Lake Mälaren: hydrological modelling to simulate the fate and transport of the faecal contamination

Master of Science Thesis

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

It is important to explore the possible ways of tracing faecal contamination sources in the catchment area of a drinking water source by means of computer modelling. The aim is to prevent or reduce the potential outbreaks of waterborne diseases caused by the presence of pathogenic microorganisms in the drinking water. To simulate the fate and transport of faecal contamination in the catchment area of Lake Mälaren, a hydrological model was set up using ArcSWAT software. The modelling results for the year 2010 showed that grazing and fertiliser operations did not cause any contamination in winter months (December, January, and February), and caused only minor contamination in April. The contamination levels started rising in May, with the highest grazing and fertiliser contamination registered in July: the maximum *Cryptosporidium* concentration was 521 oocysts/100 ml, and the highest *E. coli* concentration was 2522 CFU/100 ml. The contamination levels were high during August, September and October, and then decreased in November. In general, this computer simulation method provides a powerful tool for surface water conservation programs.

Key words: hydrological modelling, *Cryptosporidium*, *E. coli,* pathogens, manure application, grazing, ArcSWAT.

Contents

Preface

The work on this thesis has been carried out at the Department of Civil and Environmental Engineering, Division of Water Environment Technology, DRICKS research group at the Chalmers University of Technology, Sweden.

The study has been conducted by Mohammed Abdi Gudle, student at the Master Programme Infrastructure and Environmental Engineering, with Professor Britt-Marie Wilén as examiner, and Ekaterina Sokolova and Thomas Pettersson as supervisors.

I would like to thank Ekaterina Sokolova for discussions, comments and support during the process of conducting this research. I would also like to acknowledge the help provided by Johan Åström at Tyréns AB and Viktor Johansson, with whom I have shared work space and conducted research on the same subject.

Finally, I would like to thank my family for a wonderful support throughout the entire Master Programme at Chalmers.

Gothenburg, July 2014

Mohammed Abdi Gudle

Introduction

Drinking water is a precious asset for human beings and other living animals. Usually water is extracted from the surface or ground waters, in both cases protection from contaminants is required to preserve the natural quality. If contaminated, this quality will be degraded considerably, depending on the amount and the type of contamination drained in to the water, hence risking the human health.

Water resources conservation includes contamination control at point and diffuse sources. As a comparison, it is easier to monitor point sources, such as industrial and wastewater treatment plants (WWTPs), but it is difficult to locate diffuse sources caused by the rainfall or snowmelt moving over and through the ground (EPA 2014).

Pathogens (bacteria, virus and protozoa) originate from human and animal faecal matter. Pathogen contamination in streams, lakes, and reservoirs is well-known to come from a variety of sources, including animal manure application, effluents from WWTPs, on-site sewer systems, land application of wastewater and sludge, pets and wildlife (Baffaut et al. 2010). For example, the pathogen *Cryptosporidium* has caused several large outbreaks of gastrointestinal illness.

This study explores the possible ways of tracing faecal contamination sources in the catchment area of drinking water sources by means of computer modelling. Modelling has become an important management tool for estimating the contribution from each source, their combined impact, and the effectiveness of possible mitigation schemes (Baffaut et al. 2010). In particular, we are interested in Lake Mälaren at Norsborg, where the drinking water for the city of Stockholm (Sweden) is produced. The goal is to prevent or reduce the potential outbreaks of waterborne diseases, caused by pathogenic microorganisms in the drinking water.

In this project, hydrological modelling is used to simulate the fate and transport of the faecal contamination (*E. coli* and *Cryptosporidium*) within the catchment area of Lake Mälaren. The modelling results provided information about the relative contribution of different faecal contamination sources to Lake Mälaren.

Aim

The aim of this project was to simulate the fate and transport of faecal indicator *E. coli* and pathogen *Cryptosporidium* within the catchment area of Lake Mälaren, in order to assess how much different sources contribute to contamination in the vicinity of the Norsborg drinking water treatment plant (DWTP).

Background

Lake Mälaren is the third largest lake in Sweden, spanning in about 120 km from east to west with maximum depth of 64 m. The lake is a drinking water source for the whole Stockholm region, serving for recreational and fishing purposes as well. A hydrological model of the lake's catchment area was previously set up by Ekaterina Sokolova, using the Soil and Water Assessment Tool (ArcSWAT) software to simulate the transport of nutrients (Sokolova 2009). In this project, the existing model is modified and adjusted to describe the fate and transport of faecal contamination. This study covers only the catchment area that is relevant to the Norsborg DWTP.

Literature review

Surface water sources are vulnerable to be contaminated by pathogens from the surrounding catchment areas. Some outbreaks resulted from a combination of increased source contamination (mostly due to rainfall) and treatment failure (Smeets et al. 2006). This illustrates that treatment needs to be able to deal with peak events in source water that are not prevented by source protection. Rapid changes in water quality should always be considered as indicators of events.

Report written by Smeets et al. (2006) that investigated at least 30 outbreaks in Sweden indicated that 57 % of outbreaks were due to faecal contamination of raw water in combination with insufficient treatment. From 1974 to 2002, 26 out of 35 outbreaks in the USA and Canada were due to surface water treatment failure or inadequate treatment to deal with sudden peak increases of pathogen concentrations in source water (Hrudey and Hrudey 2004).

Modelling faecal indicator bacteria in surface waters serves two important purposes, according to Sadowsky et al. (2011). The first is to "ground truth" our understanding of the sources, fate, and transport of faecal contamination in environmental systems. This is generally accomplished by using deterministic models that account for specific transport and fate processes. The second purpose is to aid in the public notification of water quality conditions.

Water quality modelling technics have been focused on defining rates/extent of nutrients, pesticide and sediment losses from agricultural fields to surface waters. In contrast, little effort has been devoted to developing new models, or modifying existing models, to describe pathogen transport at a watershed or basin levels (Sadeghi et al. 2002).

Faecal coliforms have customarily been used as indicators of potential pathogen contamination both for monitoring and modelling purposes (Moore et al. 1988, Sadeghi et al. 2002). However, recent studies have documented that waterborne disease outbreaks caused by *Cryptosporidium*, Norwalk and hepatitis A viruses, and even *Salmonella* have occurred despite acceptably low levels of indicator bacteria. Sadeghi et al. (2002) have further emphasised the necessity to have a modelling tool that would allow the assessment of pathogen release and loadings into water sources, along with the nutrients and sediment evaluations.

Mocan (2006) has investigated the water quality of two small rural watersheds in southwestern Ontario through a comprehensive field monitoring program and the application of SWAT for modelling microbial pollution. This study reported that the majority of the fields studied have significant seasonal variations of bacterial concentrations in runoff, showing that bacterial concentrations were consistently higher over the warmest months of the year, from July to September, whereas the lowest concentrations were observed from January through

March (Mocan 2006). The findings were generally consistent with other studies, in that runoff water quality is generally degraded over the warmer months due to increased biological activity. One advantage of the research conducted by Mocan (2006) was the field monitoring program conducted in parallel to the SWAT simulation, to obtain sufficient stream flow and bacteriological data to calibrate the SWAT result, determining the validity of the model. Moreover, his results demonstrated that the model was able to predict *E. coli* concentrations within an order of magnitude of the observed values.

Coffey et al. (2010) used SWAT to model *Cryptosporidium* in surface water sources. This study highlighted the effectiveness of the SWAT model for assessing water sources in the context of diffuse pollution problems. The study area was 29 km^2 (extraction point for the Ennis town water supply) in the river Fergus catchment at Drumcliff, Ennis, county Clare, Ireland. This study identified the manure application as the most significant contributor (75 %) to the total *Cryptosporidium* load in the catchment. This agrees with other studies which found a significant correlation between manure application and oocyst numbers in surface waters at two locations in Ireland. Their recommendation for risk management was to focus on reducing oocyst levels in the catchment (Coffey et al. 2010).

In addition to SWAT simulation, Bougeard et al. (2010) set up an external-internal mode coupling for a hydrodynamic model for applications at regional scale (MARS-2D), which takes into account realistic wind and tide values to calculate *E. coli* concentration in the water. The objective of this research was faecal contamination modelling in water from catchment to shellfish growing area (La Mignonne River with catchment area of 113 km^2 flows into the Daoulas estuary, Bay of Brest in France). The results indicated a relationship between simulated and measured levels of the shellfish contamination (Bougeard et al. 2010).

In general, different authors agree that manure application is a significant source of pathogens.

Methodology

Study area

The study area is located in the catchment of Lake Mälaren, which drains into the Baltic Sea at Sweden's south-central east coast, where Stockholm is located.

In particular, the focus is on the area covering four municipalities in Stockholm’s Metropolitan (Storstockholm). These include Botkyrka, Ekerö, Salem and Södertälje municipalities. The total study area is 363 km^2, of which 55.02 % is water. The main focus is at Norsborg area, where Stockholm’s drinking water is produced using the raw water from Lake Mälaren. The Norsborg DWTP supplies water to about 650 000 people in Stockholm area.

In general, the land use in the study area can be categorised into four major classes, which include: arable land, forest and permanent grassland, urban, and others such as lakes or ponds (Table 1).

There are at least four dams and one wetland in the area, and the total estimated population in 2010 for these four municipalities was 209 655 persons (City Population, 2014). However, it is possible that large part of this population might live outside of this sub-catchment.

Table 2 shows published statistical data for 2010 on livestock distribution in these four municipalities (SCB 2014).

SWAT model setup

The software works as a built in ArcMap 10.1 that provides a graphical user interface for the Soil and Water Assessment Tool (SWAT). ArcSWAT 2012.10._0.1 version was used. Sub-watershed configuration, which is the primary discretisation scheme, was performed by importing Digital Elevation Model (DEM) of fine resolution (Figure 1) from the existing Norrström model. Manual watershed delineation was used to draw and edit a polygon mask. The model matched different combination of the land use, soil types and slopes; this made it possible to divide the area into 309 hydrological response units (HRU’s), from 82 sub-basins (Figure 2), specifying the minimum sub-watershed area. Watershed subdivision was made to increase the accuracy of the load prediction, assigning multiple HRU’s into areas with unique land use and soil combination.

The watershed delineation involves advanced GIS functions to aid the user in segmenting watersheds into several “hydrologically” connected sub-watersheds for use in watershed modelling with SWAT (Arnold et al. 2013).

Table 1. Land use (SCB 2014).

Land use type	Area (hectares)	Percentage of total area (%)
Agricultural Land (Generic)	4911	13.52
Pasture	215	0.59
Forest-mixed	2590	7.13
Forest-Evergreen	6998	19.27
Forest-Deciduous	514	1.42
Urban	1076	2.96
Wetlands	31	0.08
Water	19981	55.02
Total area	36317	100.00

Table 2. Livestock distribution in the study area in 2010 (SCB 2014).

Animal description / Municipality	**Ekerö**	**Botkyrka**	**Salem**	**Södertälje**	**Total**
Dairy cows	96	245		530	871
Cows for calf production	138	77	13	252	480
Heifers, bulls and steers	277	240	5	602	1124
Calves, under 1 year	227	186		550	963
Rams and ewes	529	65		1092	1686
Lambs	645	71		1455	2171
Breeding boars	--	--	--	2	2
Breeding sows	--	--	--	413	413
Fattening pigs, 20 kg and over	--	--	--	908	908
Piglets, under 20 kg	--	27	--	--	27
Poultry	25152	45	58	200	25455
Laying chickens	25	--	--	24	49
Broilers	--	--	--	--	--
Turkeys	--	--	--	--	--
Horses	1070	321	--	533	1924
Total					36073

(--) no data available
Source: Swedish Board of Agriculture
Contact: Anders Grönvall Tel: 036-15 57 91 E-mail: statistik@jordbruksverket.se

Input data

ArcSWAT requires input data from the beginning of the model set up, where ArcSWAT interface creates project geodatabase. Input data are stored in this directory, including those generated by the system such as the first "RasterStore.mdb".

In addition to the built in databases, ArcSWAT requires input data from the user to set up the model and process all necessary information in progressive technique for ultimate simulation.

Lake Mälaren dataset:

- Digital Elevation Model (DEM) with fine resolution of 25 m ("dem_25") was used to define the watershed map. It was first created to describe the whole Norrström drainage basin. The DEM defines all topographical features in the study area, such as drainage patterns, slope length / gradient of the terrain and stream network parameters. A DEM Mask grid was used to define the working area by using an available manual delineation option that allows the user to draw and edit a polygon mask. Also watercourses burn-in shape file ("rivers") was added in the watershed delineation process to define the streams. Figure 1 shows manually delineated study area in blue colour, while the green background displays the DEM of the Norrström drainage basin.
- Land use map ("reproj_lc") with land use type look-up table was imported from the existing Norrström model. The data were obtained from the land cover project CORINE coordination of Information on the Environment (www.eea.europa.eu/themes/landuse/clc-download).

- Soil types map ("soils_proj") was imported from the Norrström dataset. The map was originally obtained from the Swedish Geological Institute (Sveriges Geologiska Undersökning, SGU). The map was made from an original 1:1 250 000 scale paper map that classifies soil types into nine classes: peat, clay silt, sand gravel, glacio-fluvial sediment, clayey till, boulder clay, till, none or thin cover of quaternary deposit, till and weathered surface layer above the tree limit, lakes (Sokolova 2009).
- Weather dataset contains weather data files for the year 2010; the data were collected from the Swedish Meteorological and Hydrological Institute (SMHI 2014). The rainfall (daily) data recorded in 2010 were collected from three different rain gauges in the study area. Daily temperature recordings were collected from two gauges, and relative humidity and maximum observed daily wind speed data were collected from one gauge for the same period. ArcSWAT requires an additional precipitation gauge location table, temperature gauge location table, relative humidity gauge location table, and wind speed gauge location table. All these tables were required to be ASCII table formatted as a comma delineated text table.

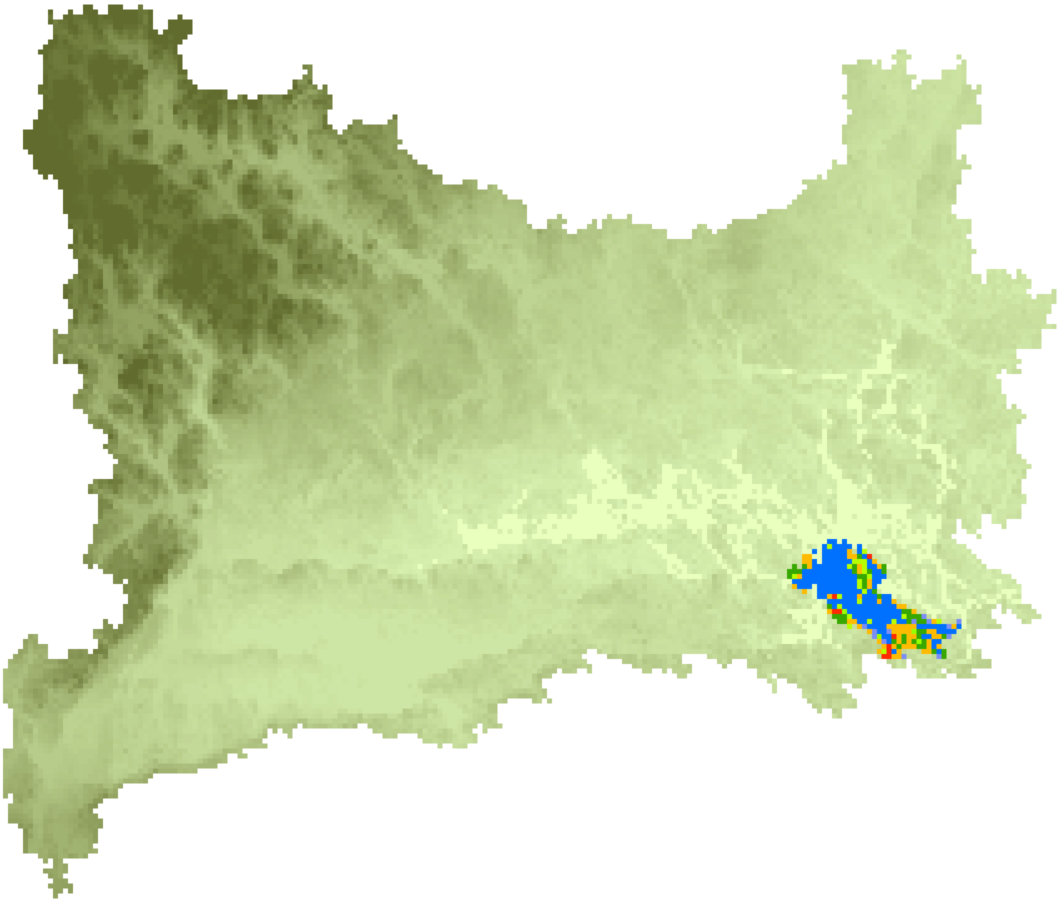


Figure 1. Digital Elevation Model (DEM) used in the Norrström drainage basin with manually delineated study area marked by blue colour.

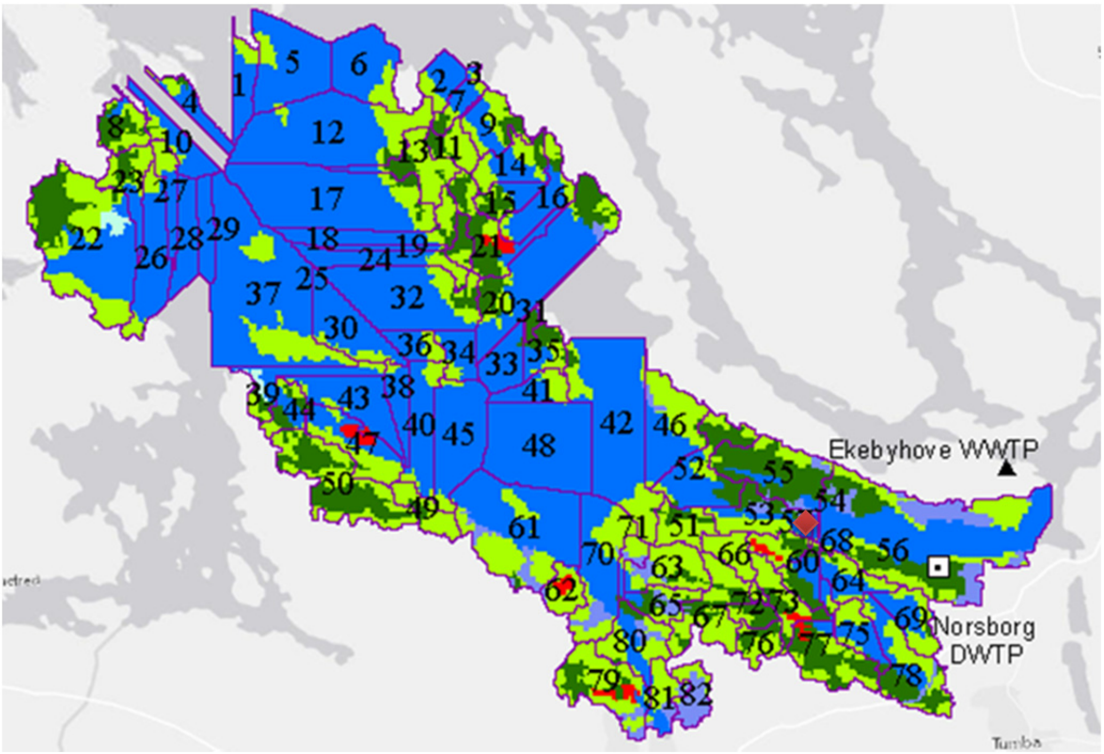


Figure 2. Sub-basins defined by SWAT. The colours represent different land use types: light green – forest; dark green – agriculture; red – pasture; blue – water; purple – urban areas.

Contamination sources

Livestock is one of the sources of faecal contamination in the study area (Table 2). Manure from confined operations is stacked on farm yards before application on grasslands (Jayakody et al. 2014). Unconfined managements are a type of extensive cattle farming, whereby animals freely roam over portions of the watershed, often drinking from water streams and ponds. Poultry operations are typically confined with poultry litter stacked in farm yards before its application on grasslands (MDEQ 1999). Other potential contamination sources are wastewater treatment plants and on-site sewer systems.

The methodology of contaminant transport estimation from livestock is based on deposition of manure from grazing animals or fertiliser application, adsorption to soil, decay, infiltration, incorporation through tillage, extraction by runoff, and transport by stream flow (Baffaut et al. 2010). SWAT simulates the survival of organisms as two different populations: (i) non-persistent organisms (e.g. *E. coli*) and (ii) persistent organisms (e.g. *Cryptosporidium*).

Grazing operations

There is animal welfare regulation in Sweden that limits minimum grazing period in summer. The pasture grazing starts between 1 April and 31 October, but the grazing period must be continuous for four months, of which at least two months should occur during the period between 15 May and 15 September. Of course there are some exceptions, when the animals should be kept inside the whole or parts of the day. Such exclusion is necessary to protect the animals or the land from damage during abnormal weather conditions (Jordbruksverket 2014). Therefore, in this study the total period of 214 grazing days was assumed. Dry manure calculation on pasture areas is summarised in Table 3. Refer to Table 2 for details on animal distribution among the municipalities.

Table 3. Dry manure calculation on grazing area [(a)].

Animal type	No	Density (No/ha)	Dry manure [(b)] (kg/day)	Total dry manure (kg/ha/day)
Dairy cows	871	4.1	5.4	21.9
Cattle	480	2.2	3.2	7.1
Heifers, bulls and steers	1124	5.2	3.0	15.7
Calves (< 1 year)	963	4.5	1.5	6.7
Sheep	3857	17.9	0.7	12.6
Horses	1924	9.0	5.4	48.3

(a) The total grazing area (pasture) is 215 ha; over this area the animal density distribution was calculated.

(b) Refer to Coffey et al. (2010) for the value used for calculating the daily dry manure production per hectare.

Fertiliser operations

Manure storing rules and regulations specify storage capacity to contain manure produced during the number of months. The storage must not lead to surface or groundwater contamination to avoid the harm to the environment or human health. Storage capacity should also be sufficient to store the manure for the time of year when it is not appropriate to spread (Jordbruksverket 2014).

After livestock housing during winter and spring (1 November – 1 April) the stored manure is used for land fertilisation during the growing season in the arable land. To simplify the method for manure calculation for different animals, Coffey et al. (2010) suggested that one livestock unit (LU) consuming 18 kg dry matter per day, produces 28 kg slurry per day and 5.4 kg dry manure per day. Compromise of weight difference is achieved with summing up all the cattle weight and dividing by one standard cow LU that weighs 550 kg, as summarised in Table 4. Similarly one ewe/ram or lam weighing 70 kg is equivalent to 0.2 LU.

When estimating the cattle weight we refer to Swedish lowland cattle (Holstein), the usual black and white cow breed with high milk production, constituting about 51 % of the controlled cows in Sweden. The cows weigh about 700 kg (Agria 2011). Furthermore Cassell (2009) recommends using Holstein heifers weight of 340 kg, while calves under 1 years weight are assumed to be 100 kg. The total weight of each group is divided by 550 kg, the standard cow LU (Coffey et al. 2010).

In poultry our reference is Swedish flower hen, the largest native breed in Sweden. Their weight ranges from 1 – 1.5 kg for small hens to 2 – 2.5 kg for the large hens (Svenska Lanthönsklubben 2014). Manure quantity and characteristics are influenced by the species, age, diet and health of the birds. Estimates of the manure excreted by 1000 birds per day are approximately 120 kg for layer chickens which means 0.12 kg/day/bird (Williams 2013).

The total stored manure (Table 4) is used for the land fertilisation in the arable land. The area of the agricultural land in the study area is 4911.44 ha (Table 1). To calculate the animal density, the standard LUs are used. That becomes: density = LUs / 4911.44, and the slurry production of 1 LU is 28 kg/day. Total stored manure = LUs * 28 * housing days. Note that in poultry (Refer to Table 4) it is used the standard LUs to calculate the stored manure from poultry, but it is also okay to use the estimated slurry daily production per bird of 0.12.

Table 4. Stored mature calculation and rate of application.

Animal type [(a)]	**No**	**Weight (kg)**	**LUs**	**Density (No/ha)**	**Housing days**	**Stored manure (kg/ha)**	**Spring (2/3)** [(b)]	**Autumn (1/3)** [(c)]
Dairy cows	871	700	1109	0.23	151	955	637	318
Cattle	480	700	611	0.12	151	526	351	175
Heifers, bulls and steers	1124	340	695	0.14	151	598	399	199
Calves (<1 year)	963	100	175	0.04	151	151	100	50
Sheep	3857	70	771	0.16	90	396	264	132
Poultry	25504	3	116	0.02	365	241	161	80
Horses	1924	700	2449	0.50	151	2108	1406	702

a) Slurry production is 28 kg/day for all animal types, using the standard livestock unit (LUs), that weighs 550 kg and produce 28 kg slurry per day, i.e. in poultry the total number is 25504 weighing 2.5 kg each, which is equivalent to 116 LUs.

b) Fraction applied in spring (1 March)

c) Fraction applied in autumn (1 September)

Wastewater treatment plants

There are several WWTPs that are located outside the study area and that discharge treated effluents into Lake Mälaren either very far upstream or downstream the Norsborg DWTP. These WWTPs are: the Bromma WWTP and the Hennriksdal WWTP in Stockholm, the Ekebyhove WWTP in Ekerö municipality, and the Kungsängens WWTP in Västerås. These WWTPs were not considered in this study due to the fact that as a result of their location they are unlikely to affect the water quality at the Norsborg DWTP.

On-site sewer systems

Some permanent or holiday living houses in rural areas often have their own facilities (Naturvårdsverket 2008), so called on-site wastewater systems. In Sweden there are about 750 000 households that are not connected to the municipal WWTPs. Sewer standards in rural areas are very diverse, and it is estimated that only about 60 % have a standard that meets the environmental requirements (Naturvårdsverket 2008).

This study does not have an exact number of on-site sewers in the area that are not connected to the municipal WWTPs. However, it is known that the municipalities take care of retrieving the sludge from septic tanks and enclosed tanks by transporting the sludge to the Ekebyhove WWTP where it is treated with wastewater. In this study the possible contribution from the on-site sewers was not taken into account.

Pathogens and faecal indicators

Criteria for faecal indicators include that the organism should be present whenever enteric (intestinal) pathogens are present and be useful for all types of water, also it should have a longer survival time than the hardiest enteric pathogens. Another important criterion is that the organism should not grow in water and should be found in intestine of warm-blooded animals. The density of the indicator organism should have some direct relationship to the degree of faecal pollution (Gerba 2000). Coliform bacteria (total coliforms and faecal coliforms) are not usually pathogenic themselves; their presence indicates faecal contamination, perhaps accompanied by disease-causing pathogens (EPA 2006). Other commonly used bacteria indicators are *Escherichia coli*, a single species within the faecal coliforms group, and enterococci, another group of bacteria found primarily in the intestinal tract of warm-blooded animals (EPA 2006). In this study *E. coli* have been used as main faecal indicator; the concentrations are reported as colony forming units (CFU)/100 ml.

Pathogens are likely to be present in most surface waters, and possibly below detection limits (Smeets et al. 2006). *Cryptosporidium* oocysts are widespread in ambient water and can persist for months in this environment (EPA 2001). A number of waterborne disease outbreaks caused by this protozoan pathogen have occurred, most notably in Milwaukee, Wisconsin, where an estimated 400 000 people become ill in 1993. *Cryptosporidium* may be more common in surface water than ground water because surface waters are more vulnerable to direct contamination from wastewater discharges and runoff. *Cryptosporidium* oocysts are also found more often in water in areas where animals such as cows are found, or where wastewater runoff from urban areas occurs (EPA 2001). In this study *Cryptosporidium* fate and transport have been studied; the concentrations are reported as oocysts/100 ml.

Input data for the calculations for *E. coli* (Tables 5 and 6) and *Cryptosporidium* (Table 7) were based on the literature data. BACTPDLB is SWAT abbreviation for concentration of less persistent bacteria in manure. Growth for both *E. coli* and *Cryptosporidium* was set to zero (WHO 2011).

Table 5. Parameters for E. coli.

Parameter	**Definition**	**Suggested value**
WDLPQ	Die-off, less persistent organisms in soil solution (n/day)	0.659 (a)
WDLPRCH	Die-off, less persistent organisms during river transport (n/day)	0.67
WDLPS	Die-off, less persistent organisms adsorbed to soil particles (n/day)	0.023 (a)
WDLPF	Die-off, less persistent organisms on foliage (n/day)	0.016 (a)
WOF_LP	Fraction less persistent organisms washed off in rainfall events	0.5 (b)

(a) Bougeard et al. (2011)

(b) Bougeard et al. (2010)

Table 6. E. coli concentrations in different types of manure.

Animal type	***E. coli* (CFU/g)**	**BACTLPDB used (CFU/g)**
Calves	4.2 x10^{5} (a)	1.1 x 10^{5} (maximum)
Cattle	4.2 x10^{5} (a), 8.2 x 10^{4} (b), 5.0 x 10^{7} (c), 1.1 x 10^{3} (d)	8.2 x 10^{4}
Cows	2.9 x 10^{4} (e), 4.0 x 10^{7} (e)	2.9 x 10^{4}
Sheep	6.6 x 10^{4} (a), 3.9 x 10^{7} (c)	6.6 x 10^{4}
Poultry	8.9 x 10^{5} (f)	1.1 x 10^{5} (maximum)

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

Table 7. Parameters for Cryptosporidium (Coffey et al. 2010).

Parameter	**Definition**	**Suggested value**
THBACT	Temperature adjustment factor	1.07
BACTKDQ	Soil partitioning coefficient	175
BACTMIX	Percolation coefficient	10
BACTKDDB	Partition coefficient	0.9
FRT_SURFACE	Manure fraction applied to the top 10mm of the soil layer	0.2
WDPQ	Die-off, persistent organisms in soil solution (n/day)	0.05 (a)
WDPRCH	Die-off, persistent organisms during river transport (n/day)	0.01
WDPS	Die-off, persistent organisms adsorbed to soil particles, (n/day)	0.003
WDPF	Die-off, persistent organisms on foliage, (n/day)	0.02 (a)
WOF_P	Fraction persistent organisms washed off in rainfall events	0.8 (a)
Oocysts/g	*Cryptosporidium* concentration	
	Calves	3643
	Cattle	398
	Cows	353
	Lambs	17976
	Ewes	837

(a) Tang et al. (2011)

Results

Microbial concentrations

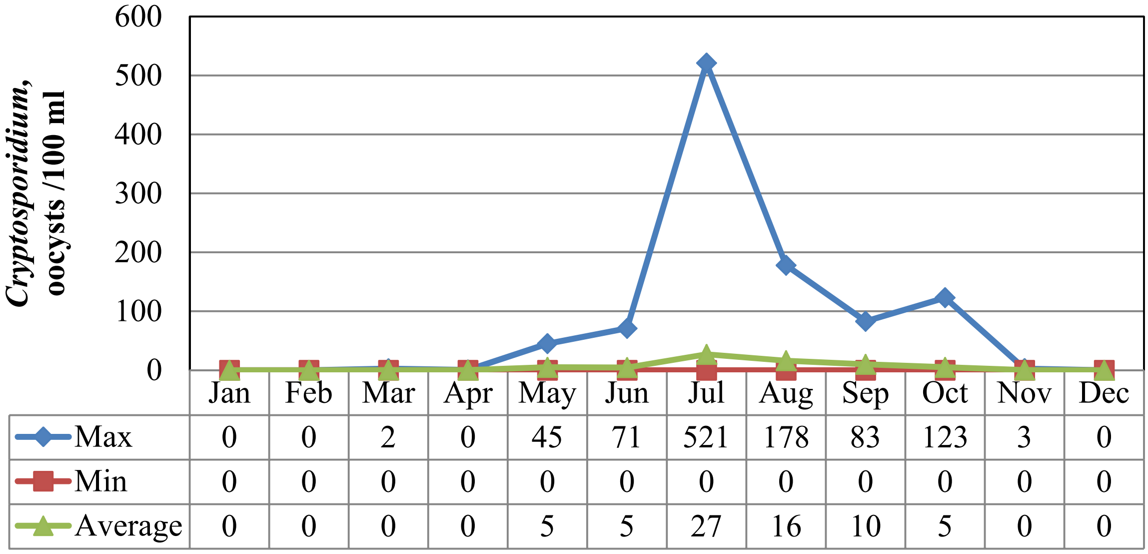
ArcSWAT model simulated daily *Cryptosporidium* and *E. coli* concentrations in each sub-basin. The sub-basin that received the contamination from the entire study area was sub-basin 56 (outlet), where the Norsborg drinking water treatment plant is located (Figure 2). This tabulated result was for HRU 205 within sub-basin 56, which is the water around the intake area. Summarised monthly concentrations and precipitation/snowmelt are demonstrated in Table 8 and Figures 3, 4 and 5. These results were calculated from the daily simulations to get maximum, minimum and average daily concentrations in each month. In Appendix the results for daily and monthly simulations are shown (Tables A1 and A2).

The concentration of *Cryptosporidium* was 0 oocysts/100 ml in the winter months December, January and February. The highest *Cryptosporidium* concentration was observed in July: 521 oocysts/100 ml (Table 8).

The results for *E. coli* are similar to those for *Cryptosporidium,* with the peak value of 2522 CFU/100 ml in July (Table 8).

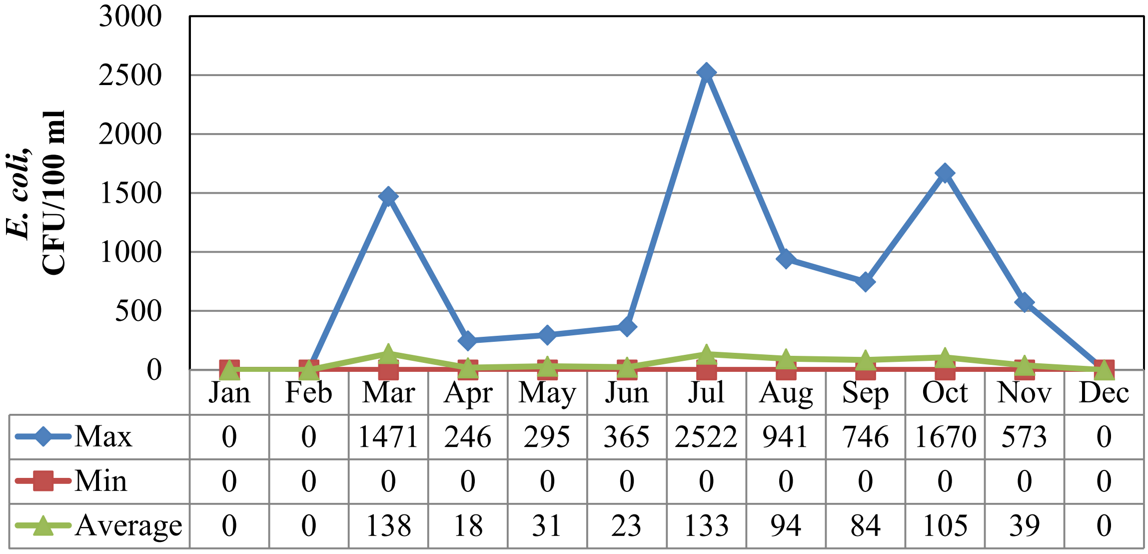
Table 8. Modelling results: Cryptosporidium concentrations, E. coli concentrations and precipitation/snowmelt during the year 2010.

Month	***Cryptosporidium*, oocysts/100 ml**			***E. coli*, CFU/100 ml**			**Precipitation/snowmelt, mm**		
	Max	**Min**	**Average**	**Max**	**Min**	**Average**	**Max**	**Min**	**Average**
January	0	0	0	0	0	0	9	0	1
February	0	0	0	0	0	0	9	0	1
March	2	0	0	1471	0	138	22	0	2
April	0	0	0	246	0	18	6	0	1
May	45	0	5	295	0	31	9	0	1
June	71	0	5	365	0	23	12	0	1
July	521	0	27	2522	0	133	67	0	4
August	178	0	16	941	0	94	16	0	3
September	83	0	10	746	0	84	12	0	1
October	123	0	5	1670	0	105	13	0	1
November	3	0	0	573	0	39	10	0	1
December	0	0	0	0	0	0	5	0	1



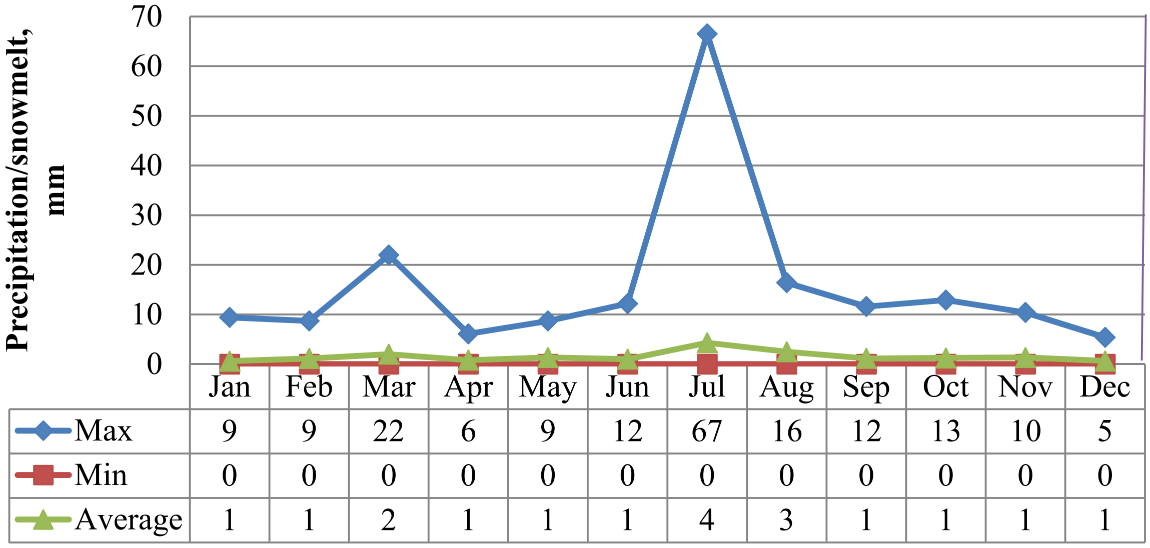
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ Max	0	0	2	0	45	71	521	178	83	123	3	0
■ Min	0	0	0	0	0	0	0	0	0	0	0	0
▲ Average	0	0	0	0	5	5	27	16	10	5	0	0

Figure 3. Monthly Cryptosporidium concentrations for HRU 205 in sub-basin 56 (year 2010).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ Max	0	0	1471	246	295	365	2522	941	746	1670	573	0
■ Min	0	0	0	0	0	0	0	0	0	0	0	0
▲ Average	0	0	138	18	31	23	133	94	84	105	39	0

Figure 4. Monthly E. coli concentrations for HRU 205 in sub-basin 56 (year 2010).

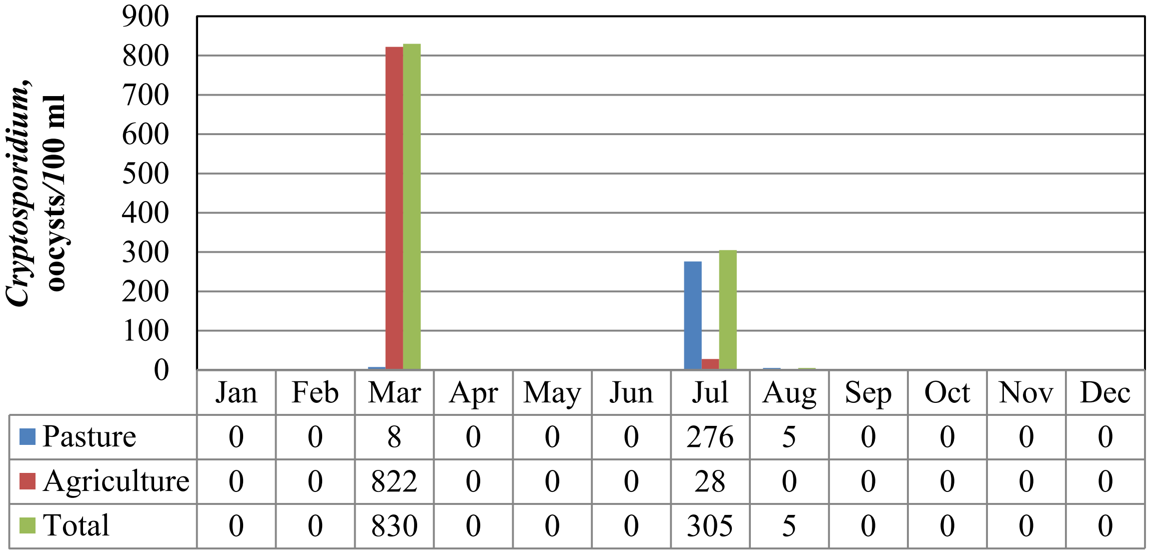


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	9	9	22	6	9	12	67	16	12	13	10	5
Min	0	0	0	0	0	0	0	0	0	0	0	0
Average	1	1	2	1	1	1	4	3	1	1	1	1

Figure 5. Monthly precipitation/snowmelt from sub-basin 56 (year 2010).

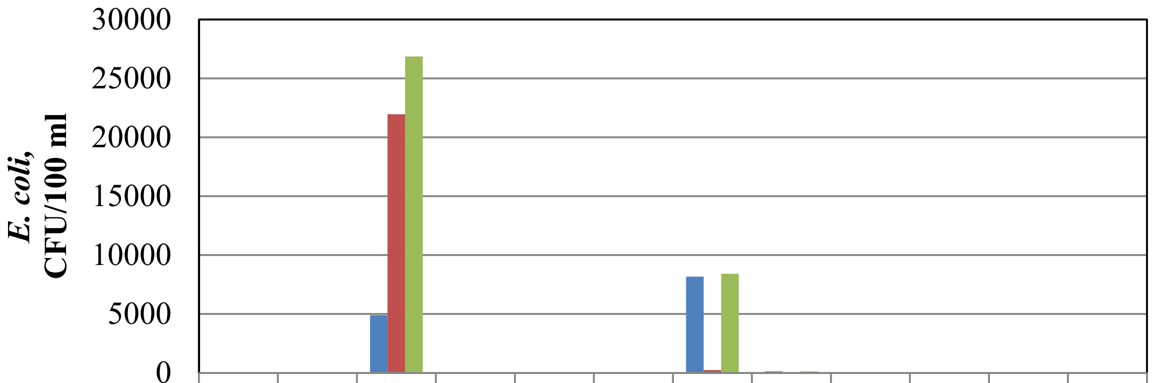
Contamination source characterisation

Sub-basin 21 was examined to assess the contributions from grazing and fertiliser application. This sub-basin consists of six different HRUs: two HRUs are forest, and thus produced no contamination; three HRUs are grazing area (pasture) with total area of 1.5 km^2; and one HRU is agriculture with area of 2.23 km^2. The assessment showed that fertiliser application (agriculture) was the main contributor to contamination in March, while livestock grazing (pasture) was the main contributor in July and August (Figures 6 and 7).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pasture	0	0	8	0	0	0	276	5	0	0	0	0
Agriculture	0	0	822	0	0	0	28	0	0	0	0	0
Total	0	0	830	0	0	0	305	5	0	0	0	0

Figure 6. Monthly total Cryptosporidium concentrations from manure application and grazing areas for sub-basin 21.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
🟦 Pasture	0	0	4897	0	0	0	8168	134	0	0	0	0
🟥 Agriculture	0	0	2196	0	0	0	244	0	0	0	0	0
🟩 Total	0	0	2686	0	0	0	8412	134	0	0	0	0

Figure 7. Monthly total E. coli concentrations from manure application and grazing areas for sub-basin 21.

Discussion

Modelling output

In this study the fate and transport of faecal indicator *E. coli* and pathogen *Cryptosporidium* within the catchment area around the Norsborg DWTP were simulated. The modelling results for the year 2010 (Figures 3 and 4) showed that grazing and fertiliser operations did not cause any contamination in winter months (December, January, and February), and caused only minor contamination in April. On two days in March it was observed that the *Cryptosporidium* concentration exceeded 2 oocysts/100 ml, and the concentration of *E. coli* in the same days was relatively high. The contamination levels started rising in May, with the highest contamination registered in July: the maximum *Cryptosporidium* concentration was 521 oocysts/100 ml, and the highest *E. coli* concentration was 2522 CFU/100 ml. The contamination levels were high during August, September and October, and then decreased in November (Figures 3 and 4).

The results clearly demonstrated that the generated faecal contamination was proportional to the rain intensity or the amount of snowmelt (Figures 3, 4 and 5). This is consistent with previous studies. For example, Coffey et al. (2010) stated that during periods of high surface runoff more organisms are generated and tend to be transported out of the catchment in larger numbers. Similarly, Jayakody et al. (2014) stated that high rainfall months accounted for high faecal coliform bacteria concentrations in the streams.

Source characterisation assessment showed that fertiliser application was the key contributor to the total contamination in March, while contamination from livestock grazing was dominant in July and August. Analysis conducted by Coffey et al. (2010) identified manure (fertiliser) application as the most significant contributor, about 75 %, to the total *Cryptosporidium* load in the catchment. Furthermore, Coffey et al. (2010) suggested that the frequency of manure spreading is an important factor. In this study, the manure was assumed to be spread only two times, in March and September. This means that there is a possibility that the applied manure is washed out in one or two heavy rain events. On the other hand, contamination from livestock grazing is continuous and can be the main faecal contamination source after degradation of the applied manure.

The main focus of this study was the area around the Norsborg DWTP, where the drinking water for Stockholm is produced. The quality of raw water is being monitored constantly by Stockholm Water Company (Stockholm Vatten AB) that operates the Norsborg DWTP. Normally, the measured concentrations of coliform bacteria are around 20 CFU/100 ml and the measured concentrations of *E. coli* are around 5 CFU/100 ml. The simulated daily *E. coli* concentrations were above 5 CFU/100 ml during 66 days in 2010 (out of 365 days), which is 18 % of the time.

ArcSWAT computer simulation method for faecal contamination constitutes a powerful tool for surface water conservation programs, because it can estimate the quantity of possible contamination, provided accurate input data are available.

Limitations

In this study the possible contamination from wastewater treatment plants, on-site sewers, wildlife and pets (dogs, cats) was not considered. Several important features that could have influenced the results were not considered in the model; these features are ground water modelling, ponds/dams, and wetlands.

Recommendations

It is recommended to develop the model further using complete and accurate data regarding the different contamination sources. It is also recommended to include ground water modelling.

Conclusions

- The developed model can be used to estimate potential contamination risks.
- The maximum simulated concentrations of *Cryptosporidium* and *E. coli* (521 oocysts/100 ml and 2521 CFU/100 ml respectively) are assumed to be very high. However, 82 % of the time in 2010 the simulated *E. coli* concentrations were under 5 CFU/100 ml.
- The fate and transport of the faecal indicators and pathogens depend on the rain intensity and the quantity of the generated surface runoff.
- Manure application causes significant contamination in March, but the contribution from the grazing animals is dominating afterwards.
- ArcSWAT computer simulation method for faecal contamination constitutes a powerful tool for surface water conservation programs, because it can be used to estimate the quantity of possible contamination, provided accurate input data are available.

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Appendix

Table A1. ArcSWAT daily simulation results for the year 2010 for HRU 205 in sub-basin 56: (A) precipitation (mm), (B) Cryptosporidium (oocysts/100 ml) and (C) E. coli (CFU/100 ml).

	January			**February**			**March**		
Date	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	1	0	0	0	0	0	1	0	59
2	0	0	0	0	0	0	7	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	9	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0
11	0	0	0	1	0	0	0	0	84
12	0	0	0	0	0	0	0	0	14
13	0	0	0	0	0	0	0	0	0
14	0	0	0	3	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0
18	0	0	0	2	0	0	1	0	0
19	6	0	0	3	0	0	0	1	788
20	0	0	0	1	0	0	0	2	1413
21	0	0	0	9	0	0	0	2	1471
22	0	0	0	0	0	0	4	0	0
23	0	0	0	0	0	0	1	0	0
24	0	0	0	1	0	0	2	1	311
25	0	0	0	0	0	0	0	0	0
26	0	0	0	1	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0
28	9	0	0	3	0	0	4	0	135
29	1	0	0				2	0	30
30	1	0	0				0	0	0
31	0	0	0				0	0	0

	April			May			June		
Date	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	0	0	0	2	0	10	0	0	0
2	2	0	37	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0
6	2	0	26	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0
9	4	0	126	8	38	296	0	0	0
10	1	0	7	0	0	0	0	0	0
11	0	0	0	0	0	0	7	33	166
12	0	0	0	0	0	0	12	71	365
13	0	0	0	0	0	0	3	8	43
14	0	0	0	0	0	0	3	10	50
15	0	0	0	4	16	88	0	0	0
16	1	0	8	0	0	0	0	0	0
17	2	0	28	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0
19	1	0	0	0	0	0	4	16	78
20	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0
22	6	0	246	0	0	0	0	0	0
23	3	0	42	8	41	175	0	0	0
24	0	0	1	2	2	11	0	0	0
25	0	0	0	4	11	55	0	0	0
26	0	0	0	9	45	254	0	0	0
27	0	0	0	0	0	0	1	0	0
28	1	0	2	1	0	0	0	0	0
29	1	0	6	1	0	0	0	0	0
30	2	0	18	4	13	76	0	0	0
31				0	0	0			

	July			August			September		
Date	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	24	178	941	2	2	7
4	0	0	0	4	19	104	0	0	0
5	0	0	0	4	12	64	0	0	0
6	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	0
8	0	0	0	16	112	540	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	3	7	36	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0
14	0	0	0	0	0	0	3	20	176
15	0	0	0	0	0	0	1	2	13
16	0	0	0	0	0	0	7	84	746
17	0	0	0	2	1	1	1	0	0
18	0	0	0	10	84	554	1	2	10
19	0	0	0	5	30	199	12	131	1101
20	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	7	60	494
22	3	7	28	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0
24	0	0	0	3	12	75	0	0	0
25	67	522	2522	0	0	0	0	0	0
26	1	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0
29	6	30	146	0	0	0	0	0	0
30	36	285	1453	1	0	0	0	0	0
31	0	0	0	6	47	409			

	October			**November**			**December**		
Date	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1	0	0	0	1	0	2	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	4	2	126	1	0	0
4	0	0	0	2	1	36	2	0	0
5	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	1	0	0
7	0	0	0	0	0	0	0	0	0
8	13	123	1671	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0
10	0	0	0	8	0	28	0	0	0
11	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0
13	0	0	0	1	2	393	0	0	0
14	1	0	0	0	0	0	0	0	0
15	0	0	0	1	0	0	0	0	0
16	0	0	0	10	3	574	0	0	0
17	0	0	0	0	0	0	5	0	0
18	0	0	0	0	0	0	1	0	0
19	1	0	3	0	0	0	1	0	0
20	5	14	344	3	0	0	2	0	0
21	0	0	0	0	0	0	0	0	0
22	3	0	0	1	0	29	0	0	0
23	0	0	0	1	0	0	0	0	0
24	3	12	429	1	0	0	0	0	0
25	9	20	770	3	0	0	0	0	0
26	0	0	0	2	0	0	1	0	0
27	0	0	0	1	0	0	0	0	0
28	1	0	13	0	0	0	1	0	0
29	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0
31	2	1	30	6	47	409	1	0	0

Table A2. ArcSWAT monthly simulation results for the year 2010 for HRU 205 in sub-basin 56.

Month	**PRECIP** [(a)]	**SNOWMELT** [(b)]	**TMP_AV** [(c)]	**BACTP** [(d)]	**BACTLP** [(e)]
January	19.4	0	-7.968	0	0
February	31.8	0	-6.607	0	0
March	22.8	64.286	-0.971	6.9224	4303.2
April	26.6	2.973	4.963	1.0212	548.31
May	41.4	0	11.206	167	964.4
June	31.1	0	14.703	138.1	702.69
July	113.8	0	20.265	843.78	4148.2
August	78.6	0	16.816	502.88	2922.7
September	35.6	0	11.263	301.49	2547.9
October	38.4	3.155	5.07	170.77	3259.4
November	40	9.888	-0.338	7.7245	1187.4
December	19.2	0	-7.497	0	0

(a) Total amount of precipitation falling on the HRU during time step (mm H_2O).

(b) Amount of snow or ice melting during time step (water-equivalent mm H_2O).

(c) Average daily air temperature (°C). Average of mean daily air temperature for time.

(d) Number of persistent organisms (C*ryptosporidium)* in surface runoff entering reach (oocysts/100 ml).

(e) Number of less persistent bacteria (*E. coli*) in surface runoff entering reach (CFU/100 ml).