PL4-303 Run-off Management

Student Project

Hydrological modelling in the Sogndal valley

Frudalselvi Catchment

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1. Introduction

Hydrological modelling is used to simplify and understand complex river systems and plays an important role in managing water resources. Runoff that originates from snow- and glacial melt is crucial for water supply and hydropower applications in Norway. Changes in glacial extent may have large impacts on the timing and magnitude of runoff, hence hydrological modelling is an important focus with regards to understanding the impact of climate change (Engelhardt, Andreassen, & Schuler, 2014).

The aim of this project was to derive a hydrological model of the Frudalselvi catchment (Figure 1) showing average daily discharge throughout a year. Discharge in glacierised catchments is highly influenced by meltwaters and contributes substantially to runoff, especially in spring- and summer months (Engelhardt, Andreassen, & Schuler, 2014). Consequently, the model was set to account for snow- and glacial melt and precipitation.

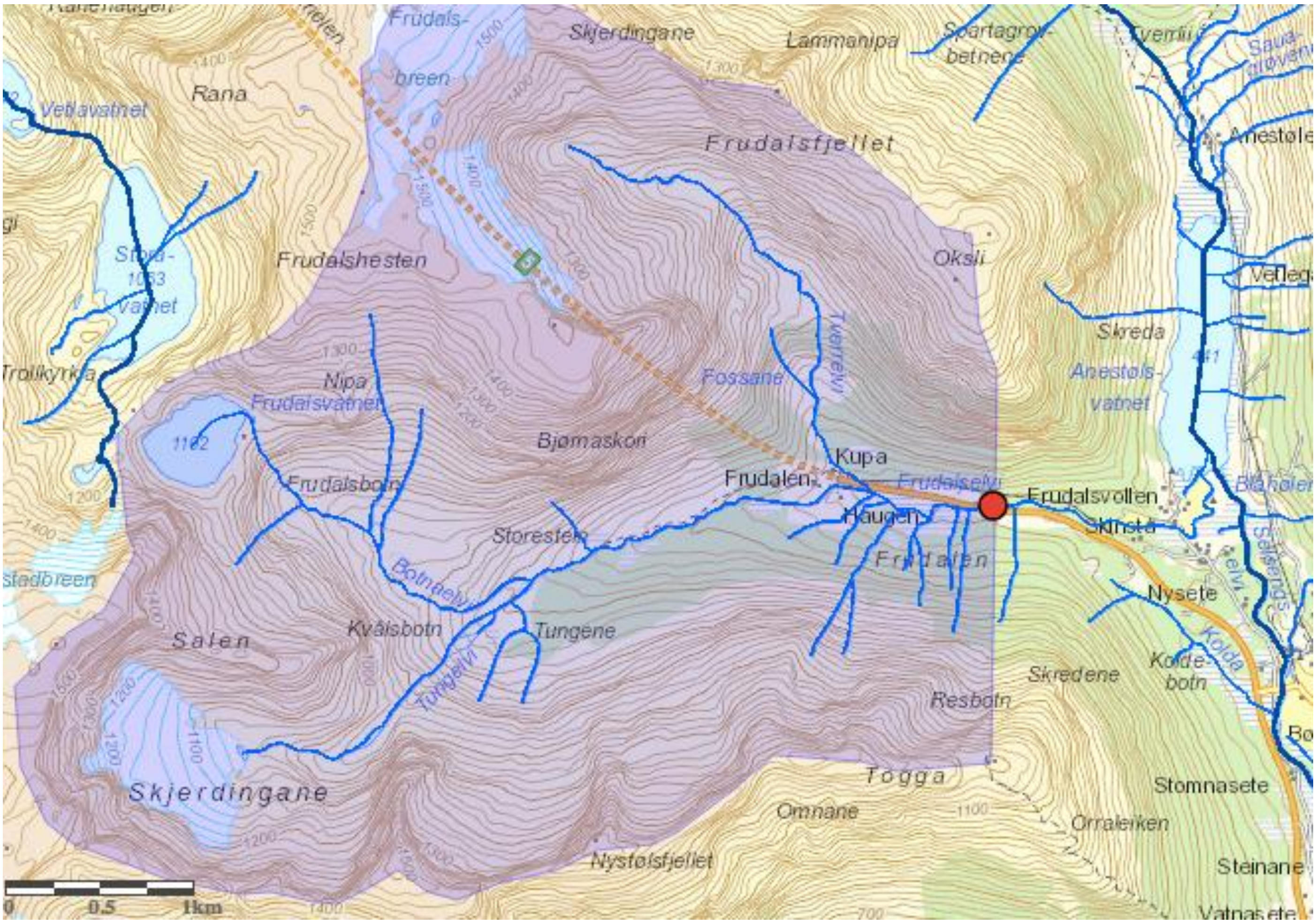

Figure 1: Frudalselvi Catchment Area. Two glaciers are located within the catchment area, as well as a small lake. The area consists of glacial valleys and bowls carved in bedrock and most of the area is bare rock (70%) (nevina.nve.no).

The input to the model is meteorological data (temperature and precipitation), and the outputs are discharge and simulated Snow Water Equivalent (SWE). The model utilizes the degree-day method for performing the simulations.

Discharge measurements were made in Frudalselvi and Selsengselvi (Figure 2) using a salt dilution method and used for validation of the developed model. SWE-measurements obtained from Anestølen were used to calibrate the model parameters.

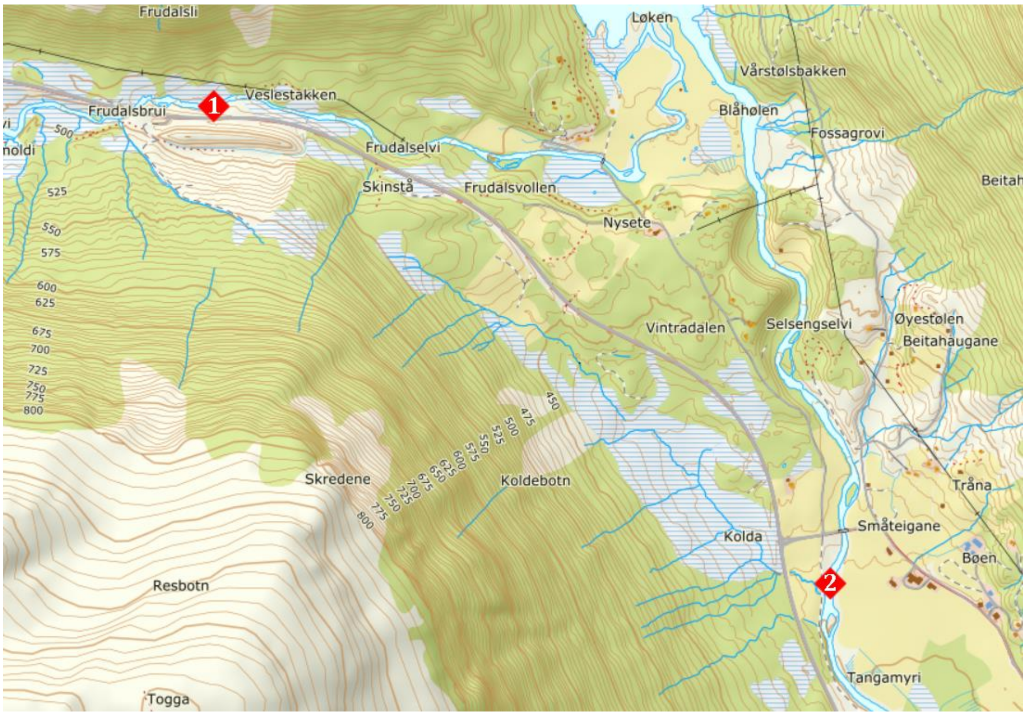

Figure 2: Area Overview with Stream Discharge Measurement Points, Frudalselvi (1) and Selsengselvi (2) (norgeskart.no)

This study assesses the following research questions:

1. How does discharge respond to temporal variations in temperature and precipitation?
2. Does the model match with measured values of discharge and SWE?
3. What are the uncertainties and inaccuracies of the model and the stream discharge measurements?

2. Method

2.1. Stream Discharge Measurement

A salt dilution method was used to measure discharge in Frudalselvi and Selsengselvi. Below is a list of the equipment used to perform the measurements (Table 1).

Equipment	Type	Quantity
Conductivity meter	WTW ProfiLine pH/Cond 3320	1
Mixing bucket	10 l bucket	2
Mixing tools	Wooden spoon Drill + Aluminium spatula	1 1
Salt	Coarse grained sea salt (25 kg)	1

Table 1: Equipment Overview

The measurements and subsequent analysis were done in accordance with the procedure provided in *USGS Measurement and Computation of Streamflow Manual, Ch. 7 - Measurement of discharge by tracer dilution* (Rantz & others, 2016).

The USGS manual suggests using 1-2 kg salt per m^3/s discharge in the river. 5 to 6 kg of salt were used for each of the measurements in the local rivers. The salt was dissolved in approximately 18 L river water by vigorous stirring before the conductivity of the solution and the background conductivity in the river were measured using a conductivity meter (WTW ProfiLine pH/Cond 3320).

The solution was released by sudden injection upstream of a turbulent section of the river. The conductivity was measured over a period of 15 minutes, 200 m and 150 m downstream in Frudalselvi (Figure 3) and Selsengselvi (Figure 4) respectively.

Figure 3: Frudalselvi injection/measurement area, showing mixing length in upper left corner (norgeibilder.no)

Figure 4: Selsengselvi injection/measurement area, showing mixing length in upper left corner (norgeibilder.no)

The arrival of the ionic wave could clearly be detected by the conductivity meter and used to plot a peak in conductivity (Figure 5).

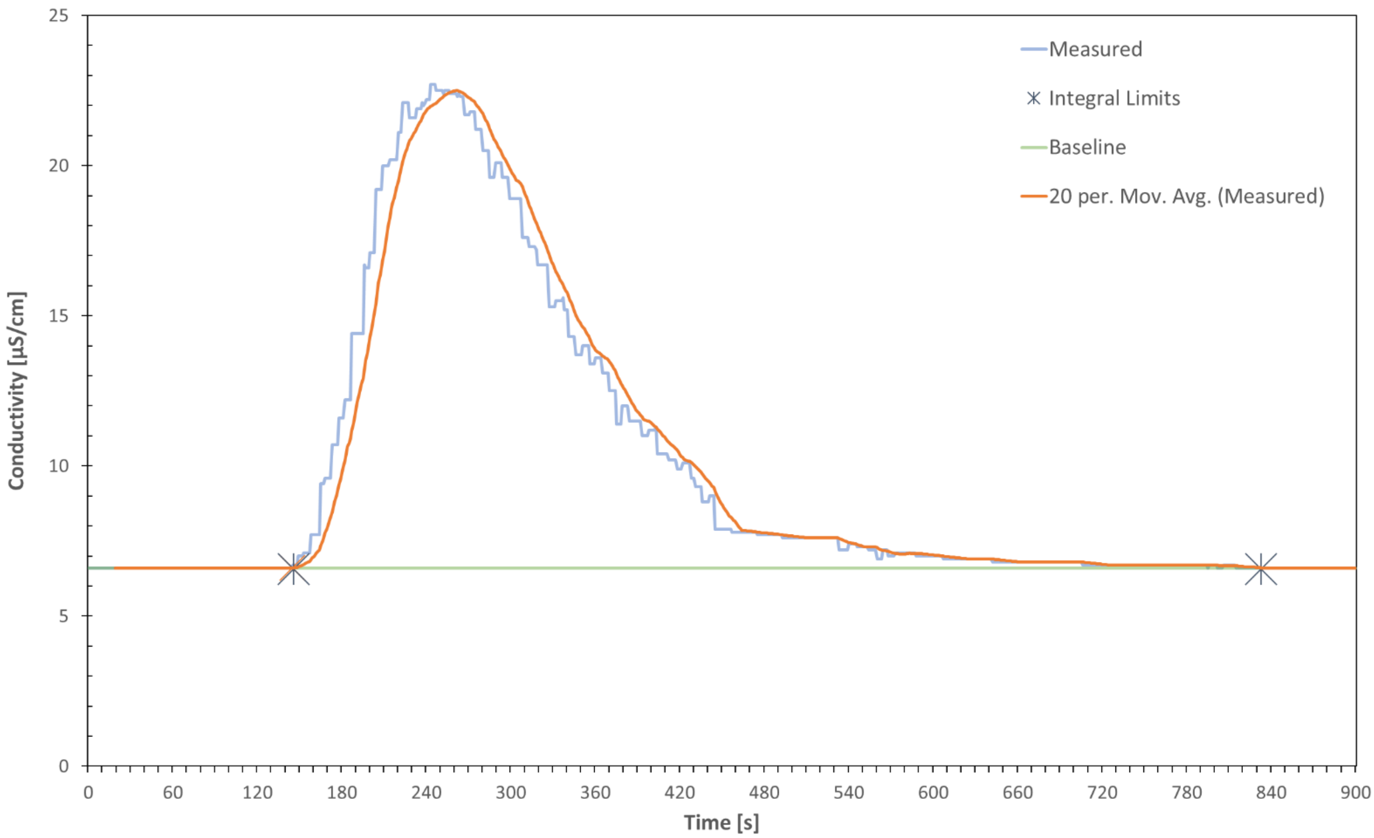

Figure 5: Plot of measurement 1, 2018-05-26 in the Frudalselvi river, showing smoothing filter (Moving Average with 20 second sample), baseline and integral limits (from first signal detection to return to baseline).

To calculate the discharge "Q" (Equation 1), measurement points were tabulated in Excel and integrated by numerical approximation using "n" samples (Equation 2).

$$Q = \frac{V_1 C_1}{\int_0^{\infty} (C - C_b)\, dt}$$

Equation 1: Equation for computing stream discharge (Rantz & others, 2016)

Where

V_1 is the volume of tracer solution injected to the stream

C_1 is the measured conductivity of the tracer solution injected to the stream

C is the measured tracer conductivity at a given time t, at the downstream sampling site

C_b is the background conductivity measured in the river

$$\int_0^{\infty} (C - C_b)\, dt = \sum_{i=1}^{n} (C_i - C_b)\,(t_{i+1} - t_{i-1})/2$$

Equation 2: Numerical approximation for integration of tabular data (Rantz & others, 2016)

2.2. Hydrological Modelling

A simple hydrological model program (Appendix B) was developed in the Python programming language to simulate discharge from the catchment. The implementation is based on selected model components from the *new version* (Seibert & Vis, 2012) of the HBV (*Hydrologiska Byråns Vattenbalansavdelning*) hydrological model. The model framework was originally made available by Sten Bergström in his book *Development and Application of a Conceptual Runoff Model for Scandinavian Catchments* (1976) and have since been adopted by educators to teach hydrological modelling concepts.

Three model components were included: snowmelt, glacial melt and precipitation.

2.2.1. Program Description

The illustration below (Figure 6) provides an overview of the various elements that constitute the model program. On the left-hand side, is the components needed for running a simulation, in the centre is the inner workings and to the right is the generated output and program features.

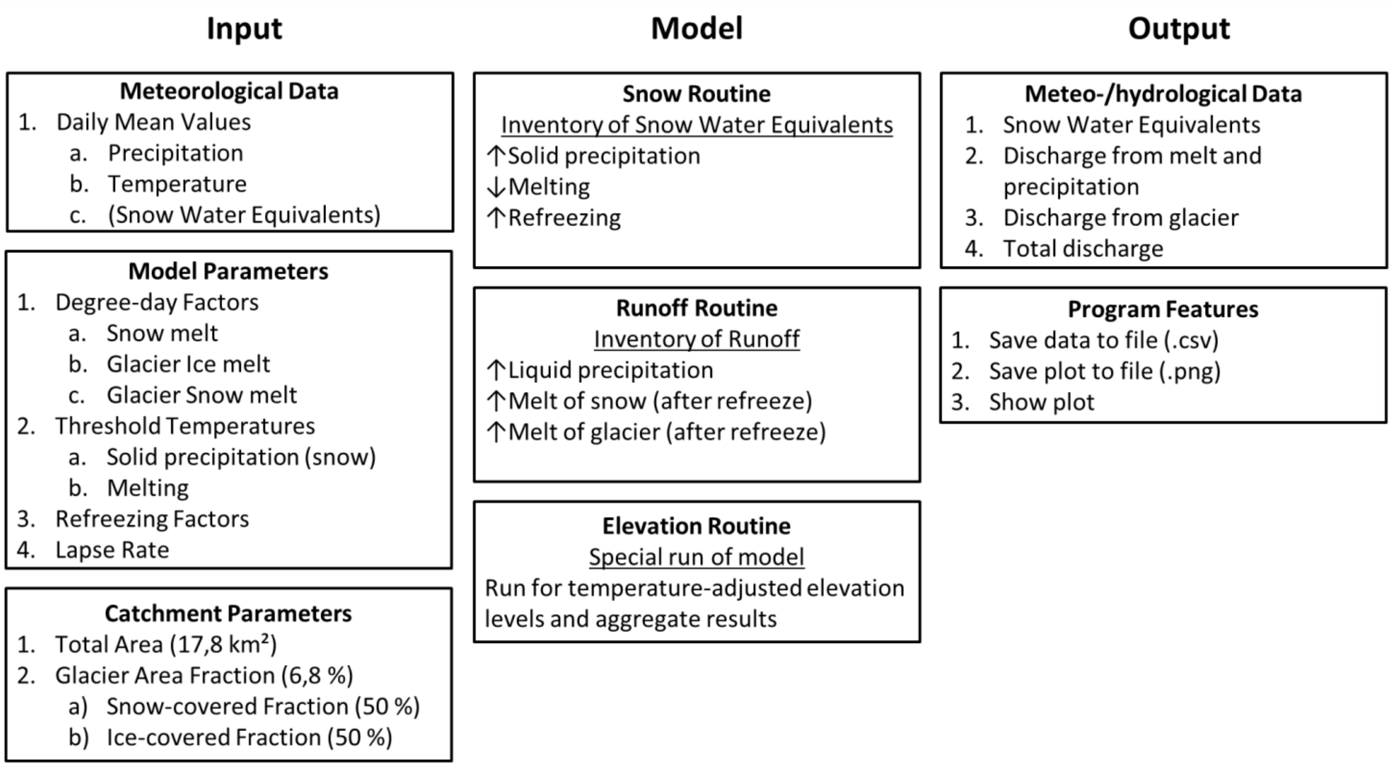

Figure 6: Overview of model, showing input elements, internal routines and output elements.

To complete a model run, a dataset containing meteorological data must be prepared as a comma-separated file (.csv), using the semicolon as separator. Other filetypes and formatting can be specified by modifying the dataset import function in the source code. The dataset must contain the following headers: “date;precip;temp”. To include observed Snow Water Equivalents, use “date;precip;temp;swe”.

Dates must be formatted according to ISO 8601 (YYYY-MM-DD). Other time resolutions can be used (model is time-agnostic) but this requires a change of values in the *unitConversion* function to get discharge output in desired units.

Other model parameters, including catchment parameters, are manually entered in the source code. The model- and catchment parameters used for the project catchment are provided in Table 2, Table 3 and in Appendix A: *Nevina Report*.

With the program file and the dataset in the same directory, the program can be executed directly from terminal or from within an Integrated Development Environment (IDE). Required modules are listed in the source code.

2.2.2. Inner Workings

Before resolving the simulation in the temporal dimension, the model is initialized by setting up intermediary arrays containing calculations of the model components. The simulation is then solved by looping through all rows in the provided dataset, executing logical statements based on the temperature "T" and precipitation "P" variables.

The logical statements in the Snow Routine are as follows:

- If *T* is below the freezing threshold (ptt), all *P* is added to *SWE*
- If *T* is above the melting threshold (pttm), *SWE* melts according to Equation 3 and melt *M* is subtracted
- If *SWE* has melted and *T* is below the freezing threshold, a fraction *R*, according to Equation 4, will refreeze and be added to *SWE*, but never more than 10 % of actual *SWE*

$$M = P_{CFMAX}(T(t) - P_{TT})$$

Equation 3: Snowmelt Model Component, degree-day method (Seibert & Vis, 2012)

$$R = P_{CFR}P_{CFMAX}\left(P_{TT} - T(t)\right)$$

Equation 4: Refreeze Model Component, degree-day method (Seibert & Vis, 2012)

The logical statements in the Runoff (RO) Routine are as follows:

- If *T* is above *ptt*, all *P* is added to *RO*
- If *T* is above *pttm*, the change in *SWE* is added to *RO*
- If *T* is above *pttm*, glaciers melt according to Equation 5, and melt M_g is added to *RO*

$$M_g = T(t)\left((ddfIce * iceArea) + (ddfSnow * snowArea)\right)$$

Equation 5: Glacial Melt Model Component, degree-day method (Pelto, 2017)

To enable the temperature correction routine, a switch can be set, on whether to simulate only based on the provided dataset or over multiple elevation levels with temperature correction for lapse rate (Equation 6 and Equation 7).

$$\Gamma = -\frac{dT}{dh}$$

Equation 6: Formal definition of Lapse Rate (American Meteorological Society, 2012)

$$T(h) = T - \Gamma\ \left(h_{ref} - h\right)$$

Equation 7: Temperature Correction Component where h_{ref} is the reference elevation (location of meteorological station)

After running on corrected levels, the model output is aggregated using an Equally Weighted Average of each run according to Equation 8.

$$\sum_{i=1}^{n} \frac{1}{n}\, SWE\big(T(h_i)\big)$$

Equation 8: Elevation Routine: Equally Weighted Average of SWE model runs for "n" temperature-adjusted elevation levels, "i".

2.2.3. Model Parameters and Model Tuning

To get a representative baseline for a simulation, parameters must be adjusted (tuned). For the project catchment, model tuning was performed to create a fit with measured Snow Water Equivalents (24 hr mean, v.3) from the NVE research station at Anestølen (collected from the xGeo portal).

Temperature data (24 hr mean, v.2) was also supplied from this station. Although all data is provided by xGeo, the precipitation data (24 hr sum, v.1) is from a separate source, approximately 4 km further down the valley: the Selseng meteorological station.

After multiple runs, an appealing fit (Figure 7) was created with the adjusted model parameters (Table 2).

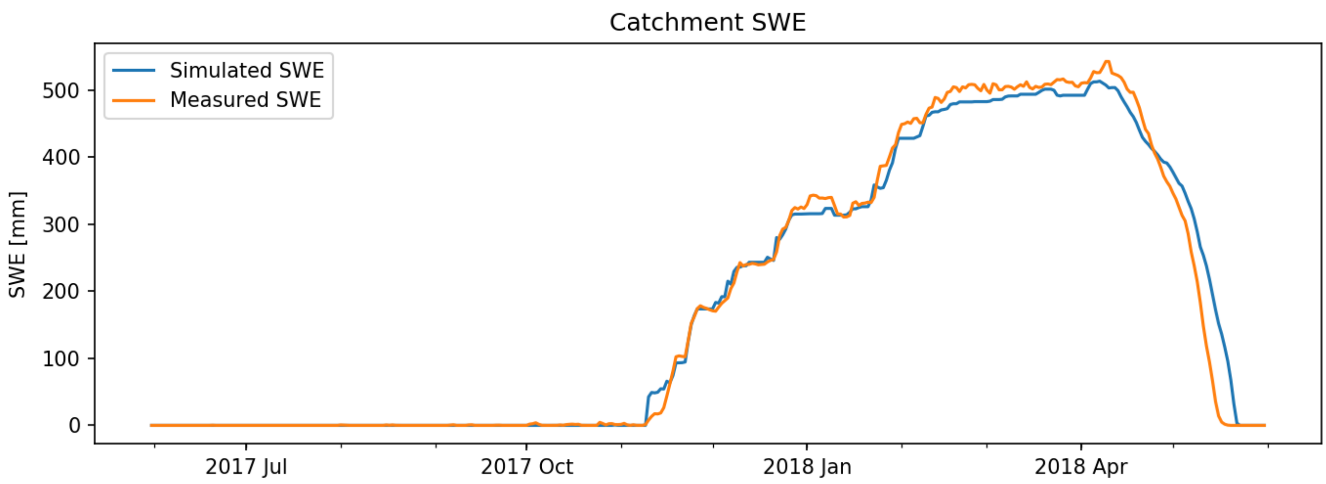

Figure 7: Simulation plot from tuning run/parameter adjustment (sum of simulated - sum of measured = 107 mm)

Model Notation	Description	Value	Unit	Reference
pcfmax	Degree-day factor, snow melt	2,75	mm d^{-1} $°C^{-1}$	Adjusted to fit observed SWE
ptt	Threshold temperature, solid precipitation	0,75	°C	Adjusted to fit observed SWE
pttm	Threshold temperature, melt	0,75	°C	Adjusted to fit observed SWE
pcfr	Refreezing factor A, degree-day factor	0,05**pcfmax*	mm d^{-1} $°C^{-1}$	(Seibert & Vis, 2012)
pcwh	Refreezing factor B, snowpack retention limit (10 % of SWE)	0,10	NA	(Seibert & Vis, 2012)

Table 2: Model Parameter Overview – Snow Routine

For glacier- and lapse rate parameters (Table 3), relevant literature was sourced. Degree-day factors for glaciers can vary greatly (Hock, 2003), as they are single empirical values which simplify/contain a complex physical process with location-specific dynamics.

As a starting point, the factors estimated for historical data on the Nigardsbreen glacier (Laumann & Reeh, 1993) was used. The same source provided a value for lapse rate, *in accordance with observations near glaciers* but as this supposedly often is overestimated the group chose a low mean value estimated for the Cascade Mountain range, United States and Canada (Minder, Mote, & Lundquist, 2010); approximately half of what it would be in a completely dry atmosphere in hydrostatic equilibrium (Equation 9).

$$\Gamma = \frac{g}{c_p}$$

Equation 9: Dry adiabatic lapse rate for 1 atm, where g is the standard gravity and c_p the specific heat (at constant pressure) of the medium, air ≈ 1, (Forelesninger - GEF1100 - Høst 2015 - Universitetet i Oslo)

Model Notation	Description	Value	Unit	Reference
ddfIce	Degree-day factor, ice-covered glacial melt	5,50	mm d^{-1} K^{-1}	Nigardsbreen (Laumann & Reeh, 1993), (Hock, 2003)
ddfSnow	Degree-day factor, snow-covered glacial melt	3,50	mm d^{-1} K^{-1}	Nigardsbreen (Laumann & Reeh, 1993), (Hock, 2003)
lapseRate	Lapse Rate	5,00	K km^{-1}	Cascade Mountain range (Minder, Mote, & Lundquist, 2010)

Table 3: Model Parameter Overview – Glacier and Elevation Routine

Catchment parameters was retrieved from NVE's NEVINA site: total area and glacier area fraction, including height profile. The fraction of snow-/ice-covered glacier is arbitrarily set as 50 / 50 %.

To define the elevation levels, the (area at height below) percentiles, minimum and maximum values were averaged to give ten levels, as illustrated in Equation 10 and Equation 11: for level 1 and level 10.

$$Level\ 1 = \frac{H_{min} - H_{10}}{2}$$

Equation 10: Calculation of Elevation Level 1

$$Level\ 10 = \frac{H_{90} - H_{max}}{2}$$

Equation 11: Calculation of Elevation Level 10

3. Results

3.1. Stream Discharge Measurement

Results from the stream discharge measurement are given in Table 4 and Table 5. A test measurement was conducted on May 24th. The main measurements were done on May 26th. The test measurement is included to provide a better understanding of diurnal fluctuations in the river. The weather conditions in this period were stable, warm without any precipitation.

Measurement #	Date	Time (middle value)	Flow Rate [m^3/s]	Comment
0	2018-05-24	20:12:09	4,881	Test measurement
1	2018-05-26	13:24:22	3,104	
2	2018-05-26	22:24:56	5,534	

Table 4: Calculated Flow Rate – Frudalselvi

Measurement #	Date	Time (middle value)	Flow Rate [m^3/s]	Comment
1	2018-05-26	15:43:23	3,513	
2	2018-05-26	23:11:20	No result	Ran out of salt

Table 5: Calculated Flow Rate – Selsengselvi

3.2. Hydrological Modelling

3.2.1. Snow Water Equivalents

Figure 8 shows the input values for temperature and precipitation, along with the output of Snow Water Equivalent simulation plot from model run with temperature-adjustment, running for one year, starting May 31st, 2017.

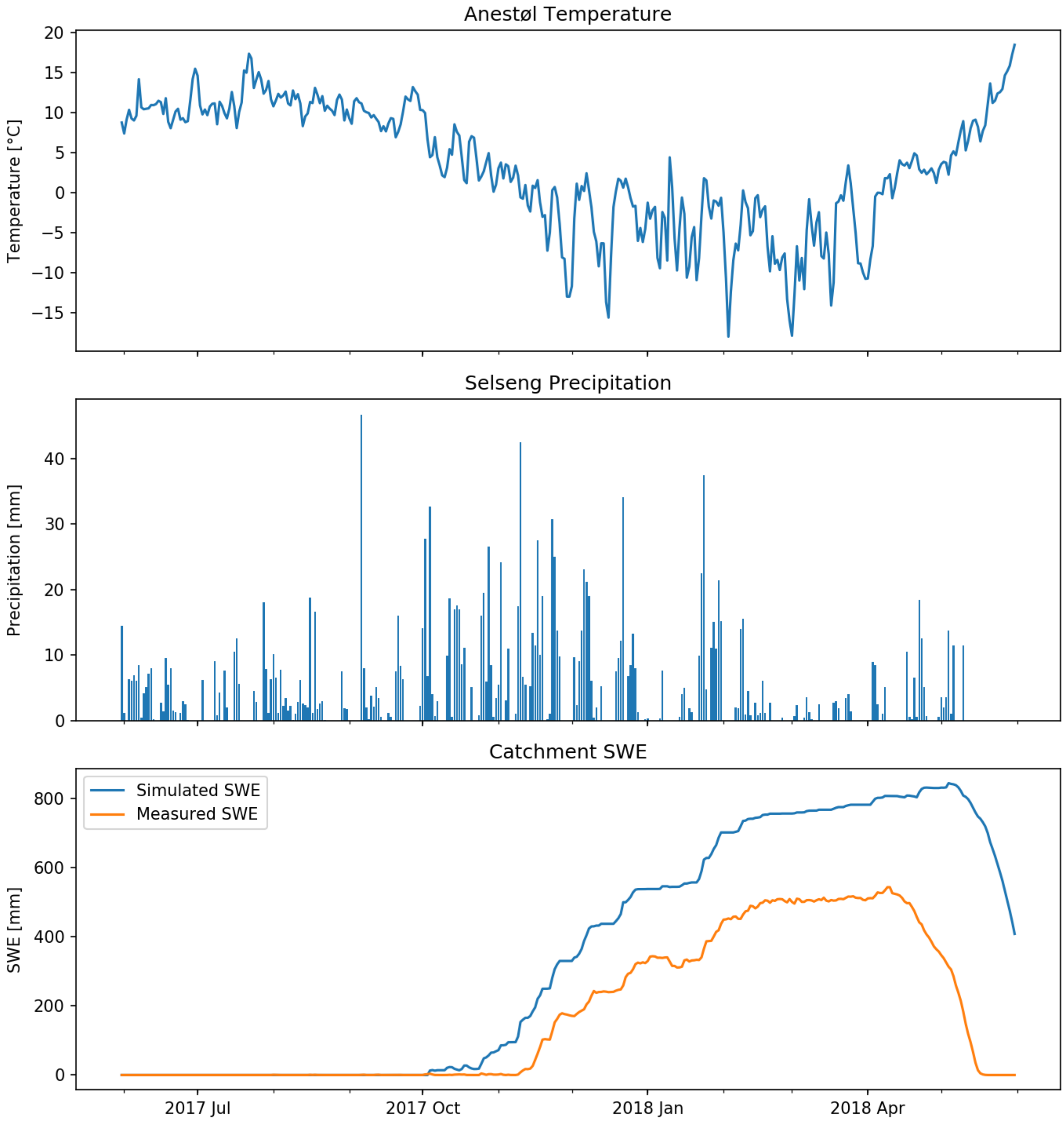

Figure 8: Simulation plot – Temperature-adjusted model run. Temperature at the top, precipitation in the middle and Snow Water Equivalents at the bottom (simulated and observed).

3.2.2. Discharge

Figure 9 shows the output plot of discharge simulation from model run with temperature-adjustment running for one year, starting May 31st, 2017.

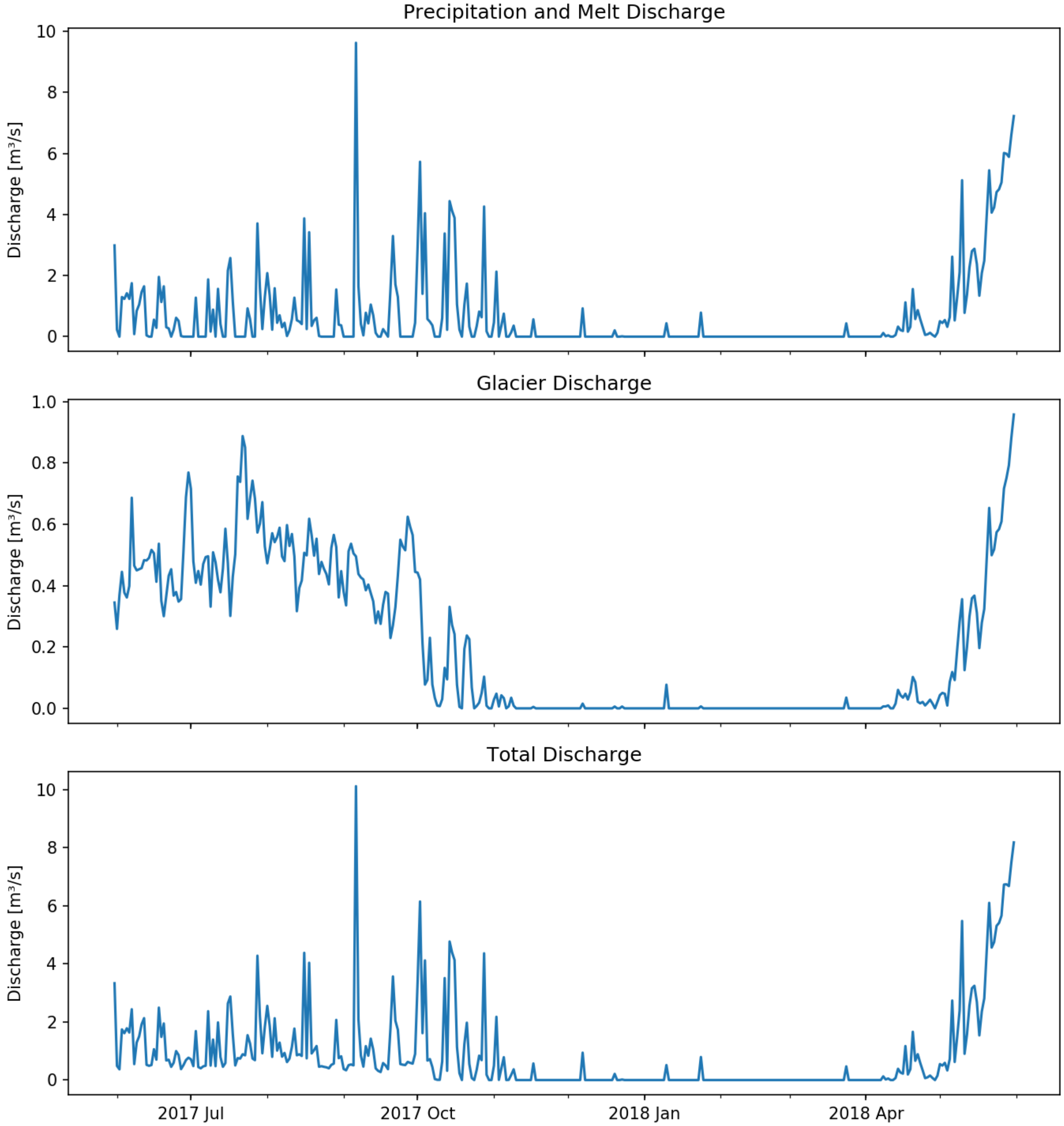

Figure 9: Simulation plot – Temperature-adjusted model run. Discharge from melting snow and precipitation at the top, glacier in the middle and sum of the respective contributions at the bottom. Scale of X-axis is different on each plot.

3.2.3. Values on days with Stream Discharge Measurement

Table 6 and Table 7 shows the values from both the adjusted and the baseline run of the model on the same days as the stream discharge measurements were done.

Model Input				**Catchment SWE [mm]**	
Date	*Precipitation*	*Temperature*	*Anestølen SWE*	*Adjusted*	*Not Adjusted*
2018-05-24	0,0	12,4	0,0	610,0	0,0
2018-05-26	0,0	13,0	0,0	562,0	0,0

Table 6: Selected output data – Both temperature-adjusted and baseline Snow Water Equivalent values for the 24th and 26th of May together with observed SWE from Anestølen.

Model Input			**Discharge [m³/s]**					
Date	*Precip.*	*Temp.*	*Precip. and Melt*		*Glacier*		*Total*	
			Adjusted	*Not A.*	*Adjusted*	*Not A.*	*Adjusted*	*Not A.*
2018-05-24	0,0	12,4	4,735	0,000	0,574	0,782	5,309	0,782
2018-05-26	0,0	13,0	5,050	0,000	0,609	0,817	5,659	0,817

Table 7: Selected output data – Both temperature-adjusted and baseline discharge values for the 24th and 26th of May.

4. Discussion

4.1. Stream Discharge Measurement

It is assumed that the results obtained from the salt-dilution experiment are representative for the two rivers. The salt dilutions were injected above turbulent areas of the rivers and sampling sites were chosen at adequate lengths downstream to facilitate sufficient mixing.

Measurements indicate that discharge increases in the evening. This pattern was expected as radiation and snowmelt increase throughout the day (Singh, Haritashya, Ramasastri, & Kumar, 2004). Discharge in Frudalselvi is of a similar magnitude to the lower Selsengselvi. This was not expected, as Selsengselvi receives more water from a larger catchment than Frudalselvi. This could indicate that Anestølsvatnet has an impact on the discharge in Selsengselvi, perhaps working as a buffer for incoming water.

Minor inaccuracies and uncertainties are present in this method, possible sources include instrumental (0,1 µS/cm for calibration and 0,1 µS/cm for resolution) and human errors.

5 to 6 kg salt were used for each measurement as this was the maximum amount of salt that could be dissolved over a practical period in the largest mixing containers we had access to. A distinct ionic wave was observed in the results and the amount of salt is therefore assumed sufficient.

Some of the tracer might be lost through chemical reactions between the dissolved salt and other substances in the river (Rantz & others, 2016). Small amounts of salt that has not been fully dissolved could sink to the bottom and not dissolve instantly. However, the solution was checked for coarse salt before it was injected and the turbulence in the rivers would likely dissolve the small amounts that could be present. Small amounts of tracer solution could also become temporarily trapped in less turbulent areas of the river, affecting the results.

The level of mixing could have been verified by measuring at multiple sampling sites in the river, had the necessary equipment been available.

Data filtering was applied to the measurement data to smooth out fluctuations in the signal. A moving average (using the Excel built in function) of the 20 or 60 preceding measurement points were used, depending on the noise level in the signal. This filtering will slightly shift and flatten the curve but retain accurate characteristics (within a few percent relative to the raw data). An alternative approach is to calculate a moving average based on an equal number of readings before and after the time point, this would eliminate time shift.

Ideally, multiple measurements would have been made in the rivers to find the daily average discharge, but the amount of salt (and time) was limited.

Uncertainties and inaccuracies in river measurements are important to take into consideration as these are the measurements used to validate the model outputs.

4.2. Hydrological Modelling

The model was simplified using three components: snowmelt, glacial melt and precipitation. When comparing the model with discharge measurements (Table 8), the output is of same magnitude, but it is evident that not all water sources and sinks have been accounted for. This is likely because runoff components such as soil, groundwater and the Frudalsvatnet lake were not included in the model. As nearly 70 % of the modelled catchment area is bare rock (*snaufjell*), the soil routine would be less significant. To include these components, a more detailed investigation of the area should be conducted. This was deemed outside of the scope of this project but could be an idea for further development of the model.

Date	Measured Discharge [m^3/s]	Model Discharge [m^3/s]	Difference [m^3/s]
2018-05-24	4,881	5,309	+ 0,428
2018-05-26	4,319 (average)	5,659	+ 1,340

Table 8: Discharge Comparison - Measured vs. Model

In addition to exclusion of components, there are inaccuracies within the model. The degree-day method used in the model is based on empirical data and relies on constant thresholds and rates for precipitation, melt and refreezing without looking further into variations across the catchment area.

With regards to the glaciers, only (a constant) surface area and approximated cover of glacier were considered when calculating the discharge. Knowing the thickness, albedo, shape and elevation of glacier would improve the accuracy of the model.

Temperature and precipitation data were obtained from meteorological stations at Anestølen and Selseng and applied to the whole catchment. A correction for altitude is applied with equal weights for ten elevation levels, but no consideration is given to microclimates. Another weighting could also be considered, for example skewing the weight in towards either end.

According to *Evaluation of Measurements of snow…* (Stranden, H.B. & Ree, B. L. (NVE), 2014), the Anestølen station is equipped with multiple types of equipment for performing the measurement but it is unclear which of these instruments are responsible for the dataset used by the group and how accurate this data is. Another aspect that contributes to uncertainty is whether model parameters are tuned correctly. Adjusting the wrong parameter may give the right answers but for the wrong reasons.

Comparing the measured discharge of Sogndalselvi (NVE Sogndalsvatn 77.3.0) to the modeled discharge of Frudalselvi, a similar pattern can be found (Figure 10). Both curves follow the expected discharge pattern of a highly seasonal regime – with high discharge in spring- and summertime, due to melt waters from snow and glaciers.

Discharge in Sogndalselvi is of a larger level of magnitude than Frudalselvi. Delays in discharge peaks might occur, as Sogndalselvi has a larger catchment area and is located further downstream in the river network. Differences could also be explained by buffering effects from lakes. These aspects are not investigated by the project group but could be further explored in a future project.

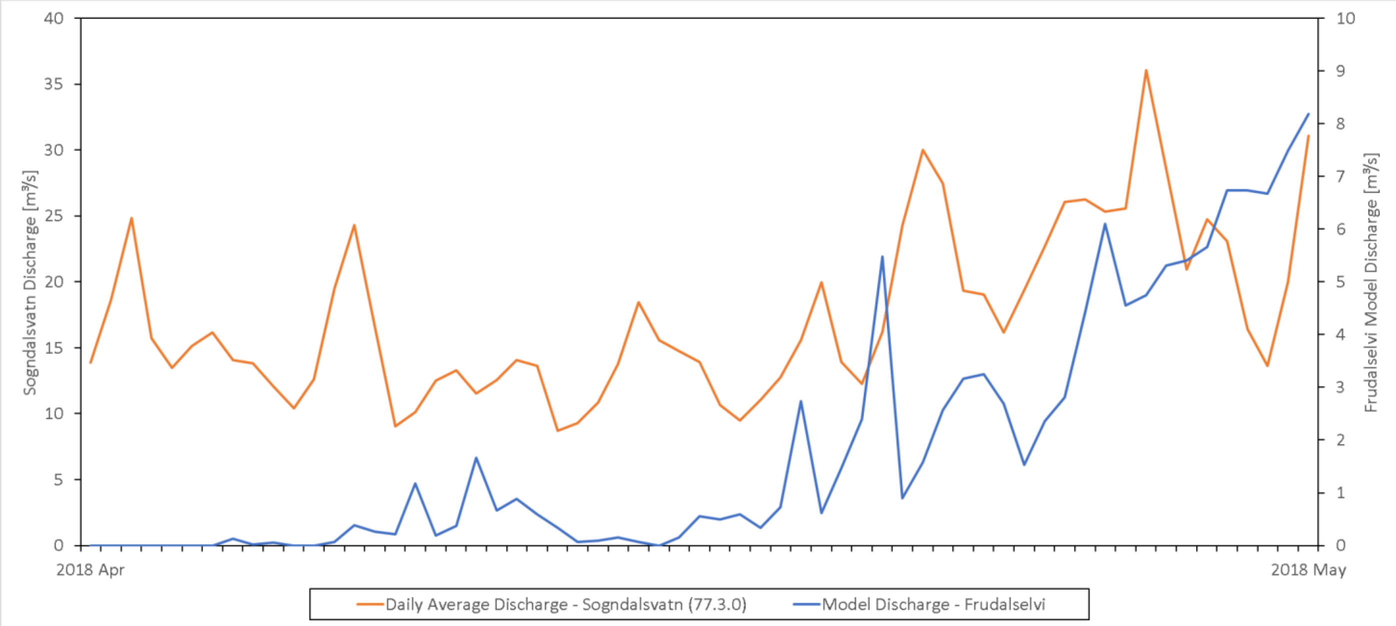

Figure 10: Excel plot of discharge at NVE's gauging station Sogndalsvatn and Model, April and May 2018 (NVE, 2018)

5. Conclusion

Discharge in the rivers were successfully measured using the salt dilution method. Some inaccuracies and uncertainties were present; however, these are thought to be of little significance to the results. The multiple measurements performed in Frudalselvi were in accordance with expected diurnal fluctuations and the values are within reasonable range, further validating our method. Reliable measurements set a good basis for modelling the discharge.

The model would benefit from more site-specific input data; however, considerations were made to use the most representative data available. Main discharge components – snowmelt, glacial melt and precipitation – have been included in the model. Seasonal variations are evident in the model output, similar to the discharge pattern of Sogndalselvi. Components that have been left out – such as groundwater, soil and lake(s) – are thought to contribute smaller amounts of discharge to the rivers but it is clear that these elements are necessary to further the realism and usefulness of the model.

Figures

Tables

Equations

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Appendix Register

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B	model.pdf	Model Source Code	7
		Total Pages:	8

Appendix A: Nevina Report for Catchment

Dummy pages for appendices (to get page count correct). Add equivalent to pages of attachments and remove from pdf.

Appendix B: Model Source Code

Dummy pages for appendices (to get page count correct). Add equivalent to pages of attachments and remove from pdf.

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