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Runoff modelling and assessment of treatment wetland performance using a triangular form based multiple flow algorithm

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A suggestion for an improved eutrophication risk model in the Björkesåkrasjön sub-catchment

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Clara Hübinger

Bachelor thesis, 15 credits *in* Physical Geography and Ecosystem Science

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Abstract

Eutrophication is one of the biggest threats to aquatic ecosystems. As nutrient load increases in marine environments in the Öresund and Baltic Sea and dead zones grow, Swedish municipalities further their efforts in limiting the amount of nutrients delivered into those environments. Since the majority of nutrients enter aquatic systems through surface flow as a result of nutrient leakage, a reliable model predicting flow accumulation and pattern is needed.

Such a model is suggested in this thesis. It utilizes a dynamic triangular form based multiple flow algorithm in combination with several physical parameters such as the surface roughness and infiltration rate. The model is shown to deliver more detailed results than a static single flow based algorithm, utilized by many municipalities today. It additionally indicates the location and amount of water accumulated during a precipitation event in the wetland in the study area. Thus, it can be utilized to analyse the capacity of treatments wetlands which are often used to filter nutrients through sedimentation before they enter water bodies. A brief analysis of the wetland's effectiveness was made for a rainfall event with a 10 year return period, showing that bigger particles (sand) were mainly deposited in the wetland, while particles of smaller sizes (silt and clay) were transported through the wetland without deposition and thus entered the downstream aquatic systems.

1. Introduction

Human activity has greatly altered the ecosystems of this earth. The consequences of those interactions are noticeable on local, as well as global levels and often, developments over a long period of time show to be much more detrimental than first assumed. Recovery from such events, if even possible, is a long and taxing process for ecosystems, hence finding appropriate measures to combat those is of great importance. One of these local phenomena is the process of eutrophication, in which water bodies become enriched with certain nutrients, leading to a number of problems, such as increase of algal bloom and a depletion of oxygen levels. If this process cannot be reversed, the water body might even become a so called "dead zone", in which life can no longer be sustained (Dybas 2005). The sources of the nutrients causing this process are manifold and a number of factors contribute to the process of eutrophication of a water body.

Eutrophication processes in Sweden, in particular the eutrophication of the Baltic Sea and the Öresund by the Swedish Coast have been long noted in the scientific community and public. The discovery of the acidification of the freshwater lake Gårdsjön – a result of excessive nutrient adage to the water body through acid rain and surface runoff - in southern Sweden and the following grand scale experiments on acidification and liming projects on this lake have garnered great attention from scientists and media alike (Gundersen et al. 1998). While interest in acidification has decreased within the last years, not least due to successful efforts in reversing this process, the problem of eutrophication is still prevailing. The increase in ocean dead zones within coastal regions and the impending dangers for marine life and ecosystem health, as well as water quality make it one of the most pressing issues today.

Dealing with the problem of eutrophication can be problematic for many communities. While the sources of the nutrients that cause the process are quite well documented, limiting the direct entry of those into the water cycle can be hard. As a result, a lot of work has been done on limiting the amount of nutrients once they have already entered the aquatic system. This is done through e.g. sedimentation in dams and wetlands and through other nutrient filtering processes. In order to know where to construct those filtering facilities, finding the location of areas of particularly high risk for nutrient leaching is crucial. Identifying those areas can be difficult, as a number of factors have to be taken into account. Nutrient leakage is dependent on land use, soil type and conditions as well as topography. Additionally, the water surface flow and vertical water movements affect the transport of nutrients within the water.

Thus, correctly analyzing surface flow patterns and identifying areas of flow accumulation where sedimentation can happen is crucial for correct classification of treatment wetlands and dams. A number of models have been developed in order to make risk assessment easier for researchers and communities. Complex models, such as the WaTEM model, use a combination of different risk factors, such as slope steepness, soil and land cover type and precipitation data in order to assess the risk of nutrient leakage and the flow of nutrients as runoff (Verstraeten et al. 2002). A simpler model developed by the environmental consultant agency Ekologigruppen uses a static flow accumulation as a proxy for nutrient transport through a selected area (Ekologgruppen 2013). Such simpler models have the advantage of being more accessible to people who are not experts in the field of physical geography and they can thus be easily used and analyzed by municipalities for decision making process.

This thesis aims at suggesting an improved methodology for assessing the nutrient leakage risk for a sub-catchment by utilizing a dynamic triangular form-based multiple flow algorithm model (Pilesjö and Hasan 2013) to model surface flow taking into account the friction and the infiltration area. It then uses this model to analyze the effectiveness in filtering nutrients of the treatment wetlands within the area and assess the wetlands future performance for cases of increased precipitation intensity events.

2. Theoretical Background

In the following the theories and background knowledge discussed in this thesis are further explained. The phenomenon of eutrophication on a global as well as on a local level for Sweden are illustrated and how wetlands can aid in reducing critical nutrient loading. Later on in the section two methods for the hydrological modeling of surface flow are introduced and compared. Finally, a description of the hydrological model used for this thesis is given.

2.1 Nutrient enrichment of aquatic systems

Soil nutrients are essential for plant growth. They are key limiting factors for plant development and low levels of nutrients can result in slow or deficient growth. In an aquatic system however, an abundance of certain nutrients can lead to unwanted plant and bacteria development. In many water bodies nutrient richness beyond a needed point results in excessive algal bloom, causing damage to the local ecosystem.

The nutrients most substantial to this process are phosphorus and nitrogen. Both nutrients are found naturally in soils as well as aquatic systems, but through anthropogenic activities they enter those systems in dangerously high numbers. There are several ways in which those nutrients are added to ecosystems, as for example through leaching from soil but also as precipitation from clouds in polluted air (Carpenter et al. 1998). Since increased nutrient loading within rivers has been linked to coastal eutrophication processes in many studies (Cloern 2001), finding the location of excessive nutrient leaching in soils can be a first step to identify the high risk areas for eutrophication. This thesis only focuses on phosphorus leaching, however, increased nitrogen input is also an important driver of eutrophication processes.

As a limiting nutrient in many soils, a low availability of phosphorus will negatively affect the development of a growing plant. Besides helping with the formation of crucial plant components such as the root system, Phosphorus helps with the formation of DNA and proteins and is thus responsible for the energy supply within the plant. (Aziz et al. 2013)

The nutrient enters soil through the weathering of minerals (Lal and Steward 2016). It is then taken up by plants roots and utilized. In a healthy ecosystem the amount of nutrients available to the plants should be sufficient to satisfy the plant´s need to allow it to grow adequately. Due to high demands of produce and modern farming practices, phosphorus amounts within soils can sink to low levels. As nutrient weathering can be a comparatively slow process, phosphorous is added to the soil through fertilizers, even, such as in many cases in Sweden (Parvage et al 2015), if there is no apparent absence of the nutrient in the soil. If too much phosphorus is present within the soil, the risk of nutrient leaching through vertical water movements is greatly increased (Paulter and Sims 2000).

Once nutrients have entered the rivers and stream networks, they make their way into fresh water lakes or the ocean. Due to the increased nutrient availability, plant growth is stimulated, resulting in a rapid increase of algae, phytoplankton and other water plants. Those plants cover the lake's or ocean's surface and give it the characteristic green color of a water body affected by eutrophication. Once all the nutrients within the water are consumed, excessive plant growth can no longer be sustained. Hence, the plants die and sink to the bottom of the lake. Here they decompose and as a result, deplete the level of available oxygen.

Organisms that rely on the oxygen in the water for survival, e.g. fish, can no longer find sufficient amounts and die. In that way eutrophication can even lead to dead zones within lakes and oceans where no live can be sustained. (Dybas 2005)

Ocean dead zones can be found all throughout the Earth's oceans, in majority along coastlines of densely populated areas. The biggest dead zones are found in the Gulf of Mexico, however in Europe the Baltic Sea shows a rapid increase, with around 60.000 km^2 of the ocean now being classified as a dead zone (Broman 2018). While nutrient enrichment is not the only cause for such dead zones and the can also occur naturally, eutrophication has been identified as one of the main drivers of such events (Broman 2018). The predicted temperature increase due to climate change is expected to further accelerate the growth of those zones (Altieri and Gedan 2014).

2.2 Eutrophication Processes in Sweden

Eutrophication has long been a recognized problem within Sweden, not least as a result of the growing eutrophication of the Baltic Sea. With Sweden being the biggest contributor of nutrient loading to this ocean (Nilsson 2013), the country has committed to a goal of zero eutrophication by the year 2020 (Swedish Environmental Protection Agency 2018). While it doesn't seem that this goal will be achieved within the given time frame, much work has been done on cutting the amount of nutrients entering the Baltic and North Sea.

In order to ensure the success of this environmental objective, laws and recommendations have been passed regulating the amount of nutrients that can enter the aquatic systems through sewage plants, surface runoff in urban communities and other point sources (Nilsson 2013). Additionally, in order to limit the amount of nutrients already found in streams, sedimentation dams have been established along polluted rivers. The same process of filtering nutrients through the sedimentation can be achieved through the (re-)establishment of wetlands. Those measures of reestablishing and promoting the health of existing wetlands have been a part of the Swedish environmental plan since 1992, when passed as a recommendation in the Helsinki Convention (Nilsson 2013).

A catchment in which a lot of work on establishing wetlands has been done is that of the river Höje in western Scania. The river Höje springs from the Häckeberga lake and flows into the Öresund, a particularly shallow part of the North Sea between the Swedish West Coast and Denmark (Swedish Environmental Protection Agency 2008), and has a length of around 35 km. Around 103 000 people live within the catchment and areas can be very densely populated, especially within the urban and residential areas (Ekologgruppen 2004).

Water conservation within the catchment has been done on a grand scale in two project over an extended amount of time, first from 1991 to 2003 and then from 2007 to 2014 (Ekologgruppen 2015). The work of those projects focused on the establishments of wetlands in the catchment in order to limit the amount of nutrients delivered into the North Sea as well as increasing the biodiversity around the local aquatic systems. As a result, 80 wetlands with a total area of 110 ha were established in the watershed. The project was successful in limiting the amount of phosphorous by 2.5 tons of phosphorous and 62 tons of nitrogen for the total area of the catchment per year (Ekologgruppen 2015). Earlier reports had measured annual nitrogen discharge in the catchment to lie between 320 to 880 tons and Phosphorous discharge between 3.4 to 12 tons (Ekologigruppen 2015).

In cooperation with the environmental consultation agency Ekologigruppen an annual report on the development of nutrient pollution of the catchment area is produced by the local counsel. Water samples are taken at 24 stations along the river. Those recipient reports show a clear trend of increased Phosphorus and Nitrogen output in the winter months and a low output during the summer months (Ekologgruppen 2018). A correlation between the nutrient output and stream discharge can be seen. As the stream discharge is highly dependent on the surface runoff delivered into the stream, a reliable hydrological model is important in order to predict the future nutrient discharge.

2.3 Hydrological modeling

When predicting flow behavior on a surface the application of a model can be useful. There is a multitude of hydrological models and different models should be used depending on which parameters should be investigated. When spatial variability is of no importance to the research question a lumped model displaying the total discharge of an area could be advantageous, when the individual behavior of streams within a watershed should be analyzed, a more complex model can be appropriate (Devia et al. 2015).

Most often when predicting and modeling the surface runoff of a certain area through geographic information systems (GIS) a model using the elevation of that area as an indicator for flow patterns is applied. The elevation pattern is usually displayed through a digital elevation model (DEM), a raster grid with varying values for the pixels, each value representing the elevation at that point. These hydrological models rely on gravitation being the main force behind surface flow behavior and create stream paths depending on the elevation differences between neighboring cells.

As elevation is the main indicator the models running on this principal are called elevation based models (Nilsson 2017). A simple elevation based model is the D8 model. In a D8 model water can flow from one cell into its 8 neighboring cells according to figure 1. Cell M can distribute water into its neighboring cells C1 to C8. The decision on in which cell the water will flow is based on the difference in elevation between cell M and cell Cn divided with a distance factor. The distance factor for directly neighboring cells is defined as 1, for diagonally neighboring cells as $\sqrt{2}$. All water eventually flows into the cell with the highest elevation drop (Nilsson 2017). D8 models are single flow algorithm models in which all water from one cell is predicted to flow into only one of the other cells, based on the aforementioned determinants. An algorithm that predicts water distribution into several neighboring cells is called a multiple flow based algorithm.

C8	C1	C2
C7	M	C3
C6	C5	C4

Figure 1: Schematic Drawing of the D8 flow algorithm. M signifies the center pixel, while Cn are the neighboring pixels.

Ekologigruppen uses the GIS software SAGA for their analysis (Ekologgruppen 2013). The software applies a DEM without any other physical inputs for their flow prediction. Since we can see from the nutrient discharge analysis however, nutrient amount shows to be dependent on total stream discharge which is not constant over time. A dynamic, model producing a result with a temporal variability could thus be useful in order to produce a more reliable prediction of nutrient loading.

Such a model has been developed by researchers at Lund University (Pilesjö and Hasan 2013). The model utilizes a Triangular form-based multiple flow algorithm in combination with other parameters to produce a dynamic flow accumulation pattern.

2.3.1 Triangular form based multiple flow algorithm modeling (TFM)

Like a simple surface runoff model, a TFM utilizes the DEM of an area to estimate the flow direction of water on its surface. However, the model does not only calculate movement between neighboring cells, but also takes internal water movement and distribution within a focus cell into account. Hence, the model aims to deliver a more realistic representation of the stream flow.

Before flow between neighboring cells is examined, the conditions of a single focus cell *M* are calculated. A cell is divided into 8 triangular facets as shown in figure 2. The cell can thus be imagined as an 8-faceted pyramid. Each one of these factors represents a first order trend surface with a specific aspect and slope. Those parameters are calculated using the two neighboring cell *C1* and *C2.*

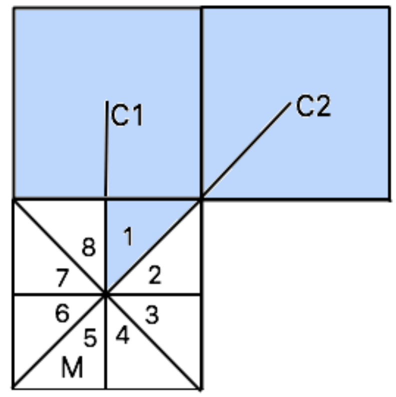

Figure 2: Schematic Drawing of the Triangular form based multiple flow algorithm. M signifies the center pixel, while C1 and C2 are the pixels that water can flow in from facet 1.

Each facet forms a plane defined as:

$$z = f(x, y) = ax + by + c \tag{1}$$

Where the parameters *a, b* and *c* are defined as*:*

$$\begin{cases} a = \frac{(y_1-y_3)(z_1-z_2)-(y_1-y_3)(z_1-z_3)}{(x_1-x_2)(y_1-y_3)-(x_1-x_3)(y_1-y_2)} \\ b = \frac{(x_1-x_2)(z_1-z_3)-(x_1-x_3)(z_1-z_2)}{(x_1-x_2)(y_1-y_3)-(x_1-x_3)(y_1-y_2)} \\ \quad c = z_1 - ax_1 - bx_1 \end{cases} \tag{2}$$

Aspect $\alpha$and slope βcan then be calculated according to:

$$\beta = arctan\sqrt{a^2 + b^2} \text{ and } \alpha = 180° - arctan\frac{b}{a} + 90°\frac{a}{|a|} \tag{3}$$

In order to estimate the internal water movement within a cell, each facet is assigned the same amount of water. Depending on the aspect of a facet, water can either move from facet from facet or stay within a cell. The different possibilities for movement are as follows:

1. If the aspect is between 0° and 45° the water stays within the cell.
2. If the aspect is between 90° and 180° or corresponding between 225° and 270° the water moves to the adjacent facet.
3. If the aspect is between 45° and 90° or corresponding between 270° and 360° the water is split between the adjacent facet and neighboring cell
4. If the aspect is between 180° and 225° is completely split between two facets with no water remaining in the original facet.

Once the internal water movement has been determined, flow between neighboring cells is examined. Water movement between a facet of the focus cell can happen according to figure 2. Facet 1 of focus cell M can deliver water into cells C1 and C2. If the elevation of M is higher than the elevation of C1, facet 1 will deliver all its water into C1. If both C1 and C2 have a lower elevation than M, the water in facet 1 will be split amongst the cells.

2.4 Treatment wetlands and their efficiency

A fifth of all Swedish landmass is covered by wetlands, however, around 80% of those wetlands are disturbed and endangered as a result of anthropogenic activities (Swedish Environmental Protection Agency 2014). Wetlands provide important services to surrounding ecosystems. They create a safe space for local flora and fauna and act as carbon sinks. Additionally, they can also act as water treatment dams, and filter out and bind toxins but also nutrients such as phosphorus and nitrogen (Abdel-Sabour 2014, Vymazal 2006).

Both, natural and constructed wetlands are used as treatment wetlands. While the exact definition of natural wetlands is subject to a long lasting academic debate (Dordio et al. 2008), basic requirements for an area to be recognized as a wetland have been defined as the US National research council as a continuous hydrological saturation of the ground, a chemically reactive substrate layer in form of soils with high organic matter content as well as the presence of biological organisms prevalent in wetlands (Committee on Characterization of Wetland 1995).

Nutrient filtering processes in wetlands can happen through several chemical, biological and physical processes. Phosphorus is mainly removed through physical processes, while Nitrogen is removed through chemical processes (Fisher and Acreman 2004). The processes aiding in the removal of nitrogen in the water are mainly chemical reactions in which nitrogen in different forms reacts with the substrate layer of the wetland. Through denitrification harmful nitrate originating from agricultural land can be transform into nitrogen gas. However, nitrification and ammonification can also take place in wetlands. (Fisher and Acreman 2004)

In biological processes, the plants in a wetland can utilize the nutrients brought in through surface flow for plants growth and development. While a great amount of nutrients can potentially be bound in such a way, the retention of nutrients is ultimately only temporary, as the nutrients are released back into the ecosystem as the plant dies and decomposes. (Vymazal 2006)

Phosphorus dissolved in water is filtered through physical sorption processes, in which it is either diffused into a liquid or a gas or bound into or solid. Another process commonly utilized in filtering dams is that of sedimentation. This can happen if the phosphorus is not dissolved in the water. Since the speed of surface flow decreases as it passes through a wetland, nutrients suspended in the water through constant hydraulic movement are sedimented into the wetland´s bottom substrate. Phosphorus is one of the main pollutants retained in wetlands in such a way (Geranmayeh et al. 2016). Due to the decrease of a stream's flow speed as well as a limiting of its hydraulic conductivity, forested wetlands and bogs that considerably slow down water movements show a higher potential for nutrient retention than non-forested wetlands (Dordio et al. 2008).

The speed with which a particle enters a wetland as well as the time spent within the wetland environment are among the main indicators on a wetland´s effectiveness at retaining the nutrients in the flow (Johnston 1991). If the stream velocity in the wetland is lower than the erosion velocity of the particle, sedimentation can occur (Johnston 1991). Hence, if the stream's velocity is higher than the erosion velocity, a particle will not sediment and additional nutrients bound within the wetland might be eroded, leading to an increase in nutrient discharge (Geranmayeh et al. 2015). As a result, nutrient retention could even be negative during strong precipitation events or floods, when water movements within the wetland are fast, especially if phosphorus loading within a wetland already is high (Søndergaard et al. 2003).

Wetlands generally appear to be more successful at filtering nitrogen than phosphorus. (Fisher and Acreman 2004). The performance of a treatment wetland and its ability at filtering nutrients are highly dependent on a great number of variables, such as the size of the wetland, the water temperature, speed with which flow enters into the wetland, the biological composition of the wetland's biota and the amount of nutrients already bound within the wetland's substrate. There are even instances of wetlands not succeeding at nutrient removal at all, but rather increasing the nutrient load within a stream. (Fisher and Acreman 2004) A general model for the analysis of a wetlands capacity at filtering nutrients is thus hard to develop.

This thesis will mainly focus on nutrient retention through sedimentation. As described above, this is not the only process in which phosphorus is bound, however, as it is highly dependent on the speed of the stream with which it enters the wetlands, it can more easily be predicted using an appropriate hydrological model.

The hydrological model used in this thesis has been developed by the staff at Lund University GIS-centrum (Pilesjö and Hasan 2013). The dynamic model used in here was developed by researchers at the centrum and presented by Hampus Nilsson in his thesis (Nilsson 2017). The above described triangular based multiple flow algorithm is used for the flow accumulation analysis, in combination with ground condition defining terms. Those are infiltration rate and surface roughness. A time step is added, making the model dynamic. In order to accumulate flow, a precipitation event is modeled over the study area. Here a precipitation event with a 10-year return period for the study area region is chosen. The model was originally developed in order to predict flooding in certain areas, however for the purpose of this thesis it can be utilized to identify areas of high flow accumulation in the area, i.e. a wetland.

Due to data and time constraints, not the entire catchment area of Höje å is analyzed. Instead the sub-catchment area of Björkesåkrasjön is chosen. This sub-catchment is selected due to it being an independent watershed, with no additional input flowing into it from other sub-catchments.

3. Methods

In the following section the methodology followed to obtain the results is described. A brief description of the study area is given. Additionally, it contains the variables used for the calculations with the TFM model as well as an explanation of the steps followed to produce the flow accumulation around the study area's wetlands. Subsequently, the methodology for the calculations of a particle's final velocity within the wetland is given.

3.1 Description of Study Area

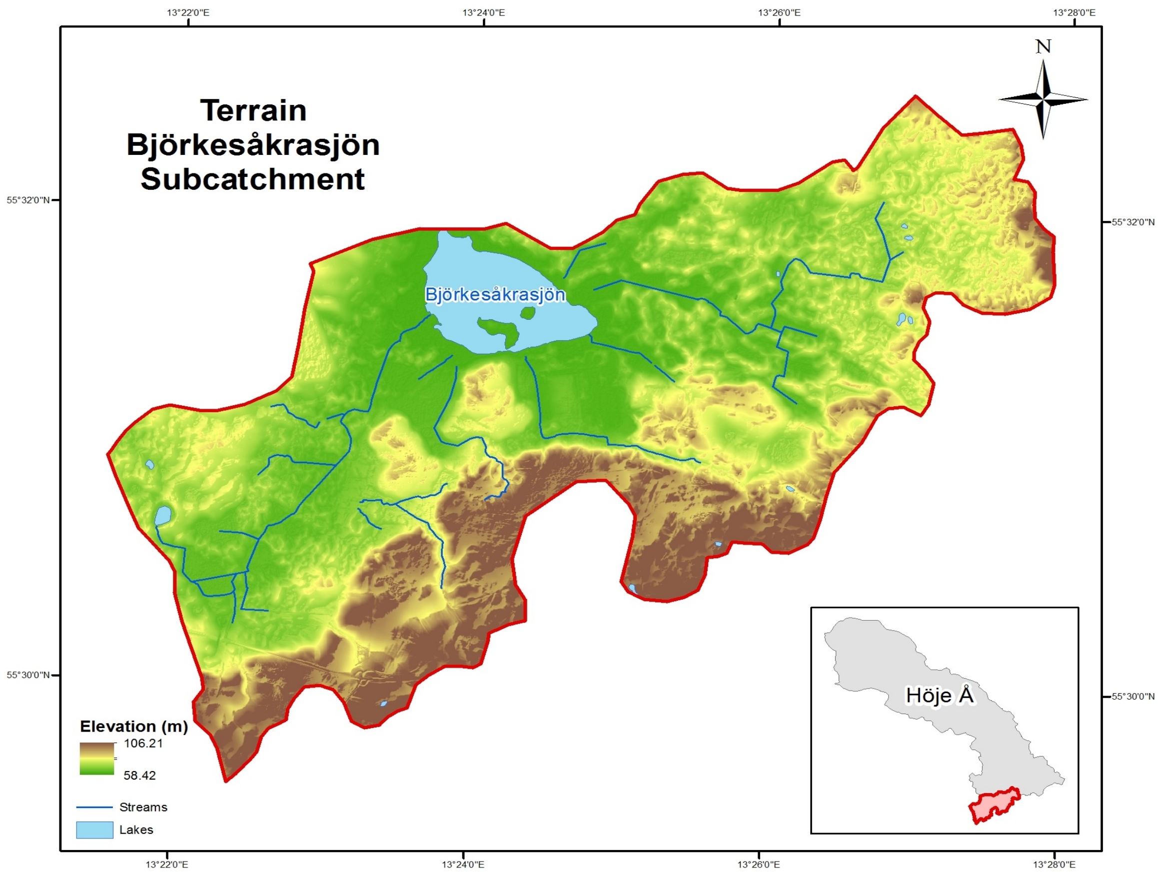

Figure 3: Terrain Map of the Björkesakrasjön sub-catchment. The data on the catchment boundaries is obtained from SMHI, the DEM was downloaded as the 2m grid from Lantmäteriet.
Author: Clara Hubinger
Projection: SWEREF99_TM

The study area chosen is the sub-catchment of the lake Björkesåkrasjön in the southeastern border of the Höje å catchment. The total area of the catchment is 16 km^2. As can be seen in figure 3 several streams are found in the catchment, delivering water into the lake. The river that springs from the lake in turn delivers water into the Häckebergasjön from which the river Höje springs. The watershed is the highest upstream sub-catchment of the Höje å catchment and there are no streams delivering water into it.

Elevation ranges from 58m to 106m and higher elevations are found along the southern border of the catchments with lower planes at the northern border around the lake. The lake is shallow and only little nutrient enrichment and plankton growth is observed (Höje Å Vattenrad 2019).

Figure 4 shows the distribution of land cover within the sub-catchment. The majority of the land in the study area is cultivated, around 50% of the land cover being agricultural land. The area around the lake is mainly covered by forest and wetland. In the west, larger fields used for grazing are found. There are only small parts of built-up areas in the sub-catchment. However, just west of the sub-catchment, the runway for Malmö Airport Sturup is located.

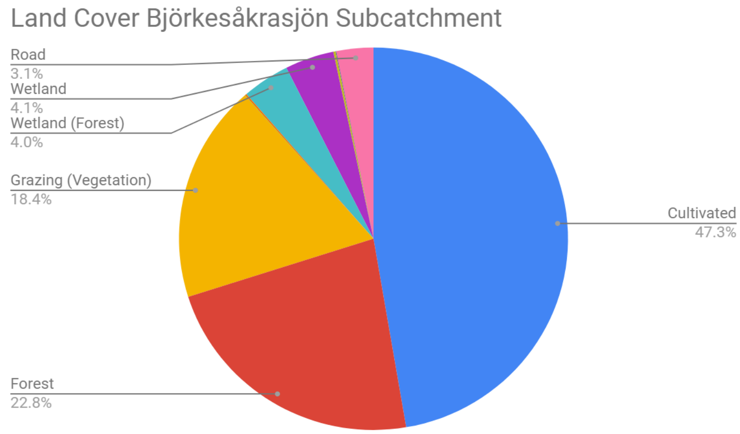

Figure 4: Land Cover Björkesakra sub.catchment
Source: Nationell Matkräckedata

Almost 5% of the sub-catchment is covered by wetlands. As can be seen in figure 5, the majority of the wetlands is located in the area surrounding the lake, however, forested wetlands are found throughout the catchment. As the terrain map shows the areas are mostly situated in the low-lying areas around the lake, acting as a natural border between the surface flow entering the lake and the remaining land. The total area of the wetlands is 0.6 km^2.

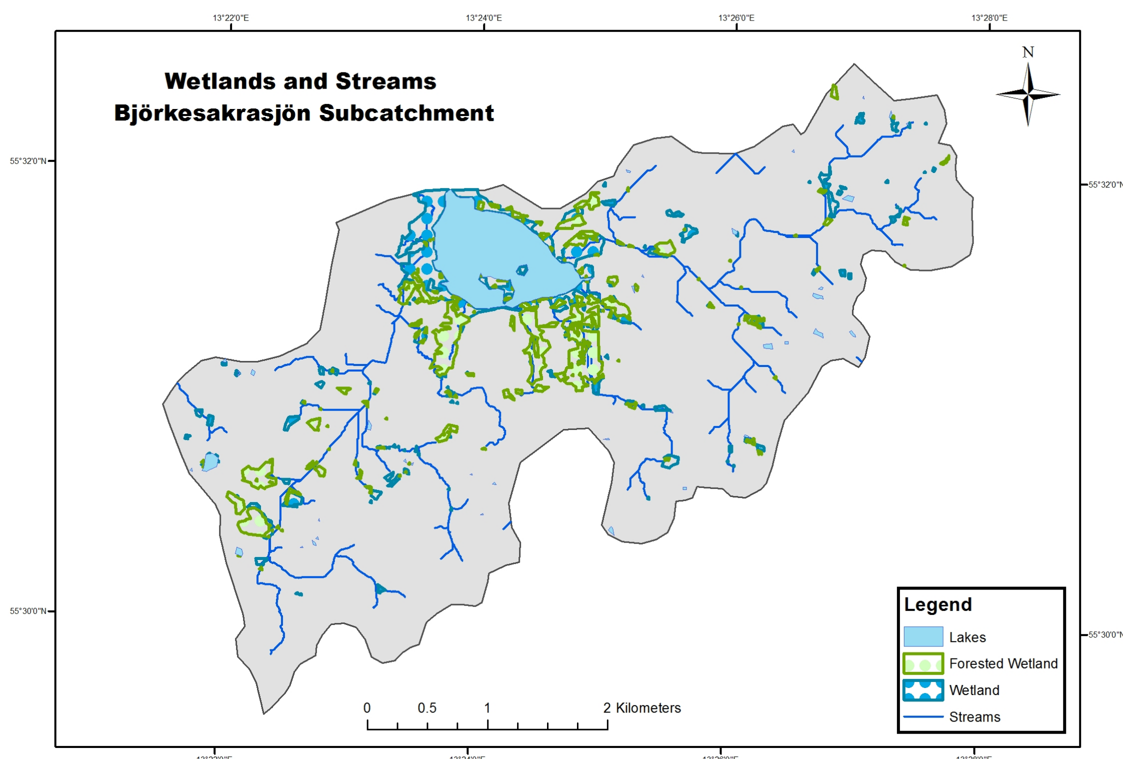

Figure 5:Wetlands in the Björkesakrasjön sub-catchment. The data on the catchment boundaries is obtained from SMHI, the land cover data was obtained from the national ground cover survey (Nationell Marktäckedata).

A more detailed map showing the land cover in the area can be found in Appendix A.

3.2 Using the TFM model to model surface runoff

In order to simulate the surface runoff over a 30-minute precipitation event period the triangular form-based multiple flow algorithm (TFM) model uses several parameters:

- DEM
- Infiltration rate in mm/h
- Precipitation rate in mm/h
- Surface roughness n (Manning friction value)

The model utilizes ASCII (American Standard Code for Information Interchange) raster of same spatial resolution for its calculations. The raster for the DEM, infiltration and surface roughness where created using ArcGIS (ESRI 2011). A spatial resolution of 5m for the in-depth flow accumulation and 20m for the time step series was chosen. The original 2m resolution of the DEM was decreased using the Resample method in ArcMap (ESRI 2011), for the interpolation the NEAREST method was chosen. The raster for infiltration and surface roughness were created by converting the polygon layers into raster layers using the conversion tool. Using the reclassify function new values were assigned to the raster according to the tables below.

A soil map in combination with a land cover map can be used to assign infiltration values. However, as the purpose of this study was to focus on the wetland´s performance - which is more highly dependent on the surface friction - a uniform infiltration value of 5 mm/h was chosen.

The surface roughness was assigned using the land cover type. The wetland in here will act as a flood plain and as such its friction value was assigned using the method suggested by the US Geological Survey (USGS) (Arcement and Schneider 1989). Land-cover specific friction values were assigned according to Natural Resource Conservation Service (NRCS 2016) suggested values. The final table is shown in table 1.

For precipitation a rainfall with a 10-year return period was chosen: 25.9 mm/h for a duration of 30 min. (Ghebremariam 2017). Using the MATLAB function a homogeneous raster with the size of the study area was created. The total duration of the rain event was 30min, the model was designed to run for 15 additional minutes after the rain had stopped. For both, the 20m raster and the 5m raster a time step of 5s was set.

The model produces a 3-dimensional flow accumulation matrix, with the raster spatial properties being the first and second entry and the time being the third. A layer of flow accumulation in volume is produced for each minute of rainfall. For the in-depth analysis of the flow accumulation on the 5m raster, the flow accumulation raster for minute 30 of the rainfall event was exported using the Writing() function of the model. The same function was used to export minute 5, 10, 15, 20, 25 and 30 flow accumulations of the raster with 20m resolution.

Table 1: Manning friction values for different land cover types.

Land Cover	**Manning's n**
Cultivated	0.035
Barren Land	0.035
Deciduous Forest	0.16
Evergreen Forest	0.16
Mixed Forest	0.16
Shrub	0.1
Grassland	0.035
Road/Urban	0.016
Woody Wetlands	0.2
Emergent herbaceous wetlands	0.2

3.3 Particle Velocity Calculations

In order to assign velocity values for each cell within the wetlands, a velocity field map was created using the 5m resolution flow accumulation raster for minute 30 and the DEM in ArcMap. The resulting velocity value on each cell is defined as the velocity of the particle suspended in the flow. Whether a particle is eroded, transported or deposited when entering the wetland depends on the particle velocity and is defined through the Hjulström diagram (Hjulström 1935).

According to the diagram, we can define a velocity range for different particle sizes shown in table 2. Each pixel is thus assigned a color-coded value showing if the particle will deposit, be transported or lead to more erosion.

Table 2: Sedimentation-, Transport- and Erosion Velocity for different particle sizes

	Particle velocity for sand (cm/s)	Particle velocity for silt (cm/s)	Particle velocity for clay (cm/s)
Deposition	<10	<0.1	-
Transport	10.1-30	0.2-50	<99.9
Erosion	>30	>50	>100

The final velocity v at each cell was calculated using an equation suggested by (Maidment et al. 1996):

$$V = V_m \frac{s^b A^c}{\left[s^b A^c\right]_m} \tag{4}$$

Where V_m is the average velocity, A is the upstream contributing area, s is the local slope, b and c are model calibration parameters.

3.4 Data collection and analysis

The 2m DEM grid used to create the terrain map has been downloaded from the Swedish national geographical survey (Landmäteriet) and was later resampled to the same cell size as the other data used in the analysis (Lantmäteriet 2019). The land cover data has been downloaded as a raster grid from the Swedishish national ground cover survey (Nationell Marktäckedata) data set from 2019 (Naturvårdsverket 2019). The soil type data used for information on infiltration is the Jordarter 1:25.000 raster from SGU (SGU 2019). The watershed boundaries used in this thesis has been obtained through SMHI (SMHI 2012).

The maps and figures in this thesis have been produced by the author. Maps were created using ESRI ArcGIS 10 with a Spatial Analyst and 3D Analyst extension (ESRI 2011). Calculations and the creation of the pie chart in figure 4 have been created using Microsoft Excel and Google Sheets. The code with the TFM model (Pilesjö and Hasan 2013, Nilsson 2017) runs on MATLAB (The MathWorks 2010).

4. Results

In the following the results of the model are presented. A simple singular flow-based flow algorithm is compared to a triangular form based multiple flow algorithm for a subsegment of the study area. The flow accumulation around the wetland area in detail, as well as a flow accumulation over the 30-minute precipitation event are shown. Lastly, the wetland effectiveness at filtering particle of different sizes through sedimentation based on the flow velocity is presented.

4.1 Single flow direction model vs. TFM Flow Accumulation

Shown below in figure 6 are the flow accumulations created using a single flow algorithm (A) and a triangular form-based multiple flow algorithm (B). The cells showing significant flow accumulation are colored as blue. In the background an excerpt of the terrain map shown in figure 3 is used.

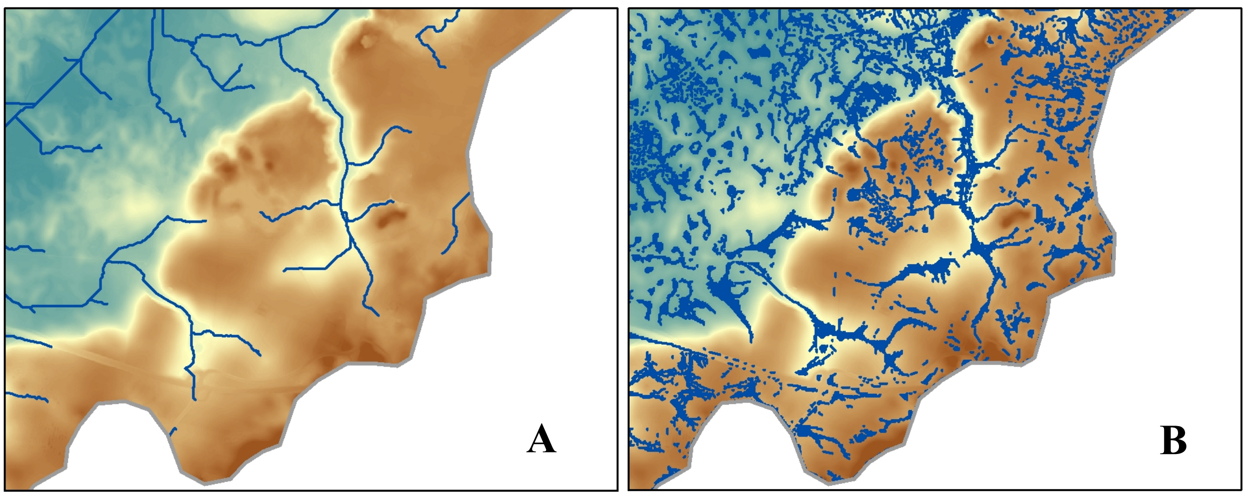

Figure 6: Comparison static flow accumulation and TFM model based static flow accumulation in the Björkesakrasjon sub-catchment. Single flow algorithm shown in A and triangular form-based multiple flow algorithm shown in B.
Author: Clara Hubinger
Projection: SWEREF99_TM

It can be seen that the single flow algorithm produces stream flow accumulations with the width of one pixel. To allow for better visualization, the line layer created from the raster in increased in width. The flow accumulation produced using the TFM model is shown here still as a raster layer. Here the blue layer representing flow accumulation is shown to have a width of up to several pixels.

4.2 Flow Accumulation around Wetlands

In figure 7 the flow accumulation produced using the dynamic TFM model around the lake Björkesåkrasjön is presented. Presented is a raster file with 5m resolution, showing the total flow accumulation at minute 30 of the model runtime. Areas of high flow accumulation are shown in dark blue, areas of low accumulation shown in light blue. The number shown in the legend signifies the amount of cells contributing flow into the cell. A polygon layer with a red border defines the forested and non-forested wetlands.

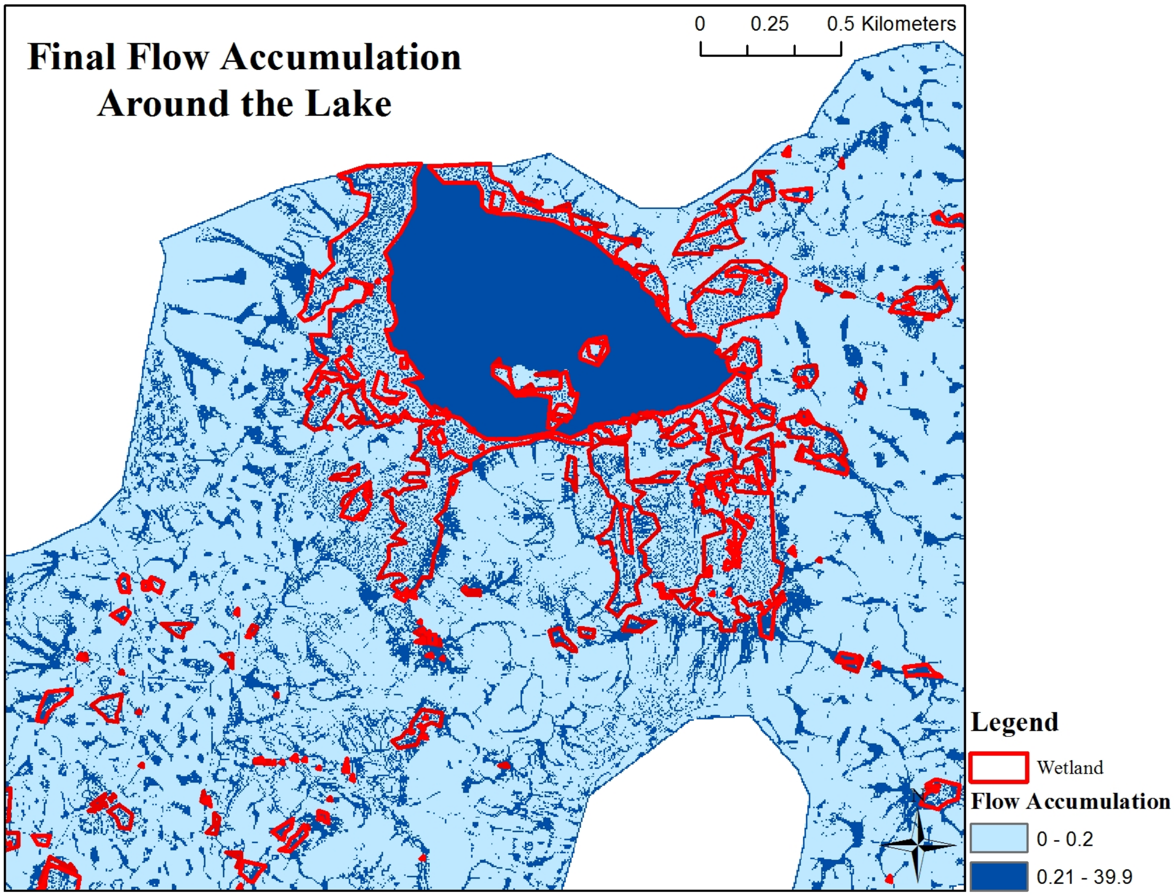

Figure 7: Flow accumulation in the wetlands around the lake.
Author: Clara Hubinger
Projection: SWEREF99_TM

It can be seen that the highest flow accumulation is found within the lake. In the wetlands flow accumulation is spread out evenly throughout the plane, rather than forming distinct streams. This same pattern of flow accumulation can be seen in some areas outside the wetland polygons, especially on the southern side of the lake.

4.3 Flow Accumulation Time Series 30 min

Presented in figure 8 is the flow accumulation over the 30 min precipitation event shown in 5-minute steps from the start of the event. The amount of accumulation is shown in the raster file as color coded from brown showing a low amount of accumulation to yellow, showing a high amount of accumulation. It is to be noted that while the color code used for each map is the same, the scales used are different. This is done to allow for better visualization of the process of accumulation around certain areas. The wetland

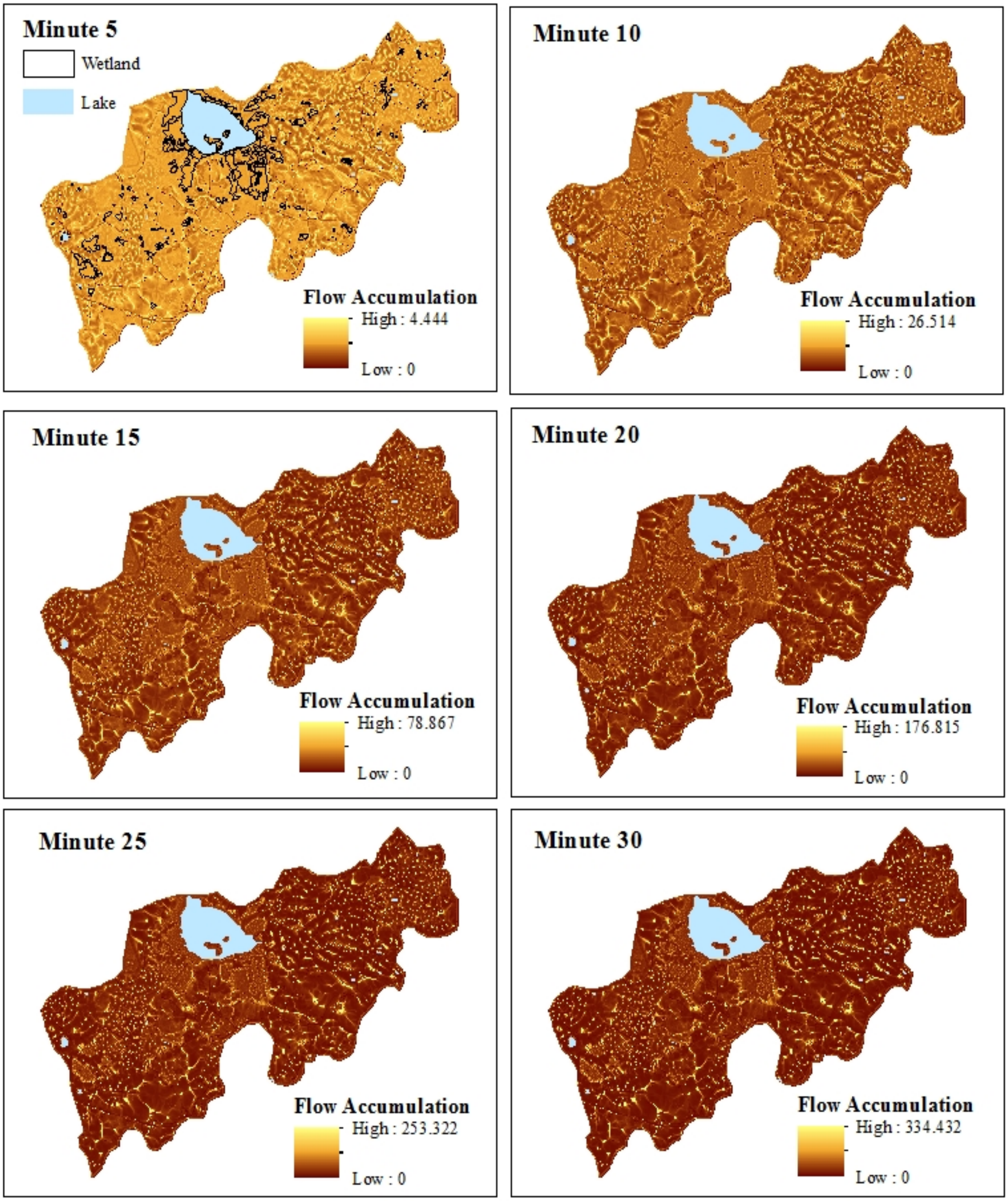

Figure 8: Flow accumulation in the wetlands around the lake using a dynamic model.
Results displayed for minute 5, 10, 15, 20, 25 and 30.
Author: Clara Hubinger
Projection: SWEREF99_TM

boundaries are shown with a black outline in the map depicting the flow accumulation for minute 5. The lake Björkesåkrasjön is shown in blue.

At minute 5 not a lot of water has accumulated. The highest accumulations are found in the areas with high elevation differences (for comparison see the terrain map (figure 3) in the methodology section). Distinct streams have not yet been formed, the flow is rather evenly distributed over a wide area. In the map showing the results for minute 10 we can see that total accumulation has increased. More distinct boundaries of high and low accumulation can be seen. Accumulation around the wetland begins.
Throughout minute 15 to minute 25 total flow accumulation increases steadily. Areas of high accumulation increase in intensity, while they decrease in stream width. The boundaries of the wetlands become distinctly visible. While an even distribution of flow is shown within the wetlands, a higher flow accumulation can also be seen just outside the wetland's boundaries. The maximum flow accumulation is reached at minute 30 of the run time. Distinct narrow stream lines are visible. The wetland´s boundaries and the area within are clearly defined by a bright yellow boundary and lighter yellow shadowing within.

4.4 Velocity Field Calculations

Shown in figure 9 are the results from the particle velocity calculations for particles the size of sand (A), silt (B) and clay (C). The maps show a raster with the size of the wetland to the west of the lake. Each raster cell signifies a velocity the particle has at that location. Particles deposited at that raster are shown in blue, particles transported are green and pixels where erosion happens are shown as yellow. The maps are created using the flow accumulation layer for minute 30 from results part 4.2.

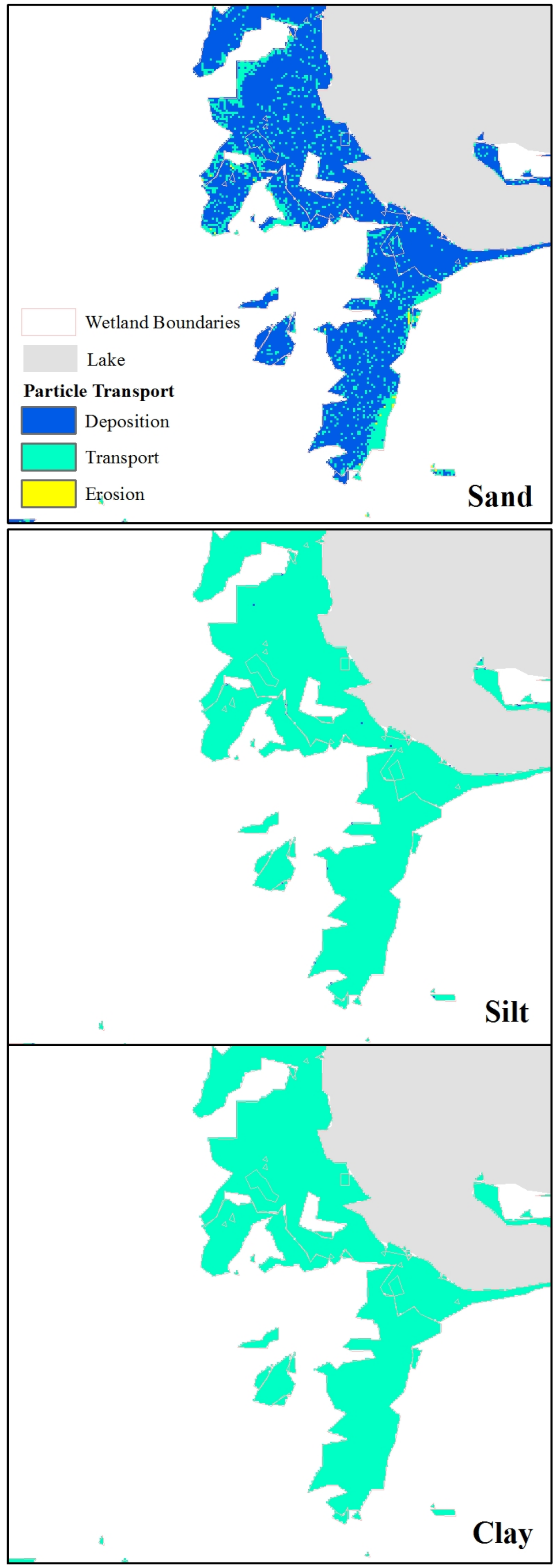

Figure 9: Velocity Raster showing behavior of particles with the size of sand (A), silt (B) and clay (C).
Author: Clara Hubinger
Projection: SWEREF99_TM

In map A showing the particle behavior for sand it can be observed that we have a high amount of deposition. Only a small number of particles are transported. Silt shows a small amount of deposition; however, the majority of particles are transported into the lake. All of the particles with the same grain size as clay are transported into the lake.

5. Discussion

This section presents the discussion of the results shown above. It aims at analyzing the differences and the advantages and disadvantages of each of the algorithms used to create the static flow accumulation. The flow accumulation around the wetlands in the maps shown in 4.2 and 4.3 and the model's performance in wetland determination are discussed. In 5.3 the velocity analysis performed in section 4.4 is analyzed. Finally, a brief error discussion is done and suggestions for improved methodology and further studies are given.

5.1 Single flow algorithm and TFM model

Assuming that nutrients enter stream networks through sediment transport in surface flow, a dynamic surface flow model could be useful in understanding sediments flow pattern during a specific rainfall event. The frequency of strong precipitation events is expected to increase within the next decades as a result of climate change. A dynamic model can thus be a useful tool in understanding catchment behavior during such an event and can help municipalities manage their nutrient output in the long run.

The model suggested by Ekologigruppen allows for a quick analysis of flow behavior, however it fails to take other important factors influencing flow patterns such as the friction of a surface or the infiltration rate of the soils in the study area into account. Such factors can be crucial when analyzing the sediment transport in runoff. The suggested model takes both these factors into account and can thus deliver a more accurate flow pattern (Pilesjö and Hasan 2013, Nilsson 2017), if the correct values for these parameters are chosen.

Result section 4.1 shows a comparison between a static D8-algorithm based flow analysis as utilized by Ekologigruppen in comparison with a flow accumulation generated using the TFM model. Both models show similar patterns of flow accumulation, identifying major stream networks at the same locations. However, the D8-algorithm produces a stream with one-pixel width only, regardless of the amount of surface flow accumulated in that area. In contrast, the TFM model produces a more spatially distributed flow accumulation with correctly identified streams. Additionally, areas of high flow accumulation are shown to be several pixels wide. Areas where flooding would occur during event of heavy precipitation can therefore be easily identified using the TFM model. The analysis performed on the wetlands shown in this thesis could not have been done using a D8-algorithm, as a simple stream flowing into the lake would have been generated. Thus, the TFM model makes it possible to assess the total amount of water accumulated within treatment wetlands.

Water treatment wetlands rely on nutrient suspension and eventual sedimentation in order to filter out nutrients from stream networks (Vymazal 2006). As runoff speed is heavily influenced by both infiltration and surface friction, they should be considered when analyzing the effectiveness and capacity of a wetland and its performance during a rainfall event. In order to allow for an accurate result, on site observations on the conditions of the wetland would be very useful. Wetlands are complex aquatic systems and there certainly isn't a simple model that can easily generalize the behavior of all wetlands during heavy precipitation events. Different factors such as the biota within the wetland, whether it is forested or not, the height of the water table and the chemical conditions of the substrate layer, heavily influence its performance. With appropriate research on the surface friction of a wetland the accuracy of the model output can be greatly improved. The methodology for determining the roughness coefficient for a flood plain used in section 3.2 could be utilized for this purpose. (Arcement and Schneider 1989)

A lot of the wetlands in southern Sweden and especially in Höje Å are constructed wetlands that have been established as part of the Höje Å project in the 1990s and early 2000s, specifically for the purpose of aiding with nutrient filtering (Ekologgruppen 2004). As detailed plans on the conditions within the wetland exist, data as size, surface conditions and flora can easily be used for the purpose of determining an accurate surface friction value. This process could be harder for natural wetlands if not detailed records of on-site conditions exist. Field work would then be required.

Ultimately, the model output can only be as accurate as the model input. If correct values for the model parameters are chosen, a more accurate flow accumulation can be expected. As with any model, it cannot replace on site measurement, however, it can give an indication on stream behavior and can be used when measurements cannot be done, as in for example when predicting performance for future climate scenarios.

The model aims at not only being applied for academic purposes, but also by municipalities for their own decision-making-processes. As such it should be easily utilizable by people who do not necessarily have a background in hydrology or physical geography. This can be achieved by the model suggested. Once the data is prepared for use and entered into the MATLAB model, no further steps are needed in order to perform the analysis. The output can be viewed directly in MATLAB or exported for further inspection using a function included in the program. Basic knowledge of a GIS software is needed, in order to prepare the data.

5.2 Flow Accumulation around wetlands

In result sections 4.2 and 4.3 we can see the flow accumulation in the wetland areas. 4.2 shows a more detailed view of the area around the lake, while 4.3 shows the accumulation process in time steps of five minutes. The maps presented in 4.2 and 4.3 show, that the model can successfully be applied to identify wetlands in the catchment. The wetland in both maps is shown to be an area of spatial equally distributed accumulation. Around the wetland’s boundaries, a distinct line of higher accumulation than within the wetland can be seen. This is not something usually observed in nature, and could be due to the fact, that according to the model the wetland has a higher friction than the surrounding areas. The water is thus slowed down upon entering and when not distributed quickly, leads to an accumulation at the point of entry. The terrain and elevation differences to not seem to be causing this pattern, as no high elevation differences are shown within the plain. This pattern disappears as the dynamic model runs on, as the water is spread out throughout the wetland.

The decision to keep the infiltration rate constant at 5mm/h over the entire study area has been made to increase the impact of surface roughness on the final flow accumulation. The value of 5 mm/h has been chosen as the standard literature value for the infiltration rate of clay. Additionally it is quite a low infiltration rate and was thus chosen to allow for a higher amount of flow accumulation. As the infiltration rate is kept constant over the entire study area, the parameters contributing to the creation of areas of high accumulation are the surface roughness and the DEM. The DEM determines the location of accumulative flow, while the surface roughness mainly determines the surface flows speed. Flow accumulation is thus shown in area where water flows due to elevation differences where it is then slowed down and allowed to distribute over a larger plain as a result of higher surface roughness.

When inspecting the pixels within the wetland, it can be seen that the model produces some pixels with slightly higher values and some pixels with low values. This is most likely due to small variations in elevations within the wetland. While no pattern is identifiable quantitatively, visually we can see a clear structure. This structure is seen mostly inside the wetland boundaries defined by the Nationell Marktäckedata, however, same structures can be found outside those boundaries. This is prominent in the southern border of the lake, where the same spatial pattern is found inside as well as right outside the wetland boundaries.

When looking at the type of land cover in the areas outside the official wetland boundaries yet displaying the same flow accumulation pattern, it can be seen that they are defined as forested and deforested areas by the Nationell Marktäckedata. This could suggest that the area originally belonged to the wetland and was later drained and converted into a managed forest.

As already mentioned in 5.1 further investigations on the conditions of the wetland should be done in order to allow for a more accurate result. The friction value for the wetlands surface obtained using the methodology described in section 3.2 was determined without performing on site observations. It can thus not be deemed as highly reliable. Using the methodology described in here in combination with on-site measurements as well as taking spatial variability in the wetlands conditions into account, such as the presence of trees and biota will lead to a more accurate result.

It is hard to verify the model quantitatively in this report, however, a qualitative verification can be done. Due to a wetland´s richness in biota and plant matter, wetland soils show to have a particularly high content of soil organic matter (Kroetsch 2011). When comparing the indicated locations of the wetland obtained using the model suggested in this thesis with a surface soil map, it is clear, that the model correctly identifies areas of high flow accumulation in areas shown to have primarily organic soils (SGU 2019). The aforementioned area identified as a wetland by the model but not identified as a wetland by Nationell Marktäckedata is similarly shown to have organic soils, further supporting the theory that this area could be a drained wetland.

5.3 Particle Velocity Analysis

In order to determine if a particle will sediment, be transported through the stream or erode, an analysis of the velocity of the particle has to be done. Methodology section 3.3 and result section 4.4 aim at suggesting a simple method and results for such an analysis. Utilizing the Hjulström diagram a sediments behavior is predicted depending on its size.

The results show that almost no sedimentation happens during the heavy precipitation event. Almost all particle of silt and clay size are simply transported into the lake. As thus, the wetland has no effectiveness in filtering the nutrients through sedimentation. Particles of a greater size are deposited even during a heavy precipitation event. It can however also be seen that those particles can lead to cases of erosion within the wetlands surface, thus possibly causing an even higher amount of nutrients suspended within the stream.

As mentioned above, the method used to obtain these results simplifies or does not account at all for many of the factors affecting particle motions in a wetland. The raster displaying the velocities was created only taking the slope and the upstream area in combination with the TFM flow accumulation into account. A more realistic model would use the surfaces friction in addition with those parameters to obtain a velocity. In a slightly improved model, a particle's velocity upon entry into the wetland and its consequent decrease in velocity due to the wetlands increased friction could be calculated. A particle would thus act in parallel to an object moving on a surface with friction *n*. If the velocity would decrease to 0 m/s the particle would sediment. In such a model the wetland´s total size would be more indicative of its effectiveness in filtering nutrients.

Wetlands, however, are not simple systems and while the above described model is an improvement to the model used in this thesis, it still does not represent a realistic solution for an analysis. Nonetheless, it can give helpful information on conditions within the wetland that can be used for further analysis. A multitude of factors such as complex hydrodynamical concepts would have to be taken into account in order to reliably predict a particle's velocity at a given point within a wetland. Studies have been conducted, analyzing those movements, which could be further utilized in order to develop an improved methodology (Some et al. 1999). A very thorough discussion of a wetlands interaction with nutrients suspended in water has been done by Johnston (1991). The methodology presented by her could be used in combination with the TFM model.

5.4 Error Discussion

As can be seen, the model and the methodology used in here provide results that can be used for thorough analysis. A detailed flow accumulation can be produced, as well as a time series of accumulations for the entire precipitation event. Throughout the process of developing a methodology a lot of conversations between raster cell sizes had to be made in order to optimize the run time of the model and visibility of results.

A lot of the inaccuracies found in here are due to those data conversions. The original DEM obtained to be used for this thesis was 2m grid created by Lantmäteriet. As a grid of such a high resolution would lead to a very long run time for the MATLAB model, the grid was resampled to a 5m grid using ArcMap. As such, the final DEM utilized here was obtained using interpolation and not measurements. Similar interpolation methods where used when creating the 5m and 20m grid for the DEM, infiltration and surface roughness raster for the TFM model. Due to low resolution of the results, small cutbacks in the results accuracy probably need to be made

5.5 Future outlook

As can be seen in the results, the model suggested can already be utilized to accurately predict surface flow accumulation and identify locations in the study area in which wetlands can be found. To continue, the model could be used for the same purpose on different areas, to examine whether the same identification is generally possible. As thus it could also be useful for the management of wetland installed to manage storm surges and prevent flooding, as water inflow could be more accurately predicted.

The model used in here defines a surface with no water accumulation at all at the start of the runtime. The surface is then filled cell by cell with water and the accumulation pattern is created. While this process can help identify the basic flow directions and points of accumulation, for a more realistic depiction it could be useful to create a surface with areas of accumulation already filled with water. The model would then depict the increase in water level in case of a heavy precipitation event instead of filling depressions in the DEM.

As already discussed above, a lot can be improved with regards to the velocity analysis performed on particles entering into the wetland. An improved methodology could be developed as suggested in section 5.3.

6. Conclusion

The TFM model suggested can successfully be used for the creation flow accumulation map in the study area. It can be seen that it produces a more detailed flow accumulation than a D8 model. Additionally, the model can successfully be used to identify wetlands within the study area. The identification can however only be done visually, as there is no constant numerical value identifiable within the wetland. The dynamic aspect of the model can be utilized to create a time series displaying the flow accumulation within wetlands in case of a heavy precipitation event. Such findings could be useful for future analysis of a wetland´s capacity.

Utilizing the produced flow accumulation, velocity values for particles within the wetland can be obtained, giving first indications on the ability of the wetlands to filter nutrients through sedimentation. The analysis performed in here is very simplified however and can be greatly improved with additionally research.

It was the aim of the thesis to suggest a model that can be utilized by municipalities to aid with decision making processes. As the model proposed here offers improvements on the now widely used static model by delivering results of higher detail and providing a dynamic aspect without greatly decreasing accessibility for the user, this aim has been achieved.

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Appendix A – Land Cover in the Björkesåkrasjön sub-catchment

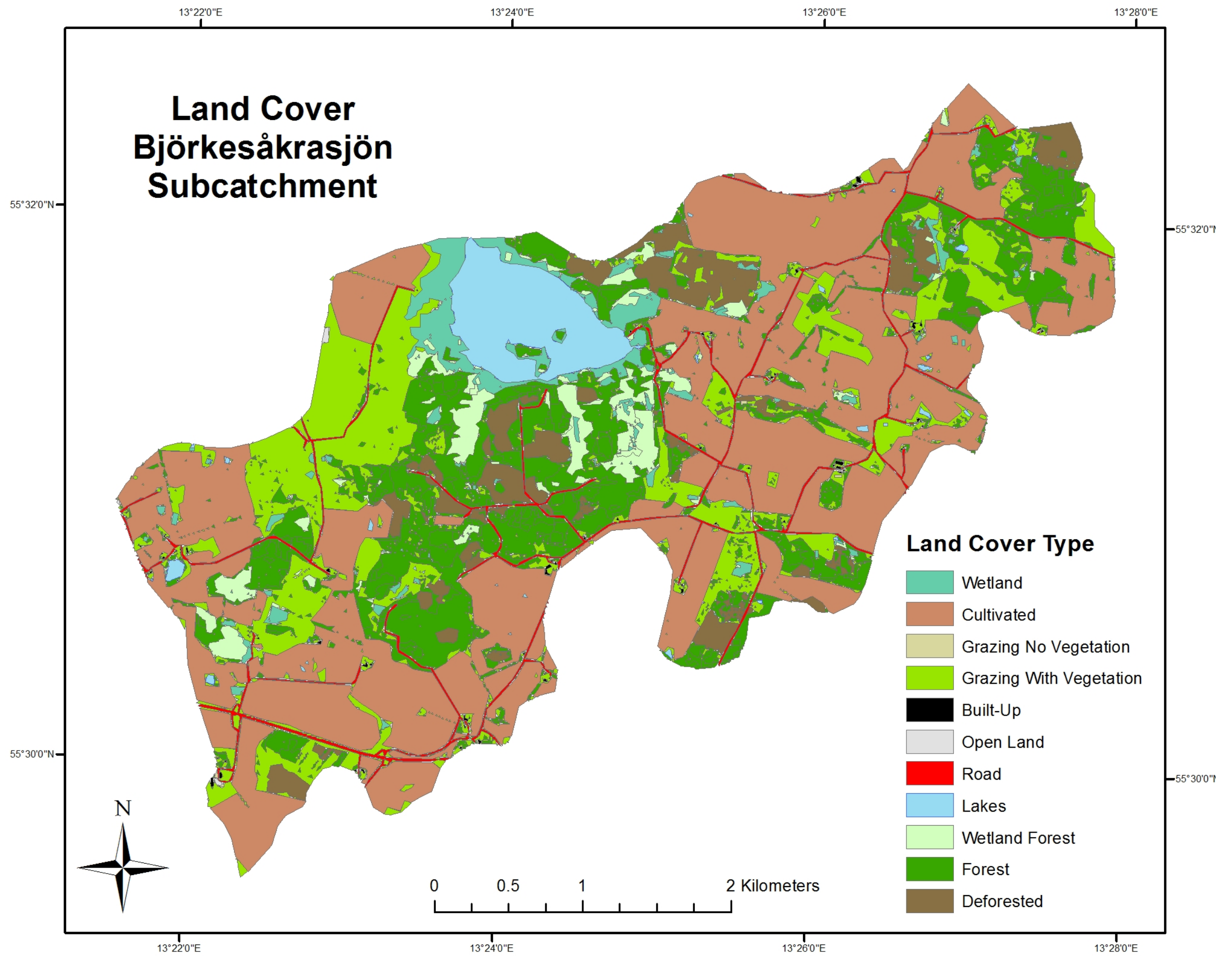

Figure A – Land-Cover in the Björkesåkrasjön sub-catchment
Author: Clara Hübinger
Projection: SWEREF99_TM