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The Impact of Boundary Condition on Groundwater Flow: Topography v/s Recharge Controlled

HARSHITHA SRIDHAR

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ARCHITECTURE & THE BUILT ENVIRONMENT

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HARSHITHA SRIDHAR

Supervisor:
Brian Babak Mojarrad

Examiner:
Anders Wörman

TRITA-ABE-MBT-20745

KTH Royal Institute of Technology

School of Architecture and Built Environment

Department of Sustainable Development, Environmental Science and Engineering

SE-100 44 Stockholm, Sweden

Abstract

Groundwater interactions at a regional scale are of great importance to characterize subsurface flow processes.Extensive researches have been conducted previously to determine the main factors controlling the regional implications on groundwater flux circulation. Groundwater circulation occurs due to variation in the groundwater table (hydraulic gradient) across the spatial scale. Previous research highlighted the correlation between groundwater table with both topography variation and the recharge from precipitation.This study aims to highlight the impact of these boundary conditions. Five catchments located across different regions of Sweden with different topographical, hydrological, and meteorological properties considered for this study: Bodalsån, Forsmarksån, Tullstorpsån, Sävaån, and Krycklan.Relevant data were collected and numerical models were set up in steady-state conditions for each of these catchments, using 3D Multiphysics COMSOL. Models were set up for both of the boundary conditions, using 10 m grid resolution.Groundwater flux profiles along the depth of the catchments were obtained as a result, in which significant differences were observed.This was associated predominantly with the difference in the nature of the topography, the slope and soil permeability in these regions. The data thus collected and the models so established have increased the understanding in these regions from a research perspective.

Keywords

Regional Groundwater flow, topography boundary condition, recharge boundary condition,3D numerical modelling, groundwater flux profile.

Svenskt Abstract

En ökad förståelse för hur grundvatten interagerar med ytvatten är av stor betydelse för att karakterisera underjordiska flödesprocesser. Omfattande undersökningar har tidigare genomförts för att bestämma de viktigaste faktorerna som styr de regionala konsekvenserna för cirkulationen av grundvattenflöde. Grundvattencirkulation uppstår på grund av variationer i grundvattentabellen (hydraulisk gradient) över den rumsliga skalan.Tidigare forskning belyste korrelationen mellan grundvattentabellen med både topografivariation och laddning från nederbörd. Denna studie syftar till att belysa effekterna av dessa gränsförhållanden. Fem avrinningsområden placerade över olika regioner i Sverige med olika topografiska, hydrologiska och meteorologiska egenskaper som beaktas för denna studie: Bodalsån, Forsmarksån, Tullstorpsån, Sävaån och Krycklan. Relevanta data samlades in och numeriska modeller sattes upp under steady-state-förhållanden för vart och ett av dessa avrinningsområden med användning av 3D Multiphysics COMSOL. Modeller konfigurerades för båda gränsförhållandena med 10 m nätupplösning. Grundvattenflödesprofiler längs avrinningsdjupet erhölls som resultat, där signifikanta skillnader observerades. Detta var främst förknippat med skillnaden i topografins natur och lutningen i dessa regioner. De data som samlats in och de så etablerade modellerna har ökat skapat en värdefull grund för vidare hydrologisk forskning i dessa regioner.

Nyckelord

Regionalt grundvattenflöde, topografi gränsvillkor, laddningsgränsvillkor, numerisk 3D-modellering, grundvattenflödesprofil.

Acknowledgements

Don’t limit your challenges; challenge your limits. Each day we must strive for constant and never-ending improvement.

- Tony Robbins

This quote resonates with my learning experience through the thesis work, which would not be possible without the support and guidance of several people, whom I would like to acknowledge. Firstly, I would like to thank my examiner, Anders Wörman (Head of Division, Resources, Energy, and Infrastructure) for considering and providing me with this opportunity, to work at the Department of SEED, on this distinctive research project. I would like to extend my deep sense of gratitude to my supervisor Brian Mojarrad (Doctoral Student at KTH) for his relentless support and guidance through our work. Your passion, dedication, boundless patience, and extensive knowledge in the field of hydrology, hydrogeology, and numerical modeling, has and will be an inspiration. A special mention to Ida Morèn (Doctoral Student at KTH), for her continuous assistance and suggestions through the progress of my thesis. Lastly, I would like to express my sincere appreciation and indebtedness to my family for their unending support and encouragement.

Definitions

Aquifer	An aquifer is a water bearing stratum of permeable rock, rock fractures and unconsolidated material (sand,silt or gravel)
Catchment	Also known as catchment basin or drainage basin, it refers to an area of land bounded by watersheds draining into a river, basin, or a reservoir.
Discharge	Volumetric flow rate of water that is transported through a given cross-sectional area.
Hydraulic Conductivity	A physical property that measures the ability of a material to transmit fluid (with ease) through pore spaces and feactures in the presence of a hydraulic gradient
Porosity	Also known as void fraction refers to the percentage of void spaces in any given material
Runoff	Is a process when water from rain, snowmelt and other sources flows over the land surface (genrally discharged into streams)

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1 Introduction

Groundwater is a principle freshwater resource and a significant moderator of hydrologic processes at the land surface and the atmosphere [3]. It constitutes to an important component of many water resource systems supplying water for domestic use, industry and agriculture [1].Intensive water resource development in the past decades has large impacts on the hydrological systems at basin-scales which increases the demand to predict regional impacts of human inferences on groundwater systems and associated environment [43]. Regional groundwater flow, and its general understanding is essential as it aids in comprehending continental-scale motion of groundwater and the driving factors to define characteristics of the flow systems. According to Tòth, knowledge of the locations and extent of the recharge and discharge areas is an important factor to understand the groundwater motion in a region [34]. The discharge and recharge areas in a region are largely characterized by the direction flow of groundwater towards or away from the water table [10].Location of the groundwater table can therefore help in conceptualizing regional groundwater flow and in examining the interactions of groundwater with the surface. Formulation of mathematical solutions to groundwater flow problems was initiated treating the water table as a ´free surface´, in which its location depending on the solution itself [13]. Dupuit, probably was the first to address this problem simplifying, by ignoring vertical flow, reduced it to a one or two-dimensional problem [6]. Forchheimer, later put forth a differential equation for water table elevation, with reference to Dupuit [8]. Hubbert [14] and Tòth [34] conceptualized the groundwater table as an exact replication of topography [13]. In humid regions with low hydraulic conductivity the theory was corroborated, that is the water-table elevation closely follows the topography. Although this simplification was a useful approximation, this correlation was not valid universally. Many studies have stated that topography may always not be a dominant controller on groundwater flow and this hypothesis resulted in over estimations in the water-table fluxes.This initiated extensive research considering climate as a factor controlling groundwater flow behaviour [13].It was observed that in arid regions, with high hydraulic conductivity, recharge/ infiltration is the fundamental component influencing the location of the water table [30]. With these theories under consideration Haitjema and Mitchell-Bruker [13] provided a criteria where we can fundamentally determine whether the groundwater flow is controlled by topography or recharge, called the Water Table Ratio (WTR). Given by:

$$\frac{RL^2}{mkHd} > 1 \quad water\ table\ is\ topography\ controlled \tag{1}$$

$$\frac{RL^2}{mkHd} < 1 \quad water\ table\ is\ recharge\ controlled \tag{2}$$

Here R (m/d) is the annual recharge rate, L(m) the average distance between water surfaces, m -a factor based on aquifer type, k (m/d) the hydraulic conductivity, H (m) aquifer thickness, and d (m) the maximum distance between average surface water levels, and terrain elevations.Figure 1.1 represents both the control conditions occurring in groundwater flow.

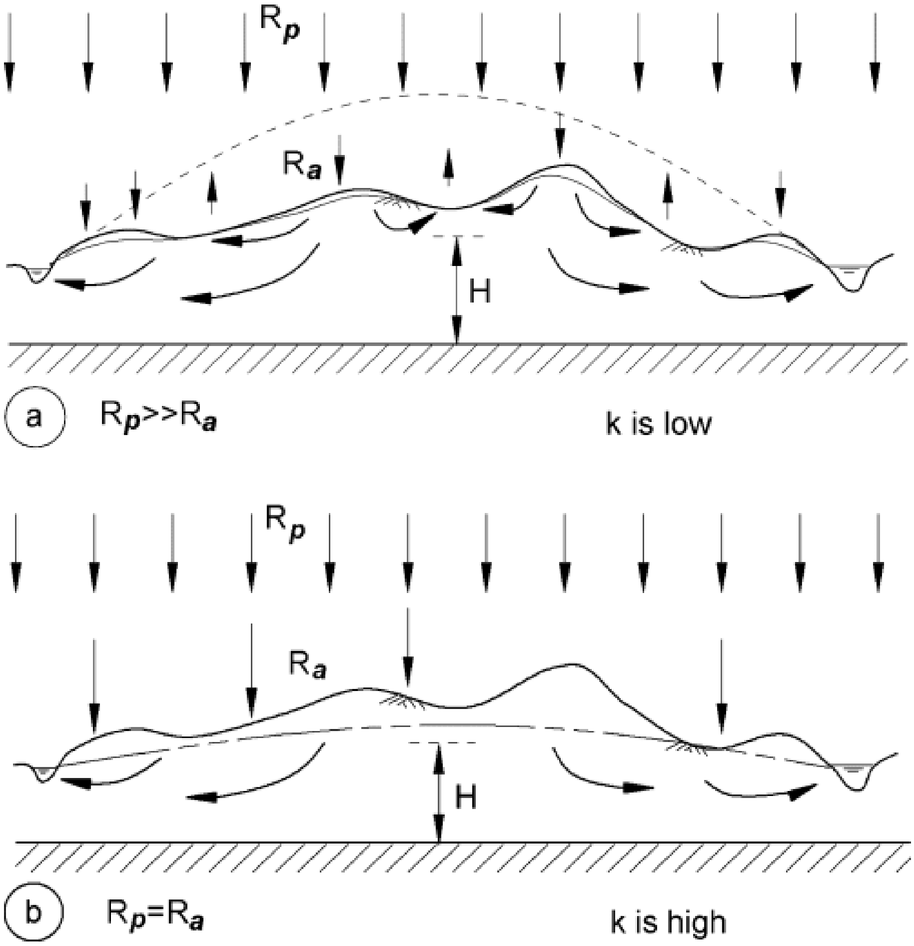

Figure 1.1: (a) Low-permeable aquifer with topography controlled water table; (b) Highly-permeable aquifer with recharge controlled water table [13]

These landscape attributes (topography) and climate (recharge) can be related to catchment-scale hydrologic responses. They allow predictions for ungauged catchments (a catchment which is not gauged for stream flow) based on these attributes and climate data and help in categorising catchments behaving in similar nature [27].

The scope of this study is to investigate and highlight the impact of the two top boundary conditions: topography controlled and recharge controlled on groundwater flow. This thesis contributes a part of ongoing study, at the Department of SEED(Sustainable Development, Environmental Science and Engineering) KTH, regarding the relation between regional and local upwelling groundwater velocity and area with different characteristics of the catchments.It focuses on 5 catchments with different selection of characteristics to relate regional scale groundwater flow field characteristics to certain general proxy parameters of a catchment.

1.1 Aims & Objectives

The fundamental aim of this study is to highlight the impact of top boundary condition on groundwater flow. The considered boundary influences are:

- Topography controlled: The water table closely follows the topography or land surface.
- Recharge controlled: Impact of climate condition (Infiltration from precipitation).

The objectives of the study in detail is concerned about:

- Collection of relevant meteorological, topographical and geological data representing the 5 catchments considered for this study.
- Formulate numerical models for each of the respective catchments for both of the aforementioned boundary conditions (topography and recharge controlled)
- Study the impact on the groundwater flux profile due to different boundary conditions.
- Study the impact on areal mean of the vertical velocity at the stream bed interface due to different boundary conditions.

2 Theoretical Background

This section briefly describes the physics involved to formulate groundwater flow models and understanding the framework used for numerical simulation.

2.1 Hydrological Processes

Previous studies have shown that one of the simplified modelling approach involves accounting for the key hydrologic processes occurring in a catchment [27].This section focuses on establishing a hydrological framework for understanding the natural processes.This provides the necessary context for understanding the boundary conditions considered for this study. The endless circulation of water as it moves in its various phases through the atmosphere, to the earth, over and through the land, to the ocean and back to the atmosphere is known as the hydrologic cycle [32]. This affects the global circulation of both the atmosphere and the oceans, thus regulating the weather and climate. Figure 2.1 illustrates the components of a hydrologic cycle.The main components of the hydrologic cycle, relevant to this study are explained below.

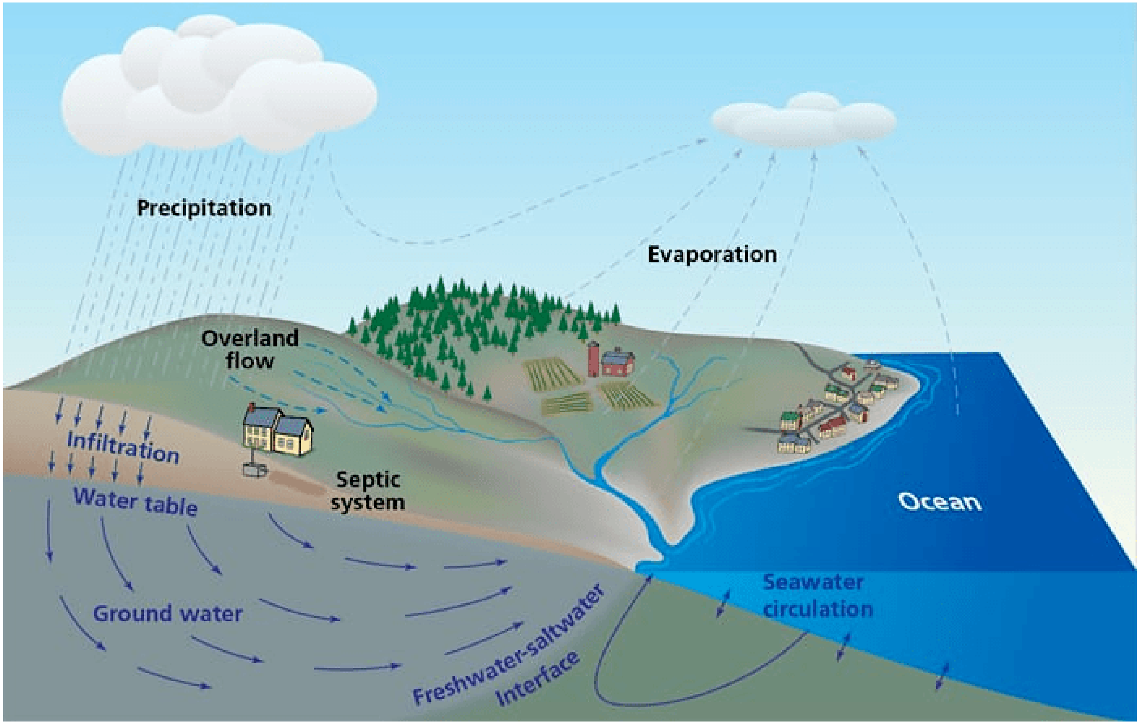

Figure 2.1: Schematic representation of the hydrologic cycle [17]

2.1.1 Precipitation and Evaporation

Precipitation is a major component of the water cycle, ensuring effective recharge of the groundwater systems. Precipitation is the water released from clouds in the form of rain, sleet, snow or hail. It proves to be the primary connection between the atmosphere and the earth [37].

Precipitation is a product of condensation and saturation of atmospheric water vapour.The condensation is generally caused as moisture is lifted or otherwise forced to rise over a layer of sub-freezing air at the surface [42]. Precipitation is often lost as runoff or Evaporation which can be generally be estimated or measured using rain gauges. However, a major portion of the precipitation so received is said to reach the groundwater table, through surface infiltration [33].
Evaporation is the process that aids in the formation of water vapor. It essentially refers to a process by which water changes from a liquid to a gas or vapour. Consequently, it proves to be a primary pathway that water changes its state in the atmospheric water cycle [36]. We can thus conclude that both these components are interlinked, as is depicted in Figure 2.1.

2.1.2 Evapotranspiration

Before we explain this terminology, first we describe the process of transpiration.It can be described as a physiological process of water loss from vegetation.It accounts to nearly 39% of the terrestrial precipitation and 61% of the evapotranspiration globally [31]. A combined effect of evaporation and transpiration results in evapotranspiration. Potential evapotranspiration (PET) is a representation of the environmental demand, and can be estimated in a numerous ways. Some indirect methods include Pan evaporation, catchment water balance method, and energy balance method. The evapotranspiration data used in this study, was obtained from the Swedish Meteorological and Hydrological Institute (SMHI), which uses the HBV Model (Hydrologiska Byråns Vattenbalansavdelning) based on the Penman-Monteith Equation for its estimation. Penman-Monteith Equation is a variation recommended by the Food and Agriculture Organization (FAO). It requires the input of daily mean temperature, wind speed, relative humidity and Solar radiation.The equation is given by:

$$ET_o = \frac{\triangle(R_n - G) + \rho_a c_p(\delta_e)g_a}{(\triangle + \gamma(1 + g_a/g_s))L_v} \tag{3}$$

Here, L_v is the volumetric latent heat of vaporisation (MJm^{-3}),$\triangle$ Rate of change of saturation specific humidity with air temperature (Pa K^{-1}), R_n Net Radiance (Wm^{-2}), G= Ground heat flux (Wm^{-2}),c_p Specific heat capacity (J $kg^{-1}K^{-1}$),ρ_a dry air density (Kgm^{-3}), δ_e vapour pressure deficit (Pa), g_a Conductivity of air (ms^{-1}), g_s Conductivity of Stoma (ms^{-1}), γ is Psychrometric constant.

2.1.3 Infiltration

The most common definition of infiltration is the process by which water on the ground surface enters the soil.Precipitation is one of the most influential factors for the amount of water that infiltrates into the sub-surface soil. It generally forms a unsaturated zone and a saturated zone as it infiltrates. A very large fraction of water falling as rain on the land surfaces is considered to move through the unsaturated zone during the subsequent process of infiltration, drainage, and evaporation [26]. Numerous factors affect the rate of infiltration which include: base flow, soil characteristics, soil saturation, land cover, slope of land, and evapotranspiration.

There are several ways in which we can estimate the rate of infiltration. In this study we use a more simplified method based on the general hydrologic budget equation. We consider the time required for water to infiltrate across the saturated zone of the soil, thus obtaining the equation as:

$$Infiltration = Precipitation - Evapotranspiration \tag{4}$$

Rainfall-induced infiltration is a primary method of natural recharge for aquifers. Natural refilling of deep aquifers is a slow process as groundwater slowly moves through the unsaturated zone. It is one the factors that is related to the hydrologic landscape of an aquifer system. Thus is further associated with the location of the water table based on the permeability of the region. In order to effectively represent recharge effectively in a groundwater model, one must consider this process controlling the rate of recharge [30].

2.2 Darcy's Law

Darcy's law is an equation that describes the flow of fluid through a porous medium. The law was formulated based on results of experiments on the flow of water through beds of sand, forming the basis of hydrogeology. It establishes a linear relationship between pressure differences and flow rate. Here the pressure refers to the hydrostatic fluid pressure which increases with depth of the column of water. It also depends on the ability of the media of flow, referred to as permeability. Thus Darcy's law can be simply expressed as:

$$Q = -K * \bigtriangledown H \tag{5}$$

where, Q is the darcy velocity vector (simply rate of flow) (m^3/s), K the hydraulic conductivity, $\bigtriangledown$ nabla operator, and H is the hydraulic head (m) [4]. The governing equation of groundwater flow is simply described by combining darcy's Law along with the equation of conservation of mass. It describes the flow of groundwater through an aquifer. The steady-state flow of groundwater is described by Laplace equations and the transient-state by a form of diffusion equation. Based on the boundary conditions that govern the aquifer, a number of simplifications were carried out by many researchers, (mentioned previously) to obtain functions and solutions for two and three-dimensional flow [41].

2.3 Numerical Modelling

There are two approaches available when formulating solutions for investigations concerning groundwater. Early research studies, were oriented towards theoretical analysis, which they believed to be best suited for initial stages of evaluation of groundwater flow patterns in an area. Tòth [34], believed that both field techniques (such as geochemical correlation, piezometric interpretation and geophysical measuring methods), and modelling techniques (such mathematical models, analytical and numerical models) can be subsequently developed to obtain exact solutions to groundwater flow patterns.

Tòth initially introduced mathematical models, in the form of solutions to boundary value problems for two-dimensional sections [10]. With this as the basis, three-dimensional solutions were developed by Allan & Witherspoon [10] representing steady-state regional groundwater flow using numerical finite-difference approach. In the later years, Huyakorn and Pinder presented an analysis of groundwater problems using a finite-element approach [15].In both the cases the equations governing groundwater flow were reduced to differential equations differing in nature based on the accuracy and efficiency of the required solutions. They result in the discretization of the space and time dimensions that allows continuous boundary-value problem for the solution of these differential equations to be reduced to a set of algebraic equations [19].In general, Numerical models are considered to be more versatile, mathematically simpler and well suited when involving computer solutions and data storage [9]. Both large-scale and small-scale flow complexities can be represented with ease using numerical mathematical modeling often considered to be superior to analytical solutions. They aid in incorporating aquifer characteristics such as permeability, transmissivities, storage coefficients, boundary values, etc., which may be uncertain as well.

2.4 Boundary Conditions

Solutions to groundwater flow problems are governed by differential equations. The solution to any form of differential equations is simply obtained by providing necessary constraints in a domain. This is known as a boundary value problem, which is essential as we model groundwater flow in an aquifer. There are different types of boundary conditions, and its choice is based on the fundamental nature of the computational problem. The different types of boundary conditions are explained below:

- Zero flow Boundary: as the name suggests there exists no flow along the boundary. Some examples of this boundary include tightly compacted clay layers, unweathered massive rock, a groundwater divide, etc. They are generally defined in regions where flows are insignificant compared to the flow in the main aquifer.
- Dirichlet or Specified Head: Also referred to as a fixed boundary condition (constant head), when applied specifies a values along the boundary of the domain. Examples of the application of this head-controlled boundary include: Lakes and streams whose water levels are not affected largely by events within the groundwater basin. Mathematically it can simply be represented as:

$$h(x, y, z) = constant \tag{6}$$

- Neumann or Specified flow: A flow-controlled boundary, also known as the recharge boundary, through which we can specify a flux or volume of groundwater that enters an aquifer per unit of time [2] . The boundary condition holds common application when there is gradient (loss or gain rate) known along the domain boundary. This boundary condition can also be used to represent streams disconnected from a groundwater system. Mathematically represented as:

$$\frac{dh(x,y,z)}{dn} = constant \tag{7}$$

- Cauchy or Specified leakages: This condition describes a relation between the leakage through a resistance layer at the bottom of a surface water and the head in the aquifer below that resistance layer [5]. A stream can also be simulated as a leaky boundary, simply the assumption changes that there exits a link between the stream stage and the groundwater system [28]. Mathematically represented as:

$$\frac{dh}{dn} + ch = constant \tag{8}$$

3 Study Areas

This section introduces the study areas. The catchments considered for this study, were chosen with an objective to cover a range of different characteristics related to topography and geological properties across Sweden.

Figure 3.1: The location of different catchments considered for study across Sweden [12]

3.1 Data

The numerical model setup in COMSOL required the input of different data. The topography of each area, grid files of resolution 10×10 m and soil type maps (scale 1:25000) were both obtained from Sveriges lantbruksuniversitet [21].The climate data in terms of precipitation, runoff and evapotranspiration was obtained from SMHI [16], for each sub-catchment, whose mean values are considered. Further sections provide a detailed description for each catchment.

BODALSÅN: The Bodalsån catchment is located north-east of Stockholm county, in the municipality of Norrtälje (59°62' N,18°60' E) with an area of 96 km^2. It is part of the outflow of the catchment area Bergshamraån into the Norrtäljeån-Åkerström coastal area. The catchment area mainly consists of forest (nearly 63 %) and agriculture (nearly 21 %) [40].The catchment area has a number of lakes namely: Svulten, Hoven, Skären, Långsjön, Norrsjön,Snävingen and Svartingen. Figure 3.2 shows the catchment area, along with its sub-catchments.

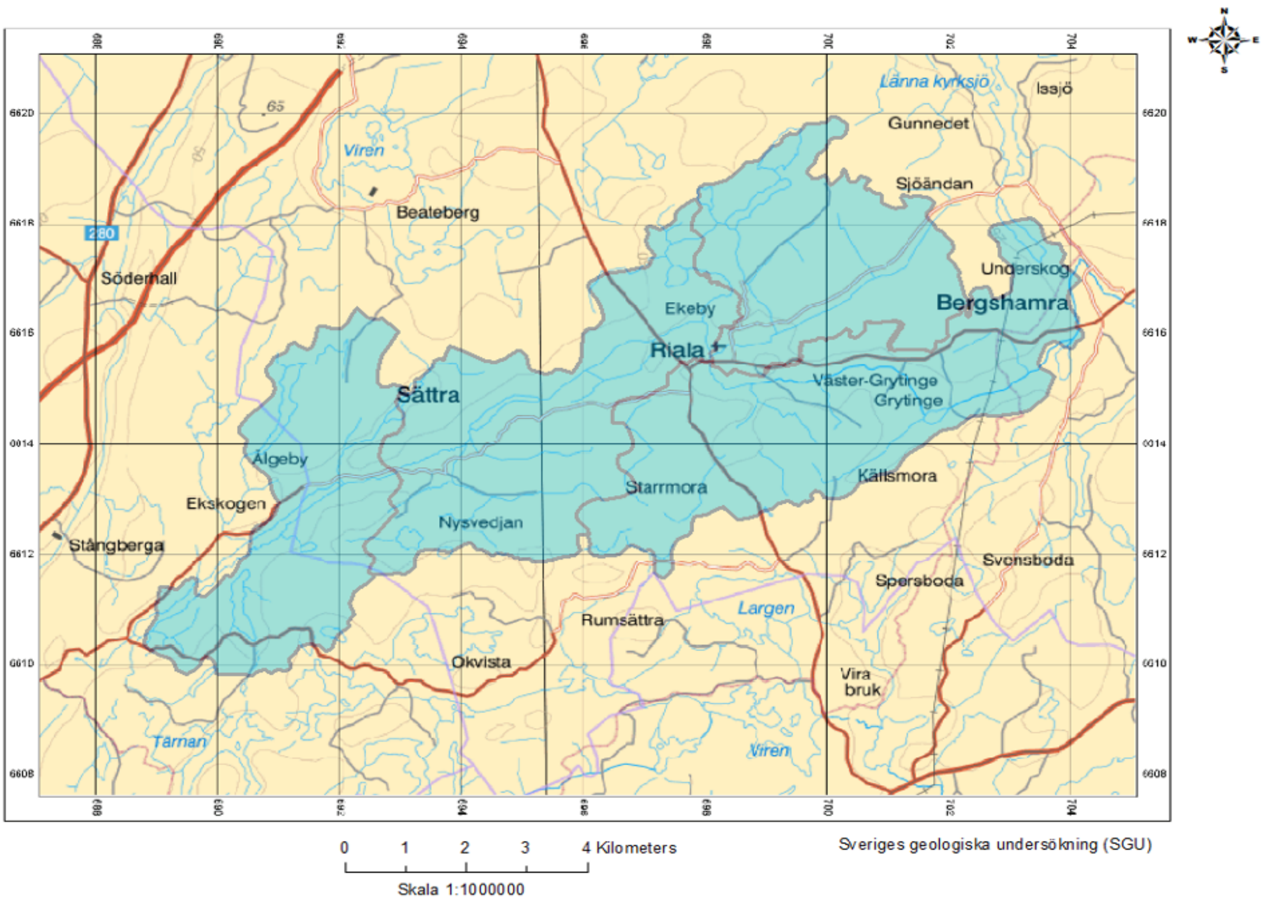

Figure 3.2: Topographical map representing a section of the Norrtälje region, location of the Bodalsån catchment with its boundaries [21]

With a considerably moderate slope along the terrain (ranging between 1.0 - 2.5 %), the maximum elevation in the catchment region is 79 m. Figure 3.3 shows the elevation range, and the river network in the catchment area.

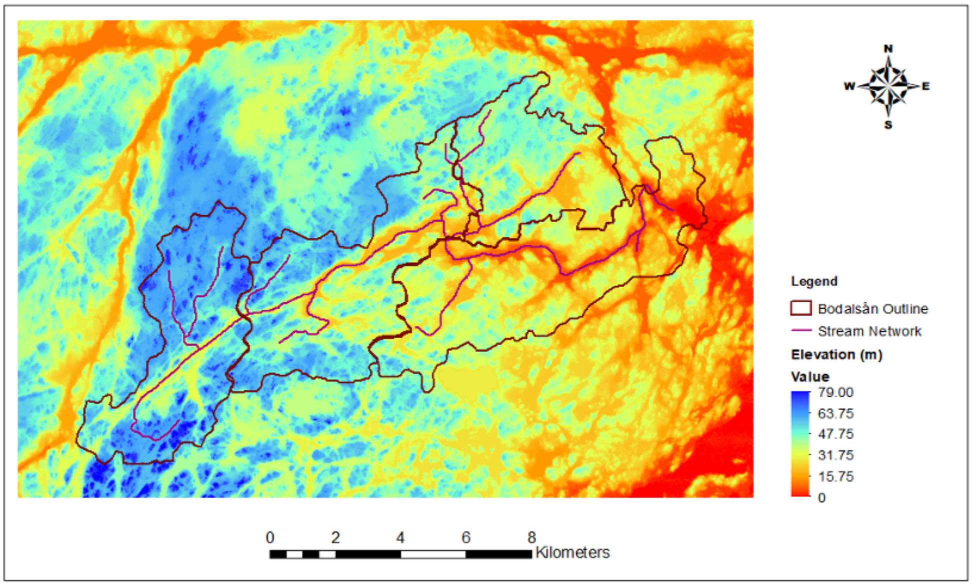

Figure 3.3: Elevation variation, catchment boundary, and stream network of the Bodalsån catchment

The average slope along the river network is 1.2%, with a mean annual discharge of 0.63 m^3/s. The region was recorded to have an annual rainfall of 662 mm/year with a runoff of 251 mm/year and evapotranspiration of 411 mm/year [16].The catchment area has an average soil depth of 5 m.The soil composition of this region is observed to have a high degree of Moraine covering 35% and bedrock outcrops nearly covering 28% of the catchment area. A varied distribution of clay-silt covering nearly 10% of the area and post glacial sediment can also be seen across the catchment. The detailed soil composition can be seen in figure 3.4.

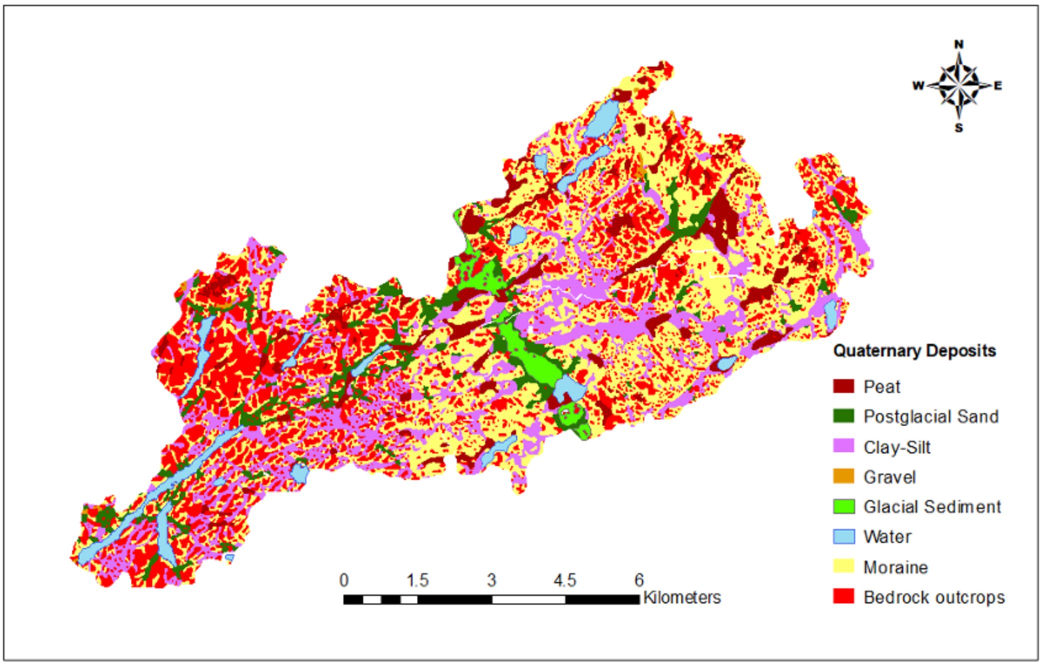

Figure 3.4: Map representing the soil composition of Bodalsån catchment

FORSMARKSÅN: The Forsmarksån catchment is located in the north-east of Uppsala county, in the municipality of Östhammar (60°22' N,18°04' E) with an area of 82 km^2. This is the projected site of a nuclear power plant and its waste repository. The catchment area has a flat topography with majorly covered with forestry (nearly 69 %) [38]. Forsmarksån comes from Norra Åsjön and Södra Åsjön in Tierp and Östhammar municipalities respectively and flows east towards Öregrundsgrepen. Forsmarksån has a number of lakes namely: Fågelfjärd, Södersjön, Sandträsket,Långträsket and Klubbträsket and is connected to, among others, Ensjön, Åkerbysjön and Lissvass. Figure 3.5 shows the catchment area, along with its sub-catchments.

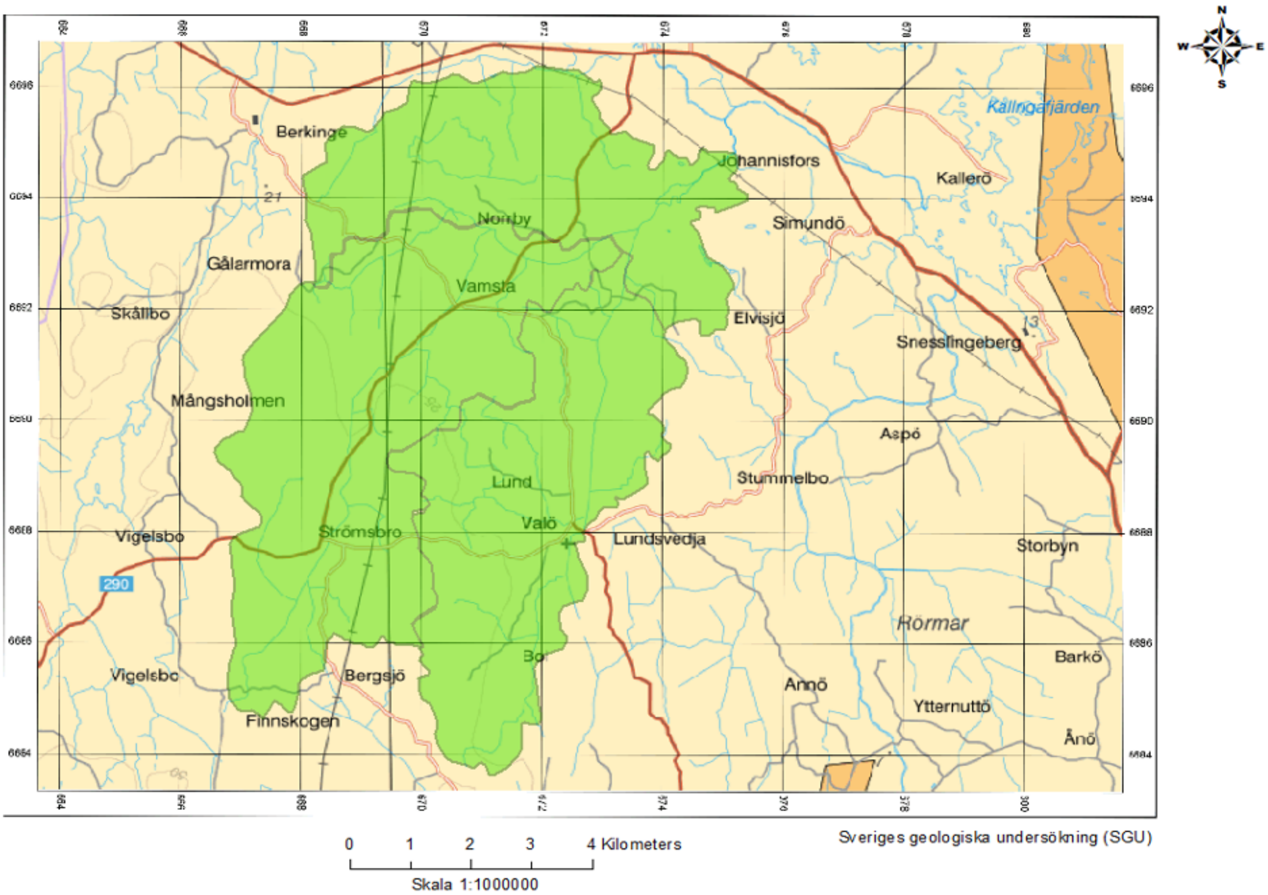

Figure 3.5: Topographical map representing a section of the Östhammar region, location of the Forsmarksån catchment with its boundaries [21]

The elevation in this regions ranges upto 54 m above sea level. Figure 3.6 shows the elevation range along with the river network in the catchment area. The average slope along the river network is 0.52%, with a mean annual discharge of 0.65 m^3/s. The region was recorded to have an annual rainfall of 667 mm/year with a runoff of 245 mm/year and evapotranspiration of 422 mm/year [16].

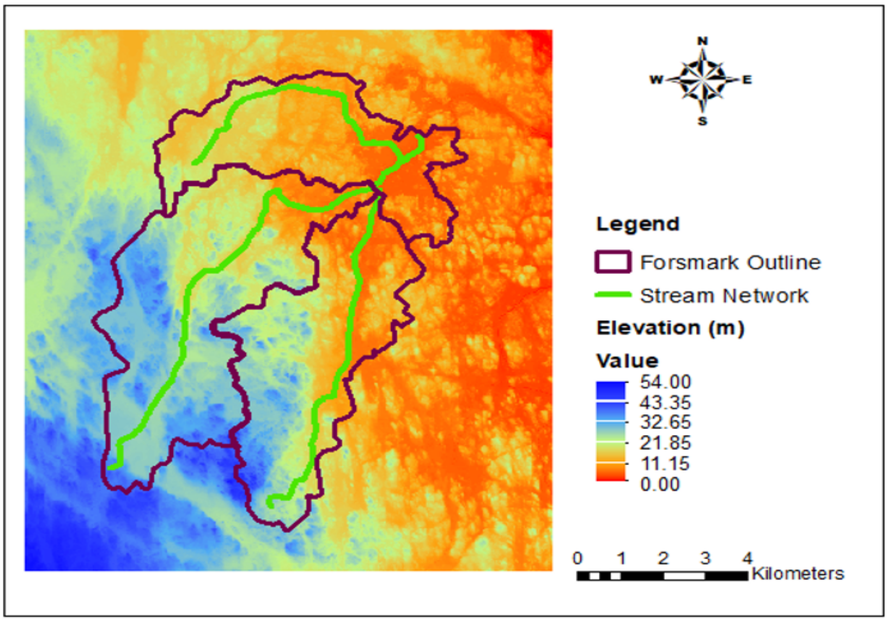

Figure 3.6: Elevation variation, catchment boundary, and stream network of the Forsmarksån catchment

The catchment area has an average soil depth less than 5m.The soil composition of this region is observed to have a high degree of Moraine covering 50% and peat nearly covering 15% of the catchment area. A varied distribution of clay covering nearly 11% and bedrock outcrops covering nearly 10% of the area can also be seen across the catchment. The detailed soil composition can be seen in figure 3.7.

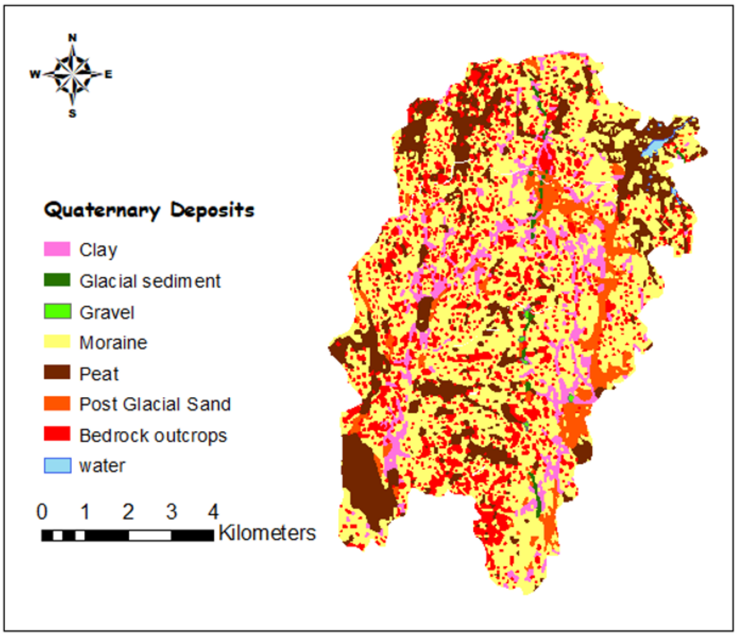

Figure 3.7: Map representing the soil composition of Forsmarksån Catchment

TULLSTORPSÅN: Tullstorpsån is located in the southern plains of Sweden, of the Skåne county in the Trelleborg municipality (55°28’ N,13°13’E) with an area of 81 km^2. This region is known for its agricultural production (covering nearly 85% of the area). Limited number of water bodies can be found in this region,in the form of lakes, but mostly populated with wetlands. Almost 39 wetland regions were identified and reconstructed with stream restoration.Figure 3.8 shows the catchment area, along with its sub-catchments.

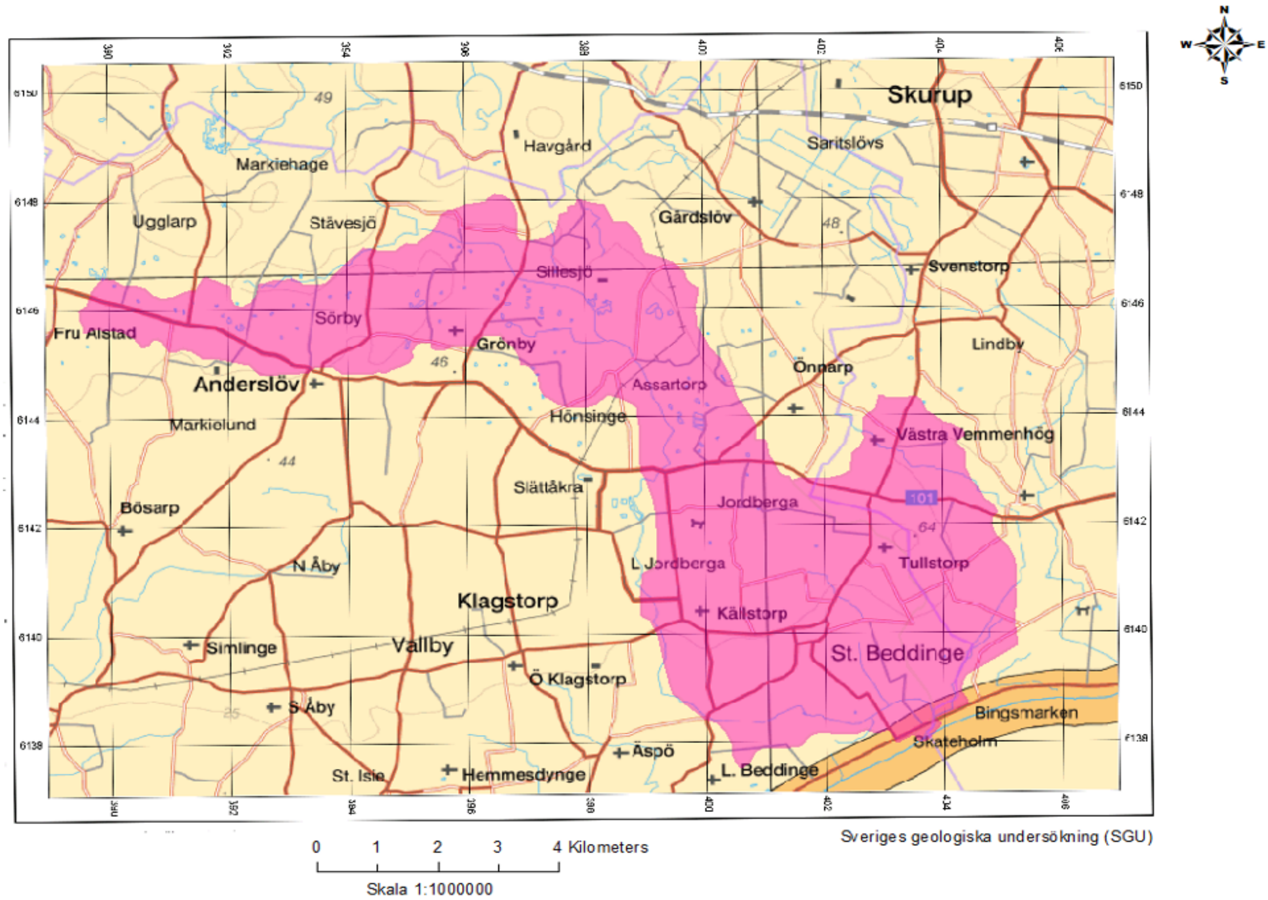

Figure 3.8: Topographical map representing a section of the Trelleborg region, location of the Tullstorpsån catchment with its boundaries [21]

The elevation in this region ranges up to 103 m above sea level. Figure 3.9 shows the elevation range in the catchment area. The average slope of the river network is 0.87%, with a mean annual discharge of 0.73 m^3/s. The region was recorded to have an annual rainfall of 686 mm/year with a runoff of 246 mm/year and evapotranspiration of 440 mm/year [16].

The catchment area has an average soil depth ranging between 10-50 m .The soil composition of this region is observed to have a high degree of moraine covering 50% and bedrock outcrops nearly covering 12% of the catchment area. A varied distribution of clay (10%) , peat (5%)and post glacial sediments (7%) can also be seen across the catchment. The detailed soil composition can be seen in Figure 3.10.

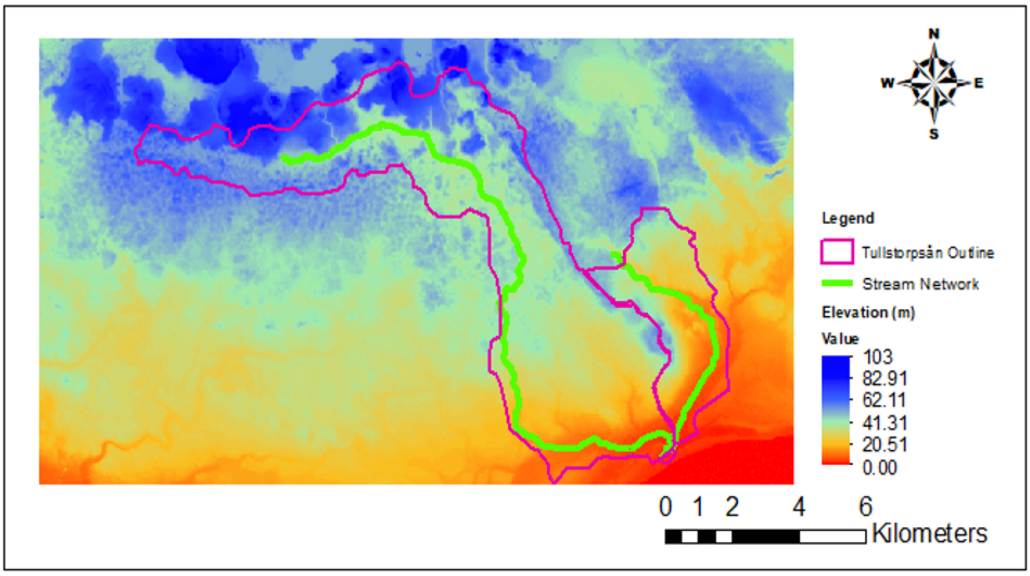

Figure 3.9: Elevation variation, catchment boundary, and stream network of the Tullstorpsån catchment

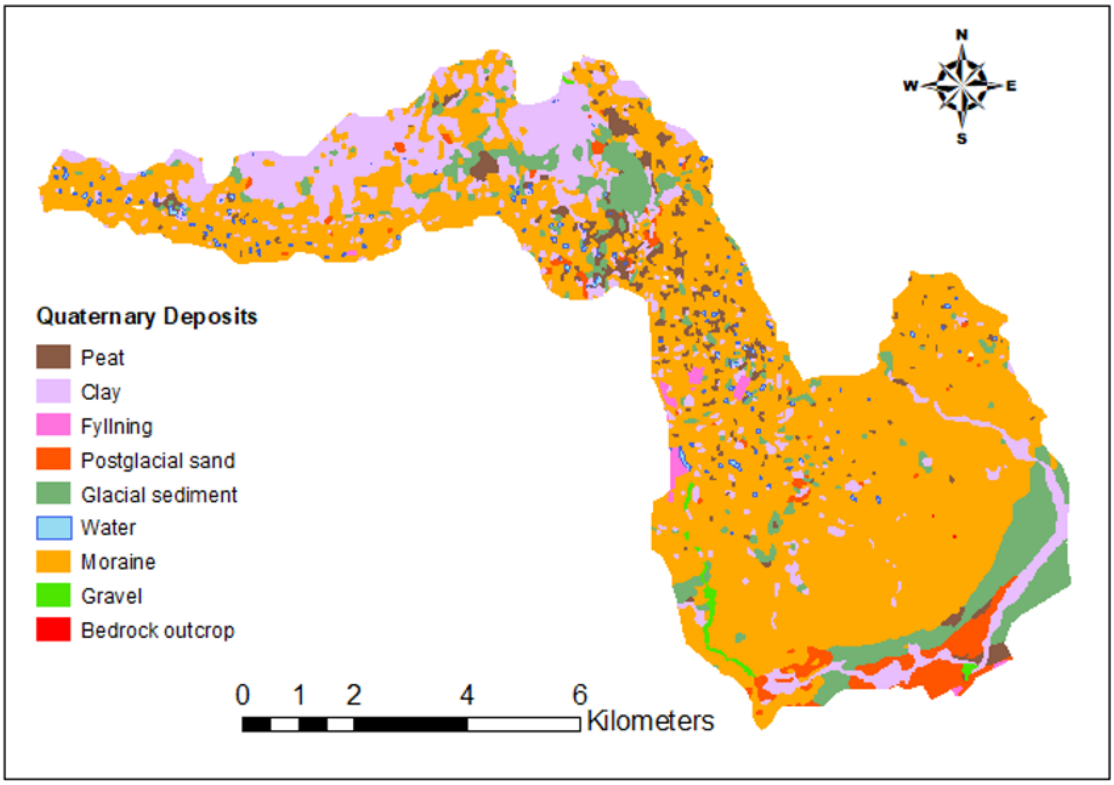

Figure 3.10: Map representing the soil composition of Tullstorpsån catchment

SÄVAÅN: Originating in the south-west region of Uppsala, Sävaån catchment is located in the Enköping municipality (55°28' N,13°13'E) with an area of 200 km^2. This catchment consists of 60% of forestry and 33% fields of meadows, with 6% wetlands and 1% lakes. The river empties into Lårstaviken in Ekoln. The major lakes found in this catchment are: Skärsjön, Bredsjön and Grissjön [39].Figure 3.11 shows the catchment area, along with the sub-catchments. The elevation in this

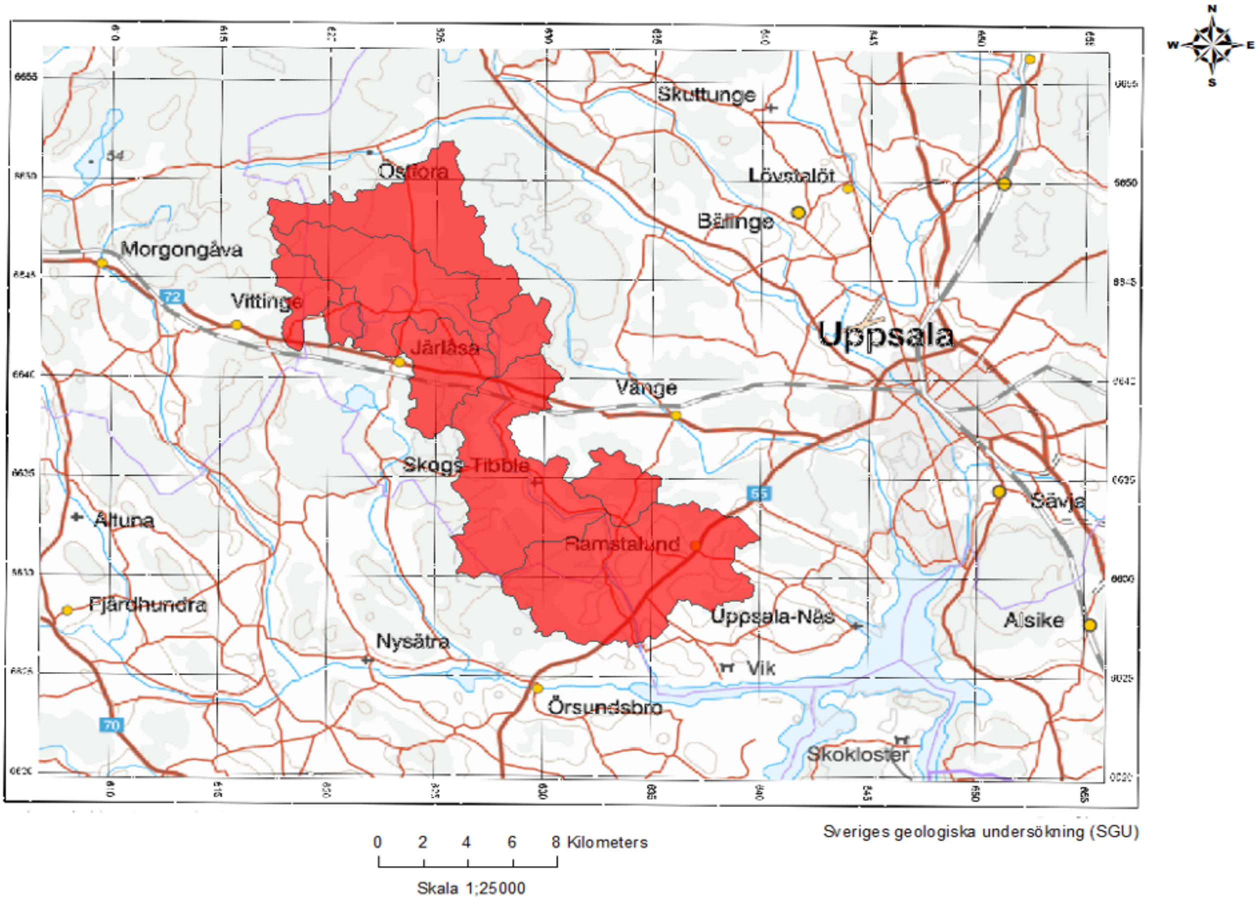

Figure 3.11: Topographical map representing a section of the Enköping region, location of the Sävaån catchment with its boundaries [21]

region ranges up to 117 m above sea level. Figure 3.12 shows the elevation range, and the river network in the catchment area. The average slope of the river network is 0.89%, with a mean annual discharge of 1.54 m^3/s. The region was recorded to have an annual rainfall of 612 mm/year with a runoff of 210 mm/year and evapotranspiration of 402 mm/year [16].

The catchment area has an average soil depth ranging between 5-10m.The soil composition of this region is observed to have a high degree of moraine covering 40% and clay nearly covering 25% of the catchment area. A varied distribution of peat covering nearly 8%, post glacial sediments covering 5% and bedrock outcrops covering nearly 10% of the area, can also be seen across the catchment. The detailed soil composition can be seen in figure 3.13.

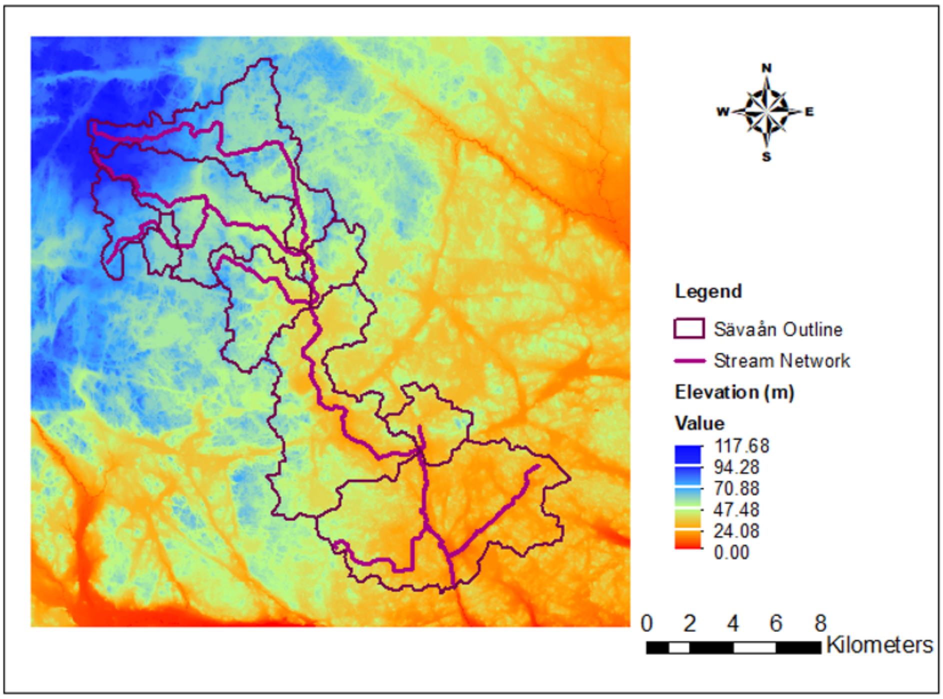

Figure 3.12: Elevation variation, catchment boundary, and stream network of the Sävaån catchment

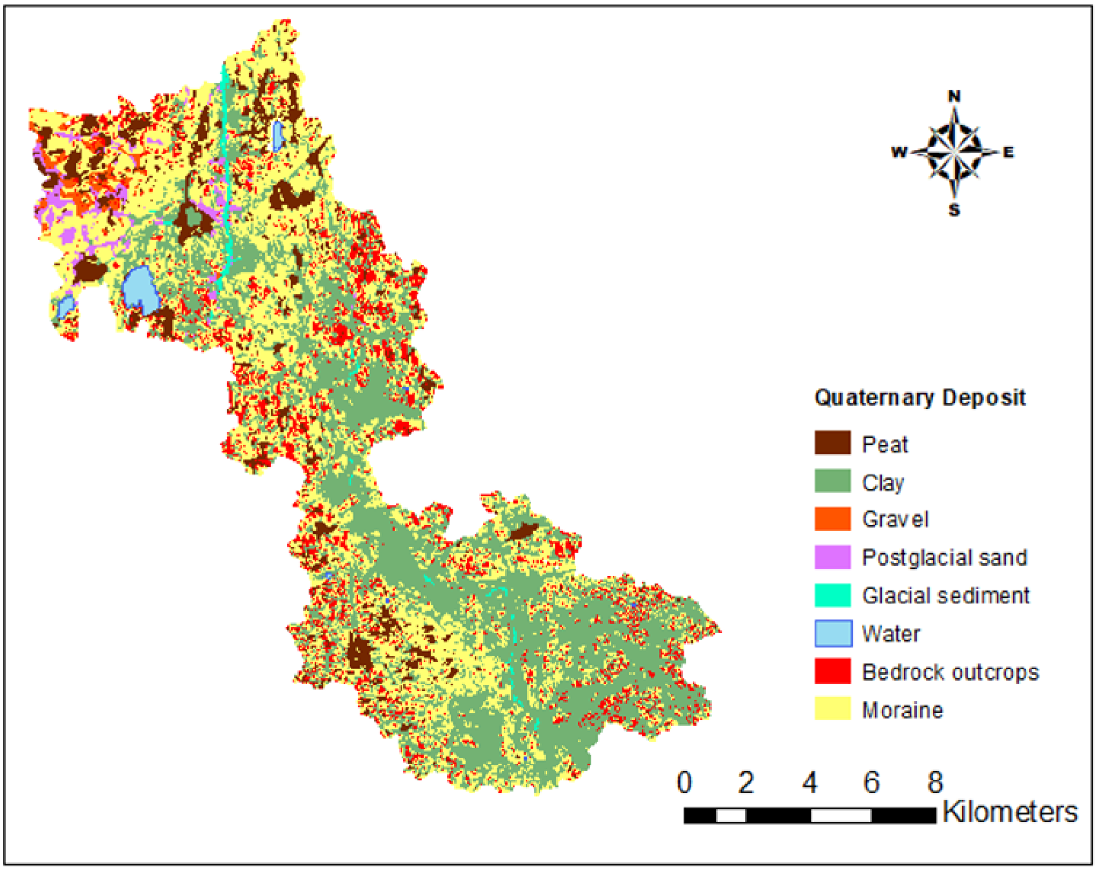

Figure 3.13: Map representing the soil composition of Sävaån catchment

KRYCKLAN: Krycklan, is an essential part of the Svartberget field research infrastructure, which belongs to the Swedish University of Agricultural Sciences (SLU). The field activities include over 50 research projects, involving several scientists from major universities in Sweden [20].The catchment is located approximately noth-west of Umeå (64°14’ N,19°46’E) in the municipality of Vindeln. The land is dominated by forestry, with 87%, 7% of thin soils and 1% rock outcrops respectively [22]. There are several small lakes, of which lake Stortjärn is one of the most expansive research sites [20]. There are a number of streams, mainly Åhedbäcken, Långbäcken, Nymyrbäcken and Krycklan [18].Figure 3.14 shows the catchment area along with the sub-catchments. Known as a highland area,this region

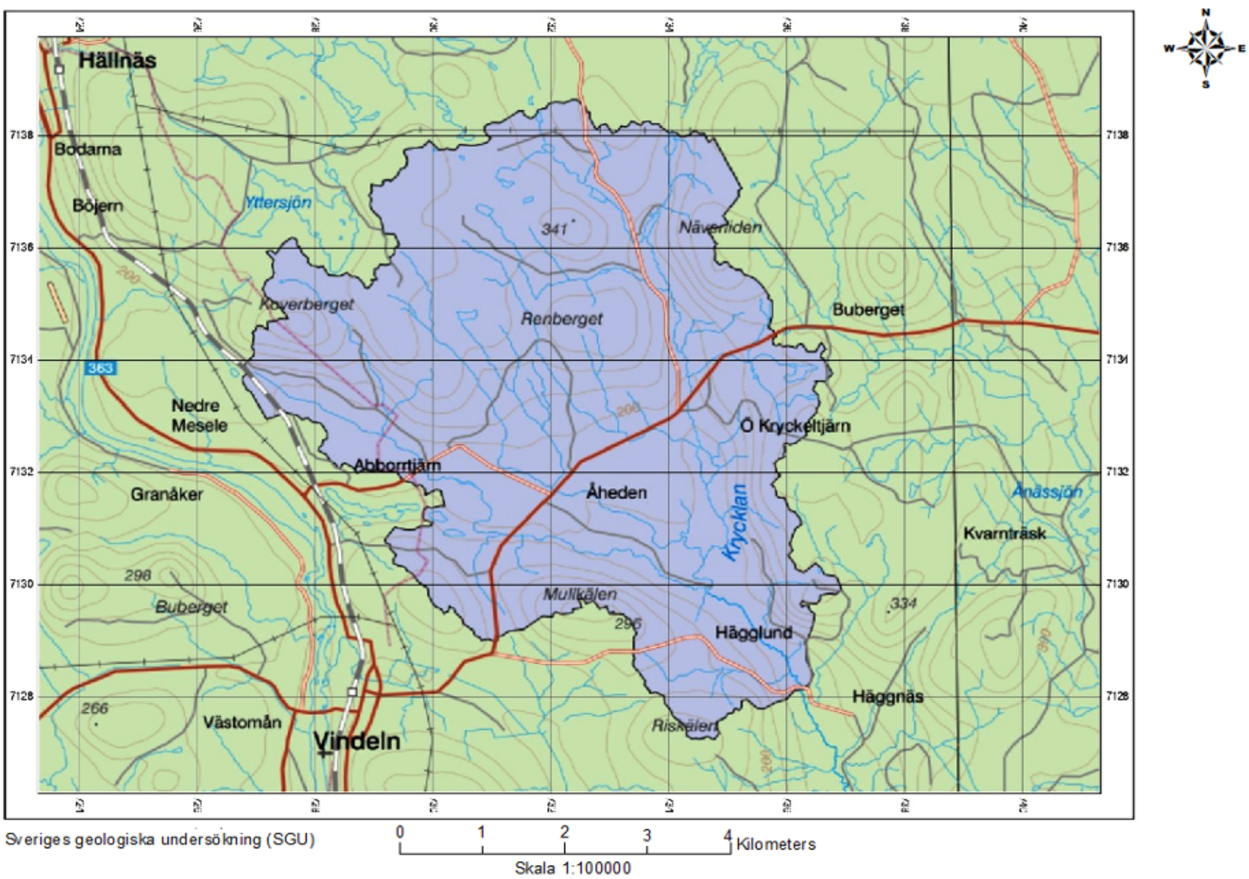

Figure 3.14: Topographical map representing a section of the Vindeln region, location of the Krycklan catchment with its boundaries [21]

is known to have a steep topography, with the elevation ranging between 114 m to 375m respectively. Figure 3.15 shows the elevation range and the river network in the catchment area. The average slope of the river network is 3.05%, with a mean annual discharge of 1 m^3/s. The region was recorded to have an annual rainfall of 695 mm/yr with a runoff of 366 mm/yr and evapotranspiration of 329 mm/yr [16].

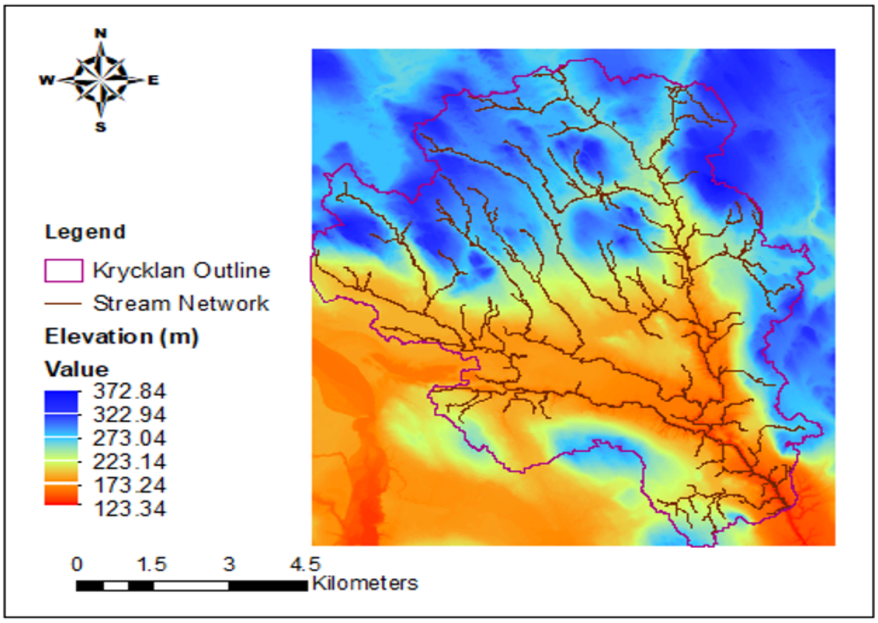

Figure 3.15: Elevation variation, catchment boundary, and stream network of the Krycklan catchment

The catchment area has an average soil depth ranges between 5-10m.The soil composition of this region is observed to have a high degree of moraine covering 51% and post glacial sediments (along the downstream) nearly covering 20% of the catchment area. A varied distribution of peat covering nearly 10%, clay nearly 8% and bedrock outcrops covering nearly 10% of the area, can also be seen across the catchment. The detailed soil composition can be seen in figure 3.16.

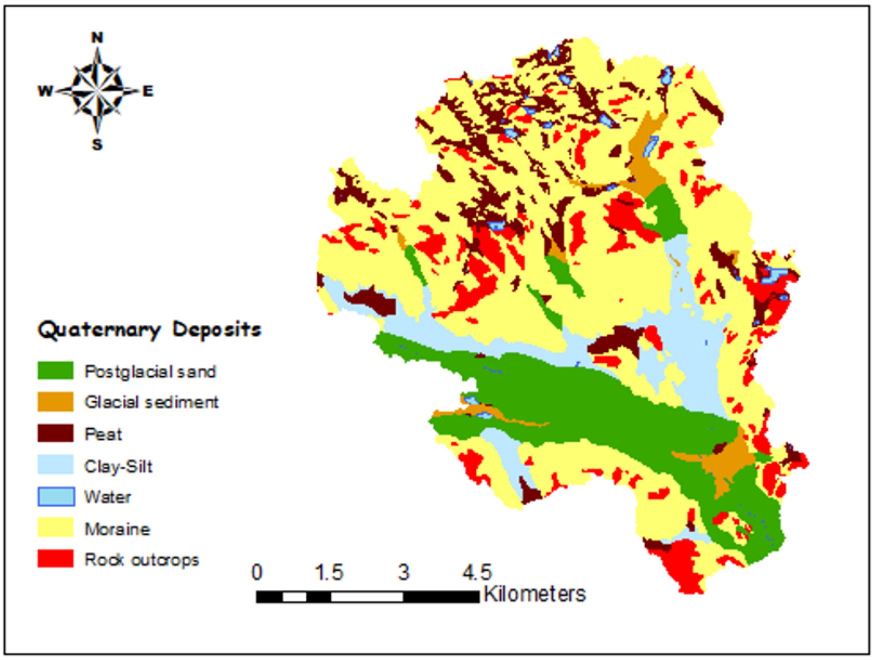

Figure 3.16: Map representing the soil composition of Krycklan Catchment

4 Methodology

This section describes the approach adopted for setting up the numerical model.It gives an insight into the application of the topography and recharge-controlled boundary conditions.

4.1 Formation of Geometry

The model domain for each catchment is established initially by building a geometry. It consists of two layers: topography and the bedrock.The geospatial data stored in the form of a DEM file, is imported and resampled into the model as shown in Figure 4.1.

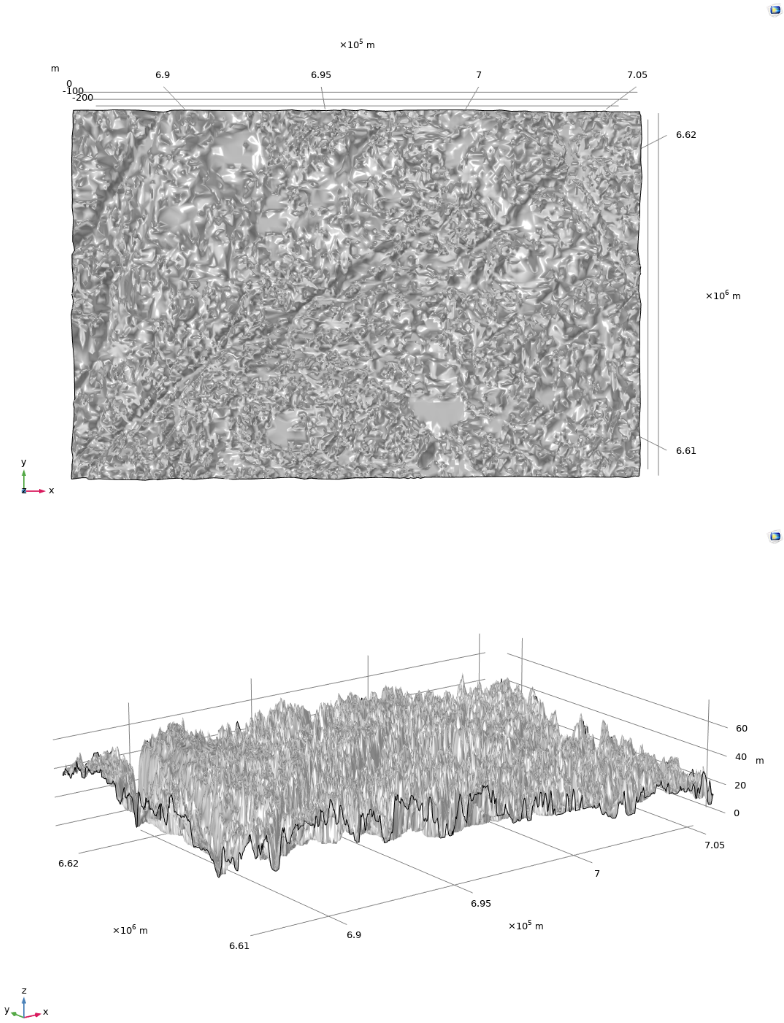

Figure 4.1: The resulting topographic surface built in COMSOL for Bodalsån

Both topography and bedrock elevation of grid resolution 10×10 m,are imported into the model, additionally allowing the necessary consideration of the bedrock outcrops. Thus the model domain ensemble is built such that we can differentiate the Quaternary Deposits and the bedrock. This is done in order to associate properties while assigning the boundary conditions.

4.2 Application of Boundary Conditions

Introducing hydraulic conductivity as a material property:

Once the geometrical sections are established, we now introduce the hydraulic conductivity to the model domain based on the initial soil type maps procured. The numerical model is setup with the assumption that the soil composition is isotropic and heterogeneous in nature.The Quaternary Deposits follows the permeability assumed from table 4.1, while the bedrock follows a decay function, given by Mojarrad et al. [24]. Initially, Saar and Manga [29], investigated four different models to establish a function that relates permeability 'k' with depth 'z'. They proposed an exponential permeability curve that indicates the behaviour from near-surface along the depths of the geological features. From which Mojarrad et al., institutes equation (9),

$$\boldsymbol{K}_i(z) = \boldsymbol{K}_{(SorD),top}\mathbf{e}^{\frac{(z-z_{top,i})}{\delta_i^{-z}}} \tag{9}$$

where the subscript *i* denotes the layes, $z_{top}(m)$ the elevation co-ordinate of the top layer *i* , $K_{(SorD),top}$ are the hydraulic conductivity at the top surface of Quaternary deposit and bedrock layer, δ is the skin depth, which Sara and Manga showed to vary between 200 to 300 m. This study adopts δ = 250 m, respectively.

Table 4.1: Assigned Hydraulic Conductivity in the numerical model for each catchment

Characteristic Soil Type	Hydraulic Conductivity (m/s)
Moraine	1E-07 to 1E-08 [11]
Bedrock outcrops	1E-08 to 1E-09 [18]
Fyllning	1E-05 to 1E-06
water	1E-07
Gravel	1E-05 [11]
Glacial sediment	1E-06 to 1E-07 [23]
Clay	1E-07 to 1E-08 [35]
Klapper	1E-07 [35]
Mud	1E-05 [35]
Peat	1E-07 to 1E-08 [25]
Post glacial sediment	1E-06 to 1E-07 [7]

Assigning the Physics and Conditional Boundary Settings:

Section 2.2 explains in detail, the conditional application of Darcy's law for this study. As such this is defined as a module in COMSOL, which can be used for modelling low velocity flows or media with very small permeability, and pressure gradient is the major driving force.

This feature allows us to associate the material properties and define the boundary conditions to the model domains.The fluid density is defined to be 1000 kg/m^3 (the standard density of water in SI units). We then define the porosity for each domain: 0.2 for the Quaternary Deposits and 0.001 for the bedrock domains. The differentiating factor in the boundary conditions is the constraints associated with defining the hydraulic head in the model domain, which is summarized below:

- Topography as the top boundary condition: We define two hydraulic head conditions: one for the top surface of the domain, to ensures the fact that the groundwater table follows the topographical surface elevation, and the other for the lateral surfaces (blue surfaces in figure 4.2), providing a constant head, to allow the water to flow outside the domain if it is needed.

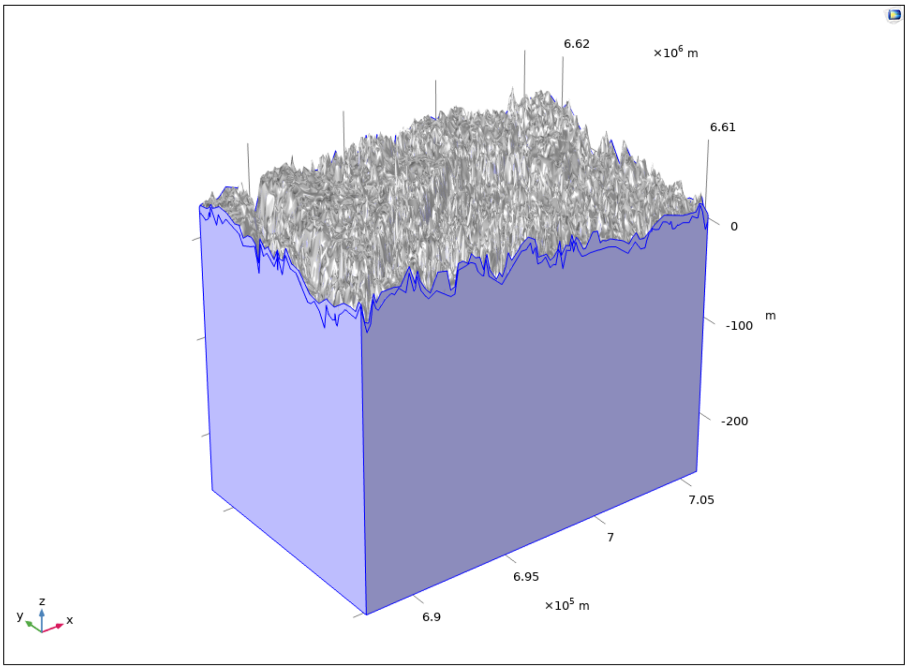

Figure 4.2: Constant head boundary condition assigned to the lateral surfaces of the catchment domain

- Recharge as the top boundary condition: For this boundary condition we need to ensure that there exists a constant rate of recharge on the top surface of the model domain by defining an inflow velocity (arrows in figure 4.3). We specify the infiltration rate based on table 4.2 for each of the catchments, obtained using equation 4. Additionally in this case we also define the constraints for the lateral surfaces similar to topography as a boundary condition.

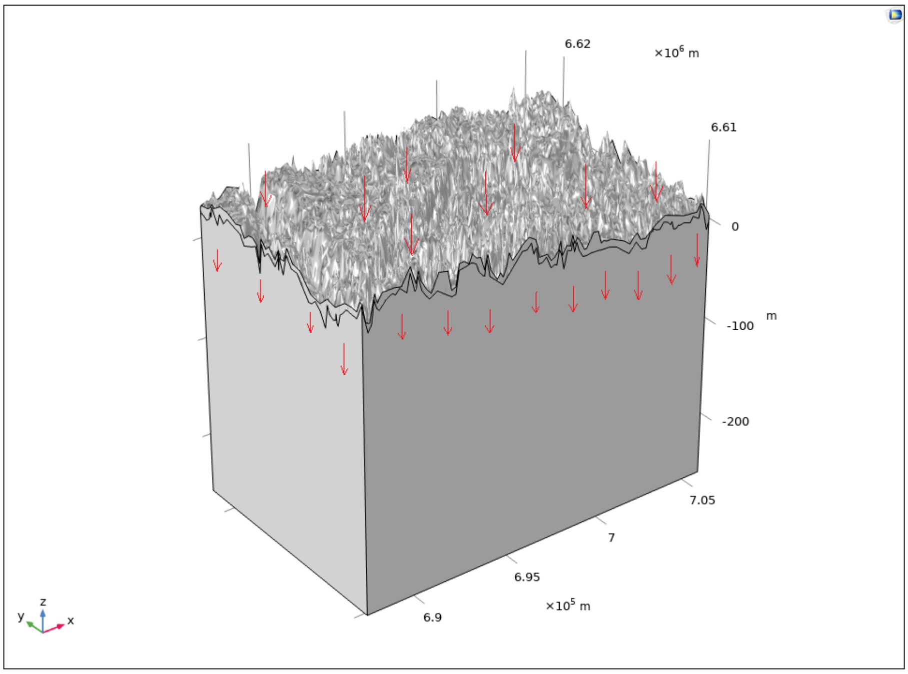

Figure 4.3: The constant rate of recharge assigned to the surface of the domain

Table 4.2: Rate of Infiltration assumed for each catchment

Catchment Name	Average Infiltration in Catchment (mm/yr.)	Infiltration in m/s
Bodalsån	237	7.515e-9
Forsmark	248	7.864e-9
Saåvan	230	7.293e-9
Krycklan	365	1.157e-8
Tullstorpsån	270	8.561e-9

Meshing the Model domain:

Once the Geometry is built, the Physics (material property) and the boundary conditions have been assigned to the model domain, we need to determine method adopted for the computation of the model. This is done by defining a mesh for the numerical model.We define a user-controlled mesh sequence,in this study, to ensure optimal analysis. There exists a number of predefined mesh sizes, varying from extremely fine to extremely coarse. We use a fine mesh for all the domains in the model, which has a high number of elements hence converging to a more accurate solution. The maximum element size predefined is 1460 m and the minimum to be 183m. The mesh size parameters, its resolution and element quality are important. Low mesh resolution and element quality cause variations in the solutions thus resulting to inaccuracy.

The following figures 4.4 and 4.5 presents an example of the meshed models.The numerical model thus setup, with the associated material properties and boundary conditions, is compiled and run using a stationary solver for steady state analysis.

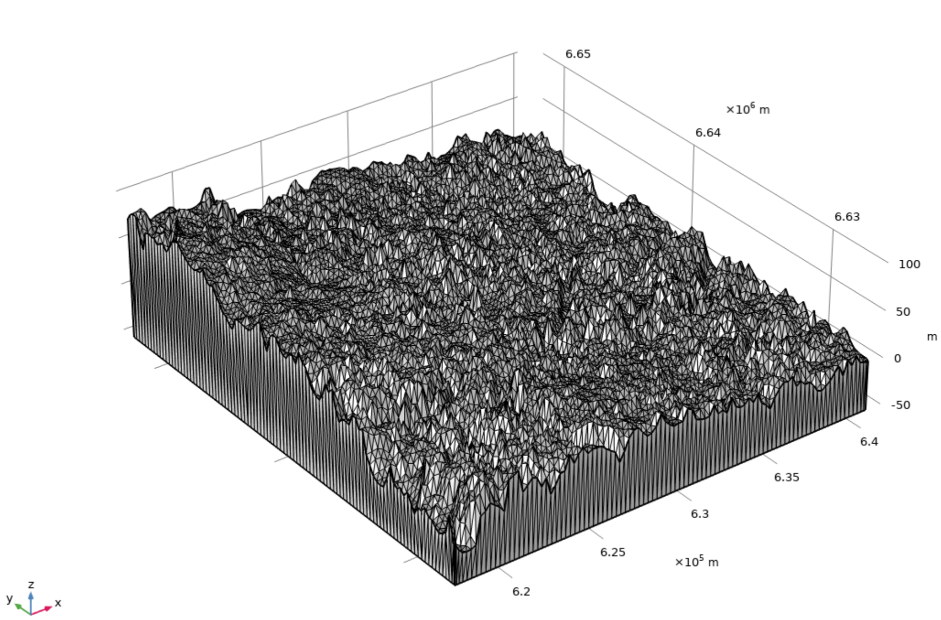

Figure 4.4: Meshed model of catchment Sävaån

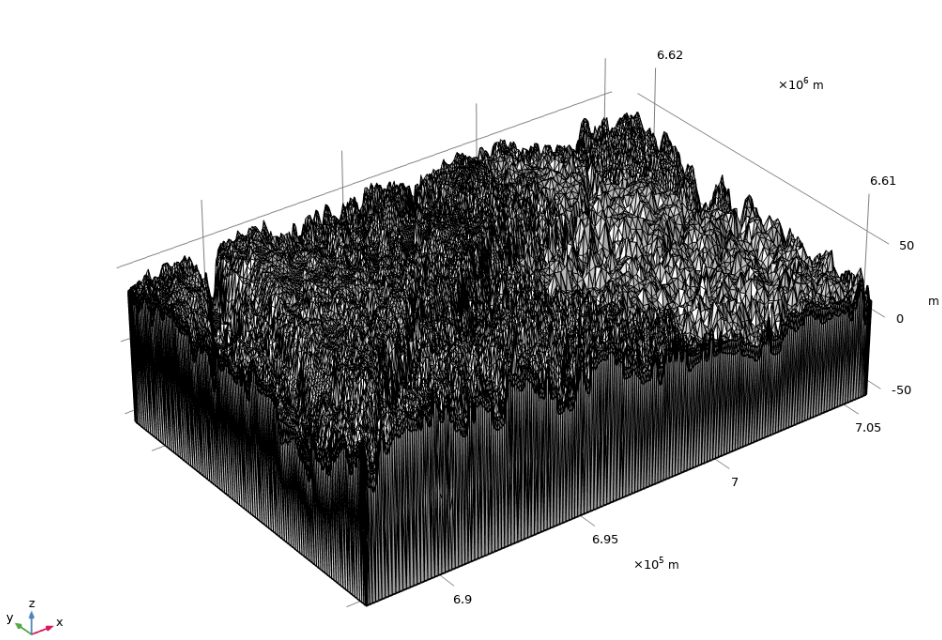

Figure 4.5: Meshed model of catchment Bodalsån

5 Results & Discussion

This section predominantly aims to present and discuss the results obtained from the numerical modelling conducted in COMSOL. The modelling results were obtained in the form of velocity fields and pressure surfaces.Figure 5.1 presents an example of Bodalsån catchment, with the flow trajectories when the constant rate of recharge boundary condition was applied.The order of magnitude of the velocity can be associated with using the colour palette available alongside in the figure.

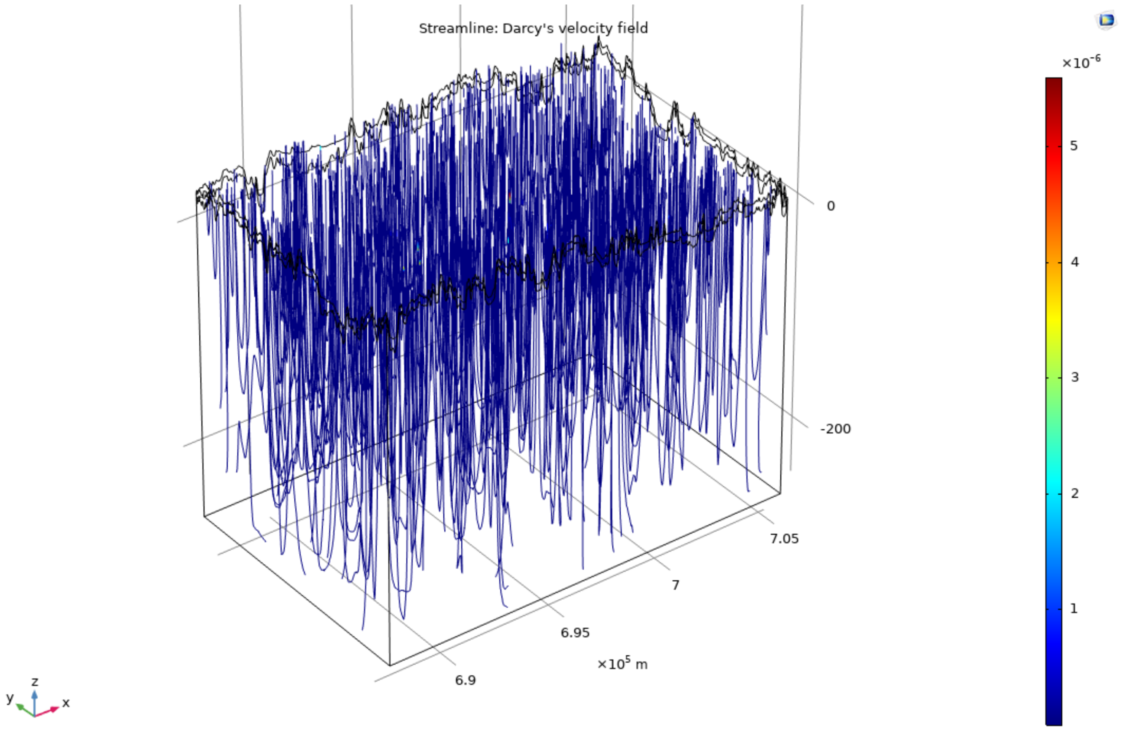

Figure 5.1: The flow lines obtained as a result of applying a constant rate of recharge as a boundary condition for Bodalsån catchment

One of the main objectives of this study, is to observe the groundwater flow profile which was quantified using absolute vertical velocity in depth. This metric was evaluated for each catchment based on the aforementioned applied top boundary conditions.

The groundwater flux profile was evaluated for the groundwater absolute vertical velocity in parallel surfaces to the topography elevation at the groundwater surface. Figure 5.2 shows an example of the parallel surface plotted at a depth of 100m in Bodalsån catchment. In each of the models, the flow depth was assumed to extend up to a depth of 250 m from the topography surface, and the absolute velocity was obtained at depth's of 10m intervals.

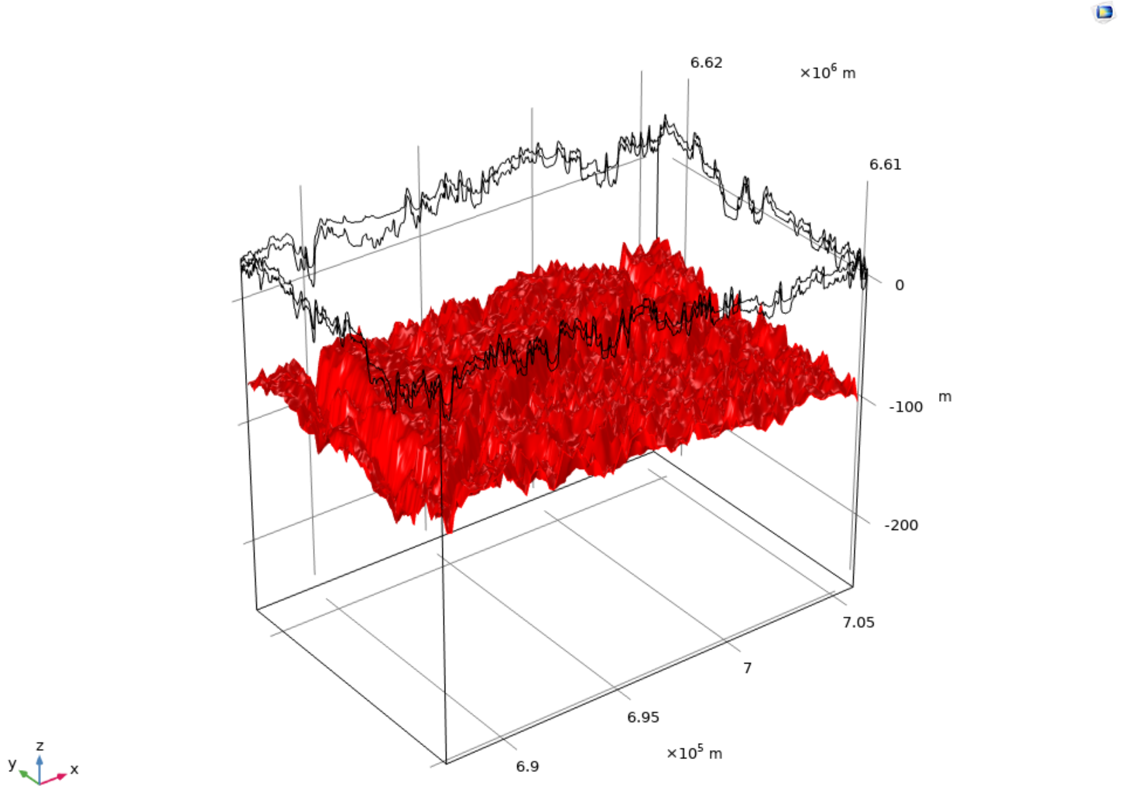

Figure 5.2: Parametric surface at a depth of 100 m from the topographic elevation in Bodalsån catchment

The following figures represent the groundwater flux profile for all the catchment. In the logarithmic graph below of Bodalsån catchment,the magnitude of the vertical flux at the topography surface can be seen to vary between 450 to 550 mm/year depending on the applied boundary condition. The impact of the hydraulic conductivity with depth can be observed in the groundwater flux profile. Significant difference can be seen in the velocity in the Quaternary deposit with topography controlled boundary condition resulting in a comparatively higher magnitude.

The decay function is seen to cause no significant difference in the magnitude of the velocities in the bedrock region as they tend to show a similar behaviour for both the top boundary conditions. Comparing figure 5.3 and the data of depth of Quaternary deposit for the Bodalsån catchment, it confirms the numerical modelling results in which a substantial decrease in the magnitude of the groundwater vertical velocity occurs at the bedrock top layer (i.e at approximately 5m).

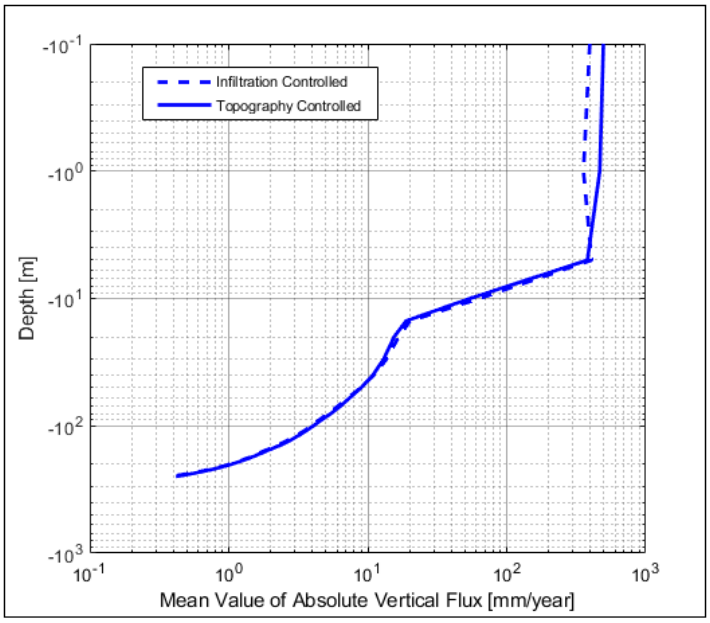

Figure 5.3: The graph representing the mean value of the absolute vertical velocity in depth for Bodalsån, for topography (solid line) and Recharge (dashed line) as boundary conditions

Similar observations can be seen in each of the other catchments. In Tullstorpsån catchment, it can be seen that the vertical flux at the topography surface is seen to vary between 250 to 450 mm/yr depending on the applied boundary condition. We can distinctively notice the soil depth extends to a depth of 50m. This is shown by the double arrow head in the graph.

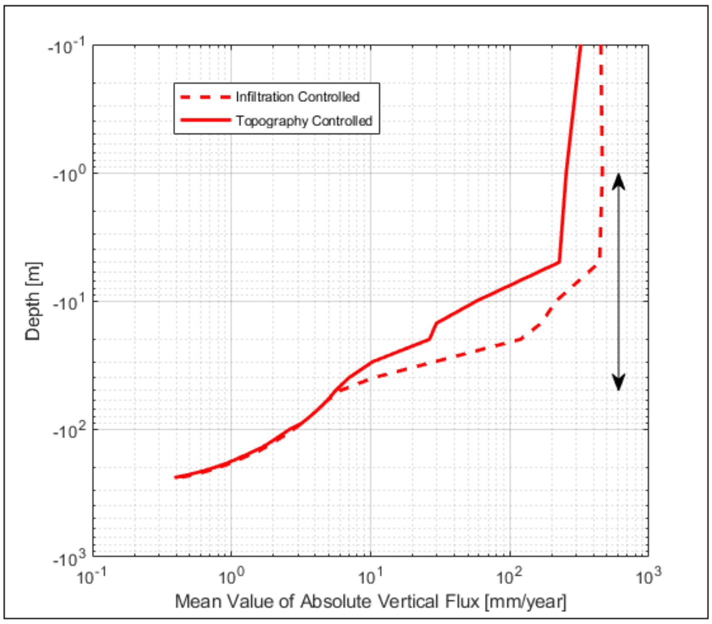

Figure 5.4: The graph representing the mean value of the absolute vertical velocity vs depth for Tullstorpsån

In case of both Bodalsån and Tullstorpsån catchments, the slope of the terrain ranges between 0.8% to 1.2%. This may have resulted in surface velocity flux magnitude to vary in the similar ranges for both the top boundary conditions.

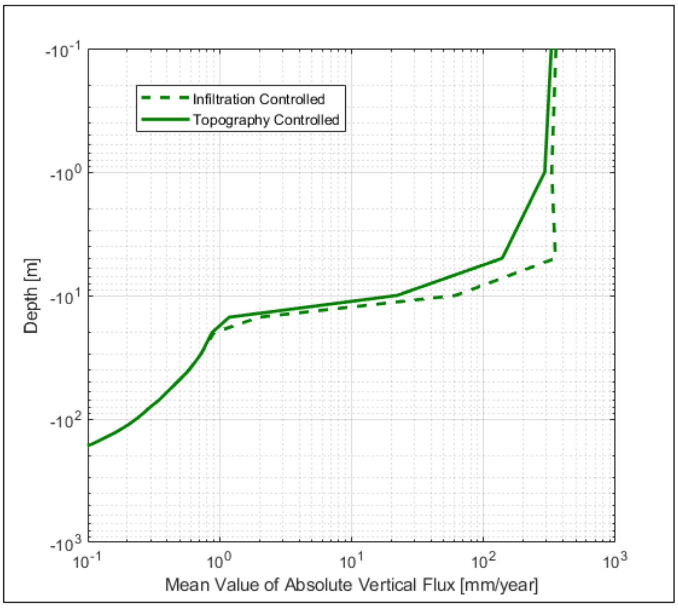

Figure 5.5: The graph representing the mean value of the absolute vertical velocity vs depth for Forsmarksån

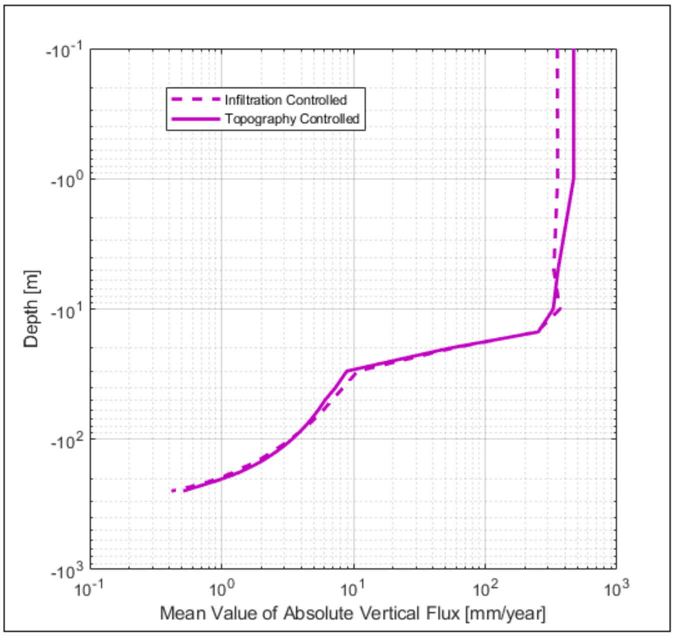

Figure 5.6: The graph representing the mean value of the absolute vertical velocity vs depth for Sävaån

We notice similar behaviour in Forsmarksån and Sävaån catchments. The magnitude of the vertical velocity varies between 350 to 450 mm/year. The nature of the topography in these regions is flat, with slope variance in the range : 0.5% to 0.8%. The heterogeneity can also be distinctively observed with the depth of Quaternary deposit extending to 15m for Forsmarksån and 10m for Sävaån respectively. Similarly, the decay function considered for the hydraulic conductivity seems to have no significant effect, on the top boundary condition, as we see the magnitude of the velocities are roughly similar below the bedrock layer.

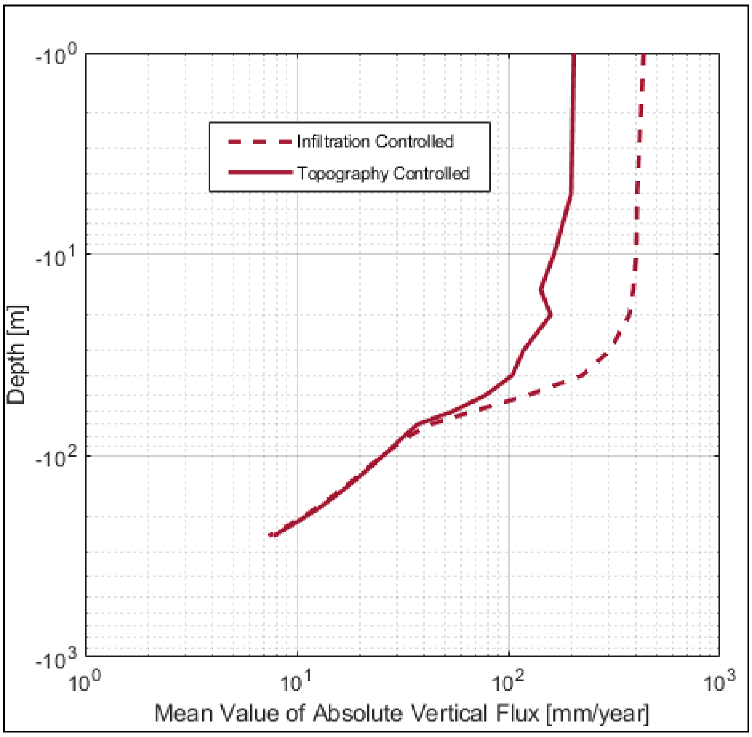

Figure 5.7: The graph representing the mean value of the absolute vertical velocity vs depth for Krycklan

However, Krycklan catchment shows a substantial difference between the two applied boundary conditions. The vertical velocity varies in the range of 200 to 500 mm/yr. The soil depth data shows that the quaternary deposit depth extends upto 50m which is consistent with the modeled groundwater flux profile results. Krycklan has a steep slope at 3% which when compared to the other regions under consideration is a highland area, which in all probability corroborates for the distinctive behaviour.
This study also made an observation on the impact of the boundary conditions on the distribution of the absolute vertical velocity at the stream bed along the river network of each catchment.These box plots present the distribution of the absolute velocity with respect to the applied boundary conditions. Some main aspects of the box and whisker plot include: The median, maximum and minimum values of the distribution, the first and third quartiles and the outliers. The median along with the maximum and minimum values in each of the catchments vary, as they are drawn from the distribution.

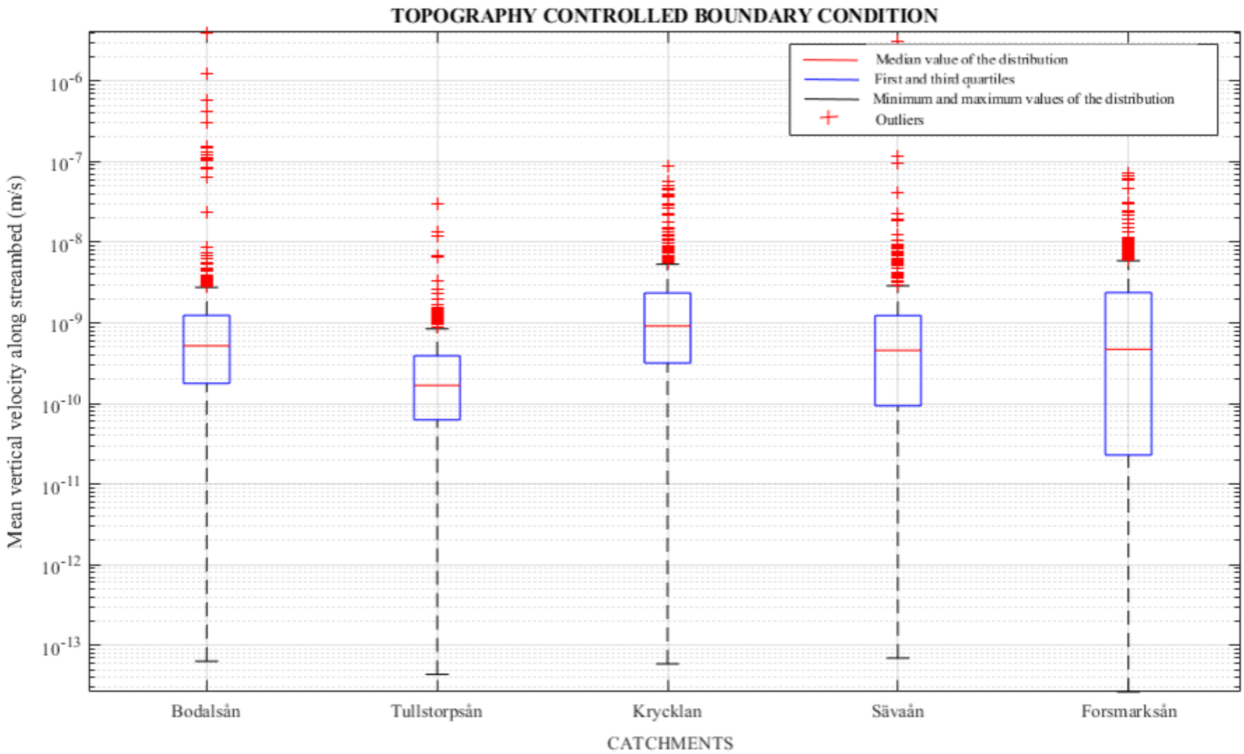

Figure 5.8: Box and whisker plot of the absolute values of mean vertical velocity along the stream bed for all the catchments when applied with topography as the top boundary condition

The plot presented above constitutes the absolute values of mean vertical velocity along the stream bed for all the catchments when applied with topography as the top boundary condition. We notice a variable distribution in each of these cases. The ranges of the data sets in each catchments can be seen to vary between the order 10^{-9} (highest) and 10^{-14} (lowest).The magnitude of median differs in each catchment, but are all of the order 10^{-10}. The interquartile range is similar in case of catchments Bodalsån,Tullstorpsån and Krycklan, but are smaller when compared to Sävaån and Forsmarksån. This indicates that there is a lower statistical dispersion in the values in case of Bodalsån, Tullstorpsån and Krycklan catchments in comparison to Sävaån and Forsmarksån.

In all the catchment distribution data,we observe numerous outliers. Outliers are data points that significantly differ from other observations in the data set. Mathematically, they are said to be more than 1.5 times of the interqaurtile range (IQR). In the current scenario, we see that the outliers lie along the upper side of the box, representing higher values. The outliers in case of Bodalsån and Sävaån catchments are more while comparing to Tullstorpsån, Krycklan and Forsmarksån which is due to the small interquartile ranges.

Figure 5.9 presents a similar plot, however, with recharge as the top boundary condition. Each of the catchments in this, shows entirely different distributions of the mean vertical velocity values along the stream bed. The range of the magnitude of the vertical velocity can be seen to vary tremendously in each catchment.

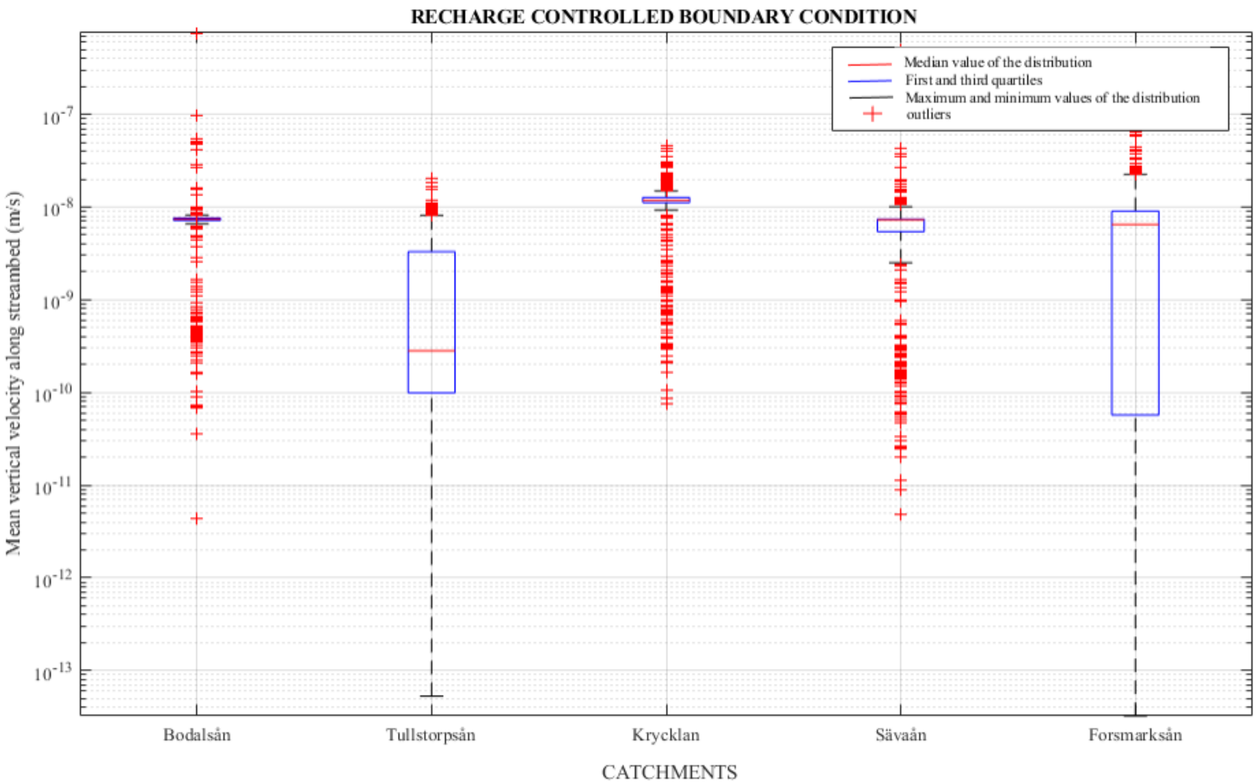

Figure 5.9: Box and whisker plot of the absolute values of mean vertical velocity along the stream bed for all the catchments when applied with recharge as a top boundary condition

In case of Bodalsån, Krycklan and Sävaån catchments the highest and the lowest values of the range are in the order 10^{-8}. In case of Tullstorpsån and Forsmarksån the ranges are in the order 10^{-8} (highest) to 10^{-13} (lowest) respectively. The magnitude of the median differs in each catchment, but all are in the order 10^{-9}. The interquartile ranges for each of the catchments are non-identical. For Bodalsån,Krycklan and Sävaån catchments the interquartile ranges are extremely small showing a higher degree of statistical dispersion in the magnitude of the velocities. This is also the very reason that we can see numerous outliers along both the sides representing the high and low values in the box plot. In case of catchments Tullstorpsån and Forsmarksån when compared to the other catchments we can see that the interquartile range is larger, therefore lower degree of dispersion and lesser number of outliers. In summary,using topography as a boundary condition has resulted in medians of magnitude of lower order 10^{-10} compared to using recharge as a boundary condition 10^{-9}. We also notice a high degree variation in the distribution of velocities when using recharge as a boundary condition.

6 Conclusion

The primary objective of this study was to highlight the impact of top boundary condition: topography and recharge-controlled on groundwater flow circulation and its velocity magnitude.The numerical modelling approach aided in establishing individual models for both the boundary conditions for all the five catchments considered for this study.

Significant differences were observed in the results when the top boundary conditions were employed. The plots of absolute vertical velocity in depth for Tullstorpsån catchment distinctively depicts the differences in the top boundary condition applied when compared to the other catchments.This can be co-related to its higher soil depth (nearly 50m) in comparison to Bodalsån, Sävaån and Forsmarksån (ranging between 5-10m). Topography controlled boundary condition resulted in higher vertical fluxes in Bodalsån and Sävaån catchments. On the other hand,recharge-controlled boundary condition developed higher vertical fluxes in Tullstorpsån, Forsmarksån and Krycklan catchments. This observation was evident only along the quaternary deposit of the catchments. Below the bedrock layer, the effect of using a top boundary condition could not be observed as there were no considerable differences in the magnitude vertical fluxes. This can be related to the hydraulic conductivity of the layers.The decay function used for the bedrock layer results in lower hydraulic conductivity, than in the quaternary deposit, hence the differences can be considered to be negligible. We notice that all five of the catchments are characterized with a high degree of low permeability soil type.The distribution of moraine and clay, dominant in each catchment can corroborate to it. This resulted in lower magnitudes of stream bed velocities.However,topography-controlled boundary condition resulted in higher median values in comparison to recharge controlled condition, in the data distribution of the stream bed velocities.

In a broad perspective, the results show that the top boundary condition predominantly effects the groundwater fluxes and its magnitudes in a given region.Thus, a prior understanding of the top boundary condition controlling the behaviour of groundwater in a region is necessary for groundwater flow analysis and modelling. To conclude, this process will augment the current research studies, being conducted in this domain contributing as research data. From data procuration to numerical model setup,this study has been very insightful, helping in gaining a better understanding of the background theories governing natural systems.It has aided in enhancing the knowledge and skillset of the author in numerical modelling and its limitations.

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