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Hydrologic modelling of the Zackenberg river basin: An applied study using the Soil and Water Assessment Tool

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ABSTRACT

Since the 1980s, the Arctic has experienced an amplified warming of more than twice the rate of the global-mean, leading to large-scale changes in the Arctic hydrologic system, ultimately having cascading feedbacks on the global climate. However, few of today's distributed models manage to capture the complex processes in Arctic hydrology, and therefore, the aim of this thesis was to evaluate the usage of the distributed Soil and Water Assessment Tool (SWAT) model, to see whether it could capture the different surface water paths and processes characterizing the Arctic water cycle. The model was applied on the Zackenberg river basin, situated in Northeastern Greenland, using spatial data of topography, soil, and vegetation cover, together with observed meteorological data from Zackenberg climate station. The model was evaluated by comparing simulated river discharge in Zackenberg river to observations, using Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2), and by comparing simulated water flows to previously modelled fluxes. The modelled river discharge had a NSE and R^2 of 0.62, indicating good agreement. Glacier melt was estimated to a mean of 930 mm w.e./year, within the range of previous estimates, while snowmelt was largely underestimated with a value of 96 mm w.e/year, possibly caused by topographic influences on snow distribution and precipitation data input. The model successfully captured seasonal freezing- and thawing cycles, but largely simplified active layer dynamics. The results indicate that the null hypothesis may be rejected. For future improvements, the methodology should include the usage of elevation bands and coupling to heat transfer algorithms, to fully capture snow distribution and seasonal permafrost dynamics.

***Keywords**: Greenland, SWAT, High Arctic, Distributed Hydrologic Modelling, GIS, Surface Water*

POPULAR SUMMARY

The Arctic, defined as the area North of the Polar Circle, has in recent years experienced a warming twice the rate compared to the global mean. The Arctic water cycle is sensitive to even minor changes in temperature due to the fine balance between the frozen and liquid state of water, and can lead to cascading impacts on the global climate and sea-level. However, although its key role on both a regional and global scale, Arctic hydrology has historically been understudied compared to lower and mid–latitudes, both in terms of hydrologic models developed for Arctic regions, as well as available data. In order to better monitor the Arctic ecosystem, research projects have been set up around the northern latitudes, of which the largest project is situated in the study area of Zackenberg, in the high Arctic Northeastern Greenland.

The aim of this thesis was to evaluate the Soil and Water Assessment Tool (SWAT) model, to see how well it managed to simulate the different processes and flows within the surface water system in the drainage area to Zackenberg river. The model was set-up using spatial data of topography, soil properties, land use properties, and weather data from the Zackenberg climate station. The model was evaluated by comparing the modelled river flow in Zackenberg river to observations from the same point, using statistical tests such as Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2), as well as by comparing the results to previously modelled flows.

The modelled river discharge got a NSE and R^2 of 0.62, indicating good agreement. Glacier melt was estimated to a mean of 930 mm w.e./year, therefore within the range of previous estimates, while snowmelt was largely underestimated with a value of 96 mm w.e/year, possibly caused by the many mountains in the study area, which influenced snow depths and precipitation differences with height. The model successfully captured the timing of freezing and melting of the frozen ground, but it oversimplified the gradual melting of the uppermost layer during summer. For future improvements, the methodology should therefore include the usage of elevation bands, which better can model the differences in snow depth and precipitation along a mountain slope, and coupling to heat transfer algorithms, to better model the melting of the frozen ground during summer.

TABLE OF CONTENT

1 INTRODUCTION

The Arctic water cycle is strongly characterized by the contrasting energy inputs between the bright summer and dark winter days, where it alternates between a liquid and frozen state following the seasonal insolation budget. This annual phase change includes modification of runoff flows from release of frozen freshwater storage in glaciers, snow cover, and permafrost (Bring et al. 2016). Small temperature changes greatly affect the balance of this seasonal variability, making the Arctic water cycle especially susceptible to temperature changes (Hinzman et al. 2005). Since the 1980s, the Arctic has experienced an amplified warming of more than twice the rate of the global-mean (IPCC 2007). The observed large-scale shifts in the hydrologic cycle from this amplification, include the retreat of glaciers, shrinking ice caps, thawing and warming of permafrost, and decreased snow cover (ACIA 2005). These changes have in turn cascading feedbacks on the global climate system, freshwater storage, and sea-level (IPCC 2007). Thus, the need to understand the Arctic hydrology is not only stretching within the boundaries of the regional system, but globally.

Although terrestrial hydrology plays an essential role in the Arctic bio-physical system, it has historically been understudied compared to lower and mid–latitudes (Ming-Ko et al. 2008; Briggs et al. 2017), and few hydrologic models are capable of capturing all its key dynamics, such as snowmelt, glacier melt, sublimation, permafrost dynamics, and snow redistribution (Krogh et al. 2017). Furthermore, data collection at high latitudes has historically been scarce due to low population density, rough climate and the often-inaccessible terrain. To meet this requirement, Arctic research projects have been initiated to facilitate research and to monitor trends in climate and terrestrial systems. One of the most comprehensive monitoring projects includes the study area of Zackenberg, situated in the high Arctic Northeastern Greenland (Meltofte 2008).

The free domain distributed model, Soil and Water Assessment Tool (SWAT), has previously been tested in mountainous to sub-Arctic regions characterized by snow (Fontaine et al. 2002; Ahl et al. 2008; Xuesong et al. 2008; Kang and Lee 2014), glacier dynamics (Rahman et al. 2013; Omani et al. 2017) and to some extent on permafrost (Hülsmann et al. 2015; Fabre et al. 2017). However, the model has not yet been applied in a high Arctic environment, characterized by strong seasonal variability in hydrologic processes and extreme climate, such as the study area of Zackenberg.

The aim of this paper was to evaluate the usage of the SWAT model in a high Arctic environment, to see how it manages to capture the different surface water paths and processes characterizing Arctic hydrology. The research question to be answered in this thesis, is:

Can SWAT be used for modelling of surface hydrology in a high Arctic catchment, largely influenced by glaciers, snow cover, and continuous permafrost?

The null hypothesis, H_0, states that SWAT cannot be applied on a high Arctic region. This will be tested against one other hypothesis;

> H_A: That SWAT can be used as a tool for Arctic surface hydrologic modelling. However, due to the present insufficient heat transfer algorithm between the atmosphere and the soil, possibilities for modelling of permafrost thawing cycles will be restrained.

The model will be evaluated by comparing simulated river discharge in Zackenberg river to observations, using statistical tests and visual interpretations. Furthermore, the simulated water flows will be compared and discussed in comparison to modelled results from previous studies.

2 THEORETICAL BACKGROUND

2.1 THE WATER BALANCE CONCEPT

2.1.1 Boundary definition

An important concept in hydrologic modelling is the idea of being able to define the boundaries of the modelled system, in order to estimate the total amount of water entering and leaving it. This area is defined as the catchment, or drainage basin, which decides the total area that contributes to the flow of water in an identified outlet point (Dingman 2015). This implies, that theoretically, all precipitation falling within the catchment will be a part of the drainage system. The area is therefore generally defined by the topography (Grip and Rodhe 1985). A catchment can furthermore be split up in smaller subbasins, where each basin consists of a defined outlet point connecting all upstream headwaters. The position of an outlet point is not a fixed location, but is, however, usually set in connection from the main channel to a larger water body or gauging site (Dingman 2015). A common scientific method to evaluate the accuracy of a hydrologic model is thus to generate all inputs of water, and thereafter compare the different simulated flows out of the system to observations of the real system (Beven 1989).

2.1.2 The water's way through the landscape

As precipitation descend, it is distributed into different flow paths and storage compartments within the hydrologic system. Some of the water is intercepted by the vegetation canopy, where it may be evaporated from the open surface back to the atmosphere. The fraction reaching the soil surface is partitioned into surface runoff, or infiltrated, i.e. transported from the soil surface into the soil profile. The surface runoff moves rather quickly to streams or water bodies collected in depressions in the landscape. The infiltrated water on the other hand, may be partitioned into three main pathways; a slower flow through the subsurface soil profile to streams; percolation further down through the soil profile, to groundwater storage in aquifers; and third, be held within the soil matric due to binding forces within the soil. The water can later be subject to evaporation or used for plant transpiration (collectively referred to as evapotranspiration (ET)). When snow is present in the landscape, sublimation occurs, where water is instantly altered from a frozen to a gaseous state (Brutsaert 2005).

2.2 ARCTIC HYDROLOGY

From a geophysical point of view, the Arctic is the region stretching north of the Arctic Circle (~66 ºN), where the insolation budget increases in summer caused by midnight sun, and drops during the contrasting dark winters with few sun hours. Like in most terrestrial hydrologic systems, precipitation contribute to the major input of water. However, in contrast to mid-latitude hydrology, a sizeable proportion of the precipitated water is stored within the Arctic system in a frozen state, with limited water flow occurring during temperatures below freezing (Bring et al. 2016). Due to the low annual temperatures, this water contributes to the water cycle in a relative short window of time during spring and summer months (Bring et al. 2016). The terrestrial water storages include glaciers, snow pack, and permafrost (i.e. frozen soils that remains at temperatures below 0 ^{0}C continuously for two or more years (Muller 1947)). During spring melt, permafrost inhibits infiltration, causing large partitioning to direct surface runoff. However, the upper part of the permafrost, defined as the active layer, is subject to seasonal thawing and freezing cycles (ACGR 1988). As the active layer increases throughout the summer months, deeper infiltration is allowed, causing subsurface flows and soil moisture to increase, at the expense of surface runoff. In autumn, insolation decreases, causing temperatures to drop, water to freeze, and water flow to cease again, marking the ending of the hydrologic year for surface water flows. This seasonal phase change of water, contributing to large transitions in water pathways and runoff quantities in summer months, is a typical characteristic of the Arctic hydrological system.

2.3 PREVIOUSLY APPLIED HYDROLOGIC MODELS IN THE ARCTIC

The absence of robust, physically based hydrologic models is today a limitation in reaching a understanding of the processes and feedbacks relating the Arctic hydrology to climate change, and vice versa (Krogh et al. 2017). There are several models developed for modelling of specific processes occurring in cold regions hydrology, such as snowmelt, glacier melt, sublimation, permafrost dynamics, and snow redistribution. However, few of them show strong enough physical basis to include algorithms for all key processes occurring, and thus often focus on one end of the system (Krogh et al. 2017). Furthermore, data scarcity across the northern latitudes contribute to large uncertainties in any model performance evaluation (Pomeroy et al. 2013).

Examples of previously used physically based, distributed models of surface hydrology in cold regions, include the ARYTHM model (Zhang et al. 2000), the TopoFlow model (Imke et al. 2007), and the CRHM model (Zhou et al. 2014). They have successfully managed to simulate snow- and permafrost properties, and furthermore, indicated good result for applications in ungauged catchments, required for many Arctic areas (Sivapalan et al. 2003). However, applications of TopoFlow on larger-scale catchments was found difficult, due to the lack of algorithms for soil properties at different depths (Fabre et al. 2017). The CRHM model was applied in western China, with results indicating good potential usage in Arctic catchments influenced by permafrost and snowmelt. The CRHM model is build-up by flexible algorithm blocks, making it possible to develop the model depending on the objective of the study and region. This may improve model performance when done adequately, but, also presumes deeper knowledge on the studied catchment area and appropriate parameter values, something many Arctic areas as of today lack. Furthermore, MIKE SHE model (Refsgaard and Knudsen 1996), developed by the Danish Hydraulic Institute (DHI), has been tested in e.g. western Greenland, with promising results for modelling of the timing of spring floods caused by snowmelt (Knudsen et al. 1999).

The Soil and Water Assessment Tool (SWAT) was initially designed to be mainly used within the agriculture sector, to predict environmental impacts of land management practices, land use, and climate change (Arnold et al. 1998). The model is thus routing both flow of water, as well as nutrient and sediment transport and cycling. Furthermore, modules for computing crop yield are incorporated, resulting in a wide variety of possible takes, relating hydrology and bio-chemistry. The SWAT model has previously been tested on mountainous to sub-Arctic regions characterized by snow (Fontaine et al. 2002; Ahl et al. 2008; Xuesong et al. 2008; Kang and Lee 2014), glacier dynamics (Rahman et al. 2013; Omani et al. 2017) and to some extent on permafrost (Hülsmann et al. 2015; Fabre et al. 2017), but not yet in a high Arctic region.

3 MATERIAL AND METHODS

The model used in this thesis was arcSWAT 2012.10.19, developed by USDA Agricultural Research Service (USDA-ARS) and Texas A&M AgriLife Research, part of The Texas A&M University System (Texas, USA). ArcSWAT is an extension compatible with ArcGIS v.10.4 (ESRI, California, USA) software. Furthermore, SWAT-CUP 2012 (USDA-ARS and Texas A&M University System, Texas, USA) calibration and uncertainty tool was used for calibration and validation of the model. The methodology can broadly be split up in the following steps: (1) Description of the study area, the used data, and the SWAT model (2) Model set-up, (3) Parameter definition, (4) Calibration, and (5) Validation by visual and statistical evaluation. The following chapter will treat each one of these steps accordingly.

3.1 ZACKENBERG RIVER BASIN

The catchment of the Zackenberg river is situated within the Northeast Greenland National park at longitude 74º28' N and latitude 20º34' W (Figure 1). It has a high Arctic climate, with an annual mean temperature of -9.5 ºC. In summer months (July-August) mean temperatures stretches from 3 to 7 ºC, while in winter, mean temperatures reach below -20 ºC. The area receives sparse amounts of precipitation, especially in summer season. Total annual amounts have been estimated to around 250 mm/year, of which 80 - 90 % falls as snow (1995-2005) (Hansen et al. 2008; Jensen et al. 2014). The Zackenberg research station is situated in the eastern part of the catchment, in the 2–3 km wide valley Zackenberdalen ("*Dalen*" is Danish for valley). The station is operated under the umbrella organisation of Zackenberg Ecological Research Operations (ZERO), housed at the Danish Polar Centre. The station was first established in 1995, with the objectives to monitor and facilitate ecosystem research in the high Arctic. It is funded by the government of Greenland and operated by Aarhus University, Department of Bioscience. As of today, around 1,500 parameters have been monitored within the valley, making Zackenberg the most comprehensive research station in the Arctic (Meltofte 2008).

The modelled catchment in this study (see Figure 1), delineated by the SWAT model, compromises approximately 509 km^2, ~1% smaller compared to previous studies (e.g. Mernild et al. 2007; Hasholt et al. 2008) which approximated it to 512 km^2. It has varying topography with elevation ranging from 0 to 1450 m a.s.l., and characterized by deep U-shaped valleys. Around 20% (101 km^2) is covered with valley glaciers, cirques, and the larger A.P. Olsen ice cap, situated west in the catchment. Most glaciers and perennial snow cover can be found at altitudes above 1000 m a.s.l. (Rasch et al. 2000). The large Greenland Ice sheet, covering ~80 % of Greenland, is situated closely to Zackenberg river basin, but is however not connected to the drainage system (Mernild et al. 2008).

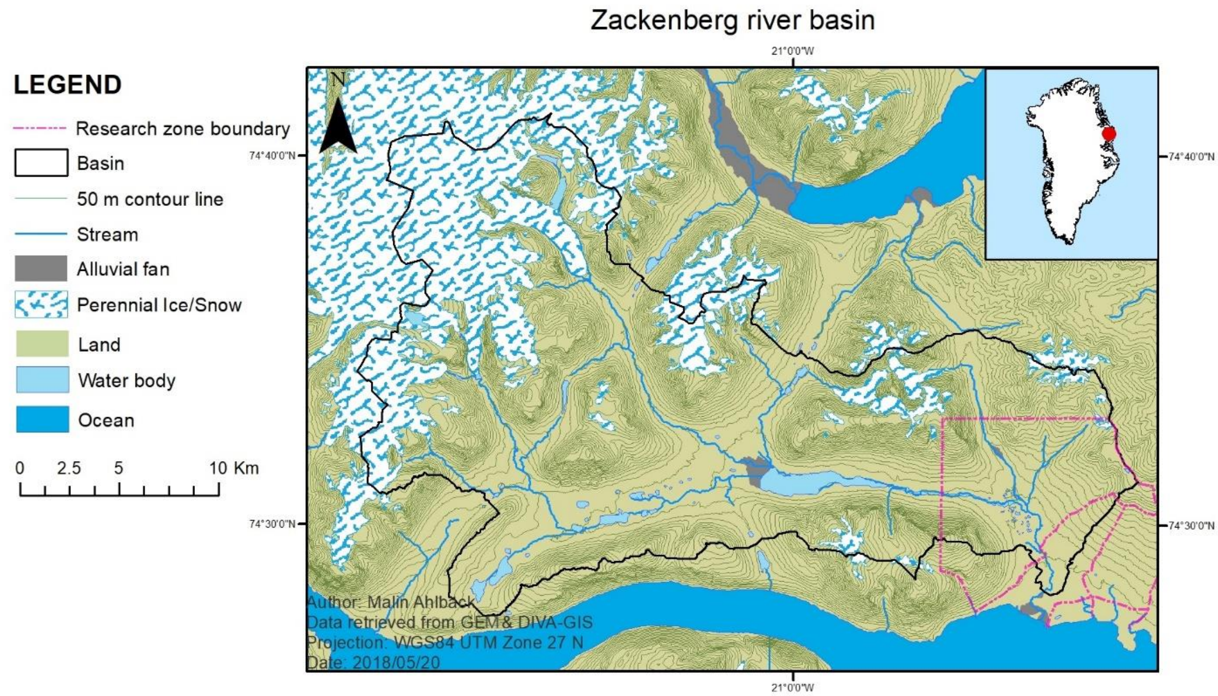

Figure 1. The studied catchment of the Zackenberg river and the extent of Zackenberg research station.

The catchment is divided by a fault zone with sandstones overlaid by basalts to the east, and gneissic and granite bedrock to the west (Koch and Haller 1971). The Zackenberg river is flowing in the central part of the catchment, from the glaciated western region down to the eastern fjord outlet in Zackenbergdalen. The river regime can be classified as purely glacial close to the A.P. Olsen ice cap, while the remaining is classified as glacio-nival, characterized by short and violent flooding in spring from thawing, and great daily-, annual-, and inter-annual variability (Pard´e 1955; Mernild et al. 2008). The streams from the western part of the basin connect to the lake Store Sø, through a large delta mainly built by sediment from glacier streams (Hasholt et al. 2008).

The active layer reaches its maximum depth around August, when it varies from about 40 to 80 cm (between 1999–2001) (Christiansen et al. 2008). The catchment in Zackenberg is underlain by a continuous layer of permafrost, meaning an extensive coverage of between 90 – 100%, estimated to be about 300 m thick (Meltofte and Rasch 2008).

3.2 DATA

The required inputs to the SWAT model are recordings of meteorological data, spatial data of land- and soil cover, and a Digital Elevation Model (DEM). Table 1 shows a summary of the different datasets used for setting up the model, as well as observed data used for model validation. All spatial data was projected in WGS84 UTM zone 27 N.

Table 1. A summary of the data used for setting up and validating the model.

Data type	Year(s)	Resolution	Source
DEM	-	5 m	Aarhus University, department of Bioscience
Land cover	-	-	ZERO project, http://zackenberg.dk/maps/
Soil cover	1974	1:5 000 000	FAO/UNESCO - Soil map of the World v. 3.6 http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/faounesco-soil-map-of-the-world/en/
Soil Parameters	-	-	FAO - Harmonized World Soil Database v. 1.2 (HWSD) http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Weather data	1995 – 2013	-	ASIAQ – Greenland survey, ClimateBasis http://data.g-e-m.dk/
	1979 – 2013	0.5 º	NCEP - CFSR dataset https://globalweather.tamu.edu/#pubs
River discharge	1999 – 2013	-	ASIAQ – Greenland survey, ClimateBasis http://data.g-e-m.dk/

3.2.1 Meteorological data

SWAT runs on weather data recordings of daily measured air temperature (º C), solar radiation (MJ/m^2/day), relative humidity (%), precipitation (mm), and wind speed (m/s). Recordings of weather data was obtained from the Greenland Ecosystem Monitoring (GEM) database (http://data.g-e-m.dk), provided by ASIAQ - Greenland Survey, Nuuk, through the ClimateBasis programme. The Zackenberg climate station dataset is compromised by the two almost identical climate stations 640 (74°28’18.9”N, 20°33’7.5”W, 44 m a.s.l.) and 641 (74°28’18.8”N, 20°33’8.6”W, 43 m a.s.l.), meant to ensure complete time series even when data outage from one mast. All parameters used for this project are measured at both stations, however, station 640 is the station primarily used for obtaining data of air temperature and relative humidity, using a sensor of type Vaisala, HMP 45D (Vaisala Oyj, Helsinki, Finland), and radiation, using Kipp & Zonen CM7B (Kipp & Zonen, Delft, Netherlands) sensor. Station 641 is primarily used for retrieving wind speed (sensor type Met One C034B, Met One Instruments Inc., Washington, USA) and precipitation, using the weighing gauges Belfort 5915 (Belfort, Baltimore, USA) and PLUVIO (OTT Hydromet, Kempten, Germany)), which weight every 60 min. Both stations have their sensors mounted 7.5 m above the terrain (apart from the precipitation gauges), on masts installed in 1995 (ClimateBasis 2010).

Data of wind speed, temperatures, and relative humidity from Zackenberg climate station were averaged into daily means, while precipitation and solar radiation data were summed into daily totals. The readings were thereafter plotted against the Climate Forecast System Reanalysis (CFSR) dataset, provided by the National Centers for Environmental Prediction (NCEP) (Saha et al. 2010). This dataset, hereby referred to as CFSR, has daily recordings from year 1979 to 2013, with reanalysed grid data at a 0.5º resolution. The CFSR dataset is based on historical and operational archives of observations, and operates on a coupled atmosphere-ocean model at a 6 h resolution, together with an interactive sea ice model and radiance data obtained from satellite images (Saha et al. 2010). The datasets were compared in terms of annual means and Coefficient of determination (R^2) (see chapter 3.6) values for each of the five weather readings (air temperature, solar radiation, relative humidity, wind speed, and precipitation) and the CFSR dataset was adjusted to be as close to observations from the climate station as possible. The adjustment was done by removing a chosen fraction of each daily value, based on the above-mentioned comparisons. This was done in order to prolong the spin-up period for the SWAT model, as well as to incorporate missing values in the dataset from the Zackenberg climate station. The missing data was often present as gaps of a few days, but sometimes for up to full months during winter and the start of season in May.

3.2.2 River discharge measurements

The hydrometric station to the Zackenberg river drainage basin is located about 2 km upstream from the river outlet at an altitude of 15 m. The station is part of the ClimateBasis program, operated by ASIAQ - Greenland Survey. The annual period of measurements in the river is varying from around the beginning to end of June, to the end of August/beginning of September (ClimateBasis 2010).

The hydrometric station takes automatic water level measurements every 15th minute, using a sonic ranging sensor mounted on the bridge, two pressure transducers, and a staff gauge. Readings on the staff gauge is manually carried out twice a day and related to a high system on land based on reference points. Discharge measurements are carried out across a fixed cross-section in close connection to the hydrometric station to establish a Q/h (river discharge (m^3/s)/water level (m)) relationship, using an Acustic Doppler Current Profiler (ADCP) of the type Qliner (OTT Hydromet, Kempten, Germany). Measurements are carried out in minimum 15 verticals and 3-4 depths. The reestablishment of Q/h relationships is performed 3 times every season (ClimateBasis 2010).

3.3 THE SWAT MODEL

The SWAT model uses Hydrologic Response Units (HRUs) as a technique to identify physically different hydrologic subunits. By using HRUs, the model can split subbasins into several smaller elements based on the Geographical Information System (GIS) layers' individual characteristics and thus use spatially varying parameters within the catchment. In SWAT, the HRUs are defined based on the combination of the three classes (1) Land use, (2) Soils, and (3) Slope. To define each HRU, a threshold is set based on the minimum areal cover a class must have in order to be classified as an individual entity (Arnold et al. 2013).

The hydrologic cycle as simulated by SWAT is based on the water balance equation (Eq. 1). The final soil water content is calculated as the difference in water entering the basin as precipitation, and the water leaving the basin as runoff, evapotranspiration, percolation, and return flow (base flow).

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

Eq. 1

t	Time in days
SW_t	Final soil water content
SW_0	Initial soil water content when $i = 0$
R	Total precipitation on day i
Q_{surf}	Daily surface runoff for day i
E_a	Daily evapotranspiration (ET) on day i
w_{seep}	Water percolating from the soil profile down to deep and shallow aquifers on day i
Q_{gw}	Total base flow on day i.

(All units are expressed in mm w.e. (water equivalent))

The water balance is calculated based on storage compartments within the model, using different algorithms of flows. These routines are not fully represented in the simplified Eq. 1, and is thus not reflecting the entire cycle as simulated by the SWAT model. The equation may therefore be seen as hydrologically incorrect (i.e. the balance does not add up); however, it is yet how the model is referred to in literature (e.g. Arnold et al. 1998; Arnold et al. 2013) and is accurately used for computations within the model.

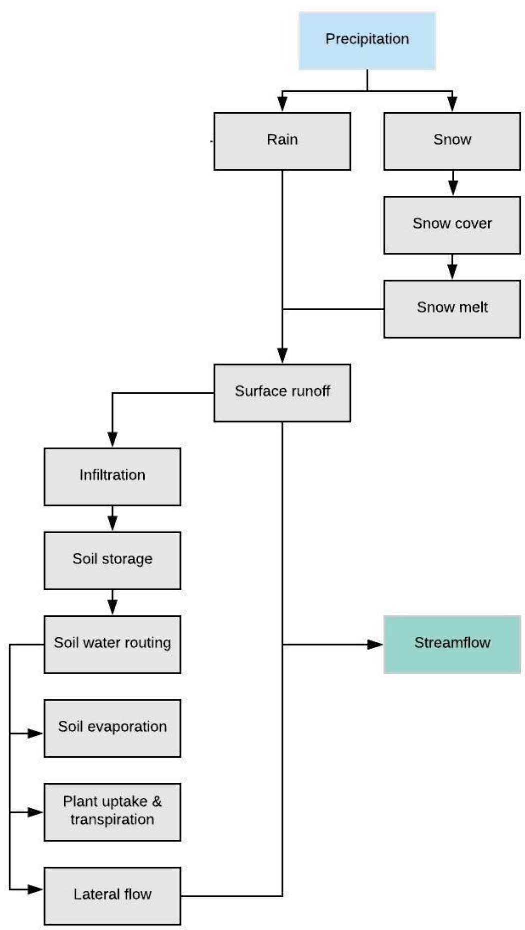

Figure 2. Representation of the modelled flows and storages used in SWAT for this project.

Infiltration is calculated as the difference between precipitation and snowmelt inputs and surface runoff. The initial rate of infiltration depends on the initial soil moisture content, and decreases as the soil layer becomes increasingly saturated. SWAT computes surface runoff using the SCS Curve Number (CN) equation (USDA-SCS 1972), where the CN value varies non-linearly with soil moisture content between an interval from 0 to 100. The CN value decreases (~0) as the soil reaches the wilting point of the soil, and increases to close to 100 as the soil approaches saturation, thus causing overland flow. Surface runoff then moves rather quickly to the stream, causing short-term stream response. The infiltrated water may take three possible routes. It may be stored within the soil profile as soil moisture and later evapotranspire, using Penman-Monteith equation (Monteith 1965). Second, it may percolate further down to shallow and deep aquifers, or, thirdly, slowly be transported as lateral subsurface flow to the stream. The model in this thesis conceptualizes permafrost dynamics by inserting an impermeable layer at a relatively shallow depth in the soil profile, thus causing no deep percolating to occur, subsequently ignoring groundwater flows in the system.

The lateral flow occurs in the upper soil profile above the permafrost layer (see chapter 3.5). A kinematic storage model (Sloan and Moore 1984), is used to predict lateral flow in each soil layer (maximum 10 layers may be defined), which depends on drainage volume of soil water, the soil porosity, and flow length. If the saturated zone rises above the soil layer, water may flow to the overlying layer. The algorithm is applied to each individual soil layer, starting at the uppermost layer. The soil temperature is calculated based on a function of damping depth (dependent upon the bulk density and soil water content), surface temperature, and mean annual temperature (Arnold et al. 1998). Lateral flow and infiltration are restricted when soil temperatures fall below 0 ºC, to simulate the decrease in infiltration and water flows during frozen conditions. However, if the soil is dry, percolation will be allowed.

3.3.1 The snow routine

The model uses the degree-day index to differentiate between snow- and rainfall, where a threshold is set at a temperature (º C) where rainfall and snowfall has equal chance of occurring. The precipitated snow is accumulated to a snow depth, thought of as a snow pack expressed in mm w.e., to simplify variations in density of the snow. To account for factors that contribute to variable snow coverage, the threshold above which there always will be 100 % snow cover in a subbasin may be specified by the user. This value is used in the areal depletion curve equation (Anderson 1976), to calculate the correlation between seasonal snow pack balance as a function of quantity of snow covering a HRU. Once the volume of water held in the snow pack exceeds the chosen threshold, the depth of the snow cover is assumed to be uniform.

The snow pack balance is calculated based on the fluxes of snowfall, sublimation, and snowmelt, by which the depth grows with additional snowfall, and decreases through sublimation and snow melt. The snow melt is calculated according to Eq. 2 (Arnold et al. 1998):

$$SNO_{mlt} = b_{mlt} \cdot sno_{cov} \cdot \left\lfloor \frac{T_{snow} + T_{mx}}{2} - T_{mlt} \right\rfloor$$

Eq. 2

SNO_{mlt}	Amount of snow melt on a given day (mm w.e.)
b_{mlt}	Melt factor for the day (mm w.e./º C)
sno_{cov}	Areal fraction of the HRU covered with snow

T_{snow}	Snow pack temperature on a given day (º C),
T_{mx}	Maximum air temperature on a given day (º C), and
T_{mlt}	Base temperature above which snow melt is allowed

T_{snow} is computed as a function of the previous day's snow pack temperature, a snow temperature lag factor, and the mean air temperature of the simulated day. T_{mlt} may be specified by the user. The amount of snow is therefore strongly depending on temperature. The snow melt is treated in the same way as rainfall (i.e. included in calculations of runoff and percolation), and is assumed to be uniformly distributed over the 24 hours of the day.

3.4 MODEL SET-UP

The DEM was used for the catchment and stream network delineation process, where a flow accumulation threshold value of 500 Ha (corresponding to 20 000 raster cells) was used to obtain stream network. With the set threshold for stream delineation, 42 outlet points, and thus also subbasins, were identified by the SWAT model at each water divide (Figure 3). The drainage point for the entire watershed was placed close to the fjord outlet, at the same location as the hydrometric station.

The two soil types Gelic Regosols and Glacier were identified (Figure 3). The Homogenized World Soil Database (HWSD) for soil parameters, provided by Food and Agriculture Organization of the United Nations (FAO) (see Appendix 8.2 for further details), was imported to the model and connected to the two soil cover classes.

The land cover layer was classified into the three classes Barren, Range Grasses and Water (Figure 3), based on the Land Use/Land Cover (LULC) database available in the SWAT 2012 database. SWAT is missing classes with adjoining parameters for glacier cover and Arctic tundra, thus, these areas were classified as Water and Range Grasses respectively, based on recommendations from the SWAT community and estimated suitability of their parameters (see appendix 8.2).

The DEM was classified into three slope classes, where the following ranges were used, based on identified thresholds for "natural breaks" in ArcGIS: ≤ 5%, 5 – 20%, and 20% ≤.

The land use, soil, and slope classes were thereafter used for HRU definition. The thresholds for minimum areal coverage for each class were set as 10% for soils, and 20% for land use and slope, based on recommendations by Arnold et al. (2013). With these thresholds, 153 HRUs were identified, with in average 3.5 HRUs in each subbasin.

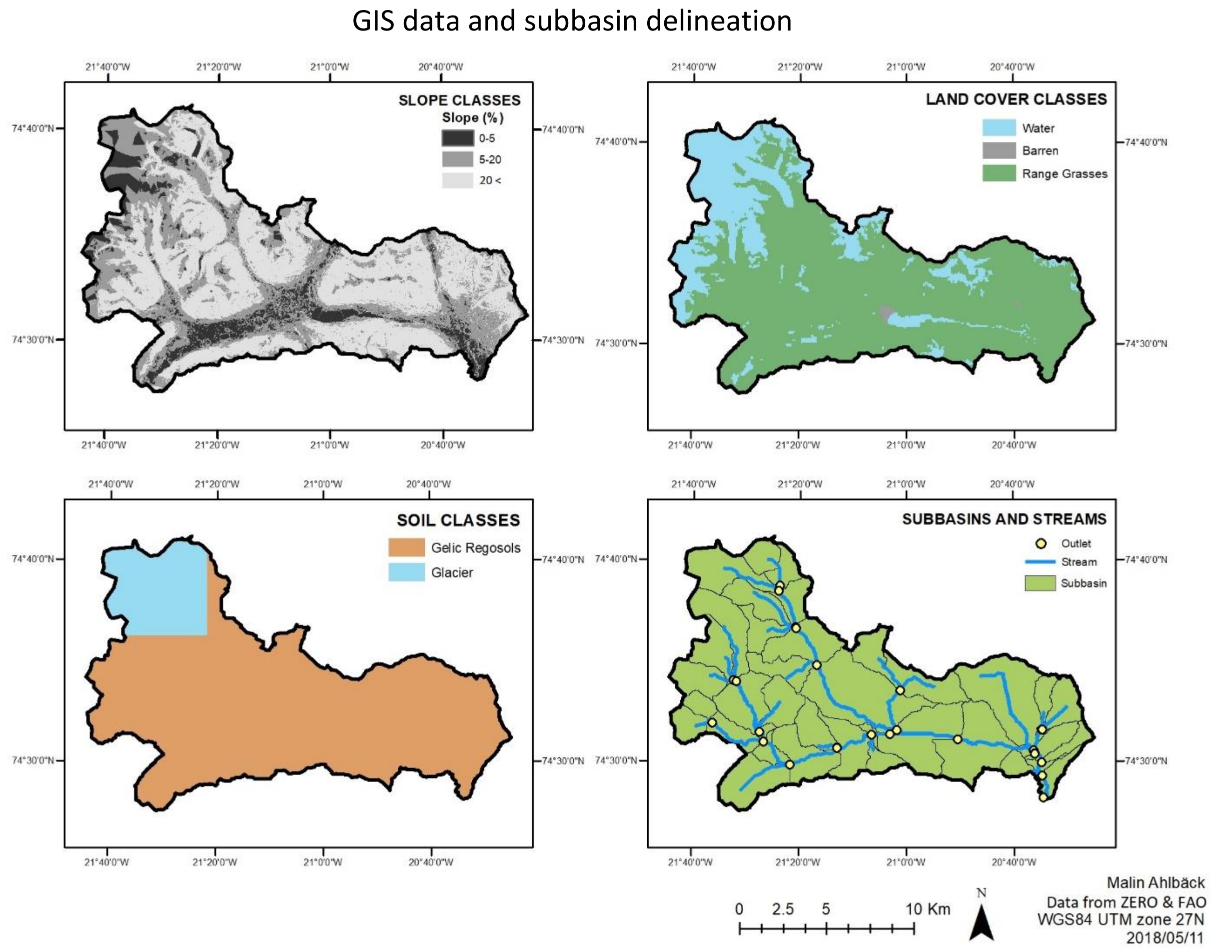

Figure 3. The classified spatial data and the delineated subbasins used for model-run.

3.5 Parameterization

Parameters for incorporating permafrost depth and glacier volumes were the two features that were assigned pre-set values before calibration. An impermeable soil layer was inserted in the model to assimilate the depth to the permafrost, a method previously used by Fabre et al. (2017) and Hülsmann et al. (2015). When water percolating through the soil profile reaches the layer of low hydraulic conductivity, ponding at the surface of the impervious layer occurs, and water is redistributed in the upper soil profile. The maximum thawing depth in Zackenberg is on average 63 cm (1997–2004) (Rasch and Caning 2005). Because SWAT does not include temporal parameterization, half of the maximum depth (31.5 cm) was chosen as modelling depth throughout the entire simulation.

In order to assimilate the glacier cover in the model, an initial snow pack depth of 1000 m w.e. was inserted in subbasins corresponding to the A.P. Olsen glacier extent (i.e. the subbasins classified as Water, see Figure 3). A total of 8 subbasins along the western boundary of the watershed were covered, a total area of 100.8 km^2, closely corresponding to the actual glacier coverage of 101 km^2. Because the SWAT model only uses the initial snow pack value the first year of the model run, in this case 1979, an excessive glacier depth was used to ensure that the glacier extent was kept throughout the simulation, until the final year in 2013. Thus, this value was not reflecting the actual glacier volume, but was solemnly used as a method for glacier melt estimation.

3.6 CALIBRATION AND MODEL PERFORMANCE EVALUATION

The model was initiated with a spin-up period of 20 years until 1999. Thereafter, it was split in two parts and evaluated by comparing simulated *vs*. observed river discharge from the hydrometric station. The years 1999 - 2006 were applied for the calibration process, and the years 2007 - 2013 were set aside for a final validation of the model.

The model was set-up and run in arcSWAT on a daily basis. Thereafter, the simulation was imported into SWAT-CUP automatic calibration and validation tool. SWAT-CUP offers four different algorithms to compute uncertainty analysis, each having slightly different approaches. The algorithm applied for this thesis was Sequential Uncertainty FItting algorithm (SUFI-2), which is a stochastic calibration tool, giving a range of possible solutions for the combination of parameters (Abbaspour et al. 2004). The main reason for choosing SUFI-2 amongst the available algorithms in SWAT-CUP, was because it has been found to require the least model runs to achieve good prediction uncertainty ranges (Yang et al. 2008), and thus less time consuming. The calibration was set with 200 model runs for 4 iterations, in total 800 runs, to find the optimal parameters. A recommended minimum of model runs per iteration are 500 (Abbaspour et al. 2017), but due to time limitations, this value was reduced.

The chosen parameters to be calibrated can be seen in table 2, together with their final calibrated value. The parameters chosen were based on papers by Fabre et al. (2017), Feyereisen (2007), and Hülsmann et al. (2015). The 8 parameters for snow were calibrated first and then removed from further iterations, as recommended by Abbaspour et al. (2017). Because the model assumes no groundwater flow, these parameters were not considered for calibration.

Table 2. The chosen parameters for calibration and validation in SWAT-CUP.
* 1: Replace value; 2: Relative change (1 + value).

Parameter	Description	Variation Rule*	Default Value	Calibrated Range	
SFTMP	*Snowfall temperature (°C)*	1	1.0	-5.1	24.7
SMFMN	*Melt factor for snow on December 21 (mm H_2O/°C-day)*	1	4.5	0.1	3.0
SMFMX	*Melt factor for snow on June 21 (mm H_2O/°C-day)*	1	4.5	-0.7	2.7
SMTMP	*Snow melt base temperature (°C)*	1	0.5	-9.7	11.7
SNO50COV	*Fraction of SNOCOVMX that corresponds to 50% snow cover*	1	0.5	0	0.5
SNOCOVMX	*Minimum snow water content that corresponds to 100% snow cover (mm H_2O)*	1	0	60.6	253.3
TIMP	*Snow temperature lag factor*	1	1.0	0.3	1.0
CH_K2	*Effective hydraulic conductivity in main channel alluvium (mm/h)*	1	0	130.6	294.3
ESCO	*Soil evaporation compensation coefficient*	2	0.95	0.5	0.8
LAT_TTIME	*Lateral flow travel time (days)*	2	0	101.0	145.1
OV_N	*Mannings "n" value for overland flow*	2	0.15	36.1	48.8
SOL_AWC	*Available water capacity of the soil layer (mm H_2O)*	2	0.175	0.6	0.8
SURLAG	*Surface runoff lag time (h)*	2	4	27.2	35.1

The daily simulated river discharge of the non-calibrated model, the calibrated model (years 1999-2006), and the validation run (years 2007-2013), in total 3 simulations, were evaluated using Nash-Sutcliff Efficiency (NSE) (Eq. 3) (Nash and Sutcliffe 1970) and the Coefficient of Determination (R^2) (Eq. 4). The non-calibrated model was evaluated before calibration to ensure the model set-up was sufficient, meaning it managed to capture the general flow and physical processes, before calibration. The calibration was thereafter evaluated after every iteration to follow improvements in model performance. The validation run was used to objectively evaluate whether the set-up model could successfully simulate years outside the calibration period.

$$E = 1 - \frac{\sum_{t=1}^{T} (Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})^2}$$

Eq. 3

$$R^2 = \frac{\left[\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})(Q_m^t - \overline{Q_m})\right]^2}{\sum_{t=1}^{T} (Q_o^t - \overline{Q_o})^2 \sum_{t=1}^{T} (Q_m^t - \overline{Q_m})^2}$$

Eq. 4

Where,
Q_o = Observed value
Q_m = Modelled value
t = Value at time t
T= End time

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). The calculated *E* thus gives an efficiency value of agreement between observed and modelled data. A value of 1 indicate a perfect fit between the model and the observations, while efficiency values less than 0 indicate that the observed mean is a better predictor than the model (Nash and Sutcliffe 1970). R^2 represents the proportions of total variance of the measured data that can be explained by the modelled data. As with NSE, values close to 1 represent better model performance.

There is generally no scientific agreement for when a hydrologic model is regarded adequate, and when it should be rejected. However, as an assumption for this thesis, supported by literature, values for NSE and R^2 higher than 0.5 are seen as acceptable values for accepting calibration and validation results on a daily time step (2007; Moriasi et al. 2015).

4 RESULTS

The following first section will focus on the seasonal patterns found in the hydrology in the Zackenberg river basin, and how these relate to each other. The second section introduce results found from weather data adjustments, and last, the model is evaluated based on statistical tests and previous studies conducted in the area.

4.1 ANNUAL PATTERNS IN WATER FLOW

The simulated fluxes were found to be closely linked to patterns in temperature, subsequently influenced by the seasonal insolation budget (Figure 4). Mean temperatures exceed 0 ºC around mid-May, and fall below freezing again in end of September, marking the main season for active water flow in the Zackenberg river basin.

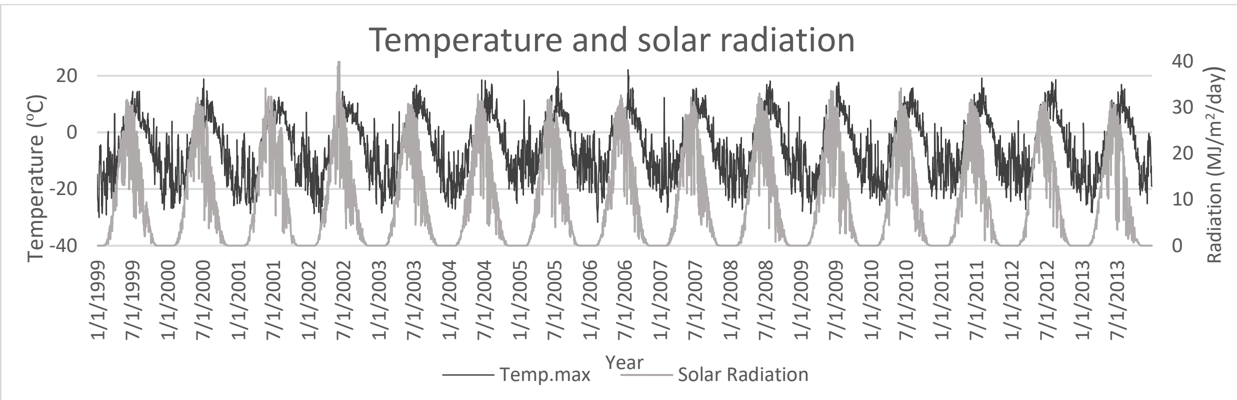

Figure 4. Input data of daily solar radiation and maximum temperature for the years 1999 - 2013.

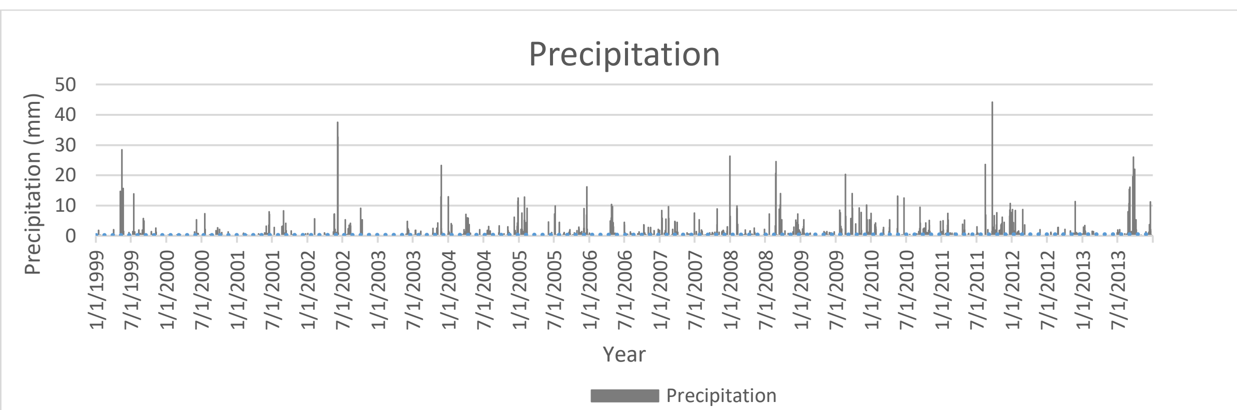

Figure 5. Input data of daily precipitation for the years 1999 – 2013. For better details, see Appendix 8.3.

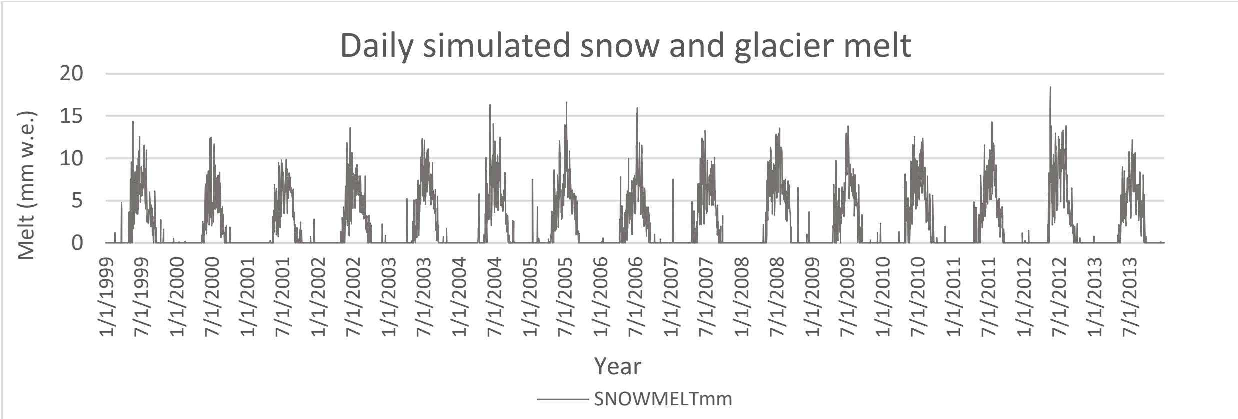

Figure 6. The simulated melt from glaciers and snow, for the years 1999 – 2013.

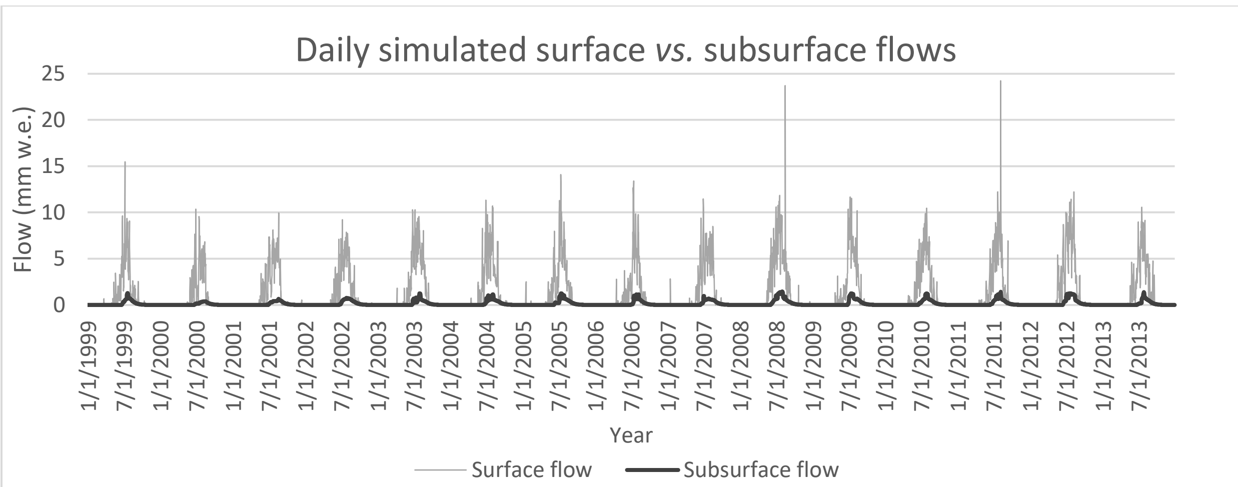

Figure 7. The simulated surface- and subsurface flow between the years 1999 – 2013.

Warmer temperatures in spring are followed by a rapid snow- and glacier melt water release (see Figure 6), peaking in end of June/mid-July, but was found to start already in early April. Surface- and subsurface flow indicated a similar pattern, implying runoff is mainly partitioned from glaciers and snow cover compared to precipitation. However, as seen in Figure 7, the two high peaks in 2008 and 2011 may be results from precipitation events. Surface runoff occurred earlier in the season than subsurface flow, due to the frozen state of the soil that did not exceed 0 ºC until around beginning of June in the model, and thereafter allowed infiltration.

The SWAT model includes sublimation in its final simulation of ET. Sublimation occurs when snow cover is present in the basin, i.e. from mainly October to May, but is in general much lower than ET, as seen in Figure 8. ET rapidly increases to a daily average of 0.5 - 1 mm w.e./day as snow cover melts and temperatures increase. The soil water content, being the sum of the simulated fluxes, is naturally following the same annual pattern, however, to a lower extent. Note that the soil moisture is based on an average of all subbasins within the watershed.

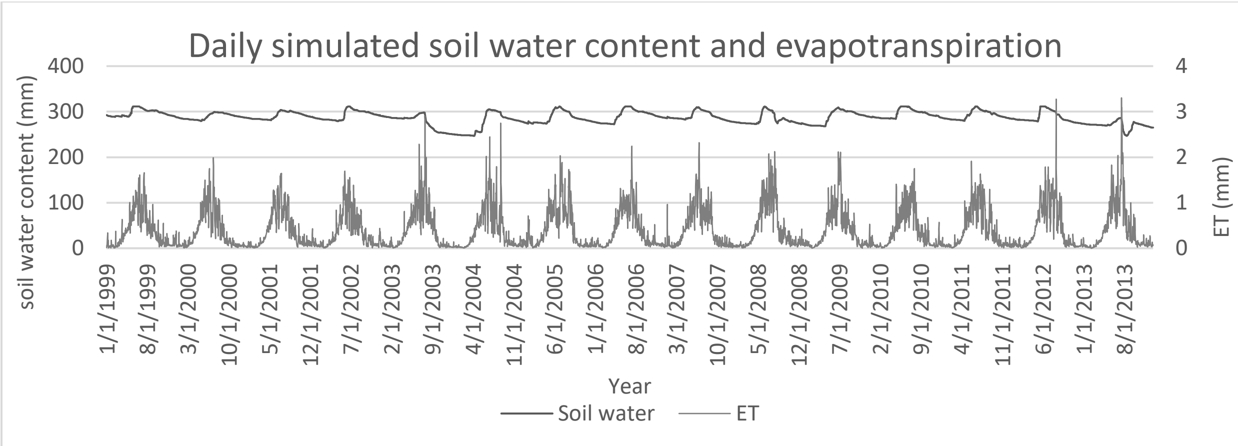

Figure 8. The simulated soil water content and ET (average of all subbasins).

The beginning of seasonal river flow in Zackenbergdalen occurs in mid-May/beginning of June and lasts until mid-September/October. The average river discharge during high flow (June – August) is 22.5 m^3/s for the simulation, and 23.5 m^3/s for observations (1999 – 2013), with the highest discharge rates commonly occurring in July (Figure 9 and 10).

Extreme flood events, indicated by the strong peaks in 2002, 2005 (calibration period, Figure 9), and 2007, 2009 (validation period, Figure 10), often occurring during a course of a few days, were largely underestimated or completely missed by the model. As seen in Figure 6 of simulated snow- and glacier melt, these peaks are not reflected, but can however be discovered in the meteorological time series for all years except 2009. The high river discharge peak in 2002 appears after days of strong solar radiation, adjoined by a rainfall event (Figure 4 and 5), while the discharge peaks in 2005 and 2007 seem to be a product of warmer days, where both events occurred shortly after relatively high maximum temperatures above 20 ºC (Figure 4). The peak in 2011 is occurring simultaneously with higher precipitation, also reflected in the surface runoff simulation (Figure 7).

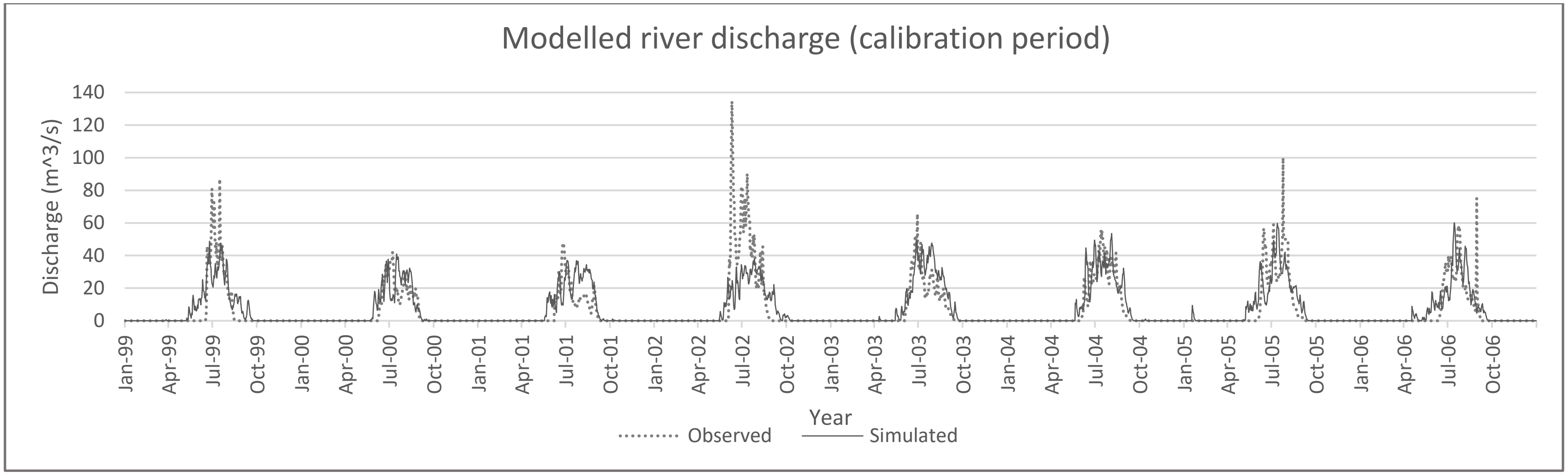

Figure 9. The simulated river discharge compared to observed river discharge at the outermost point in the catchment for the calibration period.

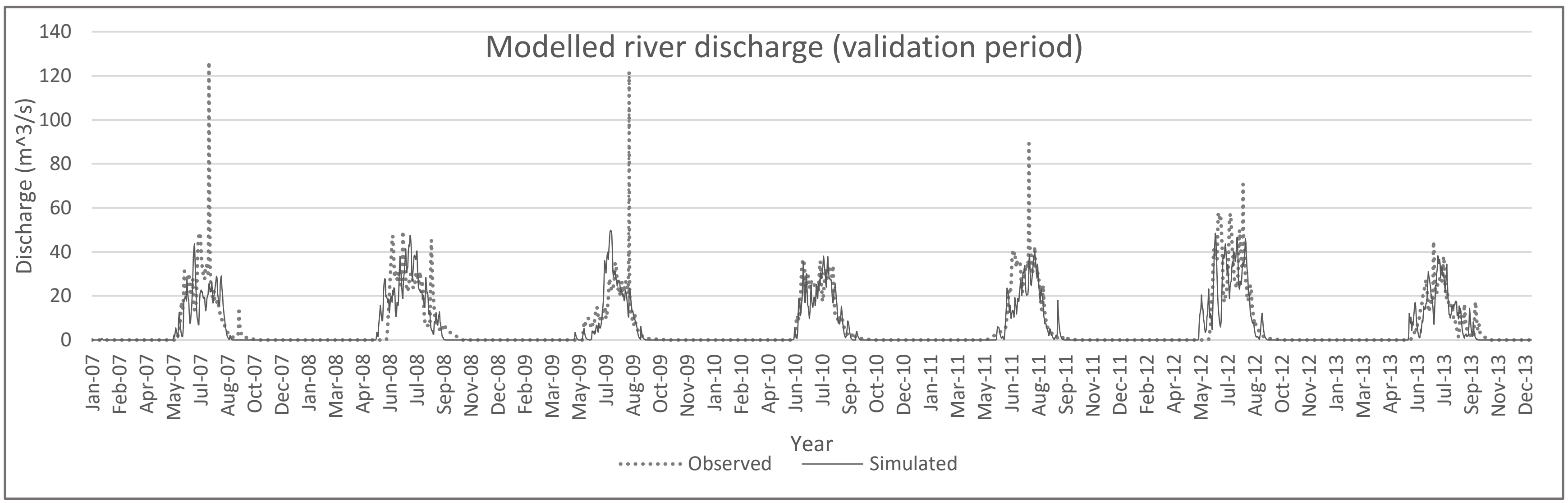

Figure 10. The simulated river discharge compared to observed river discharge at the outermost point in the catchment for the validation period.

4.2 WEATHER DATA ADJUSTMENTS

The annual weather pattern of the CFSR dataset closely corresponds to the Zackenberg climate station dataset (hereby referred to as CS) for the readings of solar radiation and temperature, while wind speed and relative humidity showed less accuracy, and precipitation little correspondence (Figure 11). In terms of wind speed and relative humidity, the values were within the same range for both datasets, but CFSR does not manage to capture short-term variations. For precipitation, the CFSR dataset recorded larger amounts of precipitation during summer compared to the CS data.

Adjustments were done for CFSR readings of temperature and precipitation, where 20% was removed to be within the same range as the CS data. The CFSR dataset was thereafter incorporated to account for missing values in the CS dataset and to be used for the spin-up period in the model. However, in terms of precipitation, the resulting adjusted data from CS used as final model input, yet indicate a up to 26 % underestimation of precipitation compared to mean annual values for the same years obtained by Jensen et al. (2014).

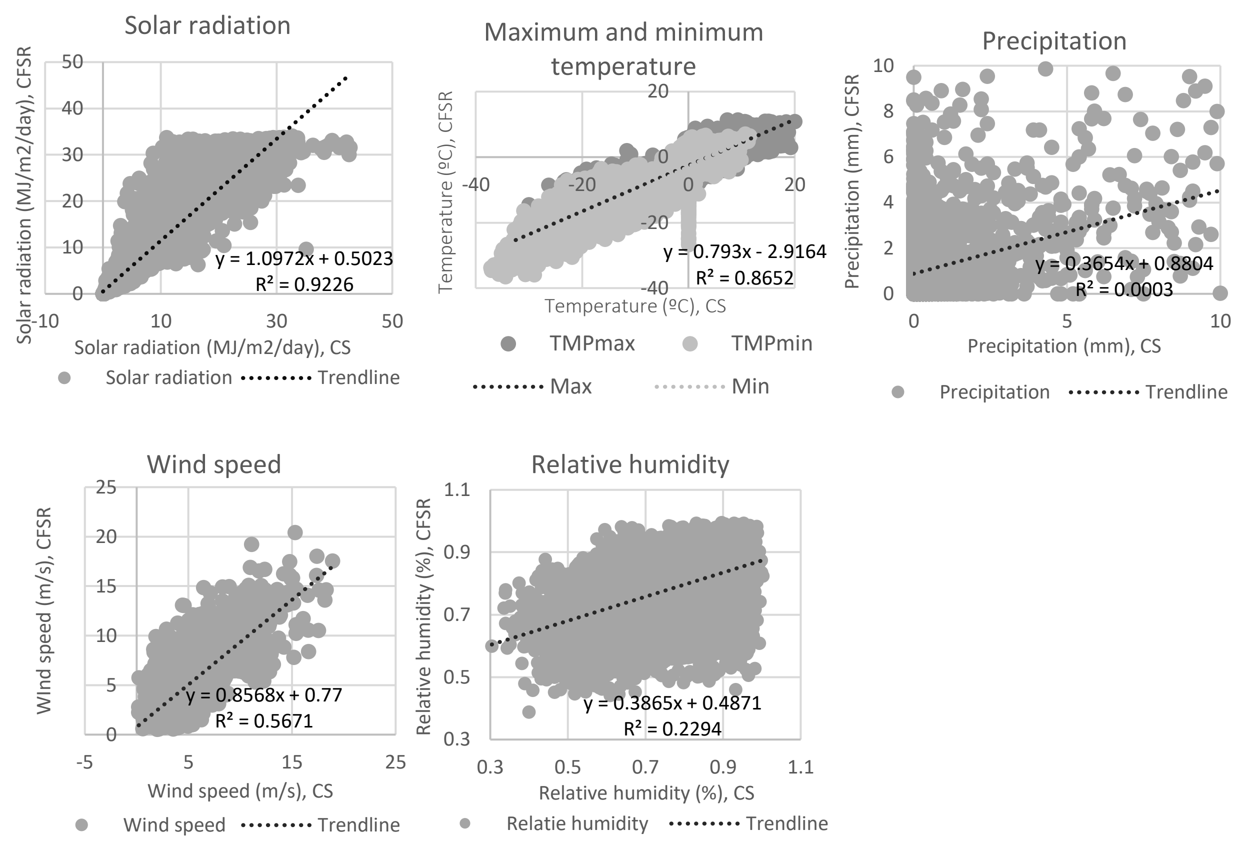

Figure 11. Scatter plots of the two weather datasets CFSR and Zackenberg climate station (CS) for the respective reading, between the years 1999 to 2013.

4.3 Evaluation of model performance

To validate the model, simulated discharge of daily values was compared against the observed discharge at the Zackenberg river hydrometric station for the years 1999 – 2013, where the years 2007 – 2013 were applied for model validation. The simulated discharge has a mean of 19.5 m^3/s during high flow period (June – August) for the validation period, 9% smaller than the observed value of 21.5 m^3/s. The resulting model explains the observations with a NSE = 0.62 and R^2 = 0.62 (Table 3) for the full season, indicating it met the set expectations (NSE/R^2 > 0.5) for model validity.

Table 3. The obtained Nash-Sutcliffe Efficiency (NSE) and Coefficient of determination (R^2) value for the calibration period (1999 – 2006) and validation period (2007 – 2013).

	NSE	**R^2**
Calibration period	0.56	0.57
Validation period	0.62	0.62

Compared to observations, the model simulated the start of seasonal flow on average 11 days too early. This trend holds true for all years except 2011, when it instead times the flood 11 days late. For the end of season, the model has a larger error of in average 13 days, and especially for the first two years 2007 and 2008 (Table 4).

Tabell 4. A comparison between the seasonal start and end of river discharge for Zackenberg river.
*: Defined as flows above 1 m^3/s

		Year						
		2007	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Start of season*	**Observations**	3-Jun	8-Jun	22-May	2-Jun	16-May	7-Jun	2-Jun
	Model	26-May	21-May	8-May	2-Jun	27-May	20-May	27-May
	Difference (days)	*8*	*18*	*14*	*0*	***-11***	*18*	*6*
End of season*	**Observations**	4-Oct	13-Oct	13-Sep	17-Sep	15-Sep	16-Sep	10-Oct
	Model	4-Sep	16-Sep	5-Sep	10-Sep	18-Sep	14-Sep	22-Oct
	Difference (days)	***30***	*27*	*8*	*7*	*-3*	*2*	*-12*

The annual precipitation partitioning simulated by the model was about 75% snowfall (133 mm w.e.) and 25% rainfall (45 mm w.e.) for the years 2007 – 2013 (Figure 12). In a study by Hansen et al. (2008) over the Zackenberg region, roughly 10% was estimated to come from rainfall, 70% from snowfall, and 20% was mixed precipitation. As indicated in Figure 12, the model tends to overestimate rainfall in winter, and snowfall during summer season.

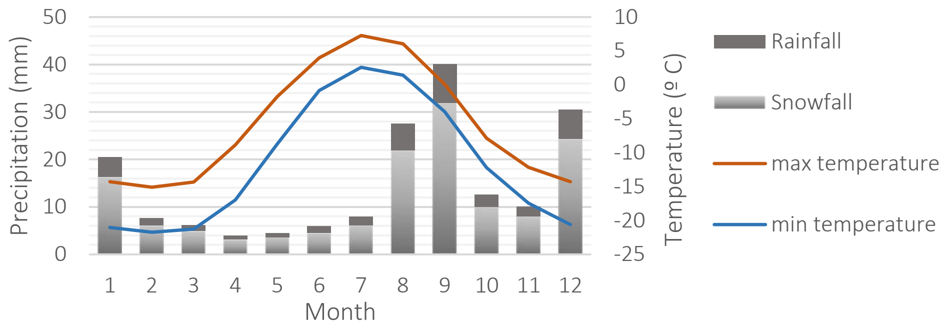

Figure 12. The simulated annual mean precipitation pattern between rainfall and snowfall, for the years 2007 – 2013.

Table 5. The annual mean flows of water within the catchment (509 km^2) for the years 2007 – 2013.

	Total mean (mm w.e./year)
Precipitation	177.7
Rainfall	44.7
Snowfall	133.0
Total snow and glacier melt	565.0
Snowmelt *(excl. Glacier cover)*	96.0
ET	146.0
Sublimation	28.7
Total water yield	363.5
Surface runoff	307.2
Subsurface flow	56.3
PET	266.3

Glacier melt contributed to an annual mean of 930 mm w.e., where it varies from a minimum of 832 mm w.e. in 2013, to a maximum of 1135 mm w.e. in 2008. In a study by Mernild et al. (2007), glacier meltwater was estimated to an average of 1198 mm w.e./year, ranging from 709 – 1723 mm w.e./year (2001-2005).

Snowmelt contributes to an annual total mean of about 96 mm w.e., excluding snowmelt occurring on glaciers, corresponding to an area loss of 101 m^2 (~20% of the catchment) (Table 5). As compared to a previous study using SnowModel over the basin, annual snowmelt values were estimated to vary between 75 mm w.e. to 372 mm w.e., averaging 207 mm w.e. over the entire catchment (2001-2005) (Mernild et al. 2007). Sublimation losses from the same study by Mernild et al. (2007), was estimated to an annual mean of 31 mm w.e., in contrast to the modelled 29 mm w.e. (Table 5).

The major pathway for rainfall, snowmelt and glacier melt was direct runoff, which contributes to about 40% of the flow. About 18% of the water reaching the soil surface is infiltrated to the impermeable layer and redistributed in the upper soil profile, or slowly flowing as lateral flow to the stream. According to Elberling et al. (2008), mean annual evapotranspiration (ET) rates from station Zackenberg was 106 mm w.e. for the years 1997 – 2005 (excluding sublimation) implying a 13% difference compared to modelled values for the period 2007 – 2013. The mean soil water content was found to be 285 mm/year (mean of all subbasins) (see Appendix 8.2 for soil description), indicating the soil profile is in general constantly saturated.

5 Discussion

5.1 Evaluation of modelled surface water flows

5.1.1 River discharge

The model deviates as compared to observed discharge for beginning and ending of season about 11 - 13 days too early, with the largest difference between observed and modelled timing of stream flow of 30 days, occurring in autumn 2007. The general difference between the model and observations may be connected to a too early snowmelt from snow cover and glacier; the modelled melt season starts in end of April/mid-May, while literature rather estimates it to occur mid-May/beginning of June (Mernild et al. 2007), thus causing river flows to shift earlier in the season. However, it should also be noted that discharge measurements from the Zackenberg river is inconsistent due to its frozen state for most of the year, making measurements of seasonal start/ending time rather a subject of practical reasons and logistics. As Mernild et al. (2008) concluded, it is therefore not suitable to compare discharge for the entire season, but should be evaluated between known intervals.

The model fails to capture the extreme river discharge events, that were suggested in the meteorological data. However, the reason for the large discharge releases may be caused by glacier lake outburst floods from the A.P. Olsen glacier. This would furthermore explain why the extremes were not seen in the modelled snow- and glacier melt, because the release of water was rather the subject from long-term accumulation. To capture such dynamics, more observations from the glacier would have been required, and specifically improved algorithms for glacier mass balance routines. Furthermore, SWAT is a continuous time model, i.e. its simulated outputs are long-term yield. The model it therefore not properly designed to capture such single-event flooding (Arnold et al. 2013).

5.1.2 Snow and glacier dynamics

Glacier melt was shown to be within previously modelled ranges, but may imply a small underestimation compared to the study by Mernild et al. (2007), and to the river discharge modelling output, that was slightly lower than the observed. However, it should be noted that no observation data was used for glacier melt modelling for this study, making model performance of glacier dynamics rather biased to chosen model parameters and river discharge data. Based on the results, SWAT could be used as a simple tool to estimate glacier runoff, in particular in areas where glacier data is scarce, but to fully accomplish glacier melt, a similar methodology to Omani et al. (2017) should be applied, where data of Equilibrium Line Altitude (ELA) and glacier mass balance is incorporated to the SWAT model. This would lessen the uncertainty and furthermore improve applications of SWAT on Arctic catchments.

The modelled snowmelt was estimated to an annual mean of 96 mm w.e., about half the amount of previously simulated melt values obtained by Mernild et al. (2007). However, the resulting snowmelt from the glacier cover was removed from the value (~20 % of snow cover), because snow- and glacier melt was treated the same in the model and could therefore not be differentiated. The annual snowfall was estimated to an average of 133 mm w.e.. Previously estimated snow depths in Zackenberg was in average 241 mm w.e. for end of May - beginning of June, with a maximum of 396 mm w.eq. and a minimum of 144 mm w.e. (1995 – 2005) (Hasholt et al. 2008), indicating that snowfall was largely underestimated. The precipitation dataset used for the model was found to account for 26 % less precipitation compared to values from the paper by Jensen et al. (2014). This was furthermore found to be particularly evident for winter months, when summoning annual mean precipitation patterns to observed trends by Hansen et al. (2008). Thus, a large fraction of the snow input is not considered in the model, leading to underestimates of the snow pack and ultimately snowmelt. If additional precipitation data were to be added, together with the snowmelt occurring on glaciers, snowmelt may be closer to an accurate estimate. SWAT has previously been applied for snow modelling using the same methodology as this study involved with adequate results (Xuesong et al. 2008). However, as noted by several authors (e.g. Fontaine et al. 2002; Ahl et al. 2008; Xuesong et al. 2008), using elevation bands, i.e. taking topographically varying climate and snow distribution into account, increases snow modelling performance in SWAT noticeably.

5.1.3 Permafrost dynamics: Surface runoff, subsurface flow and surface water

SWAT has been developed for lower latitude modelling, thus, the algorithms for estimating heat transfer between the soil and the atmosphere is a simplified version with limitations for modelling of permafrost, something that has been highlighted by e.g. Fabre et al. (2017) and Hülsmann et al. (2015). This leads to difficulties to accurately estimate elements relating to surface flow, soil moisture storage, and lateral runoff, as these are largely influenced by permafrost thawing cycles. The SWAT model inhibits flow through the soil profile when soil temperatures fall below 0 ºC, thus assimilating the frozen state of the soil and inhibited infiltration to some extent. The modelled soil temperature exceeded 0 ºC in June, and went back to a "frozen" state around mid-September, implying the model captured the observed freeze – thawing seasonality in permafrost. Due to the impermeable layer inserted in the model, no groundwater flow is assumed beyond a depth of 315 mm. Because of the continuous, deep permafrost covering the high Arctic region, little groundwater flow occurs within the system, however, as cracks in the soil-ice interface still exists, this is a clear limitation present in the model conceptualization that should be noted.

A majority of the water reaching the surface was found to flow as direct surface runoff to the stream. The ratio between surface runoff and subsurface flow was estimated 82/18, indicating very little is infiltrated into the soil. A study made by Carey and Ming-Ko (1999) suggested a 60/40 ratio between surface and subsurface flow in regions characterized by permafrost, implying that the model largely overestimates surface runoff. This may be caused by the fixed depth to the impermeable permafrost layer, that is not representable for the active layer maximum in Zackenberg, reaching twice the modelled depth in August. Thus, a deeper layer may have better accounted for this. However, the study by Carey and Ming-Ko (1999) was performed in a sub-

Arctic watershed, with discontinuous permafrost, boreal forest, and different soil properties. Thus, it is possible to assume a slightly higher surface flow partitioning in Zackenberg.

The modelled soil water content indicates that the catchment in general experienced very wet conditions. Based on the results, the SWAT model greatly overestimates soil moisture, however, it should be noted that the soil moisture is based on means of all subbasins, of which some are covered with the land use water and the soil type glacier. As measured by Elberling et al. (2008), a majority of the fen areas, found at the valley floors, were constantly saturated, while in contrast, grass and heath plots across the slopes, had access to little soil moisture. This suggests that more detailed land cover data, more evaluation of soil- and land use parameters, together with using the SWAT routines for wetlands, would have been needed to fully evaluate soil moisture on a spatial scale.

5.2 SOURCES OF ERROR

Data input plays a leading role for being able to produce a model that successfully manage to capture the observed system. In this thesis, only one measured location of weather data was used, ultimately leading to extrapolation over an extensive area with large variations in topography. Additional weather observations, together with incorporation of lapse rates for temperature and precipitation, would have diminished error in input data and therefore also modelled results. Furthermore, as previously stated by Hansen et al. (2008), the Zackenberg climate station dataset underestimates snowfall during winter season, when the station is unattended and strongly influenced by wind noise. To better account for these losses, more weather data pre-processing may have been required.

Large generalisations were made for a wide range of parameters for the spatial coverage of soil and land use. Therefore, the obtained values for soil moisture may deviate due to inaccurate soil properties. Furthermore, the chosen depth of the active layer should have been set as the maximum depth of the active layer, instead of half, as ponding may occur too early in the model. In terms of land use, a better Land use classification for glacier cover other than Water may have been more accurate, as the class Water does not allow accumulation of a snow pack. This did not affect values of snowmelt considerably, as the class was more or less corresponding to the glacier extent, but yet contributes to an error. Furthermore, little attention was drawn to the LULC database, and how the chosen parameters for Range Grasses may affect the simulation. For future usage, better knowledge of these should be established before setting up the model.

A study made by Yang et al. (2008), showed that the different optimization algorithms in SWAT-CUP (GLUE, MCMC, ParaSol, and SUFI-2) each found a different solution at different locations in the parameter spaces with roughly the same river discharge simulations. Furthermore, Kouchi et al. (2017) also showed that usage of SUFI-2, GLUE, and ParaSol resulted in the identification of different parameters ranges but with similar validation results, which ultimately led to simulation of significantly different water routing. Automatic calibration is therefore, no doubt, a powerful tool for hydrologic modelling, but should be treated with equal precaution when calibration is based solemnly on river discharge measurements.

5.3 For further research

In terms of the conceptualisation and methods of this thesis, the main improvements to be made concern the three highly dynamic processes of annual glacier-, snow- and permafrost thawing. These had to be greatly simplified to meet the timeframe of this project. Using a similar methodology by Fabre et al. (2017) and Hülsmann et al. (2015), where the model is split up in seasons according to the large annual contrasts in hydrologic processes, could have reduced uncertainties regarding model performance on runoff and subsurface flow partitioning, percolation, and soil water storage. However, incorporation of a heat transfer algorithm such as the one developed by Hinzman et al. (1998) to the SWAT model, would furthermore greatly advance the application of the model to cold regions hydrology.

Incorporating elevation bands in the methodology, as suggested by several authors (Xuesong et al. 2008; Rahman et al. 2013; Grusson et al. 2015), would allow to better model the snow pack distribution and glacier mass balance in the catchment. Addition to this, parameterization based on separate subbasins, or even HRUs, could have further improved the calibration of snow and glacier melt, as shown by e.g. Ahl et al. (2008). As suggested by Abbaspour et al. (2017), a recommended minimum of model runs for a total of 2000 should be used for calibration of the model. In this thesis, a total of 800 runs were performed until a desired output was reached (NSE > 0.5), indicating the model may have potential for further improvements.

For future studies in Zackenberg river basin, improvements in data collection include establishment of an additional meteorological station further west in the catchment, which would lessen the error caused by extrapolating weather data from the Zackenberg valley research station. Furthermore, mapping of the vegetation across the entire basin would greatly improve modelling of the area.

6 CONCLUSION

The aim of this study was to examine the possibilities and limitations of using SWAT as a tool for hydrologic modelling in a high Arctic environment. Based on the obtained results, the null hypothesis can be rejected. To conclude the results of this study, it is evident that:

- SWAT can be used for modelling glacier melt dynamics, however, a parameterization based on observed glacier mass balance data may improve the physical settings for glacier melt estimations.
- Snow dynamics were not successfully modelled in this study. However, clear improvements in methodology, such as using elevation bands, and to separately calibrate snow parameters for different subbasins, may better account for snow distribution and melt.
- SWAT showed clear limitations in mimicking permafrost dynamics and was not successfully captured by the model. Therefore, the default model is not suitable for studies on permafrost, and an additional heat transfer algorithm should be coupled to the model to better capture annual changes in soil properties.
- To improve and simplify future usage of SWAT in polar- and mountainous regions, development of a dedicated database in SWAT is needed for; permafrost soils, where heat transmissivity and the like is better incorporated; complementing land use/land cover classes for Arctic vegetation cover.

The SWAT model may be used as a tool for hydrologic analysis in cold regions, but needs more input data, further considerations of parameters, and calibration than this study involved to be able to fully capture the seasonal dynamics and physical settings in Arctic hydrology. However, there are clear possibilities to be further developed for cold regions hydrologic modelling. Furthermore, the SWAT model is bridging the hydrologic cycle to biochemical processes and routing. This may opt for additional takes on changes in vegetation in tundra landscapes, or transport of sediments and nutrients in Arctic aquatic systems, relating to climate change scenarios.

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8 APPENDIX

8.1 SOIL PARAMETERS

Table 6. The used parameters for model set-up, obtained from HWSD and originally summarized by FAO.

		Soil class	
Parameter name	**Description**	**Glacier**	**Gelic Regosols**
NLAYERS	*Number of layers*	1	2
HYDGRP	*Hydrologic group, based on infiltration capacity*	D	D
SOL_ZMX	*Depth to root layer (mm)*	1524	880
ANION_EXCL	*Porosity, excluding anions (%)*	0.5	0.5
SOL_CRK	*Crack-flow factor*	0.5	0.5
SOL_Z1	*Depth of soil layer 1 (mm)*	1524	300
SOL_BD1	*Moist bulk density of layer 1 (Mg/m3)*	2.5	1.5
SOL_AWC1	*Available water capacity of layer 1 (mm H2O/mm soil)*	0.01	0.175
SOL_K1	*Saturated hydraulic conductivity of layer 1 (mm/hr)*	99	3.26
SOL_CBN1	*Organic carbon content of layer 1 (%)*	0	2
CLAY1	*Clay content of layer 1 (%)*	5	23
SILT1	*Silt content of layer 1 (%)*	25	37
SAND1	*Sand content of layer 1 (%)*	70	40
ROCK1	*Rock content of layer 1 (%)*	98	0
SOL_ALB1	*Soil albedo*	0.23	0.0103
USLE_K1	*USLE equation soil erodibility (K) factor for layer 1*	0.01	0.2393
SOL_Z2	*Depth of soil layer 2 (mm)*	0	1000
SOL_BD2	*Moist bulk density of layer 2 (Mg/m3)*	0	1.5
SOL_AWC2	*Available water capacity of layer 2 (mm H2O/mm soil)*	0	0.175
SOL_K2	*Saturated hydraulic conductivity of layer 2 (mm/hr)*	0	4.83
SOL_CBN2	*Organic carbon content of layer 2 (%)*	0	0.8
CLAY2	*Clay content of layer 2 (%)*	0	18
SILT2	*Silt content of layer 2 (%)*	0	38
SAND2	*Sand content of layer 2 (%)*	0	44
ROCK2	*Rock content of layer 2 (%)*	0	0
SOL_ALB2	*Soil albedo*	0	0.1047
USLE_K2	*USLE equation soil erodibility (K) factor for layer 2*	0	0.2393

8.2 Land use/Land Cover parameters

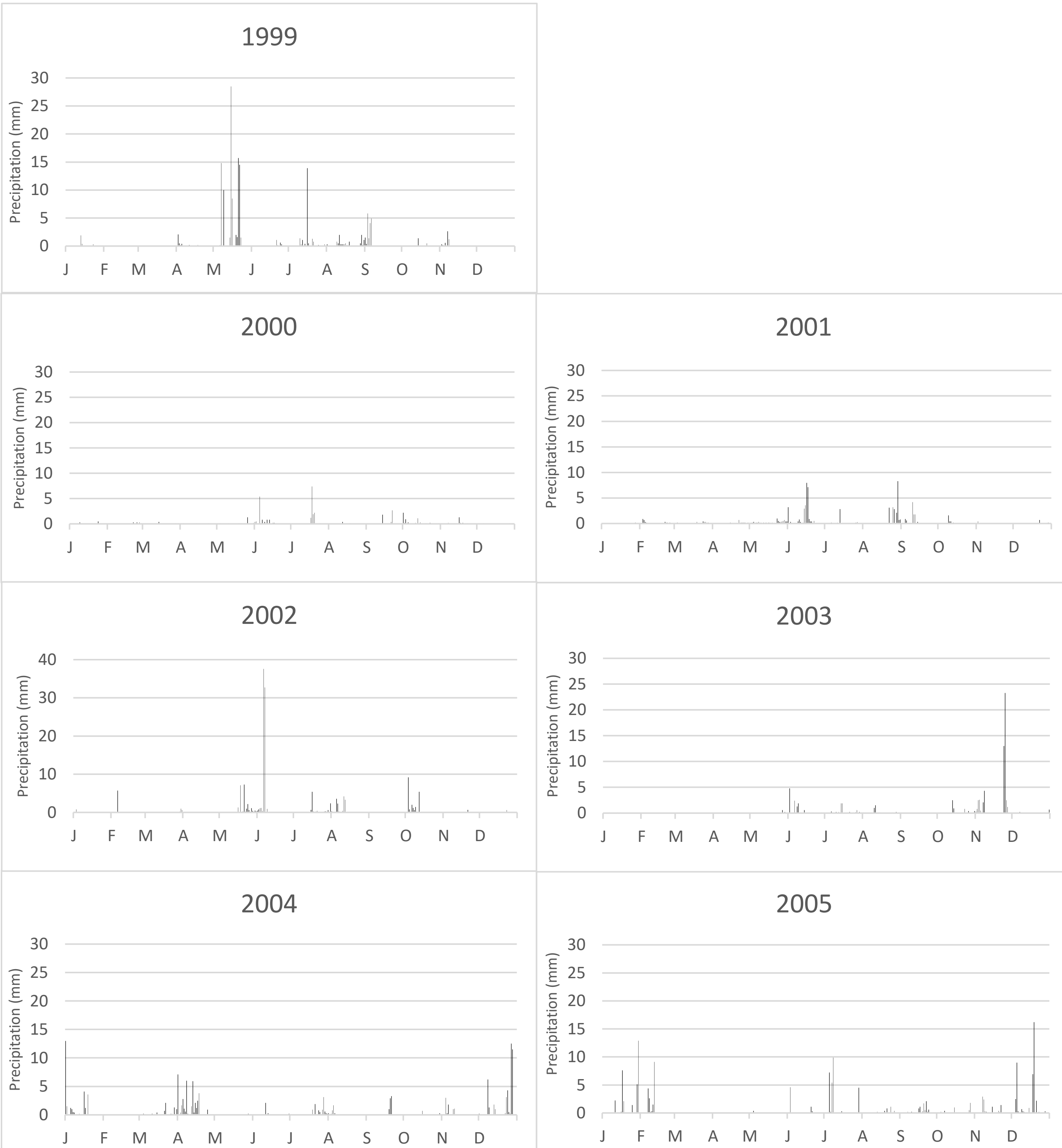
Table 7. LULC Database provided in SWAT 2012, based on classifications made by Anderson et al. (1976).

		Land use class		
Parameter name	**Description**	**Barren**	**Range-Grasses**	**Water**
CPNM	*Four-character code to represent the land cover/plant name*	BARR	RNGE	WATR
IDC	*Land Cover/Plant Classification*	6	6	6
BIO_E	*Biomass/Energy Ratio ((kg/ha)/(MJ/m^2))*	0.01	34	0
HVSTI	*Harvest index*	0.01	0.9	0
BLAI	*Max leaf area index (m^2/m^2)*	0.01	2.5	0
FRGRW1	*Fraction of the plant growing season corresponding to the 1st. Point on the optimal leaf area development curve.*	0.05	0.05	0
LAIMX1	*Fraction of the max. leaf area index corresponding to the 1st. point on the optimal leaf area development curve.*	0.05	0.1	0
FRGRW2	*Fraction of the plant growing season corresponding to the 2nd. point on the optimal leaf area development curve.*	0.49	0.25	0
LAIMX2	*Fraction of the max. leaf area index corresponding to the 2nd. point on the optimal leaf area development curve.*	0.95	0.7	0
DLAI	*Fraction of growing season when leaf area starts declining.*	0.99	0.35	0
CHTMX	*Max canopy height (m)*	0.01	1	0
RDMX	*Max root depth (m)*	0.1	2	0
T_OPT	*Optimal temp for plant growth (ºC)*	25	25	0
T_BASE	*Min temp plant growth. (ºC)*	12	12	0
CNYLD	*Fraction of nitrogen in seed (kg N/kg yield)*	0.0234	0.016	0
CPYLD	*Fraction of phosphorus in seed (kg P/kg yield)*	0.0033	0.0022	0
BN1	*Fraction of N in plant at emergence (kg N/kg biomass)*	0.06	0.02	0
BN2	*Fraction of N in plant at 0.5 maturity (kg N/kg biomass)*	0.0231	0.012	0
BN3	*Fraction of N in plant at maturity (kg N/kg biomass)*	0.0134	0.005	0
BP1	*Fraction of P at emergence (kg P/kg biomass)*	0.0084	0.0014	0
BP2	*Fraction of P at 0.5 maturity (kg P/kg biomass)*	0.0032	0.001	0
BP3	*Fraction of P at maturity (kg P/kg biomass)*	0	0.0007	0
WSYF	*Lower limit of harvest index ((kg/ha)/(kg/ha))*	0.9	0.9	0
USLE_C	*Min value of USLE C factor applicable to the land cover/plant*	0.2	0.003	0
GSI	*Max stomatal conductance (in drough condition) (m/s)*	0.005	0.005	0
VPDFR	*Vapor pressure deficit corresponding to the fraction maximum stomatal conductance defined by FRGMAX (kPa)*	4	4	0
FRGMAX	*Fraction of maximum stomatal conductance that is achievable at a high vapor pressure deficit ((g/MJ)/(k/Pa))*	0.75	0.75	0
WAVP	*Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit (µL CO_2/L air)*	10	10	0
CO2HI	*Elevated CO2 atmospheric concentration (ppmv)*	660	660	0
BIOEHI	*Biomass-energy ratio corresponding to the 2nd. point on the radiation use efficiency curve.*	0.01	39	0
RSDCO_PL	*Plant residue decomposition coefficient*	0.5	0.05	0

OV_N	*Manning's "n" value for overland flow*	0.14	0.15	0.01
CN2A	*SCS runoff curve number for moisture condition II*	77	49	92
CN2B	*SCS runoff curve number for moisture condition II*	86	69	92
CN2C	*SCS runoff curve number for moisture condition II*	91	79	92
CN2D	*SCS runoff curve number for moisture condition II*	94	84	92
BM_DIEOFF	*Biomass dieoff fraction*	0.1	0.1	0.1

8.3 PRECIPITATION TIME SERIES

Daily precipitation for the simulated years 1999 – 2005



Daily precipitation for the simulation years 2006 - 2013