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Advective transport times in the river basin of lake Vombsjön

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Advektiva transporttider i Vombsjöns avrinningsområde

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Abstract

The raw water source lake Vombsjön is situated in the center of southern Scania and provides drinking water by artificial groundwater recharge for approximately 450 000 inhabitants each day. More than 2800 households within the catchment of lake Vombsjön treats their domestic wastewater with a decentralized sewer system. The configuration of these sewer systems varies, but it is common to have some kind of soil infiltration unit as one of the treatment steps from which treated wastewater infiltrates through a soil bed towards the groundwater table. However, depending on the status of the wastewater treatment systems, contamination in form of nutrients, household chemicals, pharmaceuticals and pathogens originating from private households risk spreading with groundwater transport.

This master thesis has been carried out in collaboration with the research company Sweden Water Research (owned by Sydvatten AB among others) and aims to calculate the transport times by advective transport from source to closest water body discharging into lake Vombsjön. This represents a conservative approach of contaminant transport in the catchment area since advective transport describes the average linear velocity of groundwater in one dimension without regarding coefficients for retardation. The advective transport times were computed using Geographical Information System (GIS), in this case the software ArcMap was utilized. Transport times were modeled according to two cases depending on prevailing properties of geological deposits within the catchment, a median case indicating probable characteristics of deposits and a worst case referring to more permeable deposits.

The catchment area of lake Vombsjön can roughly be divided into two geological areas; the Vomb basin consisting of permeable glaciofluvial sediments and the shale plateau that is dominated by less permeable till and clay till. The fastest transport times for groundwater, modeled in the worst case scenario, varies between half a day up to one week at locations situated in permeable deposits along the water bodies found in the Vomb basin. Substance transport from any point located in the Vomb basin will reach the stream network within six months at most. However on the shale plateau, velocities up to over 100 years were found. In order to elaborate the modeled transport times it is recommended that the geological and hydrogeological properties within the catchment is further investigated.

Key words: Lake Vombsjön, advective transport, decentralized sewer systems, contaminant transport, transport times, ArcMap.

Sammanfattning

Vombsjön är en råvattenkälla belägen i de centrala delarna av södra Skåne som dagligen förser cirka 450 000 invånare med drickvatten via konstgjord grundvattenbildning. Mer än 2800 hushåll i Vombsjöns avrinningsområde renar sitt avloppsvatten med enskilda avlopp. Utformningen av dessa enskilda avlopp varierar, men det är vanligt att inkludera någon form av infiltration som ett reningssteg där avloppsvattnet infiltrerar genom en markbädd ner mot grundvattenytan. Vid bristande kvalitet på dessa reningsenheter kan förorening i form av näringsämnen, hushållskemikalier, läkemedel och patogener som härrör från privata hushåll riskera att spridas med grundvattnet.

Detta examensarbete har utförts i samarbete med forskningsbolaget Sweden Water Research (ägt av Sydvatten AB med flera) och syftar till att beräkna transporttiden med advektiv transport från källa till närmsta recipient som mynnar i Vombsjön. Detta representerar ett konservativt tillvägagångssätt eftersom advektiv transport beskriver grundvattnets genomsnittliga linjära flöde i en dimension utan att ta hänsyn till fördröjande effekter. De advektiva transporttiderna beräknades med hjälp av geografiska informationssystem (GIS), i detta fall programvaran ArcMap. Transporttiderna har modellerats enligt två fall baserade på rådande markegenskaper inom upptagningsområdet, ett "median" fall som representerar troliga markegenskaper och ett "värsta" fall som representerar mer genomsläppliga markegenskaper.

Vombsjöns avrinningsområde kan grovt delas in i två geologiska områden; Vombsjösänkan som består av genomsläppliga glacifluviala sediment samt skifferplatån som domineras av mindre genomsläppliga jordarter som morän och moränlera. Den snabbaste grundvattentransporten, given av "värsta" fallet, varierar mellan en halv dag upp till en vecka i Vombsjösänkans genomsläppliga jordlager. Föroreningsspridning bedöms nå närmsta vattendrag inom sex månader oavsett utsläppspunkt inom Vombsjösänkan, till skillnad från de förhållanden som råder på skifferplatån där transport med grundvatten bedöms ta upp till över 100 år. För att utveckla de modellerade transporttiderna ytterligare rekommenderas att de geologiska och hydrogeologiska egenskaperna inom avrinningsområdet kartläggs mer noggrannt.

Nyckelord: Vombsjön, advektiv transport, enskilda avlopp, föroreningstransport, transporttider, ArcMap.

Acknowledgements

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Terminology

Advective transport	Transportation of a contaminant at the same average linear velocity as the groundwater.
Absorption	Process in which substances penetrates and becomes captured in a bulk of solids or liquid.
Adsorption	Process in which substances are attracted to solid surfaces due to van der Waals forces.
Antihypertensive	Medical substance used to reduce high blood pressure.
Aquifer	Geological unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells.
Black water	Wastewater containing feces, urine and flush water from toilets.
BOD	*Biochemical oxygen demand.* Measure of the amount of dissolved oxygen needed for aerobic degradation of organic matter in a water sample during a specific time period.
Biofilm	Microorganisms that stick to each other forming a slimy film, often attached to a surface.
Capillary fringe	Part of the unsaturated zone found just above the groundwater table, where water saturation approaches 100% and the water is held in place due to negative pressure caused by capillary forces.
Catchment area	Area from which all precipitation that falls within that area flows to an outlet stream.
Closed septic tank	A closed septic tank collecting both solid and liquid waste.
Confined aquifer	Water-bearing geological deposits from which groundwater can be extracted. Confined aquifers are aquifers that are overlain by a confining (impermeable) layer, often consisting of clay.
Contaminant	Unwanted substance or pathogen intruding a system causing negative effects due to quantity and/or toxicity of named substance.
Darcy velocity	The fluid velocity through a porous medium (e.g. sand).
Decentralized sewer system	A decentralized system treating wastewater generated from a private household, i.e. a treatment process that is not connected to the centralized municipal wastewater treatment plant.
DEM	*Digital Elevation Model.* Satellite data describing how the topography varies in an area.

Diffusion	Process describing how a molecule is spread from regions with higher concentration to regions with lower concentration of the molecule.
Dispersion	Process describing how a molecule is spread faster or slower due to pore friction and the size of the pores in the medium.
Drainage system/pipes	Draining of rainwater from agricultural fields by permeable pipes installed in the ground under the fields. The permeable pipes will drain water to larger pipes discharging into ditches downstream the agricultural land.
Effective porosity	The sum of all interconnected pore space of a rock or sediment available for fluid flow through the medium.
Fault zone	Deformation zone of a volume of rock due to tectonic activity.
GIS	*Geographical Information System.* Computerized system designed to handle and analyze geographically referenced data.
Glaciofluvial sediments	Geological description of deposits formed by the movement of glacial melting water.
Gray water	Wastewater originating from kitchen, shower and laundry.
Groundwater recharge	Inflow of water to a groundwater aquifer mainly from infiltrating precipitation and melted snow.
Hydraulic conductivity	The ease with which a fluid can move through pore spaces or fractures depending on the intrinsic permeability of a material, the degree of saturation and the density and viscosity of the fluid.
Hydraulic gradient	Slope of the potential groundwater level along a given flow path.
K_{ow}	The octanol/water partition coefficient is a measure of a substance ability to dissolve in fat.
Pain relief (NSAID)	*Nonsteroidal anti-inflammatory drugs.* Drugs that provide pain-killing, fever-reducing and anti-inflammatory effects.
Pain relief (opioid)	Medical substance that act on opioid receptors producing morphine-like effects to relieve pain.
Peat	Geological description of partially degraded vegetation or organic matter.
Porosity	Percentage of all void spaces of a sediment or rock.
Post-glacial sediments	Geological description of fine grained sediments deposited by glacial melt water.

Quaternary deposits	Geological description of soil types produced during the Quaternary time period ranging from 2.58 million years ago to the present.
Radiative forcing	Difference between absorbed solar radiation by the Earth and energy returned back to space in W/m^2.
Redirecting septic tank	A septic tank consisting of two or more sections for sedimentation of solid waste from which effluent wastewater is redirected to further treatment outside of the tank.
Retardation	The process of delayed transport due to decelerating activities such as sorption to particles, microbial degradation or plant uptake.
Saturated zone	Zone in the ground where all pores are filled with groundwater, situated below the unsaturated zone located right under the ground surface.
Sedative	A medical substance that induces sedation by reducing irritability or excitement.
SGU	*Sveriges Geologiska Undersökning/Geological Survey of Sweden.*
Till	Geological description of unsorted glacial sediments constituting of different sizes of grains.
TIN	*Triangular Irregular Network.* Vector based representation of a surface created from irregularly distributed points and lines with three-dimensional coordinates that are arranged in a network of triangles.
Transport times	Travel time for a molecule traveling with groundwater from one point to another.
Unconfined aquifer	Water-bearing deposits from which groundwater can be extracted. Unconfined aquifers are aquifers that are not overlain by a confining (impermeable) layer, but are instead in direct contact with the atmosphere.
Unsaturated zone	Zone between the ground surface and the groundwater table where pores are filled with both air and water.

Contents

Chapter 1

Introduction

1.1 Background

Freshwater is one of the most essential assets for human life to thrive and prevail. It is not only used for direct consumption in form of drinking water, but freshwater of good quality is also crucial for production of food through agriculture and farming, as well as within industries and for ecosystem services. Only 2.53% of the Earth's water resources are fresh water, out of which two thirds are bound in glaciers and ice caps. Thus, all living organisms are extremely dependent on the quality of available water resources which are vulnerable to possible contamination (UNESCO 2016). Fifty percent of the Swedish drinking water resources are encountered as surface water and fifty percent as groundwater (Nordström 2005). Unfortunately, reports about reduced freshwater quality and quantity are increasingly common in public discussion which implies that our view of water as an unlimited resource is threatened. Emissions with contaminating substances directed to surface and groundwater may arise from several different sources such as industries, agricultural activities, municipal and private wastewater treatment plants (Ritter et al. 2002).

There are approximately 700 000 households in Sweden with decentralized systems for treating their sewage, meaning that the wastewater is not connected to a centralized municipal wastewater treatment plant and thus wastewater from individual households are treated on site (Havs- och vattenmyndigheten 2014). Havs- och vattenmyndigheten (2014) estimates that almost half of the 700 000 private facilities in Sweden are not approved according to Swedish law since they do not meet the requirements given by the government (Havs- och vattenmyndigheten 2014). Swedish municipalities have the responsibility to perform inspections and require that each household owner takes action in order to maintain or improve the quality of a private decentralized system. However, inspection and monitoring depend on the priorities and current economy of each municipality, which affects the quality of the decentralized sewer systems within a catchment. Pollution transport from decentralized sewage systems to the groundwater is very likely to occur if the number of decentralized systems are numerous within a limited area (Fetter 2014).

The raw water resource lake Vombsjön is situated in the south part of central Scania in Sweden, providing drinking water for approximately 450 000 inhabitants each day. The lake is eutrophic and a large part of the abundance of nutrients that reach lake Vombsjön derives from agriculture and decentralized sewer systems situated within the catchment (Schuster et al. 2008). Apart from nutrients, it is plausible to suspect further contamination from decentralized systems in the drainage basin of lake Vombsjön in form of infectious fecal microorganisms, pharmaceuticals and household chemicals that might present a risk to the water quality of the lake.

In order to manage and secure the quality of drinking water, one must evaluate the risk that contaminants pose based on quantity, toxicity and way of progression. A basic way of investigating the risk of contaminant transport in groundwater is to look at the time of contaminant transport from point of emission to closest water body. Estimated transport times for a pollutant with the groundwater can be used as the basis for more detailed substance-specific risk investigation with respect to e.g. degradation rate and sorption in the unsaturated zone above the groundwater (Persson 2011; Persson et al. 2011). Increased precipitation and temperature are effects induced by climate change that might have a severe impact on groundwater levels and thereby the contaminant transport in the future. It is therefore important to include a climactic aspect when assessing the risk of contaminant transport to foresee future effects on raw water sources (Vikberg et al. 2015).

GIS-based programs are suitable for estimating transport times on a catchment scale since available data suitable for such calculations more than often are GIS-based. Input data may include elevation, geological deposits, land use and so on. Lately, a lot of nationwide GIS-data in Sweden have become publicly available and free of charge since they are tax-funded. Estimating pollution transport with GIS-based models enables authorities and other stakeholders to graphically illustrate levels of risk for pollution transport in a simple manner, which can be used as a support when assessing future risks of possible contamination (Foster and McDonald 2000; Rönnbäck 2014).

1.2 Project proposal

Sydvatten AB is a company owned by 16 municipalities in western Scania, supplying drinking water for 900 000 inhabitants in this region. Sydvatten transmits water from lake Bolmen and lake Vombsjön to the water treatment plants Ringsjöverket and Vombsjöverket, where drinking water is produced and further distributed to municipalities (Sydvatten 2014). In 2014, Sydvatten started a research company, Sweden Water Research AB (SWR), together with VA SYD and NSVA. SWR coordinates these companies respective research with the objective to meet the future challenges of the water services sector (Sydvatten 2014).

This master thesis is developed from a project proposal from SWR and is carried out in collaboration with mentioned research company. The proposal includes two parts, primarily to investigate potential contaminants emitted from individual sewage systems like household chemicals, pharmaceutical residuals and microbial pollution and secondly to estimate the time of advective contaminant transport within the catchment area of lake Vombsjön. SWR want the result of the investigation to graphically describe levels of risk for transport of pollutants in the catchment. The graphical description should consist of GIS-produced maps showing the time of transport distribution in the catchment area, where the area with the shortest transport time should be interpreted as the area most sensitive to contamination from decentralized sewer systems. The result of the analysis and modeling are to be used as a support when assessing future risks of contamination originating from decentralized sewer systems in the river basin of lake Vombsjön.

1.3 Purpose and aim

The purpose of this master thesis is to evaluate the risk of contamination that decentralized sewer systems in the catchment area of lake Vombsjön pose on the water quality of the lake by computing the advective transport times of contaminants in the area. It is also to investigate and increase knowledge about what contaminating substances in the wastewater from decentralized sewer systems that might leach to the groundwater and pollute lake Vombsjön. The aim of this master thesis is therefore to:

1. Investigate the geological and hydrogeological conditions within the catchment area.
2. Study potential contaminants originating from decentralized sewer systems through a literature study.

3. Estimate the risk of contamination by computing the advective transport times from point of emission to nearest water body in the catchment area of lake Vombsjön using the geographical information software ArcMap.

Finally, the aim is to discuss the results in relation to changes in groundwater levels and precipitation induced by climate change.

1.4 Limitations

- This project is based on literature, archive documents and geological maps meaning that no field investigations have been conducted.
- The studied area is delimited to the catchment of lake Vombsjön which constitute a part of the larger river basin of Kävlingeån.
- Calculations only regards spreading of potential contaminants by advective transport, i.e. for substances that are soluble in water and may be transported with the groundwater flow. Calculations do neither account for sorption of different substances in varying geological deposits nor their decomposition rate or any other retardation or dilution process.
- Calculations are applied to the transport of contaminants that occur with the groundwater to lake Vombsjön or nearest water body that discharges into lake Vombsjön.
- The project focus solely on the pollution transport to lake Vombsjön. A brief description of the hydraulic conditions in the river basin will be presented, but the processes in the actual lake will not be further studied.

1.5 Project approach

As stated above, this project is based on literature, archive documents and geological maps meaning that no field investigations have been performed. Thus the project is conducted as a literature study followed by modeling in ArcMap. The literature study begins with a comprehensive survey and presentation of geological and hydrogeological characteristics in the river basin of lake Vombsjön together with theory about groundwater transport in Chapter 2. This provides a background and motivation to the modeling of transport times introduced in Chapter 3. Chapter 2 also provides a description of different types of decentralized systems and their effectiveness in treating wastewater. A presentation of contaminants that are likely to originate from domestic wastewater and hence spread with advective transport to lake Vombsjön is presented in Chapter 2 together with a motivation of the authors' selection of these substances. The result of the modeling in ArcMap is further presented in Chapter 4. Chapter 5 introduces possible impacts on groundwater and contaminant transport due to climate change followed by a thorough discussion in Chapter 6. Geological and hydrogeological information about the catchment area are gathered mainly from geological surveying reports found through correspondence with Sveriges Geologiska Undersökning (SGU) in Lund and through the search tool "GeoLagret" available on SGU's web page. The theoretical part regarding hydrogeology and contaminant transport is derived from textbooks (Fetter 2014; Knutsson and Morfeldt 1993; Grip and Rodhe 2000). The literature study concerning contaminating substances originates foremost from pharmaceutical screening projects carried out by Naturvårdsverket and Svenska Miljöinstitutet (IVL) among others. The license for the GIS software ArcMap used in the modeling in Chapter 3 is available for all students at Lund University. Input data for the model are collected as open source data from SGU and Lantmäteriet. Additional data are collected through personal communication with Sydvatten.

Chapter 2

Theory

2.1 Introduction to area

Lake Vombsjön is situated in the center of Scania, as indicated with red in Figure 2.1, and has a catchment area of 447 km^2 including the area of the lake itself (Sundahl et al. 2008). The catchment is part of the much larger drainage basin of Kävlingeån, which changes name to Lödde å before discharging into Öresund. Lake Vombsjön is divided into three parts by the municipality borders of Lund, Hörby and Sjöbo. Small parts of the catchment area are also situated in the municipalities of Eslöv and Tomelilla. There are three major water bodies that have their outlet in lake Vombsjön: Borstbäcken, Torpbäcken and Björkaån (Sundahl et al. 2008).

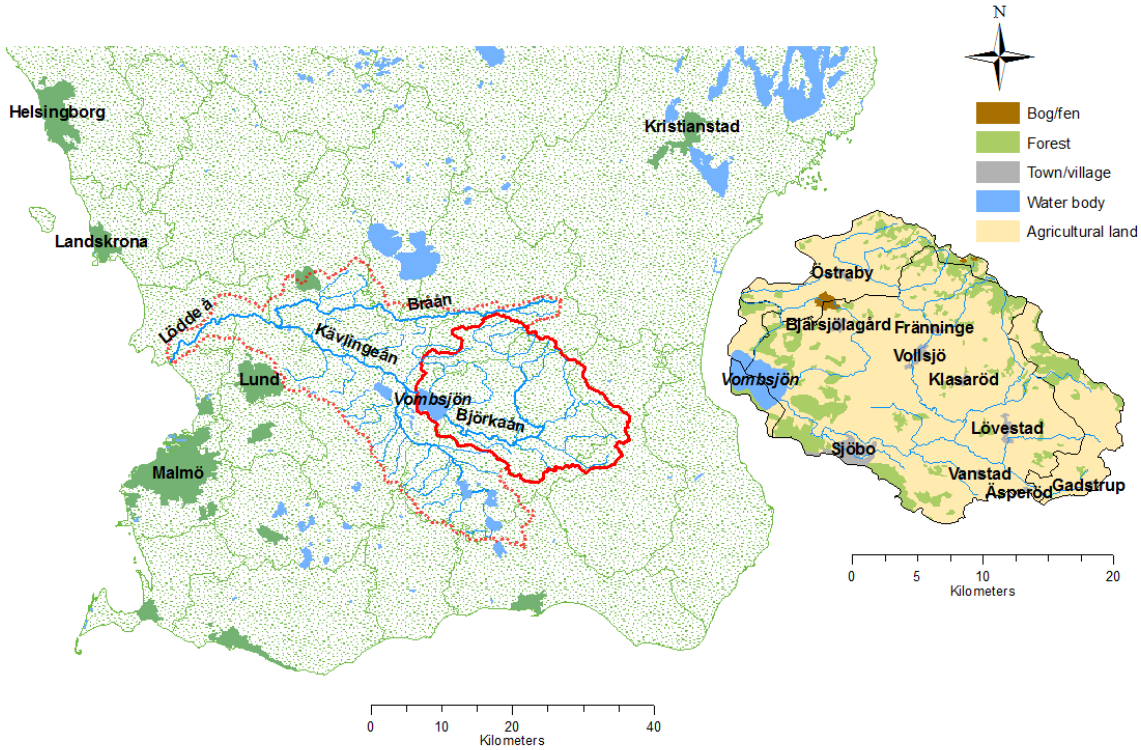


Figure 2.1: *Left: Location of the catchment area of Kävlingeån (dotted red line) and the river basin of lake Vombsjön (red line) in Scania. Right: Land use within the lake Vombsjön catchment. Maps produced in ArcMap by the authors.*

Lake Vombsjön has been a drinking water supply for the cities in the southwest of Scania since 1948. The regulation of the lake is determined by a water verdict from 1969 and is still valid today. Installation of drainage systems have been carried out in the catchment area since the 1930's to enable extensive agriculture (Schuster et al. 2008). The catchment is characterized by agricultural land (82%) and forestry (18%), see Figure 2.1. The topography varies between the highest point of elevation in the northern parts of the catchment (circa 180 meters above sea level) and the lowest point located in lake Vombsjön (circa 20 meters above sea level) (Schuster et al. 2008), see Figure 2.2.

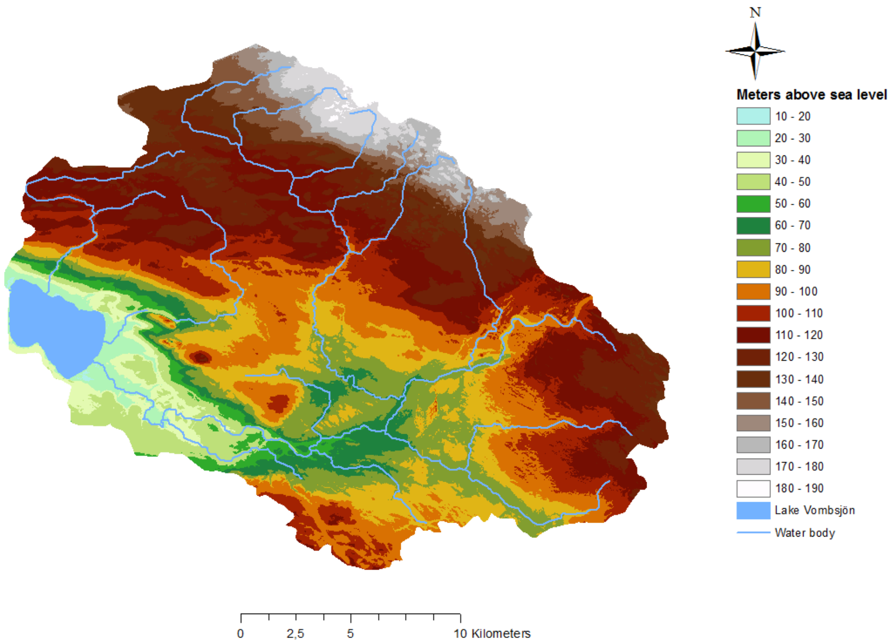


Figure 2.2: *Illustration of the topography in the catchment of lake Vombsjön. Map produced in ArcMap by the authors.*

2.2 Decentralized sewer systems

There are 2821 decentralized sewer systems densely located in the catchment of lake Vombsjön and the quality of these sewer systems varies greatly. Many of them are old and have not been inspected for a long time. Some households in the area do not have any wastewater treatment at all (Schuster et al. 2008). Figure 2.3 illustrates the location of households that treat their wastewater with decentralized sewer systems in the river basin of lake Vombsjön.

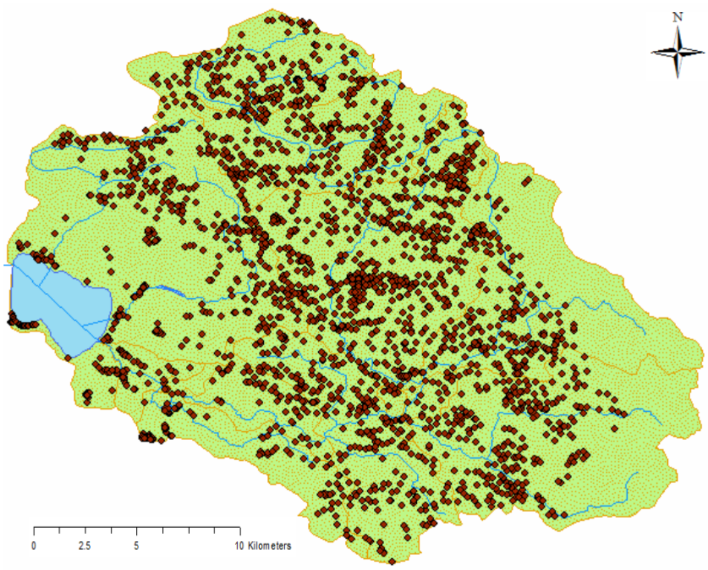


Figure 2.3: *Placement of households with decentralized systems within the catchment of lake Vombsjön. With permission from Sydvatten AB (Schuster et al. 2008).*

A decentralized sewer system may constitute of several different treatment units depending on the geological location, the quality of wastewater and the sensitivity of the surroundings. A decentralized treatment system almost always includes a septic tank that is closed or redirecting. A closed septic tank collects both solid and liquid waste, whilst a redirecting septic tank consists of two or more sections for sedimentation of solid waste from which effluent wastewater is redirected out of the tank for further treatment in another unit. The department for waste collection in each municipality has the legal responsibility to collect solid waste from septic tanks, both closed and redirecting, and treat the sludge at the municipal wastewater treatment plant (Avfall Sverige 2015). The most common decentralized sewer system is a septic tank with redirection of effluent wastewater to a soil infiltration unit. Domestic wastewater can be divided into gray water (water from shower, kitchen and laundry) and black water (feces and urine). The treatment units presented below can be rearranged to treat grey- and black water together or separately. A short presentation of the different units for treating domestic wastewater will be made below.

Figure 2.4: *Illustration of a septic tank where effluent flow is redirected to another unit (Holmberg and Sundin 2005).*

- Closed septic tank: a large tank for collection of both solid and liquid waste. Waste sludge is collected by the municipality (Avfall Sverige 2015).
- Redirecting septic tank: a large tank with two or more sections for sedimentation and anaerobic decomposition of feces and large wastewater particles, see Figure 2.4. Sludge (solid particles) is collected by the municipality, while effluent wastewater is redirected to another unit in the sewer system (Fetter 2014; Avfall Sverige 2015).
- Soil infiltration system: liquid effluent from a redirecting septic tank is carried to a field for soil infiltration. Effluent wastewater will percolate into layers of soil where microorganisms degrade wastewater substances until the water reaches the groundwater table, see Figure 2.5. A soil infiltration system can consist of natural layers of geological deposits or a artificial unit of sorted sand. The infiltration system can be built upon an impermeable foundation redirecting treated water to the closest located surface water instead of percolating directly towards the groundwater table (UMEVA 2013; Ejhed et al. 2012).

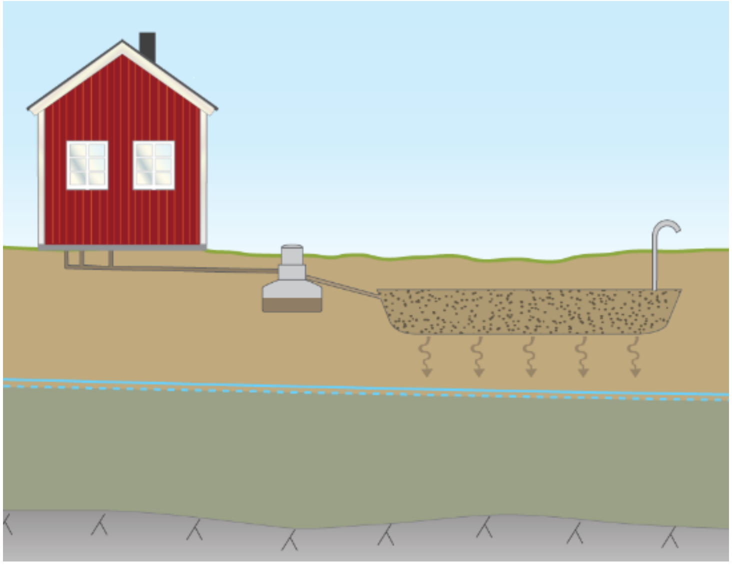


Figure 2.5: *Illustration of a redirecting septic tank and a soil infiltration unit (Holmberg and Sundin 2005).*

- Stone coffin: old and outdated decentralized sewer systems sometimes consist of a redirecting septic tank followed by a stone coffin. A stone coffin is a unit for leachate infiltration, an excavation filled with stones or large objects onto which effluent water is spilled. However, the process of infiltration in a stone coffin is uncontrolled leading to insufficient treatment of wastewater and high risk of contaminating the groundwater (Naturvårdsverket 2008).

- Small scale treatment plant: a treatment process that combines treatment of both grey- and black water using sedimentation, biological treatment and chemical precipitation in one single unit (UMEVA 2013).

- Precipitation and filtration of phosphorous: some decentralized sewer systems include extended wastewater treatment in form of filtration or precipitation of phosphorus. Chemical precipitation of phosphorus takes place within a septic tank. A flocculant that bind to phosphorus is introduced creating flocks that will settle. A filtration unit containing a filter material with high phosphorus binding capacity can be installed as post-treatment to a small scale treatment plant or to amplify the biological phosphorus reduction in a soil infiltration system (UMEVA 2013; Lusk et al. 2011).

The location and surrounding geology are of uttermost importance when installing a decentralized sewage system. In order to avoid contamination of groundwater from a sewage system with a unit of natural infiltration, the soil infiltration system should be placed at least 100 cm above the groundwater table to secure that the treatment process takes place in the unsaturated zone where the biological treatment process is optimal (Naturvårdsverket 2012; Lusk et al. 2011). A biofilm will form at the interface where effluent from the septic tank meets the coarse layer of the drain field located in the unsaturated zone. The biofilm helps treating the wastewater by slowing down the effluent flow and distributing it evenly over the infiltration unit. This results in a more effective removal of some contaminants and microbes such as bacteria and viruses, due to increased microbial activity and bio-transformation in the biofilm (Lusk et al. 2011).

Drinking water wells are often situated close to the sewage system on estates with decentralized sewer systems. Hence it is important that the infiltration unit is located downstream from where drinking water is extracted to avoid contamination (Naturvårdsverket 2012). The risk of contaminating groundwater also depends on the grain sizes of the soil used in the infiltration unit. Homogeneous soils such as sand is preferably used instead of unsorted and heterogeneous soils such as till since it is more permeable and allows for a greater flow of infiltrating wastewater (Espeby 1998).

The life-span of an infiltration unit connected to a decentralized sewer system depends on the effectiveness of treating wastewater with regards to reduction of BOD (Biochemical Oxygen Demand), nutrients, pharmaceuticals and pathogens. The function of biological treatment is relatively stable as long as the wastewater flow is constant, although pathogens are at high risk to leak through an infiltration bed regardless of the biological status. However, the chemical function of phosphorous reduction will decrease with time depending on wastewater load and availability of binding sites on minerals in the infiltration bed. A decentralized sewer system can be operated for approximately 30–40 years according to Swedish climate conditions and the general amount of wastewater loading according to present conditions (Naturvårdsverket 2012).

2.3 Geology

The catchment area of lake Vombsjön can roughly be divided into two parts: the *Vomb basin* and the *shale plateau* (English translations of the Swedish denotations: Vombsänkan and Lerskifferplatån from Bjelm and Malmberg-Persson, 1982), see Figure 2.6. The Vomb basin is characterized as a geological depression stretching from north west to south east in the catchment. The fault zone of Fyledalen separates the Vomb basin from the elevated shale plateau, which can be seen in Figure 2.7 (Kornfält et al. 2004).

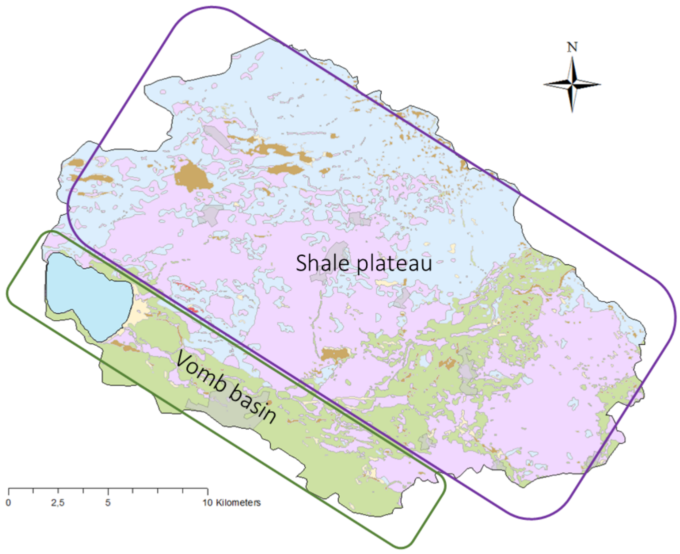


Figure 2.6: *Overview of two frequently occurring denominations of geological areas within the catchment area. Map produced in ArcMap by the authors.*

2.3.1 Bedrock

The bedrock in Scania is characterized by a tectonic zone called the Tornquist zone, a large geological deformation zone between the Baltic shield, which consists of basement rock, and the Avalonia shield composed by sedimentary rocks. It stretches from the Black Sea in southeast of Europe to the North Sea in northwest. The fault zone of Fyledalen, which is a part of the Tornquist zone, divides the bedrock in the south of Scania in several different blocks of bedrock, see Figure 2.7. One of these blocks is the Vomb basin whose northern side adjoins to Fyledalen fault zone (Kornfält et al. 2004).

The Vomb basin is a lowered block of basement bedrock formed during the younger Cretaceous period and is filled with up to 1000 meters of Cretaceous and Jurassic bedrock (Erlström and Guy-Ohlson 1994). Seven out of ten lithological units of sediment from the Jurassic time period have been detected in the Vomb basin. These lithological units indicate shallow marine conditions and are typically located directly on the Precambrian crystalline basement rock. Cretaceous bedrock is the dominating surface bedrock in the Vomb basin and constitutes a relatively uniform stratigraphy of silty-clayey sediments or fine-middle sized grains of sandstone and chalk. Lens shaped structures formed by weak bottom currents occur locally (Vajda 1988). In the fault zone of Fyledalen, dividing the geological regions of the Vomb basin and the shale plateau, one will find a small area of Precambrian gneiss close to lake Vombsjön which is superimposed by Jurassic clay and sandstone further southeast of the lake (Vajda 1988).

The plateau northeast of the fault zone of Fyledalen is formed by Silurian shale and sandstone superposing Precambrian bedrock. This plateau extends all the way to the fault zone of Kullen-Ringsjön-Andrarum in the northeast corner of the catchment area, located right next to the Linderöd horst, see Figure 2.7 (Kornfält et al. 2004).

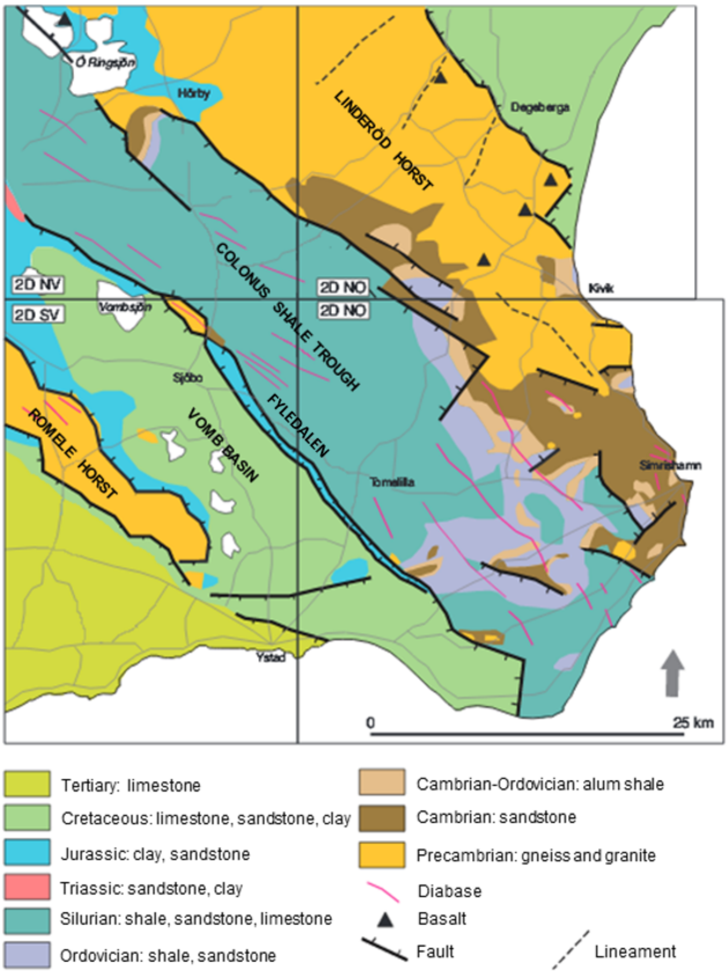


Figure 2.7: *Schematic map of the bedrock in the catchment area of lake Vombsjön translated from (Wahlgren 1999) © Sveriges Geologiska Undersökning.*

2.3.2 Geological deposits

The features of the geological deposits in Scania are characterized by the retreat of the latest glacier around 10 000 years ago. The Vomb basin was once a glacial lake formed by the melting water of a kinetically inactive glacier. The melted water accumulated between the two elevated horsts: Romele horst and Linderöd horst and thus formed a lake. From the initial glacial lake, lake Vombsjön is the only remaining water body (Daniel 1999). Figure 2.8 illustrates the general distribution of the topmost located deposits in the catchment. The illustration is based on the map over geological deposits in Sweden by SGU in the 1:1 million scale (SGU 2016c).

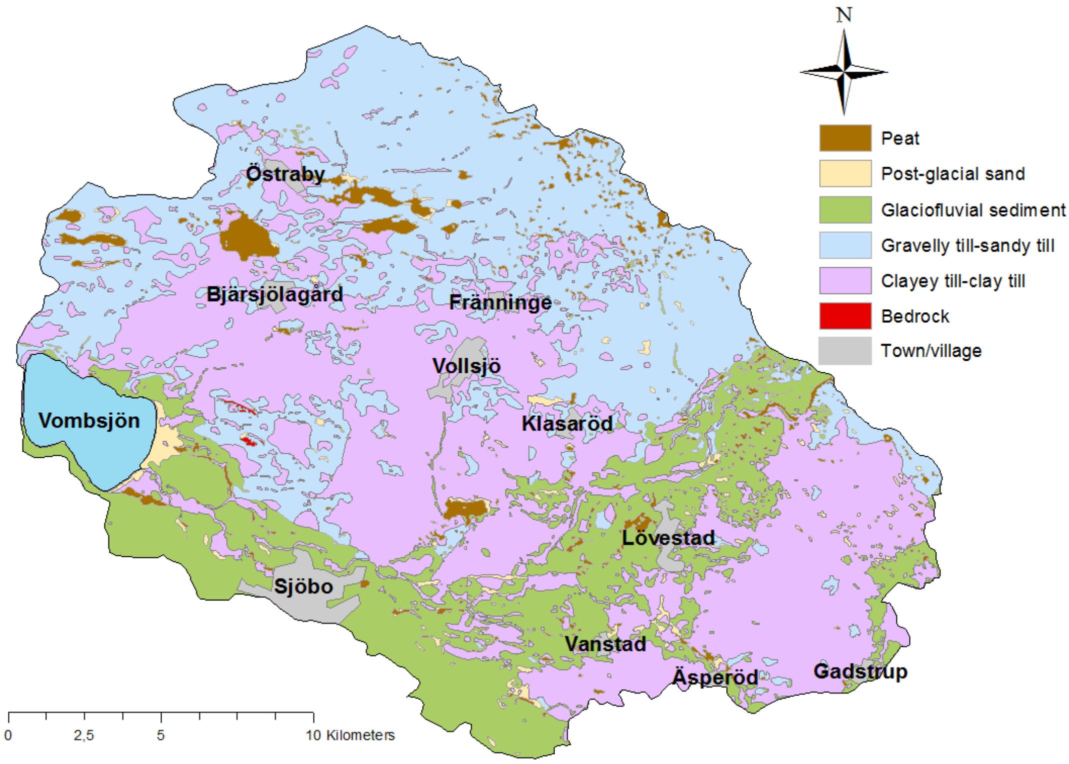


Figure 2.8: *Overview of the topmost located geological deposits in the lake Vombsjön catchment area. Map produced in ArcMap based on SGU's map over deposits in Sweden in the 1:1 million scale (SGU 2016c).*

Four conceptual cross sections are created by the authors in order to visualize the geological deposits and their thickness in different sections of the river basin, see Figure 2.9. It is very important to state that the conceptual models should only be viewed as an attempt to visualize the thickness and layering of the geological deposits and not as a correct representation of the subsurface.

The location of the cross sections are chosen according to the criteria of borehole data availability and variation in geological characteristics. The black arrows in Figure 2.9 refers to the direction and location in the catchment where the cross sections are extracted. The contours of the cross sections are created in ArcMap where the input data consists of borehole data from wells collected from SGU (2016a). The location of the wells can be seen as black dots in Figure 2.9. The depth of the deposits in the cross sections are estimations based on the map over geological deposits from SGU in the 1:1 million scale (SGU 2016c) and a geological description of the area by Bjelm and Malmberg-Persson (1982). A further description of how the cross sections are produced can be found in Appendix 1.

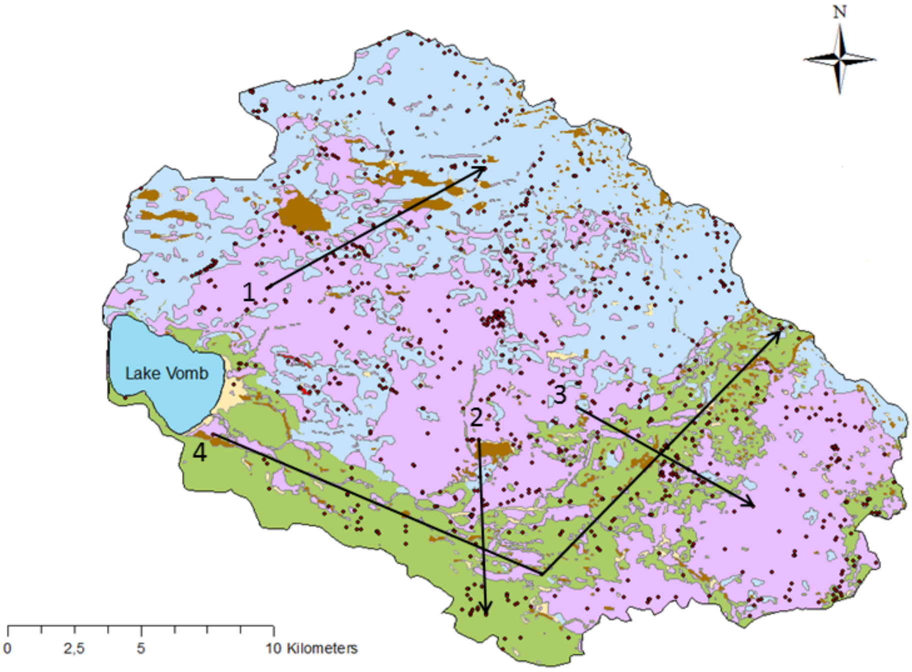


Figure 2.9: *Location of boreholes and direction of the geological cross sections. Map produces in ArcMap by the authors.*

The shale plateau is situated in the northern parts of the catchment and is dominated by till with varying clay content. The till originates from bedrock and older deposits being crushed under the glacier due to high pressure. Clayey till-clay till is most abundant in the southwest part of the shale plateau and consist of a large fraction of shale due to the influence of the underlying bedrock.

The clayey-clay till is superimposed by coarser gravelly-sandy till in the northern parts of the shale plateau. The gravelly-sandy till constitutes of a smaller fraction of shale since the bedrock consists of both crystalline rock and shale in this area. (Daniel 1999).

According to Bjelm and Malmberg-Persson (1982), the till layer on the shale plateau is rather thin with a general thickness of 5–15 meter. However, layers up to 70 meters thick have been detected southeast of Hörby and in the Vomb basin. These thicker layers are mainly localized to depressions in the bedrock, which are derived from pre-quaternary erosion or tectonic faults (Daniel 1999). A conceptual cross section over the shale plateau can be seen in Figure 2.10.

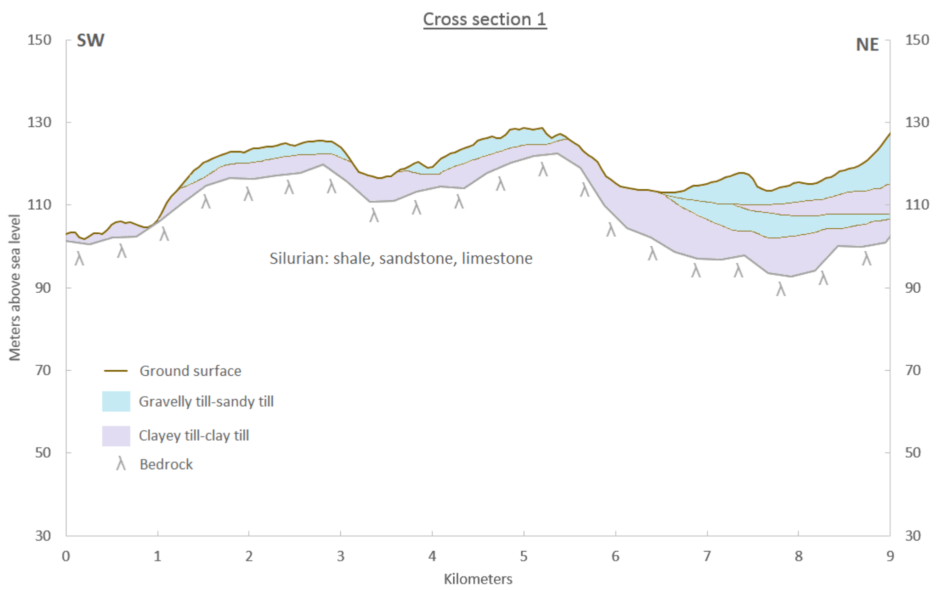


Figure 2.10: *Section 1: Cross section stretching over the shale plateau from southwest to northeast in the catchment. Illustration produced in Excel and Paint by the authors.*

The upper parts of the Vomb basin consist of glaciofluvial deposits, foremost sand and sand-gravel. This layer varies in thickness up to 20 meters from the ground surface (Daniel 1992). The glaciofluvial layer superimposes a 10–20 meter thick layer of glacial clay and at some places a deeper layer of up to 30 meter thick clay till. Lenses of coarse sediments such as sand can be found in scattered locations between the bedrock and layer of clay till (Bjelm and Malmberg-Persson 1982). Scattered clusters of peat and clay-silt can also be found west and southeast of the lake. Additionally, post-glacial sand and gravel are found on the northwest and southeast shores of lake Vombsjön. A conceptual cross section over the Vomb basin can be seen in Figure 2.11.

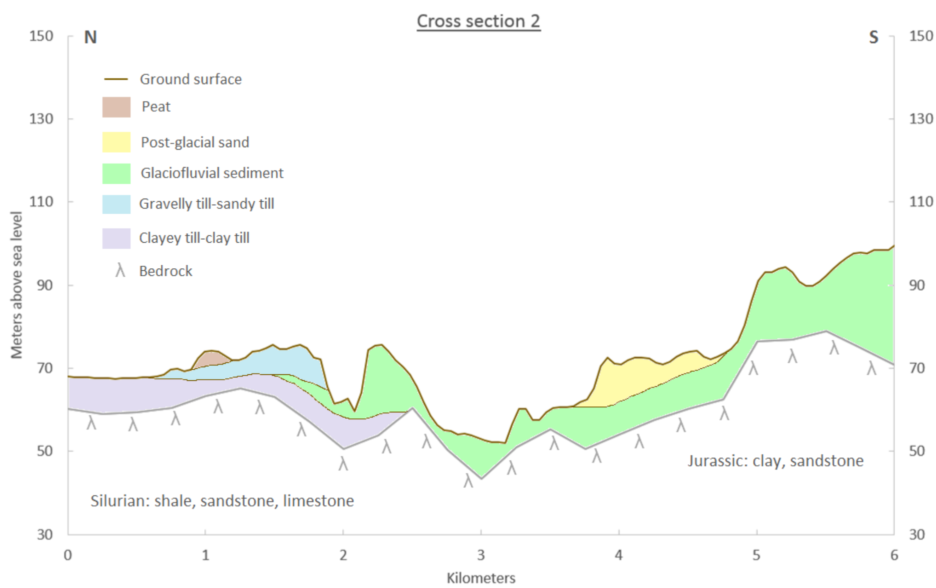


Figure 2.11: *Section 2: Cross section from north to south over the Vomb basin east of Sjöbo. Illustration produced in Excel and Paint by the authors.*

Close to Lövestad in the eastern parts of the catchment area, the thickness of the uppermost layer of glaciofluvial deposits can be up to 25 meters. The glaciofluvial deposits are situated on 5-10 meter thick till or clayey-till at some places, and at others directly on the bedrock (Bjelm and Malmberg-Persson 1982). A conceptual cross section over the eastern parts of the catchment can be seen in Figure 2.12.

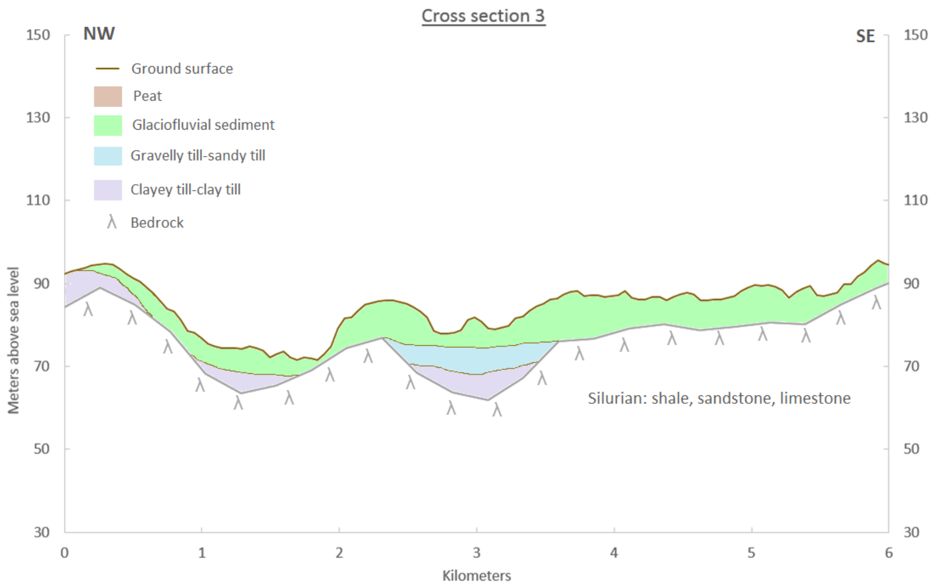


Figure 2.12: *Section 3: Cross section from north west to south east over the eastern part of the catchment. Illustration produced in Excel and Paint by the authors.*

From lake Vombsjön along Sjöbo and Vanstad to northeast of Lövestad, there is a long stretch consisting of mainly glaciofluvial deposits that can be seen in Figure 2.8. A conceptual cross section alongside the stretch is found in Figure 2.13, where the cross section is almost perpendicular to the previously presented cross sections 2 and 3.

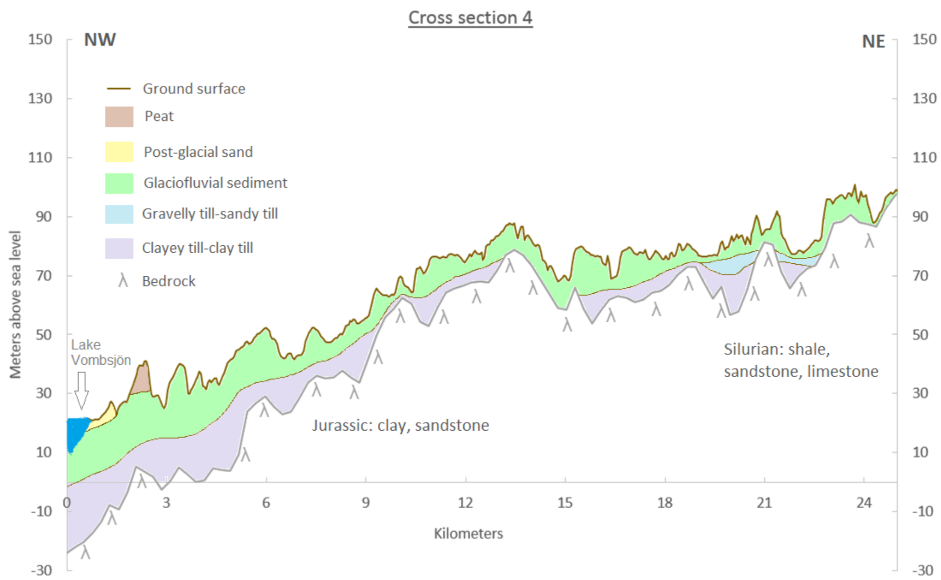


Figure 2.13: *Section 4: Cross section representing the stretch from lake Vombsjön through Sjöbo and Vanstad to north east of Lövestad.*

2.4 Hydrogeology

The groundwater level in the river basin varies between 1 and 6 meters (SGU 2016a) underneath the ground surface depending on location. An unsaturated zone where pores are filled with both air and groundwater is found directly beneath the ground surface followed by a saturated zone where groundwater has filled all pores between the grains in the geological deposits, see Figure 2.14. The capillary fringe is situated in between the unsaturated zone and saturated zone. Water is drawn upwards from the water table into the capillary fringe due to surface tension between mineral grains and the water molecules. The water is drawn upwards to different heights due to differences in pore size, which makes the surface resemble an irregular fringe (Fetter 2014). A groundwater aquifer is defined as a geological unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells, which makes the groundwater formation highly dependent on characteristics of the deposit (Fetter 2014).

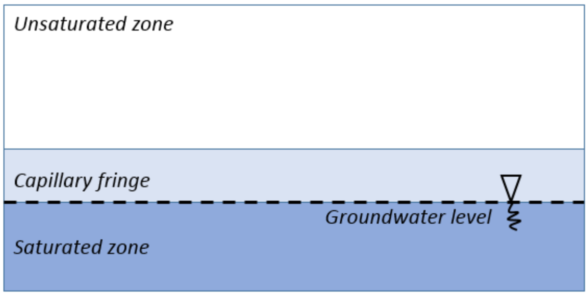


Figure 2.14: *Conceptual illustration of the location of the groundwater level between the unsaturated and saturated zone.*

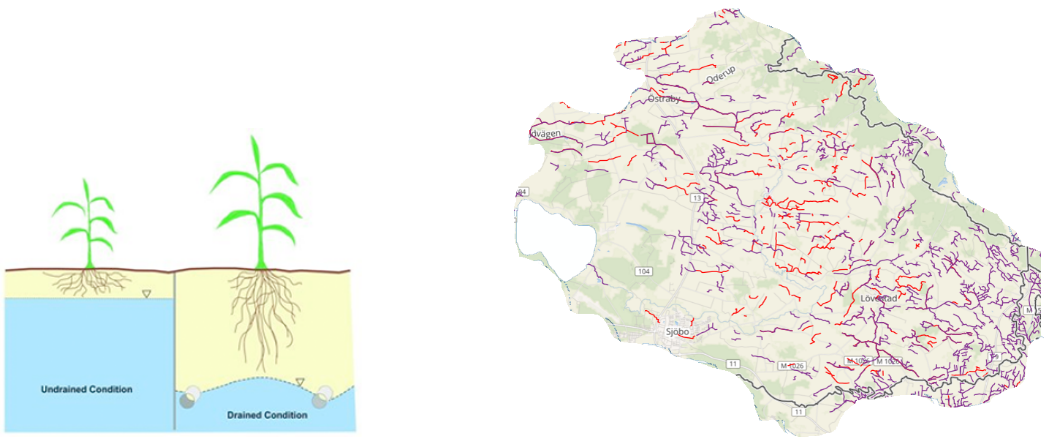
One of Scanias largest deposits of glacial sediments are located in the area surrounding lake Vombsjön. The glacial sediments in the Vomb basin stretching around lake Vombsjön have a thickness that varies between 30 and 70 meters and are considered having the capacity of storing great amounts of groundwater. According to Länsstyrelsen i Skåne (2012), the possibility of extracting water from wells is 5-10 l/s in magnitude but can be considerably less in the central parts of the Vomb basin, and more in the southeastern parts. The southwest area of the glacial sediment surrounding lake Vombsjön is used for production of drinking water by partly artificial groundwater recharge. This is made by letting surface water from the lake infiltrate through natural glacial sediments (Gustafsson et al. 2005).

An unconfined aquifer can be found in the upper deposits in the Vomb basin along the south border of the catchment, see Figure 2.11 and 2.13. This layer consists of coarse glacial sediments with very good infiltration capacity (Bjelm and Malmberg-Persson 1982). A confined aquifer is found in the bedrock and in coarse sediments found in scattered fractions between the bedrock and the deep layer of clayey till in the Vomb basin (Bjelm and Malmberg-Persson 1982).

At the east border of the catchment area, close to Lövestad, the upper deposits measures approximately 25 meters in thickness and consist of glacial sediments and creating an unconfined aquifer, see Figure 2.12. The aquifer is sometimes located directly on the bedrock and sometimes it superimposes a relatively thin layer of clayey till. Another confined aquifer where coarse sediments are superimposed by clayey till is found north of Lövestad (Bjelm and Malmberg-Persson 1982). The shale plateau north of the Vomb basin is very uniform and dominated by clayey till. The possibilities for infiltration of water is small and groundwater is not stored in larger amounts in the shale. At tectonic zones in this region one may find fractures which may support groundwater storage. However, between lake Vombsjön and Vollsjö in the Öved-Ramsåsa layer, a section of porous bedrock with soft sandstone is located which may ease formation and transport of groundwater in this region (Bjelm and Malmberg-Persson 1982).

2.4.1 Ditching and drainage pipes

During the later part of the 19th century widespread and intensive cultivation of marshes and flat land occurred in Sweden. By lowering lowland lakes and draining wet fields new arable land for cultivation was gained. A majority of the cultivated land in Sweden are a result of this extensive ditching (NE 2016a). Rain water falling on flat agricultural land will form slow running surface runoff creating meandering streams on arable land. In order to avoid flooding and formation of meandering streams that erode crop land during heavy rain, fields can be divided into artificial sections by creating ditches and installing drainage pipes. Drainage pipes are permeable pipes installed in the ground under agricultural fields. These permeable pipes will lower the groundwater level, making the unsaturated zone larger and allow more space for the crop root zone, see Figure 2.15a. Excess surface runoff that has percolated through the unsaturated zone is transported away from the crop land by the drainage pipes and into ditches. The flow in a drainage pipe or ditch is faster than the regular groundwater flow, which makes the transport of nutrients and contaminating substances from surface- and groundwater faster in comparison (Natur och miljö 2016).



(a) A tile drainage system under drained- and undrained conditions (FarmTilePro 2016).

(b) Illustration of installed drainage pipes (red and purple lines) in the river basin. Map modified from VattenAtlas (2016).

Figure 2.15: Overview of how a tile drainage system works and the placement in the river basin of lake Vombsjön.

Extensive ditching and installation of drainage pipes have been carried out in a large part of the river basin of lake Vombsjön. Ditching and lowering of lakes and streams are regulated according to requirements presented by the Environmental Code in Sweden (Länsstyrelsen i Skåne 2016). The regulation of lake Vombsjön was set as a water verdict in 1969 and is still valid (Schuster et al. 2008). The water level in lake Vombsjön is regulated according to a flow meter measuring the outflow from Kävlingeån/Lödde å at the outlet to Öresund. Large variations in surface- and groundwater flow has been observed as a consequence of the extensive ditching since the catchment of lake Vombsjön is dominated by agricultural land (Schuster et al. 2008).

2.5 Hydraulic conductivity and effective porosity

Movement of a fluid through sediments and rocks is only possible in the interconnected void spaces between the solid grains. Darcy's law describes flow in a porous media with consideration to resistance of the flow, see equation 2.1. Resistance of the flow can be created due to both properties of the fluid (e.g. viscosity) and of the media (e.g. pore size).

$$Q = -KA(\frac{dh}{dl}) \tag{2.1}$$

$$\begin{aligned} Q &= \text{flow } [m^3/s] \\ K &= \text{hydraulic conductivity } [m/s] \\ A &= \text{area of cross-section } [m^2] \\ \tfrac{dh}{dl} &= \text{hydraulic gradient } [-] \end{aligned}$$

The hydraulic conductivity, K, in equation 2.1 is a function of both the properties of the porous media and the fluid passing through it, which can be seen in equations 2.2 and 2.3. The hydraulic conductivity can be estimated through various mathematical models, a laboratory device called a permeameter or by using values found in literature which are based on field investigations for the geological deposit in question (Fetter 2014).

$$K = K_i(\frac{\gamma}{\mu}) = K_i(\frac{\rho g}{\mu}) \tag{2.2}$$

$$\begin{aligned} K &= \text{hydraulic conductivity } [m/s] \\ K_i &= \text{intrinsic permeability } [m^2] \\ \gamma &= \text{specific weight of the fluid } [N/m^3] \\ \mu &= \text{dynamic viscosity of the fluid } [kg/(s \cdot m)] \\ \rho &= \text{density of the fluid } [kg/m^3] \\ \text{g} &= \text{acceleration of gravity } [m/s^2] \end{aligned}$$

$$K_i = Cd^2 \tag{2.3}$$

$$\begin{aligned} Ki &= \text{intrinsic permeability } [m^2] \\ C &= \text{shape factor } [-] \\ d &= \text{pore diameter } [m] \end{aligned}$$

The porosity of a sediment or rock is the percentage of the material that is void space. However, the effective porosity is the percentage of the sediment or rock available for fluid flow. In other words, the effective porosity does not account for the pores that are too small in size relative to the size of the molecules in the fluid or pores that are not interconnected (Fetter 2014).

The hydraulic conductivity and effective porosity of the geological deposits found in the catchment of lake Vombsjön have been adapted after values presented by Carlsson and Gustafsson 1991, Knutsson and Morfeldt 1993 and Grip and Rodhe 2000 which are based on field investigations, see Table 2.1. It should however be stated that the values in the table are based on the assumption that glaciofluvial sediments and post-glacial sand contain grain sizes in the range of fine gravel-middle sand respectively middle sand-coarse silt. The hydraulic conductivity value for peat is highly dependent on the organic matter content, but is assumed to resemble field measurements of peat conducted in Finland according to Grip and Rodhe (2000). The large intervals for hydraulic conductivity and effective porosity that are presented in Table 2.1 reflects the heterogeneity of deposits which gives rise to large variations in permeability and water storage within each geological unit.

Table 2.1: *Adapted values of hydraulic conductivity (Carlsson and Gustafsson 1991; Knutsson and Morfeldt 1993; Grip and Rodhe 2000) and effective porosity Grip and Rodhe (2000) for different geological deposits.*

Geological deposit	Hydraulic conductivity [m/s]	Effective porosity [–]
Peat	$10^{-5} - 10^{-7}$	$0.01 - 0.03$
Post-glacial sand	$10^{-4} - 10^{-6}$	$0.05 - 0.10$
Glaciofluvial sediments	$10^{-2} - 10^{-4}$	$0.10 - 0.30$
Gravelly till-sandy till	$10^{-5} - 10^{-8}$	$0.02 - 0.05$
Clayey till-clay till	$10^{-8} - 10^{-11}$	$0.01 - 0.03$

2.6 Transport of contaminants

Contaminating solutes are spread in the environment through various transport processes. These transport processes can be expressed mathematically although it is uncertain, in some cases, how to acquire the needed field input data to be able to use the mathematical relationships (Fetter 2014).

In risk assessments, the working process is often to assess the "worst case scenario" of the solute spreading (Naturvårdsverket 2007). For groundwater and surface water this often means that the maximum velocity of a contaminant is approximated with the average linear velocity, i.e. the advective transport. The maximum velocity can then be further adjusted to include retardation, which means to consider decelerating sorption processes like adsorption, absorption and ion exchange. To further improve the description of contaminant movement the hydrodynamic dispersion is taken into consideration. As contaminated fluid moves with the groundwater it will be mixed and diluted with non-contaminated water, resulting in a dissemination of the contaminating fluid and thus a delay and decrease of the peak concentration of the solute (Fetter 2014). A solute can also undergo biological, chemical or radioactive degradation where parts of, or the whole substance disappear.

2.6.1 Advective transport

Advection is the process by which a contaminant dissolved in water is transported at the same average linear velocity as the groundwater without spreading out (Fetter 2014). Equation 2.4 originates from Darcy's law and describes the advective transport in one dimension (see equation 2.1).

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \tag{2.4}$$

v_x = average linear velocity $[m/s]$
K = hydraulic conductivity $[m/s]$
n_e = effective porosity $[-]$
$\frac{dh}{dl}$ = hydraulic gradient $[-]$

2.6.2 Hydrodynamic dispersion

Hydrodynamic dispersion is the combination of the two processes: molecular diffusion and mechanical dispersion. The processes have been grouped together since they can not be separated in flowing groundwater.

The driving force behind molecular diffusion is to level out a concentration gradient of a solute in a medium, this means that contaminants will move from areas with higher concentration to areas with lower. Dispersion on the other hand, is the process where contaminant molecules will travel faster or slower due to friction in the pores and the size of the pores in the medium. Some molecules will have a longer path of transport since solids grains block the way. The overall effect of both molecular diffusion and mechanical dispersion is dilution of the contaminated water (Fetter 2014).

The phenomenon of spatial variations in hydraulic properties and porous media in a geological unit is called heterogeneity (Fetter 2014). Heterogeneity and thereby hydrodynamic dispersion increases with distance from point of emission since the contaminant transport covers a greater area where there might be great variations in geology.

2.6.3 Retardation and decay

Contaminant transport may decelerate due to sorption processes such as adsorption, absorption and ion exchange or chemical, biological and radioactive decay which changes the molecular structure of the contaminating substance which will affect the behavior of transport (Fetter 2014).

Deceleration due to adsorption means that contaminating ions react with charged mineral surfaces present in geological deposits (Lusk et al. 2011). The process of sorption also includes absorption, i.e. the uptake of a substance by a volume of media. Contaminants can be absorbed through membranes of organic materials encountered within a deposit or by plant roots (McMurry 2003). Decay of a contaminant in the ground implies chemical, biological or radioactive degradation where the substance is decomposed into smaller fragments. Chemical decay is stimulated by change in temperature, pH and humidity in the ground, causing molecules to change into smaller fractions with another chemical composition. Biodegradation is the chemical decomposition of a contaminant by microorganisms such as bacteria and fungi, stimulated by increased temperature and humidity (Sims and Cupples 1999). Radioactive decay refers to the process where the nucleus of an atom loses energy by emitting radiation whilst changing the atom composition (Loveland et al. 2006).

Deceleration of a contaminant depends on factors concerning temperature, deposit and water properties as well as chemical properties of the contaminant itself. Contaminating substances possess a broad variety of chemical properties affecting its behavior of transport. The molecular structure of each substance will affect its likeliness to dissolve in water, undergo biological degradation or be affected by sorption processes. The octanol/water partition coefficient (K_{ow}) is a measure of a substance ability to dissolve in fat, i.e. the hydrophobicity of a substance, and is one way to estimate a substance likeliness of being transported with water. Hydrophobic contaminants have water repellent functional groups and tend to bind to organic substances such as humus particles. Hydrophilic and polar contaminants are easily dissolved in water and tend to bind to electrically charged surfaces or molecules (Ejhed et al. 2012).

Mentioned factors above may decelerate or even stop the transport of a contaminant traveling through the unsaturated zone towards the groundwater table or with the groundwater flow.

2.7 Potential contaminants

There are several potential contaminants in wastewater that originates from decentralized sewer systems. Nutrients such as nitrogen primarily derives from metabolites of digested food whilst phosphorous steam from both consumption of food and from household chemicals (Naturvårdsverket 2012; MPCA 1999). New pharmaceuticals and products for improvement of everyday health are released to the market each year causing the consumption of drug related products to constantly increase (Chang et al. 2015). Consequently this has affected the awareness of what possible impacts residuals from personal health care product may have on aquatic environments. Pharmaceuticals and personal health care products often consist of synthetic chemicals originating from anti-inflammatory drugs, antibiotics, hormones etc. The potential negative impact on humans and ecosystems from such substances is considered to be high although concentrations of pharmaceutical and personal health care products only have been detected at trace levels in aquatic environments (Chang et al. 2015). Pathogens such as parasites and bacteria originating from humans and domestic animals are often effectively removed in decentralized sewage systems containing infiltration beds, sometimes even better than at municipal wastewater treatments (Naturvårdsverket 2012). However, viruses are very difficult to target with treatment methods provided in decentralized systems and a very small dose of viruses or other resistant pathogens may cause serious health effects and widespread propagation (MPCA 1999).

In Table 2.2 probable substances originating from decentralized sewage systems that might pose a risk of contamination to the water body of lake Vombsjön are presented. These substances are selected and compiled from a number of sources in order to give a comprehensible collection of which contaminants that are likely to be found in the effluent of decentralized sewer systems. The selection is divided into four sub-categories: nutrients, household chemicals, pharmaceuticals and pathogens, in order to present contaminants originating from different applications within a household. The criteria for selection is based on substances that are frequently occurring in reports regarding contamination of water bodies in Sweden, or found on the European Commission watch list of priority substances, or substances that have been detected from water samples in lake Vombsjön.

Table 2.2: *Overview of selected contaminants, field of application and criteria for selection.*

Contaminant	**Field of application**	**Criteria for selection**
Nutrients		
Nitrogen Phosphorus	Human excreta, food waste Human excreta, food waste, detergents	Known to cause eutrophication in lake Vombsjön (Schuster et al. 2008). *Regeringens skrivelse 2009/10:213, Åtgärder för levande hav* (2009) and Naturvårdsverket (2012).
Household chemicals		
PFAS Nonylphenol	Cleaning products, impregnating agent Cleaning products, lubricator in care products	PFAS and nonylphenol are stated as priority substances on the European Commission watchlist, European Commission (2016), Kemikalieinspektionen (2004), Borg and Håkansson (2012), and Livsmedelsverket (2015).
Pharmaceuticals		
Hydrochlorothiazide* Metoprolol Diclofenac Ibuprofen* Naproxen* Tramadol* Estradiol Ethinylestradiol Oxazepam	Antihypertensive Antihypertensive Pain relief (NSAID) Pain relief (NSAID) Pain relief (NSAID) Pain relief (opioid) Hormone Hormone Sedative	Diclofenac and ethinylestradiol are stated as priority substances on the European Commission watchlist, (2016). Pharmaceuticals marked with an asterix (*) have been detected in lake Vombsjön (Pott 2016). Ejhed et al. (2012), Fick et al. (2011) and Apoteket (2005).
Pathogens		
Escherichia coli Campylobacter Giardia lamblia Cryptosporidium Norovirus	Bacteria Bacteria Parasite Parasite Virus	Probability and historically observed presence of selected microorganisms in fresh water in Sweden. Lindberg and Lindqvist (2005), Folkhälsomyndigheten (2015b).

2.7.1 Nutrients

Nitrogen (N) and phosphorous (P) are essential nutrients for all living organisms since they are, among other things, the building blocks of nucleic acids and proteins (NE 2016b). P is a limiting factor for algal growth in fresh surface waters, and anthropogenic contribution of the nutrient is the major cause of eutrophication (Chapman 1996). Purifying eutrophic surface water for drinking water purposes is coupled with immense problems in waterworks due to clogging of filters, bad taste and odor (Walker 1983). Vigorous algal blooms take place in lake Vombsjön annually due to elevated levels of nutrients such as N and P. Increased growth of toxin producing cyanobacteria constitutes a potential threat to the drinking water quality of the surface water. The main cause of the elevated nutrient load to the lake is due to use of fertilizers on surrounding farmland. However, decentralized sewer systems in the area contributes to the increased nutrient load to some extent (Schuster et al. 2008). Further descriptions of the behavior of N and P in geological deposits are found in the sections below.

Nitrogen

N in domestic sewer systems originates from human body waste, food waste from kitchen sinks and dishwashers (Toor et al. 2011). N in a septic tank mainly exist in the forms: organic N and ammonium (NH_4^+). The different processes for removing N in a sewer system of the most common constitution located in the river basin of lake Vombsjön are illustrated in Figure 2.16. Organic N can be mineralized into ammonium by bacteria under anaerobic conditions in the tank. If the septic tank is connected to a soil infiltration system, there are several possible ways of transformation and removal of ammonium, e.g. nitrification, volatilization, adsorption and plant- and microbial uptake. Among these, nitrification (i.e. conversion of ammonium to nitrate (NO_3^-) by aerobic bacteria) is the most probable process while oxygen is present (Toor et al. 2011; Gilmour et al. 2003). Nitrification occurs in the unsaturated zone where soil pores are not completely filled with water. Volatilization is the conversion from ammonium to ammonia gas (NH_3), which only occurs in alkaline soils with pH<8 or inside a septic tank. The positively charged ammonium ion can also be adsorbed to negatively charged minerals or organic matter. Microbial uptake occurs all the time since N is required for microbial growth. Plant uptake of ammonium on the other hand, is less likely to occur since soil infiltration systems normally are situated lower than the plant roots reach (Toor et al. 2011).

Nitrification is followed by denitrification, leaching, plant or microbial uptake which will remove or transform nitrate from the soil infiltration system. Dentrification is an anaerobic or anoxic process where nitrate is converted into nitrogen gas (N_2) which occurs near the groundwater table where soil pores are almost filled with water i.e. in the capillary fringe. Nitrate is a large, negatively charged ion, which is not easily absorbed to minerals, thus one could suspect downward leaking of the ion towards the groundwater table (Fetter 2014). As with ammonium, nitrate can also be subject for plant- or microbial uptake (Toor et al. 2011).

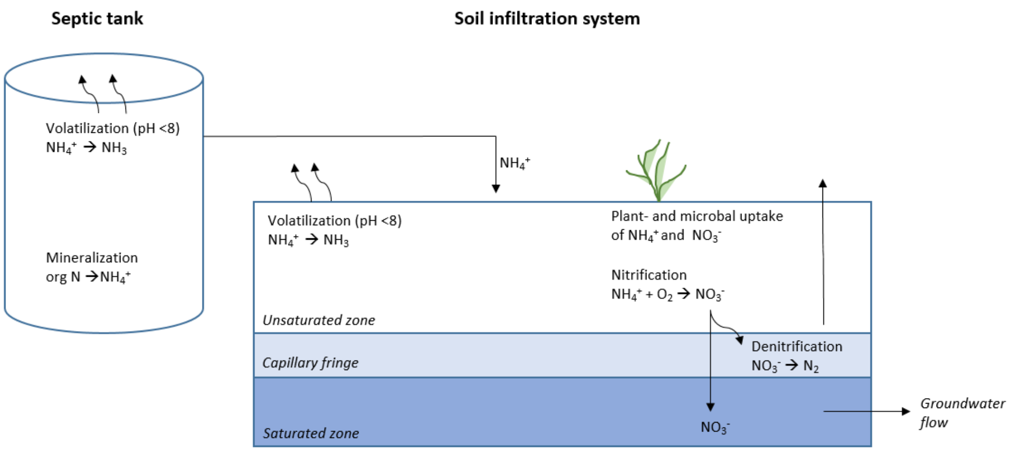


Figure 2.16: *Conceptual model over nitrogen treatment in a decentralized sewer system with soil infiltration.*

Phosphorous

Phosphorous does not exist in elemental form in the environment since it quickly reacts with oxygen to form phosphate (Chapman 1996). The abbreviation P will therefore refer to phosphorous as phosphate in continuation. P has a low solubility and is not toxic in itself but can have a large impact on the water quality in surface and groundwater even in low concentrations (Busman et al. 2002). P in septic tank effluents can be divided into two groups; organic- and inorganic P. Organic P originates from food waste, human excreta and is present in form of sugars, phospholipids, and nucleotides. Inorganic P is found in cleaning products such as soaps, laundry and dishwasher detergents. Inorganic P exist as ortophosphate (ortho-P) and polyphosphate (poly-P). Ortho-P is also known as reactive- or bioavailable P. Poly-P consist of chains of ortho-P and are unstable in water and may convert into ortho-P (Lusk et al. 2011).

The different processes for removing P in a sewer system of the most common constitution located in the river basin of lake Vombsjön are illustrated in Figure 2.17. If there are no special treatment targeting removal of P in a septic system, P will be reduced from wastewater through the settling of solids in a septic tank (Lusk et al. 2011). When organic P enters a infiltration bed it will transform into bioavailable ortho-P due to mineralization by microorganisms. Poly-P will also break down into ortho-P when entering the infiltration bed. The ortho-P is then adsorbed onto positively charged mineral surface components like organic matter, calcium, iron, and aluminum, and additionally on manganese oxides and hydroxides (Lusk et al. 2011; Schuster et al. 2008; Naturvårdsverket 2012). If the adsorbed P is coated by a mineral like iron- or aluminum oxides it becomes entrapped and absorbed into the mineral, which makes it unavailable for plant uptake. P can also be removed from the pore water through precipitation of P minerals, a process that is pH dependent. In alkaline soils (pH>7) calcium is the dominating cation that reacts with P. In acid soils (pH<5.5) aluminum and iron are the dominating cations and various insoluble aluminum- and iron phosphates are formed (Busman et al. 2002).

In conclusion it can be said that soils have a large capacity of retaining P. If there is a heavy load of P at a site, all of the P might not attach to minerals and an increased amount of dissolved P might percolate through the soil towards the water table. Attachment of P to minerals occur to a larger extent in soils with fine particles than with coarser grains. Fine particles are easily carried away with groundwater into a lake where sediment containing P could act as either a sink or source of P (Busman et al. 2002). Since soil chemistry is complex, absorption and precipitation should be regarded as only two of multiple processes that occurs simultaneously. Additionally, there are still much uncertainty (and contradictions in scientific papers) regarding the importance and extent of retention of P in the unsaturated- and saturated zone.

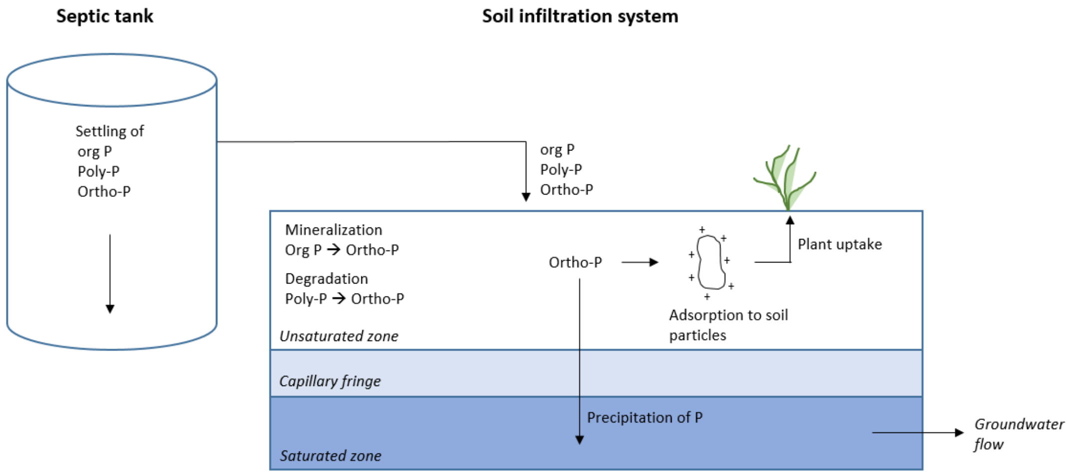


Figure 2.17: *Conceptual model over phosphor treatment in a decentralized sewer system with soil infiltration.*

2.7.2 Household- and industrial chemicals

Perfluorinated and polyfluorinated substances

Perfluorinated and polyfluorinated substances (PFAS) are an all-embracing term for over 800 industrially manufactured highly fluorinated chemicals which are found in products used both within domestic households and industries. Perfluorinated substances with long carbon chains have the ability to repel both water and oil. They also have the ability to resist degradation by heat and chemical influences (Kemikalieinspektionen 2004). They are commonly found in products where an oleophobic- and water repellent coating is desired, for example as impregnating agent on textiles and leather, in frying pans, food packages and in household cleansers (Naturvårdsverket 2015; Livsmedelsverket 2015; Svenskt Vatten 2015). The reason for their persistence is strong covalent bonds between carbon and fluorine, which forms a protective cover over the weaker carbon-carbon bonds, making them difficult to break down (Kemikalieinspektionen 2004). Small concentrations of PFAS substances are spread to decentralized sewer systems from mentioned domestic sources due to day-to-day cleaning procedures.

PFAS substances bind to proteins when ingested by living organisms. The highest levels of PFAS are found in blood- and liver cells bound to albumin and fatty acid-binding proteins, since many PFAS are chemically similar to fatty acids (Borg and Håkansson 2012). Many of the PFAS substances are not acutely toxic when ingested by humans but accumulate gradually in the body since they are hard to degrade. Thus there are diverse opinions whether PFAS may cause adverse health effects to humans exposed to small concentrations of PFAS in drinking water during a lifetime. Animals exposed to PFAS during experiments have shown negative effects on the reproductive-, immune- and endocrine systems which suggests a risk of humans being influenced in similar ways (Naturvårdsverket 2015; Livsmedelsverket 2015; Svenskt Vatten 2015).

Transport of different PFAS from an infiltration bed to the groundwater table in a decentralized system will depend on the chain length and functional group of the PFAS molecules and the chemical characteristics of the surrounding geological deposits. PFAS with longer chain lengths binds stronger to minerals whilst shorter chains have lower binding capacity which increases the rate of transport to the groundwater (Gellrich et al. 2011). The adsorption of PFAS molecules to minerals also depends on the functional group of the molecule. Adsorption is higher for PFAS with SO_3H-groups, than for those with COOH-groups (Higgins and Luthy 2006). The characteristics of the surrounding deposits, such as pH, organic carbon content and concentration of calcium ions will also affect the mobility of the PFAS molecules. Higgins and Luthy (2006) showed that some substances of PFAS adsorb more to deposits with low pH, high concentration of Ca^{2+} and organic carbon content. According to Ahrens et al. (2009) the sorption of tested PFAS substances to minerals increase when pH decrease in deposits where the concentration of organic matter is high.

Nonylphenols

Nonylphenols arises from the environmental degradation of nonylphenol ethoxylates, a family of substances used for manufacturing antioxidants, lubricating oil additives, detergents and as stabilizer in plastic food packaging. 4-nonylphenol is the most widely produced and marketed nonylphenol (Soares et al. 2008). The predominant source of nonylphenols in the environment originates from treated wastewater effluent and biosolids used as fertilizer on agricultural land (Kim et al. 2005). From decentralized sewer systems, one can estimate that nonylphenols derive from household cleaning- and personal care products being washed out with grey water. The solubility in water ranges between 1.6-7mg/l and the Log K_{ow}=5.77 (EPA 2009), indicating that molecules of nonylphenols are rather non-polar and hence tend to bind to organic particles. Thus nonylphenols may settle with organic compounds in a septic tank or adsorb to particles in an infiltration unit (WHO 2012). Some fractions will leak to the groundwater table in soluble form and adsorb to organic microparticles.

Nonylphenols are endocrine disrupting compounds that mimic the natural female hormone 17β-estrogen by binding to estrogen receptors and induce estrogenic actions (Kim et al. 2005). Concentrations of 4-nonylphenol have been found in the range of 0.11-180μg/l in surface waters (Tanghe and Verstraete 2001) and several studies indicate that estrogenic effects are measurable at around 10-20μg/l (WHO 2012). Nonylphenols are persistent in aquatic environments and bioaccumulate in water dwelling organisms. Concentrations 10-1000 times higher than the concentration found in surrounding environment have been detected in some aquatic organisms (WHO 2012).

2.7.3 Pharmaceuticals

Several different types of pharmaceuticals and pharmaceutical residuals leave the human body through urine and feces. The potential negative impact on humans and ecosystems from such substances are considered to be high although the concentrations of pharmaceuticals only have been detected at trace levels in aquatic environments (Chang et al. 2015). A presentation of some topical pharmaceuticals is presented in Table 2.3. The selection of presented substances is based on a couple of criteria as follows: a couple of substances have been detected in water samples taken from the surface water of lake Vombsjön by Sydvatten (Pott 2016); hydrochlorothiazide, ibuprofen, naproxen and tramadol. Diclofenac and ethinylestradiol are two commonly used pharmaceuticals that the European Commission has targeted as *priority substances*. Priority substances pose a significant risk to aquatic environments and are potent hazardous pollutants to water according to the Water Framework Directive (European Commission 2016). The three remaining substances, metoprolol, estradiol and oxazepam, were chosen due to their frequent occurrence in reports concerning investigations of pharmaceutical residuals in Swedish environment (Apoteket 2005; Ejhed et al. 2012; Fick et al. 2011).

Table 2.3 presents the selected pharmaceuticals that may pose a risk to the aquatic environment in lake Vombsjön and their mode of action as a substance. The table also illustrates if a selected substance has been detected in lake Vombsjön or not. The column *Patients/1000 inhabitants* is a measure based on the amount of patients per 1000 inhabitants living in Scania between the age of 0-85 years that consumed said pharmaceuticals during 2014 (Socialstyrelsen 2016). This is a measure of the substances relative utilization among inhabitants living in Scania and can thus also be seen as an indication of the prevailing utilization in the catchment of lake Vombsjön.

Table 2.4 presents the logarithmic octanol/water partition coefficient, Log K_{ow}, for the substances in question. Pharmaceuticals are a very heterogenic group of substances where each substance has its own physical and chemical characteristics. Pharmaceuticals with a Log $K_{ow}>3$, such as diclofenac, ibuprofen, naproxen and ethinylestradiol, are relatively non-polar and are thus attracted to geological deposits with lipid character. These layers often contain large amounts of organic carbon to which the non-polar substances attach. Theoretically, pharmaceuticals with a Log $K_{ow}>3$ should pose a smaller risk of being drained from a decentralized sewer system since there are a lot of organic material in both the septic tank and the infiltration bed. Substances with a Log $K_{ow}<3$, such as hydrochlorothiazide, metoprolol, estradiol and oxazepam, are relatively polar meaning that they pose a larger risk of leaching from an infiltration bed to the groundwater in a decentralized system (Ejhed et al. 2012).

Table 2.3: *Overview of selected pharmaceuticals, their mode of actions (Ejhed et al. 2012), usage among the population (0-85 years) in Scania during 2014 (Socialstyrelsen 2016) and if detected in lake Vombsjön by Sydvatten (Pott 2016).*

Contaminant	Mode of action	Patients/1000 inhabitants	Detected in lake Vombsjön
Hydrochlorothiazide	*Antihypertensive*	5.490	Yes
Metoprolol	*Antihypertensive*	60.63	No
Diclofenac	*Pain relief (NSAID)*	43.61	No
Ibuprofen	*Pain relief (NSAID)*	20.47	Yes
Naproxen	*Pain relief (NSAID)*	18.56	Yes
Tramadol	*Pain relief (opioid)*	23.58	Yes
Estradiol	*Hormone*	27.28	No
Ethinylestradiol	*Hormone*	–	No
Oxazepam	*Sedative*	30.48	No

Table 2.4: *Octanol/water partition coefficient, $LogK_{ow}$, for selected pharmaceuticals (Ejhed et al. 2012).*

Contaminant	$LogK_{ow}$
Hydrochlorothiazide	-0.07
Metoprolol	1.79
Diclofenac	4.06
Ibuprofen	3.72
Naproxen	3.00
Tramadol	–
Estradiol	2.50
Ethinylestradiol	4.52
Oxazepam	2.31

2.7.4 Pathogens

Groundwater contamination in form of pathogens such as bacteria, viruses and parasites from decentralized sewer systems are relatively common (Naturvårdsverket 2012). Many of the organisms in question are excreted in feces from infected, or healthy people and animals. The amount of secreted organisms varies depending on the type of microorganism involved and whether a resulting infection is in its acute phase or not (Lindberg and Lindqvist 2005; Folkhälsomyndigheten 2015b).

Pathogenic microorganisms differ from chemical pollution when it comes to spreading. Primarily they occur in singular forms and not in solutions, making it difficult to estimate a hazardous dose based on the average occurrence of measured microorganisms in a water sample. Furthermore, each exposure to a single microorganism is an independent event and there will be no accumulation of dose. Instead one single microorganism may cause extensive health effect to the person who is unfortunate enough to ingest it (Lindberg and Lindqvist 2005; Folkhälsomyndigheten 2015b). The risk of microorganism transport from a decentralized system to the groundwater increases if the water table is located less than one meter below the unit of an infiltration bed processing black water or if there is no biofilm at the interface between effluent flow from a septic tank to the infiltration bed since these factors lessen the possibility of biological degradation (MPCA 1999).

A short presentation of pathogens that are relatively common in black water and constitutes a risk of spreading from decentralized sewer systems to reservoirs of drinking water will be presented below. Some of these has been the subject of public discussion after hazardous outbreaks.

Escherichia coli (*E. coli*)

The group of coliform bacteria consists of several different genera of bacteria in the Enterobacteriaceae family, which includes *Escherichia coli* (abbreviated *E. coli*) (Hammer and Hammer 2014). Coliforms reside in the intestinal tract of warm-blooded animals and are excreted in large numbers via the feces. In one gram of feces there are on average 50 million coliforms present and the corresponding number in 100 ml of domestic wastewater is more than 3 million (Hammer and Hammer 2014).

There is in turn a diverse group of bacteria belonging to the group of *E. coli*, generally viewed upon as being non-pathogenic since they play an important role in a healthy intestinal tract and commonly used as indicator organisms for fecal contamination of drinking water. However, there are at least six strains of *E. coli* known to be pathogenic to humans via the fecal-oral route. The most noticeable type of *E. coli* responsible for large outbreaks is the shigatoxin-producing *E. coli* (STEC), also known as verocytotoxin-producing *E. coli* (VTEC) or enterohemorrhagic *E. coli* (EHEC). Sources include not only contaminated water but also contaminated food, raw milk, contact with cattle or contact with feces of infected people (Centers for Disease Control and Prevention 2014).

Campylobacter

The bacteria; *Campylobacter jejuni (C. jejuni)* and *Campylobacter coli (C. coli)* belonging to the genera *Campylobacter* is the most common cause of intestinal infection in Sweden. *Campylobacter* are present in the intestinal tract of humans and animals and are excreted via the feces. Infection of humans occurs via the oral-fecal route already a low dose of *Campylobacter* (500 bacteria). Diarrhea, abdominal pain and vomiting are common symptoms and the origin of disease are often contaminated food or water. The waterborne outbreaks documented in Sweden known to be caused by *Campylobacter* have been due to contamination of surface water for drinking water purposes by birds or bacteria in private wells (Wallén Norell et al. 2013), the latter relating to closely or densely located decentralized sewer systems.

Giardia lamblia

Giardia lamblia is a flagellated protozoan parasite of which some genotypes are capable of infecting humans by attaching to the epithelium of the small intestine. The organisms exists in its idle form as a trofozoit and in its infective form as a cyst in the intestine. The infectious dose is low since less than 100 cysts per host may cause an infection. *Giardia* is excreted through feces and is normally spread through fecal contaminated water or through ingestion of contaminated groceries (Folkhälsomyndigheten 2015a). The protozoan parasite is relatively resistant and will survive at temperatures between 0° and 60°C. It may not reproduce outside of its host and is sensitive to drying out. Common symptoms of *Giardia* infection is diarrhea, abdominal cramping and fatigue. However some people host the parasite without experiencing any symptoms (Folkhälsomyndigheten 2015a).

Cryptosporidium

Cryptosporidium is a genus of apicomplexan protozoan parasites which affects the intestinal and respiratory system of its host, causing watery diarrhea and sometimes persistent cough

(Sponseller et al. 2014). The dominating species detected in human hosts is the *Cryptosporidium hominis* (Folkhälsomyndigheten 2016b). The infectious agent is the oocyst, that is the *Cryptosoridium* spore phase, which is foremost spread from fecal contaminated waters or food products to its host. The oocyst can survive for several months in cool surface waters but is dependent on a host in order to reproduce (Hammer and Hammer 2014). According to Folkhälsomyndigheten (2016b) the dose of infection is very low and Kosek et al. (2001) reports that as low as one to ten oocysts is enough to cause infection in susceptible individuals.

Norovirus

Noroviruses (formerly called Norwalk-viruses) are a large group of viruses which consist of several genotypes within the family of human *caliciviruses.* These viruses are the most common pathogens detected in connection with outbreaks of gastroenteritis across the industrialized world and are the reason for the yearly outbreaks of winter-vomiting disease in Sweden (Folkhälsomyndigheten 2016a). Transmission of noroviruses occurs from one person to another, from virus contaminated water or cold food courses which are insufficiently cooked.

The infectious dose is very low since as little as 10-100 microorganisms may infect a host. This may be compared to the 10^7-10^8 particles of noroviruses that can be found in 1 gram of feces or vomit from an infected person. Noroviruses can survive temperatures as high as 60°C and are quite resistant to freezing and chlorination. Outbreaks are often linked to contaminated water supplies since small amounts of the virus can pass simple water filters and remain infectious despite routine chlorination of the water (Svenungsson and Hedlund 2013; Folkhälsomyndigheten 2016a).

Chapter 3

Material & method

3.1 GIS model

3.1.1 Input data and model overview

Geographical Information System (GIS) refers to a computerized system that is *"designed to capture, manage, analyze, and display all forms of geographically referenced information"* (ESRI 2016). The modeling of transport times of potential contaminants within the river basin of lake Vombsjön was carried out in ArcMap, a software belonging to a collection of ArcGIS 10.2.2 programs developed by the company ESRI. The ArcGIS extension Spatial Analyst Tool provides a range of spatial modeling- and analysis tools, and have been frequently used in the modeling.

A compilation of gathered input data used in the modeling can be seen in Table 3.1. Data from Lantmäteriet and SGU are available as open source whereas the data from Sydvatten was collected through personal contact. The input data consist of two types of formats: raster- and vector data. Raster data is made up of a continuous matrix of cells or pixels organized in a grid where each cell contains a value that represents a certain information such as elevation, groundwater velocity or gradient/slope. In contrast to continuous raster data, vector data is used for describing geometrical objects as points, lines and polygons with the help of coordinates (Harrie 2013). This is useful when the information the data describes does not vary within the geometrical object, e.g. a polygon describing a certain geological deposits within the catchment. It is also possible to connect additional data to the geometrical object, e.g. hydraulic conductivity and effective porosity to the deposit-polygon.

The input Digital Elevation Model (DEM) is a raster layer with a cell size of 50m·50m, which means that the entire river basin is divided into a large number of cells each describing the mean elevation of an area of 2500 m^2. Every operation in ArcMap produces a new layer, which means that the produced layers originating from the DEM-raster also consist of a grid with 50m·50m cells. Therefore the input vector layers need to be converted into raster layers since ArcMap only permits mathematical operations between layers of the same format.

Table 3.1: *Format, cell size and source of the input data used in ArcMap.*

Input data	Format	Cell size [m]	Source
Digital Elevation Model (DEM)	Raster	50·50	Lantmäteriet
GSD Overview map	Vector	–	Lantmäteriet
Towns	Polygon	–	Lantmäteriet
Lakes	Polygon	–	Lantmäteriet
Municipal borders	Lines	–	Lantmäteriet
Water bodies	Lines	–	Lantmäteriet
Bedrock	Polygon	–	SGU
Geological deposits	Polygon	–	SGU
Lake Vombsjön catchment area	Polygon	–	Sydvatten

A conceptual model illustrating the essential parts of the procedure carried out in the software ArcMap is presented in Figure 3.1 in order to get an idea of how the modeling is performed. The DEM-raster, used as the first input data, is shown in grey scale in the center of the conceptual model and the ArcMap layer of deposit-polygons is found in the top-left corner. Remaining maps and illustrations presented in Figure 3.1 are created through various operations described in greater detail in the following sections. A more detailed flowchart over the operations performed in ArcMap can be found in Figure A2 in Appendix 2.

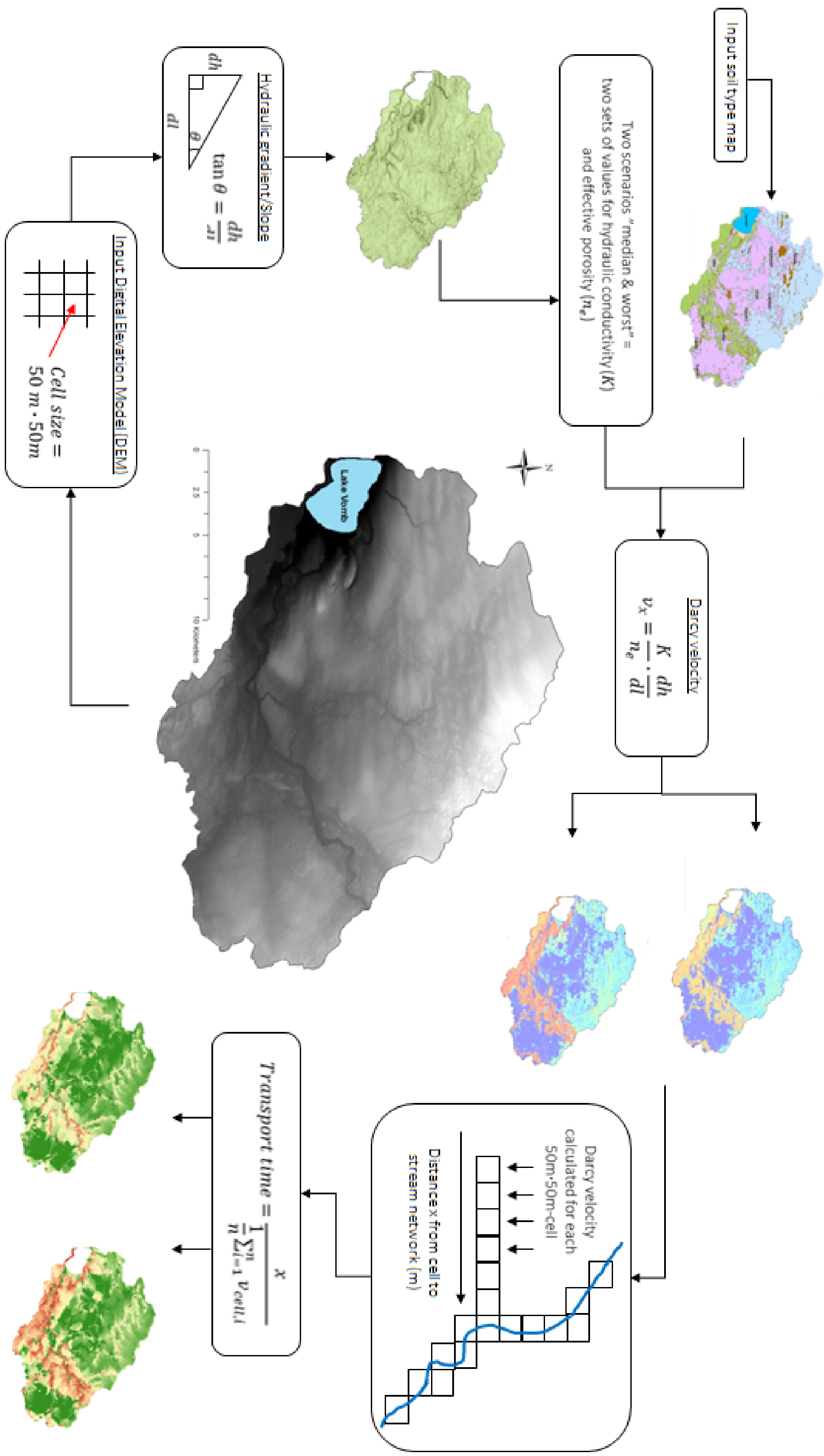


Figure 3.1: *Conceptual model over the working process in ArcMap. The process starts with the DEM raster layer in the middle and continues in clockwise order towards the final map showing the advective transport times. The maps will be further explained in the following sections.*

3.1.2 Hydraulic gradient

The first step in the modeling is to generate a raster displaying the hydraulic gradients, that is how the groundwater table varies over the entire catchment area. The hydraulic gradient is here approximated as the difference in hydraulic head (groundwater level) divided by the corresponding difference in horizontal distance. Values of measured groundwater levels could not be found within the river basin and therefore the hydraulic gradient is assumed to resemble the slope of the ground surface, an assumption that is commonly used when estimating the hydraulic gradient in an area with few hydraulic investigations (Schilling and Wolter 2007; Fetter 2014; Rönnbäck 2014).

The hydraulic gradient in the catchment area is made visible using the operation *Spatial Analyst Tool/Surface/Slope* on a raster describing the topographical elevations in the catchment, also called a Digital Elevation Model (DEM). The *Slope* command generates the slope in every 50m·50m cell in percent by applying the mathematical formula: $\tan\theta =$ elevation of cell/ length of cell. The slopes in the area varies between 0.0004 and 54%, which can be seen in Figure 3.2. A maximum slope of 54% indicates extreme values of the hydraulic gradient which are not possible to find in reality. Cells where the slope reaches extreme values are located on surface exposed bedrock or alongside river banks where steeper slopes are encountered. To assume that these extreme values reflect the hydraulic gradient at these locations is a source of error that will be further discussed in Chapter 6.

Initially, two other DEM's with cell sizes of 2m·2m and 20m·20m were used for calculating the hydraulic gradient. However, generating slopes in the range of 600% they were disregarded as unlikely since smaller cell sizes give a too well defined resolution for representing the hydraulic gradient. A cell size of 50m·50m is a better representation of how the hydraulic gradient varies over a larger area since the slope of the groundwater table is assumed to be more smooth than the actual surface elevation.

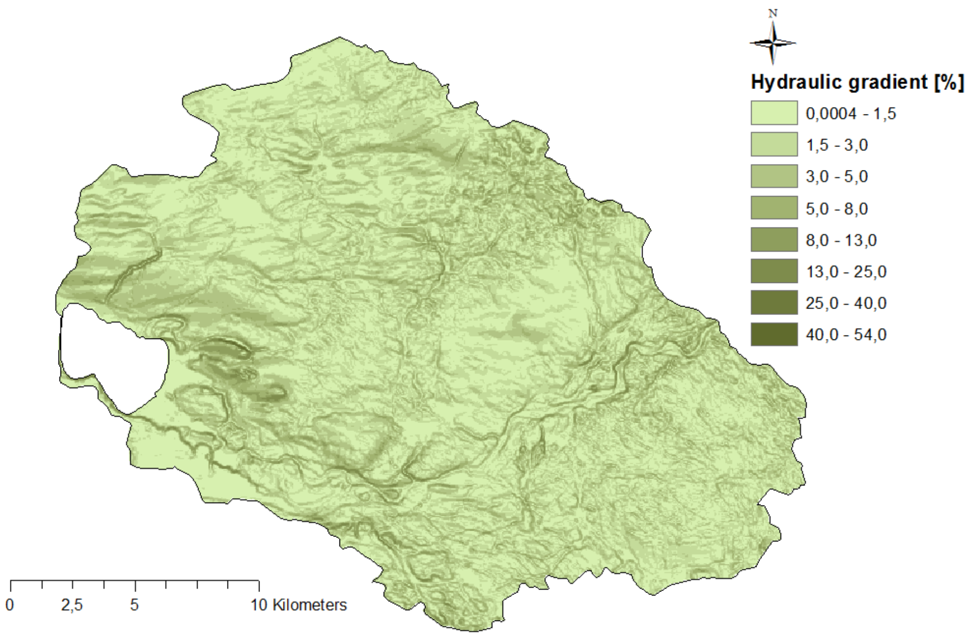


Figure 3.2: *Illustration of the variations of the estimated hydraulic gradient within the catchment of lake Vombsjön. A darker color indicates a steeper gradient. Map produced in ArcMap by the authors.*

3.1.3 Geological deposits and case scenarios

Originally the input Quaternary deposits layer from SGU consisted of 30 different types of geological deposits. The 30 types of deposits were by the authors grouped into six resulting fractions with similar hydraulic properties within each fraction. This was done due to the difficulty of finding literature values of hydraulic conductivity and effective porosity for such a variety of geological deposits and hence they where merged into six fractions in order to be manageable. The merging of 30 to six deposit fractions is presented in Figure A3 in Appendix 3. The resulting six fractions of geological deposits is presented in Figure 3.3 and estimated values of hydraulic conductivity and effective porosity in Table 3.2.

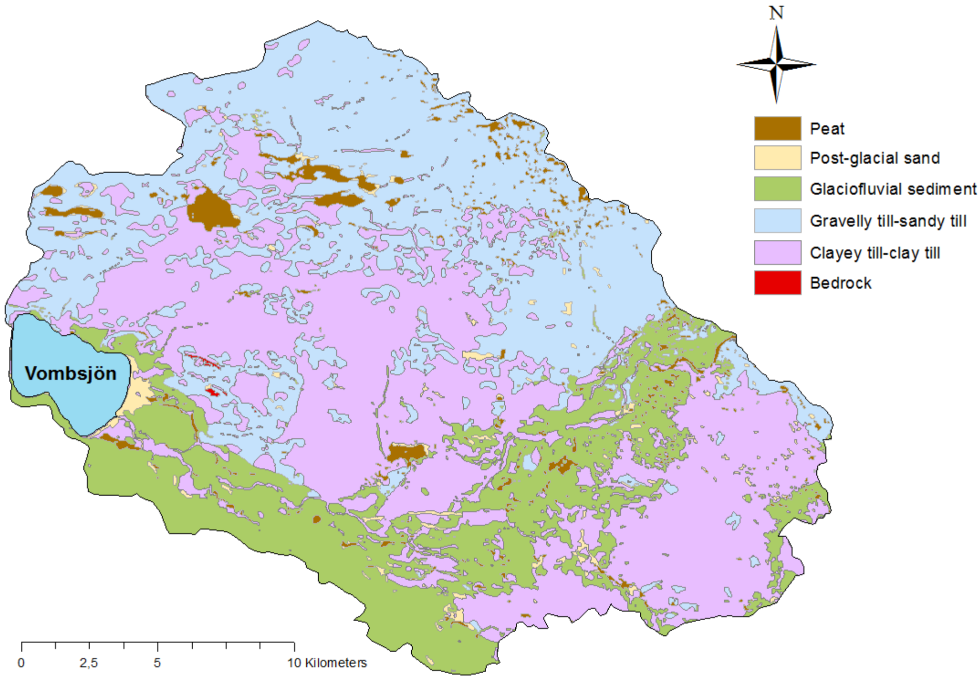


Figure 3.3: *Overview of the geological deposits within the catchment area. Map produced in ArcMap by the authors.*

The model considers two different scenarios regarding the properties hydraulic conductivity and effective porosity of the geological deposits. These scenarios are further called the *median case* and the *worst case*. They are based on two different sets of values regarding hydraulic conductivity and effective porosity presented in Table 3.2 and presented in literature, one describing a median scenario which is defined as the median value of the intervals describing the geological properties shown earlier in Table 3.1, and a conservative scenario, worst case, which is defined as the largest values in the interval representing more permeable deposits and thus a faster transport. The reason for dividing the values into two sets is because even if the geological classification of the deposits is e.g. "till" the hydraulic conductivity and effective porosity might vary by a few orders of magnitude.

Table 3.2: *Mean and worst case values for hydraulic conductivity and effective porosity for different geological deposits. Derived from values presented in Table 2.1.*

Geological deposit	Hydraulic conductivity [m/s]		Effective porosity [–]	
	Median	Worst case	Median	Worst case
Peat	10^{-6}	10^{-5}	0.02	0.03
Post-glacial sand	10^{-5}	10^{-4}	0.075	0.10
Glaciofluvial sediments	10^{-3}	10^{-2}	0.20	0.30
Gravelly till-sandy till	$5 \cdot 10^{-7}$	10^{-5}	0.035	0.05
Clayey till-clay till	$5 \cdot 10^{-10}$	10^{-8}	0.02	0.03

Values for median- and worst case scenario of hydraulic conductivity and effective porosity are added to the attribute table for each deposit-polygon layer in ArcMap in the same manner as seen in Table 3.2. The polygon layers are then converted into four rasters by using the command *Conversion Tool/To Raster/Polygon to Raster* generating rasters representing the median- and worst case of hydraulic conductivity (K) and effective porosity (n_e).

3.1.4 Advective transport

The advective transport is calculated by utilizing the raster calculator in ArcMap. The rasters representing the median- and worst case of hydraulic conductivity (K) are divided by rasters representing the effective porosity (n_e) and multiplied with the raster representing the hydraulic gradient in the catchment, using equation 3.1.

$$v_x = \frac{K}{n_e}\frac{dh}{dl} \tag{3.1}$$

The resulting rasters illustrating the advective transport over the catchment are presented in Figure 3.4 and 3.5. The velocities are based on median- and worst case scenarios for the hydraulic conductivity and effective porosity given in 3.2. The advective transport reaches maximum values of 102 m/day in the median scenario and 680 m/day in the worst case scenario at areas where the steepest slopes and the most permeable deposits are found.

Median case scenario

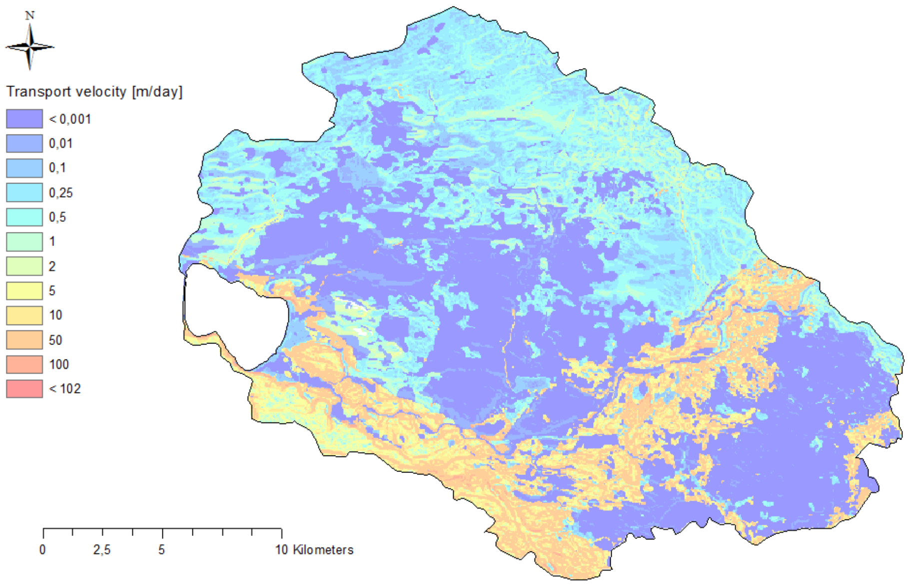


Figure 3.4: *Illustration of the modeled advective transport representing the groundwater velocity. Scenario for median values of hydraulic conductivity and effective porosity presented in Table 3.2. Map produced in ArcMap by the authors.*

Worst case scenario

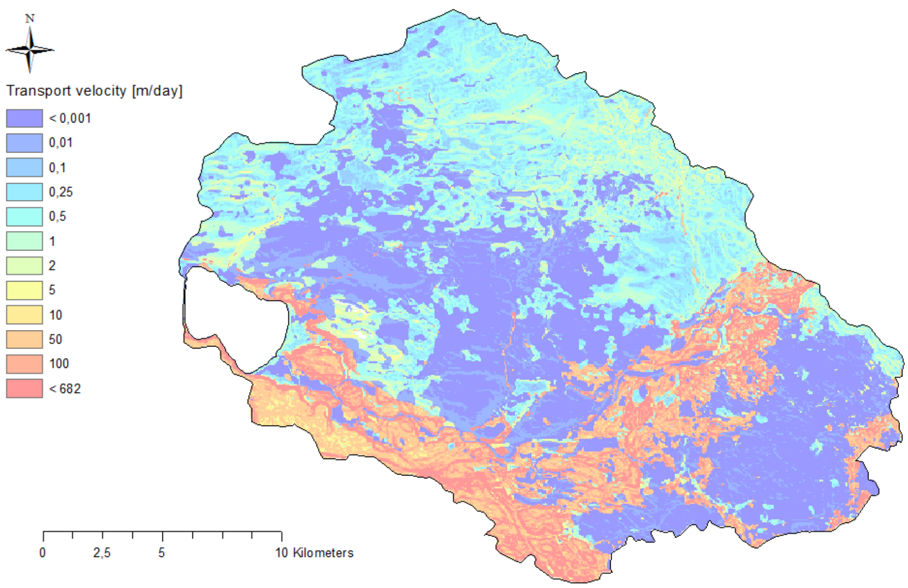


Figure 3.5: *Illustration of the modeled advective transport representing the groundwater velocity. Scenario for worst case values of hydraulic conductivity and effective porosity presented in Table 3.2. Map produced in ArcMap by the authors.*

3.1.5 Transport times

In order to calculate transport times of potential contaminants moving with advective transport in the groundwater compartment in the catchment, a series of operations are carried out in ArcMap. The first operation is to get rid of all sinks i.e. extreme depressions in the DEM. Sinks (and peaks such as extreme heights) are often errors due to the resolution of data or rounding of elevations to the nearest integer value. If there are sinks without outlets in the raster, water will cease and start accumulating in these cavities. Consequently, sinks should be filled in order to ensure that the derived drainage network is not discontinuous. Sinks are filled using the operation *Spacial Analyst Tool/Hydrology/Fill.*

From the filled DEM the flow direction of water in each cell is calculated. Using the operation *Spacial Analyst Tool/Hydrology/Flow Direction* a value representing the flow direction in each cell is calculated, which describes the movement of a single drop of water entering the cell. The flow direction is determined by the direction of steepest descent, or maximum drop, from each cell in the DEM. When the direction of steepest descent is found, the cell is coded with a value representing that direction. There are eight directions for coding related to the eight adjacent cells surrounding a particular cell from which water could travel with the values; 1, 2, 4, 8, 16, 32, 64 or 128 illustrating the flow direction.

From the flow direction raster the accumulated movement of water in the catchment is calculated by using the operation *Spacial Analyst Tool/Hydrology/Flow Accumulation.* This generates a raster where cell values represent the sum of all cells that drain into a particular cell. Cells with a high value thus symbolize areas with an accumulated water flow in the river basin, which can be used to identify stream channels. The resulting raster illustrating accumulated water that forms a network of streams due to the flow direction of simulated groundwater movement can be seen in Figure 3.6 as red lines. This simulated stream network is verified by comparing it to vector lines of water bodies provided by Lantmäteriet, illustrated as dotted black lines in Figure 3.6. It is possible to verify that cells with more than 1000 cells draining into them, thus creating a stream in the simulated raster, can be considered to constitute a part of a realistic stream network since they correspond well to the illustration of existing water bodies provided by Lantmäteriet, see Figure 3.6. Each cell with a 1000 cells draining into them and thus creating a stream corresponds to a drainage area of 2.5km^2. The vector lines of water bodies provided by Lantmäteriet (dotted lines) is based on satellite pictures and does not completely correspond to the simulated flow paths (red lines). However, some of the simulated flow paths may be an overestimation by ArcMap since the procedure is originally based on the DEM which provides the average ground elevation of each $50\text{m}\cdot 50\text{m}$ cell and not the actual groundwater level in each cell.

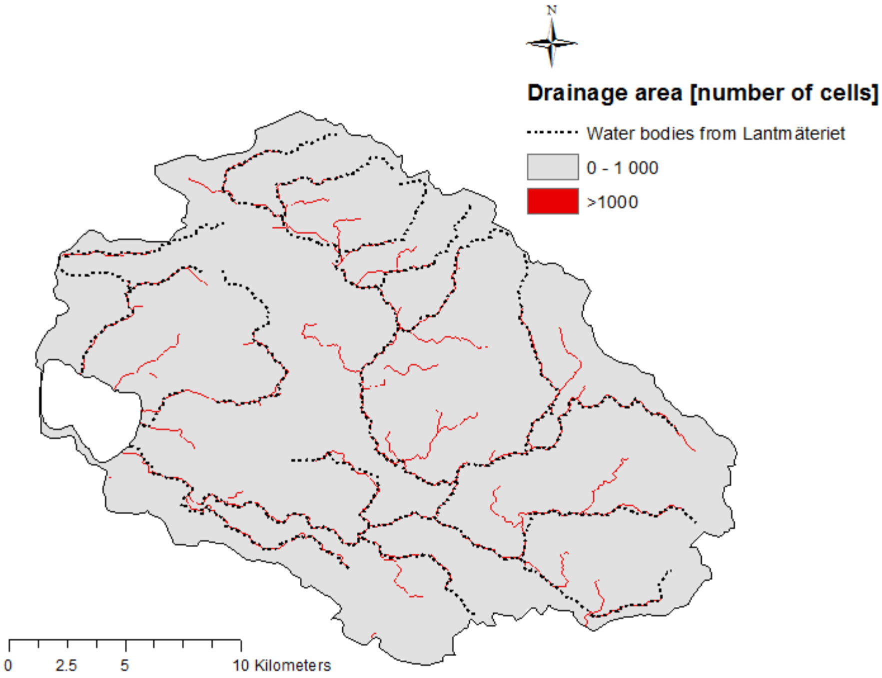


Figure 3.6: *Illustration of accumulating flow paths generated by the operation Flow Accumulation in ArcMap (red lines) compared to the location of water bodies provided by Lantmäteriet (dotted lines). Map produced in ArcMap by the authors.*

In order to calculate the length of the longest flow path and generate a pattern of possible flow paths for groundwater within the river basin, the operation *Spacial Analyst Tool/Hydrology/Flow Length* was used, see Figure 3.7.

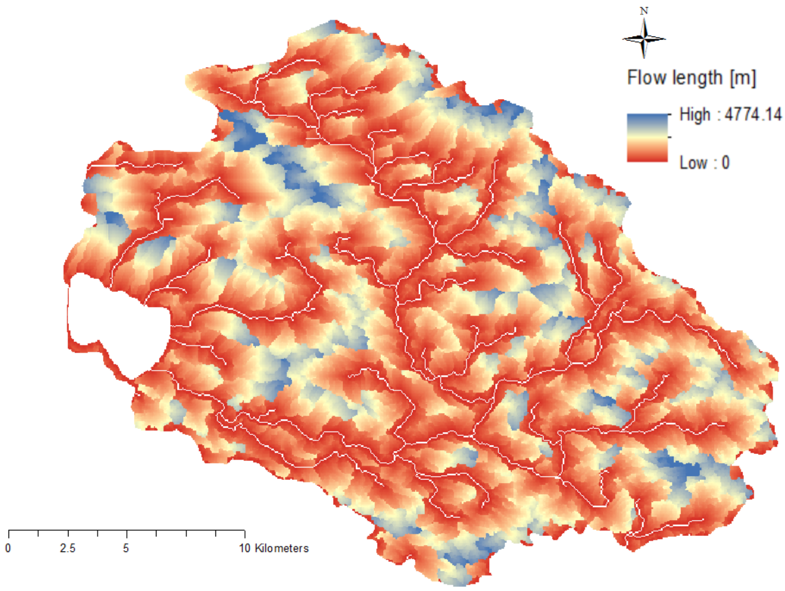


Figure 3.7: *Illustration of how distances vary from a specific cell to a stream in meters. Map produced in ArcMap by the authors.*

The operation *Flow Length* assigns a value describing the flow length for each cell, this length is determined by the distance from the cell to the nearest stream. The groundwater velocity for each cell is determined from the average velocity throughout the flow path. Thus the transport time for each 50m·50m cell to the stream network is calculated by multiplying the rasters giving the averaged groundwater velocities for the median and worst case scenario with the raster providing flow lengths from each cell to the stream network, see Figure 3.8.

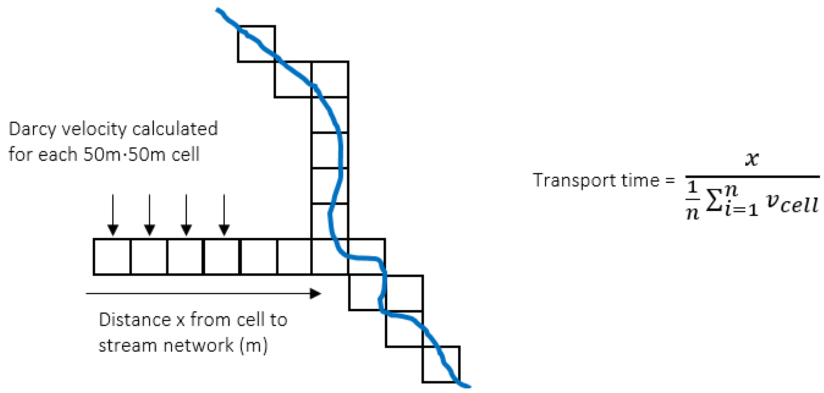


Figure 3.8: *Conceptual model over calculations of transport times. Figure produced by authors, inspired by Schilling and Wolter 2007.*

The resulting rasters from this procedure illustrate the final results of the modeling of transport times in ArcMap and is further presented in Chapter 4.

Chapter 4

Results

4.1 Transport times

The modeling procedure carried out in ArcMap, described in Chapter 3 results in two raster layers illustrating the transport times of simulated groundwater flow within the catchment area of lake Vombsjön. Transport times are modeled for two scenarios, median case and worst case, depending on two scenarios regarding the hydraulic conductivity and effective porosity for present geology, see Table 3.2. Figure 4.1 illustrates the median case scenario and Figure 4.2 illustrates the worst case scenario. The modeled transport times represents the groundwater movement and thus the advective transport of contaminants that may be transported with water to the closest recipient. Transport times are presented in the time scale days to years, where red indicates a very fast transport of half a day, orange indicates 1-2 weeks, yellow indicates half a year and deep green indicates transport times as slow as over 100 years. The time of transport from cell to cell depends on the prevailing characteristics of deposits and slope in each 50m·50m cell.

Figure 4.1 illustrates the median case scenario where shorter transport times of half a day to 1 week are found close to the stream network situated in permeable deposits such as in the Vomb basin and the eastern part of the catchment, remember Figure 2.6 presenting frequently occurring denominations of geological areas within the catchment. However on the shale plateau, velocities ranging up to over 100 years are found.

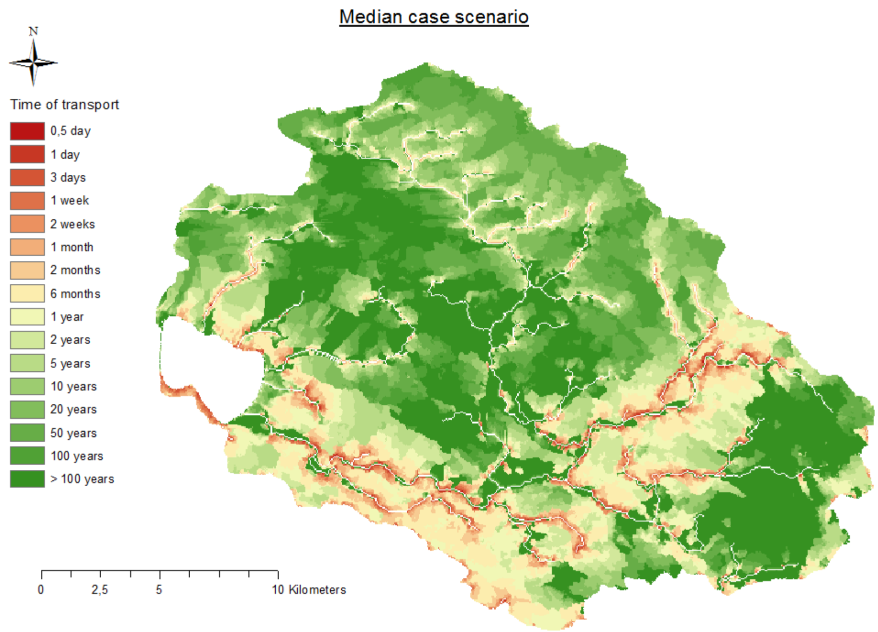


Figure 4.1: *Estimated transport time to nearest water body based on the median case scenario. Map produced in ArcMap by the authors.*

Figure 4.2 illustrates the worst case scenario and shows an obvious increase in transport times compared to the median case throughout the river basin. Larger areas around the stream network situated in the Vomb basin and in the eastern parts of the catchment indicate transport times between half a day to 1 week. On the shale plateau one will find a larger variety of transport times compared to the median case, even though times as slow as over 100 years still occurs in some parts.

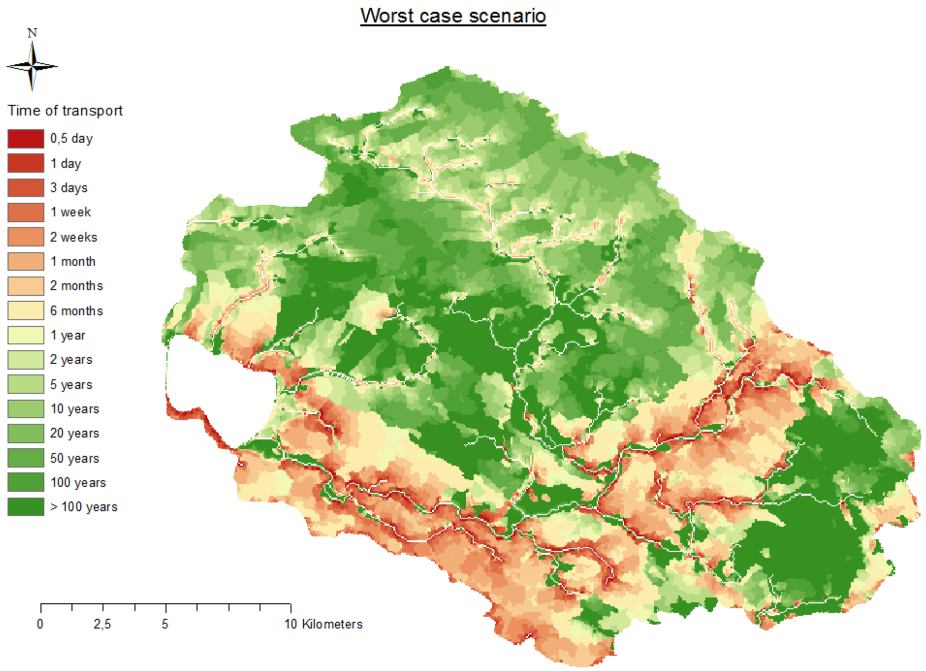


Figure 4.2: *Estimated transport time to nearest water body based on the worst case scenario. Map produced in ArcMap by the authors.*

4.2 Potential contaminants

Movement of contaminants in a natural environment depends on the specific properties of each substance such as the density, volatility, water solubility, potential biological and chemical degradation. These are characteristics that will affect which contaminating substances that are transported from a source of emission such as an infiltration bed in a decentralized sewer system to a recipient. A compilation, by the authors, of the selected potentially contaminating substances in wastewater from decentralized sewer systems that might leach to the groundwater and their characteristics regarding water solubility, sorption and microbial uptake is found in Table 4.1. High and low water solubility of a substance is defined after having an octanol/water partition coefficient larger respectively lower than 3. However, PFAS comprises a large variety of chemical characteristics depending on the length of the carbon chain and what substances that are attached to the molecule in question. Thus PFAS substances may be more or less prone to solve in water. The substances nitrogen, hydrochlorothiazide, metoprolol, estradiol, oxazepam and all of the pathogens have a high water solubility meaning that they pose the highest risk of leaching through the unsaturated zone, reach the groundwater and eventually end up in lake Vombsjön. Furthermore, the model in ArcMap is most accurate for these substances since they mainly move with advective transport after reaching the groundwater.

Table 4.1: *Compilation of contaminants originating from decentralized sewer systems and their chemical properties regarding water solubility, potential sorption and microbial uptake.*

Contaminant	**Water solubility**		**Prone to sorption**	**Microbial uptake**
	High	Low		
Nutrients				
Nitrogen	X		X	X
Phosphorus		X	X	X
Household chemicals				
PFAS	X	X	X	
Nonylphenol		X	X	
Pharmaceuticals				
Hydrochlorothiazide	X			
Metoprolol	X			
Diclofenac		X	X	
Ibuprofen		X	X	
Naproxen		X	X	
Tramadol	-	-	-	-
Estradiol	X			
Ethinylestradiol		X	X	
Oxazepam	X			
Pathogens				
Escherichia coli	X			X
Campylobacter	X			X
Giardia lamblia	X			X
Cryptosporidium	X			X
Norovirus	X			X

Chapter 5

Groundwater in a changing climate

Since drinking water is one of the most fundamental human needs, it is important to study and foresee long-term changes in groundwater supply and quality due to effects induced by climate change. Variations in groundwater levels are specific for each region and occur naturally throughout the year due to precipitation, evaporation and plant uptake. Increased precipitation and temperature in the future might transform this behavioral pattern and result in an increased or decreased groundwater recharge, which in turn affects the groundwater supply on a regional scale. Climate change is a frequently discussed topic with several on-going research regarding various forecasts for future trends in climatic behavior. The latest group of climate scenarios and their possible effects on groundwater level and groundwater contamination are presented below.

5.1 Climate scenarios

The Intergovernmental Panel on Climate Change (IPCC), the climate panel of the United Nations (UN) published their fifth evaluation report regarding climate change in 2013 (IPCC 2013). The report presents a new generation of modeled climate scenarios named Representative Concentration Pathways (RCP's), which describes four different pathways for the development of future concentrations of greenhouse gases, aerosols and other factors affecting the climate (SMHI 2015). The RCP's are named after the possibly reached intensity of radiative forcing in 2100, where radiative forcing is defined as the difference between absorbed solar radiation by the Earth and energy returned back to space in W/m^2. Radiative forcing is the "positive" forcing from greenhouse gases and "negative" forcing from aerosols, where a net positive forcing equals a heating system and vice versa. The four scenarios are denoted RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, where e.g. RCP 2.6 corresponds to the scenario where the concentrations of greenhouse gases in 2100 generates a radiative forcing of 2.6 W/m^2 compared to pre-industrial levels. Coupled with each RCP are certain socio-economic developments until the year 2100 stated and can be seen below (SMHI 2015).

RCP 2.6

Population: 9 billion.
Vigorous climate politics.
CO_2 increases until 2020.
Low energy intensity.
Reduced use of oil.
No significant change in agricultural areas.
Methane emissions reduced by 40%.

RCP 4.5

Population: almost 9 billion.
Strong climate politics.
CO_2 increases until 2040.
Low energy intensity.
Extensive afforestation programs.
Less area needed for agriculture due to higher yields and changed consumption patterns.

RCP 8.5

Population: 12 billion.
Stagnant climate politics.
High emissions of CO_2.
High energy intensity.
Dependence on fossil fuels.
Increased need for arable land for agriculture.
Methane emissions rising sharply.

The RCP climate scenarios are in turn based on a mean value of a collection of climate scenarios to increase their reliability. Table 5.1 shows the results from the RCP's regarding increase of precipitation and temperature for Scania between 2071-2100 compared to a reference period 1971-2000 (SMHI 2016).

Table 5.1: *Estimated increase of annual precipitation [%] and temperature [°C] between 2071-2100 compared to a reference period 1971-2000. Data collected from the climate simulator by SMHI for the catchment area of Kävlingeån (SMHI 2016).*

	RCP 2.6		RCP 4.5		RCP 8.5	
Season	Prec. [%]	Temp. [°C]	Prec. [%]	Temp. [°C]	Prec. [%]	Temp. [°C]
Spring	5 – 10	1 – 2	15 – 20	1 – 2	25 – 30	3 – 4
Summer	5 – 10	1 – 2	5 – 10	2 – 3	5 – 10	3 – 4
Autumn	0 – 5	1 – 2	5 – 10	2 – 3	15 – 20	3 – 4
Winter	5 – 10	1 – 2	15 – 20	2 – 3	25 – 30	3 – 4
Annual average	5 – 10	1 – 2	10 – 15	2 – 3	15 – 20	3 – 4

5.2 Future groundwater levels in Scania

Frequently returning and intensified rainfalls are expected to be a consequence of warmer temperatures, even though there might be local and regional differences (Klimatanpassningsportalen 2014). Precipitation in the south-eastern parts of Scania is estimated to slightly increase depending on different seasons and climate scenarios presented in Table 5.1. However, according to studies conducted by SGU, groundwater levels are expected to generally decline in the region of south-eastern Scania as a consequence of higher temperatures, increased evaporation and longer agricultural seasons due to warmer climate (Vikberg et al. 2015; Sundén et al. 2010). The model in the study by Vikberg et al. (2015) is based on data of historic levels of groundwater in 109 catchments provided by SMHI for the reference period 1961-1990 and the climate scenarios RCP 4.5 and RCP 8.5. Resulting changes in groundwater levels are estimated for the periods 2021–2050 and 2069–2098 compared to the reference period. Figure 5.1 visualizes the consequences on groundwater for the RCP 8.5 scenario which is simulated for south-eastern Scania where the river basin of lake Vombsjön constitutes a part. The simulation suggests that groundwater levels are expected to decrease in the spring and autumn primarily. The decrease in the autumn might be due to increased evaporation during summer and a prolonged agricultural season that drains the groundwater (Vikberg et al. 2015). It can also be seen that the recharge by melted snow water will occur earlier in the spring contributing to an earlier draw down of the groundwater, which in turn causes decreased levels during summer and early autumn. Precipitation in the form of snow will rather fall as rain in the future causing higher groundwater levels in the winter months.

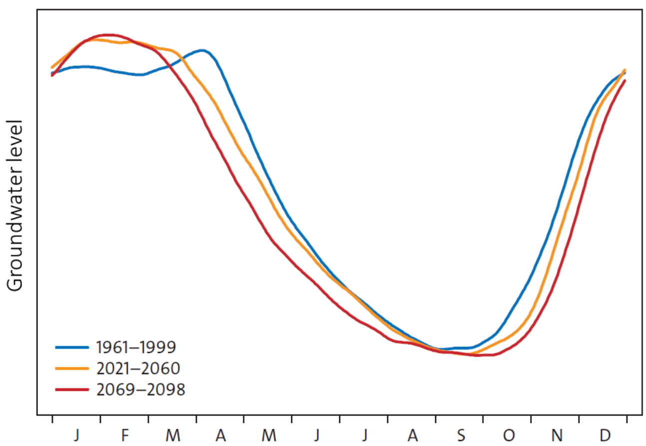


Figure 5.1: *Daily mean values of groundwater levels in the river basin of lake Vombsjön (a part of the simulation for south-eastern Scania) for the climate scenario RCP 8.5 (Vikberg et al. 2015) © Sveriges Geologiska Undersökning.*

5.3 Climate impact on groundwater contamination

Intensified rainfalls and an increased frequency of extreme weather with elements of droughts and floods as a result of climate change may increase the risk of both chemical and microbial contamination of groundwater. Lowered groundwater levels as a result of a dryer climate will enlargen the unsaturated zone resulting in increased oxygen supply and biological activity which accelerates degradation processes. Consequently there will be a larger amount of substances in solute form seeping through layers of geological deposits with penetrating water and further transported via groundwater to adjacent recipients (Hultgren et al. 2014). Increased degradation of substances in a larger unsaturated zone may also increase immobilization of contaminants since some residues may bind to organic matter and minerals in the unsaturated zone (Hultgren et al. 2014; SGU 2016b). A dryer climate will also shorten the periods of ground frost and thus allows for contaminant movement during larger parts of the year.

Intensified rainfalls results in higher groundwater levels and thus a reduction of the unsaturated zone since water will rise towards the ground surface, increasing the mobility of polluting substances such as nutrients, household chemicals, pharmaceuticals and/or pathogens situated in the unsaturated zone (SGU 2016b; Waller et al. 2012). This may result in "pollution thrusts" meaning that an increased leaking of mineral bound pollution occurs due to increased mobility with the surrounding water.

There is a significant impact on the quality of groundwater during high intensity rains that cause floods. Depending on the land use of the flooded area, various types of pollution can be expected (Waller et al. 2012). Flooded cropland increases the amount of solved pesticides and nutrients, flooded pasture land increases the amount of feces related bacteria and nutrients in water seeping down towards the groundwater table. The unsaturated zone situated between the ground surface and the groundwater table is reduced or even eliminated for short periods during floods. Reduction of the aerated soil layer constituting the unsaturated zone affects the quality of water seeping down to the groundwater table since this zone is very important when it comes to reducing the amount of pathogens and chemical residues (Waller et al. 2012). Thus flooded land near households with decentralized sewer systems will affect the unsaturated zone in soil infiltration systems resulting in less reduction of possible contaminants from decentralized sewer systems.

Chapter 6

Discussion

It is important to once again point out that this project is based on literature, archive documents and geological maps meaning that no field investigations have been performed. Consequently all stated assessments are based on data from previous investigations and literature leading to estimations of topography, geology and conditions concerning groundwater and probable transport of contaminants.

6.1 Transport times

Looking at Figure 3.4-3.5 illustrating groundwater velocities and Figure 4.1-4.2 illustrating transport times within the catchment of lake Vombsjön, it is obvious that there is a relatively large difference depending on the two simulated scenarios of *mean* and *worst case* together with large variations depending on the permeability of deposits. Large parts of the river basin constitute of low permeability deposits resulting in flow paths with long transport times, where the general risk of contamination can be interpreted as small regardless of scenario. However, there is a large difference in transport times in flow paths going through the more permeable deposits according to the simulated scenarios. It is possible that the simulated transport times in certain situations are shorter than what is presented by the two scenarios. Flowing groundwater will always take the easiest flow path and might in some parts of the catchment area find its way through layers with higher permeability than those used in the simulations or find its way through fractures in the bedrock. Contaminating substances may thus travel faster than if all possible flow paths were situated solely in the deposits covering the catchment according to the geological map, Figure 3.3. Since possible flow paths in bedrock fractures and subsoil layers can not be excluded one should consider the conservative scenario, that is the worst case scenario, primarily.

In the median case scenario the largest risk of contamination transport is found in permeable deposits situated close to water bodies, such as in the Vomb basin and the eastern part of the catchment. Transport times can be as short as half a day up to 5 days here. Some locations with varying topography registered in the DEM have generated unrealistically steep slopes that affect the simulated groundwater gradient resulting in very short transport times. The transport times might therefore be shorter than what is realistic and must be considered as an overestimation of the groundwater transport. The worst case scenario derives as short transport times as the median case (0.5-5 days) but in larger stretches around water bodies located in permeable deposits. The Vomb basin and water bodies located in glaciofluvial deposits in the eastern part of the river basin seems to be the most sensitive areas regarding pollution transport. Households with decentralized sewer systems located in these stretches pose the most probable risk of contaminating nearby water bodies. In the most impermeable areas found on the shale plateau and east of the Vomb basin simulated transport times reach over 100 of years, in some parts even up to 100 millions of years.

The catchment of lake Vombsjön is dominated by agricultural land which has undergone extensive ditching where a lot of drainage pipes have been installed, resulting in effects on the "natural" flow of surface runoff and groundwater. Rain falling on permeable land will form surface runoff and groundwater in different amounts depending on the fraction of water that is allowed to penetrate the ground. Since drainage pipes and ditches are installed at lower elevations than surrounding land, formed groundwater might drain to these collection systems and hence shorten the groundwater pathways going through geological deposits. This may result in a decreased potential of retardation of contaminants since the flow path through the unsaturated zone is shortened which affects chemical and biological degradation, but also a much faster transport of contaminated groundwater to the closest water body. Consequently the actual transport times may be faster than what is suggested by the simulation of the worst case scenario.

6.1.1 Contaminant transport

Dispersion of contaminants in a natural environment depends on the specific characteristics of each substance. Density, volatility, water solubility, potential biological and chemical degradation are properties that will affect the amount of substance that is transported from origin to recipient. Substances with high water solubility usually follows with the groundwater flow. Substances with higher density than water and low solubility have a tendency to penetrate the ground surface and leak by gravity through all permeable geological deposits. These substances tends to accumulate in organic material such as humus and aquatic organisms, hence the amount of substance that is potentially transported with groundwater decreases (Hultgren et al. 2014). Considering the presented substances in Table 2.2 nitrogen, PFAS, hydrochlorothiazide, metoprolol, estradiol, oxazepam and all of the pathogens have a high water solubility meaning that they pose the highest risk of leaching through the unsaturated zone, reach the groundwater and eventually end up in lake Vombsjön.

Table 2.3 presents statistics of pharmaceutical usage in Scania during 2014 (Socialstyrelsen 2016), which is assumed to be valid for inhabitants living within the river basin of lake Vombsjön as well as for the rest of Scanias population. The statistics reveal that metoprolol with 60.63 patients/1000 inhabitants is the most used pharmaceutical, and thereafter in falling order: oxazepam (30.48), estradiol (27.28) and hydrochlorothiazide (5.49). Among these hydrochlorothiazide is the only substance detected in lake Vombsjön even though it is more scarcely used than other denoted drugs. Possible explanations for this is that the water sampling and screening has not been addressed towards targeting other pharmaceutical residues. Each substance has its own level of detection when screening a water sample, and for some substances this level needs to be rather high in order for the substance to be detected at all. The statistics for Scania might therefore not be an accurate representation of the pharmaceutical usage in the catchment area of lake Vombsjön.

Diclofenac is the most used among the pharmaceuticals with low water solubility with 43.61 patients/1000 inhabitants while the rest of the compounds are distributed as follows in decreasing order of usage: ibuprofen (20.47), naproxen (18.56) and ethinylestradiol (no statistics). Both ibuprofen and naproxen have been detected in lake Vombsjön but not diclofenac. Only judging by the octanol/water partition coefficient, i.e. the water solubility, these compounds are more non-polar in their nature and one could suspect certain possibilities of retardation factors in soil due to sorption or microbial uptake of these substances. It seems that no clear connection is to be found from the water solubility, pharmaceutical usage and detection in lake Vombsjön. The complexity of the behavior of pharmaceuticals in soil is well known and suggests that each specific compound and its transportation routes and transformations in the unsaturated zone has to be investigated individually.

The unsaturated zone located between the ground surface and the groundwater table is crucial when it comes to reduction of pathogens and chemical residues (Waller et al. 2012). The percolation of the wastewater effluent through the natural top layer of deposits is what an infiltration system takes advantage of to accomplish a high degree of water purification (UMEVA

2013). Many of the decentralized sewer systems in the river basin uses some kind of infiltration system. The groundwater levels in south-east Scania are estimated to decrease as a result of climate change scenario RCP 8.5 whereas the precipitation is estimated to increase (Vikberg et al. 2015). A lowered groundwater table results in a larger unsaturated zone allowing for more extensive biological degradation and hence greater reduction of contaminants. On the other hand, increased precipitation could lead to more frequently occurring flooding events, which in the vicinity of a decentralized sewer system affects the aerated soil layers by filling them with water and thus result in a lower reduction of possible contaminants since less biological degradation can take place.

6.2 Model applicability

Modeling flow paths and transport times for groundwater and contamination with ArcMap are relatively easy to achieve today. Internet provides a lot of easily accessible tutorials and the ESRI homepage offers a profound supply of information regarding possible operations for hydrological applications (ESRI 2016). Input data in form of topography, placement of water bodies and cities among others are available as open source for most catchments located in Sweden.

Maps illustrating the transport times can be used to easily identify areas that are particularly sensitive to contamination and illustrate probable pathways for transport in order to initiate effective precautions to minimize the risk of contamination. They can be used as a valuable support for decision making regarding urban planning and water management where areas sensitive to contamination needs to be identified. Knowledge provided by the maps of contamination transport within a river basin can be utilized to prevent placement of activities that constitute a pollution risk to protected areas such as drinking water sources and other water bodies. Other potential applications of this type of model could be to identify locations where groundwater velocities and transport times should be more closely investigated due to very high risk of contaminant transport. Such areas should be further investigated by measuring groundwater levels and performing hydraulic tests before evaluating possible measurements to lessen the pollution load.

Using ArcMap as a tool for modeling groundwater flow has worked well in general, given that ArcGIS is not an explicit program for modeling of water. ArcGIS have rather been used for the ability to illustrate the results graphically. There are however tools within the program that allows for more extensive modeling than what has been performed in this study. However, these tools have not been used since they require input data that is not available for the chosen catchment.

6.2.1 Assumptions and uncertainties with model

The elevation data (DEM) collected from Lantmäteriet with a pixel size of 50m·50m is based on air-photos and elevation contours, mainly produced in the 1980's but lastly revised in 2004. Mean error of the model is measured to 2 meters, but might be greater at some locations due to the large pixel size (Lantmäteriet 2016). The greatest assumption of the ArcMap model regards the hydraulic gradients, i.e. slopes of the groundwater table, that are assumed to coincide with the mean ground surface slope in each 50m·50m pixel. This approximation could lead to underestimations as well as overestimations of the hydraulic gradient, especially in terrain with highly varying topography. According to Figure 3.2 there are slopes that reaches 54% which is not realistic and will thus result in unreasonably fast transport times. The groundwater table is more smooth than the topography in general, which is the reason for choosing a larger pixel size to decrease the influence of local peaks in the terrain.

Since no sampling of the geological deposits and hydraulic tests have been conducted in the river basin, the values of hydraulic conductivity and effective porosity are based on a range of values presented in literature for each deposit present in the area. The median and highest number in the span of type values were then used to symbolize the median and worst case scenario for both hydraulic conductivity and effective porosity. Furthermore, out of the original 31 classes of geological deposits in the GIS-data from SGU only 6 classes were kept after merging together deposits with similar hydraulic properties resulting in an even larger approximation of the characteristics of the geological layers. The merging of 31 deposits into 6 depending on geological characteristics is further described in Appendix 3.

The flow pattern of the groundwater is estimated to be an approximation of the mean ground surface slope, i.e. the slope generates a flow direction for each pixel to an adjacent pixel creating a pattern for water bodies in the river basin. When a manually decided number of pixels, in our case 1000, drains to a particular pixel that pixel is considered to represent a stream. In Figure 3.6 it can be seen that the resulting stream network produced in ArcMap do not match entirely with the superimposed stream network map from Lantmäteriet. However, it has come to our knowledge that our model takes the small stream Borstbäcken into account which the stream network from Lantmäteriet does not. Therefore, the result of creating our own stream network in ArcMap that generates a greater amount of small streams and creeks, could either provide a more accurate model or simulate shorter transport times since some of the streams in ArcMap might be dry trenches and not actual water bodies.

Chapter 7

Conclusions & recommendations

Conclusions based on literature, archive material and geological maps imply that the river basin of lake Vombsjön may be roughly divided into two different sections regarding their geological properties. These are named the Vomb basin, which is dominated by permeable geological deposits, and the shale plateau where less permeable deposits dominate. Among the potentially contaminating substances that have been presented in the thesis it can be concluded that those with hydrophilic character are more likely to spread with advective transport to surrounding water bodies. This implies that water soluble pharmaceuticals such as hydrochlorothiazide, metoprolol, estradiol and oxazepam as well as pathogens are at high risk for spreading with groundwater transport.

Conclusions based on the simulation of groundwater transport carried out in the software ArcMap imply that the risk of advective transport for water soluble substances is very high in areas dominated by permeable deposits such as in the Vomb basin. The simulation of a worst case scenario implies that transport times can be as fast as 12 hours in riverbanks consisting of highly permeable deposits. Visualization of results as maps illustrating the simulated flow paths for groundwater through geological deposits, i.e. transport times in different regions within the catchment, may be utilized in various ways. Foremost it can be used by inspectors from municipalities as a tool for deciding where and how to prioritize control and monitoring of decentralized sewer systems to prevent risk of contamination of water bodies and transmission of disease.

Consequently, it is recommended to perform more extensive mapping of the geology and hydrogeology within the catchment. Focus should lie on areas which are densely populated by households with decentralized sewer units for soil infiltration situated on coarse deposits. This is foremost in the glaciofluvial sediments that dominate the Vomb basin. Maps of transport times may be utilized for evaluating which areas within the catchment that are of importance when establishing water protection areas in order to ensure the water quality of lake Vombsjön and surrounding water bodies. It is also recommended to develop a way of controlling soil infiltration beds since this is where biological and chemical degradation of contaminating substances will occur and thus its functionality is of great importance for the amount of leaking pollutants. Sydvatten and involved municipalities are recommended to implement longtime educational projects for the citizens living within the catchment area concerning how to prevent harmful substances from entering surface or groundwater.

7.1 Future model development

In order to further develop the model it is recommended to perform geological and hydrogeological field investigations within the catchment. Such measurements include comprehensive mapping of geological deposits and their respective thickness, regular measurement of groundwater levels and properties such as transmissivity, hydraulic conductivity and chemical composition for the relevant deposits. With data of transmissivity and aquifer thickness one may apply more extensive hydrological calculations and modeling provided by the tool *Spatial Analyst/Hydrology* in ArcMap.

By investigating the properties of the different deposits in the catchment it is possible to have a more thorough scientific discussion regarding how contaminants such as nutrients, household chemicals, pharmaceuticals and pathogens presented in this study would interact and behave due to their chemical and biological properties. Knowing how a contaminant reacts due to its chemical surrounding would give an indication of the possible impact of retardation. With a known retardation coefficient for each substance one could perform individual modeling of distribution scenarios and transport times with groundwater. To create a more advanced groundwater transport model there are other modeling tools more adapted for the task than ArcMap. Using such a program could simplify the creation of the model even though the results might not be presented as graphically as with ArcMap.

The nitrogen and phosphorus load leaking into lake Vombsjön and the upstream water bodies due to surface runoff from agricultural land in the catchment have been surveyed and confirmed in studies performed by Sydvatten AB (Sundahl et al. 2008). However, it would be interesting to take samples of sludge in septic tanks and effluent water in decentralized sewer systems as well as in private wells for drinking water in order to confirm or write of the occurrence of suggested household chemicals and pharmaceuticals. Furthermore, it would be of interest to perform water sampling not only in lake Vombsjön as of today, but also in the upstream water bodies in order to map out the concentration differences along the transport pathway. To get an idea of the possible load of chemicals originating from private households, one could also investigate the quantity and frequency of medical use and what household chemicals that may contribute to an increased loading of harmful substances. What are the statistics regarding medical use and dose amongst the population living within the river basin of lake Vombsjön? What harmful water soluble substances can be found in household and health care products?

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Appendix 1: Cross-sections

The contours of the four geological cross-sections, i.e. the lines representing the ground surface and bedrock surface, are created in ArcMap. The input data for the contour of the ground surface constitutes of a Digital Elevation Model (DEM) with a cell size of 50 m·50 m collected as open source data from Lantmäteriet.

The input data for the contour of the bedrock surface is based on borehole data gathered from SGU (SGU 2016c) in form of a point layer providing the coordinates and depth to bedrock in each borehole. This point layer is imported to ArcMap. To make the depth to bedrock cover the whole catchment, the point layer is interpolated by creating a Triangular Irregular Network (TIN) using the *3D Analyst tool.* A TIN is a vector based representation of a surface created from the irregularly distributed points with three-dimensional coordinates (geographical coordinates of north, east and depth to bedrock) that are arranged in a network of triangles (ArcGIS 2010). Since the depths to the bedrock are defined in the input data as positive values, the TIN surface needs to be subtracted from the ground surface (i.e. the DEM raster layer) to make the bedrock surface appear below the ground surface. This is done by first performing a rasterization of the TIN surface to permit mathematical operations with the DEM raster layer and then performing the subtraction using *Raster Calculator*.

The contours from both the ground and bedrock surface are then extracted from the four chosen locations by using *3D Analyst/Contour* and pasting the data into an Excel sheet. This is done in order to create the conceptual layers of Quaternary deposits in between the ground surface and bedrock. The thickness and type of deposits are sketched conceptually in between the estimated ground surface and bedrock formed in ArcMap. These sketches are based on a database *Brunnsarkivet* (SGU 2016a) where SGU provides more detailed geologically referenced borehole data and a geological description of the catchment of lake Vombsjön by Bjelm and Malmberg-Persson 1982.

Appendix 2: GIS flowchart

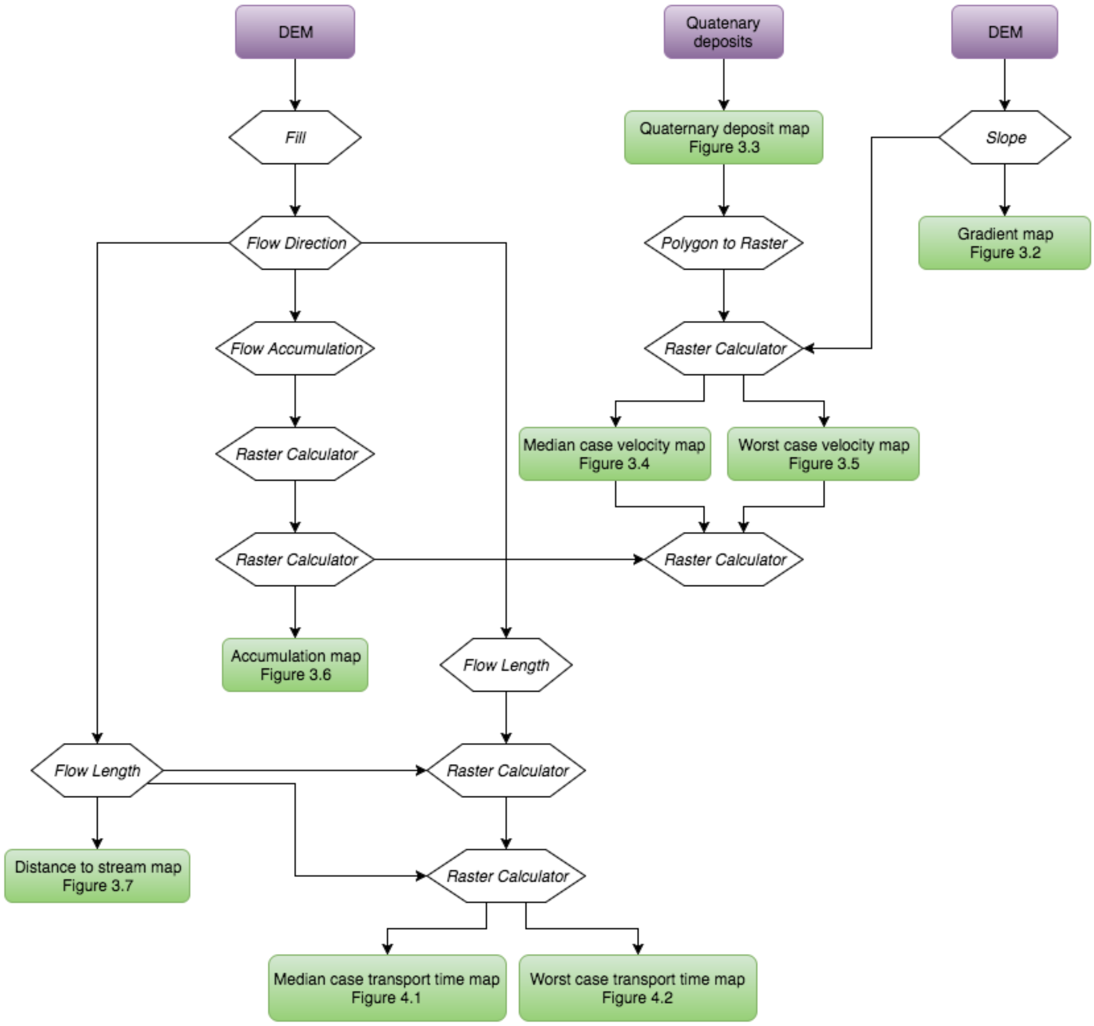

Figure A2: *Process scheme showing the relationship between the input data (purple), operations (white) and produced maps (green) in ArcMap. Flowchart produced by the authors.*

Appendix 3: Merging of geological deposits

	English naming of geological deposit	Svensk benämning av jordart
Peat (torv)	Fen peat	Kärrtorv
	Bog peat	Mosstorv
Post-glacial sand (postglacial sand)	Postglacial sand	Postglacial sand
	Postglacial fine sand	Postglacial finsand
	Fluvial sediment	Svämsediment
	Fluvial sediment-sand	Svämsediment - sand
	Drifting sand	Flygsand
Glaciofluvial sediments (Isälvsavlagring)	Filler material	Fyllning
	Glaciofluvial sediments	Isälvsavlagring
	Glaciofluvial sediments-sand	Isälvsavlagring - sand
Gravelly till - sandy till (grusig-sandig morän)	Gravelly till	Grusig morän
	Sandy till	Sandig morän
Clayey till - clay till (lerig morän-lermorän)	Glacial clay (fine)	Glacial finlera
	Glacial clay (coarse)	Glacial grovlera
	Glacial silt (coarse)	Glacial grovsilt
	Glacial silt	Glacial silt
	Mud	Gyttja
	Clayey mud	Lergyttja
	Clayey till	Lerig morän
	Clay till (fine)	Morän finlera
	Clay till (coarse)	Morängrovlera
	Postglacial clay (fine)	Postglacial finlera
	Postglacial clay	Postglacial lera
	Postglacial silt	Postglacial silt
	Silty till	Siltig morän
	Silt	Silt
	Fluvial sediments clay-silt	Svämsediment ler-silt
Bedrock (berggrund)	Fanerozoisk diabase	Fanerozoisk diabas
	Sedimentary rock	Sedimentärt berg
	Bedrock	Urberg

Figure A3: *The 30 geological deposits originating from vector data provided by SGU merged into six larger fractions of deposits depending on their geological properties.*