer periods. Contribution of faecal contamination from OWTSs and manure application was spatially divided into different subbasins. Results show that subbasins 3, 15, 22 and 25 have a high density of *E. coli* contribution. It should be noticed that even areas with low contribution significantly add to the total load of faecal contamination as well.

Simulated concentrations of *E. coli* in Stäket outlet were above acceptable levels for bathing water. Simulated *E. coli* concentrations are representing the concentrations in the total runoff from the whole drainage basin, while concentrations in Bonäsbadet are measured in Lake Mälaren thus no direct comparison can be made between these two concentrations. Comparing simulated *E. coli* levels with Swedish bathing qualities and a WWTPs effluent (Ohlsson et al. 2011), Stäket drainage point shows more resemblance to a WWTP effluent than water for recreational activities at some times during the year. Mean *E. coli* concentration was 6563 cfu/100 ml, monthly values ranging from 850 to 19480 cfu/100 ml. Even though concentrations were above accepted bathing water quality levels, simulated *E. coli* concentrations were in the same range (Bougeard et al. 2010, Bougeard et al. 2011b) or approximately one (Bougeard et al. 2011a, Coffey et al. 2010a) or two (Coffey et al. 2012, Kim et al. 2010) $\log_{10}$ units larger than reported by other studies. Concentration peaks were in the same range as most other studies. The fact that different studies have different concentration ranges can be due to either discrepancies between different drainage basin locations and settings or could indicate inaccurate inputs of *E. coli* or inaccurate parameters for *E. coli* transport and survival. It can also be the result from not entering lake compartments into the model, which probably would dilute the concentrations. *Cryptosporidium* spp. oocyst mean concentrations were 0.55 oocysts/100 ml, monthly values ranging from 0.15 to 1.2 oocysts/100 ml. This is in the same range compared to Coffey et al. (2010b) who reported monthly values between 0.0004-0.48 oocysts/100 ml. Although mean value in this study was substantially larger than the reported mean of 0.09 oocysts/100 ml by Coffey et al. (2010b). Tang et al. (2011) reported daily values of 0-4 oocysts/100 ml; this range overlaps the concentration range in this study.

5.6 Future research

Future research with SWAT to model faecal and pathogen contamination in the Stäket drainage basin can take different approaches. Modelling a smaller area could increase accuracy of model outputs. Oxundaån catchment area could be suitable. It is 272 km^2 and has an organisation “Oxunda Vattensamverkan” (Oxunda Vattensamverkan 2014) that is providing extensive information on the catchment area and on agricultural practices within the area. There is also a water flow gauge located in the Oxundaån that could provide the model with measured data on water flow.

Model calibration and validation using measured *E. coli* or *Cryptosporidium* spp. oocyst concentrations as well as entering water reservoirs would increase the reliability and accuracy of the model. Comparison between large and small drainage basins is another field for future research. Another field to improve is to increase data quality. More accurate information on Swedish soil parameters, *Cryptosporidium* spp. prevalence and *Cryptosporidium* spp. oocyst concentration in different animal manure in Sweden are important data for improving the model. Furthermore it is necessary to only account for the species of *Cryptosporidium* spp. that can infect humans.

Both NSE and R^2 has biases towards high flows and it is recommended to also report on biases (McCuen et al. 2006) and display scatter plots (Jain & Sudheer 2008) when using NSE. Therefore a review of statistical methods for evaluation the model is of interest. Developing a methodology for including SWAT into the risk assessment and raw water source quality estimation associated with drinking water is probably the most essential for maximising the use of SWAT model results produced in the future.

6 Conclusions

Modelling fate and transport of faecal contamination can be a useful tool for estimating the water quality in drinking water sources and for health risk assessments. SWAT is assessed to model faecal contamination with a high accuracy and it is frequently used worldwide for this purpose. Setting up SWAT for Stäket drainage basin showed difficulties regarding the detail level of input data, the parameterisation of faecal contamination attributes, and the lack of observations for calibration and validation of the model in terms of microbial concentrations. One important conclusion is that it was possible to create a SWAT model for modelling faecal contamination in a drainage basin in Sweden. If quality and resolution of input data are improved and given that proper methodology is developed, the model could be used in the context of identifying water protection areas and quantifying the risks for water sources used for drinking and recreational purposes. Following conclusions were drawn on the basis of the modelling results:

- SWAT model set up in Stäket drainage basin showed poor performance evaluating the water flow. Both NSE and R^2 were below accepted levels.

- Modelling results showed that, within Stäket drainage basin, wastewater treatment plants are the largest contributor of faecal contamination to Lake Mälaren.

- The important faecal contamination sources within Stäket drainage basin are the nine identified wastewater treatment plants, as well as temporary loads from agricultural manure application.

- Simulated concentrations of *E. coli* were higher than accepted for bathing water quality. *Cryptosporidium* spp. oocysts concentrations in Stäket drainage point are within ranges reported by other studies or slightly higher.

- Before using the SWAT model of Stäket drainage basin to further evaluate the faecal contamination fate and transport, calibration should be performed on either *E. coli* or *Cryptosporidium* spp. oocysts and parameterisation of *E. coli* and *Cryptosporidium* spp. oocysts attributes should be adjusted.

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Appendix I

OWTS density per municipality

Municipality	Total residential properties (Properties) [a]	OWTS (Numbers)[b]	OWTS density (OWTS/Property)
Uppsala	40234	10600	0.263458766
Enköping	26368	7000	0.265473301
Håbo	2939	150	0.051037768
Heby	13264	3000	0.226176116
Knivsta	7198	2000	0.27785496
Sigtuna	5924	2000	0.337609723
Tierp	7405	4000	0.540175557
Upplands-Bro	3719	400	0.107555795
Vallentuna	6000	2000	0.333333333

a) GSD-Fastighetsdatabas. More information on http://lantmateriet.se/Kartor-och-geografisk-information/Kartor/Fastighetskartan/GSD-Fastighetskartan-vektor-/
b) Personal communication with each municipality.

Residential properties located in each subbasin divided per municipality[a]

Subbasin	1	2	3	4	5	6	7	8	9	10	11	12
Uppsala	710	2754	2	3252	1205	1695	4491	658	2288	5025	712	1136
Enköping												
Håbo												
Heby							64					
Knivsta									99	490	16	
Sigtuna												
Tierp	13	3092		17								
Upplands-Bro												
Vallen-tuna												

Subbasin	13	14	15	16	17	18	19	20	21	22	23	24
Uppsala	6	1947	875	1	5	3104	987	1		109	780	949
Enköping						227	690	1755	931	119		1
Håbo											1	8
Heby						29	7	1098				
Knivsta				1	2336						127	1
Sigtuna					667							
Tierp												
Upplands-Bro												
Vallen-tuna												

Subbasin	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**
Uppsala	1	1	1		1		19				
Enköping	11	645	2708	1678	706						
Håbo	1				2057	359					
Heby			1811								
Knivsta						1286	2002		1		
Sigtuna						994	1797	1	872	44	
Tierp											
Upplands-Bro					125	1189			169	1	224
Vallen-tuna								632		66	

a) Based on:
GSD-Fastighetsdatabas. More information on http://lantmateriet.se/Kartor-och-geografisk-information/Kartor/Fastighetskartan/GSD-Fastighetskartan-vektor-/ ,
GDS-Administrativ indelning 1:250 000, more information on http://www.lantmateriet.se/Kartor-och-geografisk-information/Kartor/Geografiska-teman/GSD-Administrativ-indelning-1250-000/ and
Subbasin definition made by SWAT.

Appendix II

Animal density per municipality

Municipality	Total agricultural land area (m^2)[a]	Animal	Total number of animals in municipality (Numbers)[b]	Animal density (Numbers/m^2)
Enköping	515460000	Sheep	2198	4.26415E-06
		Goat	82	1.59081E-07
		Pig	8630	1.67423E-05
		Poultry	23321	4.52431E-05
		Cattle	7810	1.51515E-05
Heby	194947142.9	Sheep	1382	7.0891E-06
		Goat	51	2.61609E-07
		Pig	1024	5.25271E-06
		Poultry	13364	6.85519E-05
		Sheep	3178	1.63019E-05
Håbo	39344545.45	Sheep	250	6.35412E-06
		Pig	1504	3.82264E-05
		Cattle	81	2.05874E-06
Järfälla	2133636.364	Sheep	53	2.48402E-05
		Goat	4	1.87473E-06
		Poultry	6	2.8121E-06
		Cattle	214	0.000100298
Knivsta	70370000	Sheep	386	5.48529E-06
		Goat	9	1.27895E-07
		Pig	204	2.89896E-06
		Cattle	560	7.95794E-06
Norrtälje	262332727.3	Sheep	6174	2.3535E-05
		Goat	63	2.40153E-07
		Pig	8496	3.23864E-05
		Poultry	25560	9.74335E-05
		Cattle	7604	2.89861E-05
Sigtuna	91486363.64	Sheep	759	8.29632E-06
		Goat	9	9.83753E-08
		Pig	1136	1.24172E-05
		Poultry	19765	0.000216043
		Cattle	1012	1.10618E-05
Sollentuna	1612727.273	Sheep	12	7.44081E-06
		Goat	2	1.24014E-06
		Cattle	225	0.000139515
Tierp	203140909.1	Sheep	1478	7.27574E-06
		Goat	25	1.23067E-07
		Pig	672	3.30805E-06
		Cattle	7198	3.54335E-05
		Poultry	40499	0.000199364
Upplands-	13008181.82	Sheep	122	9.37871E-06

Väsby				
		Goat	7	5.38123E-07
		Pig	1	7.68747E-08
		Poultry	100	7.68747E-06
		Cattle	113	8.68684E-06
Upplands-Bro	52436363.64	Sheep	297	5.66401E-06
		Pig	75	1.43031E-06
		Cattle	474	9.03953E-06
Uppsala	506253636.4	Sheep	5500	1.08641E-05
		Goat	151	2.98269E-07
		Pig	2961	5.84885E-06
		Poultry	89755	0.000177293
		Cattle	14001	2.76561E-05
Vallentuna	76424545.45	Sheep	882	1.15408E-05
		Goat	108	1.41316E-06
		Pig	1622	2.12235E-05
		Cattle	1682	2.20086E-05
		Poultry	2000	2.61696E-05
Östhammar	162189090.9	Sheep	2612	1.61047E-05
		Goat	50	3.08282E-07
		Pig	845	5.20997E-06
		Cattle	9310	5.74021E-05
		Poultry	13600	8.38527E-05

a) Jordbruksverkets statistikdatabas
b) Personal communication

Agricultural area in each subbasin divided per municipality

Subbasin	Municipality	Agricultural area (m^2)[a]
1	Tierp	2274777.435
	Uppsala	26930318.9
	Östhammar	36810184.08
2	Tierp	112595486.1
	Uppsala	63378976.83
	Östhammar	684599.1597
3	Uppsala	168750
4	Tierp	160618.2575
	Uppsala	61540660.69
5	Uppsala	28753125
6	Uppsala	47027904.9
7	Heby	514980.0334
	Uppsala	112332003
8	Uppsala	19447500
9	Knivsta	4189433.172
	Uppsala	39693713.03
10	Knivsta	8143362.271

	Uppsala	78812262.73
11	Knivsta	526208.7272
	Uppsala	11437541.27
12	Uppsala	28767500
13	Uppsala	8503750
14	Uppsala	48969375
15	Uppsala	13351250
16	Knivsta	492966.5054
	Uppsala	123283.4946
17	Knivsta	41297985.01
	Sigtuna	15381263.06
	Uppsala	400.94
18	Enköping	7164554.596
	Uppsala	76505904.89
19	Enköping	20859796.22
	Heby	36312.49753
	Uppsala	9105141.286
20	Enköping	48926239.54
	Heby	32557510.46
21	Enköping	31444951.65
22	Enköping	2444513.584
	Uppsala	1288611.416
23	Knivsta	1935000
	Uppsala	17921875
24	Håbo	761250
	Uppsala	18955625
25	Enköping	375000
26	Enköping	16456939.64
	Uppsala	109999.2472
27	Enköping	94353315.38
	Heby	43625051.88
28	Enköping	51260608.23
29	Enköping	22982463.57
	Håbo	37234809.63
	Upplands Bro	5687489.419
30	Håbo	9782973.613
	Knivsta	19307500
	Sigtuna	8578083.9
	Upplands Bro	30592173.33
31	Knivsta	40675061.29
	Sigtuna	38821199.65
	Uppsala	209364.0532
32	Sigtuna	2445643.63
	Upplands Väsby	639383.0439
	Vallentuna	25748335.99

33	Knivsta	5845.713276
	Sigtuna	30062904.29
	Upplands Bro	9945244.684
34	Järfälla	685137.1765
	Sigtuna	28927392.38
	Sollentuna	3717854.744
	Upplands Väsby	22782713.61
	Vallentuna	7882181.638
35	Järfälla	418750
	Upplands Väsby	1907500
	Upplands Bro	6041965.097

a) Defined by GDS-Administrativ indelning 1:250 000, more information on http://www.lantmateriet.se/Kartor-och-geografisk-information/Kartor/Geografiska-teman/GSD-Administrativ-indelning-1250-000/

b) Based on SWAT area defined as RNGE, FESC or AGRL within the area of each municipality