**NTNU – Trondheim**
Norwegian University of
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# Hydrological forecasting in catchments with glaciers

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Hydropower Development
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**Environmental Engineering**

# M.Sc. THESIS IN
# HYDROPOWER DEVELOPMENT

**Candidate: Angele Nahat**

**Title: Hydrological forecasting in catchments with glaciers**

## 1 BACKGROUND

Glaciers are an important component of the hydrology in many high mountain areas and have impacts on the runoff generation and the utilization of water. There has been a growing interest in glacier hydrology over the latest decades due to the potential impacts of a warming climate on the glacier mass balance and how this will influence water for hydropower production, irrigation and water supply in the future. Glaciers and glacier runoff is also a component in the computations of design floods and for safety assessments of infrastructure in mountainous catchments. Glaciers are handled in many hydrological models, but not to the extent that the detailed glacier mass balance is included in the simulation to handle glacier retreat or advancement as an integral part of the model. The purpose of this thesis is to include are more detailed glacier model in the Excel based HBV model and to use this model to hindcast and forecast runoff and glacier development in a mountainous catchment.

## 2 MAIN QUESTIONS FOR THE THESIS

1. Do a literature review on existing models of glacier dynamics and previous work integrating glaciers in hydrological models. The outcome of the literature review should be a glacier model that can be integrated with the Excel HBV.
2. Decide on a mountainous study catchment in western Norway with a significant glacier percentage and available data on glacier dynamics. Collect the necessary runoff and climate data for setting up the model, perform data quality assessment and prepare the data for the HBV model. The necessary catchment data should also be collected and prepared.
3. Implement the glacier model from task 1 into the Excel HBV and integrate it with the current model structure.
4. Calibrate and validate the model for a recent period. Test the glacier model within the total hydrological model. Evaluate the results and potential uncertainties in data.

5. Simulate historical data to see if the model is able to reproduce observed glacier development and run long term forecasts based on scenarios of precipitation and temperature to investigate glacier development. Evaluate the impacts of changes in glacier volume on water resources.
6. Document the new model and its data needs for future use.

## 3 SUPERVISION, DATA AND INFORMATION INPUT

Professor Knut Alfredsen will be the supervisor of the thesis work.

Discussion with and input from colleagues and other research or engineering staff at NTNU, SINTEF, power companies or consultants are recommended. Significant inputs from others shall, however, be referenced in a convenient manner.

The research and engineering work carried out by the candidate in connection with this thesis shall remain within an educational context. The candidate and the supervisors are therefore free to introduce assumptions and limitations, which may be considered unrealistic or inappropriate in a contract research or a professional engineering context.

## 4 REPORT FORMAT AND REFERENCE STATEMENT

The thesis report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) and decision makers as the main target group.

The summary shall not contain more than 450 words it shall be prepared for electronic reporting to SIU. The entire thesis may be published on the Internet as full text publishing through SIU. Reference is made to the full-text-publishing seminar during NORADS winter-seminar. The candidate shall provide a copy of the thesis (as complete as possible) on a CD in addition to the A4 paper report for printing.

The thesis shall be submitted no later than 10th of June 2015.

Trondheim 10th of January 2015

Knut Alfredsen
Professor

# FOREWARD

This master thesis “Hydrological forecasting in catchments with glaciers” has been accomplished under the supervision of Professor Knut Alfredsen, Department of Hydraulic and Environmental Engineering at the Norwegian University of Science and Technology, in Trondheim, Norway.

The thesis started in January 2015 and was finished in June 2015.

I hereby confirm that all the work accomplished in this thesis in my own and that all the substantial help received have been notified in the acknowledgement.

Angèle Nahat

June 2015

Trondheim, Norway

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I would like to thank all the people who helped and supported me during the thesis.

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I would like to continue this acknowledgment by thanking my loved ones, my parents and brother, who have never stopped encouraging me in the accomplishment of my studies, and all my family.

I will not forget to have a thought for my friends of Norway and flatmates for all the priceless support they showed me during thesis period.

# ABSTRACT

The runoff forecast is crucial in Norway because the country bases most of its electricity from hydropower. The hydrological model has thus been improved for years in order to foresee the runoff in the best possible way. In Norway, there are many catchments with extensive water storage: glaciers. Those catchments represent a significant part of the catchments where hydropower is produced. Therefore knowing the right amount of outflow from a catchment with glaciers is essential but more challenging.

The runoff forecast has been assessed on catchments where the glacier area is decisive for the runoff regime. The catchments chosen are located in Jostedalsbreen, the biggest glacier in Europe, in south Norway. The catchments have specific characteristics in slope, land types etc. which can test the robustness of the hydrological model used, HBV-model. This simple model is not specifically built for glacier behaviour analysis and thus does not include complex calculation on the glacier part. Hence, forecasting runoff with HBV-model for a catchment with glaciers is expected to be arduous.

After several trials, two calibrations were done for the two purposes: one strictly hydrological runoff oriented and the other glaciers behaviour related. The simulations were realised in different catchments on a long period of fifty-two years. The concern about the accuracy of the HBV-model to generate a consistent runoff in the catchments selected proved to be unfounded. The first calibration gives so good results in term of runoff that an update of the model for catchments with higher portion with glaciers does not seem necessary. However, to get those results the model passes through calculations which do not fit with what happens in the physical system especially in climatological part and in the snow routine. So the second calibration was realised in order to have routines closer to the physical phenomena.

The two different simulation results were then studied for their glacier changes. It appears that both calibrations give reversely extreme glacier mass balances. Therefore, it is difficult to conclude anything for glacier mass balance values in the catchment.

After, the climate change in the region was studied to forecast the runoff in the next hundred years. Two different scenarios were evaluated. They give relatively close results in term of the runoff forecast. The glacier mass balances are also close to each other. The scenario A with the highest increase of temperature has stronger impact on the runoff and mass balance of the glaciers. However, it is difficult to conclude on the glacier state at the end of the period with the only two calibrations used, but they will eventually decrease.

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# ABBREVIATIONS

| | |
|---|---|
| °C | degree Celsius |
| DEM | Digital Elevation Model |
| EPOT | Potential evapotranspiration |
| ESRI | Environmental System Research Institute |
| h | hour |
| HBV | Hydrologiska Byråns Vattenbalansavdelning |
| J, F, M, | January, February, March etc. |
| Jan., Feb. Etc. | January, February etc. |
| $km^2$ | Kilometer square |
| Lat. | Latitude |
| Long. | Longitude |
| m | Meter |
| m.a.s.l | meter above sea level |
| m.w.e. | meter water equivalent |
| $m^3/s$ | Cubic meter per second |
| min | minutes |
| Mm | Millimetre |
| NVE | Norges Vassdrags- og Energidirektorat<br>(Norwegian Water Resources and Energy Directorate) |
| P, Precip. | Precipitation |
| Qo | observed runoff |
| Qs | simulated runoff |
| R2 | Nash Sutcliffe coefficient |
| S.o.F. | Sogn of Fjordane |
| T, Temp. | Temperature |
| UTM | Universal Transverse Mercator |

# 1 INTRODUCTION

## 1.1 BACKGROUND

Glaciers represent approximately 75% of the world's freshwater storage, hence their crucial importance in the water system (Khadka et al., 2014). Even though only 0.5 of the world's glaciers are mountainous glaciers (Khadka et al., 2014), they can represent an important part in the hydrological phenomena in several catchments located in high mountain areas.

The concerns raised by glaciers have been taking into consideration more seriously in the last years since a climate change, warmer climate, has been evaluated. In a scenario where constant warming conditions affect those areas with significant proportion of ice and snow storage, glaciers might have a crucial implication in the water availability in the future. Glaciers affect the water balance thus the water resources, especially through the runoff they can generate at high temperature in summer. The importance of glaciers becomes greater since they produce most water during hot, dry periods when precipitation is lacking (Jansson et al., 2003).

In Norway, there are in total 2534 (3143 glacier units) glaciers covering 2692 km². 1252 of them are located in southern Norway, that to say 1282 situated in northern Norway. The glaciers in the south cover 1523 km² or 57% of the total glacier area. In addition to those glaciers, about 24 km² of land has been identified as "possible snow field". In total, glaciers and perennials snow fields cover approximately 0.7% of the land area in Norway. (Andreassen et al., 2012).

The discharge pattern in catchments with glaciers is affected by snow and glacier melt water (Engelhardt et al., 2014). Changes in the glacier mass and glaciers runoff would affect many water utilisations, water supply, irrigation, hydropower production but also flood forecasting, sediment transport, safety assessments of infrastructures etc. In Norway, 96.7% of the electric energy is generated by hydropower (Directorate, 2013). Of all the glaciers, 60% of the total glacier area (1610 km²) is located in catchments regulated for hydropower (Andreassen et al., 2012). Therefore glaciers are fundamental for those hydropower productions (Andreassen et al., 2012). Hence, the best integration of glaciers in hydrological modelling has become more relevant.

The Norwegian glaciers are monitored for many years. The length changes of the central flow line in some glaciers have been recorded for years. In addition to the length change, the mass balance has also been monitored for few glaciers. The glacier mass is the accurate value to determine whether the glacier can or cannot produce more runoff. During the 1990s unlike the observations made in the rest of the world regarding the glaciers movement, many of the Norwegian glaciers advanced significantly. But after 2000, they follow the global pattern and retreat.

## 1.2 OBJECTIVES OF THE PROJECT

The thesis motivation lies in the combination of the forecast in a specific catchment with glaciers and the use of a hydrological model, the HBV-model.

Glaciers appear in hydrological model HVB more as an unmovable entity than a fluctuant quantity with either glacier retreat or advancement. The purpose of the project was to include a more detailed glacier model that would take into account these internal changes in the glacier. The new model would then forecast retirement or growth of the glaciers to determine the glacier development in the future years and thus give a better fit for runoff during hindcast and forecast for catchments where glaciers are playing a decisive part.

## 1.3 SCOPE OF THE PROJECT

The scope of the project includes:

- Literature review on existing hydrological models, glacier dynamics and climate
- Choice of a catchment where the glacier percentage is important,
- Collection of geographical data over the catchment area,
- Collection of the meteorological data of the catchment area (precipitation and temperature),
- Collection of the hydrological data of the catchment area (runoff),
- HBV model set-up, calibration and validation for a recent period,
- Evaluation of the results and the uncertainties,
- Simulation of historical data,
- Modification of the HBV model to improve the snow part,

- HBV model set-up, calibration and validation for a recent period,
- Simulation of long term forecast and investigation of runoff and glacier development.

## 1.4 METHODOLOGY OF THE SUBJECT

The methodology of the subject includes:

- Theory review,
- Collection of input data: geographical, meteorological and hydrological,
- Control of input data series,
- Analysis of input data series,
- HBV-model setup,
- Hindcast on the past period after calibration,
- Analysis of the glacier behaviour in the HBV-model,
- Analysis of the forecasted climate change for input data,
- Forecast runoff and glacier behaviour.

## 1.5 STRUCTURE OF THE THESIS

Chapter II will present the catchments' characteristics: the catchments area, the land types, the topography, and the glaciers located in the area that has been chosen.

Chapter III is a summary of the data acquisition and control. The data has been collected from several sources. And after collection, they have been corrected and completed to have a long period of recorded data.

Chapter IV is the presentation of the HBV-model setup.

Chapter V is the calibrations of the HBV-model. It has been done two different calibrations in order to fulfil two different expectations: the runoff forecast and the glacier behaviour forecast.

Chapter VI focuses on the glacier behaviour in the HBV-model: how can the results from the model calibration help to determine the glacier changes.

Chapter VII is about the forecast in the region.

Chapter VIII will summarize the conclusions and discussion and will propose some recommendation for further studies.

## 1.6 LIMITATIONS

The initial goal of the thesis was to update the HBV-model structure. But after consideration of the first results and given the complexity of the internal structure of the HBV-model, modification of the model has not been pursued.

The input data of the catchments have been modified especially the temperature series. The accuracy of the results has thus to be handle carefully to some extent.

The glaciers mass balanced in the selected catchment has not been monitored. So many assumptions have been in order to guess the glacier behaviour.

# 2 INTRODUCTION TO THE CATCHMENTS' CHARACTERISTICS

## 2.1 SOURCES

The data were collected from different sources: Lavvann, Statkart, NVE and CryoClim:

- The land use comes from Statkart and Lavvann: after comparison, the data from Lavvann has been used,
- The glacier areas comes from NVE (Beatlas and CryoClim available on the website) and Lavvann: after comparison, the data from Lavvann has been used.

## 2.2 IDENTIFICATION OF THE STUDY AREA

### 2.2.1 Introduction

Norway has several glaciers located both in south and north.

See Appendix A: Norway and its glaciers

The largest glacier, which is also the widest glacier in Europe, is Jostedalsbreen in southern Norway. This region has thus been selected for the study.

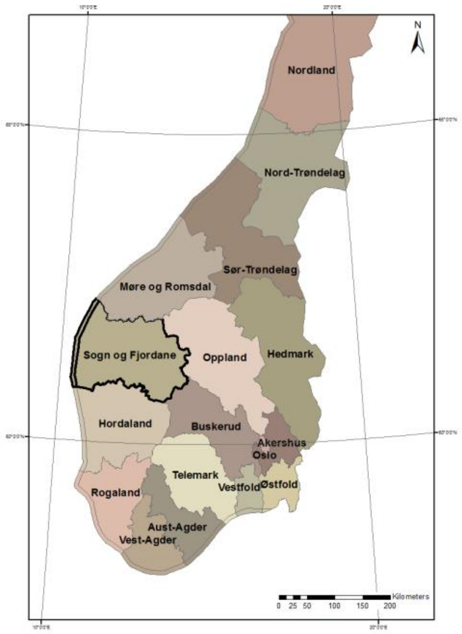


**Figure 2.2-1: South Norway – Regions**

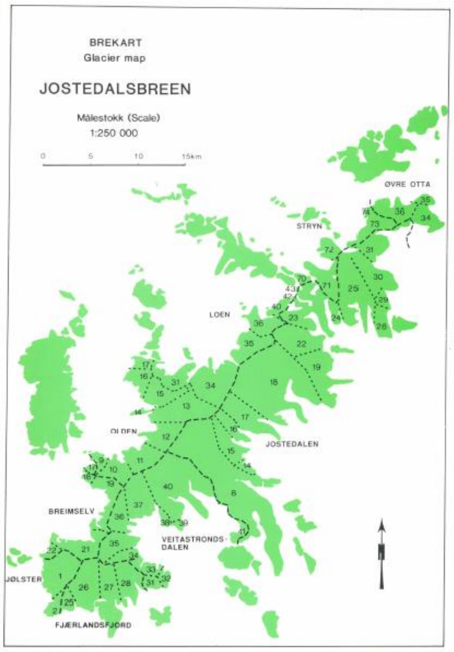


**Figure 2.2-2: Jostedalsbreen (Østrem et al., 1988)**

The glacier Jostedalsbreen is situated in the region Sogn og Fjordane in south western Norway. The glacier has 81 glaciers units and covers an area bigger than 474 km$^2$ (Andreassen et al., 2012). It spreads on four different communes Jølster, Luster, Sognal and Stryn. Jostedalsbreen can be divided in nine main catchments (from north-east to north-west): Øvre Otta, Jostedalen, Veitastrondsdalen, Fjærlandsfjord, Jølster, Breimselv, Olden, Loen and Stryn (Østrem et al., 1988). The sides of the catchment are oriented north-east, south-east south-west and north-west.

Three catchments in the north-west side of the glacier have been then selected: Olden, Loen and Stryn. This side is placed in the commune Stryn.

*Selection of the catchments:*

The selection has been made for several reasons. This side presents discharges station in each off the three lake outlets. The precipitation station is in the middle of the first catchment Olden, temperature stations are also on the catchments. The three catchments are relatively similar. They are subject to the same climatic effects and thus must share similar behaviour. Investigation on the glacier length has been made on glacier in Olden and mass balance review has been made for glacier in the surrounding area. Their selection will allow realisation of many different analyses.

### 2.2.2 Studied area

Olden, Loen and Stryn are three different catchments on the northwest side slope of the glacier Jostedalsbreen. They are quite similar, except Stryn which is twice bigger:

- The percentage of glaciers in the catchment is great: around 40% for the first two, less than 20% for Stryn,
- There is almost no urbanisation of the area,
- The catchment shape is a U-shape valley: narrow valley with steep straight side. Stryn is different with a wider surface,
- The outlet of the catchments is located downstream of large lakes,
- The hypsography of the area shows steep catchments.

These characteristics made the catchments chosen particular and interesting to investigate.

**Table 2.2-1: Catchments' area**

| Catchment | Area [km$^2$] |
|---|---|
| Olden | 202.12 |
| Loen | 234.60 |
| Stryn | 488.19 |

*Expected effects of the size and shape on the runoff:*

The basin size affects the runoff. Generally speaking, small catchments, Olden and Loen, give a fast response with sharp peak compared to bigger catchments, Stryn, which give slow response but long peak. The effect will be even limited by the shape of the catchments: Olden and Loen are relatively narrow which gives a larger time of travel while Stryn is wide.

### 2.2.3 Land type

The catchments have not been too much modified by humans. Most of the upstream areas of the catchments are protected area. Therefore, the area has remained natural to some extent. They are mostly mountainous, but have some forest downstream and glaciers upstream. Lakes represent also an important part of the catchment.

See Appendix B: Lavvann catchment maps

See Appendix C: land type maps

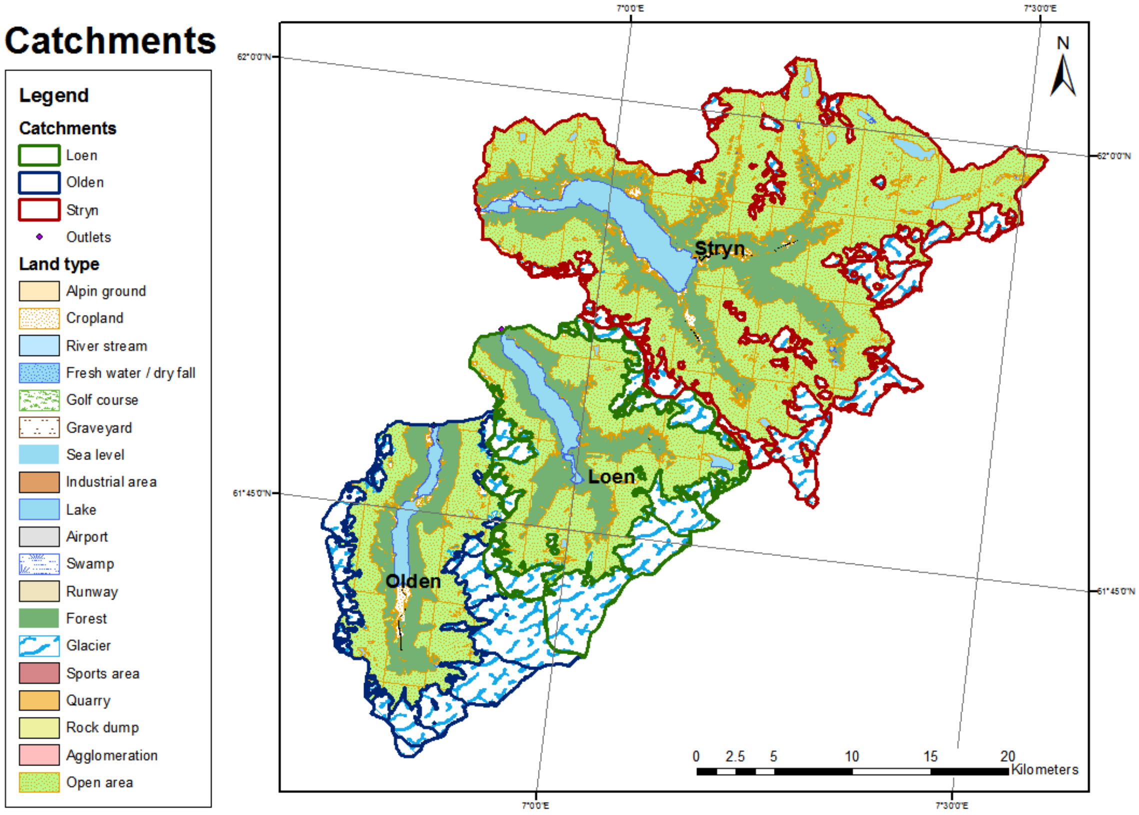


Figure 2.2-3: Catchments area land type (Statkart, 2015)

Table 2.2-2: Land types (Lavvann, 2015)

| Area [%] | Olden | Loen | Stryn |
|---|---|---|---|
| Mountain | 32.8 | 40.2 | 53.7 |
| Cropland | 1.7 | 0.2 | 1.5 |
| Lake | 4.2 | 5.1 | 6.2 |
| Effective lake | 3.3 | 4.5 | 4.8 |
| Swamp | 0.0 | 0.0 | 0.0 |
| Forest | 17.6 | 14.8 | 14.7 |
| Glacier | 40.2 | 37.0 | 17.6 |
| Urban area | 0.0 | 0.0 | 0.0 |

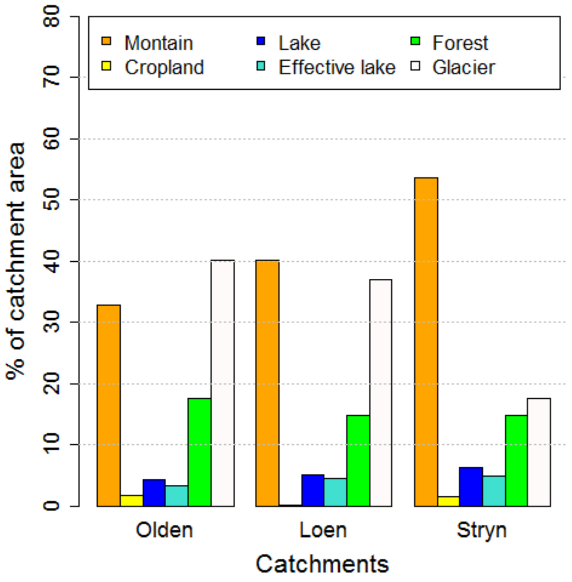


Figure 2.2-4: Land types

For all the catchments, few observations can be made:

- The proportion situated in the mountain is important: above 30 %,
- The proportion of glaciers is also substantial: above 15% for Stryn and around 40% for Olden and Loen,
- The lakes take a great part of the catchment: around 5%,
- The area has not been urbanized or modified by human:
    - The croplands represent less than 2%,
    - The urban areas appear as negligible (Stryn is the most urbanized catchment with 0.01%).

See Appendix D: Land type repartition

### Rivers

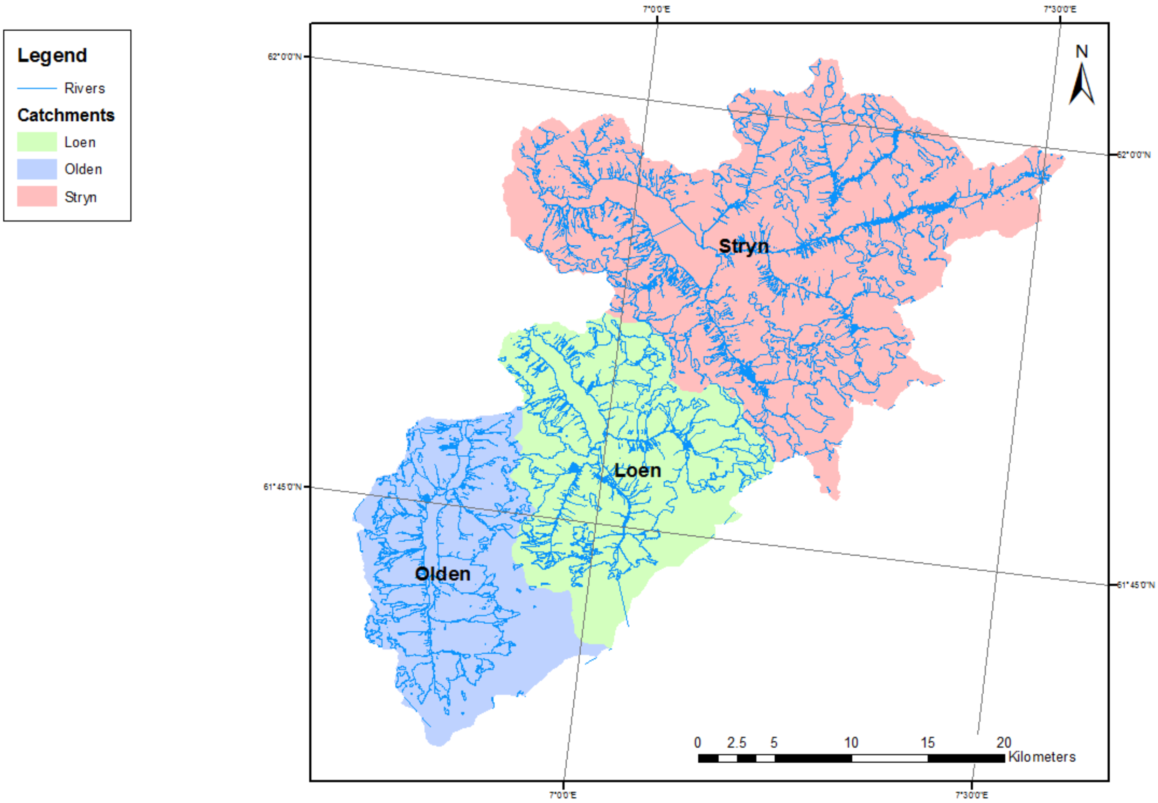


**Figure 2.2-5: Catchments' rivers**

**Table 2.2-3: River length (Lavvan, 2015)**

| Catchment | Olden | Loen | Stryn |
|---|---|---|---|
| Area [km$^2$] | 202.12 | 234.60 | 488.19 |
| River length [km] | 22.1 | 18.8 | 43.7 |

Olden has a longer river length than Loen despite its smaller area. The river length is twice larger in Stryn than in Olden and Loen, which is not surprising considering that the catchment is twice bigger than the other two.

*Expected effects of the land type on the runoff:*

Upstream the glaciers delay the runoff. They prevent precipitation to run off immediately after the event (Jansson et al., 2003). The precipitation is stored in the winter season and released in the summer season.

Forest and trees decrease the runoff mostly because of the evapotranspiration they produce in summer. However the area cover by forest is not so important compared to an average catchment. So it could not be observed a discernible impact of forest on the catchment's answer to a precipitation event.

The catchments are covered by rivers. Runoff travels more easily in the rivers where the outflow has usually a higher discharge rate. So the drainage would be higher in Olden than Loen and Stryn which have a lower ration river length – area. However, the surfaces are mostly bed rock, so the time of concentration will not be different for the rivers the catchments.

Furthermore, downstream in the catchment the lake will temper the runoff. The presence of the lakes is important especially because they are located at the outlet. Their effectiveness is high because it impacts the major part of the catchment. Most of the runoff will pass through the lake.

So, in a first analysis from the land type observed in the catchment, it could be expected that basin's response will be delayed by glaciers on top, but finally tempered by lakes at the bottom. Because of the glacier, the runoff will have an alpine glacial runoff regime: peak in summer, low in winter.

### 2.2.4 Slope of the catchments

The topography of the catchment also affects the watershed's response.

The hypsographic curve of a catchment, also called elevation-area curve, describes the repartition of the elevations in the catchment. The curve is important for the model because all the input data corrections depend on it: precipitation and air temperature are calculated in each elevation zone.

**Table 2.2-4: Hypsographic data (Lavvann, 2015)**

| Altitudes [m.a.s.l.] | Zones | Olden | Loen | Stryn |
|---|---|---|---|---|
| $H_{min}$ | 1: H> | 33 | 52 | 29 |
| $H_{10}$ | 2: H> | 168 | 213 | 195 |
| $H_{20}$ | 3: H> | 530 | 616 | 550 |
| $H_{30}$ | 4: H> | 862 | 934 | 797 |
| $H_{40}$ | 5: H> | 1106 | 1176 | 989 |
| $H_{50}$ | 6: H> | 1305 | 1339 | 1130 |
| $H_{60}$ | 7: H> | 1444 | 1488 | 1251 |
| $H_{70}$ | 8: H> | 1560 | 1593 | 1379 |
| $H_{80}$ | 9: H> | 1645 | 1667 | 1498 |
| $H_{90}$ | 10: H> | 1742 | 1744 | 1595 |
| $H_{max}$ | | 1953 | 2076 | 1933 |

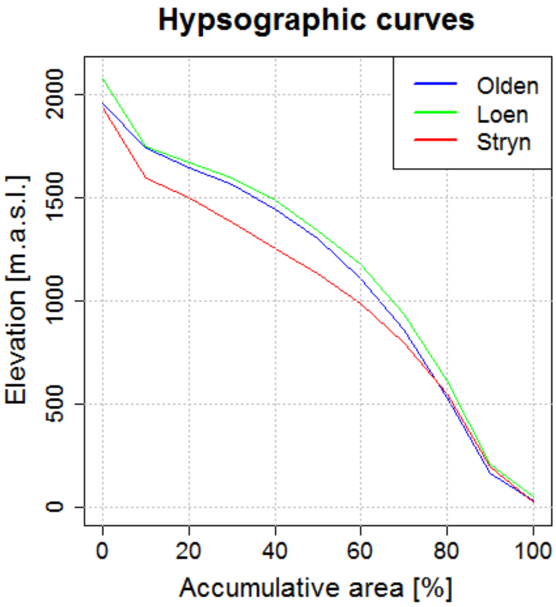


**Figure 2.2-6: Hypsographic curves**

Olden and Loen are really close. Between their highest elevations, around 2000 m and 1500 m, Olden and Loen are relatively flat. Those parts located in this range represent an important portion of the catchments 40%. As there is around 40% of the area covered by glaciers in those catchments, it will be considered that those highest elevation zones are entirely covered by glacier in the HBV-model. Between 1000 m and the outlet, the catchments become steeper as with a difference of 250 m in 10% of the catchments' area.

Stryn has a similar pattern but the hypsographic curve got smoother after the third elevation zone (elevation higher that 800 m). Only 20% of the catchments are located above 1500 m.a.s.l., in high mountains (40% for Olden and Loen). Those two highest elevation zones are glaciated.

See Appendix E: hypsographic curves

**Table 2.2-5: River gradients**

| Catchment | Olden | Loen | Stryn |
|---|---|---|---|
| River gradient [m/km] | 59.2 | 65.4 | 31.2 |

The rivers gradients are high in Olden and Loen when it is half of their magnitude in Stryn which can be explained by the steepness of the catchments.

*Expected effects of the topography on the runoff:*

Precipitation and temperature are dependant of the elevation. With a steep watershed, precipitation in the model will increase quickly from the bottom to the top of the catchment. The orographic effect of the mountain participates to the precipitation formation since this side of the glacier faces the ocean. On the other side, temperature will decrease also rapidly. So on a large part of the catchment situated on high elevation, association between low temperature and high precipitation will give a massive amount of precipitation as snowfall.

Steepness also participates in mechanical effect such as avalanches. The repartition of snow will then not depend only on the climatological factors that are precipitation and temperature as the HBV-model handles it. And this ablation of snow from the high elevations to the low ones where the temperature is higher enhances the melt of the average snow amount on the catchment.

Concerning the runoff, the steepness of the sides accelerates the basin’s response as the gravity effect is more important. The rivers gradient which represents the hydrological steepness of the catchment indicates the velocity of water in the streams. It is sensitively the same in Olden and Loen, and smaller in Stryn. So the response of storm flow would be quicker on the first two catchments than on the bigger one.

So the topography of the catchment would create much precipitation from the precipitation data station, especially snowfall with low temperature, and will accelerate the watershed response to an event.

### 2.2.5 Glaciers

NVE provides the Breatlas which lists much information about the glaciers in Norway. There are two concerning the glacier in northern Norway and two in southern Norway where Jostedalsbreen is situated. The most recent one was done in 1988.

**Table 2.2-6: Glaciers characteristics for the 3 catchments (Breatlas, 1988)**

| Catchment | Olden | Loen | Stryn |
|---|---|---|---|
| Drainage area [km²] | not defined | 234 | 493 |
| Number of glaciers | 21 | 32 | 52 |
| Total glacier area [km²] | 77.89 | 81.74 | 70.29 |
| Mean glacier elevation [m.a.s.l] | 1433 | 1507 | 1457 |
| Estimated ice volume [km$^3$] | 5.65 | 5.88 | 5.42 |
| Estimated average ice thickness [m] | 72.54 | 71.94 | 77.11 |

Those data have been compared with data extracted from Lavvann and from Cryclim:

**Table 2.2-7: Glaciers area in % from all sources**

| Catchments | Olden | Loen | Stryn |
|---|---|---|---|
| Lavvann 2015 | 40.20 | 37.00 | 17.60 |
| Cryoclim gao no 1955-1986 | 38.48 | 36.20 | 17.63 |
| Cryoclim gao no 1999-2006 | 35.45 | 32.80 | 14.71 |
| Statkart (no date) | 34.31 | 31.56 | 14.31 |
| Breatlas 1969 | 37.53 | 33.28 | 25.15 |
| Breatlas 1988 | 38.53 | 34.83 | 14.39 |

The percentage given by Lavvann is relatively close to the data in the CryoClim in 1955-1986. Therefore the data from Lavvann has been selected and used thereafter.

*Expected effects of the glaciers on the runoff:*

In basin located in alpine area where there is a substantive portion covered by glaciers, the runoff has glacial regime: a regime led by glacier’s behaviour. It means a high outflow when the temperature is high, a unique peak in July-August when glacier ice and snow melt accur that to say in summer, and a very low discharge in winter.

### 2.2.6 Climate of the studied area

The region Sogn og Fjordane is located in Eastern Norway which is situated in northern Europe on the west coast of the continent.

The climate in this area is an oceanic climate. The climate is relatively cool in summer and colder in winter, but the temperature difference between summer and winter is not considerably significant. Though, the high elevation of the top of the catchments (approximately 2000 m) can give very low temperature. Precipitation is around a meter and half, 40% in summer and 60% in winter.

Due the high latitude of Norway, the catchments (latitude of 62°) are affected by an important gradient of solar exposition between winter and summer: 5h 30 min of sun in December against 19h 30 in June.

*Expected effects of the climate on the runoff:*

Precipitation occurs mainly in winter when the temperature decrease. So if it can be observed high runoff in autumn when the precipitation increases, it will be reduced as the temperature falls below the threshold of rain/snow. A part of the potential runoff will be stocked until the temperature rises again. This would be consistent with a snow regime, which is based on the snow melt while glacial regime depends only on glacier ice melt. So the regime could be snow-glacial.

The solar exposition has an effect on the evaporation therefore on the water balance of the area. It can be expected a great difference of the evaporation between winter and summer. This would reduce the runoff magnitude in summer.

# 3 DATA ACQUISITION AND CONTROL

The data were collected from different sources: Lavvann, Senorge, Eklima and met.no:

- The meteorological data, precipitation and air temperature, come from the website Eklima and Senorge:
    - Daily values from Eklima,
    - Maps from Senorge,
- The discharge data have been provided by met.no.

Then the data series have been completed when missing data were identified, and controlled in different ways to identify possible error in data series:

- Visual inspection on curve,
- Accumulation plot,
- Double mass analysis.

To assess the model goodness on the glacier part, the period covered by the data series needs to be relatively long so it can include periods with different glaciers behaviour change.

See Appendix F: Map stations

## 3.1 ACQUISITION OF METEOROLOGICAL DATA

The daily meteorological data can be found on Eklima. The precipitation and air temperature stations in and around the catchments have been extracted.

All the stations from Eklima giving data located in the commune Stryn and the bordering communes were considered. Then the stations of the east side of the glacier were removed, same as the stations which were too far from the catchments.

See Appendix G: stations

### 3.1.1 Precipitation data

#### *3.1.1.1 Climate: precipitation*

**Table 3.1-1: Precipitation for the three catchments (Lavvann, 2015)**

| Precipitation | Olden | | Loen | | Stryn | |
|---|---|---|---|---|---|---|
| | [mm] | % | [mm] | % | [mm] | % |
| Year | 1674 | | 1640 | | 1354 | |
| Summer | 606 | 36% | 609 | 37% | 465 | 34% |
| Winter | 1067 | 64% | 1031 | 63% | 889 | 66% |

According the Table 3.1-1, Olden is the catchment with the highest precipitation number, closely followed by Loen. Stryn receives less precipitation, both in summer and winter. The repartition of the precipitation along the year is sensitively the same for the three catchments.

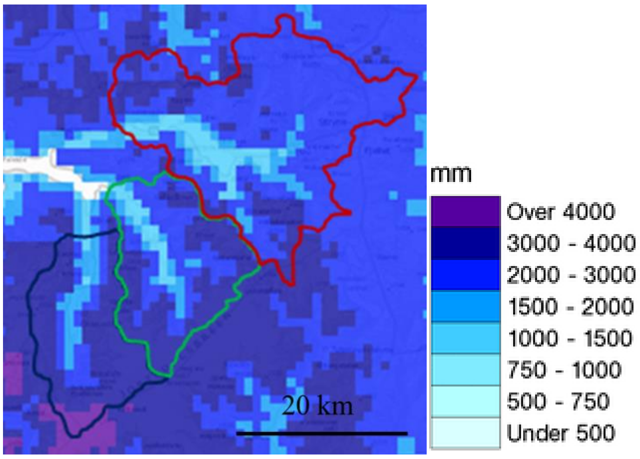


**Figure 3.1-1: Annual precipitation for the normal period 1961-1990 (Senorge, 2015)**

As it can be expected the higher the elevation is, the higher the precipitation is. Big precipitation is located up in the mountain where the surface is covered by glaciers while the lakes downstream see less precipitation. Olden has a very high precipitation amount on its entire area except on the lake and its borders, and the precipitation on the south of the catchment is extreme. Precipitation on Loen is less important. For Stryn, precipitation covering the catchment area is not as high as in the other catchments.

#### 3.1.1.2 Data collection

There are many precipitation stations in and around the three catchments.

**Table 3.1-2: Precipitation stations**

| Station n° | Name | Starts | Ends | Data | Missing data | |
|---|---|---|---|---|---|---|
| 15890 | Grotli III | 01.10.2008 | 31.12.2013 | 1918 | 0 | 0.0% |
| 57390 | Skei I Jølster | 01.07.1969 | 31.12.2013 | 16255 | 0 | 0.0% |
| 58120 | Klakegg - Bolset | 01.09.1985 | 31.05.2004 | 6817 | 0 | 0.0% |
| 58320 | Myklebust i Breim | 01.01.1900 | 31.12.2013 | 41638 | 0 | 0.0% |
| 58370 | Utvik | 01.06.1962 | 31.01.1969 | 2437 | 212 | 8.7% |
| 58390 | Innvik - Heggdal | 17.10.2005 | 31.12.2013 | 2997 | 0 | 0.0% |
| 58400 | Innvik | 01.01.1950 | 06.01.2006 | 20460 | 0 | 0.0% |
| 58430 | Olden – Vangberg | 02.07.1973 | 30.09.1992 | 7031 | 29 | 0.4% |
| 58480 | Briksdal | 01.01.1900 | 31.12.2013 | 41638 | 33 | 0.1% |
| 58500 | Loen | 01.04.1971 | 31.03.1988 | 6210 | 92 | 1.5% |
| 58700 | Oppstryn | 01.01.1900 | 31.01.1991 | 33268 | 467 | 1.4% |
| 58880 | Sindre | 01.01.1957 | 29.06.2005 | 17712 | 33 | 0.2% |
| 58900 | Stryn - Kroken | 02.05.2002 | 31.12.2013 | 4262 | 37 | 0.9% |
| 58960 | Hornindal | 01.01.1900 | 31.12.2013 | 41638 | 5 | 0.0% |

Despite the large amount of stations available in and around the area, their range of operation does not cover a long period and some have numerous missing data. So the only precipitation station that has been considered is Briksdal station where precipitation was recorded from 1900 to 2013.

Briksdal station is located in the middle of Olden catchment (Lat: 61°61’, Long: 6 °81’), at an altitude of 40 m next to the lake.

#### 3.1.1.3 Fill in the missing data

There are some missing data in the precipitation series. The missing data can be filled using three different equations:

- Missing data as station average:

$$p = \frac{1}{G}\sum_{i=1}^{G} p_i \tag{1}$$

- Normal ration method:

$$p = \frac{1}{G}\sum_{i=1}^{G} \frac{P_O}{P_i} p_i \tag{2}$$

- Inverse distance:

$$p = \frac{1}{D}\sum_{i=1}^{G} \frac{p_i}{{d_i}^b} \text{ with } D = \sum_{i=1}^{G} \frac{1}{{d_i}^b} \tag{3}$$

With:

- P: missing data
- O: index of the station where the data is missing,
- G: number of gauges,
- $p_i$: precipitation in the gauge of the station i,
- $P_i$: annual precipitation in the gauge of the station i,
- $P_0$: annual precipitation in the gauge at the station 0 where the data is missing,
- $d_i$: distance between the station i and the station 0,
- b: coefficient taken as equal to 1.

The different methods give close results. The formula used is the inverse distance method.

See Appendix H: Precipitation missing data

#### *3.1.1.4 Control of the data from Briksdal station*

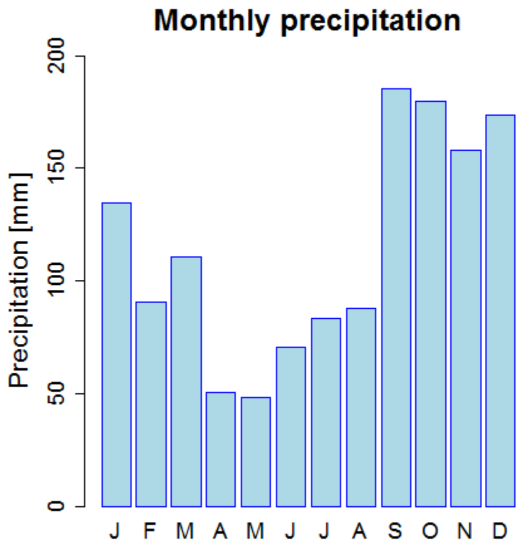


**Figure 3.1-2: Monthly precipitation over the normal period 1961-1990 for Briksdal station**

The repartition of precipitation is consistent with the climate of the station location: highest precipitation in winter and lowest precipitation in summer.

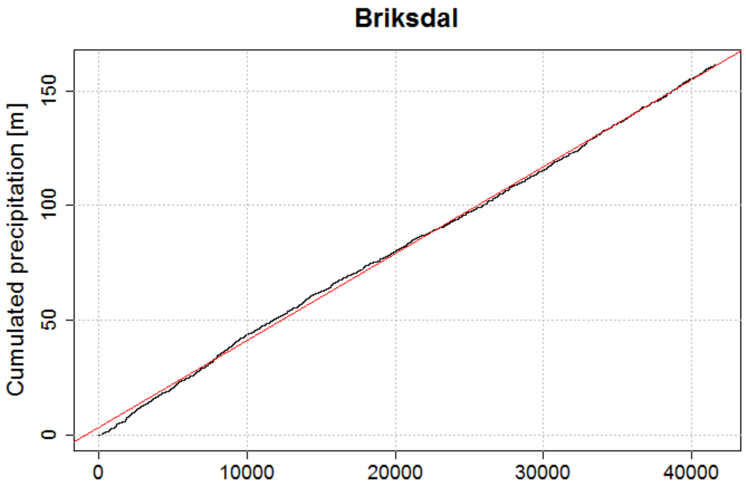


**Figure 3.1-3: Cumulated precipitation over the entire period of record for Briksdal station**

The cumulated precipitation does not show a change in the gradient which mean that the precipitation record is consistent.

### *3.1.1.5 Precipitation on the normal period*

**Table 3.1-3: Normal seasonal precipitation in Briksdal station**

| Normal period 1961-1990 | Hydrological year | Winter season | Summer season |
|---|---|---|---|
| Annual precipitation [mm] | 1356 | 1072 | 283.37 |

The hydrological year A starts the 1st of September of the year A and ends the 31st of August of the year A+1. The winter of this hydrological year starts the 1st of September and ends the 31st of April. The summer starts the 1st of May and ends the 31st of August.

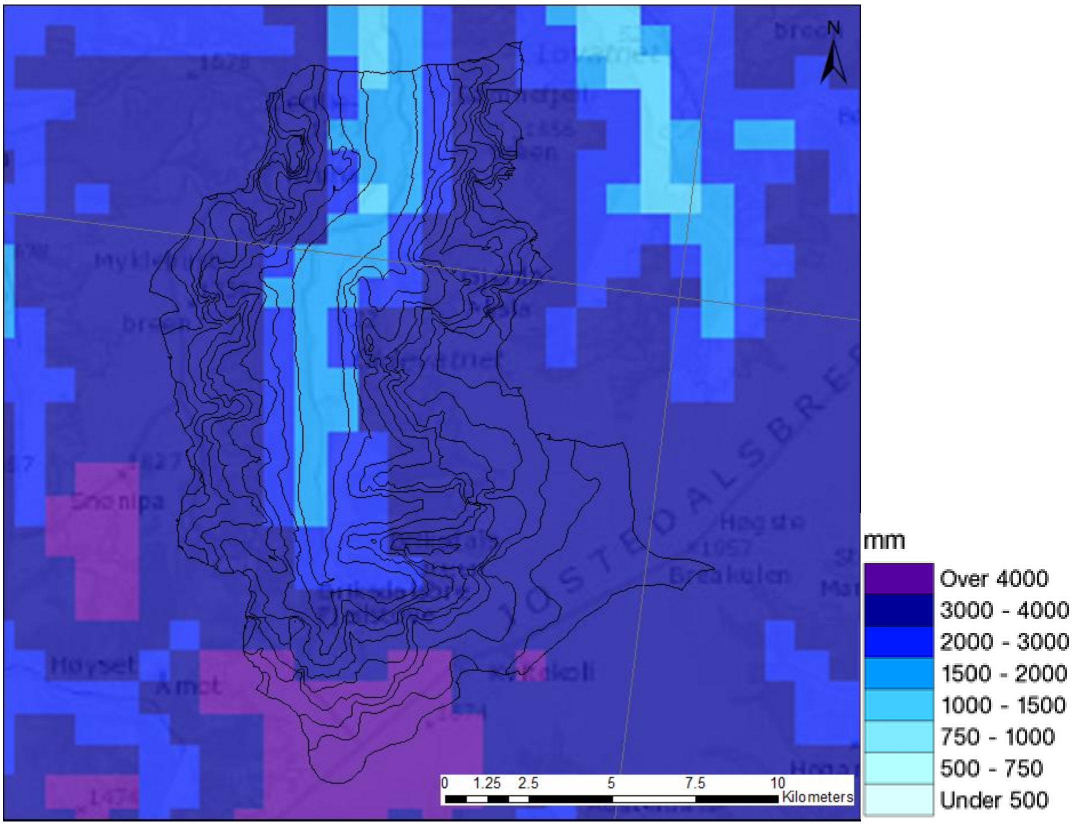


**Figure 3.1-4: Map of normal annual precipitation for Olden catchment**

**Table 3.1-4: Annual precipitation ranges for Olden catchment**

| Zones | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Precipitation ranges (mm) | 1500<br>2000 | 2000<br>3000 | 2000<br>3000 | 2000<br>3000 | 3000<br>4000 | 3000<br>4000 | 3000<br>4000 | 3000<br>4000 | 3000<br>4000 | 3000<br>and<br>over |

So the areal precipitation for the catchment would be within the range 2550 -3500 mm.

### 3.1.1.6 Precipitation over the period

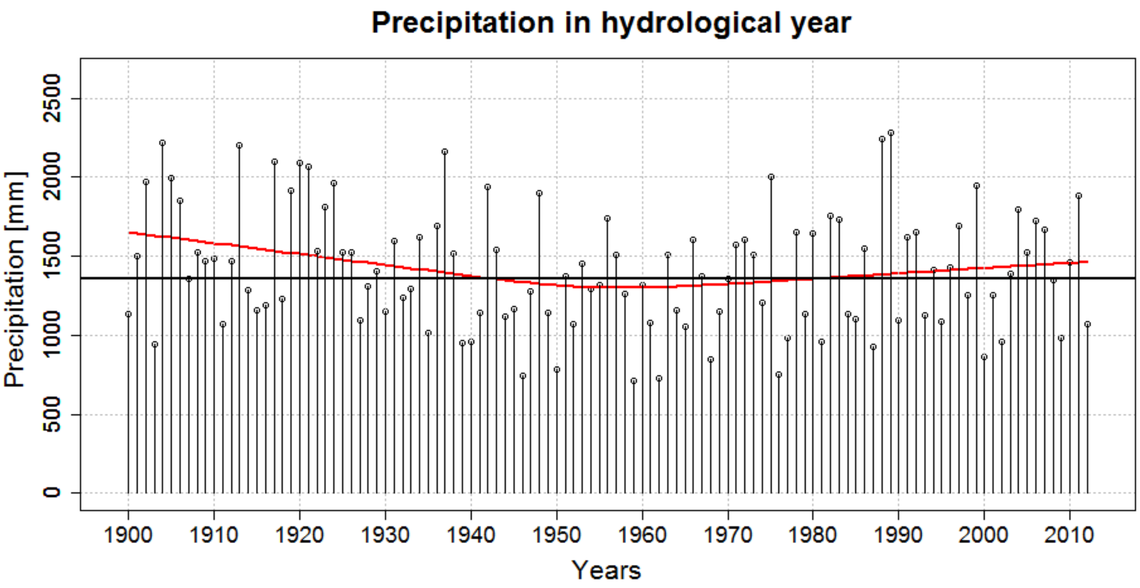


**Figure 3.1-5: Annual precipitation for Briksdal station**

*The bold line represents the normal annual precipitation and the red line represents the tendency of the annual precipitation.*

There is no clear tendency of the annual precipitation to increase or decrease between 1900 and 2012. Annual precipitation was high before 1930. Then it was lower between 1930 and 1990 with some wet years. Then precipitation has been increasing slightly since 1990.

See Appendix I: Precipitation record

### 3.1.2 Temperature data

#### *3.1.2.1 Climate: air temperature*

**Table 3.1-5: Air temperature in the three catchments outlets (Lavvann, 2015)**

| Temperature [° C.] | Olden | Loen | Stryn |
|---|---|---|---|
| Year | -0.4 | -0.1 | 1.1 |
| Summer | 4.5 | 4.4 | 5.2 |
| Winter | -3.8 | -3.3 | -1.8 |

According the Table 3.1-5, Olden is the colder catchment closely followed by Loen and Stryn is the warmest catchment. The difference in the annual temperature appears mainly because of the winter temperature which is 2°C warmer in Stryn than in Olden while the difference in summer between the two catchments is less than one.

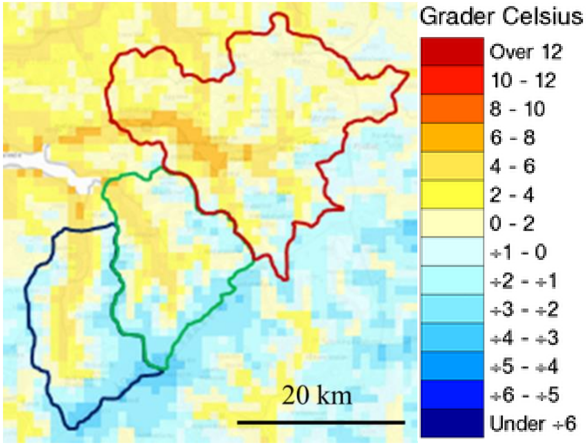


**Figure 3.1-6: Annual temperature for the normal period 1961-1990 (Senorge.no, 2015)**

As it can be expected the coldest temperature is observed up in the mountain where the surface is covered by glaciers and the warmest is in downstream on the lake. The difference of temperature between the three catchments is also visible. Stryn has warmest values on its lake than the other two catchments. The glacier part in Olden is the coldest of all the glacier part. Unlike Stryn, Olden and Loen do not have many areas with intermediate range of temperature values (white on the map). The temperature changes within a catchment are consistent with their respective slope.

#### 3.1.2.2 Data collection

There are also several temperature stations around the area.

**Table 3.1-6: Temperature stations**

| Station n° | Name | Starts | Ends | Data | Missing data | |
|---|---|---|---|---|---|---|
| 15890 | Grotli III | 01.10.2008 | 31.12.2013 | 1918 | 0 | 0.0% |
| 58370 | Utvik | 01.06.1962 | 31.01.1969 | 2437 | 212 | 8.7% |
| 58430 | Olden – Vangberg | 02.07.1973 | 30.09.1992 | 7031 | 28 | 0.4% |
| 58500 | Loen | 01.04.1971 | 31.03.1988 | 6210 | 92 | 1.5% |
| 58530 | Rake | 20.11.1974 | 05.05.1983 | 3089 | 359 | 11.6% |
| 58531 | Rake II | 20.11.1974 | 05.05.1983 | 3089 | 363 | 11.8% |
| 58532 | Rake III | 20.11.1974 | 11.04.1983 | 3065 | 358 | 11.7% |
| 58660 | Flo | 13.05.1983 | 31.08.1988 | 1938 | 189 | 9.8% |
| 58700 | Oppstryn | 01.01.1957 | 31.01.1991 | 12449 | 0 | 0.0% |
| 589 00 | Stryn – Kroken | 24.11.1993 | 31.12.2013 | 7343 | 635 | 8.65% |

Even though there are many stations, their range of operation does not cover all the same period as Briksdal station for precipitation and some of them have numerous missing data. So association and correction of data will be needed to get a record on a long period. The only temperature stations that have been kept for further study are Oppstryn, Olden-Vangberg and Stryn-Kroken. Only Oppstryn is in one of the catchments (Stryn), the two others are downstream of the catchments.

#### 3.1.2.3 Comparison of the three temperature stations

With the three different stations that have been selected, it is possible to build a temperature series that covers the period 1957 to 2013. The temperature will be corrected to be used as it was temperature from only one station. The repartition is as following:

- From 1957 to 1991: temperature from Oppstryn n°58700,
- From 1991 to 1992: temperature from Olden- Vangberg n°58430,
- From 1992 to 1993: normal temperature from Oppstryn n°58700,
- From 1993 to 2013: temperature from Stryn-Kroken n°58900.

**Table 3.1-7: Temperature stations selected**

| Station n° | Name | Altitude [m.a.s.l.] | Lat. | Long. | Annual normal temperature [°C] |
|---|---|---|---|---|---|
| 58430 | Olden – Vangberg | 78 | 61°86’ | 6°76’ | 5.892623 |
| 58700 | Oppstryn | 201 | 61°93’ | 7°23’ | 5.722131 |
| 58900 | Stryn – Kroken | 208 | 61°92’ | 6°56’ | 4.942896 |

The stations Oppstryn and Olden-Vangberg do not have the same altitude but have a slight difference in their annual normal temperature (0.2°C), whereas the stations Oppstryn and Stryn-Kroken have a bigger difference in their annual normal temperature (0.8°C) but share an altitude in the same range (201 to 208 m.a.s.l.).

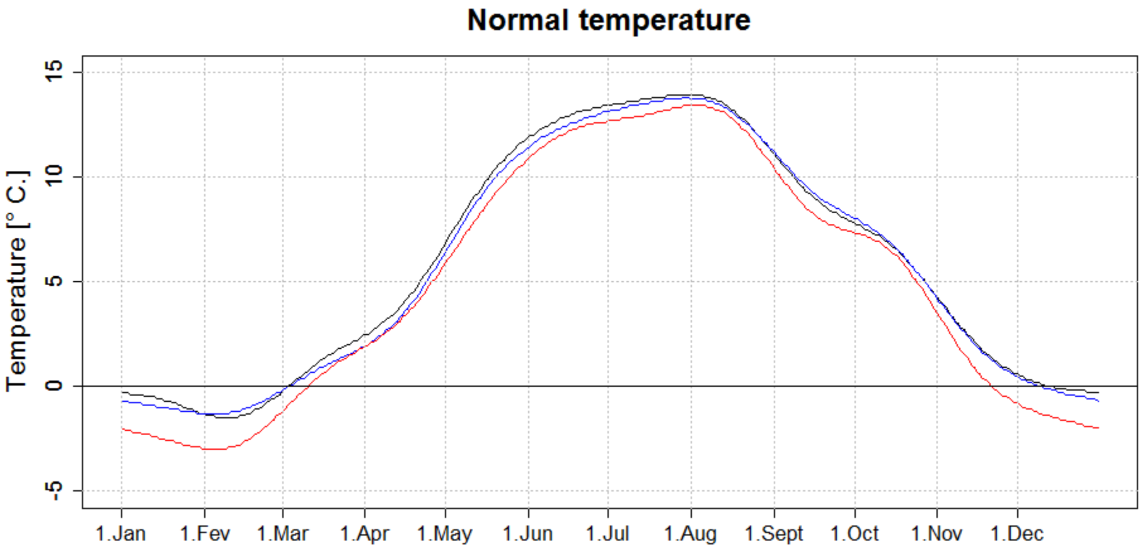


**Figure 3.1-7: Normal daily temperature for the three temperature stations selected**

See Appendix J: Comparison temperature data

The temperature patterns are very similar on the Figure 3.1-7. So the temperature will be corrected as said previously. The results obtained will be controlled because the runoff might however show a difference between the periods due to those differences.

#### 3.1.2.4 Fill in the missing data

- First part: the temperature from Oppstryn station are selected

$$T_{f-1} = T_{Oppstryn} \tag{4}$$

The Oppstryn station does not have missing data in its period of record.

See Appendix K: Oppstryn temperature

- Second part: adding the Olden-Vangberg station temperature data

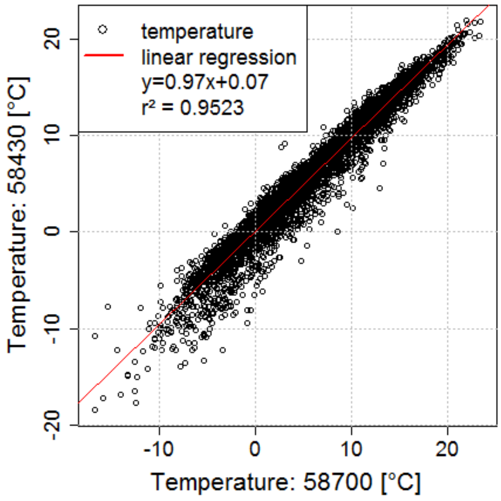


**Figure 3.1-8: Correlation between Oppstryn and Olden-Vangberg stations on the overlapping period**

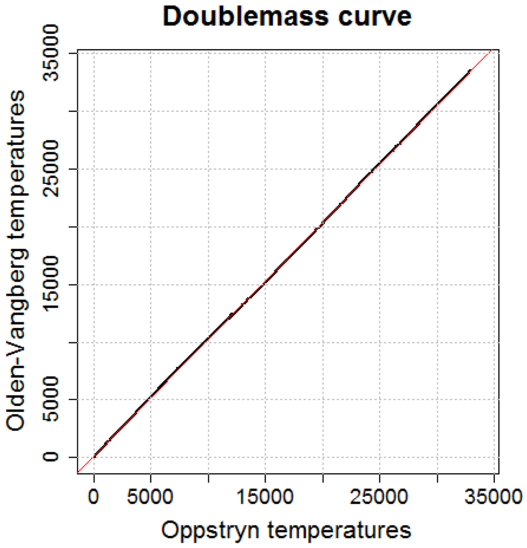


**Figure 3.1-9: Doublemass curve for Oppstryn - Olden-Vangberg stations**

The temperature series from Olden-Vangberg and Oppstryn are correlated with a good factor.

The double mass analysis consists in evaluating if the data need correction, due to a possible change in the data record. It helps in checking if the consistency of a record is good enough to further use. The double mass plot shows that the two stations have consistent data recorded. So the use of this station is an acceptable choice.

The temperature added to the final temperature data are calculated as flowing:

$$T_{f-2} = T_{Olden} + (\text{avg.}\, T_{Oppstryn} + \text{avg.}\, T_{Olden}) \tag{5}$$

- Third part: adding the normal values of temperature

There is no data between the 30.09.1992, when Olden-Vangberg data series stops, and 24.11.1993, when Stryn-Kroken data series starts. So the temperature taken is the normal temperature of Oppstryn.

$$\mathrm{T_{f-3} = T_{Oppstryn-normal}} \tag{6}$$

This period will not give good results but it is used in order to have a complete series starting from 1957 to 2013.

- Fourth part: adding the Stryn-Kroken's temperature data

Unlike Oppstryn and Olden temperature series, there are missing data in the Stryn-Kroken series in the period that will be used. The period with missing data should be filled in with shifted values from series with the best correlation with Stryn-Kroken. However as there is no other temperature data series that cover the same period as this station, the method cannot be used. So the missing data are replaced by the normal temperature of Stryn-Kroken:

$$\mathrm{T_{Stryn}} = \begin{cases} \mathrm{T_{Stryn}} & \text{if } \mathrm{T_{Stryn} \neq NA} \\ \mathrm{T_{Stryn-normal}} & \text{if } \mathrm{T_{Stryn} = NA} \end{cases} \tag{7}$$

This method will also give bad results on the period where many consecutive data are missing.

Then, the temperature for Stryn-Kroken is shifted before being added to the final temperature data:

$$\mathrm{T_{f-4} = T_{Stryn} + \left(avg.\,T_{Oppstryn} + avg.\,T_{Stryn}\right)} \tag{8}$$

So the final temperature record is:

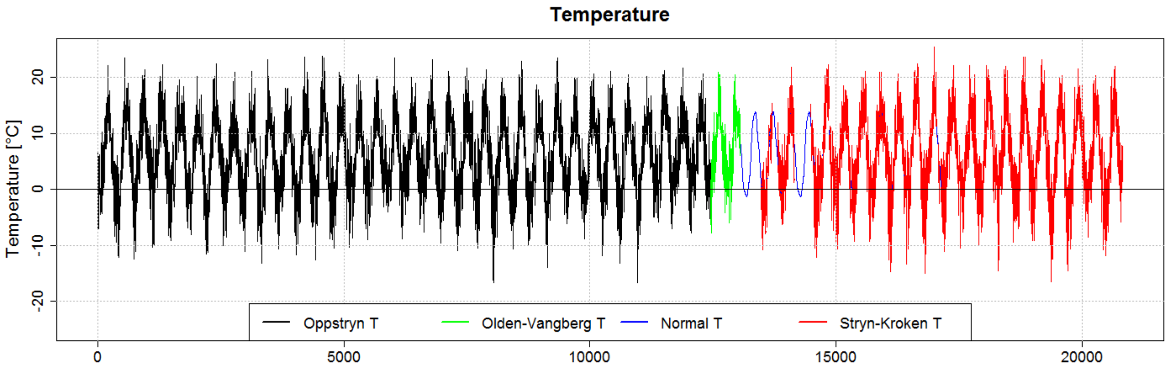


**Figure 3.1-10: Temperature completed for Oppstryn station over the period 1957-2013**

The years where there is blue data are the years where the calibration of the model cannot be proceed and where the results will not be considered for assessment and validation of the model.

### 3.1.2.5 Control of the data from Oppstryn

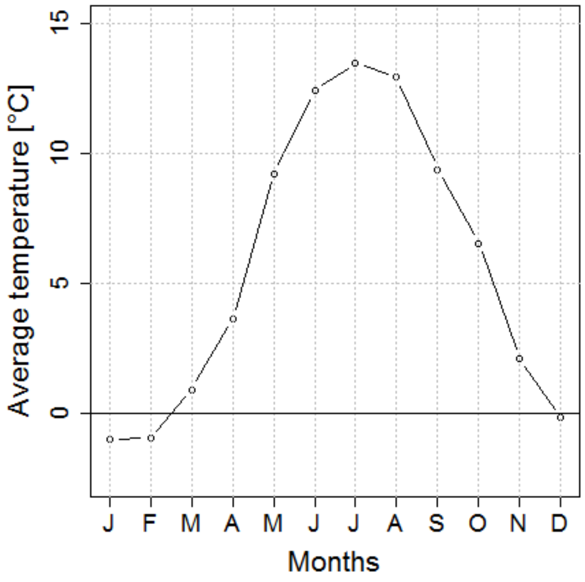


**Figure 3.1-11: Average temperature over the normal period 1961-1990**

The average temperature in each month is consistent with location of the station Oppstryn: highest temperature in summer and lowest temperature in winter.

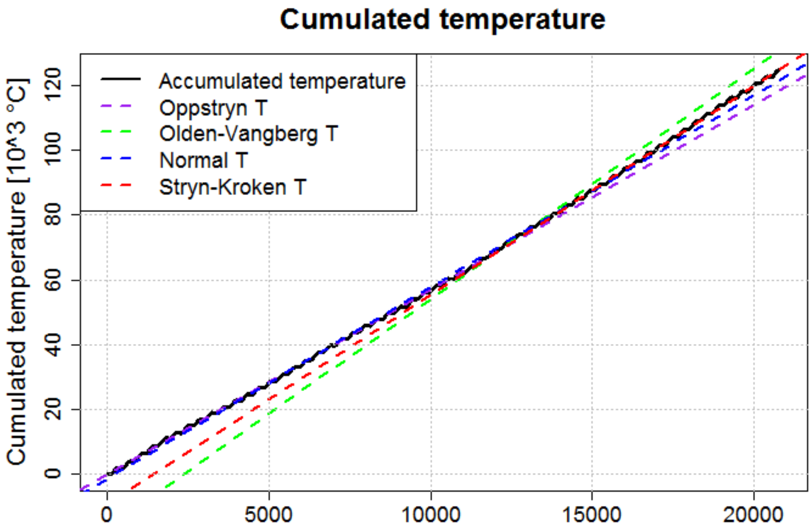


**Figure 3.1-12: Cumulated temperature with the new temperature data series over the entire period**

The cumulated temperature shows a gradient change which increases. That gradient could be due to the climate change inducing an increase in the temperature. So no further correction has been made to the temperature data.

### 3.1.2.6 Temperature over the normal period

**Table 3.1-8: Normal seasonal temperature for Oppstryn station**

| Normal period 1961-1990 | Hydrological year | Winter season | Summer season |
|---|---|---|---|
| Temperature [°C] | 5.72 | 2.55 | 11.94 |

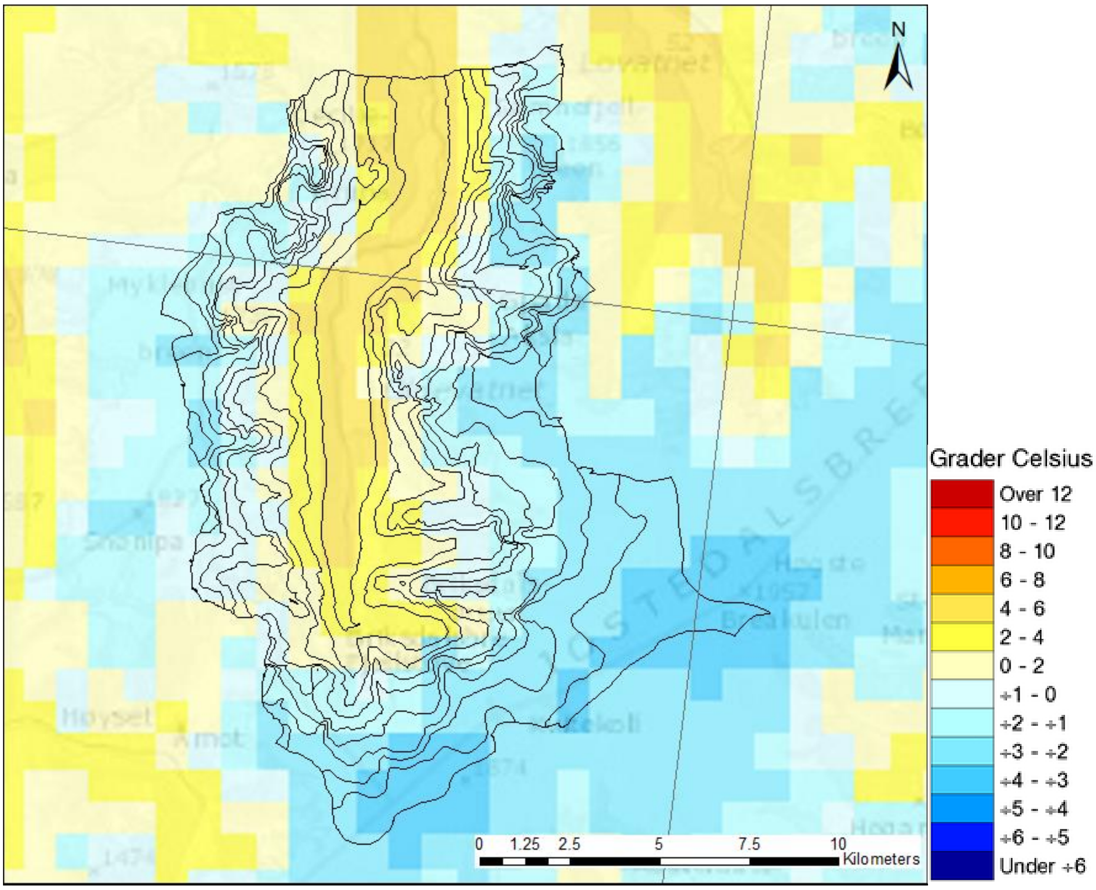


**Figure 3.1-13: Map of normal annual temperature in Olden catchment**

**Table 3.1-9: Normal annual temperature ranges for Olden catchment**

| Zones | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 4 | 2 | 0 | 0 | -1 | -1 | -1 | -2 | -2 | -3 |
| ranges (mm) | 6 | 4 | 2 | 2 | 0 | 0 | 0 | -1 | -1 | -2 |

So the areal temperature for the catchment would be within the range -0.4 to 1 °C.

#### *3.1.2.7 Temperature over the period*

The temperature finally covers the period 1957 to 2012.

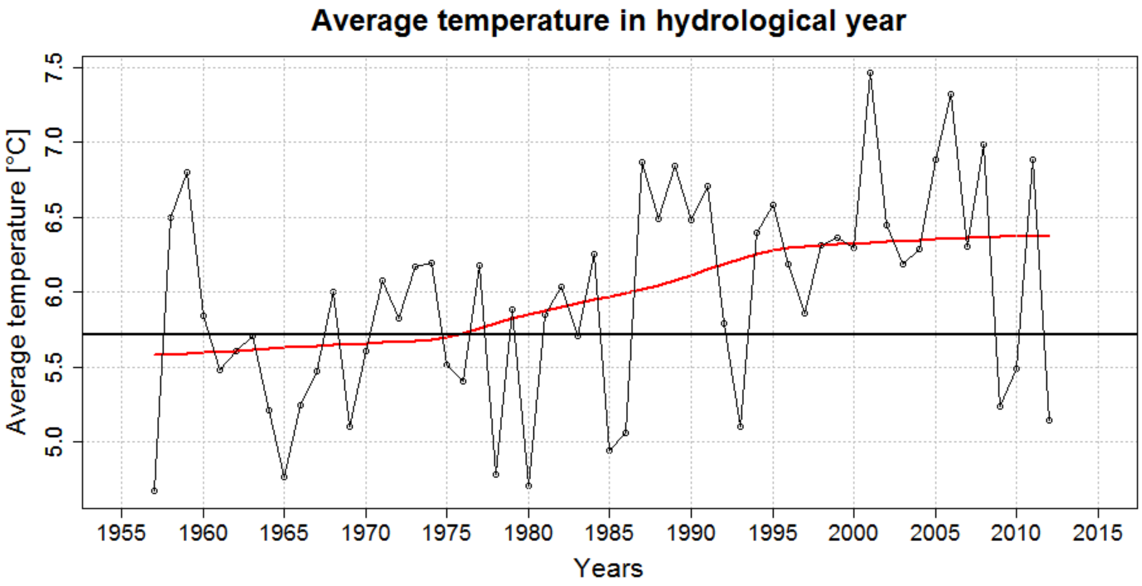


**Figure 3.1-14: Annual temperature for Oppstryn station**

*The bold line represents the normal annual temperature. The red line represents the tendency of the annual temperature calculated.*

There is a clear tendency of the annual precipitation to increase from 1957 to 2012. Between 1987 and 2012, the average temperature dropped below the normal temperature only four times. This temperature change will seriously affect the glacier changes.

See Appendix L: Temperature record

### 3.1.3 Evapotranspiration data

There is no record of evapotranspiration. So it has been calculated with the Thornthwaite equation (1948):

$$\mathrm{PET} = 1.6 * \frac{\mathrm{L}}{12} * \frac{\mathrm{N}}{30} * \left(\frac{10 * \mathrm{T_a}}{\mathrm{I}}\right)^{\alpha} \tag{9}$$

With:

- PET: estimated potential evapotranspiration (cm/month)
- L: number of days in the month considered
- N: average day length in hours for the month considered
- $T_a$: average daily temperature in °C for the month considered (0 if negative)
- I: heat index depending on the 12 monthly mean temperature $T_{ai}$

$$I = \sum_{\mathrm{i}=1}^{12} \left(\frac{\mathrm{T_{ai}}}{5}\right)^{1.514} \tag{10}$$

- α: coefficient

$$\alpha = (6.75*10^{-7})*I^3-(7.71*10^{-5})I^2+(1.792*10^{-2})I+0.49239 \tag{11}$$

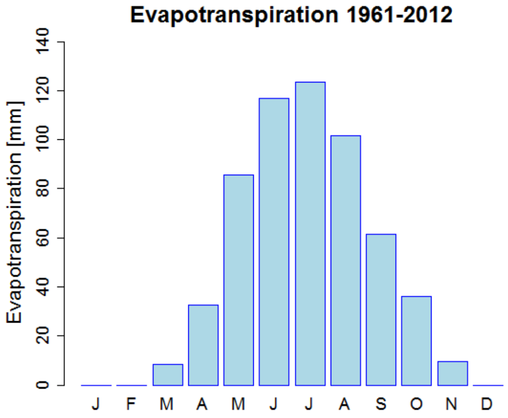


**Figure 3.1-15: Evapotranspiration PET for the period calculated for Oppstryn station**

The evapotranspiration calculated seems very high for the region. A correction coefficient will be applied to it when running the HBV-model.

See Appendix M: Evaporation data

## 3.2 ACQUISITION OF HYDROLOGICAL DATA

### 3.2.1 Runoff characteristics

**Table 3.2-1: Specific runoff for the three catchments (Lavvann, 2015)**

| Catchment | Olden | Loen | Stryn |
|---|---|---|---|
| Area [$km^2$] | 202.12 | 234.60 | 488.19 |
| Specific runoff [$l/s/km^2$] | 75.70 | 64.80 | 60.00 |
| Runoff expected [$m^3/s$] | 15.30 | 15.20 | 29.29 |

Even though Olden has the smaller area than Loen, it has a little bit higher runoff because of the important specific runoff it has.

### 3.2.2 Runoff data collection

The hydrological data has been collected from the Norwegian Meteorological Instistue met.no. There are the discharge series from tree gauging stations, one in at the outlet of each catchment.

Gauging stations:

- Catchment 1 Olden: station Nordre Oldevatn, no. 88.30.0 ,
- Catchment 2 Loen: station Lovatn, no 88.4.0,
- Catchment 3 Stryn: station Strynsvatn, no 88.11.0.

The hydrological data include discharge series from 1901 to 2013 but there are some interruptions in the measurements for Stryn. Finally, the data for the three gauging stations that has been taking into account are:

- Olden: station Nordre Oldevatn
    - Data collection starts: 13.05.1902
    - Data collection ends: 31.12.2013
- Loen: station Lovatn
    - Data collection starts: 20.03.1901

  - Data collection ends: 31.12.2013
- Stryn: station Strynsvatn,
  - First period: starts 12.05.1902 - ends: 30.11.1924,
    - Periods where discharge equals 0 which are not considered:
      - 11.02.1922-23.02.1922
      - 14.03.1923-22.03.1923,
  - Second period: starts: 01.08.1967 - ends: 24.02.1994,
  - Third period: starts 13.08.1994 - ends 02.11.1996,
  - Fourth period: starts 01.01.1997 - ends 30.12.2013.

### 3.2.3 Control of hydrological data

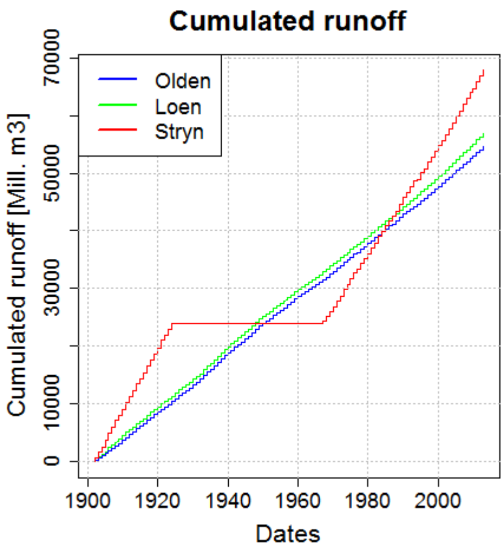


**Figure 3.2-1: Cumulated runoff for the three catchments**

There is a significant gap in the data record for the station Strynsvatn between 1924 and 1967.

The control of the hydrological data passed through a double mass analysis. The double mass analysis performed here is a double mass curve between the discharges collected in the gauging stations in each of the three catchments.

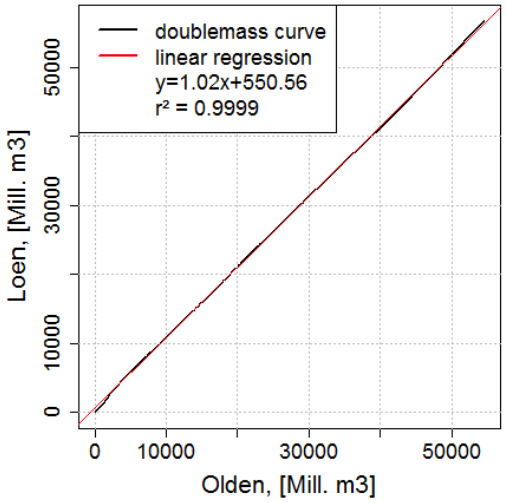


**Figure 3.2-2: Double mass curve for Olden - Loen**

The double mass analysis performed between Nordre Oldevatn (Olden) and Lovatn (Loen) gives a curve showing that the data records are very similar and thus do not need further correction. There is a good correlation between Lovatn and Stryn in the period where the data were collected.

### 3.2.4 Hydrological data acquisition summery

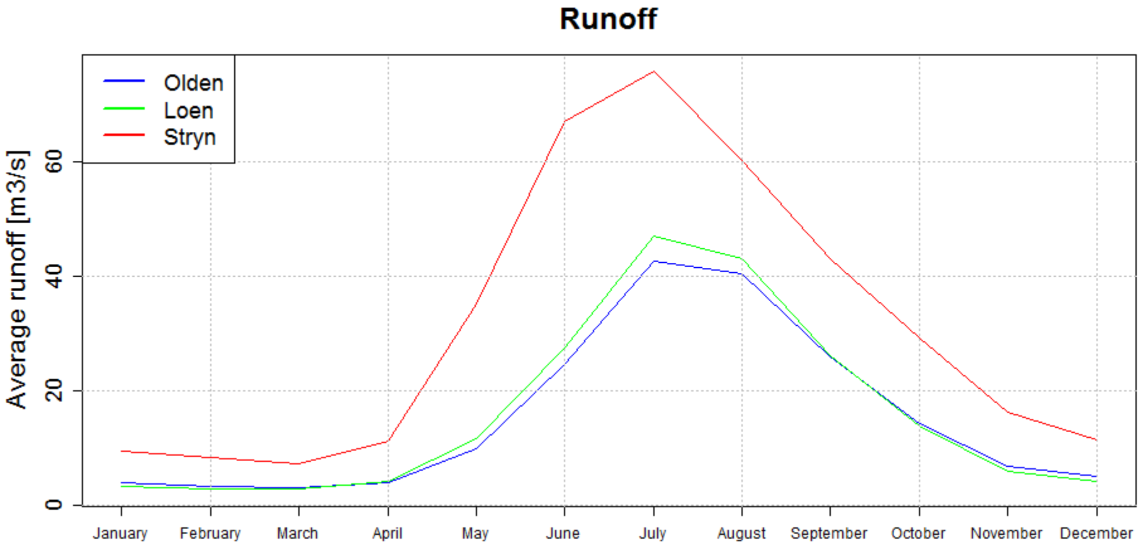


**Figure 3.2-3: Runoff in the three catchments**

On the total period from 1901 to 2012, the runoff seems to follow a snow-glacial regime. The highest runoffs occur in the middle of summer in July for the three catchments. The base flow is around 4 $m^3/s$ for Olden and Loen, and 9 $m^3/s$ for Stryn.

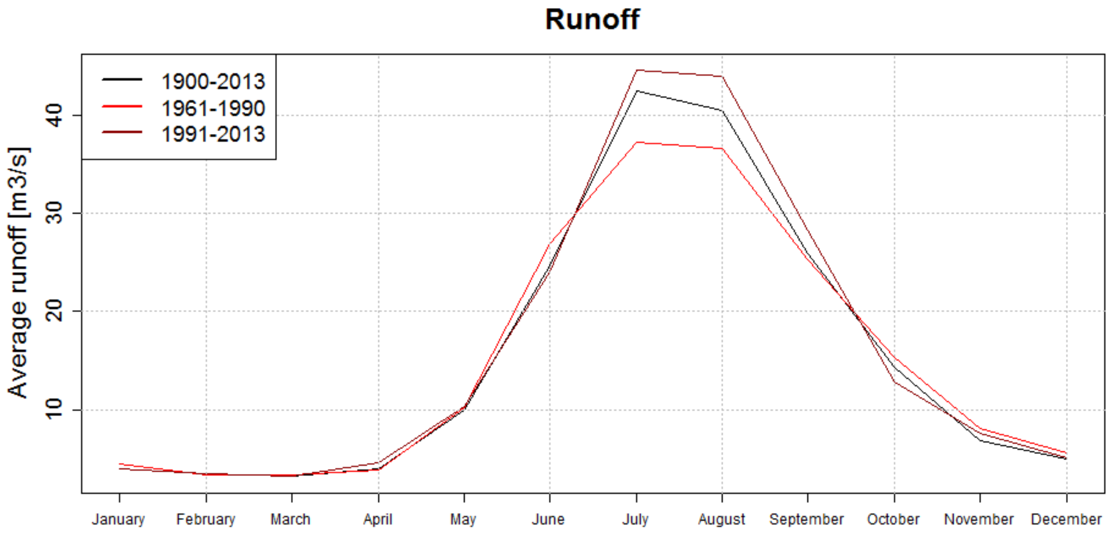


**Figure 3.2-4: Average monthly runoff [m3/s] in Olden catchment outlet**

It can be seen on the Figure 3.2-4 that the base flow does not change from the normal period to the recent period. But the average runoff reaches highest peak in July and August. As said before the precipitation does not increase so much in the last year but the temperature has been increasing since 1985. This consequential rise can be attributed to the glacier melt due to the temperature increase.

See Appendix N: Runoff data

### 3.3 DISCUSSION AND CONCLUSION ON THE INPUT DATA

*Precipitation:*

The precipitation data comes from Briksdal station, station located in the middle of Olden station. So the station is very well situated for the calibration of the HBV-model for the catchment. Furthermore, it covers a very long period from 1900 to 2012 and has very few missing data. So the Briksdal station is a very good for its use in the Olden calibration.

The Oppstryn station could have been used to have the same station for precipitation and temperature but the period was not long enough and would have required correction and addition of data from other stations. So the choice of Briksdal station was the best for a calibration in Olden catchment.

*Temperature:*

The temperature data come from three different stations: Oppstryn, Olden-Vangberg and Stryn-Kroken. The stations are respectively in Stryn catchments and downstream the studied area. So the locations to the stations are not ideal. Even though the general overview of those three stations shows a good correlation, problems can appear in the results after a calibration specially if the calibration period uses data from one station. The years where normal temperature of Oppstryn station have be used to fill in the missing data will not be considered relevant to assess the goodness of the model in order to validate the calibration. The temperature data finally covers a period from 1957 to 2012.

*Runoff:*

The discharge for the two catchments Olden and Loen are similar. That can be explained by the numerous similarities between the two catchments' characteristics: the catchment area, the hypsographic curve representing the catchment, and the repartition of the land type with a substantial proportion for glacier.

# 4 HBV-MODEL

## 4.1 BACKGROUND ON HYDROLOGICAL MODELLING

Hydrological modelling is the quantitative description of the movement of water: the hydrological response of the system. The environment where all hydrological phenomena occur is divided in different sub systems which describe a phenomenon while models embed the phenomenon's mechanism.

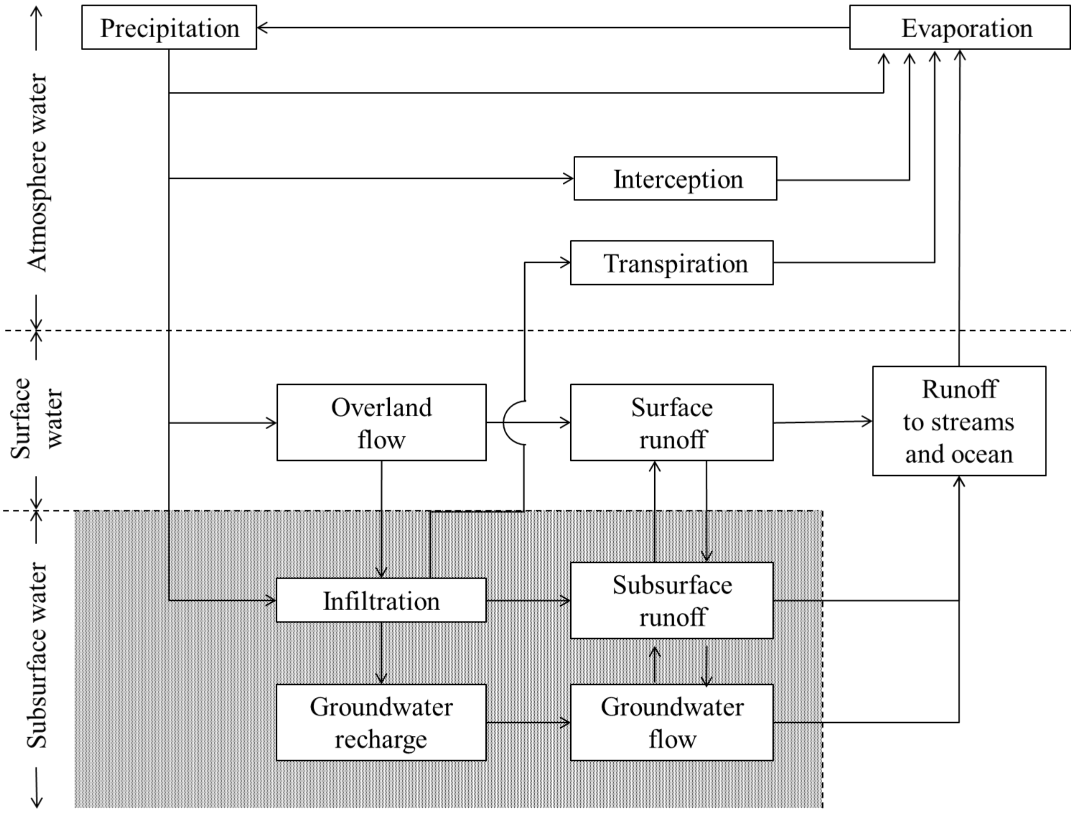


**Figure 4.1-1: A systems view of the hydrological cycle (adapted from (Chow et al., 1988))**

A hydrological model is a representation of the real physical hydrological system. The model must imitate the real system response. The hydrological models uses watershed as spatial unit for water system (Killingtveit and Sælthun, 1995). Therefore, hydrological models have been created to determine the behaviour of a catchment in response to an event (rain, snow, flood or drought).

The hydrological models include the following events that are on the land phase in a catchment.

- Precipitation, rainfall and snowfall, on land
- Storage of water in snow, ice, soil, rivers and lakes,
- Evapotranspiration form land and plants back to the atmosphere,
- Gravitational flow through soil and surface streams to the outlet.

A catchment can be seen as a transformation operator in models, while precipitation is the input and runoff the output data.

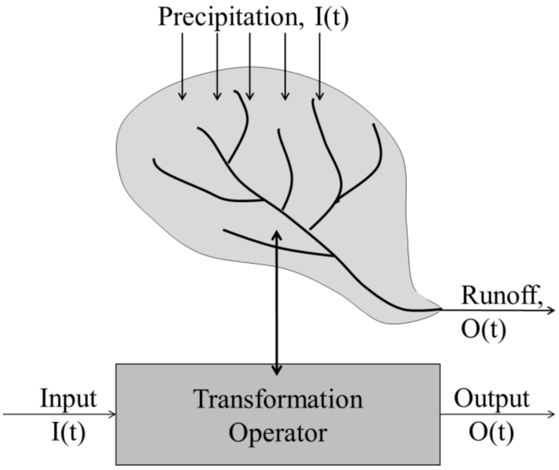


**Figure 4.1-2: An watershed seen as a hydrological transformation operator (Killingtveit and Sælthun, 1995)**

Hydrological models can be based on two different kind of modelling concepts: they can be physical models and or they can be abstract models. In the physical models, nature is reproduced on a laboratory scale. In the abstract models, mathematical equations describe the physical system. These equations are ordered to give an algorithm which can be coded in a program.

The hydrological models are classified following three criteria:

- Randomness: deterministic (no randomness) or stochastic,
- Spatial variation: lumped (homogeneous surface) or distributed,
- Time variability: time independent or dependent.

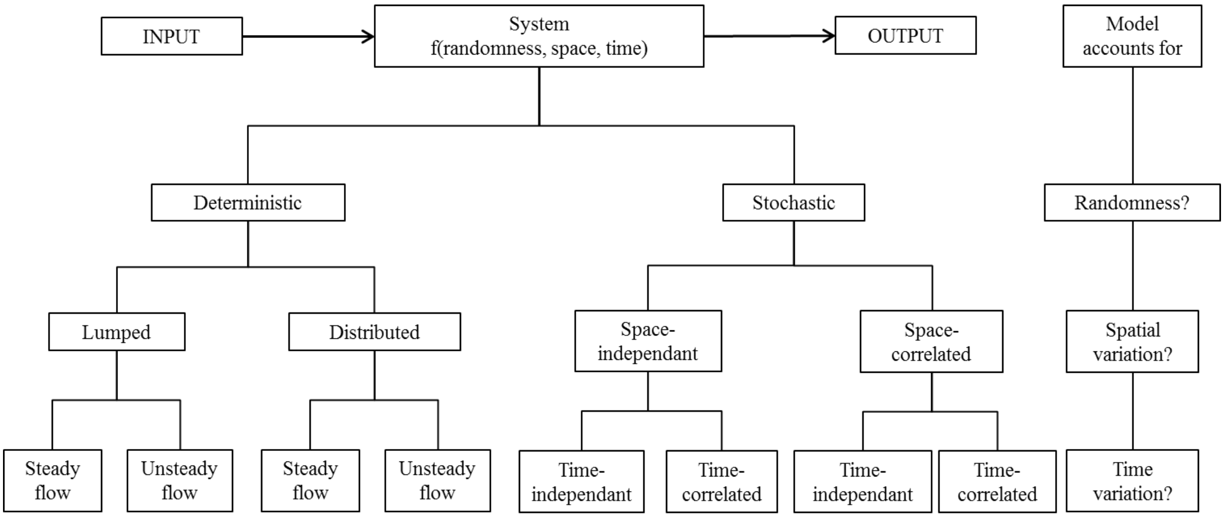


**Figure 4.1-3: Classification of hydrological models (adapted from (Chow et al., 1988))**

The simplest model is thus a deterministic lumped time-independent model (Killingtveit and Sælthun, 1995)

## 4.2 HBV-MODEL

HBV-model stands for Hydroligiska Byråns Vattenbalansavdeling (SMIH, Sweden). HBV-model is a hydrological model and used for making of runoff/inflow forecasts. The HBV-model is:

- A deterministic model: no randomness,
- A lumped precipitation-runoff model: homogeneous surface,
- A conceptual model: only main physical elements of the real system are represented,
- A linear model (to some extent): mostly linear equations describe the hydrological cycle,
- A mathematical model that has to be calibrated.

The scope of the HBV model is wide: runoff and flood forecasting, generation of runoff data series, filling missing runoff data, analysis of land use impacts, groundwater and soil moisture, water quality and climate change studies (Killingtveit and Sælthun, 1995).

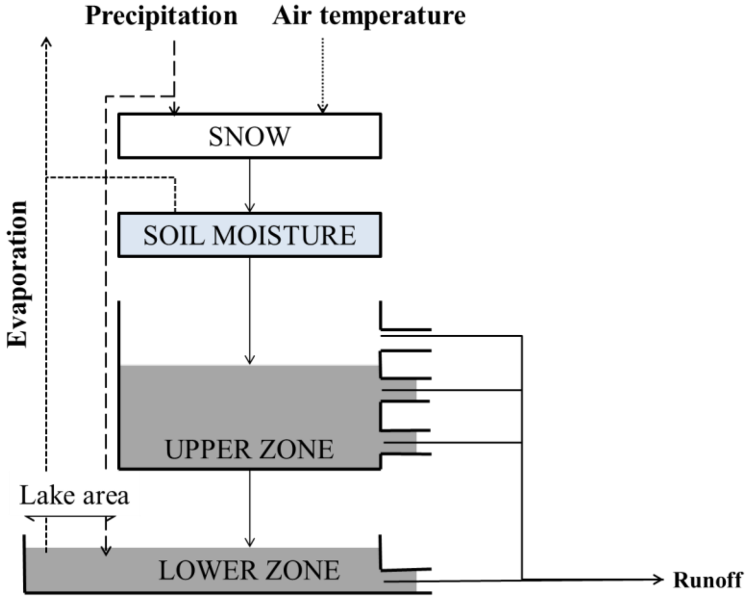


**Figure 4.2-1: Main structure of the HBV-model (adapted from Bergstroem, 1975)**

## 4.3 STRUCTURE OF THE MODEL

The HBV model is divided into ten zones for the snow routine.

This is the division for the Olden catchment:

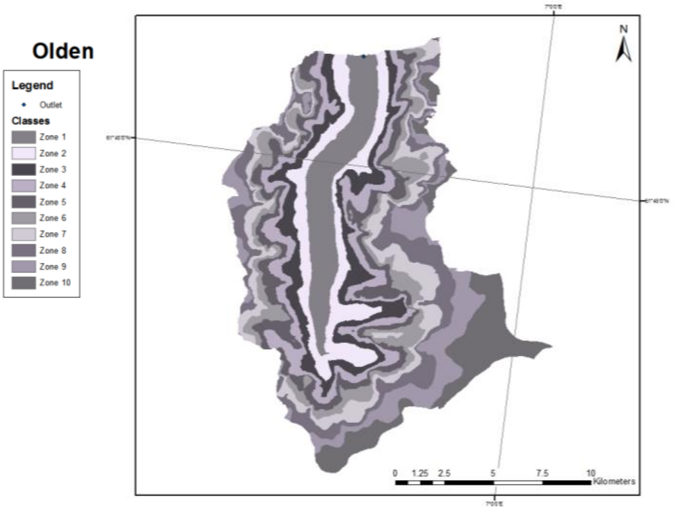


**Figure 4.3-1: Olden - elevation zones**

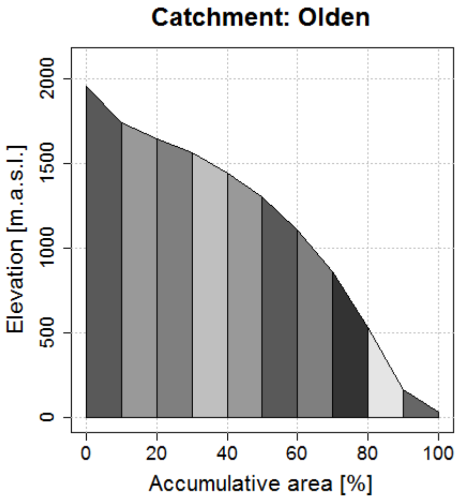


**Figure 4.3-2: Olden - hypsographic curve with zones**

### 4.3.1 Correction of the meteorological data

The model needs areal data which means one precipitation value and one temperature value for one surface at an elevation zone. So the model computes:

- Areal precipitation $P_{area}$ [mm],
- Areal temperature $T_{area}$ [°C].

The model estimates those data from precipitation and temperature data $P_{obs}$ and $T_{obs}$ which come from station(s) at a certain elevation, elevation $H_{station}$. Therefore those point measurements must be corrected to correspond to the data in each elevation zone $H_{area}$.

#### *4.3.1.1 Correction of temperature*

- If the day has no precipitation, $P_{obs}<0$:

$$T_{area} = T_{obs} + TCGRAD * \left(\frac{H_{area} - H_{station}}{100}\right) \qquad (12)$$

- If the day has precipitation, $P_{obs}>0$:

$$T_{area} = T_{obs} + TPGRAD * \left(\frac{H_{area} - H_{station}}{100}\right) \qquad (13)$$

Parameters:

- TCGRAD: temperature lapse rate with elevation on clear days [˚C/100 meter],
- TPGRAD: temperature lapse rate with elevation on cloudy days [˚C/100 meter].

#### *4.3.1.2 Correction of precipitation:*

- If the temperature in the precipitation station is higher than temperature threshold rain/snow, precipitation is rain:

$$P_{corr} = P_{obs} * PCORR \qquad (14)$$

- If the temperature in the precipitation station is lower than temperature threshold rain/snow, precipitation is snow:

$$\mathrm{P_{corr}} = \mathrm{P_{obs}} * \mathrm{PCORR} * \mathrm{SCORR} \tag{15}$$

Then

$$\mathrm{P_{area}} = \mathrm{P_{corr}}\left[1 + \mathrm{PGRAD} * \left(\frac{\mathrm{H_{area}} - \mathrm{H_{obs}}}{100}\right)\right] \tag{16}$$

Parameters:

- PCORR: precipitation correction factors for rain,
- SCORR: precipitation correction factors for snow,
- PGRAD: precipitation increase coefficient with elevation [%/100 meter].

### 4.3.2 The Snow Routine

#### *4.3.2.1 Snow*

In the snow routine are computed the snow accumulation and the snowmelt in the catchment based on the precipitation and temperature observed. The temperature gives the precipitation type – snow or rain – and is used to calculate the snowmelt from on the amount of snow already on the catchment or the accumulation of fresh snow to add the snow existing on the area. The water outflow is also calculated based on the rainfall and the snowmelt.

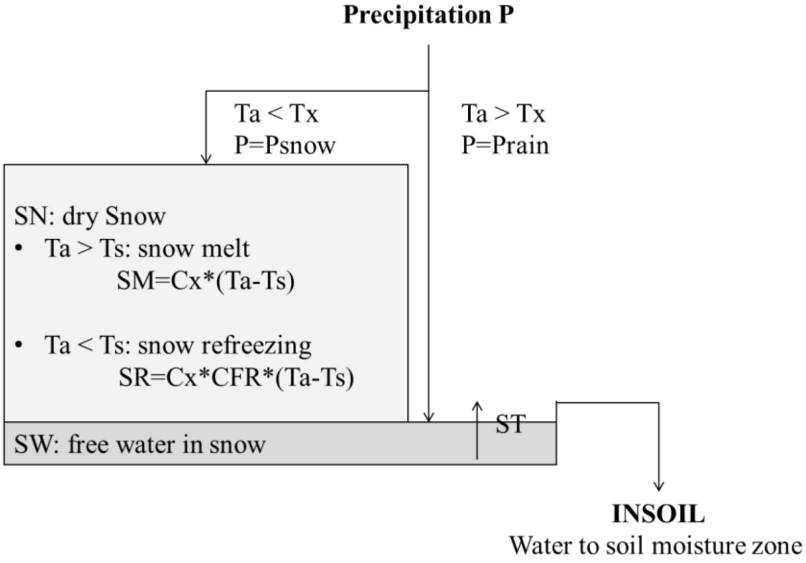


**Figure 4.3-3: HBV-model - snow routine**

Precipitation type: precipitation can be rainfall or snowfall depending on the air temperature $T_a$:

$$P_t = \begin{cases} P_{rain} & \text{if } T_a > T_x \\ P_{snow} & \text{if } T_a < T_x \end{cases} \quad (17)$$

Phase changes in the snow: the snow can either melt or refreeze depending on the air temperature:

- Snowmelt SM [mm]:

$$SM = \begin{cases} CX * (T_a - T_S) & \text{if } T_a > T_S \\ 0 & \text{if } T_a < T_S \end{cases} \quad (18)$$

- Snow refreezing SR [mm]:

$$SR = \begin{cases} 0 & \text{if } T_a > T_S \\ CX * CFR * (T_a - T_S) & \text{if } T_a < T_S \end{cases} \quad (19)$$

Snow composition: the snow cover is composed by dry snow and by the water it contains

- Dry snow storage SN [mm]:

$$\mathrm{SN}_{t+1} = \mathrm{SN}_t + \mathrm{P}_{\mathrm{Snow}} - \mathrm{SM}_t + \mathrm{SR}_t \tag{20}$$

- Maximum free water content in snow ST [mm]:

$$\mathrm{ST}_t = \mathrm{SN}_t * \mathrm{LWMAX} \tag{21}$$

- Snow free water content SW [mm]:

$$\mathrm{SW}_{t+1} = \mathrm{Min}\begin{cases}\mathrm{SW}_t + \mathrm{P}_{\mathrm{rain}} + \mathrm{SM}_t - \mathrm{SR}_t \\ \mathrm{ST}_t\end{cases} \tag{22}$$

Snow routine outflow: water to soil moisture zone INSOIL [mm]:

$$\mathrm{INSOIL}_{t+1} = \mathrm{Max}\begin{cases}\mathrm{SW}_t - \mathrm{ST}_t \\ 0\end{cases} \tag{23}$$

Parameters:

- $T_x$: temperature threshold between rain and snow [°C],
- $T_s$: temperature threshold for snowmelt [°C],
- CX: degree day factor,
- CFR: degree day factor refreezing,
- CPRO: maximum free water in snow (LWMAX).

#### *4.3.2.2 Glaciers*

The HBV-model includes a glacier routine assuming that in the area where there is glacier, glacier ice can melt if there is no snow on top and if the temperature is high enough. The model turns the snow leftover into ice. The ice melt will produce runoff. But the glacier area will not change in the time and growth or decrease of the glacier volume will not be computed.

### 4.3.3 The Soil Moisture Routine

In the soil routine the input data can the precipitation or the water outflow from the snow routine. The water infiltrates the vadose zone (unsaturated zone) and is stored: soil moisture. The outputs from the vadose zone are evapotranspiration back to the atmosphere and the net precipitation to the upper zone.

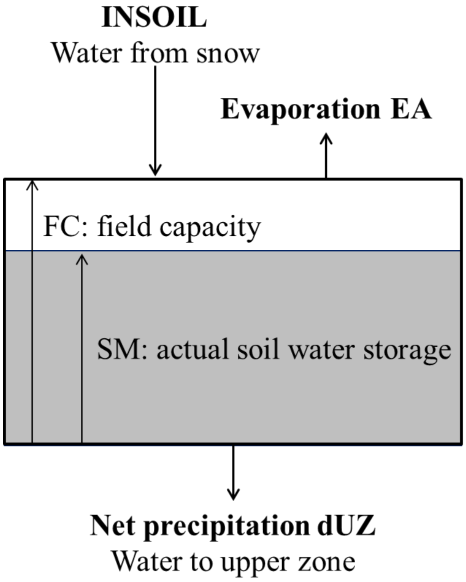


**Figure 4.3-4: HBV-model - soil moisture routine**

Actual evaporation EA [mm]:

$$\mathrm{EA} = \begin{cases} \mathrm{EPOT} * \left(\frac{\mathrm{SM}}{\mathrm{LP}}\right) & \text{if SM} < \mathrm{LP} \\ \mathrm{EPOT} & \text{if SM} > \mathrm{LP} \end{cases} \tag{24}$$

Net precipitation, water going to the upper zone dUz [mm]:

$$\mathrm{dUz} = \mathrm{INSOIL} * \left(\frac{\mathrm{SM}}{\mathrm{FC}}\right)^{\beta} \tag{25}$$

Actual soil water storage SM [mm]:

$$\mathrm{SM}_{t+1} = \mathrm{SM}_t + \mathrm{INSOIL} - \mathrm{dUZ} - \mathrm{EA} \tag{26}$$

Parameters:

- LP: threshold for evapotranspiration,
- EPOT: potential evapotranspiration,
- β: coefficient.

### 4.3.4 The Runoff Response Routine

#### *4.3.4.1 Upper zone*

The net precipitation calculated in the soil moisture routine goes to the upper zone where the storage is (active groundwater storage) and where the "storm runoff" comes out. The quick, medium quick and slow surface runoffs are calculated. This outflow is strongly dependant of the precipitation event (rainfall or snow melt). A part of the groundwater storage percolates in the lower zone.

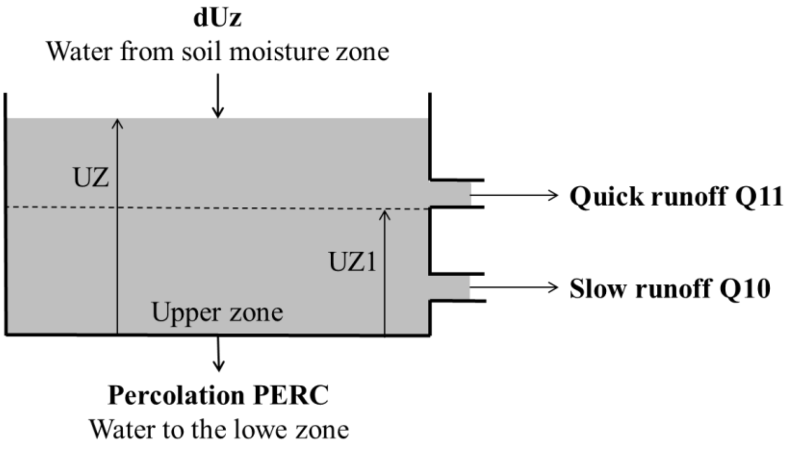


**Figure 4.3-5: HBV-model - upper zone routine**

Water storage in the upper zone UZ [mm]:

$$\mathrm{UZ_{t+1} = UZ_t + dUZ - PERC - Q_{10} - Q_{11}} \tag{27}$$

Fast runoff $Q_{11}$ [mm]:

$$\mathrm{Q_{11} = Max}\begin{cases}\mathrm{KUZ_{11} * (UZ_t + dUZ - PERC - UZ_1)} \\ 0\end{cases} \tag{28}$$

Slow runoff $Q_{10}$ [mm]:

$$Q_{10} = \mathrm{Min}\begin{cases} KUZ_{10} * (UZ_t + dUZ - PERC) \\ KUZ_{10} * UZ_1 \end{cases} \tag{29}$$

Parameters:

- UZ: water level in the upper zone [mm],
- KUZ10: time constant, upper zone [1/t],
- KUZ11: time constant, upper zone [1/t],
- PERC: percolation [mm/day]

#### 4.3.4.2 *Lower zone*

The percolation enters the lower zone. In the lower zone is located the storage of the deep groundwater and lakes. From the lakes' surface evaporation occur. And from lakes and groundwater storage is computed the slow runoff "base flow". This runoff is less dependent of the precipitation event; it will last longer after it occurred.

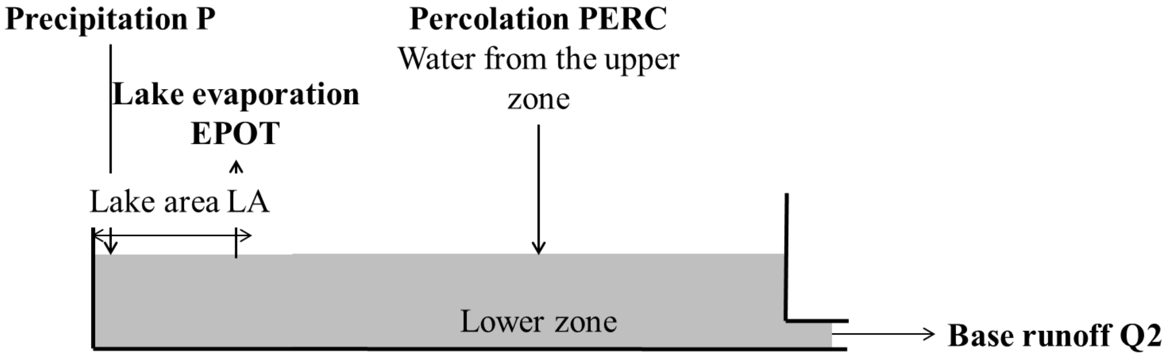


**Figure 4.3-6: HBV-model - lower zone routine**

Water storage in the lower zone LZ [mm]:

$$LZ_{t+1} = LZ_t + PERC + (P - EPOT) * LA\% - Q_2 \tag{30}$$

Base flow LW [mm]:

$$Q_2 = KLZ * LZ_t \tag{31}$$

Parameters:

- P: precipitation [mm],
- PERC: percolation [mm/day]
- LZ: water level in the lower zone [mm],
- KLZ: time constant, lower zone [1/t]
- EPOT: potential evaporation [mm],
- LA%: lake area [%].

## 4.4 PARAMETERS

### 4.4.1 Introduction

The HBV-model requires three types of parameters.

- The confined parameters: catchment characteristics,
- Semi-confined parameters: regional hydro-meteorological values, and/or “stable or insensitive” parameters,
- Unconfined parameters: process parameters and coefficients.

The confined and semi-confined parameters are blocked on the model and will not change during the calibration of the model. The unconfined parameters are free and need to be determined through the calibration process.

### 4.4.2 Free parameters

*Correction of meteorological data:*

- TCGRAD: temperature lapse rate with elevation on clear days [˚C/100 meter],
- TPGRAD: temperature lapse rate with elevation on cloudy days [˚C/100 meter].

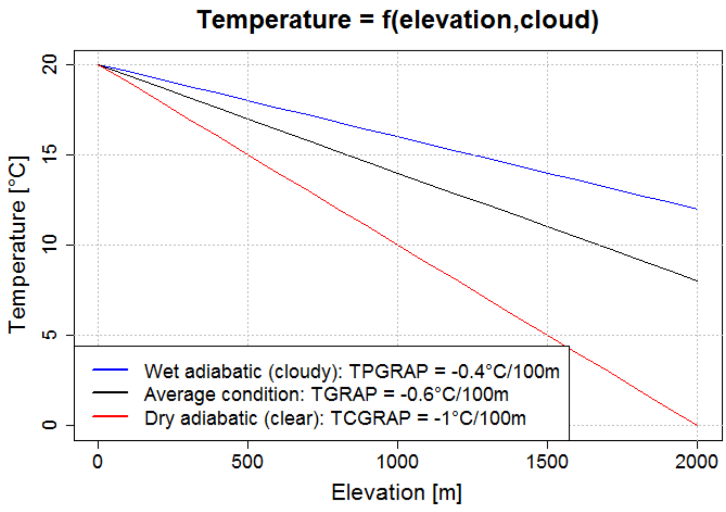


**Figure 4.4-1: HBV-parameters - temperature correction**

The lowest the temperature lapse is, the lowest the temperature gradient is. A extreme temperature lapse rate will decrease the temperature too fast then, make the rain transformed to snow at low elevation zones because the temperature will cross the threshold rain/snow while it should not have been snow. It will also generate snow to soon in high elevation zones where the precipitation should have been still rainfall and also reduce and delay the snow melt on low elevation zones because the temperature will cross the threshold snow melt/snow refreeze too late. Therefore, the runoff will be delay because of the production of storage that should not exist and its late emptying.

If the temperature is good at the beginning (lowest elevation zones) and then drops too quickly in the elevation zone due to an excessive temperature lapse rate, the temperature lapse must be decreased because it creates many side effects affecting processes which all directly and indirectly depend on temperature.

- PCORR: precipitation correction factor for rain,
- SCORR: precipitation correction factor for snow,
- PGRAD: precipitation increase coefficient with elevation [%/100 meter].

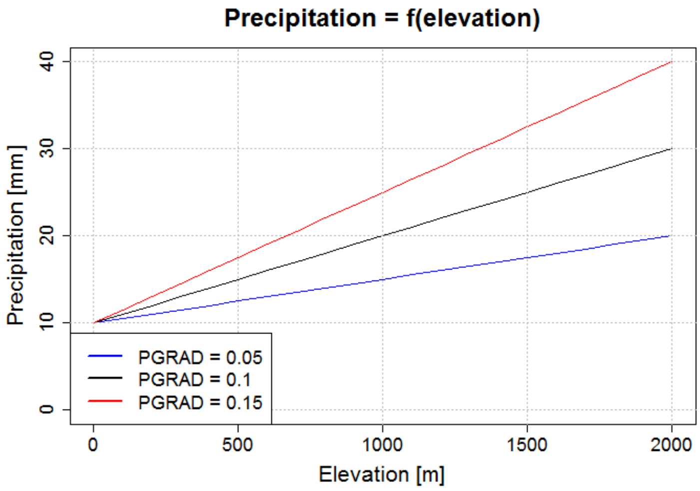


**Figure 4.4-2: HBV-parameters - precipitation correction**

PCORR and SCORR increase the precipitation, as rain or snowfall on all catchment. If there is too much precipitation on all the elevation zones, the precipitation factors must be corrected. If the precipitation is too important on the top, it can be due to a high precipitation elevation coefficient with which rises the precipitation with the elevation.

*Snow routine:*

- $T_x$: temperature threshold between rain and snow [°C],
- $T_s$: temperature threshold for snowmelt [°C],
- CX: degree day factor
- CFR: degree day factor refreezing
- CPRO: maximum free water in snow (LWMAX)

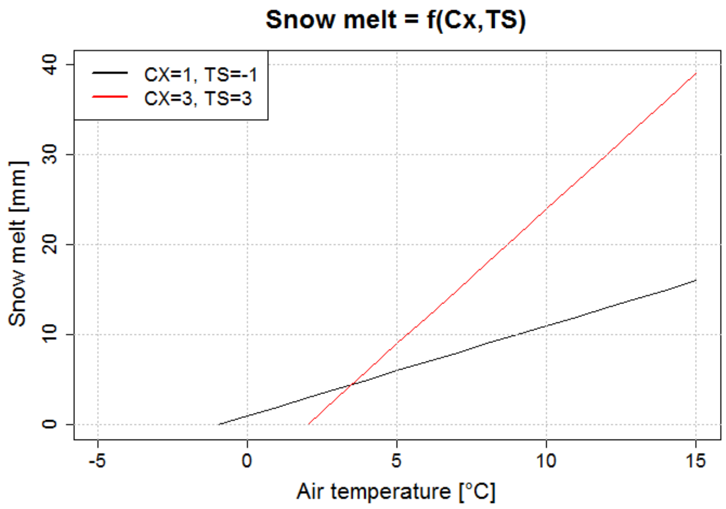


**Figure 4.4-3: HBV-parameters - snow routine**

If the rain turns into snow too early in the year, it could be because the threshold between rain and snow is too high: the temperature and precipitation could be accurate but threshold too high gives snow while it should still be rainfall. On this other side, disproportionate threshold for snow melt will maintain a big storage as snow and thus delay the snowmelt and runoff. The threshold affects the start of the snow production or snowmelt. Meanwhile the degree day factor affects the quantity of snowmelt produce when it has been started. A small degree day factor will not release the water quick enough (delay) whereas a big one will free the water too soon (advance).

### 4.4.3 Free parameters ranges and initial states

The HBV-model presents usually free parameters in the ranges presented in the Table 4.4-1

**Table 4.4-1: HBV-parameters – free parameters ranges (Killingtveit and Sælthun, 1995)**

| Name | Meaning | Value range | | Default value | Unit |
|---|---|---|---|---|---|
| | | Min | Max | | |
| PKORR | Precipitation correction – rainfall | 1.05 | 1.2 | 1.05 | |
| SKORR | Temperature correction – snowfall | 1.15 | 1.5 | 1.2 | |
| TTGRAD | Temperature lapse rate for clear days | -1 | -0.6 | -1 | °C/100m |
| TVGRAD | Temperature lapse rate during precipitation | -0.6 | -0.4 | -0.4 | °C/100m |
| PGRAD | Precipitation lapse rate | 1.0 | 1.10 | 1.05 | |
| Cx | Degree-day factor | -3.0 | 6.0 | 4.0 | mm/°C*Day |
| Tx | Threshold temperature rain/snow | -1.0 | 2.0 | 1.0 | °C |
| Ts | Threshold temperature for snowmelt | -1.0 | 2.0 | 0.0 | °C |
| CFR | Re-freezing efficiency in snow | 0.00 | 0.01 | 0.005 | |
| FC | Field capacity in soil moisture zone | 75 | 300 | 150 | mm |
| β | Parameter in soil moisture routine | 1.0 | 4.0 | 2.0 | |
| LP | Threshold value for potential evapotranspiration in soil moisture | 70 | 100 | 100 | % of FC |
| KUZ1 | Recession constant in upper zone | 0.1 | 0.5 | 0.3 | 1/day |
| KUZ2 | Recession constant in upper zone | 0.05 | 0.15 | 0.1 | 1/day |
| PERC | Percolation from upper to lower zone | 0.5 | 1.0 | 0.6 | mm/day |
| UZ1 | Threshold level for quick runoff in upper zone | 10 | 40 | 20 | mm |
| KLZ | Recession constant for lower zone | 0.002 | 0.100 | 0.002 | 1/day |

# 5 CALIBRATION AND VALIDATION OF THE MODEL

## 5.1 MODEL SETUP

The HBV-model used has been coded on developed by Killingtveit (1987). The interface that is seen form the user is on Excel files. The calculation and the calibration are done in a “black box” coded on C++.

## 5.2 INPUT DATA PREPARATION

The HBV model requires as input data:

- Time series data:
    - Precipitation [mm],
    - Air temperature [°C],
    - Runoff [$m^3/s$].
- Parameters values and
- Initial states values.

### 5.2.1 Time series data

The series data HBV-model uses must be:

- Series without any missing data,
- Series starting the 1st of September and ending the 31st of August (hydrological years).

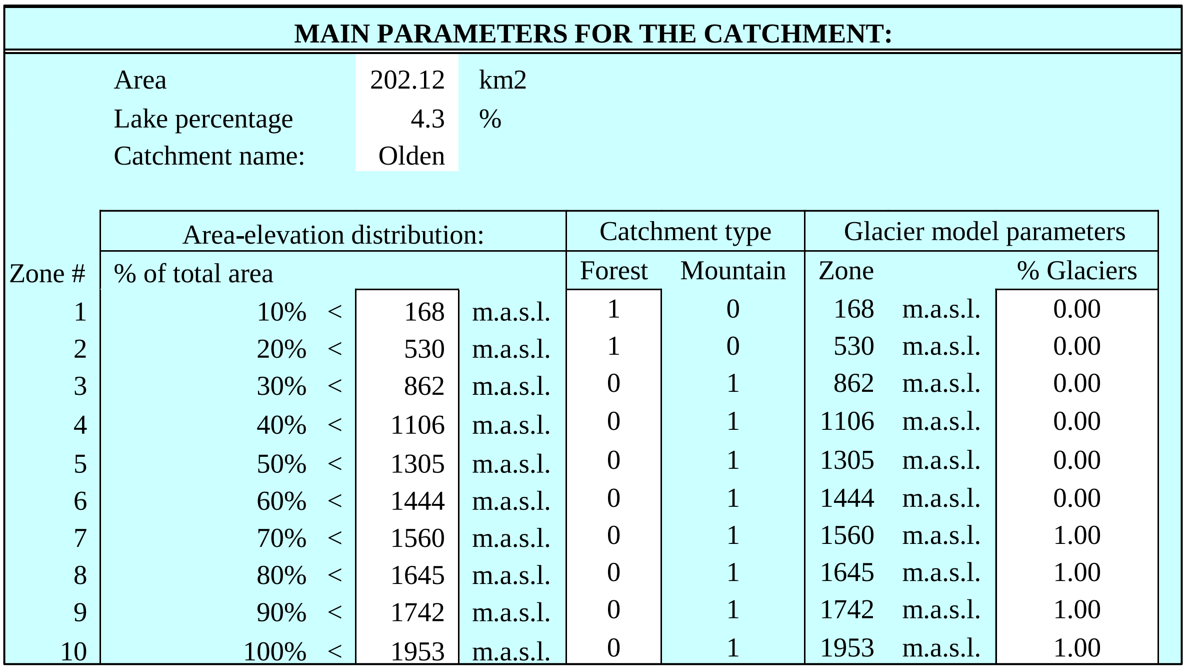
So the series that could have been used – precipitation, temperature and runoff – start in 1957 and end in 2012. However there is no data concerning glacier mass balance in the region, which start before 1961. So the final period considered covers only the years 1961 to 2012 which is a long period (52 years).

### 5.2.2 Parameters

#### 5.2.2.1 Confined parameters

All the parameters of the catchments' behaviour are dependent on the area elevation distribution. In the HBV-model, depending on the zone, the catchment type can be either forest or mountainous. And it has a certain percentage of glaciers.

**Table 5.2-1: HBV-setup - main parameters for the catchment**



**MAIN PARAMETERS FOR THE CATCHMENT:**

| | | |
|---|---|---|
| Area | 202.12 | km2 |
| Lake percentage | 4.3 | % |
| Catchment name: | Olden | |

| | Area-elevation distribution: | | | | Catchment type | | Glacier model parameters | | |
|---|---|---|---|---|---|---|---|---|---|
| Zone # | % of total area | | | | Forest | Mountain | Zone | | % Glaciers |
| 1 | 10% | < | 168 | m.a.s.l. | 1 | 0 | 168 | m.a.s.l. | 0.00 |
| 2 | 20% | < | 530 | m.a.s.l. | 1 | 0 | 530 | m.a.s.l. | 0.00 |
| 3 | 30% | < | 862 | m.a.s.l. | 0 | 1 | 862 | m.a.s.l. | 0.00 |
| 4 | 40% | < | 1106 | m.a.s.l. | 0 | 1 | 1106 | m.a.s.l. | 0.00 |
| 5 | 50% | < | 1305 | m.a.s.l. | 0 | 1 | 1305 | m.a.s.l. | 0.00 |
| 6 | 60% | < | 1444 | m.a.s.l. | 0 | 1 | 1444 | m.a.s.l. | 0.00 |
| 7 | 70% | < | 1560 | m.a.s.l. | 0 | 1 | 1560 | m.a.s.l. | 1.00 |
| 8 | 80% | < | 1645 | m.a.s.l. | 0 | 1 | 1645 | m.a.s.l. | 1.00 |
| 9 | 90% | < | 1742 | m.a.s.l. | 0 | 1 | 1742 | m.a.s.l. | 1.00 |
| 10 | 100% | < | 1953 | m.a.s.l. | 0 | 1 | 1953 | m.a.s.l. | 1.00 |

*Note: in glacier, if the value is 1, the total area is glaciated (100% glaciers)*

Concerning the stations, their elevation is indicated. Several stations for precipitation or for temperature could have been used with a weight depending on their influence on the catchment. As said before, only one station for each parameter, precipitation and temperature, has been used. A single station can be used for the model because the catchment only 202.12 $km^2$ large.

**Table 5.2-2: HBV-setup - stations parameters**

| Precipitation stations Nr | Name | m.a.s.l. | Weight | Temperature stations Nr | Name | m.a.s.l. | Weight |
|---|---|---|---|---|---|---|---|
| 1 | Briksdal | 40 | **1** | 1 | Oppstryn | 201 | **1** |
| | N/A | | **0** | | N/A | | **0** |

The confined parameters are fixed during the simulation.

### 5.2.2.2 *Semi-confined parameters*

The semi-confined parameters are regional hydro-meteorological values, and/or "stable or insensitive" parameters. The evaporation of each month of the year is a semi-confined parameter.

The evaporation has been calculated with the Thornthwaite equation that gives the evapotranspiration for each month. The HBV model gives an estimation of each day of the month and recalculates the monthly values. The model takes then the daily values for all the duration of the simulation.

**Table 5.2-3: HBV-setup - evaporation values given**

| Evaporation | Mean for whole observation period (mm/month) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Months | Jan. | Feb. | Mars | April | Mai | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
| Mean | 0 | 0 | 8.3 | 32.7 | 85.7 | 116.9 | 123.3 | 101.5 | 61.5 | 36 | 9.8 | 0 |
| Estimation | 0 | 0.7 | 10.6 | 35.4 | 84 | 113 | 120.2 | 99.2 | 62.9 | 36 | 11.7 | 1.2 |
| # days | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 31 | 30 | 31 | 30 | 31 |

The evapotranspiration calculated are two high compared to the region so a correction factor has been applied in order to decrease the values.

**Table 5.2-4: HBV-setup – evaporation correction for the year**

| Evaporation station(s)<br>Correction Factors (if needed) | | |
|---|---|---|
| Correction factor | **0.75** | |
| Annual Pot. evap. | **431** | mm |

The semi-confined parameters are also fixed during the simulation.

#### 5.2.2.3 Free parameters

The unconfined parameters or free parameters are process parameters and coefficients. They must be determined by the model calibration.

**Table 5.2-5: HBV-setup - free parameters**

| PARAMETERS IN THE HBV-MODEL: | | | | Units | Optimizer<br>Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| PREC | Rain - correction: | PKORR | 1.00 | | 1.00 | 1.30 |
| | Snow - correction: | SKORR | 1.20 | | 1.00 | 1.50 |
| | Elevation correction: | HPKORR | 5.0 | % pr. 100 m | 5.00 | 10.00 |
| SNOW | Degree-day factor: | CX | 4.00 | mm/degree C./day | 2.50 | 4.00 |
| | Threshold snow-melt: | TS | 0.13 | Degree C. | -1.00 | 1.00 |
| | Threshold rain/snow: | TX | 0.42 | Degree C. | -1.00 | 1.00 |
| | Liquid water: | CPRO | 9.90 | % of dry snow | 5.00 | 10.00 |
| SOIL | Field capacity: | FC | 150 | mm | 50 | 150 |
| | Beta: | BETA | 2.00 | | 1.00 | 2.50 |
| | Threshold evaporation: | LP% | 100 | % | 60 | 100 |
| UPPER ZONE | Fast drainage coefficient: | KUZ2 | 0.30 | 1/day | 0.10 | 0.40 |
| | Slow drainage coefficient: | KUZ1 | 0.10 | 1/day | 0.01 | 0.10 |
| | Threshold: | UZ1 | 20 | mm | 10 | 40 |
| | Percolation: | PERC | 0.60 | mm/day | 0.20 | 1.50 |
| LOWER ZONE | Drainage coefficient: | KLZ | 0.010 | 1/day | 0.002 | 0.100 |
| REFREEZE | | PRO | 10.00 | % of normal melt rate | 10.00 | 10.00 |
| | Temperature lapse rate: | | | | | |
| Tlp | At precipitation | | -0.40 | Degree C./100 m | -0.40 | -0.70 |
| Tlo | No precipitation | | -1.00 | Degree C./100 m | -0.50 | -1.00 |

**Table 5.2-6: HBV-setup - melt increase factor**

| | | | |
|---|---|---|---|
| Melt increase in mountain | 1 | Melt increase in glaciers | 1.5 |
| CX-mount. | 3 | CX-Glacier | 4.5 |
| Min | 0.75 | Min | 1 |
| Max | 1.5 | Max | 1.5 |

The melt increase factor in glacier is set up higher than in the mountain because the ice melts faster than the snow (Khan et al., 2015). This gives a higher CX in the glacier part than in the rest of the catchment.

All those parameters will be modified during the calibration within their ranges of values.

### 5.2.3 Model initial states

The model needs initial states data to start the simulation. The initial states are important for the first year of simulation but do not affect the following years.

At the beginning of every hydrological year, the snow is converted to ice. That means that the snow depth will restart at zero every 1st of September. In the physical model it would mean that snow that was on the glacier is converted into ice and that the snow that was on other surface has been removed. The conversion snow to ice glacier is a phenomenon that occurs. However, removing the snow on the part where there is no glacier is physically incorrect and all the snow on glacier could not turn into ice. Yet, this solution is used on Senorge.

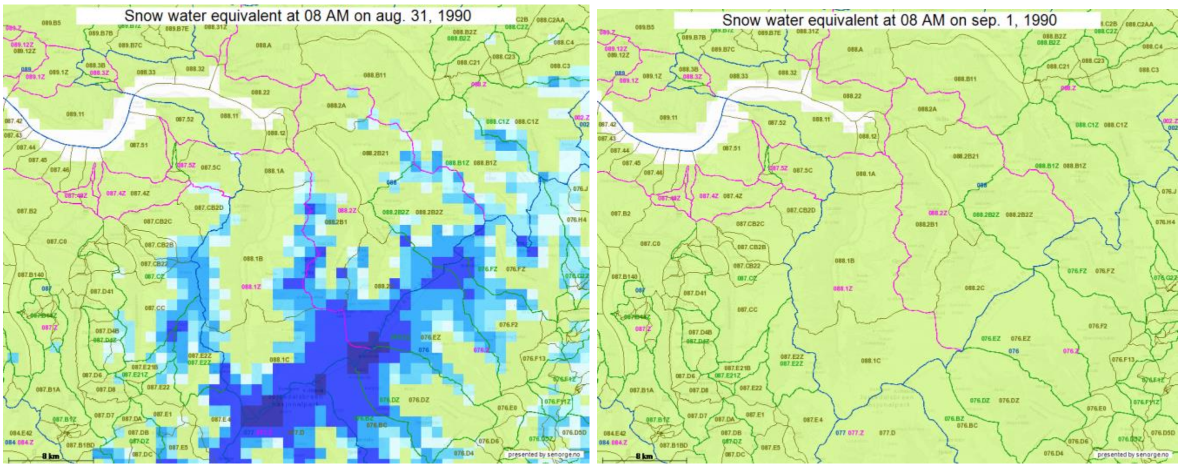


**Figure 5.2-1: Difference of snow water equivalent at the end and beginning of an hydrological year**

So the initial states are setup as zero for all the elevation zones. The upper and lower zone storages are defined to make the simulated runoff fit the observed runoff in the very beginning of the year. The initial soil water storage is 80 % of the soil water storage.

**Table 5.2-7: HBV-setup - initial states**

**MODEL STATES AT START:**

| Elevation-zone | | Snow pack (mm) | | Free water content | |
|---|---|---|---|---|---|
| | | | | % | mm |
| 168 | m.a.s.l | 0 | mm | 0 | 0 |
| 530 | m.a.s.l | 0 | mm | 0 | 0 |
| 862 | m.a.s.l | 0 | mm | 0 | 0 |
| 1106 | m.a.s.l | 0 | mm | 0 | 0 |
| 1305 | m.a.s.l | 0 | mm | 0 | 0 |
| 1444 | m.a.s.l | 0 | mm | 0 | 0 |
| 1560 | m.a.s.l | 0 | mm | 0 | 0 |
| 1645 | m.a.s.l | 0 | mm | 0 | 0 |
| 1742 | m.a.s.l | 0 | mm | 0 | 0 |
| 1953 | m.a.s.l | 0 | mm | 0 | 0 |
| Mean values | | 0 | mm | 0 | 0 |
| Soil water storage | | 120 | mm | Maximum: | 150 |
| Upper zone storage | | 40 | mm | Threshold: | 13 |
| Lower zone storage | | 10 | mm | | |
| Runoff, computed: | | | m3/sec (at start) | | |
| Runoff, observed: | | | m3/sec (at start) | | |

## 5.3 MODEL CALIBRATION

### 5.3.1 Calibration process

The calibration is made in order to determine the optimal value of all the free parameters of the model to have the best simulation results compared to the observed data.

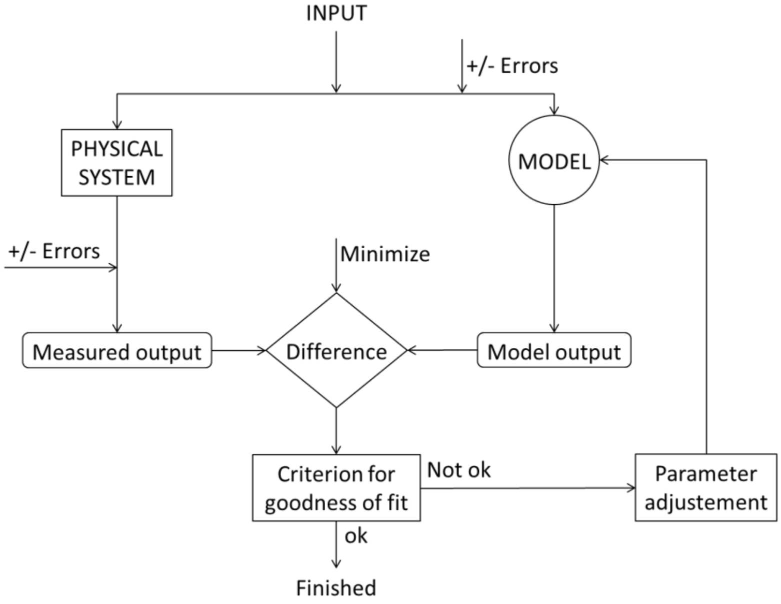


**Figure 5.3-1: Model calibration process (Killingtveit and Sælthun, 1995)**

The calibration can be based on two different kinds of methods:

- Subjective method or
- Objective methods.

The subjective method consists in looking at graphs where the simulated and observed runoffs are compared whereas objective methods use numerical criterion – an error function – which is derived from differences between the observed and the simulated runoff over the calibration period. In the model, the criterion for goodness of fit is the Nash-Sutcliffe criterion.

The Nash-Sutcliffe efficiency criterion $R^2$ is equal to:

$$R^2 = 1 - \frac{\sum(Q_S - Q_O)^2}{\sum(Q_O - \overline{Q_O})^2} \tag{32}$$

With:

- $Q_S$: daily simulated runoff,
- $Q_O$: daily observed runoff,
- $\overline{Q_O}$: average observed runoff (on the year)

$R^2$ can vary from 1 to -∞: the higher $R^2$ is, the better the model fits with the physical system. $R^2=1$ means that the model fit perfectly: the parameters calibrated give, with the observed input data, the same results in the model than the real system. Normal values during HBV-model calibrations are within the range 0.6-0.9 (Killingtveit and Sælthun, 1995).

### 5.3.2 Calibration period

The HBV-model requires a period between 5 and 10 years to be calibrated. The model was meant to be calibrated for the period 1985-1989 which is the most recent period of the input data with the temperature coming from Oppstryn station only. The model was run a first time and then an automatic calibration was performed.

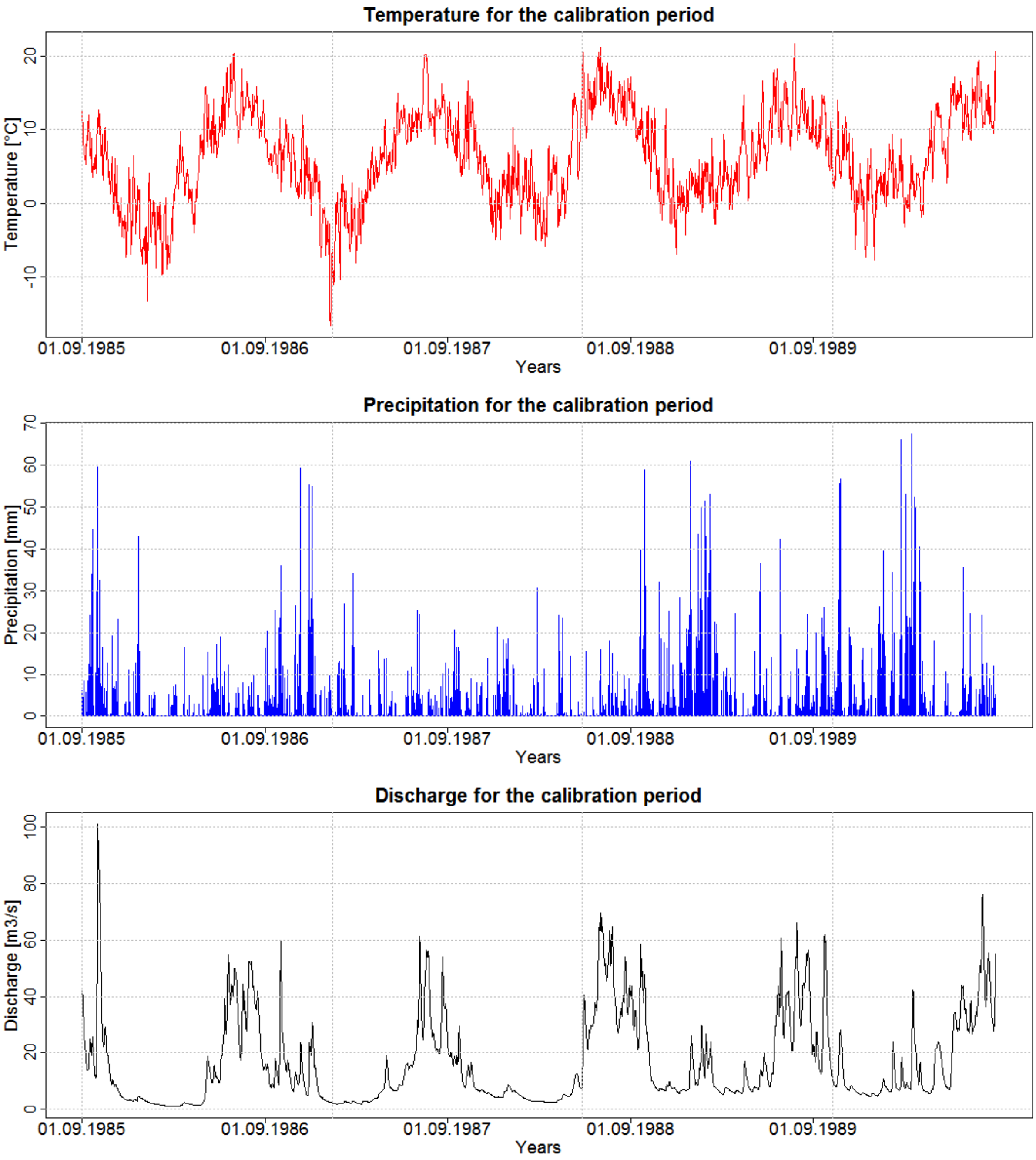


**Figure 5.3-2: HBV-setup - input data series for calibration**

The calibration period covers two “cold” years (1985-1986) and three “warm” years (1987-1989). Regarding the precipitation, 1985 and 1987 have less annual precipitation, 1987 is the driest year in the calibration period, while 1986 have more precipitation. 1988 and 1989 are two wet years.

**Table 5.3-1: Climatic characteristics of the years of calibration**

| Year | | Temperature | | | | Precipitation | | |
|---|---|---|---|---|---|---|---|---|
| | | Annual | Winter | Summer | | Annual | Winter | Summer |
| 1985 | Cold | -- | --- | + | Dry | -- | -- | + |
| 1986 | Cold | -- | -- | -- | Wet | + | + | + |
| 1987 | Warm | +++ | ++ | ++++ | Dry | -- | -- | - |
| 1988 | Warm | ++ | ++++ | -- | Wet | +++++ | ++++ | + |
| 1989 | Warm | +++ | ++++ | + | Wet | +++++ | +++++ | + |

**Table 5.3-2: Classification of type of years**

| Code | Temperature difference with the normal temperature [°C] | Precipitation difference with the normal precipitation [mm] |
|---|---|---|
| ++++++ | > 2.5 | |
| +++++ | > 2 | > 800 |
| ++++ | > 1.5 | > 600 |
| +++ | > 1 | > 400 |
| ++ | > 0.5 | > 200 |
| + | > 0 | > 0 |
| - | > -0.5 | > -200 |
| -- | > 1 | > -400 |
| --- | < 1 | > -600 |
| ---- | | < -600 |

## 5.4 FIRST CALIBRATION: FOCUS ON THE ANNUAL RUNOFF

### 5.4.1 Parameters and initial states

**Table 5.4-1: HBV-calibration - free parameters values**

| PARAMETERS IN THE HBV-MODEL: | | | | Units | Optimizer Range | |
|---|---|---|---|---|---|---|
| | | | | | Min | Max |
| PREC | Rain - correction: | PKORR | 1.30 | | 1.00 | 1.30 |
| | Snow - correction: | SKORR | 1.50 | | 1.00 | 1.50 |
| | Elevation correction: | HPKORR | 10 | % pr. 100 m | 5.00 | 10.00 |
| SNOW | Degree-day factor: | CX | 4.00 | mm/degree C./day | 2.50 | 4.00 |
| | Threshold snow-melt: | TS | 0.14 | Degree C. | -1.00 | 1.00 |
| | Threshold rain/snow: | TX | 0.53 | Degree C. | -1.00 | 1.00 |
| | Liquid water: | CPRO | 10 | % of dry snow | 5.00 | 10.00 |
| SOIL | Field capacity: | FC | 90 | mm | 50 | 150 |
| | Beta: | BETA | 1.12 | | 1.00 | 2.50 |
| | Threshold evaporation: | LP% | 69 | % | 60 | 100 |
| UPPER ZONE | Fast drainage coefficient: | KUZ2 | 0.19 | 1/day | 0.10 | 0.40 |
| | Slow drainage coefficient: | KUZ1 | 0.07 | 1/day | 0.01 | 0.10 |
| | Threshold: | UZ1 | 19 | mm | 10.00 | 40.00 |
| | Percolation: | PERC | 1.04 | mm/day | 0.20 | 1.50 |
| LOWER ZONE | Drainage coefficient: | KLZ | 0.080 | 1/day | 0.002 | 0.100 |
| REFREEZE | | PRO | 10.00 | % of normal melt rate | 10.00 | 10.00 |
| | Temperature lapse rate: | | | | | |
| Tlp | At precipitation | | -0.675 | Degree C./100 m | -0.40 | -0.70 |
| Tlo | No precipitation | | -0.70 | Degree C./100 m | -0.50 | -1.00 |

**Table 5.4-2: HBV-calibration - CX**

| | | | |
|---|---|---|---|
| Melt increase in mountain | 0.91 | Melt increase in glaciers | 1.5 |
| CX-mount. | 3.6 | CX-Glacier | 4.5 |
| Min | 0.75 | Min | 1 |
| Max | 1.5 | Max | 1.5 |

**Table 5.4-3: HBV-calibration - initial states**

| MODEL STATES AT START: | | | | | |
|---|---|---|---|---|---|
| Elevation-zone | | Snow pack (mm) | | Free water content | |
| | | | | % | mm |
| 168 | m.a.s.l | 0 | mm | 0 | 0 |
| 530 | m.a.s.l | 0 | mm | 0 | 0 |
| 862 | m.a.s.l | 0 | mm | 0 | 0 |
| 1106 | m.a.s.l | 0 | mm | 0 | 0 |
| 1305 | m.a.s.l | 0 | mm | 0 | 0 |
| 1444 | m.a.s.l | 0 | mm | 0 | 0 |
| 1560 | m.a.s.l | 0 | mm | 0 | 0 |
| 1645 | m.a.s.l | 0 | mm | 0 | 0 |
| 1742 | m.a.s.l | 0 | mm | 0 | 0 |
| 1953 | m.a.s.l | 0 | mm | 0 | 0 |
| Mean values | | 0 | mm | 0 | 0 |
| Soil water storage | | 72 | mm | Maximum: | 90 |
| Upper zone storage | | 65 | mm | Threshold: | 19 |
| Lower zone storage | | 60 | mm | | |
| Runoff, computed: | | | m3/sec (at start) | | |
| Runoff, observed: | | | m3/sec (at start) | | |

### 5.4.2 Objective function: criterion R$^2$

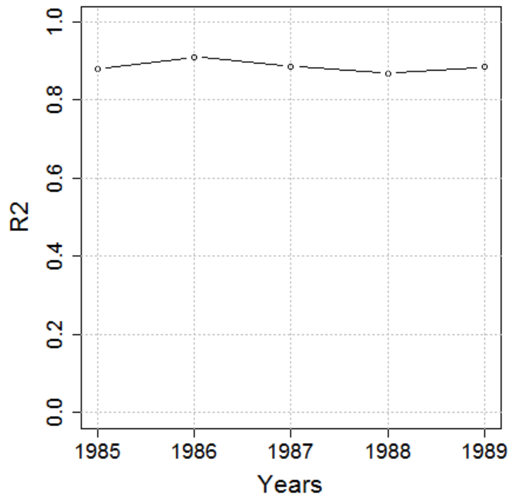


Figure 5.4-1: HBV-calibration - R$^2$

**Table 5.4-4: HBV-calibration - R$^2$**

| Year | R$^2$ |
|---|---|
| 1985 | 0.88 |
| 1986 | 0.91 |
| 1987 | 0.89 |
| 1988 | 0.87 |
| 1989 | 0.88 |

Looking at the coefficient R$^2$, the calibration gives very good results with values within the range 0.80 to 0.91. So the simulated runoffs are close to the observed data. The calibration does not have much different result regarding the climatologic state of the year (dry or wet year, cold or warm year) which shows that the calibration is good.

### 5.4.3 Average annual runoff

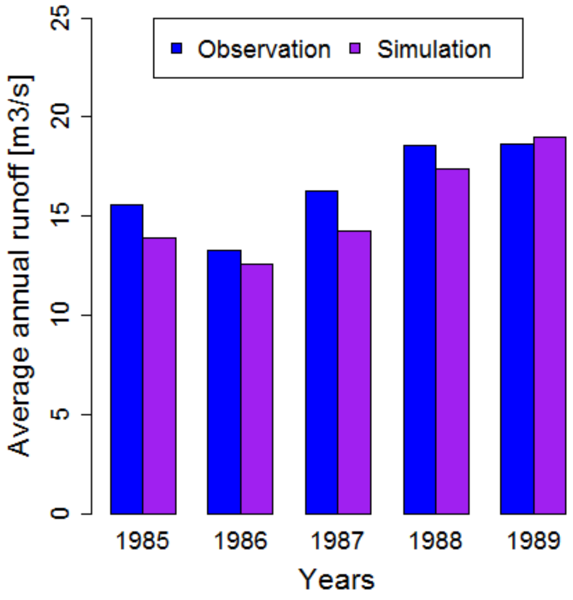


Figure 5.4-2: HBV-calibration - comparison observed and simulated Q

**Table 5.4-5: HBV-calibration - comparison observed and simulated Q**

| Year | R$^2$ | Obs. Q | Sim. Q |
|---|---|---|---|
| 1985 | 0.88 | 15.58 | 13.91 |
| 1986 | 0.91 | 13.27 | 12.58 |
| 1987 | 0.89 | 16.28 | 14.26 |
| 1988 | 0.87 | 18.53 | 17.36 |
| 1989 | 0.88 | 18.66 | 18.97 |

It can be seen that the average annual runoff simulated is close to the observation for each year. In the four first years, the model underestimated the runoff, and overestimated the last year.

The two years 1988 and 1989 are very wet years in the calibration. However the difference is that 1989 have much more precipitation in winter and little more precipitation in summer while 1988 have more precipitation in winter and summer. So the years which have lot of precipitation in winter could have an overestimated average runoff, while the other years have an underestimated runoff. The difference could also be due to the difference of temperature in summer (cold summer in 1988, warm in 1989) but it is relatively small.

### 5.4.4 Analysis of data for the first year 1985-1986

In 1985-1986, the precipitation and temperature records are:

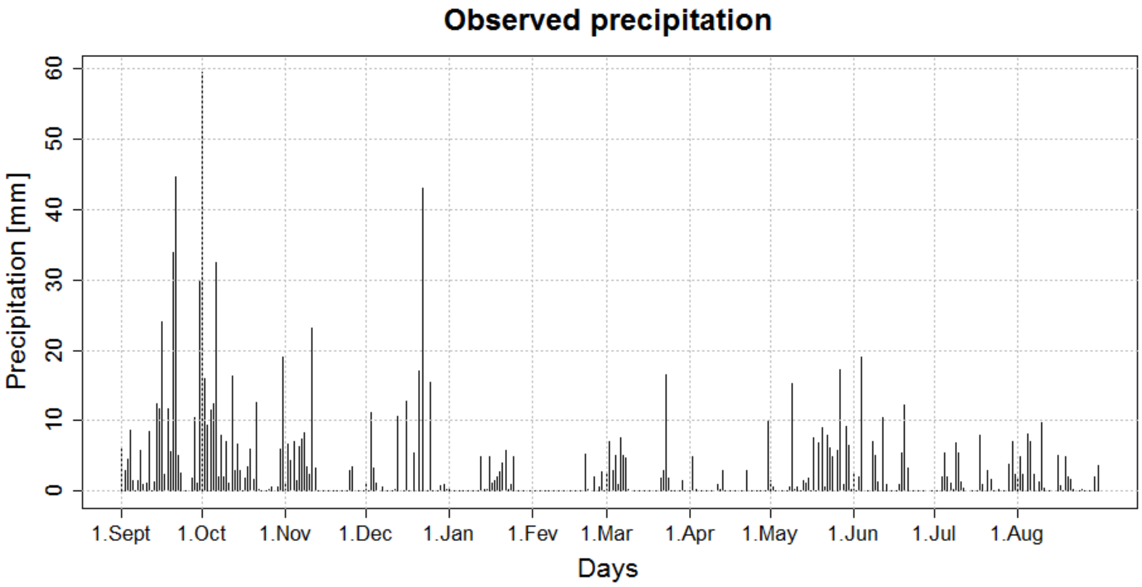


**Figure 5.4-3: Precipitation for Briksdal station (1985-1986)**

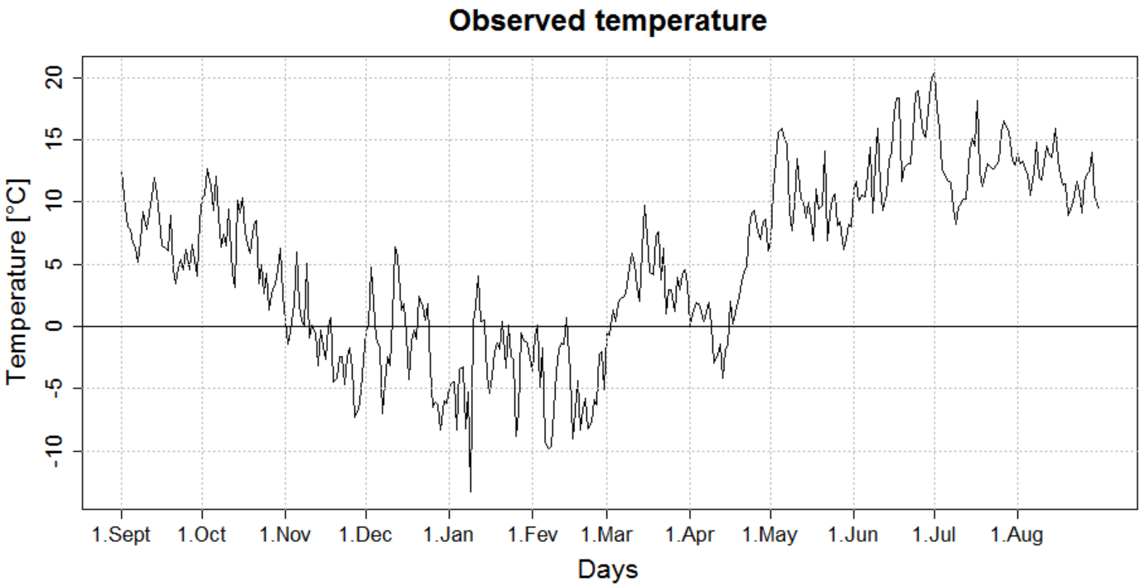


**Figure 5.4-4: Temperature for Oppstryn station (1985-1986)**

*Runoff comparison:*

For validation of the calibration of the model, the model's hydrograph should recreate the same trend in the flow variation during the year. It means that it should have the same timing and magnitude of flood event and lack of runoff period. It should also give the same accumulated volume of runoff.

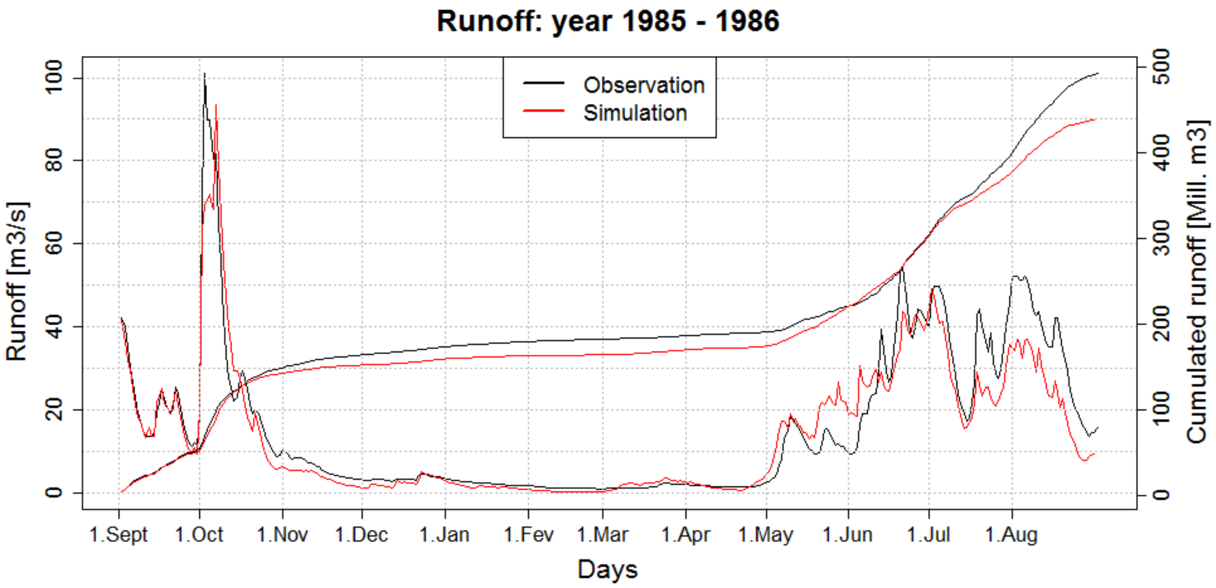


**Figure 5.4-5: HBV-calibration - comparison observed and simulated Q (1985-1986)**

Like most of the hydrological simulation, the results after the calibration show:

- Difficulties to match the observed runoff in magnitude (peak in October),
- Difficulties to fit the observed runoff in timing (start the runoff increase in May).

However the simulation trends are following the observed ones.

*Simulated runoff:*

In September the simulation values fit perfectly the observed values.

In October the simulation managed to fit the time of the peak in a very good ways but does not reach its magnitude, gets close to it but delayed. And then it decreases a little bit too late and not quickly enough in the first part and too much and too soon for the second part.

It could be caused by a small first time constant in the upper zone time constant in the upper zone which does not a peak in the runoff. Then it could be a big second time constant in the upper zone which gives too much runoff at the beginning and thus empty the storage too fast.

The base flow runoff that is seen between January and April fit the observed data in a relative good way.

In May the simulated runoff increases too soon in comparison with the observed one but reach the peak. But then it is much bigger than the simulated until mid-June, fits until mid-July and then is too low. It could be due the melt of the snow which happen to quickly at the beginning and empty the storage to soon which then cannot reach the outflow magnitude in late summer.

*Snow routine*

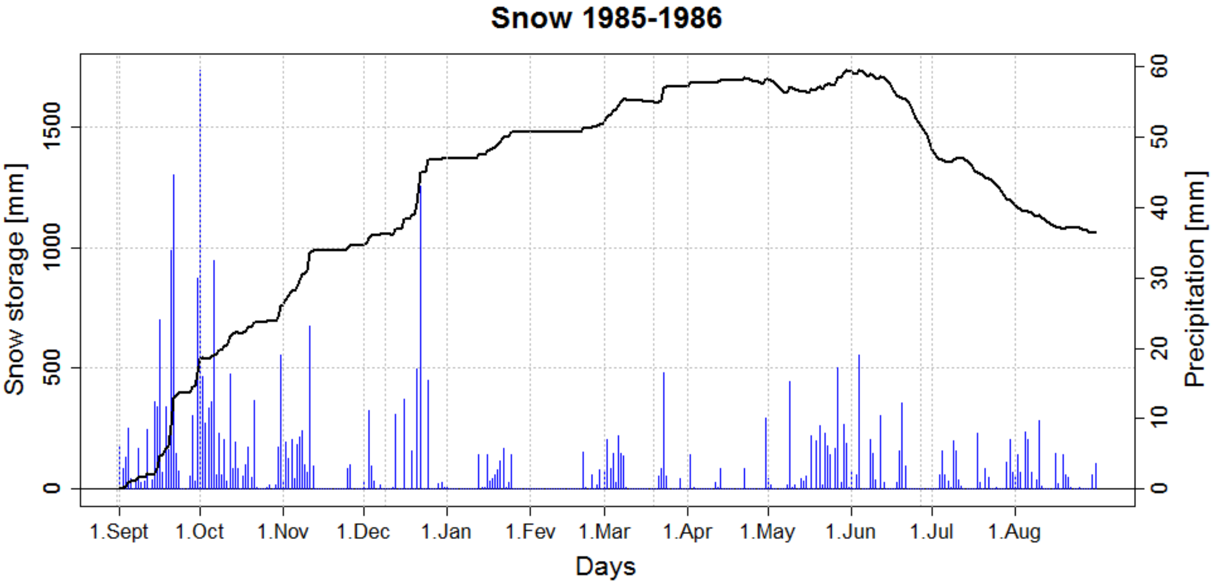


**Figure 5.4-6: HBV-calibration - snow storage (1985-1986)**

The snow storage increases from September to May. It decreases from May to August with the increase of temperature. The general pattern of the snow storage is consistent. However, in late May, beginning of June, the snow storage increases due to precipitation event while the temperature keeps increasing. So the temperature must still be to negative (compared to the temperature threshold snow-rain) on top of the catchment.

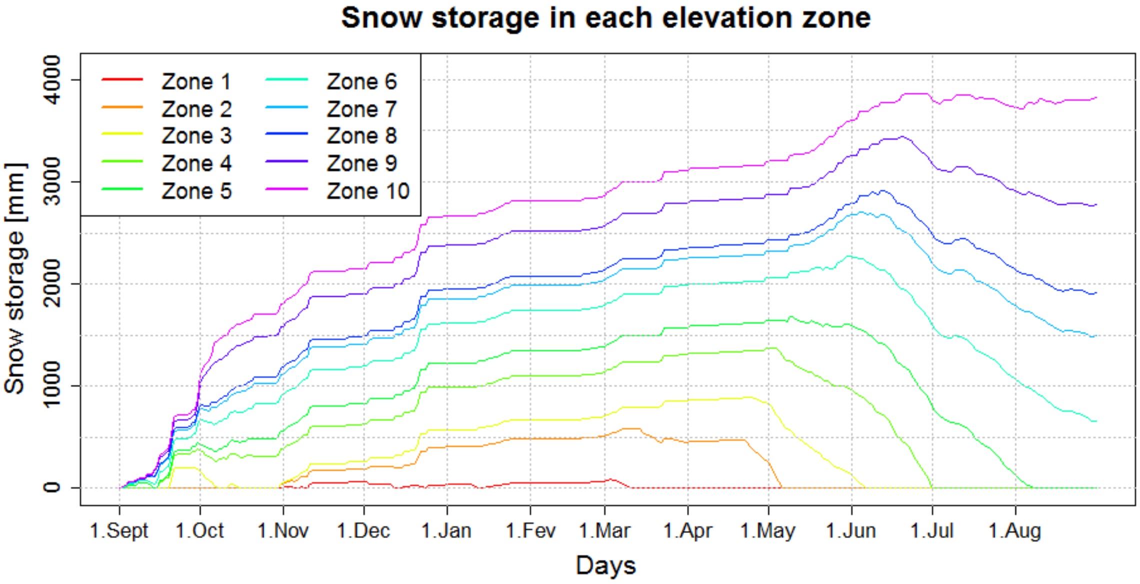


**Figure 5.4-7: HBV-calibration - snow storage in each zone (1985-1986)**

For all the zones, the snow water equivalent reaches value twice higher to the one given by Senorge.

Zone 1: the snow starts melting in March and from April till the end of the hydrological year and there is no snow on the area. This corresponds to the data from Senorge.

Zones 2 to 5: the snow starts melting during May for all those zones and there is no snow after July for those areas. This pattern corresponds also to the data from Senorge.

Zones 6 to 9: the snow starts melting during June for all those zones but at the end of August, there is still snow. According to Senorge, there is no more snow at the end of the year in the lowest zones and much less snow (less than 1000 mm) on the highest ones. And they see their snow storage increase at the beginning of June. This is probably due to the precipitation that has been turned into snow because of low temperature calculated on this upper part of the catchment.

Zone 10: the snow starts melting during July but at the end of August, there is still snow with a water equivalent higher than 3000 mm. The snow melt starts at the same time on Senorge, however, there is little snow at the end of the year: less than 500 mm.

See Appendix O: snow equivalent

Form this snow repartition; it can be concluded that problems of the calibration parameters are potentially:

- On the temperature lapse rates or/and
- On the temperature threshold snowmelt or/and
- On the melt increase on mountain/ degree day factor.

*Soil moisture routine*

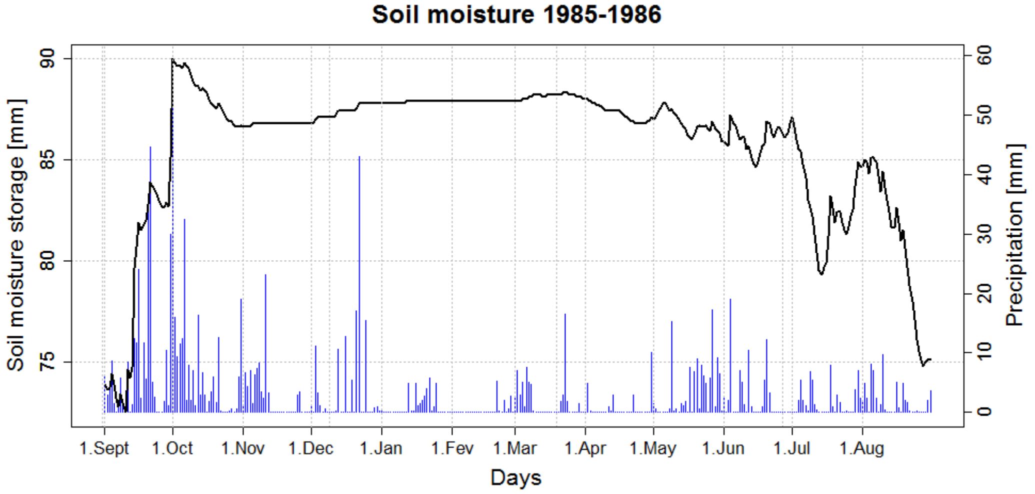


**Figure 5.4-8: HBV-calibration - soil moisture storage (1985-1986)**

The field capacity is 90 mm. The soil moisture storage starts at 80% of its total capacity 72 mm. But after the first day the soil moisture storage varies mostly between 75 and 87 mm. It has its higher rate in October when there was a massive precipitation event and between January and March when the temperature is negative and when there is no evapotranspiration. It increases with every precipitation event and decreases with the augmentation of the temperature thus the increase of evapotranspiration. This pattern is consistent.

*Runoff routine:*

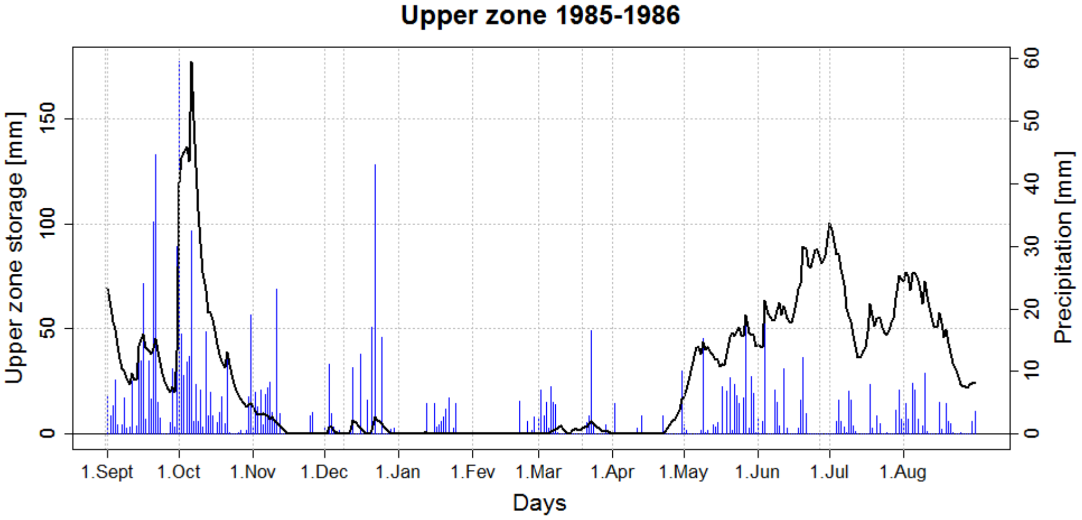


**Figure 5.4-9: HBV-calibration - upper zone storage (1985-1986)**

The upper zone has two outlets for quick and medium quick runoff. The threshold for the fast runoff is 19 mm. Between January and March, the upper zone storage is close to zero: it correspond to negative temperature and weak precipitation. The storage can be related to the strongest precipitation event and will give the peak in the simulated runoff (peak in October). It increases with every precipitation event, especially when the lower zone storage is already high. But it does not increase if the lower zone is "empty" which happens at the end of November, January, February and April. This pattern is consistent.

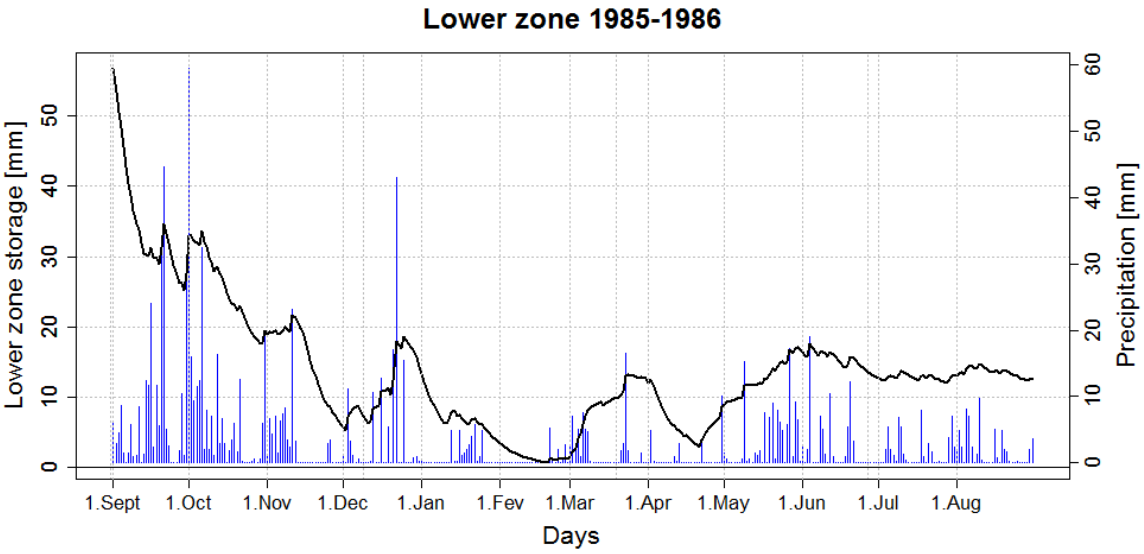


**Figure 5.4-10: HBV-calibration - lower zone storage (1985-1986)**

The lower zone has one outlet for the slow runoff or base flow. The lower zone storage is always positive. It gives the runoff when the upper storage is zero. It increases during every precipitation event. It reaches the lowest values at the end of February: there is no rain, no snowmelt, the soil moisture is high and the upper zone is empty. This pattern is consistent.

*Temperature and precipitation corrections*

**Table 5.4-6: HBV-calibration - precipitation and temperature corrected (1985-1986)**

| | Elevation [m.a.s.l.] | Annual temperature [°C] | Temperature ranges [°C] | Annual Precipitation [mm] | Precipitation Ranges [mm] |
|---|---|---|---|---|---|
| Observed | | 5.03 | 4 to 6 | 1101 | 1500 to 2000 |
| Zone 1 | 168 | 5.25 | 4 to 6 | 1666 | 1500 to 2000 |
| Zone 2 | 530 | 2.77 | 2 to 4 | 2201 | 2000 to 3000 |
| Zone 3 | 862 | 0.48 | 0 to 2 | 2692 | 2000 to 3000 |
| Zone 4 | 1106 | -1.19 | 0 to 2 | 3052 | 2000 to 3000 |
| Zone 5 | 1305 | -2.56 | -1 to 0 | 3346 | 3000 to 4000 |
| Zone 6 | 1444 | -3.51 | -1 to 0 | 3552 | 3000 to 4000 |
| Zone 7 | 1560 | -4.31 | -1 to 0 | 3723 | 3000 to 4000 |
| Zone 8 | 1645 | -4.89 | -2 to -1 | 3849 | 3000 to 4000 |
| Zone 9 | 1742 | -5.56 | -2 to -1 | 3992 | 3000 to 4000 |
| Zone 10 | 1953 | -7.01 | -3 to -2 | 4304 | 3000 and over |
| Catchment | | -2.05 | 0.4 to 1 | 3238 | 2550 to 3500 + |

The annual temperature in 1985-1986 is below the normal which is 5.76°C. So the temperature expected for all the elevation zones should also situated on the lower part of the ranges. But the difference of magnitude between the annual temperature in each zone and their range of values is substantial, especially after the zone 3. This must be due to a too big temperature lapse rate.

The annual precipitation in 1985-1986 is below the normal 1356 mm. So the precipitation expected for all the elevation zones is also on the lower part of the ranges. But in most of the zone, the annual precipitation is on the upper part of the ranges. This could be due to a too large precipitation correction factor – PCORR or SCORR - which produces a higher amount of precipitation. It could also be caused by HPCORR which is very high 10% and increase the precipitation with the elevation.

So the problem of the model is that too low temperature associated with too high precipitation makes the snow routine inconsistent for the high storage its reaches and it left at the end of the year.

The problem could also be partially caused by the fact that HBV-model considers only one type of ablation which is the snowmelt. But what could happen is also that other types of ablation occur: avalanches, wind, glacier motion etc. which transport the snow at lower zones where the snow could melt more quickly. Yet it cannot explain the excess of precipitation generated.

### 5.4.5 Hydrographs on the calibration period

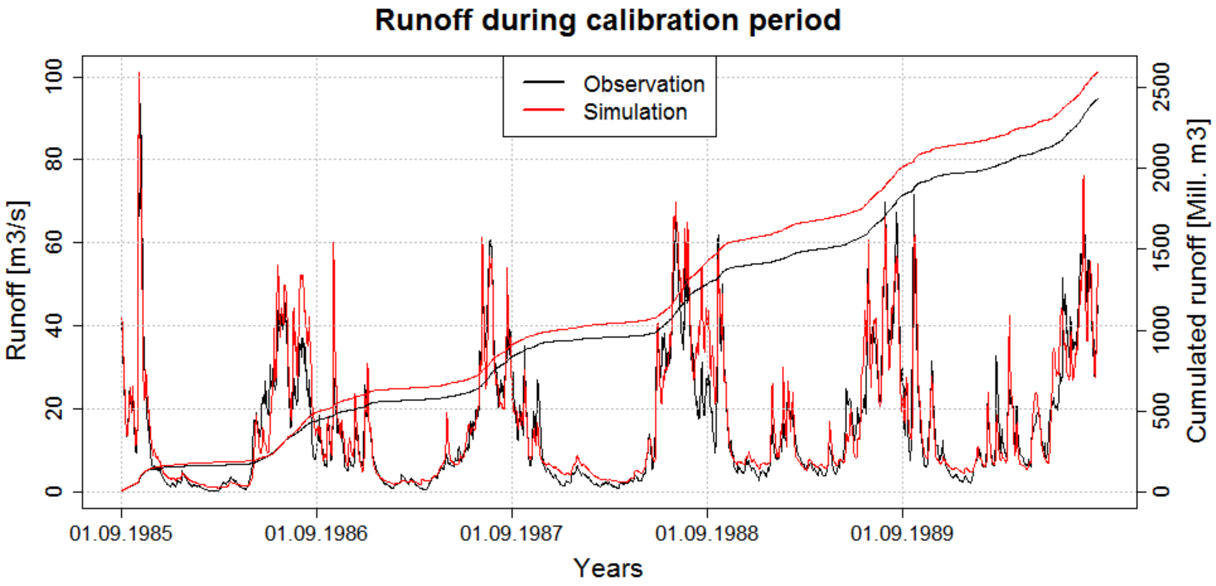


**Figure 5.4-11: HBV-calibration – hydrograph**

Every year, the simulated runoff is close to the observed one. Problems of timing and magnitude appear regularly, but generally, it matches very well.

The snow routine is the main concern about the calibration. So its behaviour on the different years of the calibration has been investigated.

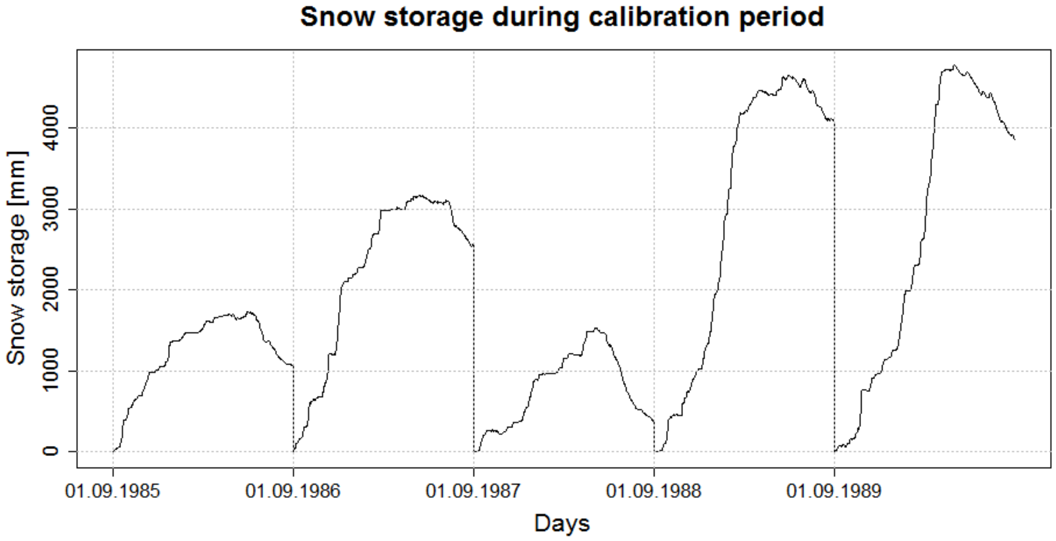


**Figure 5.4-12: HBV-calibration - snow storage**

**Table 5.4-7: Climatic characteristics of the years of calibration on the snow storage**

| Year | Year | | | Winter | | | Summer | | |
|---|---|---|---|---|---|---|---|---|---|
| | T | P | Snow | T | P | Snow formation | T | P | Snowmelt |
| 1985 | -- | -- | Little | --- | -- | Soon | + | + | Soon |
| 1986 | -- | + | Much | -- | + | Soon | -- | + | Late, slowly |
| 1987 | +++ | --- | Very little | ++ | -- | Soon, slowly | ++++ | - | Soon, quickly |
| 1988 | ++ | +++++ | Much more | ++++ | ++++ | Late | -- | + | Late, slowly |
| 1989 | +++ | +++++ | Much more | ++++ | +++++ | Late, slowly | + | + | Soon, quickly |

So the temperature and precipitation affect the snow storage in a normal way.

- Warm temperature in winter slows down the snow formation,
- Much precipitation in winter increases the snow storage amount,
- Cold temperature in summer decelerates the snowmelt.

The problem is only about the amplitude of the changes in the storage.

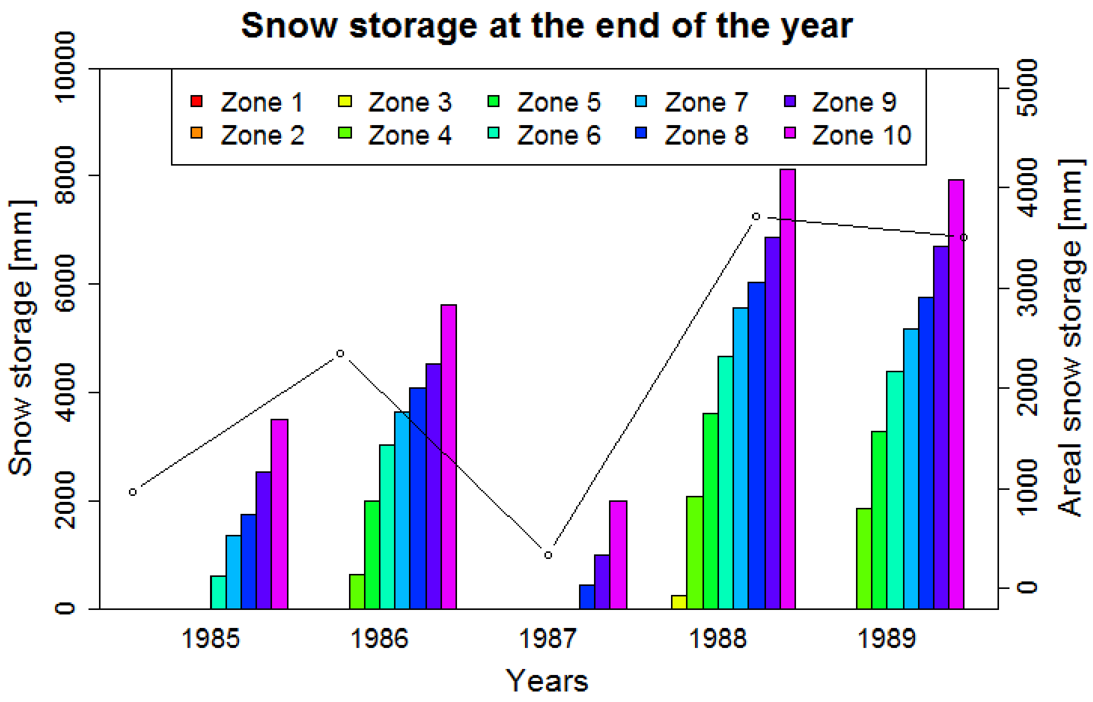


**Figure 5.4-13: HBV-calibration - snow storage in each elevation zone at the end of the years**

The snow storage on each zones are overestimated. This is a problem because even on the years where the mass balance is negative in the surrounding glaciers, there is snow remaining on the highest elevation zones of the catchment. So the mass balance for Olden would always be positive which seems unlikely.

*Other routines*

On all the calibration years, a similar regime in soil moisture, upper and lower zone storage can be observed. The differences can be explained with the variation of temperature and precipitation observed.

See Appendix P: Calibration 1

## 5.5 SECOND CALIBRATION: FOCUS ON THE SNOW ROUTINE

The second calibration has been made in order to get more consistent result for the snow part because it is difficult to forecast the snow part and the glacier mass balance when the precipitation is overestimated.

As the first calibration gave the best results in term of runoff, the second one will give a worse fit in term of discharge. But this second calibration must maintain a good $R^2$ in order to be used afterwards.

The focus for this second calibration was on the temperature, precipitation corrector factors, the temperature thresholds snow/rain and snowmelt, the melt increase and degree-day factor.

### 5.5.1 Parameters and initial states

The modifications made were:

- Decrease of the precipitation elevation correction which was very high in the first calibration (10% per 100 m) was modified to get less precipitation overall the all year,
- Decrease of the temperature threshold snow-melt: the snow will melt at a temperature which is inferior.
- Increase of the melt increase in mountain to accelerate the snowmelt.
- Decrease of the temperature lapse rate to have less snow.

**Table 5.5-1: HBV-calibration 2 - free parameters values**

| **PARAMETERS IN THE HBV-MODEL:** | | | | **Units** | Optimizer Range Min | Max |
|---|---|---|---|---|---|---|
| PREC | Rain - correction: | PKORR | 1.30 | | 1.00 | 1.30 |
| | Snow - correction: | SKORR | 1.50 | | 1.00 | 1.50 |
| | Elevation correction: | HPKORR | 2 | % pr. 100 m | 5.00 | 10.00 |
| SNOW | Degree-day factor: | CX | 4.00 | mm/degree C./day | 2.50 | 4.00 |
| | Threshold snow-melt: | TS | 0.14 | Degree C. | -1.00 | 1.00 |
| | Threshold rain/snow: | TX | 0.53 | Degree C. | -1.00 | 1.00 |
| | Liquid water: | CPRO | 10 | % of dry snow | 5.00 | 10.00 |
| SOIL | Field capacity: | FC | 90 | mm | 50 | 150 |
| | Beta: | BETA | 1.12 | | 1.00 | 2.50 |
| | Threshold evaporation: | LP% | 69 | % | 60 | 100 |
| UPPER ZONE | Fast drainage coefficient: | KUZ2 | 0.19 | 1/day | 0.10 | 0.40 |
| | Slow drainage coefficient: | KUZ1 | 0.07 | 1/day | 0.01 | 0.10 |
| | Threshold: | UZ1 | 19 | mm | 10.00 | 40.00 |
| | Percolation: | PERC | 1.04 | mm/day | 0.20 | 1.50 |
| LOWER ZONE | Drainage coefficient: | KLZ | 0.080 | 1/day | 0.002 | 0.100 |
| REFREEZE | | PRO | 10.00 | % of normal melt rate | 10.00 | 10.00 |
| | Temperature lapse rate: | | | | | |
| Tlp | At precipitation | | -0.60 | Degree C./100 m | -0.40 | -0.70 |
| Tlo | No precipitation | | -0.70 | Degree C./100 m | -0.50 | -1.00 |

The elevation correction has been decrease from 10 to 2% per 100m. So the increase of precipitation along the elevation will be much lesser.

The temperature lapse rate has been decreased to have warmer temperature when there is precipitation. So the precipitation will be rain instead of snow more often, which will give less snow storage.

**Table 5.5-2: HBV-calibration 2 – CX**

| | | | |
|---|---|---|---|
| Melt increase in mountain | 1.5 | Melt increase in glaciers | 1.5 |
| CX-mount. | 6 | CX-Glacier | 6 |
| Min | 0.75 | Min | 1 |
| Max | 1.5 | Max | 1.5 |

The melt increase in mountain has been increased to accelerate the snow melt in the mountain.

So the changes were made only on the precipitation elevation factor, temperature correction factor at precipitation, the melt increase factor. The first factor has been change to get less precipitation on the elevation zones, the second one to get less snow storage thanks to a warmer temperature and the third one to increase the snowmelt.

### 5.5.2 Objective function: criterion $R^2$

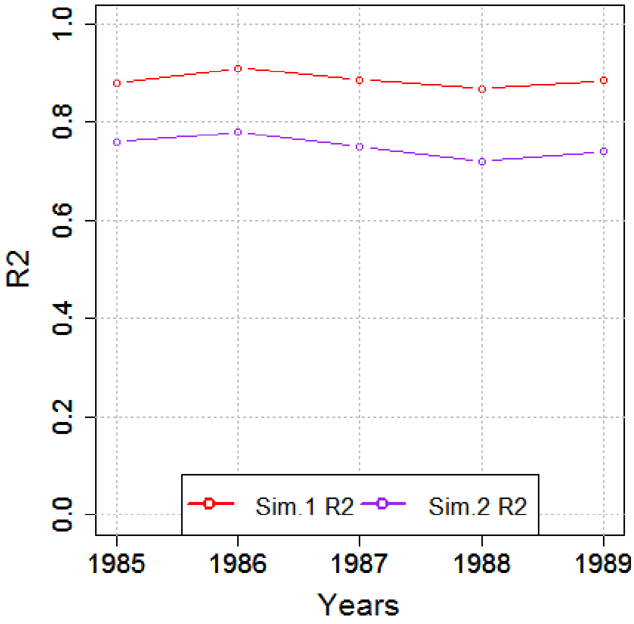


**Figure 5.5-1: HBV-calibration 2 - $R^2$**

**Table 5.5-3: HBV-calibration 2 - $R^2$**

| Year | Calibration 1<br>$R^2$ | Calibration 2<br>$R^2$ |
|---|---|---|
| 1985 | 0.88 | 0.76 |
| 1986 | 0.91 | 0.78 |
| 1987 | 0.89 | 0.75 |
| 1988 | 0.87 | 0.72 |
| 1989 | 0.88 | 0.74 |

Looking at the coefficient $R^2$, the calibration 2 still gives good results with values within the range 0.74 to 0.78. So the simulated runoffs are close to the observed data.

The coefficient follows the same pattern which could means that the calibration goes through the same problems to make the simulation fit the observed data and thus must worsen the effects: for instance the overestimation of calibration 1 are even more overestimated in the calibration 2.

### 5.5.3 Average annual runoff

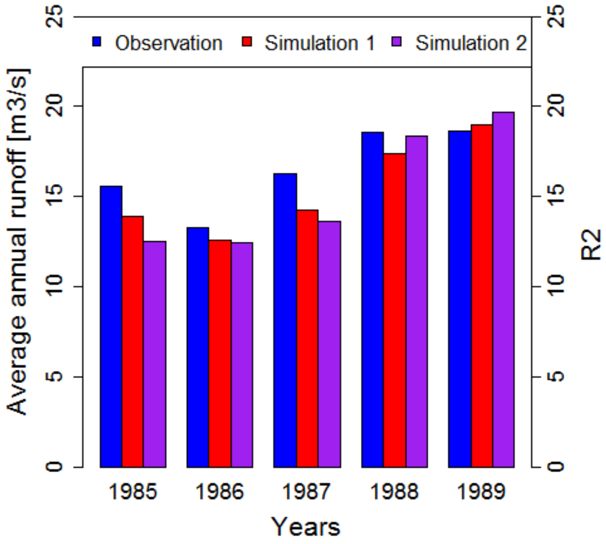


**Table 5.5-4: HBV-calibration 2 - comparison observed and simulated Q**

| Year | $R^2$ | Obs. Q | Sim.1 Q | Sim.2 Q |
|---|---|---|---|---|
| 1985 | 0.76 | 15.58 | 13.91 | 12.50 |
| 1986 | 0.78 | 13.27 | 12.58 | 12.40 |
| 1987 | 0.75 | 16.28 | 14.26 | 13.59 |
| 1988 | 0.72 | 18.53 | 17.36 | 18.36 |
| 1989 | 0.74 | 18.66 | 18.97 | 19.69 |

**Figure 5.5-2: HBV-calibration 2 - comparison observed and simulated Q**

It can be seen from Figure 5.5-2 that the average annual runoff simulated is worse than the previous calibration as expected from the criterion $R^2$. It underestimated or overestimated the runoff even more than the calibration 1 did, except for the year 1988 where the result is better. The $R^2$ was not better though so it means that the differences on the daily runoffs are worse but give a better average.

### 5.5.4 Analysis of data for the first year 1985-1986

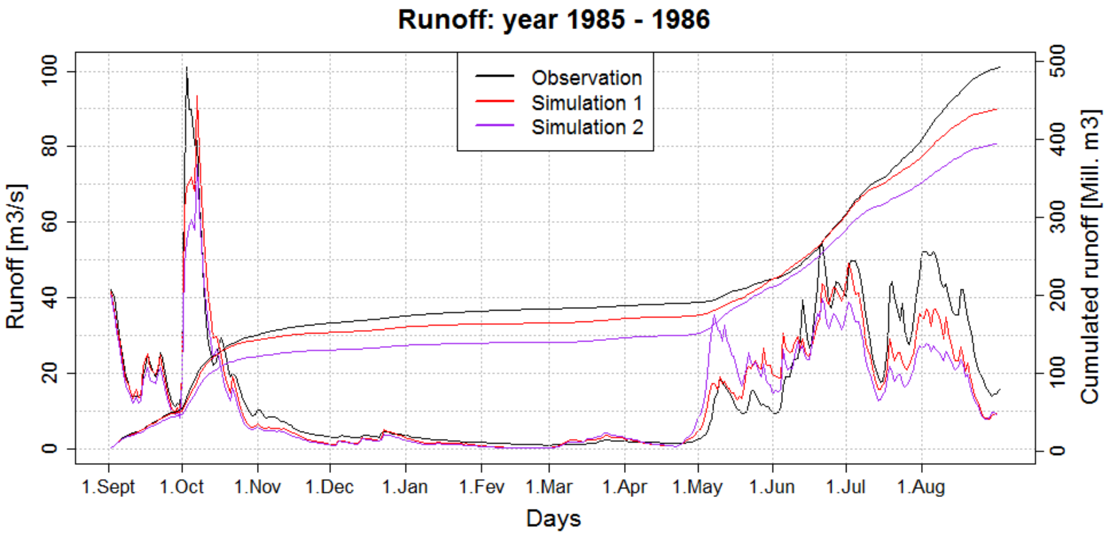


**Figure 5.5-3: HBV-calibration 2 - comparison observed and simulated Q (1985-1986)**

So as expected from the results showed in the criterion of goodness, the calibration 2 accentuates the problem already existing in the calibration 1.

### *Temperature and precipitation correction*

**Table 5.5-5: HBV-calibration - precipitation and temperature corrected (1985-1986)**

| | | Temperature [°C] | | | Precipitation [mm] | | |
|---|---|---|---|---|---|---|---|
| | Elevation | Cal. 1 | Cal. 2 | Ranges | Cal. 1 | Cal. 2 | Ranges |
| Observed | | 5.03 | 5.03 | 4 to 6 | 1101 | 1101 | 1500 to 2000 |
| Zone 1 | 168 | 5.25 | 5.24 | 4 to 6 | 1666 | 1506 | 1500 to 2000 |
| Zone 2 | 530 | 2.77 | 2.89 | 2 to 4 | 2201 | 1613 | 2000 to 3000 |
| Zone 3 | 862 | 0.48 | 0.74 | 0 to 2 | 2692 | 1710 | 2000 to 3000 |
| Zone 4 | 1106 | -1.19 | -0.84 | 0 to 2 | 3052 | 1782 | 2000 to 3000 |
| Zone 5 | 1305 | -2.56 | -2.13 | -1 to 0 | 3346 | 1840 | 3000 to 4000 |
| Zone 6 | 1444 | -3.51 | -3.03 | -1 to 0 | 3552 | 1881 | 3000 to 4000 |
| Zone 7 | 1560 | -4.31 | -3.78 | -1 to 0 | 3723 | 1915 | 3000 to 4000 |
| Zone 8 | 1645 | -4.89 | -4.33 | -2 to -1 | 3849 | 1940 | 3000 to 4000 |
| Zone 9 | 1742 | -5.56 | -4.96 | -2 to -1 | 3992 | 1969 | 3000 to 4000 |
| Zone 10 | 1953 | -7.01 | -6.32 | -3 to -2 | 4304 | 2031 | 3000 and over |
| Catchment | | -2.05 | -1.65 | 0.4 to 1 | 3238 | 1819 | 2550 to 3500 + |

The purposes of the changes in the parameters were:

- Increasing the temperatures and
- Decreasing the precipitation.

The temperature values increased in all the elevation zones. They still reach low annual temperature but it gets closer to the ranges.

The precipitation values decreased in all the zones. They are now much lower than the ranges, which is consistent with the fact that the year 1985 was dry but the figures might be excessively low.

*Snow routine*

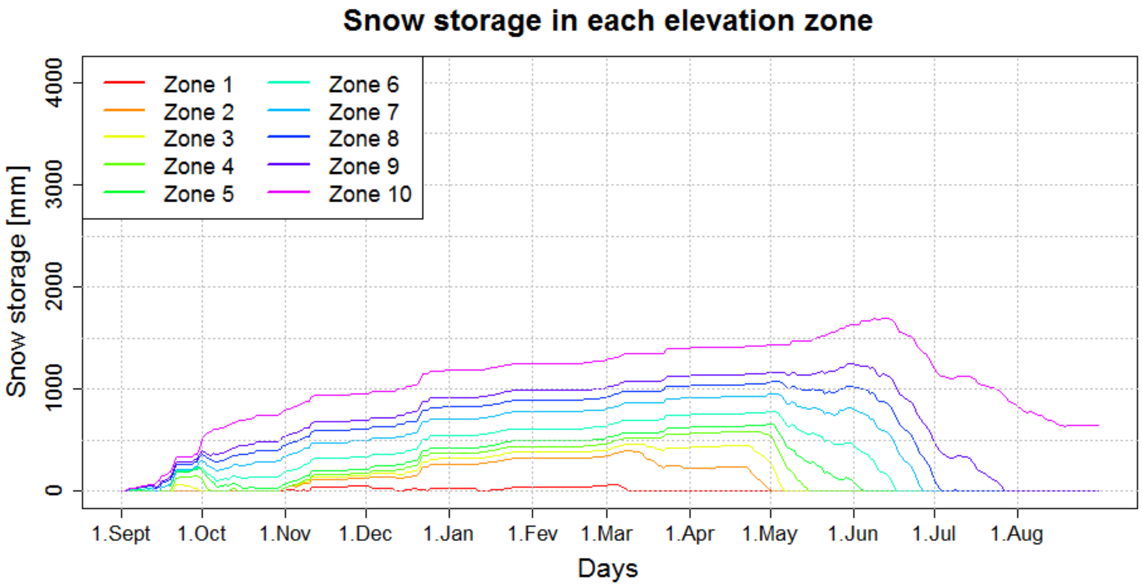


**Figure 5.5-4: HBV-calibration 2 - snow storage in each zone (1985-1986)**

For all the zones, the snow water equivalent is much lower along the year and fits better with Senorge values.

Zones 1 to 5: they have the same pattern as in the simulation 1.

Zones 6 to 9: the snow starts melting in May (instead of June). The snow storage increases for all those zones in late May (like simulation 1), and decreases to but at the end of August, there is no snow left. So this is a better fit with Senorge.

Zone 10: the snow storage follows the same pattern but at the end, the snow storage is consistent with the one showed in Senorge.

So the snow water equivalent is consistent with the snow that much remains on the catchment.

### 5.5.5 Hydrographs

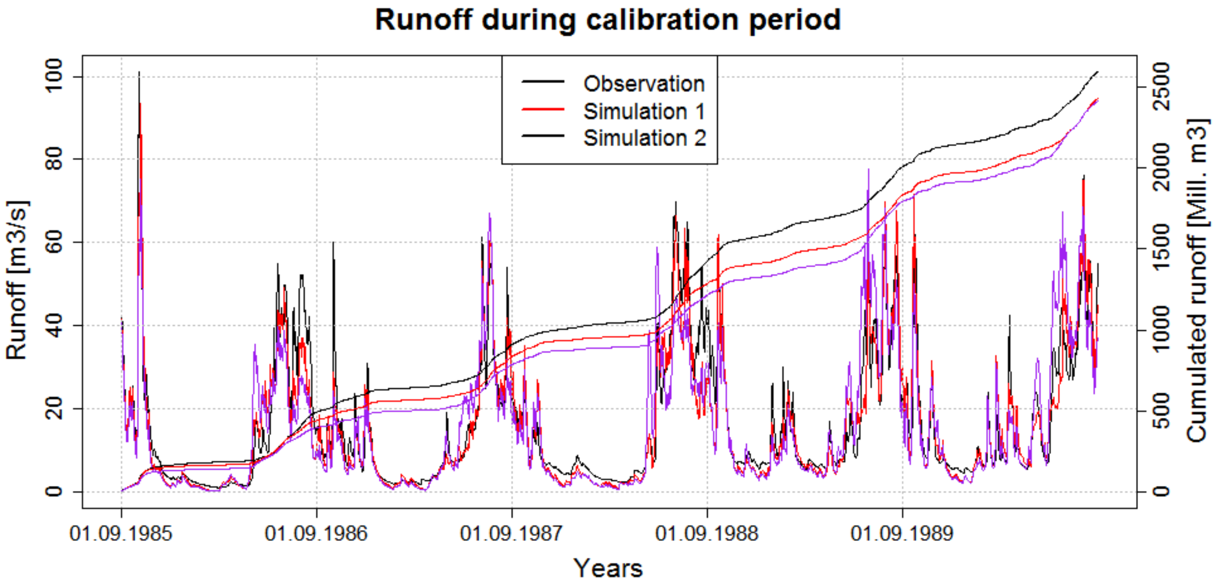


**Figure 5.5-5: HBV-calibration 2 – hydrograph**

The difference between the two calibrations can be seen on the cumulated runoff. The gap widens when the calibration 1 underestimates the runoff and it decreases when it overestimates the runoff. At the end of the simulations, the cumulated runoff might be better but thought the year the daily runoff is usually worse.

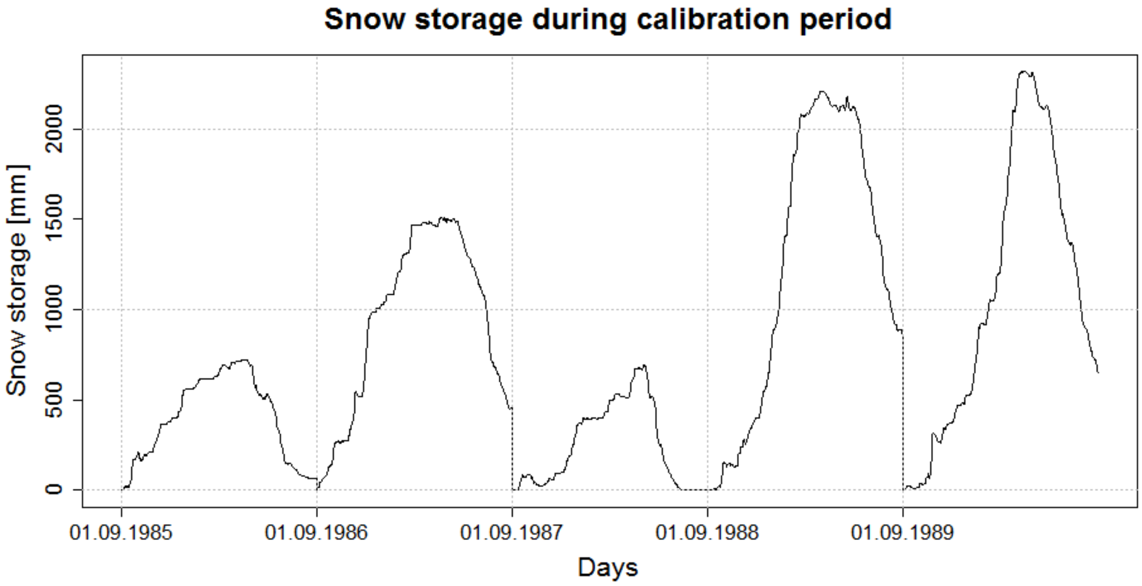


**Figure 5.5-6: HBV-calibration 2 - snow storage**

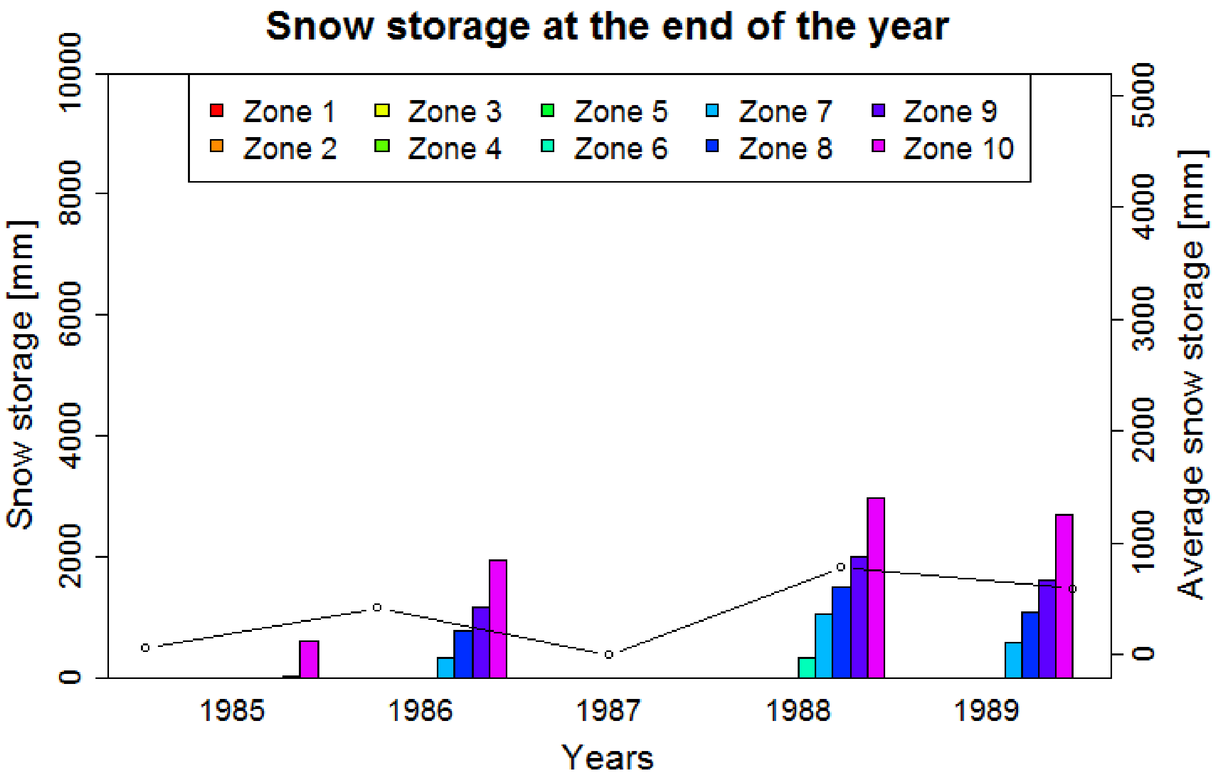


**Figure 5.5-7: HBV-calibration - snow storage in each elevation zone at the end of the years**

The snow water equivalent is really low compared to the calibration 1. At the end of each year, fewer zones have remaining snow and the amount of snow is twice smaller.

See Appendix Q: Calibration 2

## 5.6 COMPARISON BETWEEN THE TWO SIMULATIONS

**Table 5.6-1: Comparison of the climatological data between the two calibrations**

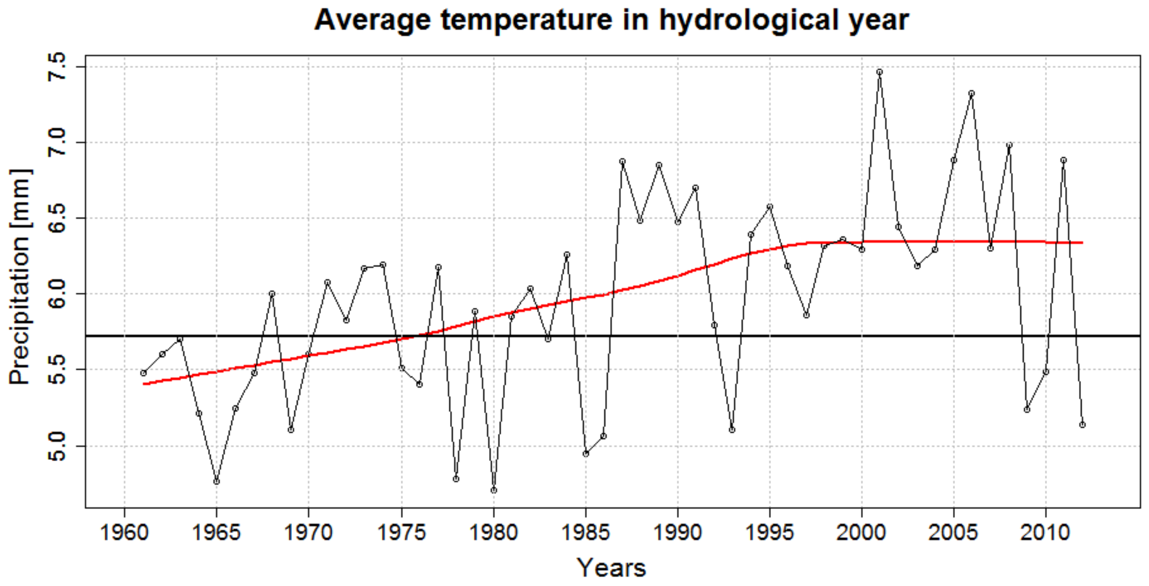
| | Simulation | | Difference | |
|---|---|---|---|---|
| | Sim. 1 | Sim. 2 | [°C], [mm] or [m$^3$/s] | [%] |
| Runoff [m$^3$/s] | 15.02 | 14.47 | -0.55 | -4% |
| Air temperature [°C] | -1.06 | -0.66 | 0.39 | 37% |
| Precipitation [mm] | 4136 | 2312 | -1824 | -44% |
| Rain [mm] | 1081 | 791 | -290 | -27% |
| Snow [m.w.e.] | 3055 | 1521 | -1534 | -50% |

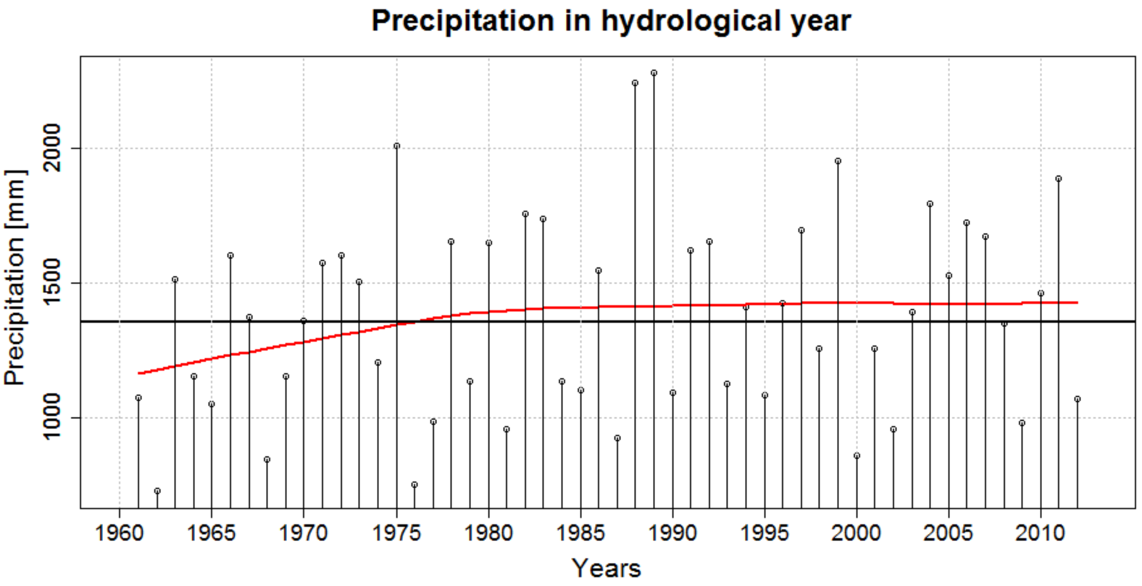
The runoff generated by the two simulations is globally the same, but the climatological parameters from which the outflow was calculated are very different. With low temperature and high precipitation, the runoff obtained is about the same than with high temperature and low precipitation with the snowmelt.

The difference between precipitations comes mainly from the difference in the snowfall and results in the very distinct snow routine. This difference in precipitation will create a very different pattern for the glaciers behaviour: the calibration 1 will produce a positive mass balance while the calibration 2 will engender a much lesser mass balance.

## 5.7 VALIDATION

### 5.7.1 Period of validation





### 5.7.2 First calibration

The simulation has been run for the period from 1961 to 2012.

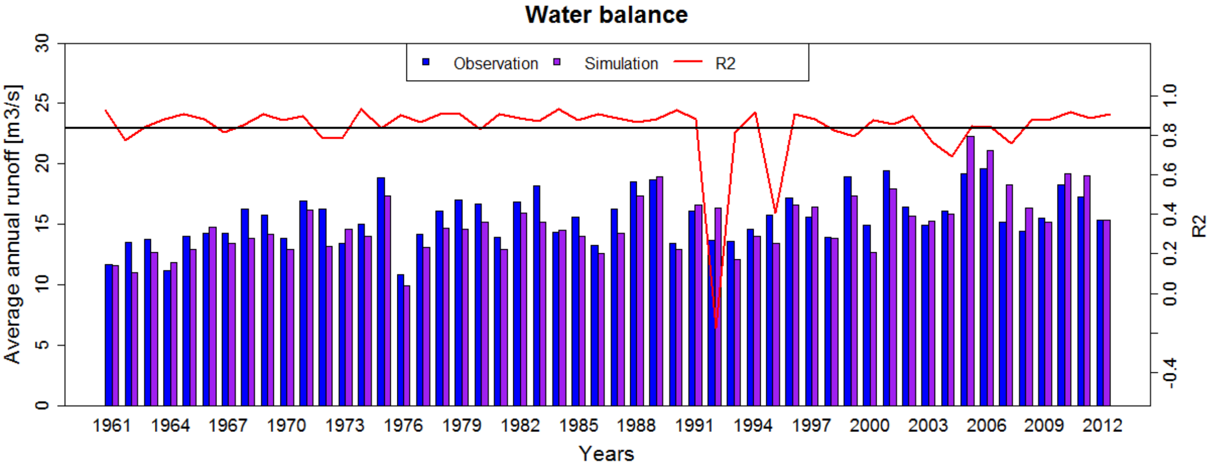


**Figure 5.7-1: HVB - validation - calibration 1**

The simulation shows good results. Most of the years have an underestimated runoff, some have an overestimated runoff. Unlike for the calibration period, it is not possible to conclude whether the runoff is overestimated or underestimated from the amount of precipitation compared to the normal annual precipitation (or winter precipitation).

*Temperature extension*

**Table 5.7-1: Comparison between the $R^2$ in the different periods of temperature records**

| Years | Temperature | Average: $R^2$ |
|---|---|---|
| 1961-1990 | Oppstryn | 0.876 |
| 1991 | Olden – Vangberg | 0.881 |
| 1992 | Oppstryn normal | -0.177 |
| 1993-2012 | Stryn – Kroken | 0.828 |
| 1961-2012 | | 0.837 |

So the average $R^2$ for the period 1961-1990 is better than the one for the period 1993-2012.

It might be to the fact the period of calibration was dependant only on the Oppstryn data and thus gives better fit than for the rest. To check this hypothesis, a calibration on a period where temperature depends on one station for some years and on a different one for the rest must be performed. This was not possible in this case because there is a year in between the two different stations records with no data (1992) where the temperature are filled in with normal temperature. It could also be due to the fact that during the normal period, the runoff was more dependent on the precipitation than after 1990 when the temperature increases and affect the glaciers which thus take a greater part in the water balance. However, except in the case of a big change of glacier area and depth, the simulation can produce more runoff from the glacier with an increase of temperature. The problem could appear on a longer term when there is no glacier whereas the model still generates ice melt. Nevertheless, the glaciers are usually covered by snow the all years with this calibration. So this might not be the main reason for this reduction of $R^2$.

However the difference is small enough to consider that the filling of missing data by correcting the data from these other stations was good.

It is not possible to conclude anything for the year 1991 as there is only one year of data where the temperature comes from Olden – Vangberg station.

As expected, it is not possible to forecast the runoff with normal data: so the years 1992 and 1995 are not taken into account.

*Glacier effect*

The period is relatively long, 52 years, which could have shown a difference due to the glacier changes: shredding or expanding which are not included in the HBV-model. It could mean that the glaciers in Olden have not changed too much in 52 year, kept their general characteristics to maintain some continuity during the simulation. In this way the model cannot compute to much or not enough runoff from ice melt that would appear on the general average runoff.

The calibration made it possible to estimate the right runoff using only climatological data: temperature and precipitation.

*Validation*

With an average of $R^2$ of 0.837, the model calibration 1 is validated for the runoff forecast.

### 5.7.3 Second calibration

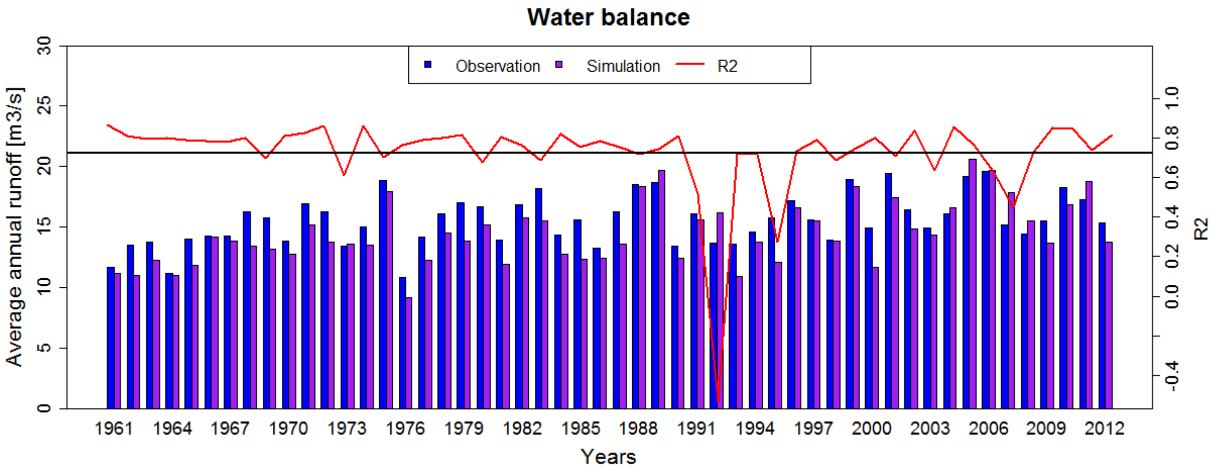


**Figure 5.7-2: HVB - validation - calibration 2**

**Table 5.7-2: Comparison between the $R^2$ in the different periods of temperature records for the second calibration**

| Years | Temperature | Average: $R^2$ |
|---|---|---|
| 1961-1990 | Oppstryn | 0.776 |
| 1991 | Olden – Vangberg | 0.518 |
| 1992 | Oppstryn normal | -0.532 |
| 1993-2012 | Stryn – Kroken | 0.716 |
| 1961-2012 | | 0.723 |

The simulation on the long period from the calibration 2 brings the same conclusions as the simulation on the long period from the calibration 1:

- Better fit with the first period 1961-1990,
- No conclusion for 1992,
- No viable result for the year 1992 and 1995.

With this calibration, the difference of $R^2$ between the first and the second period could be explained by the modification of the glaciers themselves more than with the first calibration: the glaciers are less often covered by snow with this calibration and participates more in the global runoff.

*Validation*

With an average of $R^2$ of 0.723, the model calibration 1 is also validated for the runoff forecast.

## 5.8 USE OF THE MODEL CALIBRATION FOR THE TWO OTHER CATCHMENTS

### 5.8.1 Catchment: Loen

The exact same calibration parameters determined for the catchment Olden were used for Loen catchment.

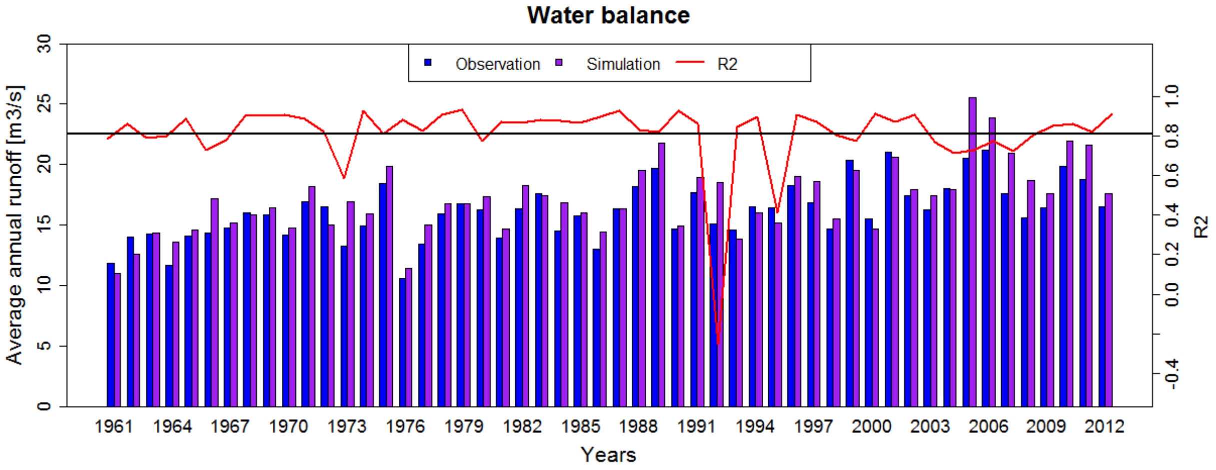


**Figure 5.8-1: HVB - validation - Loen calibration 1**

**Table 5.8-1: Comparison between the R2 in the different periods of temperature records in Loen catchment**

| Years | Temperature | Average: $R^2$ |
|---|---|---|
| 1961-1990 | Oppstryn | 0.849 |
| 1991 | Olden – Vangberg | 0.862 |
| 1992 | Oppstryn normal | -0.256 |
| 1993-2012 | Stryn – Kroken | 0.809 |
| 1961-2012 | | 0.812 |

The HBV model calibrated for the catchment Olden gives very good results for the calibration period. Generally the model overestimates the average runoff. It could be due to the fact that the calibration was made for Olden which must have characteristics, land type, river which gives higher runoff. Even by changing the features of the catchment in the confined parameters, the free parameters keep track of the catchment for the one they have been calibrated.

However, the good results shows that the calibration done for a catchment can be transported to another catchment if they share numerous similarities their properties (area, shape, topography, land use, climatology etc.).

### 5.8.2 Catchment: Stryn

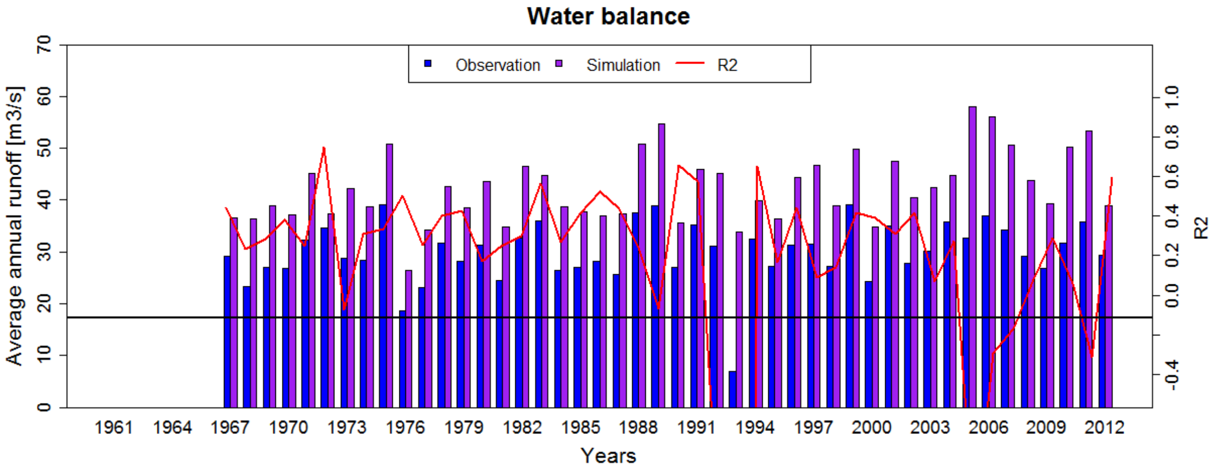


**Figure 5.8-2 : Figure 5.8-3: HVB - validation -Stryn calibration 1**

The average $^{R2}$ is negative. So it is not possible to transport the model to a catchment if its features are really different from the catchment where the model has been calibrated.

*N. B.: The runoff data has not been completed so the years 1993 and 1996 cannot be calculated.*

## 5.9 DISCUSSION AND CONCLUSION

The calibrated model gives very good results for the runoff part. The calibration process is made in order to get the best runoff fit possible. So the inside routines can be wrong, if their impacts cancels each other giving a good final results, it will not be taking into account in the criterion of goodness $R^2$. So the model would be easily used for the runoff forecast if there was project of implantation of a hydropower plant.

The model shows that the correction of temperature data to get long period does not worsen the results, even though the calibration has been done using only one station. It is helpful to have this continuity of results considering that some stations record can be stopped and another one at a different location can be started.

It is also an example of the utility of regional model with the good results of the transposition of the calibration on a simulation to a very similar catchment.

There are numerous problems concerning the calibrations about the precipitation, temperature, snow and glacier routine:

- Excess of precipitation: difficulties to assess glacier mass balance,
- Wrong amount of snow:
    - the snow storage is too important which prevents ice glacier from melting,
    - Transformed all the snow into ice: overestimation of the mass gain (not really the case for the HBV model as it does not calculate the mass balance)

The HBV-model is not detailed enough for the glacier because there is:

- No information on the depth of the glacier which would show the glacier mass associated with the area,
- No reports on the glacier melt states.

# 6 GLACIER'S BEHAVIOUR: MASS BALANCE

## 6.1 GLACIERS' BEHAVIOUR

*Description*

The glacier can be divided into two different zones: an accumulation area where there is addition of snow/ice and an ablation area where the glacier mass is removed. The boundary between those two zones where there is no mass change is called the equilibrium line (Paterson, 1994). The accumulation regroups all processes whereby material is added to the glaciers: it is usually snow which gradually turns to ice (Paterson, 1994). The ablation involves all processes whereby material is removed from the glacier: melting and runoff, evaporation etc. (Paterson, 1994).

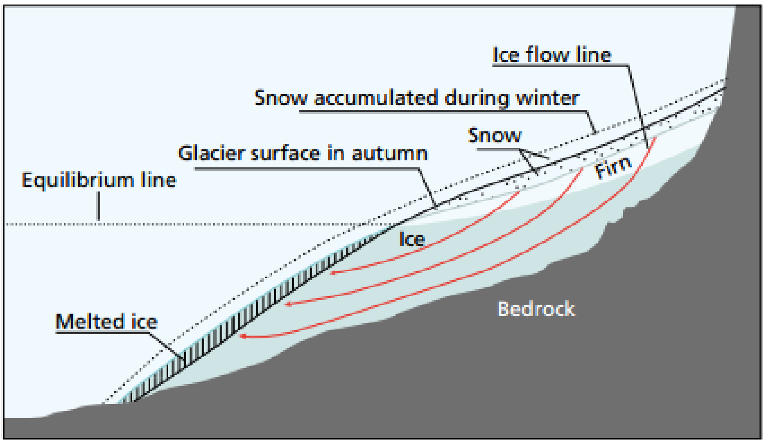


**Figure 6.1-1: Cross-section of a typical valley glacier. Graphics: Rune Stubrud, NVE (Andreassen et al., 2012)**

*Mass balance*

The annual mass balance is the combination of accumulation and ablation (Andreassen et al., 2012). In the upper zone, the balance is positive: there is a great accumulation during winter, an accumulation which is less important in summer. In the lower zone, the balance is negative: a slight ablation occurs in winter, an ablation which increases considerably in summer. The net balance is positive in winter due to the high accumulation in the first area, and drops in summer due to the substantial ablation in the second area. The annual net balance can be either positive or negative at the end of the year.

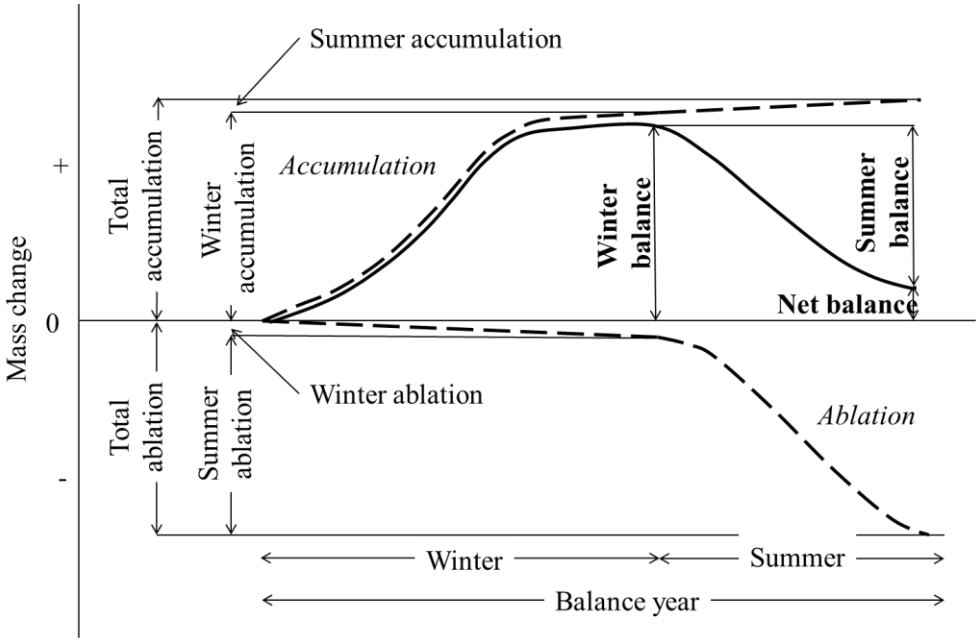


**Figure 6.1-2: Definition of mass balance terms (Paterson, 1994)**

*Transformation of snow to ice*

The water in the HBV model is of two forms: liquid water and snow. In the glacier though, there are different kinds of water phases: snow, firn and ice. The “snow” is the snow as it is commonly defined that has not changed much since it fell (Paterson, 1994). The “firn” is wetted snow that has survived one summer without being transformed to ice (Paterson, 1994). The “firn” becomes glacier ice when there is no more air passages between the grains (Paterson, 1994).

**Table 6.1-1: Typical densities (kg.m$^{-3}$) (Paterson, 1994)**

| | |
|---|---|
| New snow (immediately after falling in calm) | 50-70 |
| Damp new snow | 100-200 |
| Settled snow | 200-300 |
| Depth hoar | 100-300 |
| Wind packed snow | 350-400 |
| Firn | 400-830 |
| Very wet snow and firn | 700-800 |
| Glacier ice | 830-917 |

In the HBV-model, the transformation from snow to ice is a punctual phenomenon which occurs at the end of the year before the 1st of September of the next year. However the glacier as itself does not change along the years in the HBV-model.

*Snow melt*

In the HBV-model, the snow routine, melt and refreeze, is estimated with only one parameter: the temperature. But to get snow melt or snow refreeze, there are many more parameters that should be taken into account. The catchments with glacier have a runoff which is more "energy" dependant than "precipitation" related (Jansson et al., 2003). The reason is that most of the precipitation is stored and then release with the snowmelt. The snowmelt depends on the energy available (Paterson, 1994):

$$Q_M + Q_i = Q_l + Q_s + Q_h + Q_g + Q_r \tag{33}$$

With:

- $Q_m$: energy available for melting snow [W/m2],
- $Q_i$: internal energy changes through heating or cooling of the snowpack [W/m2],
- $Q_s$: net shortwave radiation [W/m2]: depends of the day of the year, the latitude and the cloudiness, snow age,
- $Q_l$: net longwave radiation [W/m2]: depends in the temperature (air, surface) and on the cloudiness,
- $Q_h$: sensible heat [W/m2]: depends on the temperature gradient and wind,
- $Q_e$: latent heat [W/m2]: depends on vapour pressure, wind,
- $Q_g$: ground heat flux [W/m2]: depends on soil temperature,
- $Q_r$: heat from precipitation [W/m2].

In the HBV model, only the air temperature appears. The other parameters do not appear.

*Calculation of the mass balance*

The hydrological way of calculating the glacier mass balance is (Paterson, 1994):

$$\mathrm{B} = \mathrm{P} - \mathrm{R} - \mathrm{E} \tag{34}$$

With:

- B: annual net mass balance,
- P: precipitation over the basin,
- R: runoff from the basin,
- E: evaporation of the basin.

Mass balances are expressed in equivalent volumes of water per unit area, or meter water equivalent [m.w.e.] (Paterson, 1994).

*Climate change*

In a simpler way, the mass balance of the glaciers can be seen as dependant of the climatic conditions in the area where they are located. High precipitation associated with low temperature could add ice on the accumulative season and while high temperature in the ablation season would reduce the summer mass balance. The combination of both phenomena will give the annual net mass balance.

In the future higher temperature and higher precipitation are expected. With an increase of the air temperature, the glacier foot located in the lowest part of the catchment where the temperature are the highest will tend to melt which give a reduction of the glacier area and a fall of the water storage volume. But with an augmentation of the precipitation, at the top of the glacier the precipitation will create snow accumulation, snow that can turn to ice, which can increase the water storage volume. So the water balance might not be change if the increase of temperature and precipitation are two phenomena happening in parallel and on the right proportion. However, if the glacier mass is stored higher, it means that the runoff could still decrease because the melt will not happen so high in the mountain.

Another phenomenon in the glaciers is not entirely linked to the climate but it is more a mechanical effect: glacier sliding. The glacier cap can go down in the valley which will enlarge the length of the glacier on its foot but decrease the depth. It does not affect the mass balance when it occurs but can have repercussion in the following years.

The volume of the glacier is not only proportional to its area it covers. This is the reason why the area or the length of a glacier is not the best way to estimate the glacier volume. The only parameter is the mass balance.

## 6.2 GLACIERS STUDIES IN THE AREA

### 6.2.1 Glacier mass balance in the region

The mass balance of glaciers on the catchments Olden, Loen or Stryn has never been measured. But mass balance investigations have been carried out in other glaciers in the region:

- Nigardsbreen which is on the other side of the glacier Jostedalsbreen and
- Ålfotsbreen which is closer to the coast.

Even though the two glaciers are not the same face of Jostedalsbreen, they present a good correlation for their mass balance:

**Table 6.2-1: Pearson's correlation between Nigardsbreen and Ålfotbreen mass balance**

| Glaciers | | Ålfotbreen | | |
|---|---|---|---|---|
| | season | year | winter | Summer |
| Nigardsbreen | year | **0.868** | 0.756 | 0.555 |
| | winter | 0.728 | **0.848** | 0.196 |
| | summer | 0.713 | 0.402 | **0.734** |

So it can be assumed that glaciers within the same region share common pattern in their mass balance.

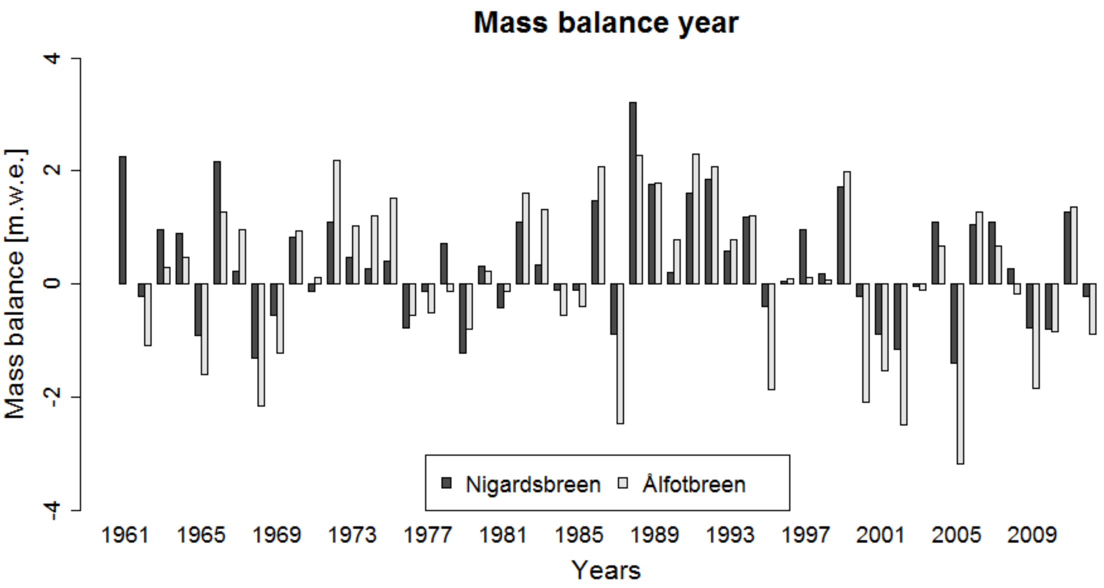


**Figure 6.2-1: Comparison between two mass balances**

The mass balances are following the same trends along the years. However the magnitudes of the glacier mass balance can vary widely. Generally the mass balances are much extreme, positively and negatively, on the coast, for Ålfotbreen which is subject to very high precipitation winter and high temperature in summer, than inland for Nigardsbreen which does not go through those high climatological aspects.

So considering that Olden is located inland, the mass balance will have magnitudes close to Nigardsbreen.

See Appendix R: Mass balances

### 6.2.2 Briksdalsbreen's length

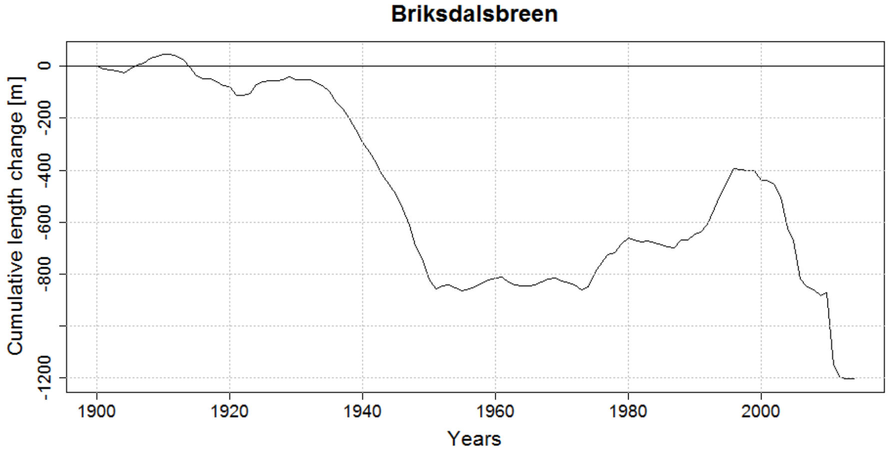


**Figure 6.2-2: Briksdal's cumulative length change between 1900 and 2014 (NVE, 2015)**

As can be seen on the Figure 6.2-2, Briksdalsbreen has seen its length moving during the last year. In the beginning of the 1900s, the glacier declined of several meters before growing in the rest of the 1900s and advanced up to 50 m more than it was in 1900. After a new fall of its length between 1910 and 1921, and a small recovery until 1930, the glacier lost surface with the collapse of its length for 20 years. After stagnation between 1950 and 1970 and two periods of increase in the 1980s and 1990s, the length collapsed again in the 21st century. Between 1900 and 2014, Briksdalsbreen will have lost 1.2 km length.

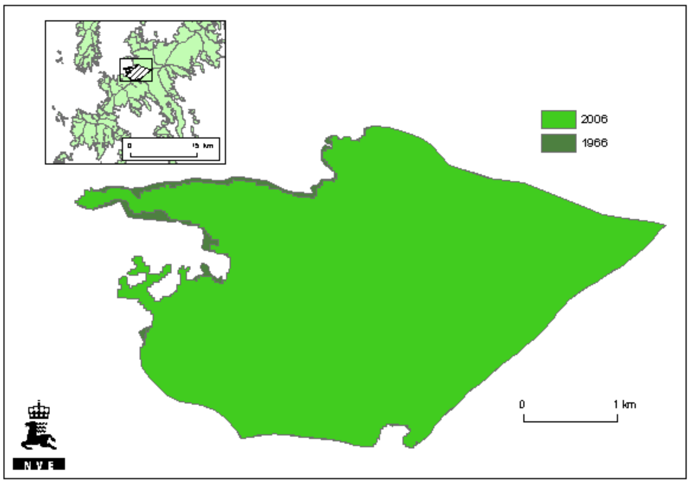


**Figure 6.2-3: Briksdalsbreen's area change (NVE, 2015)**

See Appendix S: Briksdalsbreen evolution

### 6.2.3 Correlation between mass balance and length of a glacier

The Norwegian glaciers have been monitored in two different ways: their length and/or their mass. Usually, loss of area or loss of length is associated with loss of glacier mass. But it is not possible to conclude whether a glacier is losing mass from the area it covers.

Assuming that the glaciers within the same region must have a common pattern in their mass balance, the correlation between the mass balance of the glaciers Nigardsbreen and Ålfotbreen and the Briksdalsbreen length has been calculated.

**Table 6.2-2: Pearson's correlation glacier mass balance and length of Briksdalsbreen**

| | Nigardsbreen | Ålfotbreen |
|---|---|---|
| Year | 0.220 | 0.240 |
| Winter | 0.191 | 0.094 |
| Summer | 0.178 | 0.302 |

The From the Table 6.2-2, it can be seen that there is not a strong link between the length of a glacier and the mass balance of a glacier. This shows the impact of the "mechanical" phenomena that occur in a glacier that are not related to the climatic conditions. So in order to assess the glacier status, reference should be made on its mass not on its length.

## 6.3 CALCULATION OF THE MASS BALANCE FOR OLDEN: HYDROLOGICAL METHOD

### 6.3.1 Hydrological method

The equation to estimate the glacier mass balance is:

$$\mathrm{B} = \mathrm{P} - \mathrm{R} - \mathrm{E} \tag{35}$$

With:

- B: annual net mass balance [m.w.e.],
- P: precipitation over the basin: sum of
  - Rain [m],
  - Snow [m.w.e.],
- R: runoff from the basin [m]
- E: evaporation of the basin [m]

*Calculation of Olden glaciers mass balance*

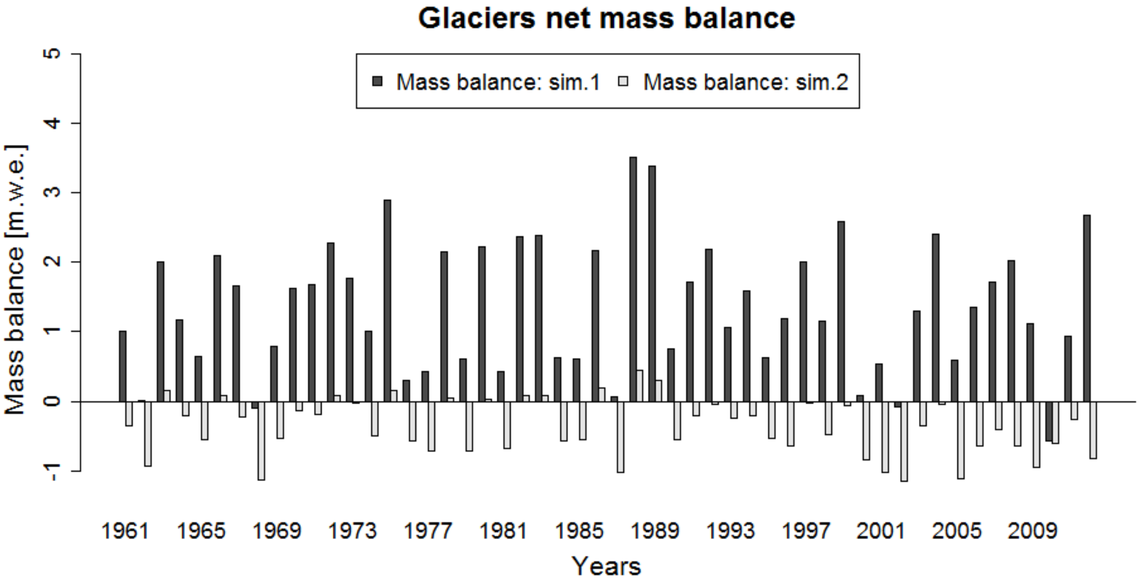


**Figure 6.3-1: Glacier mass balance – method 1**

The glaciers in Olden have a very different mass balance if the calibration 1 or 2 is used.

With the calibration 1, glaciers gained mass almost every year while with the calibration 2 their mass balance is negative most of the years. The difference in the mass balance comes from the difference in precipitation observed in the comparison of the two simulations data: the simulation 1 which estimates a lot of precipitation gives a positive mass balance while the simulation which has low precipitation gives a negative mass balance.

**Table 6.3-1: Correlation between glacier mass balances**

| Simulation | Nigardsbreen | Ålfotsbreen |
|---|---|---|
| Olden: sim.1 | 0.766 | 0.724 |
| Olden: sim.2 | 0.823 | 0.833 |

Both simulations seem to give a very extreme glacier mass balance. However, when compared with the glacier mass balances from the region, the patterns appear be consistent. The tendency obtained from the simulation 2 is closer to the ones from the other glaciers though, which means that the calibration 2 should be used for the evaluation of the mass balance if similar behaviour for all the glaciers is expected.

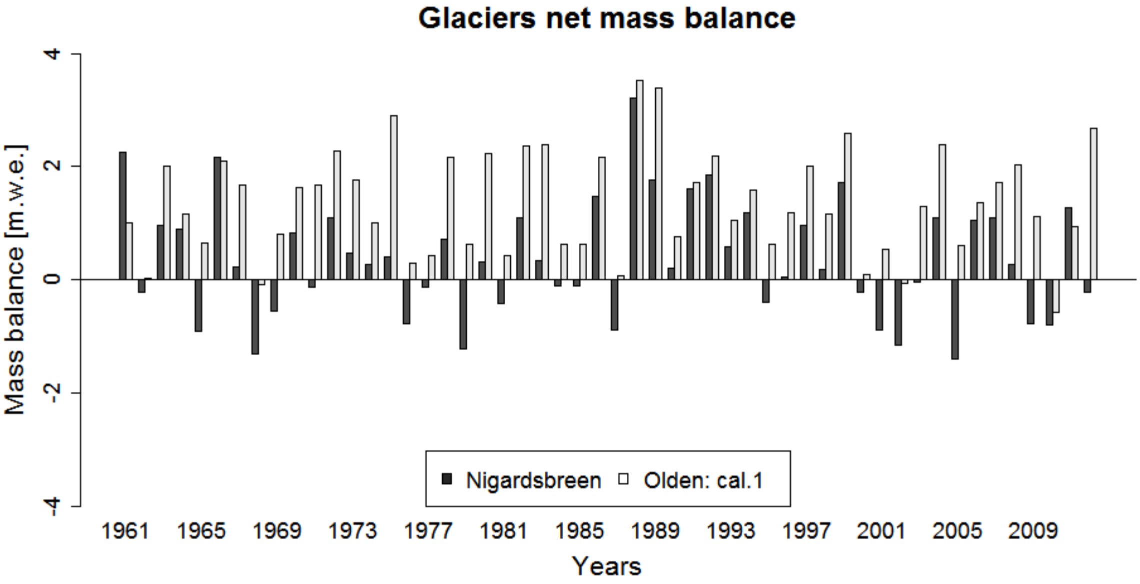


**Figure 6.3-2: Comparison between mass balance in Nigardsbreen and Olden - cal.1**

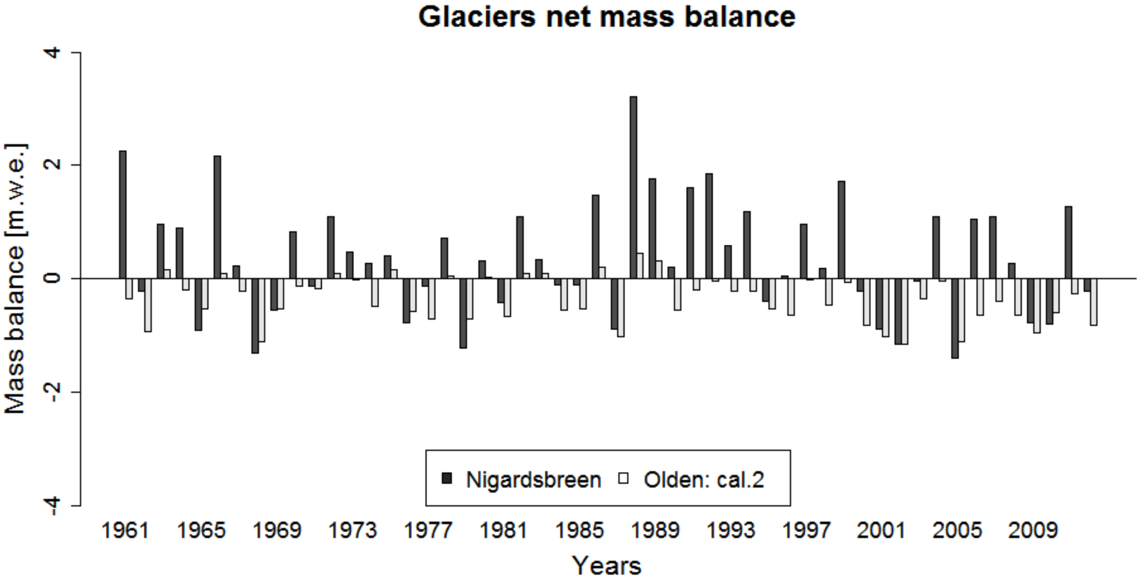


**Figure 6.3-3: Comparison between mass balance in Nigardsbreen and Olden - cal.1**

Assuming that the mass balance of the Olden glacier must follow the trends from Nigardsbreen mass balance, the calibration 1 and 2 seem to be complementary. The first one managed somehow to estimate the positive mass balance while the second one managed to estimate the negative mas balance.

Olden is on the west side of the Jostedalsbreen like Ålfotsbreen, while Nigardsbreen is on the other side. So it was foreseen that the Olden glaciers behaviour would be closer the Ålfotsbreen behaviour because it is subject to the same conditions. However, the glacier mass balance is closer to Nigardsbreen when the calibration 1 is used.

### 6.3.2 Comparison between ice gain and ice melt.

The equation used in the hydrological method considers the entire catchment while it should only take into account the glacier part in the catchment because water is not only stored in the glacier but also in the soil moisture zone, the upper and the lower zones.

So another equation was used to calculate the glacier mass balance to evaluate the impact of the other zones storage:

$$B = S - I \tag{36}$$

With:

- B: annual net mass balance [m.w.e.],
- S: snow at the end of the year that is turned intto ice in the HBV-model [m.w.e.],
- E: ice melt from the glacier [m.w.e.].

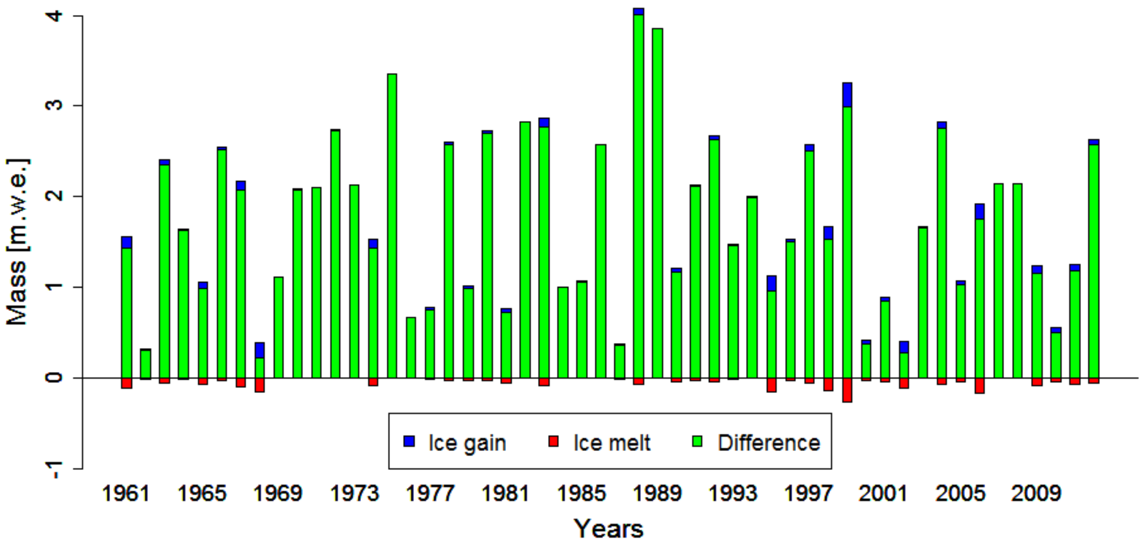


**Figure 6.3-4: Glacier mass balance – method 2 – cal.1**

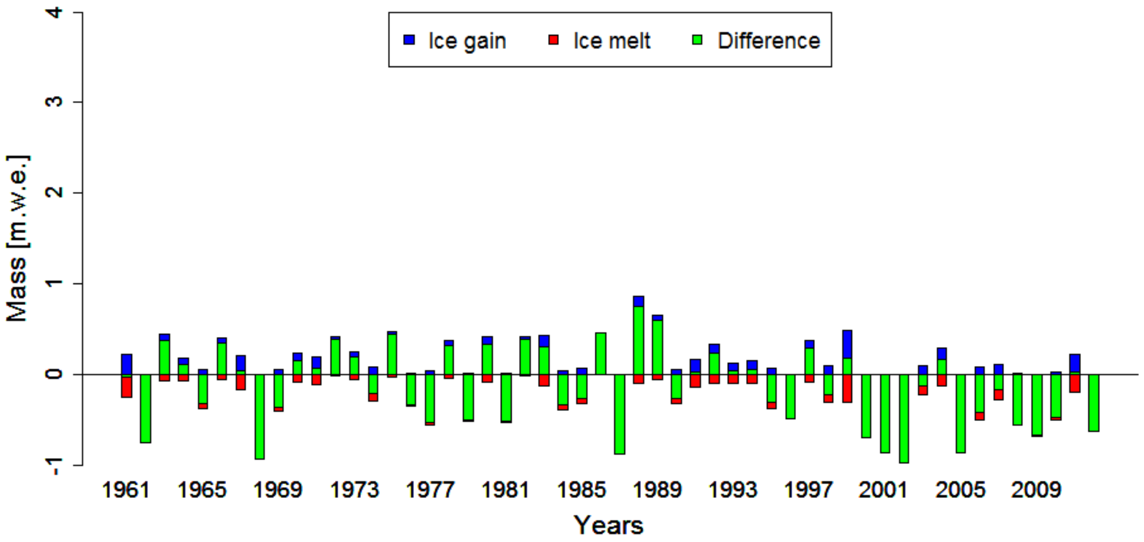


**Figure 6.3-5: Glacier mass balance – method 2 – cal.2**

**Table 6.3-2: Correlation between glacier mass balances**

| Method | Ice difference: sim.1 | Ice difference: sim.2 |
|---|---|---|
| Balance: sim.1 | 0.988 | |
| Balance: sim.2 | | 0.995 |

From the Figures 6.3-2, 6.3-3 and the Table 6.3-2, the two difference methods very similar results

But the ice difference gives higher mass balance than the hydrological method applied on the entire catchment.

**Table 6.3-3: Difference of the mass balances**

| Mass [m.w.e.] | Hydrological balance | Ice difference | Difference between the 2 methods |
|---|---|---|---|
| Simulation 1 | 1.361 | 1.740 | 0.38 |
| Simulation 2 | -0.377 | -0.144 | 0.23 |

The difference could be explained by the storage of this other zones of the catchment.

Thereafter, only the hydrological method will be used.

## 6.4 CALCULATION OF THE WATER EQUIVALENT IN THE GLACIER

The Breatlas (1988) provides estimated values of the glacier:

**Table 6.4-1: Estimated ice volume in glaciers (Østrem et al., 1988)**

| Reference river basin | Olden | Loen | Stryn |
|---|---|---|---|
| Total glacier area [km²] | 77.89 | 81.74 | 70.29 |
| Mean glacier elevation [m] | 1433 | 1507 | 1457 |
| Estimated ice volume [km$^3$] | 5.65 | 5.88 | 5.42 |
| Estimated ice thickness [m] | 72.54 | 71.94 | 77.11 |

The values are corrected to match the values that have been used in the HBV-model.

**Table 6.4-2: Estimated ice volume in glaciers**

| Reference river basin | Olden | Loen | Stryn |
|---|---|---|---|
| Drainage area [km²] | 202.12 | 234.60 | 488.19 |
| Total glacier area [%] | 40.2 | 37.0 | 17.6 |
| Total glacier area [km²] | 81.25 | 86.80 | 85.92 |
| Estimated ice volume [km$^3$] | 5.89 | 6.24 | 6.63 |
| Estimated ice thickness [m] | 72.54 | 71.94 | 77.11 |

To estimate the water volume, the density of the ice glacier is taken equal to 0.85 g/cm$^3$, (850 kg/m$^3$).

**Table 6.4-3: Estimated water volume in glaciers**

| Reference river basin | Olden | Loen | Stryn |
|---|---|---|---|
| Estimated ice volume [km$^3$] | 5.89 | 6.24 | 6.63 |
| Estimated ice thickness [m] | 72.54 | 71.94 | 77.11 |
| Estimated water volume equivalent [km$^3$] | 5.01 | 5.31 | 5.63 |
| Estimated thickness in meter water equivalent [m.w.e] | 61.66 | 61.15 | 65.54 |

# 7 RUNOFF AND GLACIERS VOLUME FORECAST

Overall the temperature on the earth increases everywhere. This phenomenon affects also Norway. This augmentation of temperature will result in modification of the water balance in the future.

The climate change is likely to be the only modification that the catchments will experience. The land use will probably stay the same as the area is protected.

## 7.1 FORECASTED CLIMATE CHANGE WITH HADLEY SCENARIO

The data for temperature and precipitation changes come from the website NoSerC.met.no which provides data for the two scenarios A2 and B2.

**Table 7.1-1: Climate change data**

| Scenario | Climate model | Data | Period |
|---|---|---|---|
| A2 | HADAm3 | Daily temperature [°C] and precipitation [mm] | 2071-2100 |
| B2 | HADAm3 | Daily temperature [°C] and precipitation [mm] | 2071-2100 |
| Control | HADAm3 | Daily temperature [°C] and precipitation [mm] | 1961-1990 |

The scenarios are presented by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Emissions Scenarios (SRES) published in 2000. The scenarios 2 are based on a heterogeneous world: a regionalisation of the change is calculated. The scenario A2 is more focused on the economy and estimates the change considering a “regionally oriented economic development” while the scenario B2 concentrates on the environment and considers “local environment sustainability”.

The scenario A2 forecasts higher temperatures than the scenario B2.

See Appendix T: Climate change map

### 7.1.1 Scenarios

**Table 7.1-2 : Climate change - scenario A2**

| Parameter | Precipitation [mm] | | | Temperature [°C] | | |
|---|---|---|---|---|---|---|
| | 1961-1990 | 2071-2100 | change [%] | 1961-1990 | 2071-2100 | change [%] |
| January | 118 | 120 | 1.90% | -1.17 | 1.22 | 2.39 |
| February | 92 | 86 | -6.20% | -1.09 | 0.87 | 1.96 |
| March | 99 | 89 | -9.40% | 0.78 | 3.23 | 2.45 |
| April | 53 | 57 | 7.40% | 3.61 | 6.75 | 3.13 |
| May | 41 | 48 | 16.50% | 9.23 | 13.43 | 4.2 |
| June | 53 | 50 | -5.80% | 12.38 | 14.81 | 2.43 |
| July | 74 | 77 | 3.60% | 13.45 | 15.68 | 2.23 |
| August | 73 | 69 | -5.40% | 12.92 | 15.67 | 2.75 |
| September | 130 | 111 | -14.10% | 9.32 | 13.68 | 4.36 |
| October | 136 | 142 | 4.10% | 6.49 | 10.46 | 3.97 |
| November | 118 | 124 | 5.10% | 1.99 | 6.75 | 4.76 |
| December | 151 | 158 | 4.90% | -0.3 | 3.23 | 3.53 |
| Year | 1136 | 1130 | 0.22% | 5.63 | 8.82 | 3.18 |

**Table 7.1-3: Climate change - scenario B2**

| Parameter | Precipitation [mm] | | | Temperature [°C] | | |
|---|---|---|---|---|---|---|
| | 1961-1990 | 2071-2100 | change [%] | 1961-1990 | 2071-2100 | change [%] |
| January | 117.6 | 120.4 | 2.30% | -1.17 | 1.05 | 2.22 |
| February | 91.8 | 92.7 | 0.90% | -1.09 | 0.43 | 1.52 |
| March | 98.5 | 67.9 | -31.10% | 0.78 | 2.91 | 2.13 |
| April | 52.9 | 52 | -1.70% | 3.61 | 6.51 | 2.89 |
| May | 41.1 | 50.6 | 22.90% | 9.23 | 12.35 | 3.13 |
| June | 52.6 | 61.4 | 16.70% | 12.38 | 13.38 | 1 |
| July | 73.9 | 82.6 | 11.70% | 13.45 | 14.67 | 1.22 |
| August | 73.2 | 63.5 | -13.30% | 12.92 | 15.48 | 2.56 |
| September | 129.8 | 121.2 | -6.60% | 9.32 | 12.44 | 3.12 |
| October | 135.9 | 159.2 | 17.10% | 6.49 | 10.2 | 3.71 |
| November | 117.9 | 138 | 17.10% | 1.99 | 5.92 | 3.93 |
| December | 150.6 | 160 | 6.30% | -0.3 | 2.36 | 2.66 |
| Year | 1136 | 1170 | 3.53% | 5.63 | 8.14 | 2.51 |

### 7.1.2 Forecasted values

The scenarios value come from the climate model HADAm3. They were downscaled to the station Oppstryn. So the changes are kept and applied on the original data.

A linear change is assumed between 1961-1990 and 2071-2100 to get results for a continuous period that covers the years 1961 to 2116.

**Table 7.1-4: Forecasted values used - scenario A2**

| Period | From 2013 | | | From 2065 | | |
|---|---|---|---|---|---|---|
| Climate change parameter | Temp. | Precip. | Evap. | Temp. | Precip. | Evap. |
| Months | °C | % | Mm | °C | % | mm |
| January | 0.98 | 0.9 | 0.03 | 2.39 | 1.9 | 0.12 |
| February | 1.22 | -3.1 | 0.00 | 1.96 | -6.2 | 0.11 |
| March | 1.57 | -4.7 | 0.17 | 2.45 | -9.4 | 0.26 |
| April | 2.10 | 3.7 | 0.17 | 3.13 | 7.4 | 0.30 |
| May | 1.22 | 8.2 | 0.27 | 4.20 | 16.5 | 0.54 |
| June | 1.12 | -2.9 | 0.06 | 2.43 | -5.8 | 0.14 |
| July | 1.38 | 1.8 | 0.04 | 2.23 | 3.6 | 0.10 |
| August | 2.18 | -2.7 | 0.09 | 2.75 | -5.4 | 0.19 |
| September | 1.98 | -7.1 | 0.21 | 4.36 | -14.1 | 0.42 |
| October | 2.38 | 2.1 | 0.14 | 3.97 | 4.1 | 0.28 |
| November | 1.77 | 2.6 | 0.19 | 4.76 | 5.1 | 0.34 |
| December | 0.00 | 2.4 | 0.15 | 3.53 | 4.9 | 0.24 |
| Year | 1.49 | 0.107 | 46.0 | 3.18 | 0.213 | 92.3 |

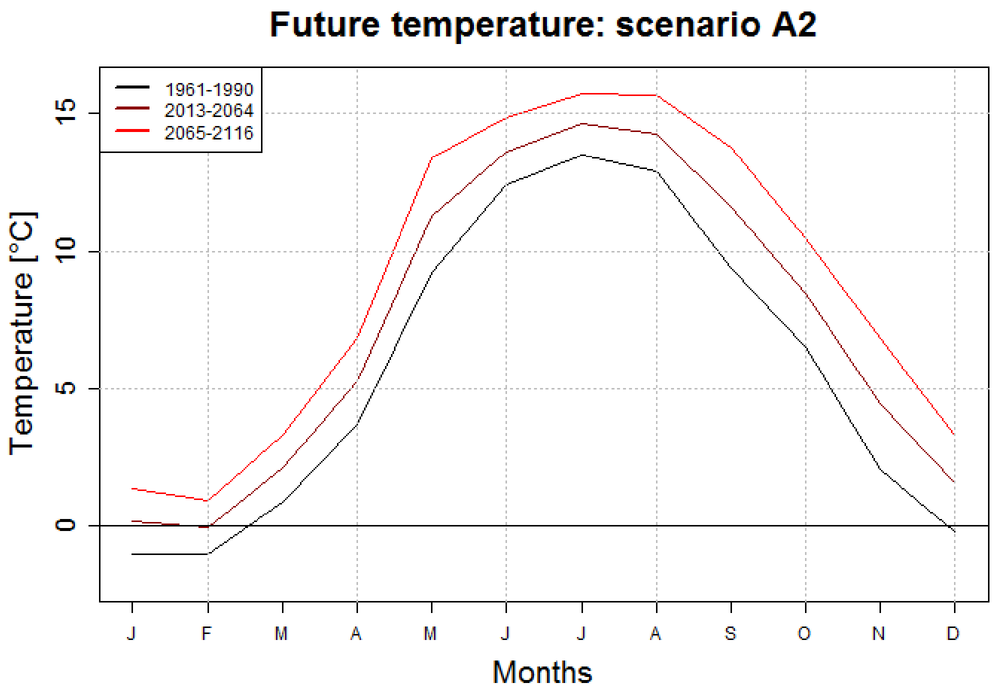


**Figure 7.1-1: Future temperature - scenario A2**

**Table 7.1-5: Forecasted values used - scenario B2**

| Period | From 2013 | | | From 2065 | | |
|---|---|---|---|---|---|---|
| Climate change parameter | Temp. | Precip. | Evap. | Temp. | Precip. | Evap. |
| Months | °C | % | Mm | °C | % | mm |
| January | 1.11 | 1.2 | 0.02 | 2.22 | 2.3 | 0.12 |
| February | 0.76 | 0.5 | 0.00 | 1.52 | 0.9 | 0.07 |
| March | 1.07 | -15.5 | 0.16 | 2.13 | -31.1 | 0.27 |
| April | 1.45 | -0.9 | 0.19 | 2.89 | -1.7 | 0.34 |
| May | 1.56 | 11.5 | 0.19 | 3.13 | 22.9 | 0.38 |
| June | 0.50 | 8.4 | -0.07 | 1.00 | 16.7 | -0.14 |
| July | 0.61 | 5.9 | -0.03 | 1.22 | 11.7 | -0.06 |
| August | 1.28 | -6.7 | 0.12 | 2.56 | -13.3 | 0.24 |
| September | 1.56 | -3.3 | 0.14 | 3.12 | -6.6 | 0.28 |
| October | 1.86 | 8.6 | 0.16 | 3.71 | 17.1 | 0.31 |
| November | 1.97 | 8.5 | 0.17 | 3.93 | 17.1 | 0.30 |
| December | 1.33 | 3.2 | 0.12 | 2.66 | 6.3 | 0.20 |
| Year | 1.25 | 1.766 | 35.4 | 2.51 | 3.534 | 70.4 |

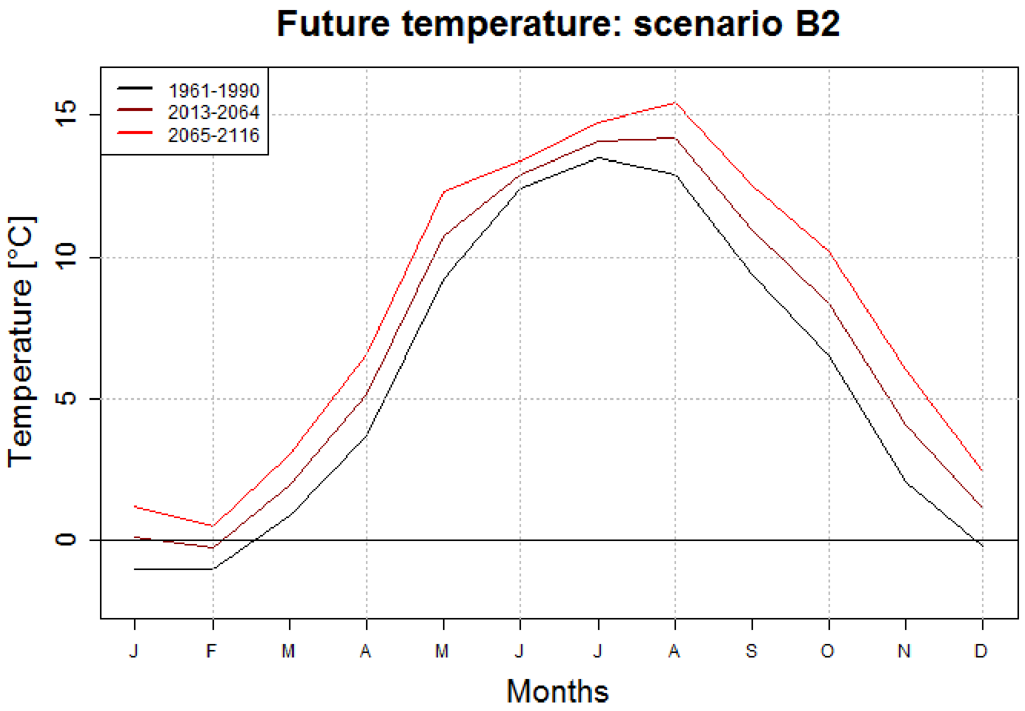


**Figure 7.1-2: Future temperature - scenario B2**

**Table 7.1-6: Comparison between scenarios A and B**

| Period | From 2065 | | | From 2013 | | |
|---|---|---|---|---|---|---|
| Climate change parameter | Temp. | Precip. | Evap. | Temp. | Precip. | Evap. |
| Scenario | °C | % | mm | °C | % | mm |
| Scenario A2 | 1.49 | 0.107 | 46.0 | 3.18 | 0.213 | 92.3 |
| Scenario B2 | 1.25 | 1.766 | 35.4 | 2.51 | 3.534 | 70.4 |

A said before, the scenario A2 foresees higher temperatures than the scenario B2, which induces more evaporation.

See Appendix U: Climate change evaporation

## 7.2 RUNOFF FORECAST

### 7.2.1 Calibration 1

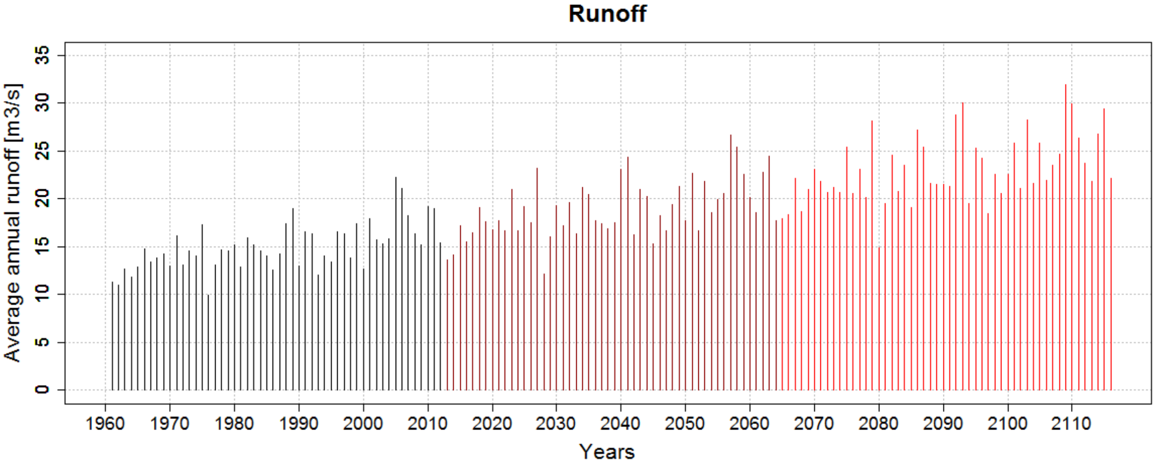


**Figure 7.2-1: Forecast - cal.1 - scenario A – runoff**

**Table 7.2-1: Forecast - cal.1 - scenario A2 - runoff differences**

| Period | Simulated runoff | | Simulated areal precipitation | |
|---|---|---|---|---|
| | [m$^3$/s] | Change [%] | [mm] | Change [%] |
| 1961-1990 | 14.01 | | 4037 | |
| 1991-2020 | 16.44 | 17.4% | 3983 | -1.3% |
| 2021-2050 | 18.58 | 32.7% | 4156 | 3.0% |
| 2051-2080 | 21.25 | 51.7% | 3886 | -3.7% |
| 2071-2010 | 22.48 | 60.5% | 4015 | -0.5% |
| 2080-2110 | 23.75 | 69.5% | 4103 | 1.6% |

The scenario A2 implies an increase of the runoff of 60.5% between 1961-1990 and 2071-2010. This is an extremely large growth which must be explained by a diminution of the glaciers mass, hence an increase of the glacier runoff, because the precipitation did not rise.

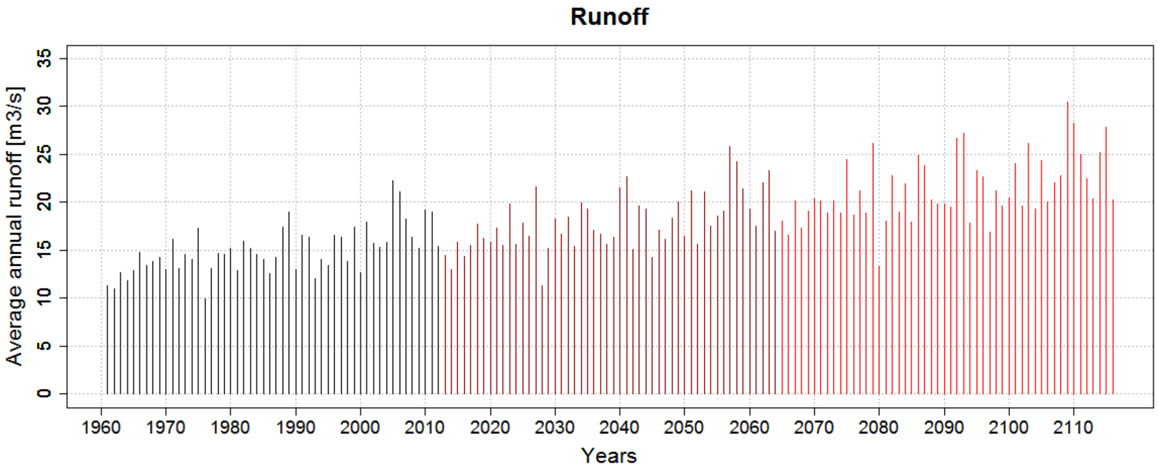


Figure 7.2-2: Forecast - cal.1 - scenario B2 – runoff

Table 7.2-2: Forecast - cal.1 - scenario B - runoff differences

| Period | Simulated runoff | | Simulated areal precipitation | |
|---|---|---|---|---|
| | [m$^3$/s] | Change [%] | [mm] | Change [%] |
| 1961-1990 | 14.01 | | 4036.6 | |
| 1991-2020 | 16.12 | 15.1% | 3998.8 | -0.9% |
| 2021-2050 | 17.49 | 24.8% | 4225.5 | 4.7% |
| 2051-2080 | 19.85 | 41.7% | 4010.3 | -0.7% |
| 2071-2010 | 20.80 | 48.5% | 4185.9 | 3.7% |
| 2080-2110 | 22.01 | 57.1% | 4271.9 | 5.8% |

The scenario B2 implies a smaller increase of the runoff of 48.5% between 1961-1990 and 2071-2010 against 60.5% for the scenario A2. This is still an extremely large growth which cannot be explained only by the gain of precipitation but must be mainly due to a great diminution of the glaciers and the generation of ice melt runoff.

### 7.2.2 Calibration 2

**Table 7.2-3: Forecast - cal.2 - scenario A2 - runoff differences**

| Period | Simulated runoff | | Simulated areal precipitation | |
|---|---|---|---|---|
| | [m$^3$/s] | Change [%] | [mm] | Change [%] |
| 1961-1990 | 13.60 | | 2274.71 | |
| 1991-2020 | 15.63 | 14.9% | 2248.08 | -1.2% |
| 2021-2050 | 17.33 | 27.4% | 2345.33 | 3.1% |
| 2051-2080 | 19.78 | 45.4% | 2193.58 | -3.6% |
| 2071-2010 | 20.87 | 53.5% | 2267.38 | -0.3% |
| 2080-2110 | 22.09 | 62.4% | 2316.68 | 1.8% |

**Table 7.2-4: Forecast - cal.2 - scenario B2 - runoff differences**

| Period | Simulated runoff | | Simulated areal precipitation | |
|---|---|---|---|---|
| | [m$^3$/s] | Change [%] | [mm] | Change [%] |
| 1961-1990 | 13.60 | | 2274.7 | |
| 1991-2020 | 15.35 | 12.8% | 2257.4 | -0.8% |
| 2021-2050 | 16.34 | 20.1% | 2386.0 | 4.9% |
| 2051-2080 | 18.39 | 35.2% | 2263.2 | -0.5% |
| 2071-2010 | 19.13 | 40.7% | 2362.3 | 3.8% |
| 2080-2110 | 20.31 | 49.3% | 2411.2 | 6.0% |

In the same way of the calibration 1 did, the calibration 2 shows higher runoff expectations for the scenario A2: 53.5%, whereas the scenario foresee an increase of only 40.7%. The difference between the two scenarios is bigger with the calibration 2.

## 7.3 GLACIER MASS BALANCE FORECAST: ESTIMATION

### 7.3.1 Correlation glacier mass balance and parameters

The glacier mass balance is difficult to measure and both calibrations generate extreme scenarios for the mass balance.

So the correlations between measured mass balances in the region and parameters for Olden catchments have been calculated for both calibrations.

**Table 7.3-1: Olden: Pearson's correlation between glacier states and parameters**

| | | Mass balance | | | | | | | Length |
|---|---|---|---|---|---|---|---|---|---|
| Glacier | | Nigardsbreen | | | Ålfotbreen | | | Olden | Briksdalsbreen |
| Period | | y. | w. | s. | y. | w. | s. | y. | y. |
| Temp. | y. | 0.03 | 0.21 | -0.17 | -0.01 | 0.23 | -0.34 | -0.06 | -0.11 |
| | w. | 0.41 | 0.42 | 0.27 | 0.31 | 0.43 | -0.03 | 0.19 | 0.03 |
| | s. | **-0.65** | -0.31 | **-0.79** | -0.58 | -0.30 | **-0.65** | -0.45 | -0.27 |
| Precip. | y. | 0.68 | **0.76** | 0.39 | **0.70** | **0.76** | 0.25 | **0.80** | 0.01 |
| | w. | 0.62 | **0.75** | 0.29 | 0.69 | **0.78** | 0.20 | 0.76 | 0.03 |
| | s. | 0.38 | 0.21 | 0.44 | 0.20 | 0.09 | 0.24 | 0.33 | -0.05 |
| Areal temp. | | -0.07 | 0.13 | -0.24 | -0.14 | 0.14 | -0.44 | 0.02 | -0.02 |
| Areal precip. | | 0.65 | **0.74** | 0.36 | 0.65 | **0.72** | 0.21 | **0.94** | 0.07 |
| Snow | z. 1 | NA | NA | NA | NA | NA | NA | NA | NA |
| State | z. 2 | NA | NA | NA | NA | NA | NA | NA | NA |
| | z. 3 | 0.39 | 0.39 | 0.28 | 0.22 | 0.21 | 0.12 | 0.33 | 0.02 |
| | z. 4 | 0.63 | 0.66 | 0.39 | 0.60 | 0.62 | 0.26 | 0.76 | 0.10 |
| | z. 5 | 0.81 | 0.80 | 0.57 | 0.80 | 0.78 | 0.41 | 0.84 | 0.17 |
| | z. 6 | **0.82** | 0.78 | 0.61 | **0.84** | 0.79 | 0.46 | 0.85 | 0.13 |
| | z. 7 | 0.80 | 0.76 | 0.59 | **0.84** | 0.78 | 0.47 | 0.86 | 0.10 |
| | z. 8 | 0.79 | 0.76 | 0.57 | 0.82 | 0.78 | 0.45 | 0.86 | 0.09 |
| | z. 9 | 0.77 | 0.75 | 0.55 | 0.80 | 0.77 | 0.43 | 0.86 | 0.07 |
| | z.10 | 0.76 | 0.75 | 0.54 | 0.79 | 0.76 | 0.41 | 0.86 | 0.04 |
| | Catch. | 0.80 | 0.77 | 0.57 | 0.82 | 0.78 | 0.44 | **0.87** | 0.10 |

**Table 7.3-2: Olden calibration 2: Pearson’s correlation between glacier states and parameters**

| | | mass balance | | | | | | | Length |
|---|---|---|---|---|---|---|---|---|---|
| Correlation | | Nigardsbreen | | | Ålfotbreen | | | Olden | Briksdalsbreen |
| Period | | y. | w. | s. | y. | w. | s. | y. | y. |
| Temp. | y. | 0.03 | 0.21 | -0.17 | -0.01 | 0.23 | -0.34 | -0.24 | -0.11 |
| | w. | 0.41 | 0.42 | 0.27 | 0.31 | 0.43 | -0.03 | 0.16 | 0.03 |
| | s. | -0.65 | -0.31 | **-0.79** | -0.58 | -0.30 | **-0.65** | **-0.75** | -0.27 |
| Precip. | y. | 0.68 | **0.76** | 0.39 | **0.70** | **0.76** | 0.25 | **0.76** | 0.01 |
| | w. | 0.62 | **0.75** | 0.29 | 0.69 | **0.78** | 0.20 | **0.70** | 0.03 |
| | s. | 0.38 | 0.21 | 0.44 | 0.20 | 0.09 | 0.24 | 0.39 | -0.05 |
| Areal temp. | | -0.068 | 0.10 | 0.27 | -0.11 | 0.04 | 0.29 | -0.31 | -0.19 |
| Areal precip. | | 0.650 | 0.68 | **0.77** | 0.39 | **0.71** | **0.77** | 0.26 | **0.77** |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Snow | z. 1 | NA | NA | NA | NA | NA | NA | NA | NA |
| State | z. 2 | NA | NA | NA | NA | NA | NA | NA | NA |
| | z. 3 | NA | NA | NA | NA | NA | NA | NA | NA |
| | z. 4 | 0.08 | -0.06 | 0.20 | 0.02 | -0.14 | 0.21 | 0.19 | 0.00 |
| | z. 5 | 0.09 | -0.04 | 0.20 | 0.03 | -0.13 | 0.22 | 0.18 | 0.00 |
| | z. 6 | 0.41 | 0.38 | 0.31 | 0.22 | 0.17 | 0.17 | 0.31 | 0.02 |
| | z. 7 | 0.56 | 0.54 | 0.40 | 0.43 | 0.42 | 0.22 | 0.53 | 0.04 |
| | z. 8 | 0.68 | 0.64 | 0.50 | 0.56 | 0.52 | 0.33 | 0.76 | 0.12 |
| | z. 9 | 0.74 | 0.67 | 0.58 | 0.67 | 0.59 | 0.42 | 0.87 | 0.15 |
| | z.10 | **0.79** | 0.69 | 0.64 | **0.77** | 0.67 | 0.50 | **0.95** | 0.20 |
| | Catch. | 0.77 | 0.70 | 0.61 | 0.71 | 0.63 | 0.44 | 0.90 | 0.16 |

So there is a good correlation between:

- The winter mass balance and the winter precipitation,
- The summer mass balance and the summer temperature,
- The annual mass balance and the winter and annual precipitation.

However, the best correlation appears with the snow states at the end of the year because the snow storage is a result of the precipitation and temperature during the year.

### 7.3.2 Estimation of glacier mass balance: Ålfotsbreen and Nigardsbreen

A snow storage of zero means that there has been glacier ice melt but it is no apparent on the final states of the simulation. So unlike the first simulation, it is much more difficult to predict the glacier mass balance with the calibration 2 because there is a “limitation” in the glacier mass balance which corresponds to no snow storage. In the first one, a certain amount of snow would signify a glacier mass balance of 0 and less that this value would means a negative mass balance.

It is not possible to rely only on the following estimations, but it gives a general overview of the potential tendency of the glacier behaviour.

#### 7.3.2.1 Ålfotbreen

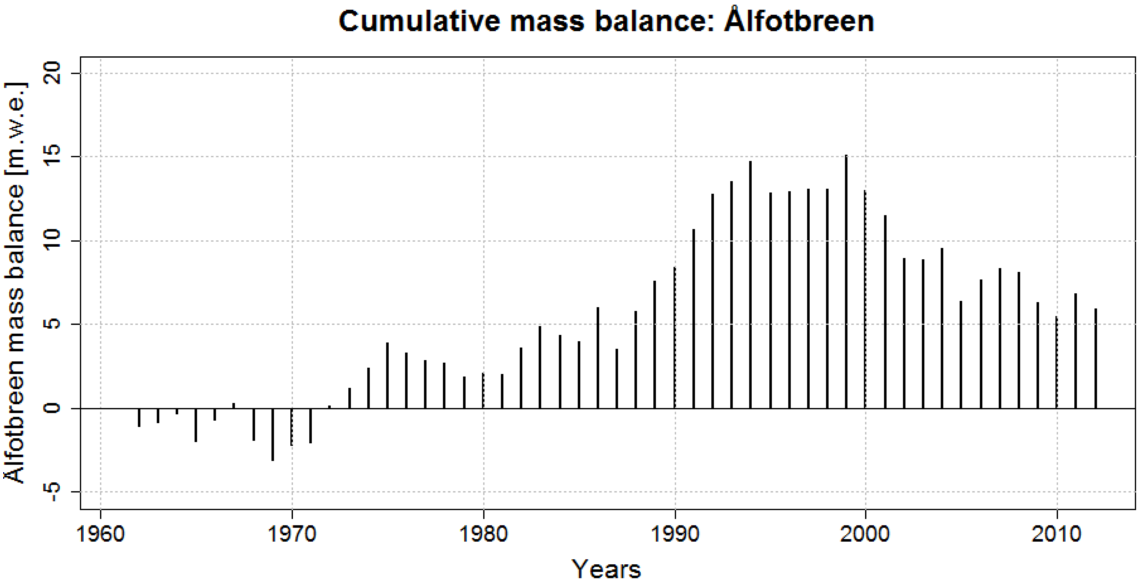


**Figure 7.3-1: Cumulative mass balance for Ålfotbreen**

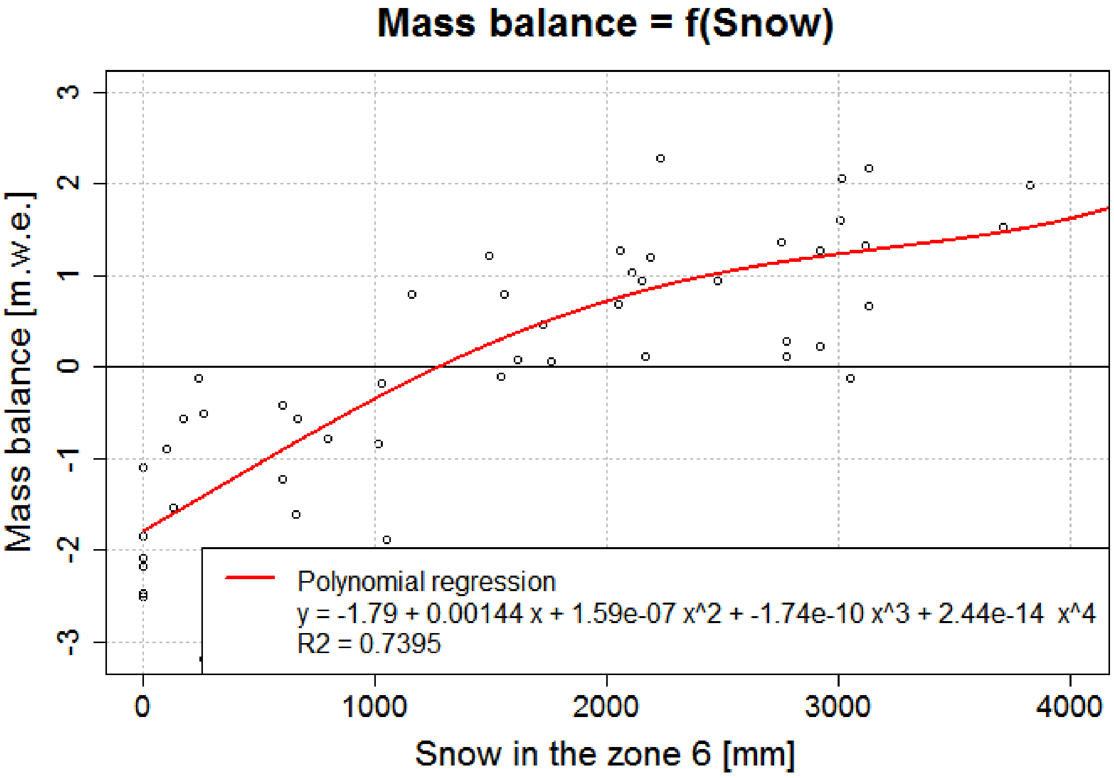


**Figure 7.3-2: Polynomial regression between mass balance in Ålfotbreen and snow storage in the zone 6 of Olden**

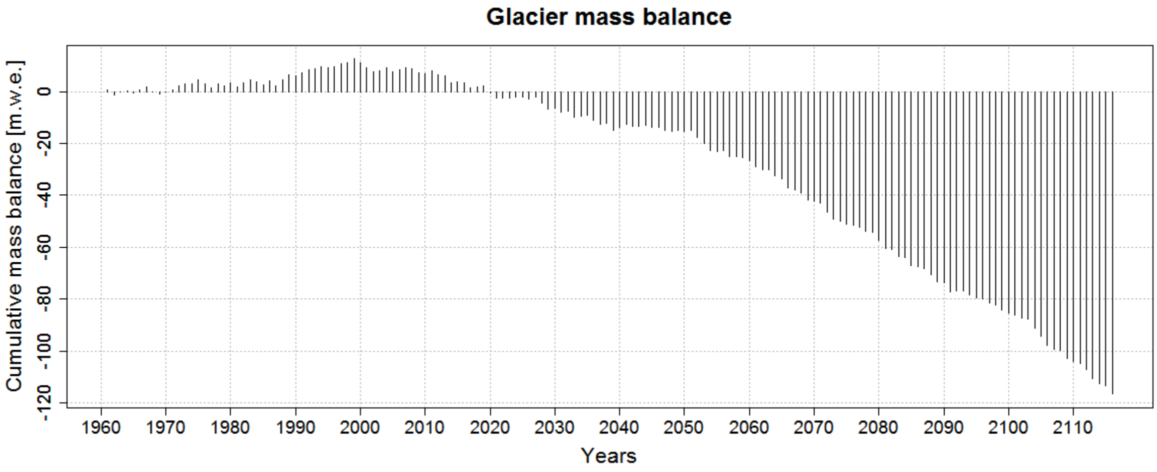


**Figure 7.3-3: Scenario A2 - cumulative mass balance for Ålfotbreen**

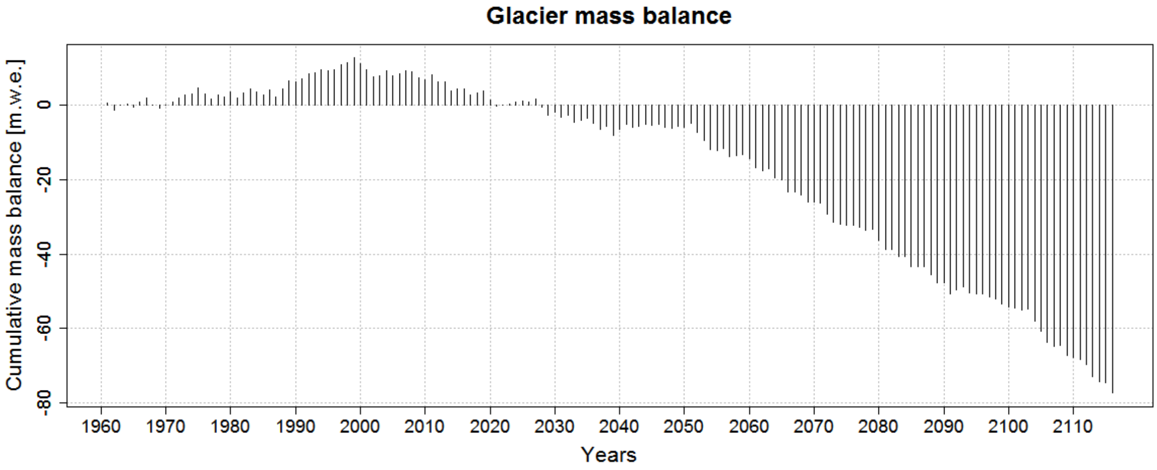


**Figure 7.3-4: Scenario B2 - cumulative mass balance for Ålfotbreen**

In the scenario A2, Ålfotbreen reaches the same mass it had in 1961 in 2020 and then sees its mass decrease. In the scenario B2, the glacier loses the mass it gained from 1961, eight year later in 2028. The glacier loses its mass quickly with the scenario A2 than the scenario B2: difference of 40 m.

### 7.3.2.2 Nigardsbreen

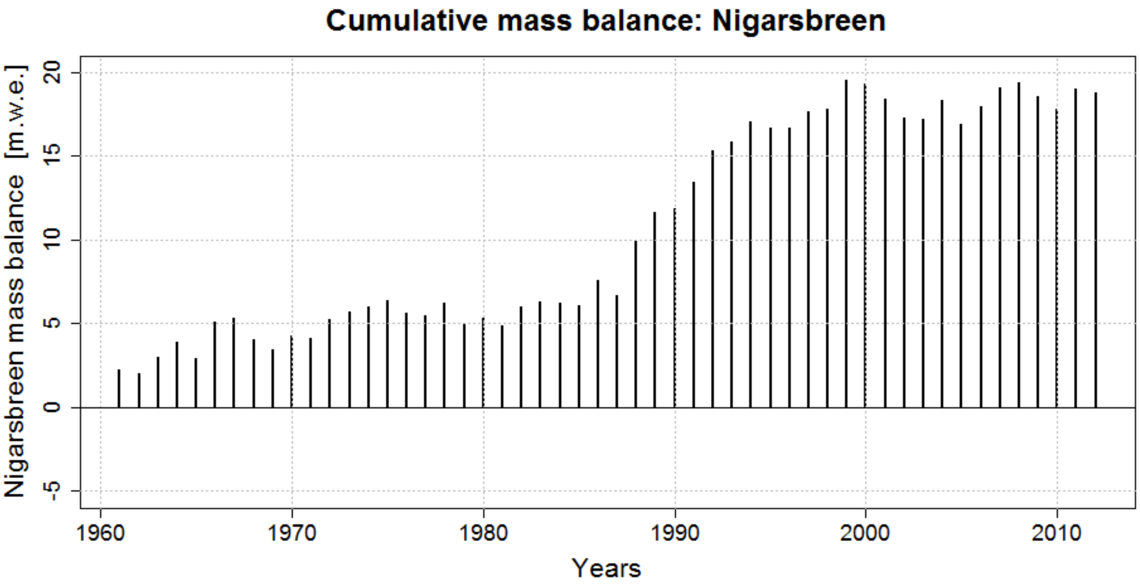


Figure 7.3-5: Cumulative mass balance for Nigardsbreen

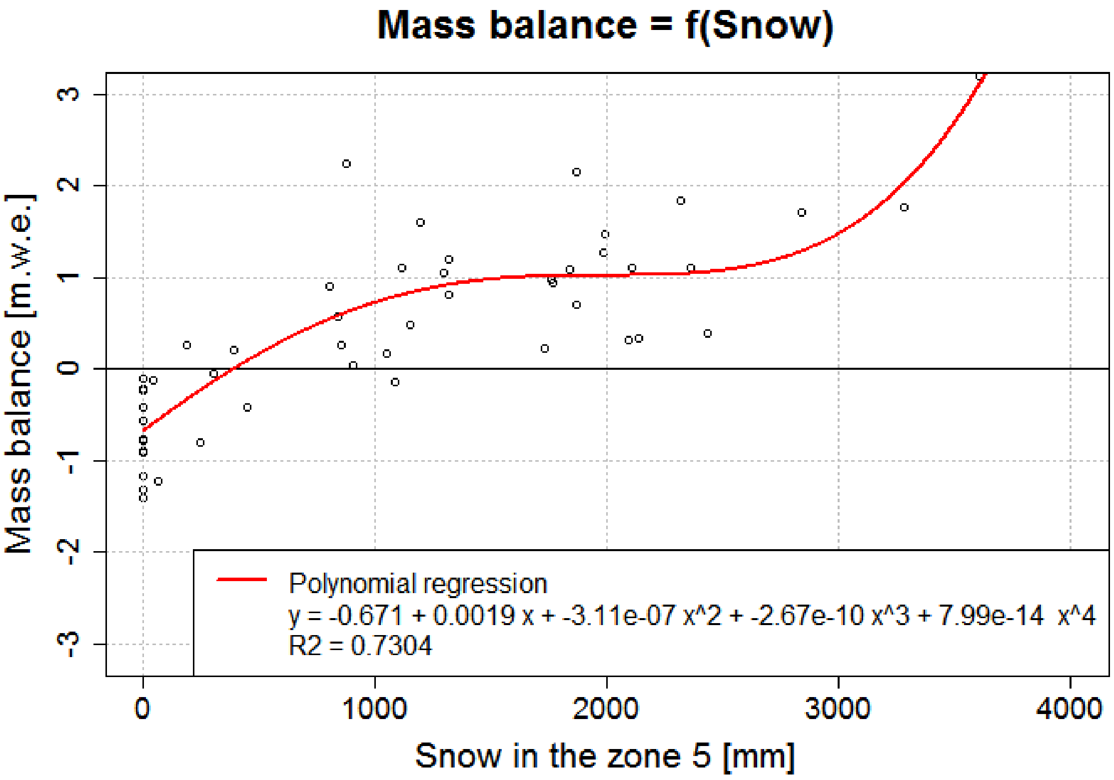


Figure 7.3-6: Polynomial regression between mass balance in Nigardsbreen and snow storage in the zone 5

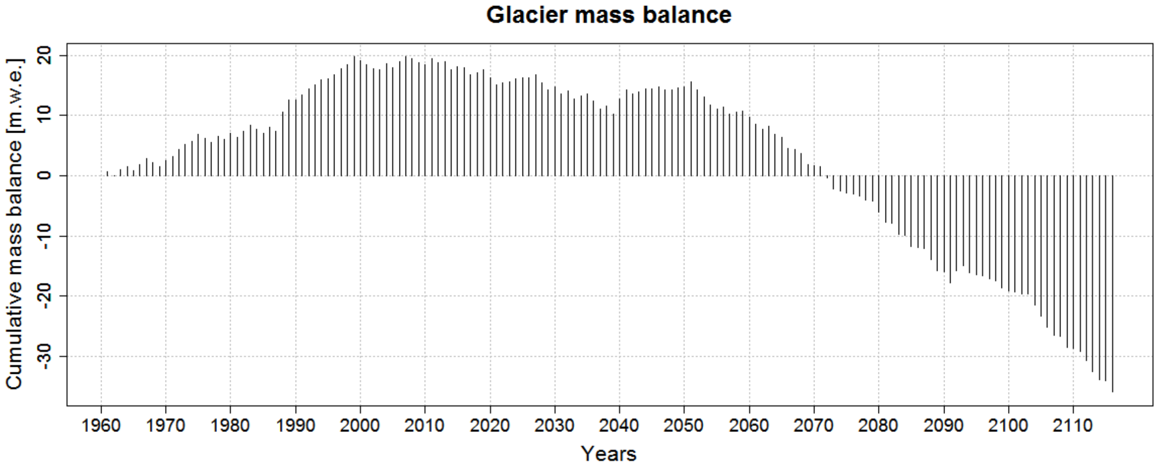


**Figure 7.3-7: Scenario A2 - cumulative mass balance for Nigardsbreen**

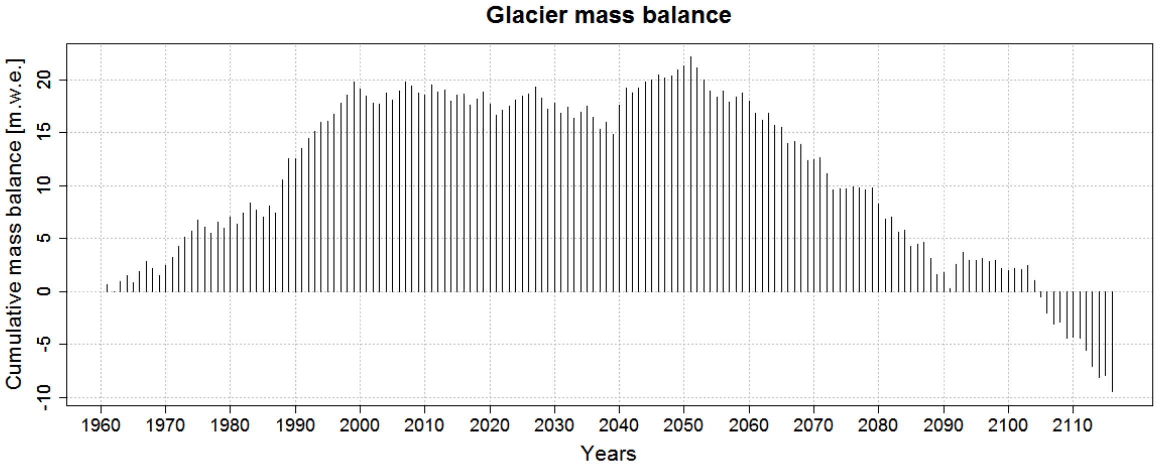


**Figure 7.3-8: Scenario B2 – cumulative mass balance for Nigardsbreen**

Nigardsbreen follows the same trends than Ålfotbreen for both scenario but negative mass balance occurs much later than for Ålfotbreen. If the beginning of the mass loss (compared to 1961) start with only eight years of difference for the two scenarios in Ålfotsbreen, the diference is much bigger for Nigardsbreen: thirty years. However the difference between the two final states of the glacier volume is only 20 m.

#### *7.3.2.3 Conclusion*

The scenario A2 is the worst scenario for the conservation of glaciers. It forecasts a quicker and heavier loss in the glassier mass balance either on the coast or inland. However the inland glacier appeared to be in a safer place.

## 7.4 GLACIER MASS BALANCE FORECAST: CALCULATION

### 7.4.1 Calibration 1

#### *7.4.1.1 Scenario A*

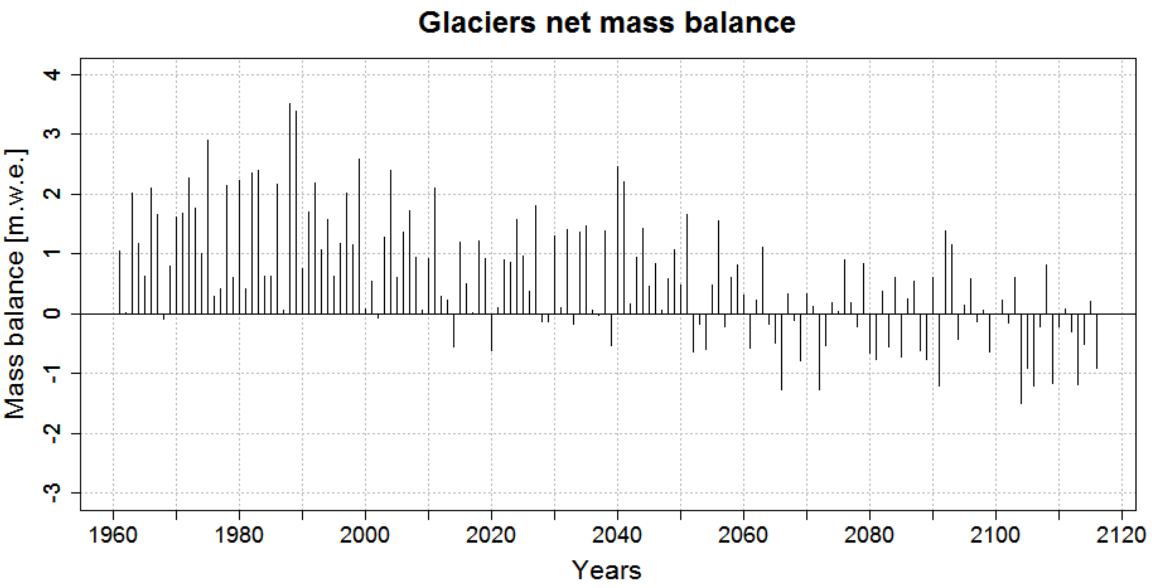


**Figure 7.4-1: Forecast - cal.1 - scenario A2 - mass balance**

With the increase of temperature and precipitation almost constant, the glaciers in Olden have more and more often negative masse balance. However, the cumulative mass balance of the glacier shows.

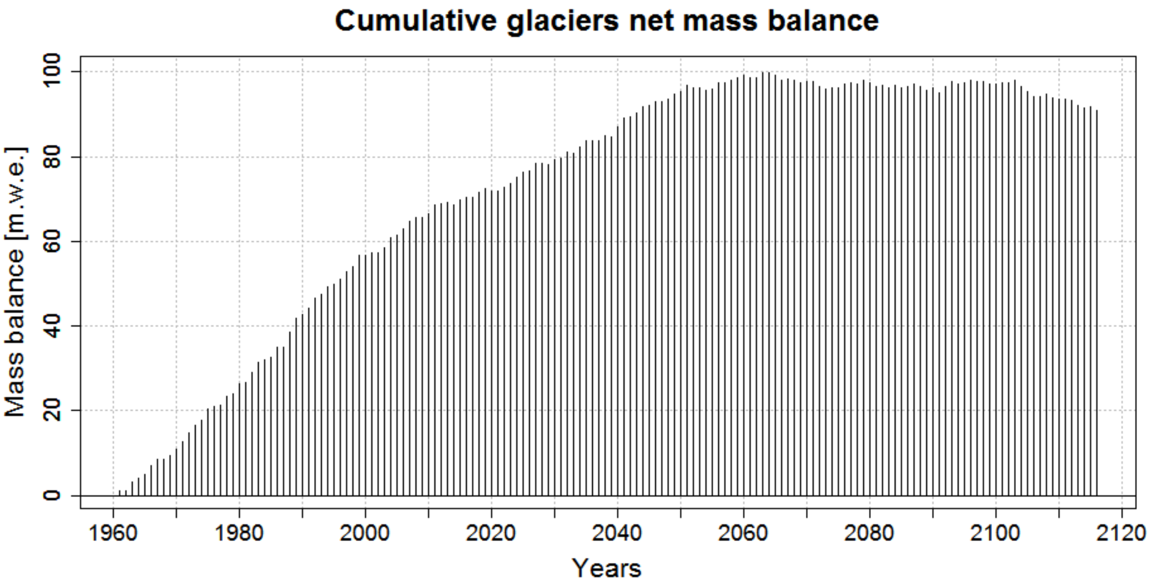


**Figure 7.4-2: Forecast - cal.1 - scenario A2 - cumulative mass balance**

### 7.4.1.2 Scenario B

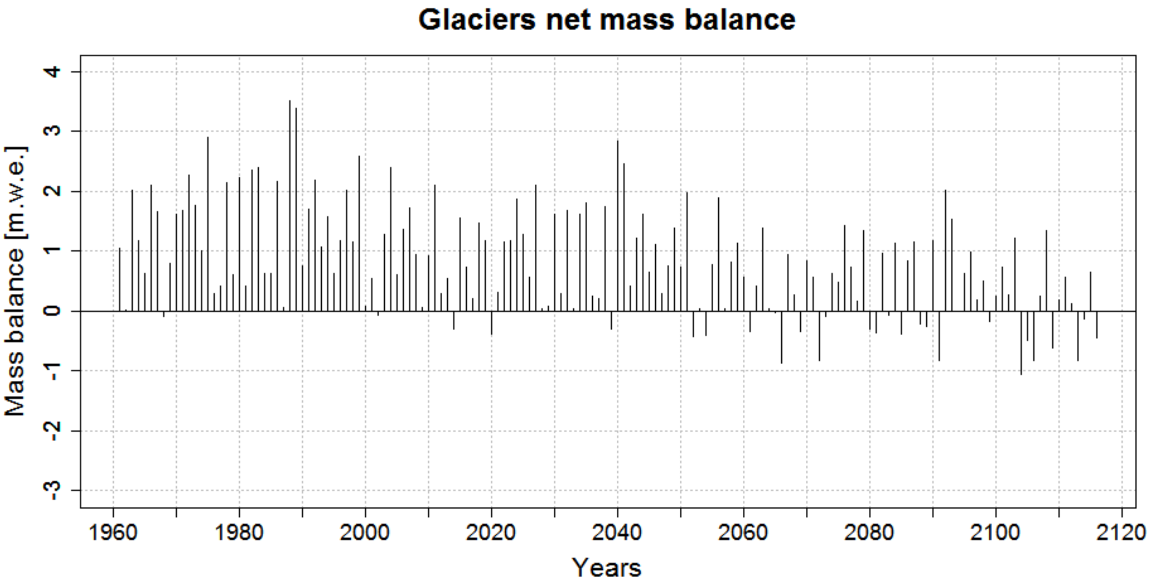


**Figure 7.4-3: Forecast - cal.1 - scenario B2 - mass balance**

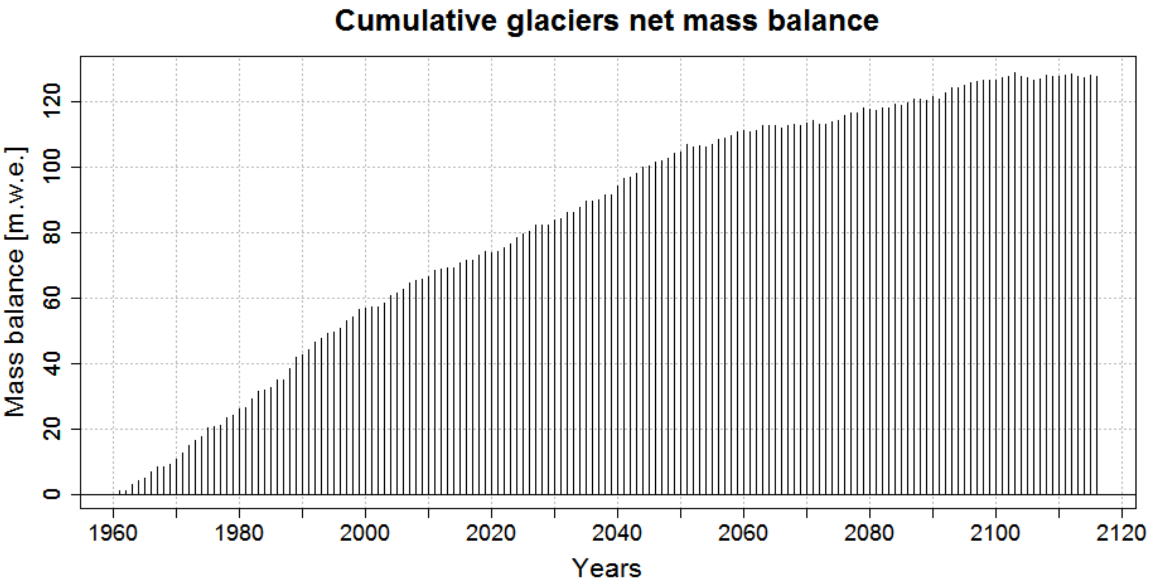


**Figure 7.4-4: Forecast - cal.1 - scenario B2 - cumulative mass balance**

The cumulative mass balance gives a higher volume in the scenario B2 because the temperature rises less than with the scenario A2.

### 7.4.2 Calibration 2

#### *7.4.2.1 Scenario A*

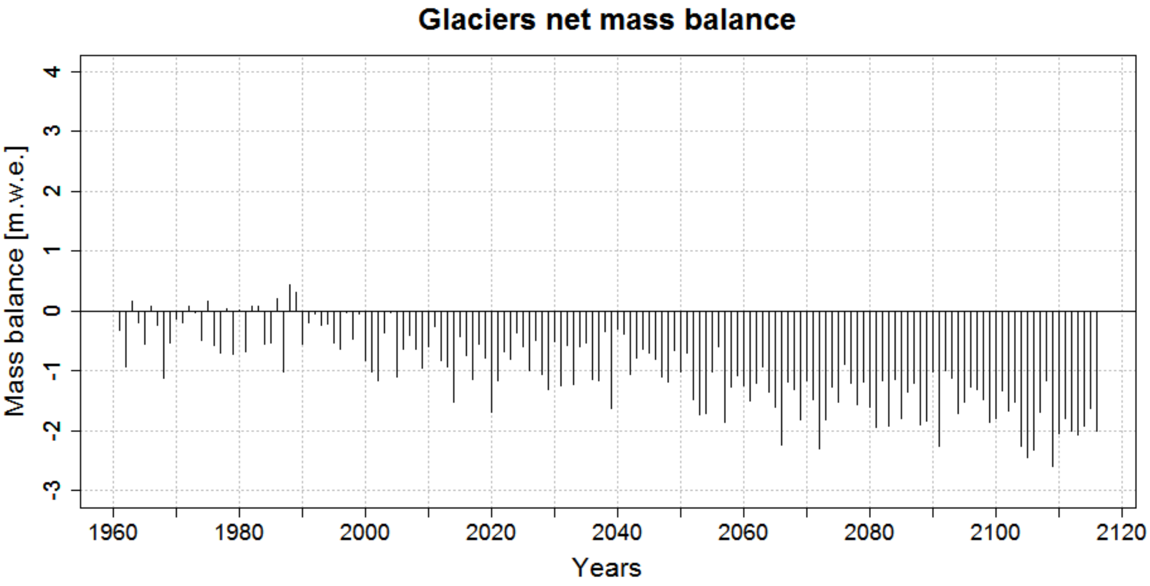


**Figure 7.4-5: Forecast - cal.2 - scenario A2 - mass balance**

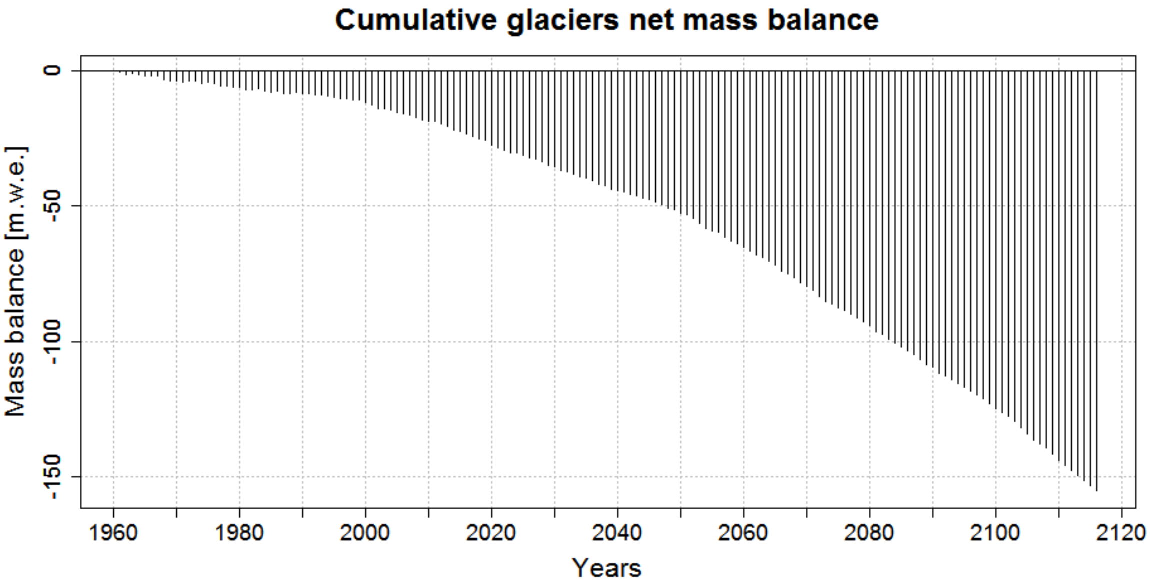


**Figure 7.4-6: Forecast - cal.2 - scenario A2 - cumulative mass balance**

#### *7.4.2.2 Scenario B*

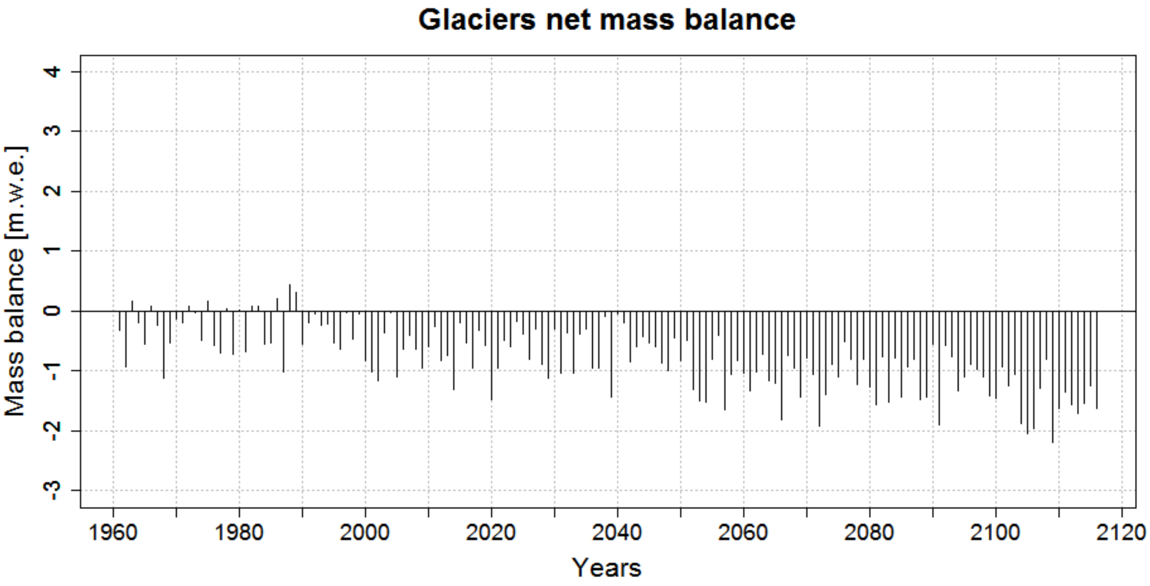


**Figure 7.4-7: Forecast - cal.2 - scenario B2 - mass balance**

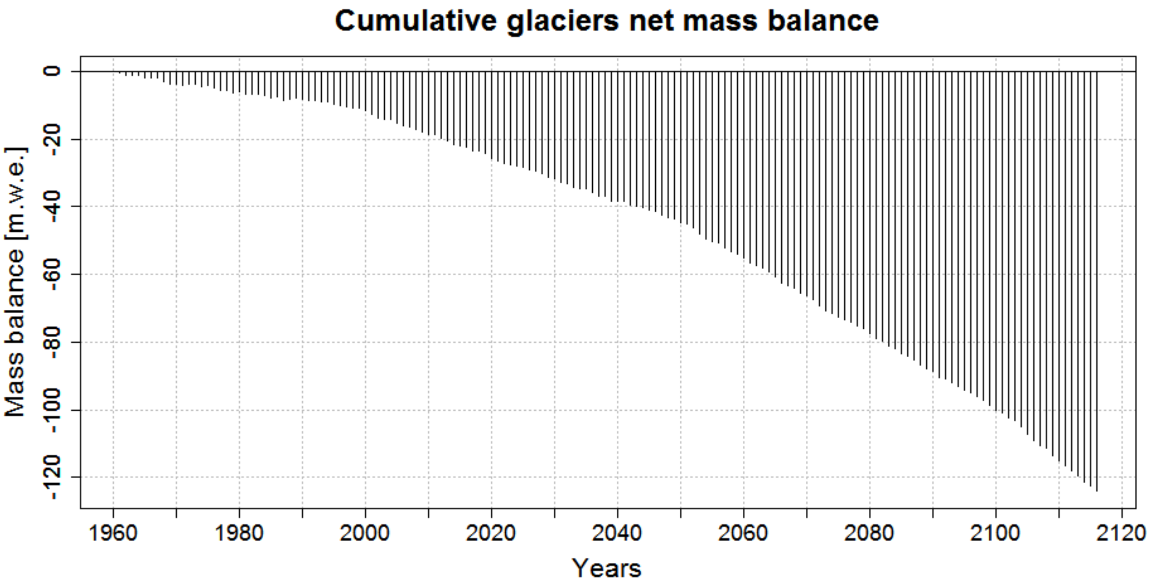


**Figure 7.4-8: Forecast - cal.2 - scenario B2 - cumulative mass balance**

In the same way of the calibration 1, the calibration 2 shows worse mass losses in the scenario A2 than in the scenario B2.

### 7.4.3 Conclusion

It is more difficult to conclude about the glacier status because the mass balances calculated for each calibration of each scenario seemed too extreme. In both calibrations, the scenario A2 is the one which will show the lowest values (increase or decrease), which means that whatever the calibration used, the glaciers will disappear more rapidly with the scenario A2.

If the mass balance was an average of the two mass balances calculated with each calibration, the final masse balance would be:

**Table 7.4-1: Total mass balance**

| Scenario | A2 | B2 |
|---|---|---|
| Calibration 1: gain | 90.87 | 127.71 |
| In 1988 | 38.45 | 38.45 |
| Total gain | 52.41 | 89.26 |
| Calibration 2: loss | -155.34 | -124.08 |
| In 1988 | -8.12 | -8.12 |
| Total loss | -147.22 | -115.96 |
| Average between the two calibrations | -94.81 | -26.70 |

The estimated thickness of the glacier water equivalent in 1988 is 61.66 m.

A forecast climate following the scenario A2 would mean a total disappearance of the glaciers in Olden, while the scenario B2 would induce the disappearance of more than 40% of the glacier mass balance.

# 8 CONCLUSION AND RECOMMENDATION

## 8.1 CONCLUSION

The HBV-model focus is mainly on the runoff. It is not a glacier model. Therefore, the glacier part is simplified. The glacier area is notified, its melt factor appears and it can lose mass. However, it is not enough, especially on a long period of simulation. The limitations of the HBV-model concerning the glacier part come from the fact that the glacier does not evolve each year. The glacier area stays constant so there is not shredding or spreading considered. The glacier ice melt happens however there is no indication of the depth of the glacier. So the glacier could melt entirely but still be present in the model. It could also extend with growing in the model.

Despite all those limitations, the calibrated HBV-model succeeded very well in reproducing the runoff in Olden catchment, which is covered at 40% by glaciers, on a long period of 52 years. So even though the model does not do many computations on the glacier itself, it found a way to handle the input data, precipitation and temperature, to forecast the runoff. This shows the robustness of the HBV-model.

Two calibrations have been made in order to fulfil two different objectives: runoff forecasting and glacier forecasting. The two calibrations give good results for the runoff forecast. However, the first calibration overestimates the snow storage and it is not possible to reduce it without decrease the runoff forecast. The second calibration is a compromise between runoff forecast and consistency in the snow routine of the model. The results concerning the glacier behaviour are more realistic in the second calibration. There is a need to find a third calibration which would be a compromise between the two calibrations to get net mass balances that are coherent with the glacier mass balances of the area.

The same calibrated free parameters have been used for forecasting the runoff in two very similar catchments Olden and Loen. The HBV-model gives good results for the second catchment Loen with the calibrated parameters for the first catchment Olden. So, after a calibration of Loen, the two set of parameters could be associated to give a third set of free parameters in order to forecast both catchments runoff with high accuracy. With the same parameters, it is possible to forecast two different catchments which share numerous features like Olden and Loen do. This shows the utility of the regional model.

The glacier mass balance is difficult to estimate with a model that is not made for this specific purpose. It is possible though to see the trends of the mass balance of the glaciers in the catchment. The magnitude is the most challenging part of the estimation. The catchments that were studied did not have any mass balance record. So it was not possible to calibrate the model to get consistent results with observed data. In that case, the studies on the mass balance are usually made considering glaciers in the surrounding area where those investigations have been carried out. The glaciers in the area, one facing the same side, oriented to the sea, Ålfotbreen and one sharing very close location inland Nigardsbreen, had been selected. Those two glaciers have roughly the same pattern but the values differ considerably. The difference comes from the climate of the region: the glacier located on the coast is subject to "extem" event such has very high precipitation and very high temperature while the second one inland does not encounter the same high event. Located inland but facing the sea, Olden must have the same trends as Ålfotbreen but the similar values as Nigardsbreen. The two calibrations give extreme opposite tendency in the mass balance. The first calibration which creates a lot of precipitation presents a balance almost always positive while the second one which generates much less precipitation produces a balance almost always negative. Assuming the same trend as the other glaciers, there is a need to find a third calibration which would be a compromise between the two calibrations to get net mass balances that are more coherent with the glacier mass balances of the area.

The best parameter to foresee the glacier mass balance is the snow state at the end of the year because it is a result of precipitation (mostly winter precipitation) and temperature (summer temperature). On the other hand, the length of a glacier is not correlated with any of those parameters. This shows the limit of the climatological effects, precipitation and temperature, on the glacier length and area. The area cannot constitute the only way to assess the glacier volume increase or decrease.

Catchments with an extensive part covered by glaciers did not seem to be easily handled by a simple hydrological model like HBV-model. However the model is very robust and gives consistent results for the runoff forecast and workable results for glacier behaviour.

## 8.2 RECOMMENDATIONS

The study area has been chosen for reason that offers analyses on different topics: runoff forecast on catchment with glaciers was the main goal but it was also possible with these catchments to assess the utility of regional calibrated models, glacier mass balances and glacier length behaviour.

However in order to focus more on the glacier mass balance, a catchment where investigations have been implemented would be better to calibrated the model to get consistent results for both runoff and glacier behaviour with the same calibration.

For further research on glacier with utilisation of HBV-model, the glacier part of the HBV-model can be improved in a simpler way with a more exhaustive writing of results. To help the analysis for the glacier part, it would be an improvement to add in the result file:

- Exportation of the snow fall and rain fall,
- Exportation of the ice glacier melt,
- Exportation of the areal temperature.

The model can also be improved in order to add yearly glacier modifications in change the computation process:

- Modification of the parameters:
  - Addition of the water volume of the glacier,
  - Addition of the depth of the glacier in each elevation zone,
- Modification of the routine:
  - Recalculation of the glacier depth every year,

The phenomena that occur in a glacier are complex. Many assumptions and simplification have been made during the thesis. However many conclusions have been drawn.

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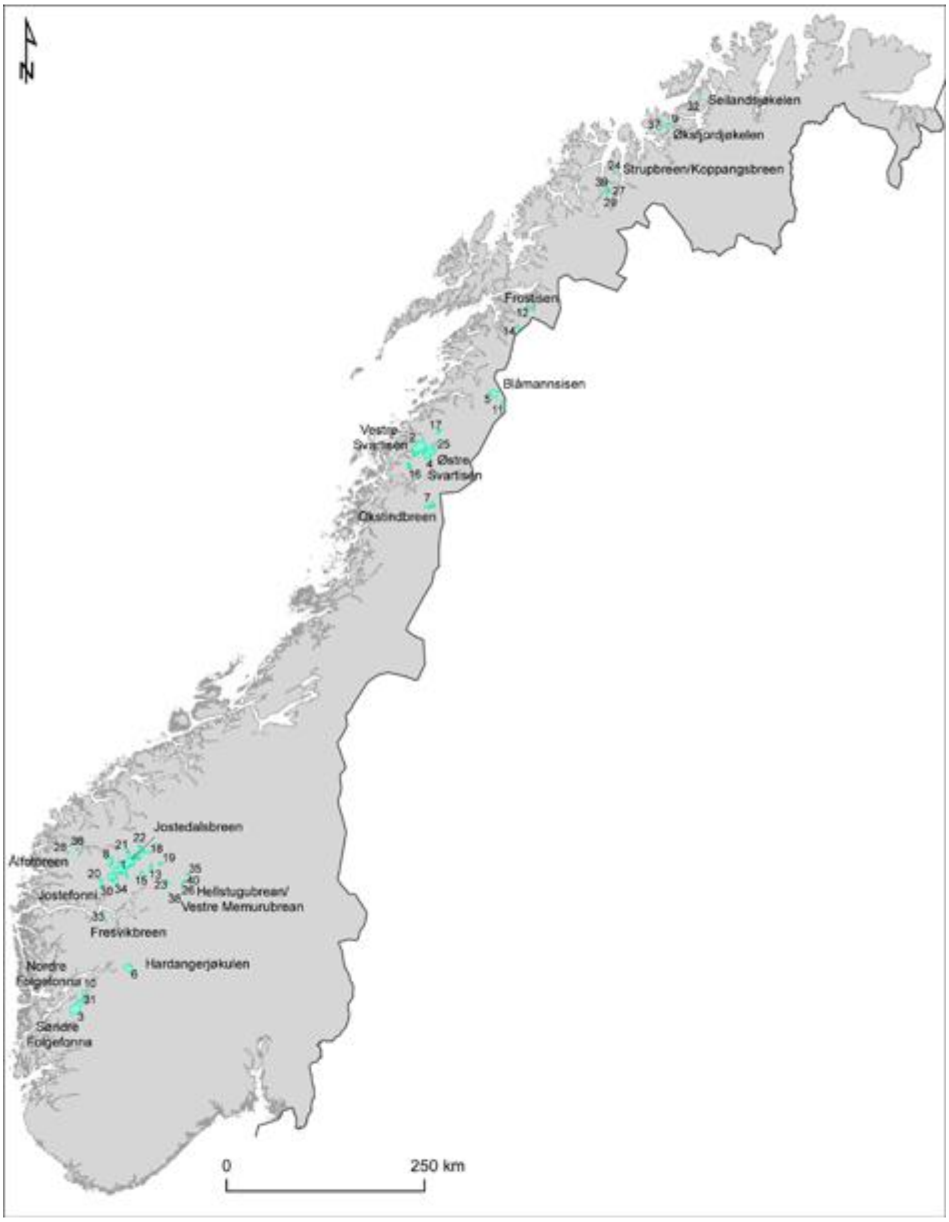
# 10 APPENDIX

## A. NORWAY AND ITS BIGGEST GLACIERS



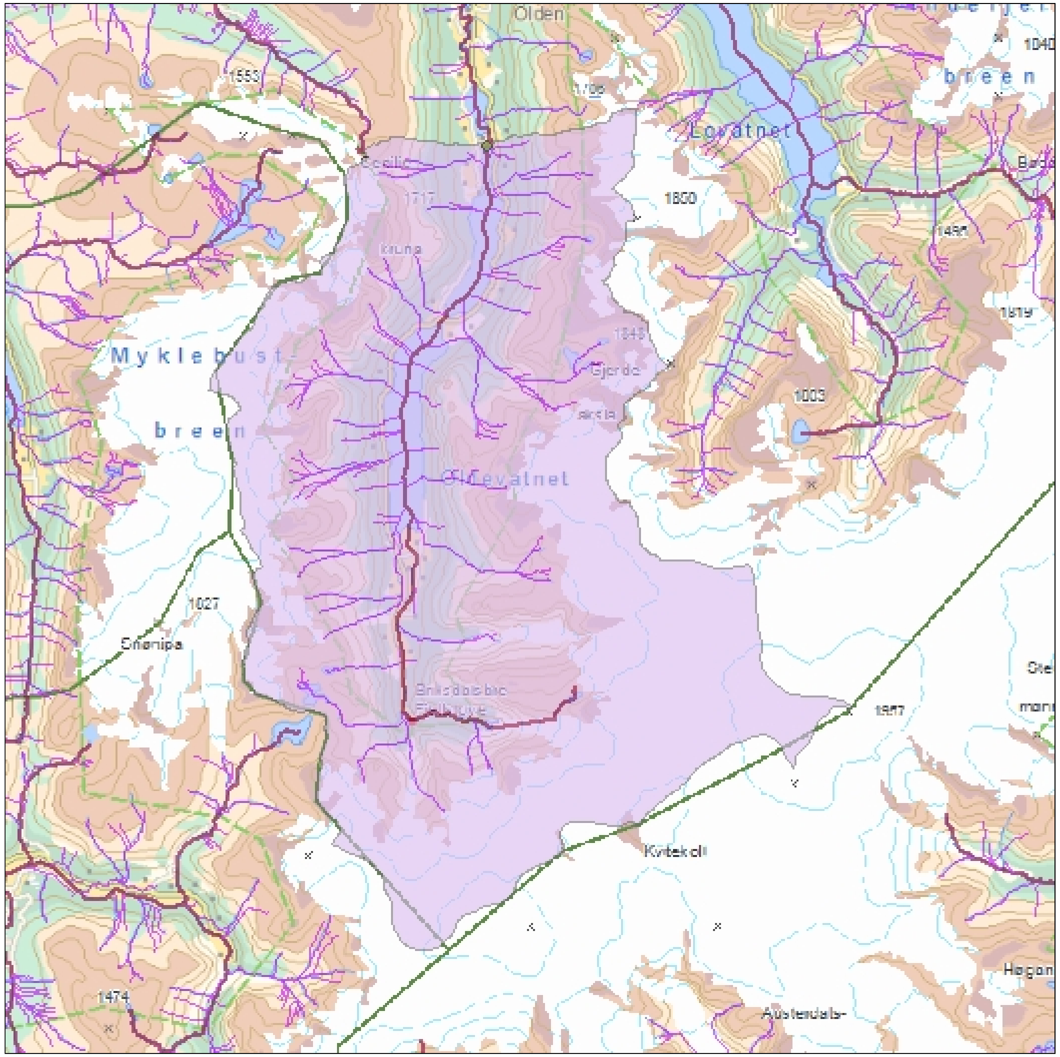
The 40 largest glaciers in Norway. The glaciers are shaded in green. Numbers 1-40 mark the glaciers, number 1 Jostedalsbreen is the largest glacier in Norway

## B. LAVVANN CATCHMENT MAPS

### *a) Olden*

### *b) Loen*

### *c) Stryn*



NVE

**Norges vassdrags- og energidirektorat**

|  |  |
|---|---|
| Kartbakgrunn: | Statens Kartverk |
| Kartdatum: | EUREF89 WGS84 |
| Projeksjon: | UTM 33N |

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

# Lavvannskart

|  |  |
|---|---|
| Vassdragsnr.: | 088.1A |
| Kommune: | Stryn |
| Fylke: | Sogn og Fjordane |
| Vassdrag: | OLDENVASSDRAGET |

Vannføringsindeks, se merknader

|  |  |  |
|---|---|---|
| Middelvannføring (61-90) | 75,7 | l/s/km² |
| Alminnelig lavvannføring | 0,0 | l/s/km² |
| 5-persentil (hele året) | 0,0 | l/s/km² |
| 5-persentil (1/5-30/9) | 0,0 | l/s/km² |
| 5-persentil (1/10-30/4) | 0,0 | l/s/km² |
| Base flow | 0,0 | l/s/km² |
| BFI | 0,0 |  |

Klima

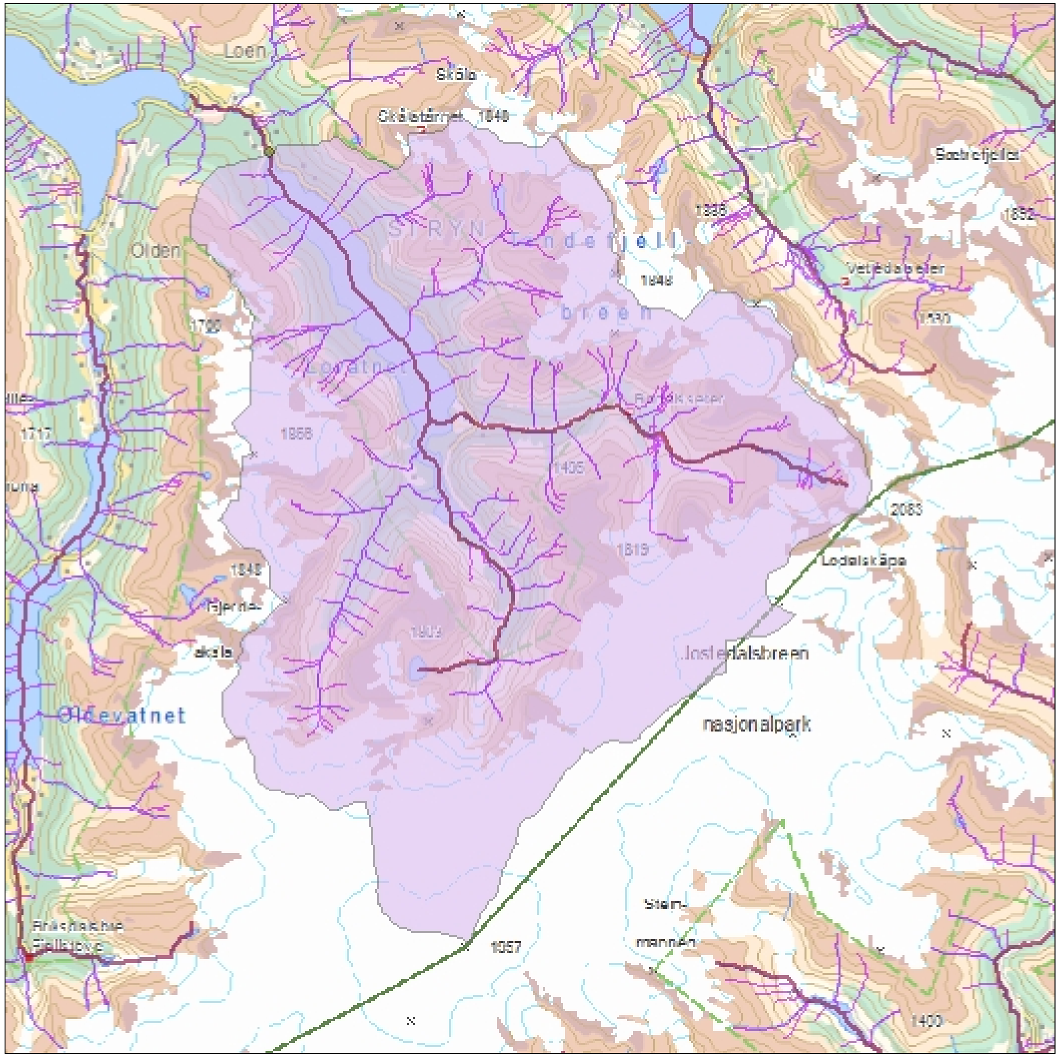
|  |  |  |
|---|---|---|
| Klimaregion | Bre-Sor |  |
| Årsnedbør | 1673 | mm |
| Sommernedbør | 606 | mm |
| Vinternedbør | 1066 | mm |
| Årstemperatur | -0,4 | °C |
| Sommertemperatur | 4,5 | °C |
| Vintertemperatur | -3,8 | °C |
| Temperatur Juli | 6,3 | °C |
| Temperatur August | 7,2 | °C |

Feltparametere

|  |  |
|---|---|
| Areal (A) | 203,2 km² |
| Effektiv sjø ($S_{eff}$) | 3,3 % |
| Elvelengde ($E_L$) | 22,1 km |
| Elvegradient ($E_G$) | 59,2 m/km |
| Elvegradient$_{1085}$ ($G_{1085}$) | 18,8 m/km |
| Feltlengde($F_L$) | 21,4 km |
| $H_{min}$ | 33 moh. |
| $H_{10}$ | 168 moh. |
| $H_{20}$ | 530 moh. |
| $H_{30}$ | 862 moh. |
| $H_{40}$ | 1106 moh. |
| $H_{50}$ | 1305 moh. |
| $H_{60}$ | 1444 moh. |
| $H_{70}$ | 1560 moh. |
| $H_{80}$ | 1645 moh. |
| $H_{90}$ | 1742 moh. |
| $H_{max}$ | 1953 moh. |
| Bre | 40,2 % |
| Dyrket mark | 1,7 % |
| Myr | 0,0 % |
| Sjø | 4,2 % |
| Skog | 17,6 % |
| Snaufjell | 32,8 % |
| Urban | 0,0 % |

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.



**Norges vassdrags- og energidirektorat**

**N V E**

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

# Lavvannskart

| | |
|---|---|
| Vassdragsnr.: | 088.2B1 |
| Kommune: | Stryn |
| Fylke: | Sogn og Fjordane |
| Vassdrag: | LOENVASSDRAGET |

## Vannføringsindeks, se merknader

| | | |
|---|---|---|
| Middelvannføring (61-90) | 64,8 | l/s/km² |
| Alminnelig lavvannføring | 0,0 | l/s/km² |
| 5-persentil (hele året) | 0,0 | l/s/km² |
| 5-persentil (1/5-30/9) | 0,0 | l/s/km² |
| 5-persentil (1/10-30/4) | 0,0 | l/s/km² |
| Base flow | 0,0 | l/s/km² |
| BFI | 0,0 | |

## Klima

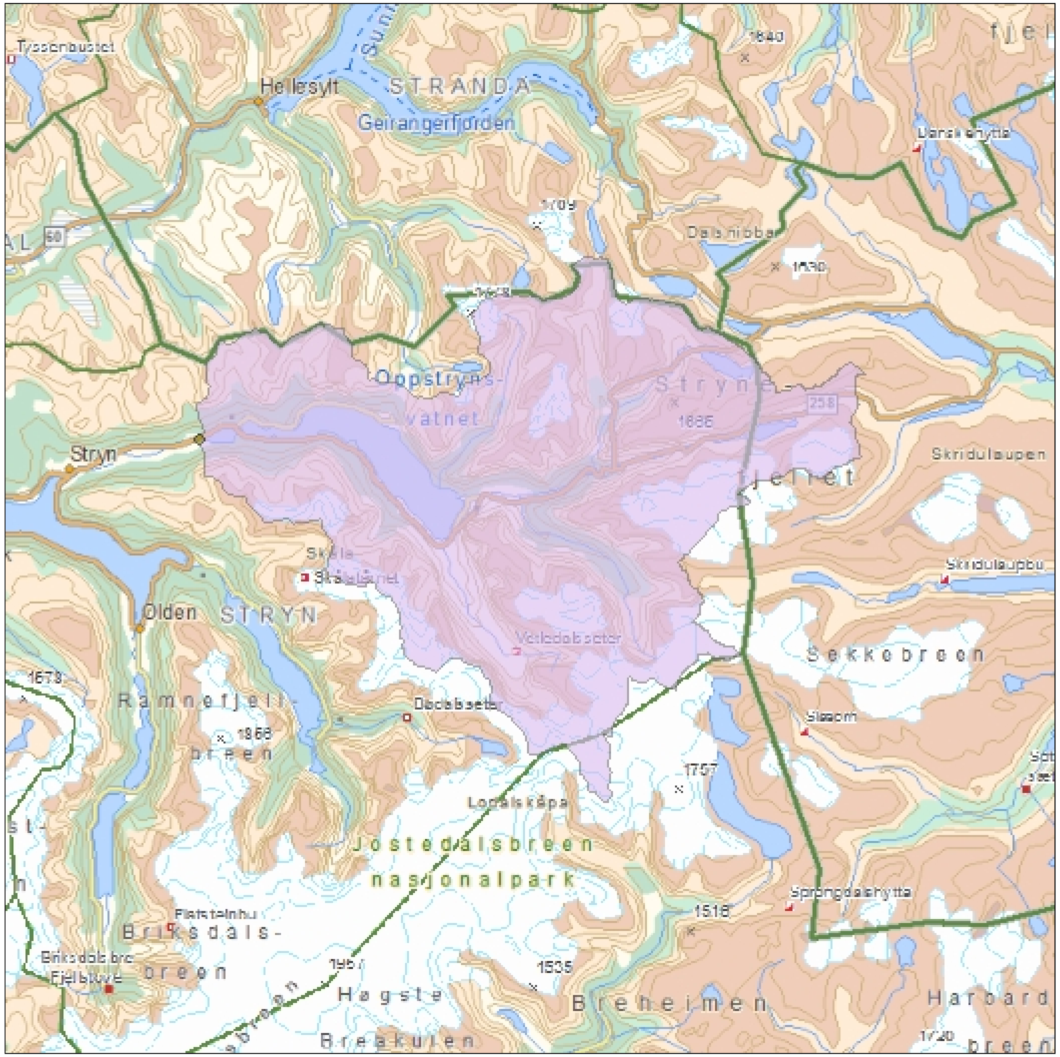
| | | |
|---|---|---|
| Klimaregion | Bre-Sor | |
| Årsnedbør | 1640 | mm |
| Sommernedbør | 609 | mm |
| Vinternedbør | 1031 | mm |
| Årstemperatur | -0,1 | °C |
| Sommertemperatur | 4,4 | °C |
| Vintertemperatur | -3,3 | °C |
| Temperatur Juli | 6,1 | °C |
| Temperatur August | 7,2 | °C |

## Feltparametere

| | |
|---|---|
| Areal (A) | 234,5 km² |
| Effektiv sjø ($S_{eff}$) | 4,5 % |
| Elvelengde ($E_L$) | 18,8 km |
| Elvegradient ($E_G$) | 65,4 m/km |
| Elvegradient$_{1085}$($G_{1085}$) | 5,1 m/km |
| Feltlengde($F_L$) | 21,6 km |
| $H_{min}$ | 52 moh. |
| $H_{10}$ | 213 moh. |
| $H_{20}$ | 616 moh. |
| $H_{30}$ | 934 moh. |
| $H_{40}$ | 1176 moh. |
| $H_{50}$ | 1339 moh. |
| $H_{60}$ | 1488 moh. |
| $H_{70}$ | 1593 moh. |
| $H_{80}$ | 1667 moh. |
| $H_{90}$ | 1744 moh. |
| $H_{max}$ | 2076 moh. |
| Bre | 37,0 % |
| Dyrket mark | 0,2 % |
| Myr | 0,0 % |
| Sjø | 5,1 % |
| Skog | 14,8 % |
| Snaufjell | 40,2 % |
| Urban | 0,0 % |

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.



**Norges vassdrags- og energidirektorat**

NVE

Kartbakgrunn: Statens Kartverk

Kartdatum: EUREF89 WGS84

Projeksjon: UTM 33N

Nedbørfeltgrenser, feltparametere og vannføringsindekser er automatisk generert og kan inneholde feil. Resultatene må kvalitetssikres.

# Lavvannskart

Vassdragsnr.: 088.B21
Kommune: Stryn
Fylke: Sogn og Fjordane
Vassdrag: STRYNEVASSDRAGET

## Vannføringsindeks, se merknader

| | | |
|---|---|---|
| Middelvannføring (61-90) | 60,0 | l/s/km² |
| Alminnelig lavvannføring | 0,0 | l/s/km² |
| 5-persentil (hele året) | 0,0 | l/s/km² |
| 5-persentil (1/5-30/9) | 0,0 | l/s/km² |
| 5-persentil (1/10-30/4) | 0,0 | l/s/km² |
| Base flow | 0,0 | l/s/km² |
| BFI | 0,0 | |

## Klima

| | | |
|---|---|---|
| Klimaregion | Bre-Sor | |
| Årsnedbør | 1352 | mm |
| Sommernedbør | 464 | mm |
| Vinternedbør | 887 | mm |
| Årstemperatur | 1,2 | °C |
| Sommertemperatur | 5,3 | °C |
| Vintertemperatur | -1,7 | °C |
| Temperatur Juli | 6,8 | °C |
| Temperatur August | 8,0 | °C |

## Feltparametere

| | |
|---|---|
| Areal (A) | 482,3 km² |
| Effektiv sjø ($S_{eff}$) | 4,8 % |
| Elvelengde ($E_L$) | 43,7 km |
| Elvegradient ($E_G$) | 31,2 m/km |
| Elvegradient$_{1085}$($G_{1085}$) | 32,3 m/km |
| Feltlengde($F_L$) | 35,4 km |
| $H_{min}$ | 29 moh. |
| $H_{10}$ | 195 moh. |
| $H_{20}$ | 550 moh. |
| $H_{30}$ | 797 moh. |
| $H_{40}$ | 989 moh. |
| $H_{50}$ | 1130 moh. |
| $H_{60}$ | 1251 moh. |
| $H_{70}$ | 1379 moh. |
| $H_{80}$ | 1498 moh. |
| $H_{90}$ | 1595 moh. |
| $H_{max}$ | 1933 moh. |
| Bre | 17,6 % |
| Dyrket mark | 1,5 % |
| Myr | 0,0 % |
| Sjø | 6,2 % |
| Skog | 14,7 % |
| Snaufjell | 53,7 % |
| Urban | 0,0 % |

Det er generelt stor usikkerhet i beregninger av lavvannsindekser. Resultatene bør verifiseres mot egne observasjoner eller sammenlignbare målestasjoner.

I nedbørfelt med høy breprosent eller stor innsjøprosent vil tørrværsavrenning (baseflow) ha store bidrag fra disse lagringsmagasinene.

## C. LAND TYPE: MAP

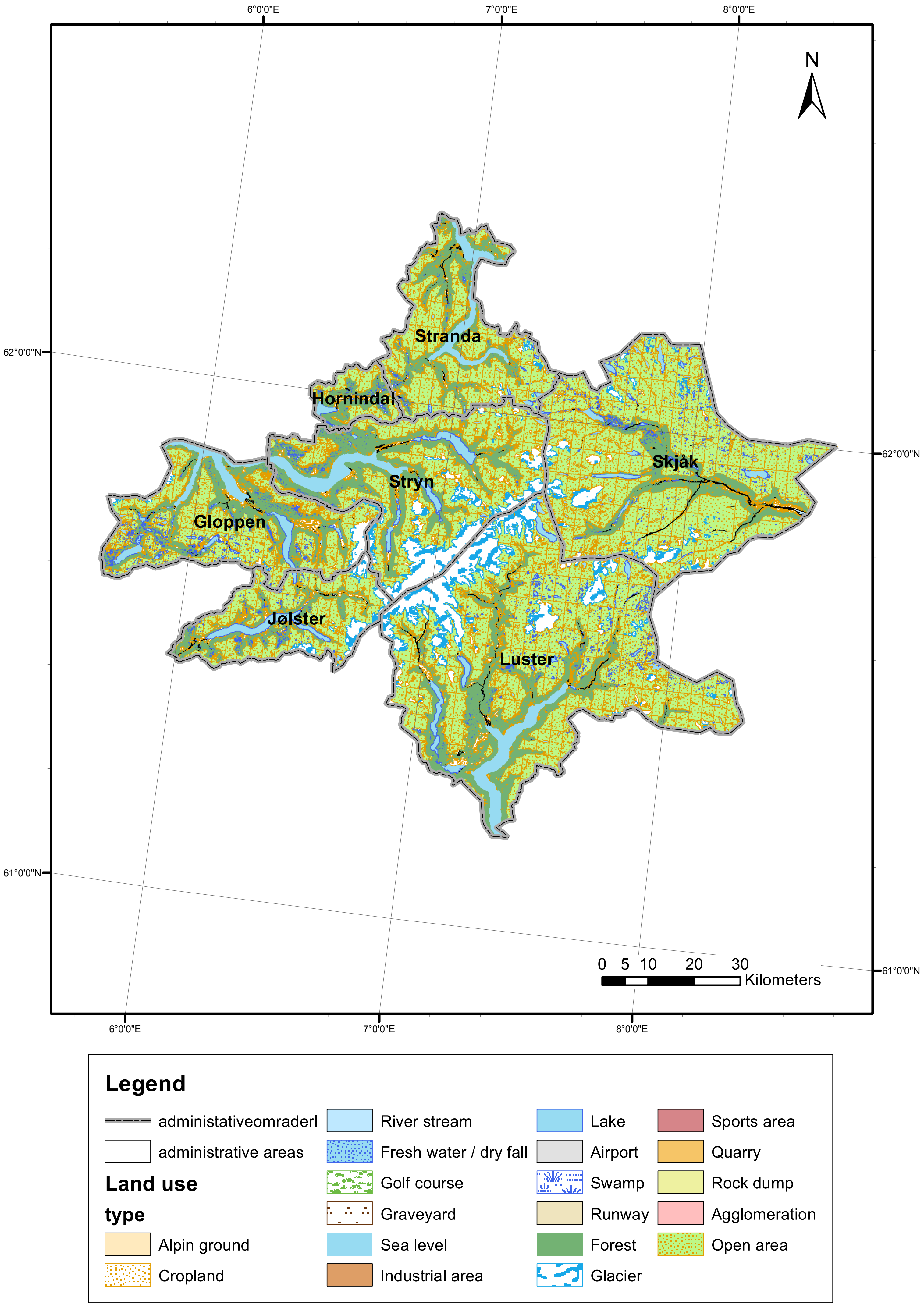
### *a) Region*

### *b) Olden and Olden glaciers*

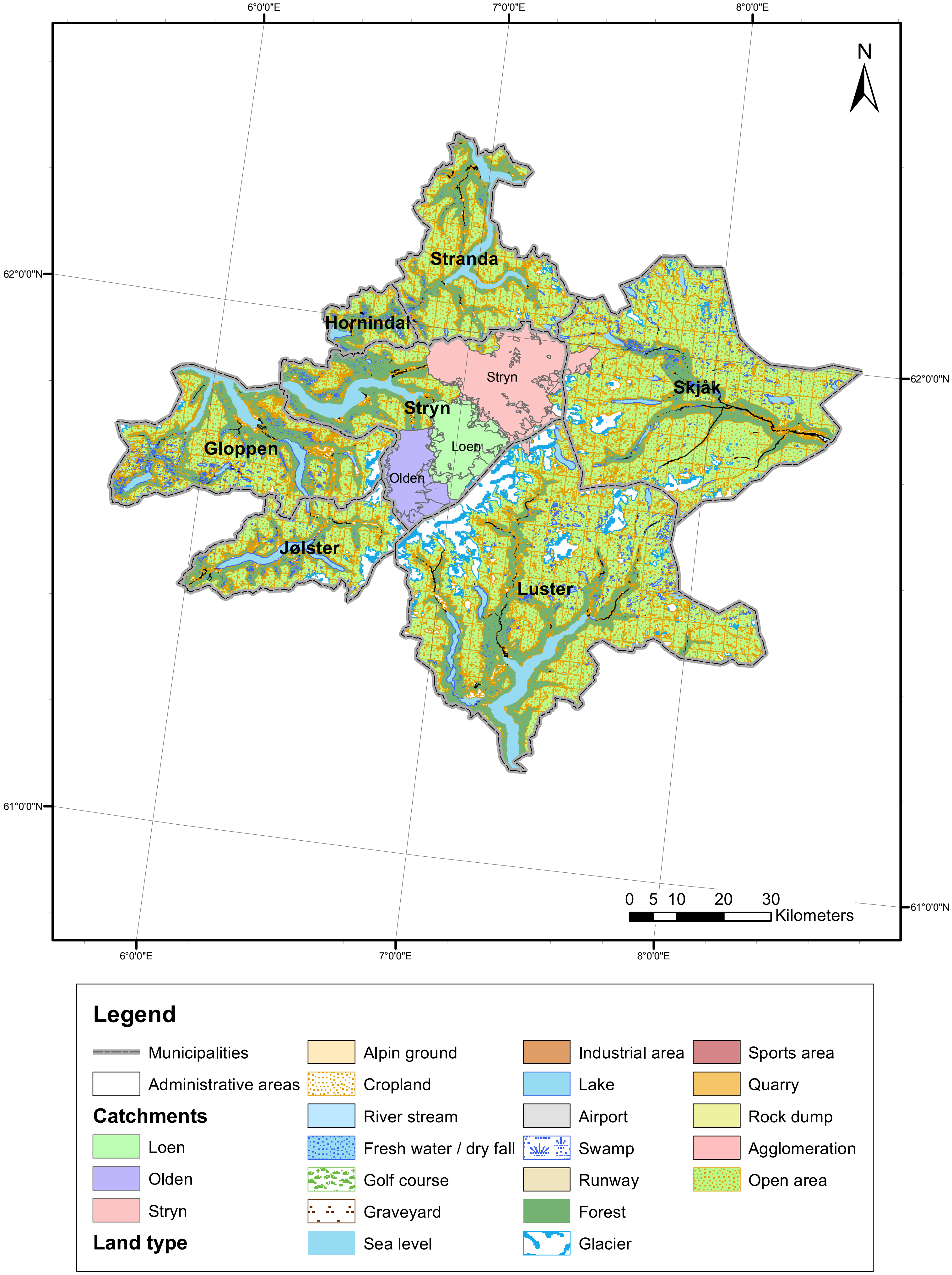
### *c) Loen and Loen glaciers*

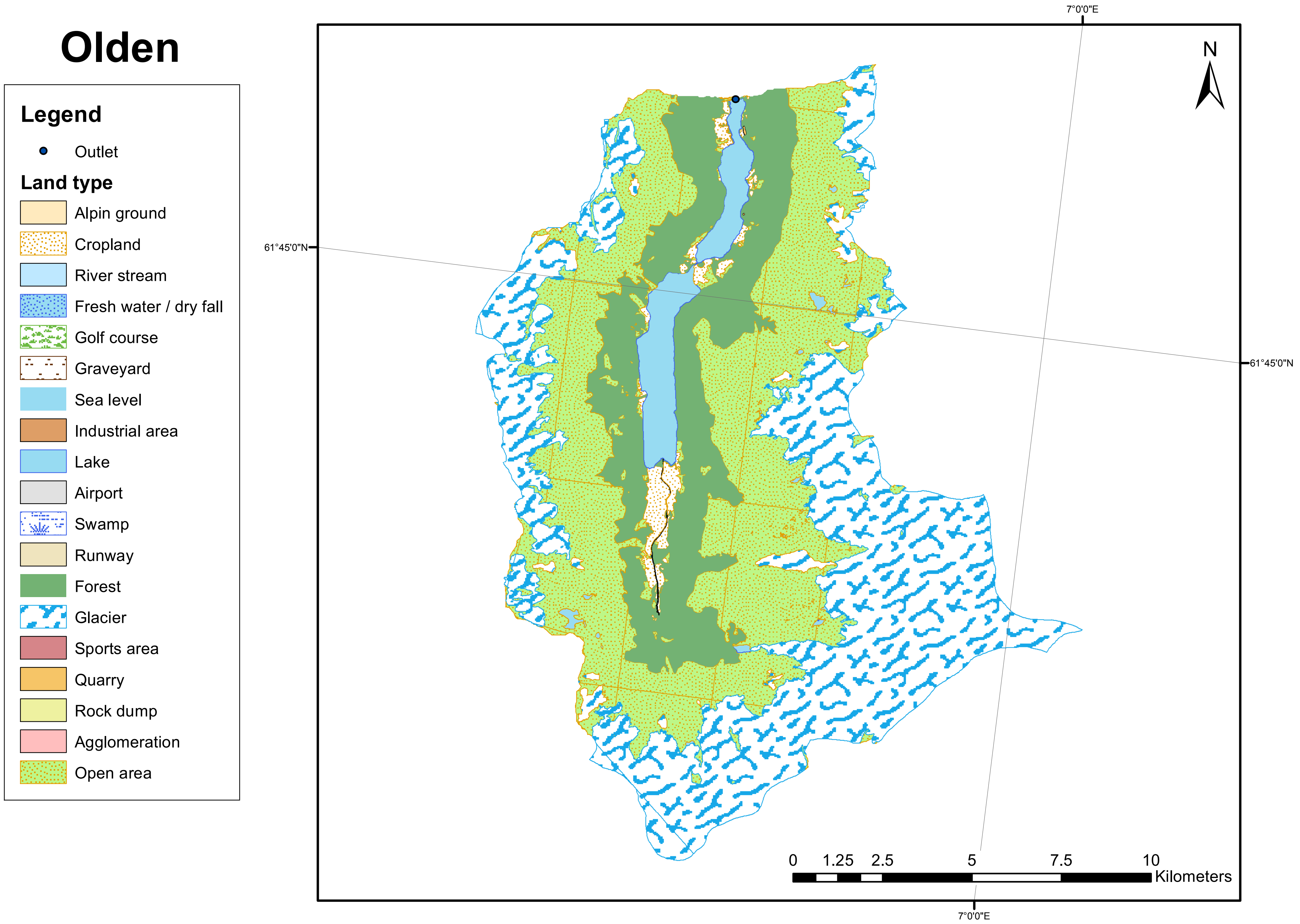
### *d) Stryn and Stryn glaciers*

## D. LAND TYPES: REPARTITION

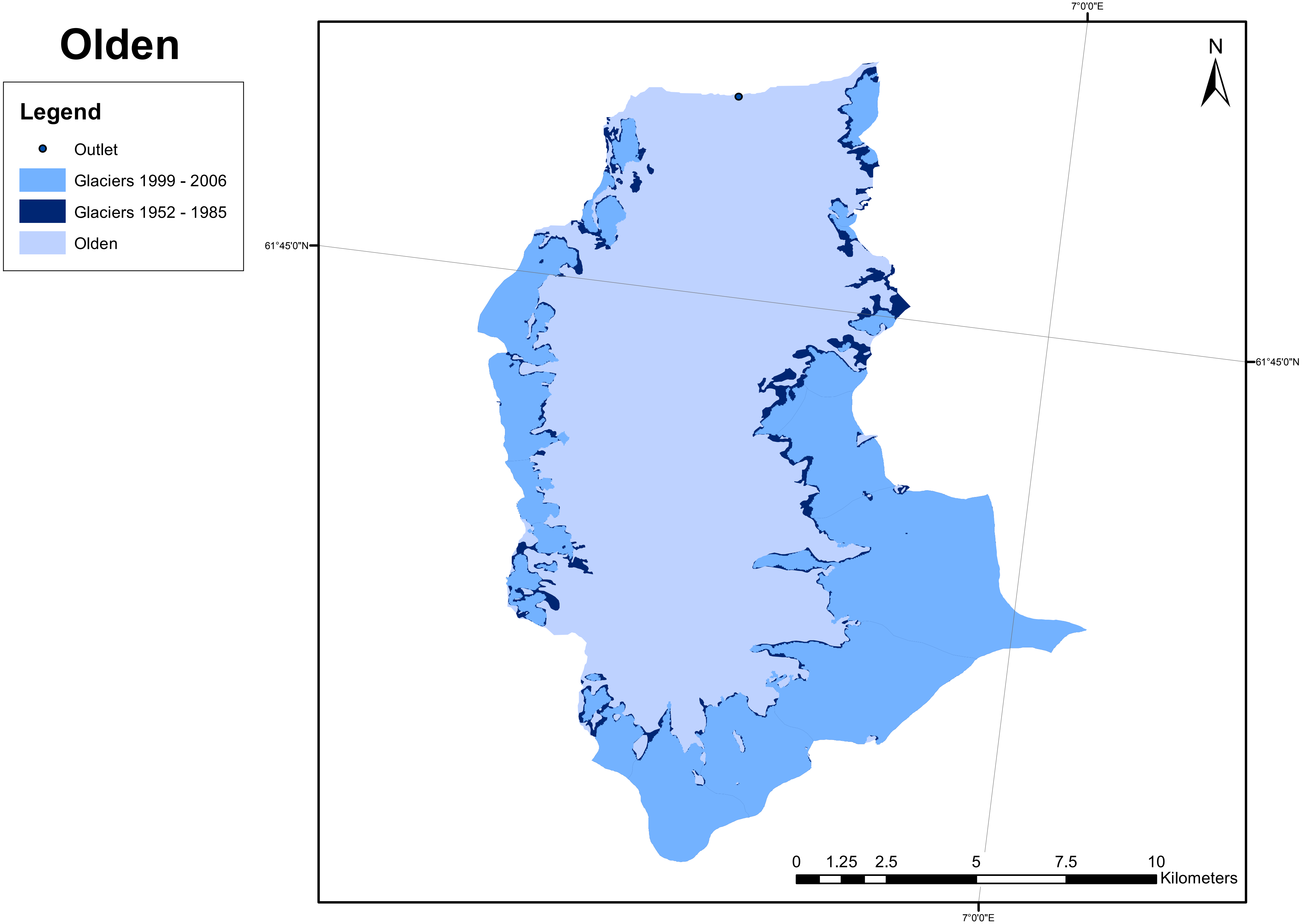

6°0'0"E
7°0'0"E
8°0'0"E
62°0'0"N
61°0'0"N
N
Stranda
Hornindal
Stryn
Skjåk
Gloppen
Jølster
Luster
0 5 10 20 30
Kilometers
Legend
administativeomraderl
administrative areas
Land use type
Alpin ground
Cropland
River stream
Fresh water / dry fall
Golf course
Graveyard
Sea level
Industrial area
Lake
Airport
Swamp
Runway
Forest
Glacier
Sports area
Quarry
Rock dump
Agglomeration
Open area

# Catchments area

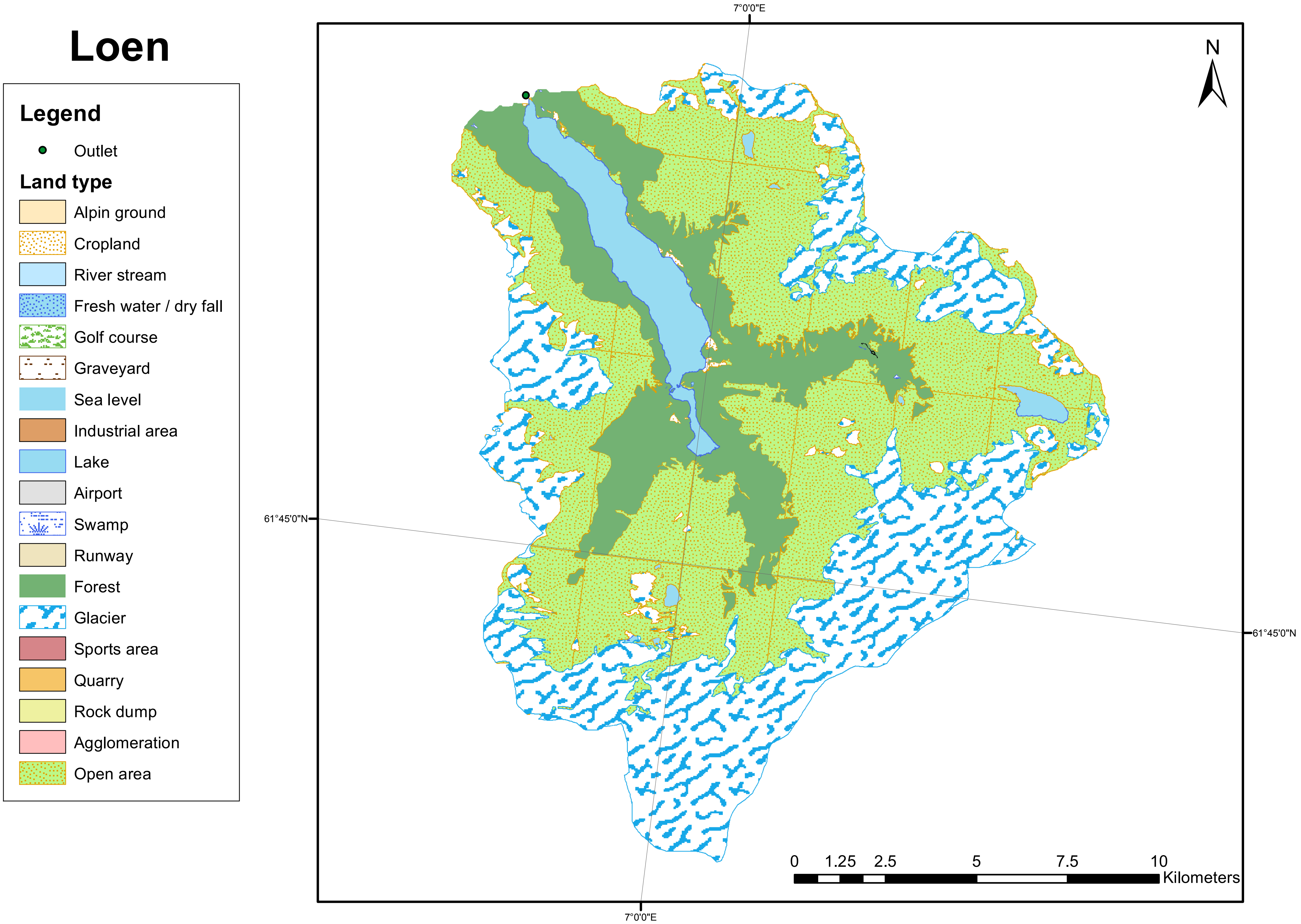



Olden
Legend
● Outlet
Land type
Alpin ground
Cropland
River stream
Fresh water / dry fall
Golf course
Graveyard
Sea level
Industrial area
Lake
Airport
Swamp
Runway
Forest
Glacier
Sports area
Quarry
Rock dump
Agglomeration
Open area
N
7°0'0"E
61°45'0"N
61°45'0"N
7°0'0"E
0
1.25
2.5
5
7.5
10
Kilometers

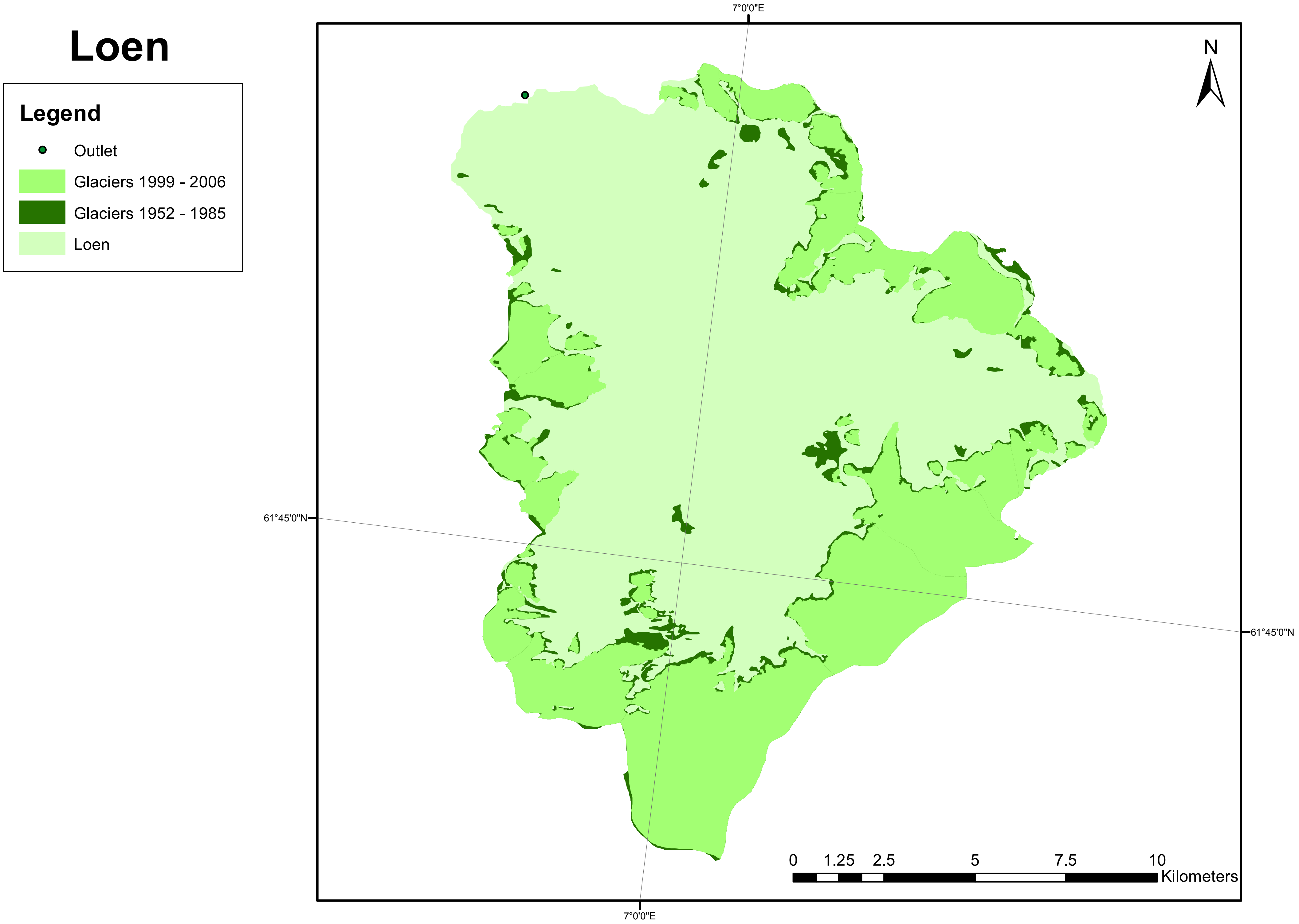
# Olden


Legend
● Outlet
Glaciers 1999 - 2006
Glaciers 1952 - 1985
Olden
N
7°0'0"E
61°45'0"N
61°45'0"N
7°0'0"E
0
1.25
2.5
5
7.5
10
Kilometers

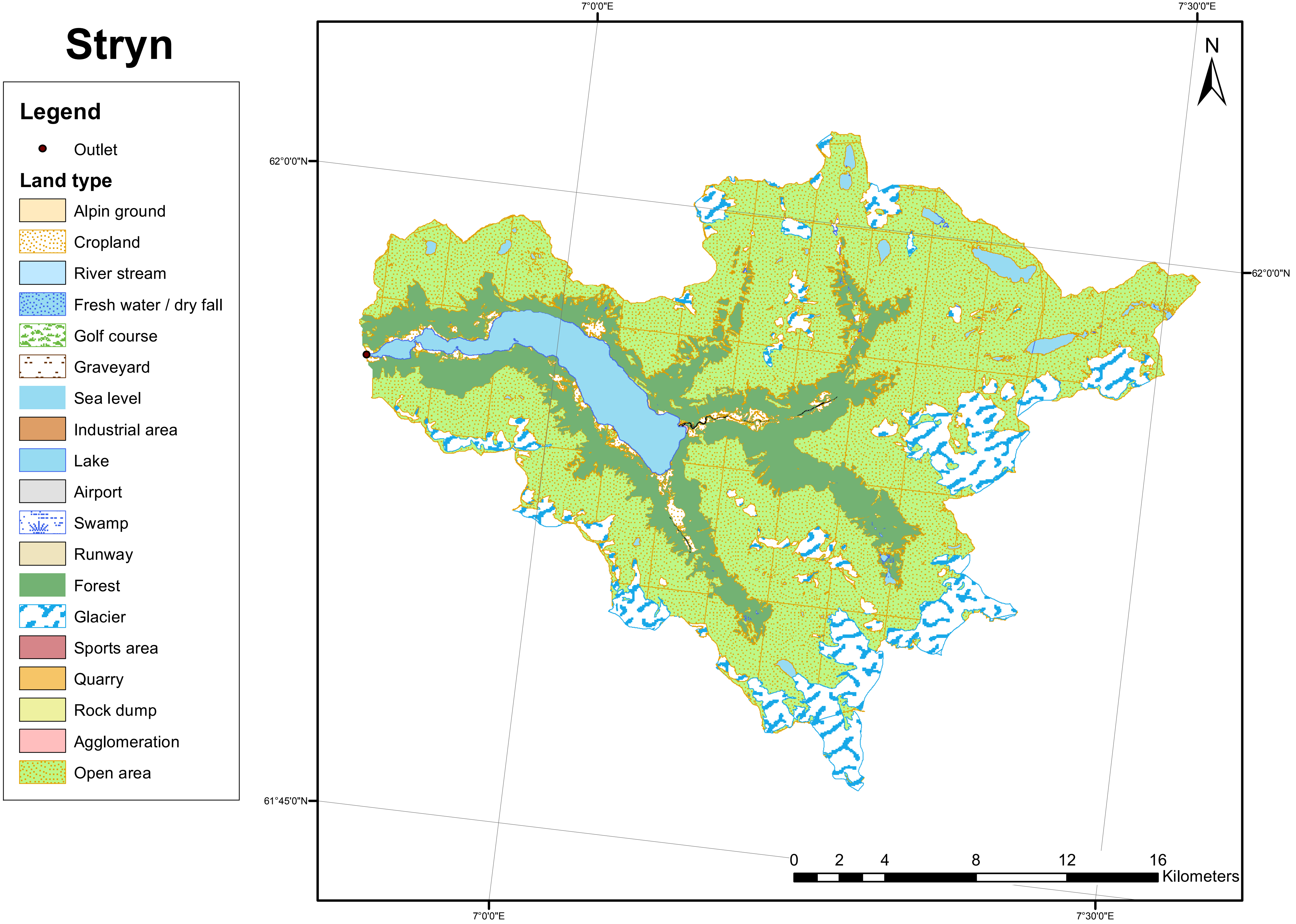
# Loen


Legend
Outlet
Land type
Alpin ground
Cropland
River stream
Fresh water / dry fall
Golf course
Graveyard
Sea level
Industrial area
Lake
Airport
Swamp
Runway
Forest
Glacier
Sports area
Quarry
Rock dump
Agglomeration
Open area
7°0'0"E
61°45'0"N
61°45'0"N
7°0'0"E
N
0
1.25
2.5
5
7.5
10
Kilometers

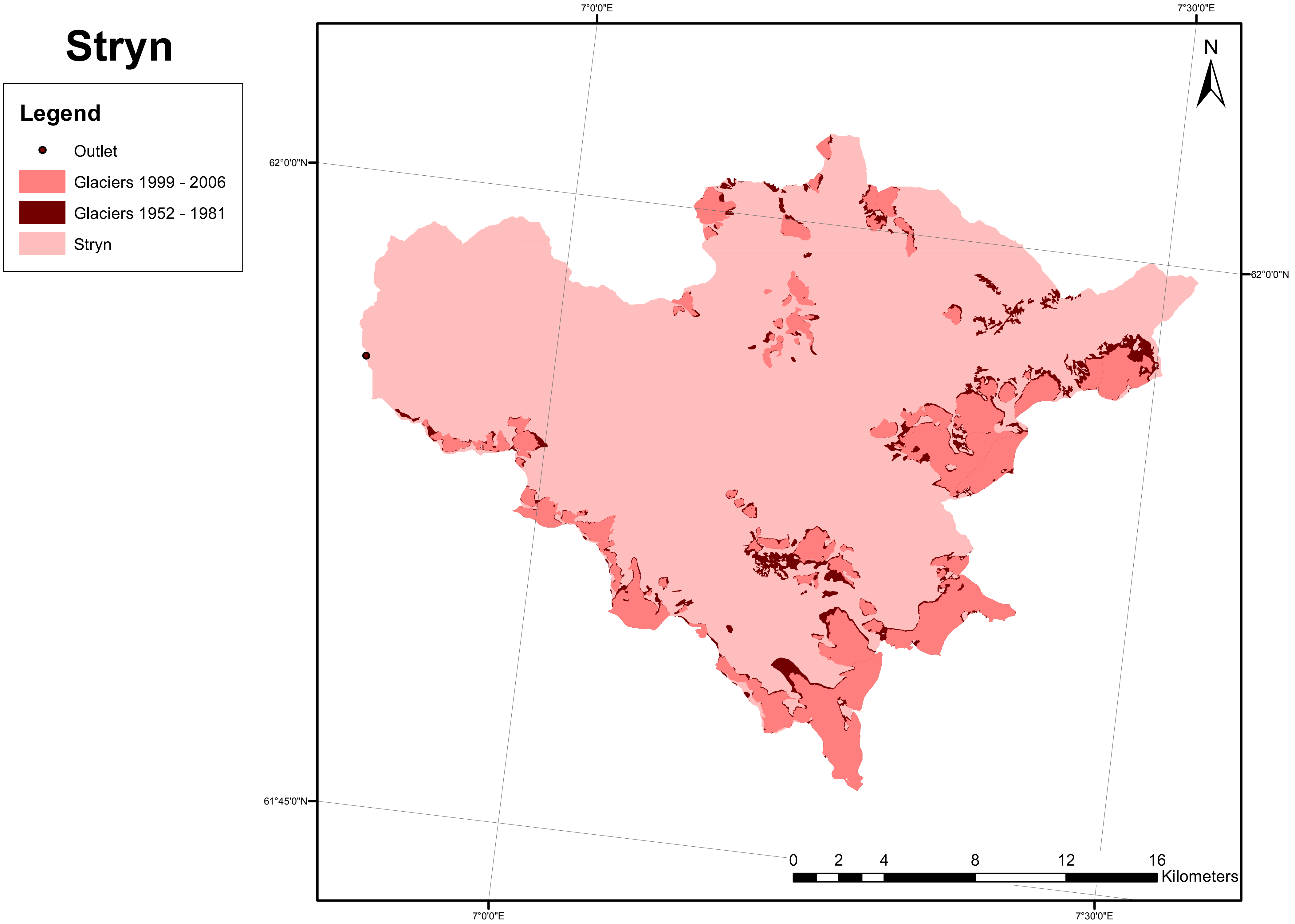
# Loen


Legend
● Outlet
🟩 Glaciers 1999 - 2006
🟩 Glaciers 1952 - 1985
🟩 Loen
7°0'0"E
N
61°45'0"N
61°45'0"N
0
1.25
2.5
5
7.5
10
Kilometers
7°0'0"E

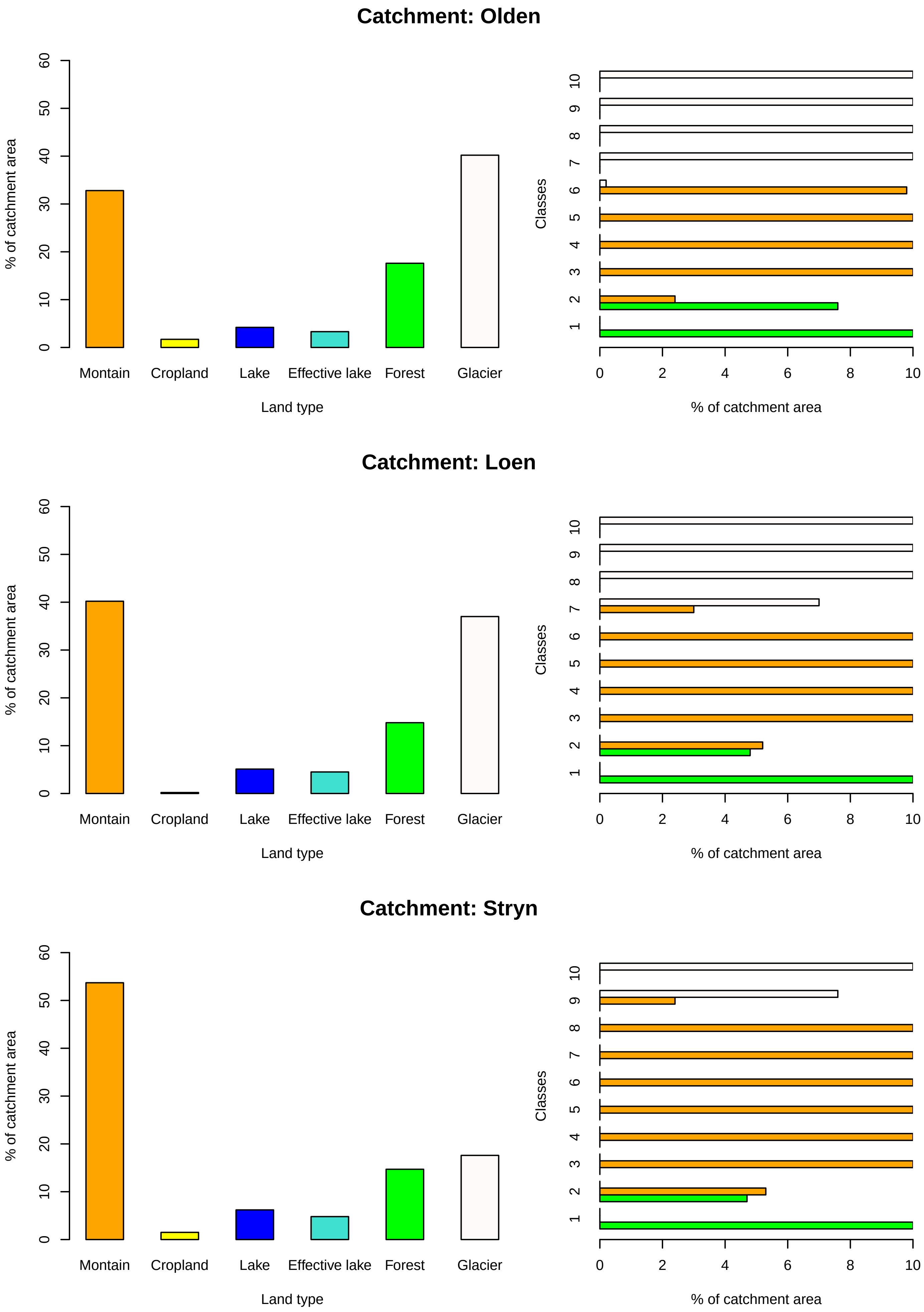
# Stryn


Legend
Outlet
Land type
Alpin ground
Cropland
River stream
Fresh water / dry fall
Golf course
Graveyard
Sea level
Industrial area
Lake
Airport
Swamp
Runway
Forest
Glacier
Sports area
Quarry
Rock dump
Agglomeration
Open area
7°0'0"E
7°30'0"E
62°0'0"N
62°0'0"N
61°45'0"N
N
0
2
4
8
12
16
Kilometers
7°0'0"E
7°30'0"E

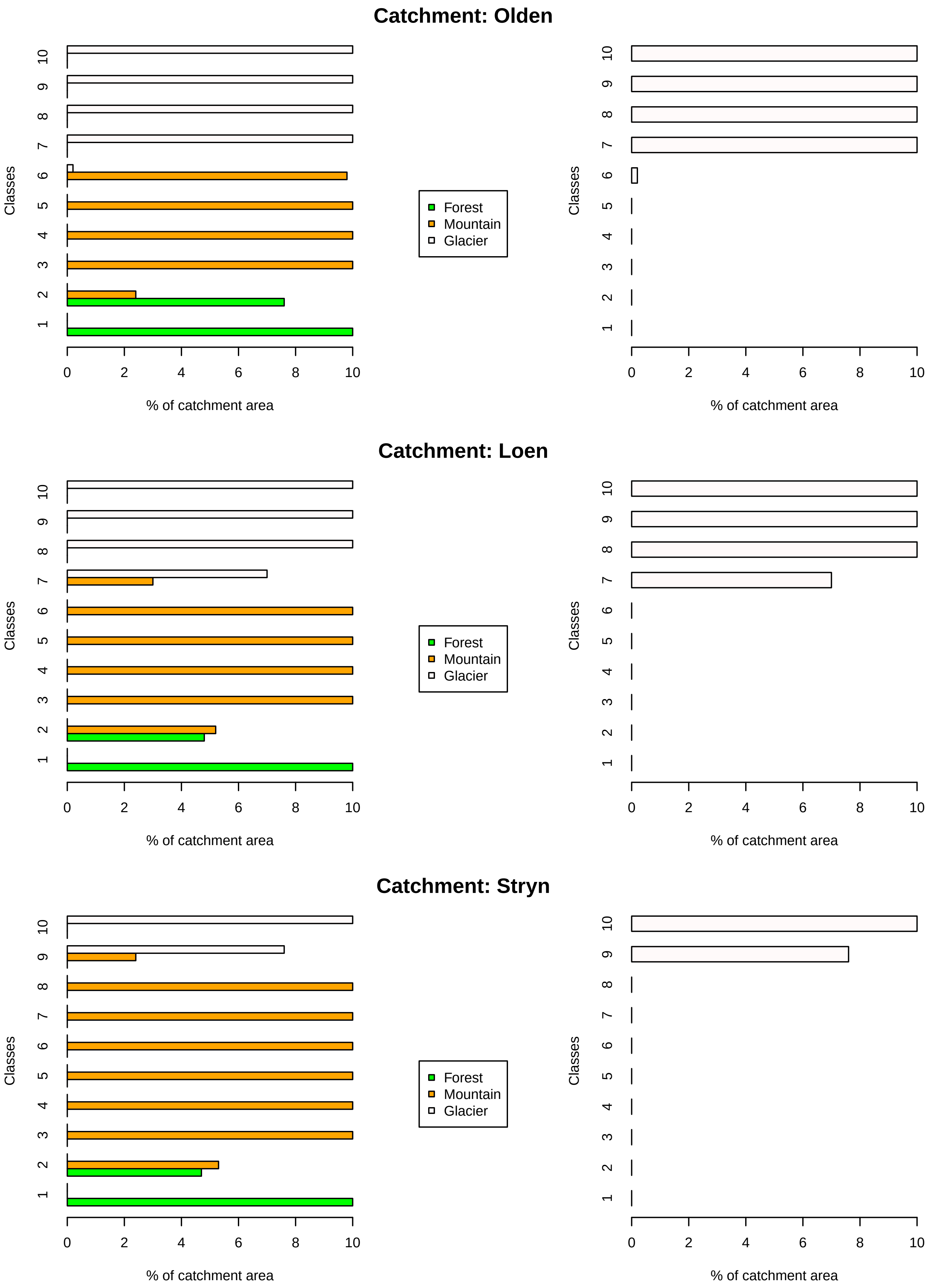
# Stryn


Legend
Outlet
Glaciers 1999 - 2006
Glaciers 1952 - 1981
Stryn
7°0'0"E
7°30'0"E
62°0'0"N
62°0'0"N
61°45'0"N
7°0'0"E
7°30'0"E
N
0
2
4
8
12
16
Kilometers

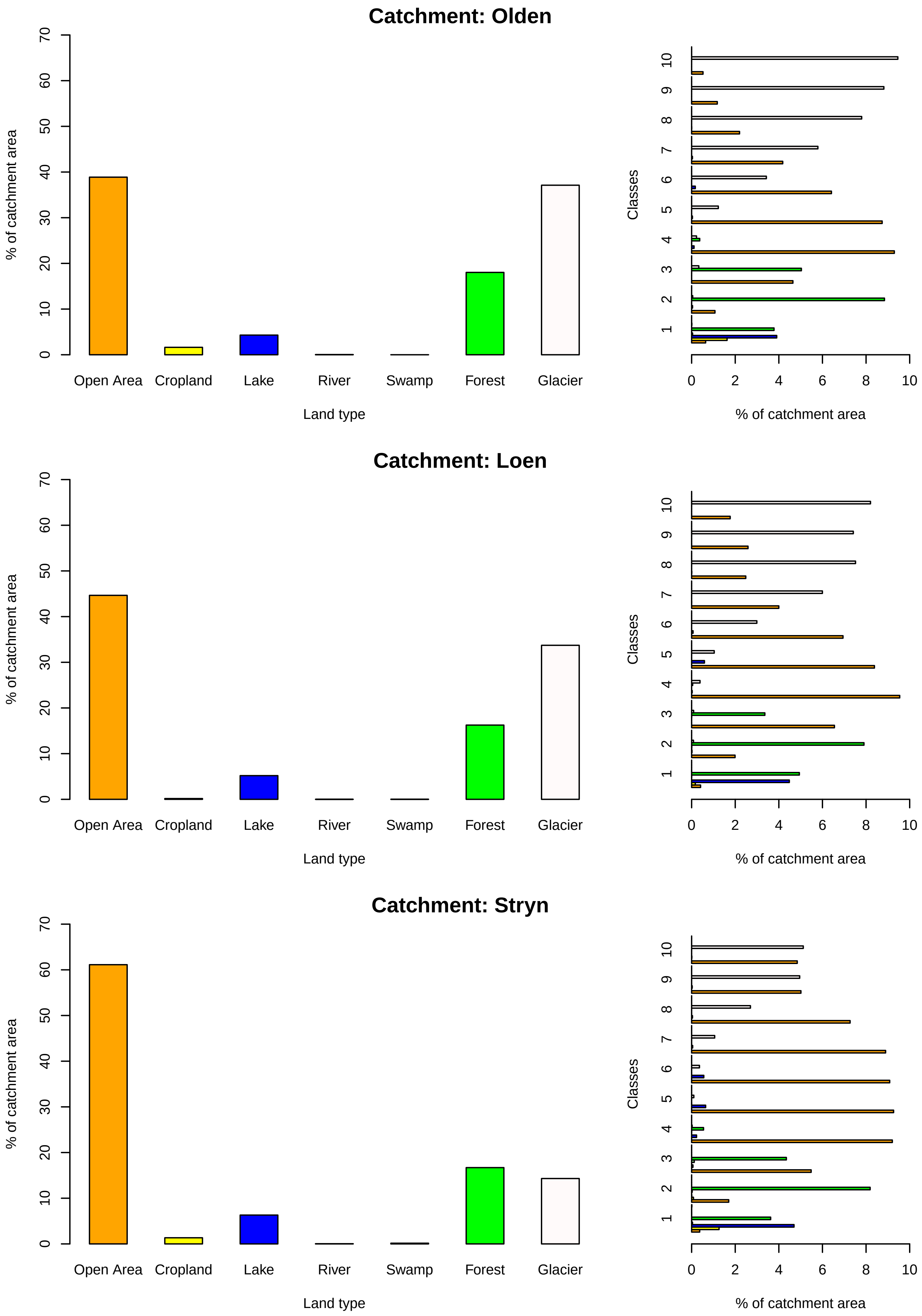
# Proportion of land type in each catchment



## Proportion of land type in each catchment

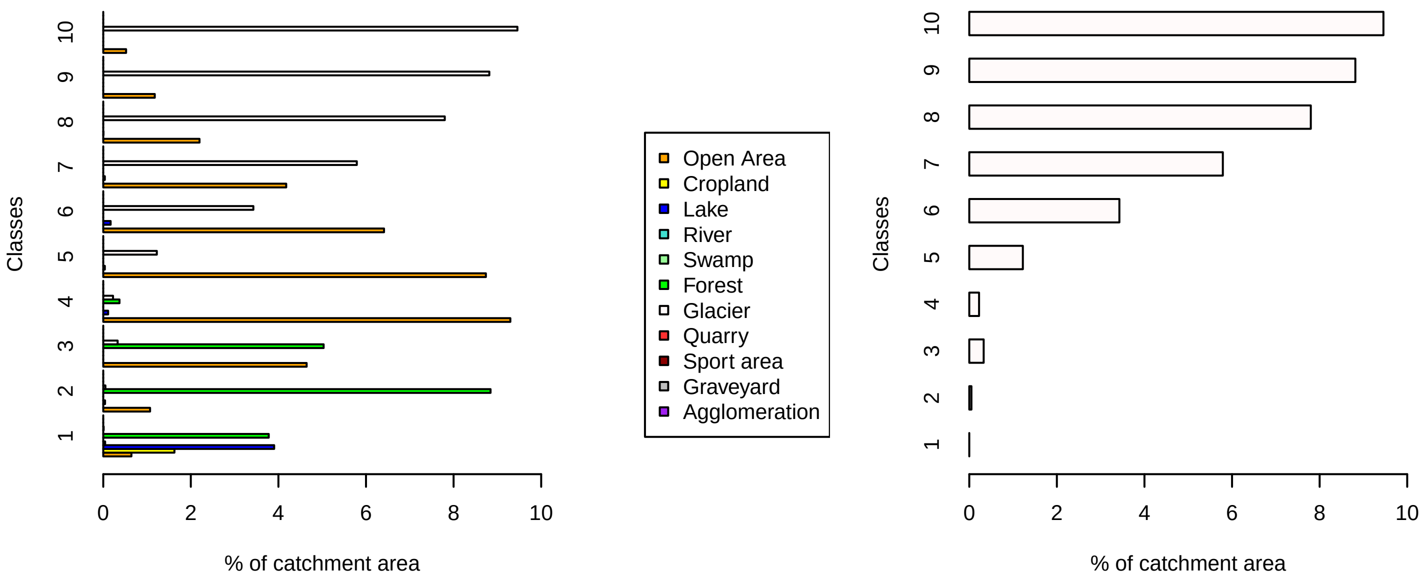


# Proportion of land type in each catchment

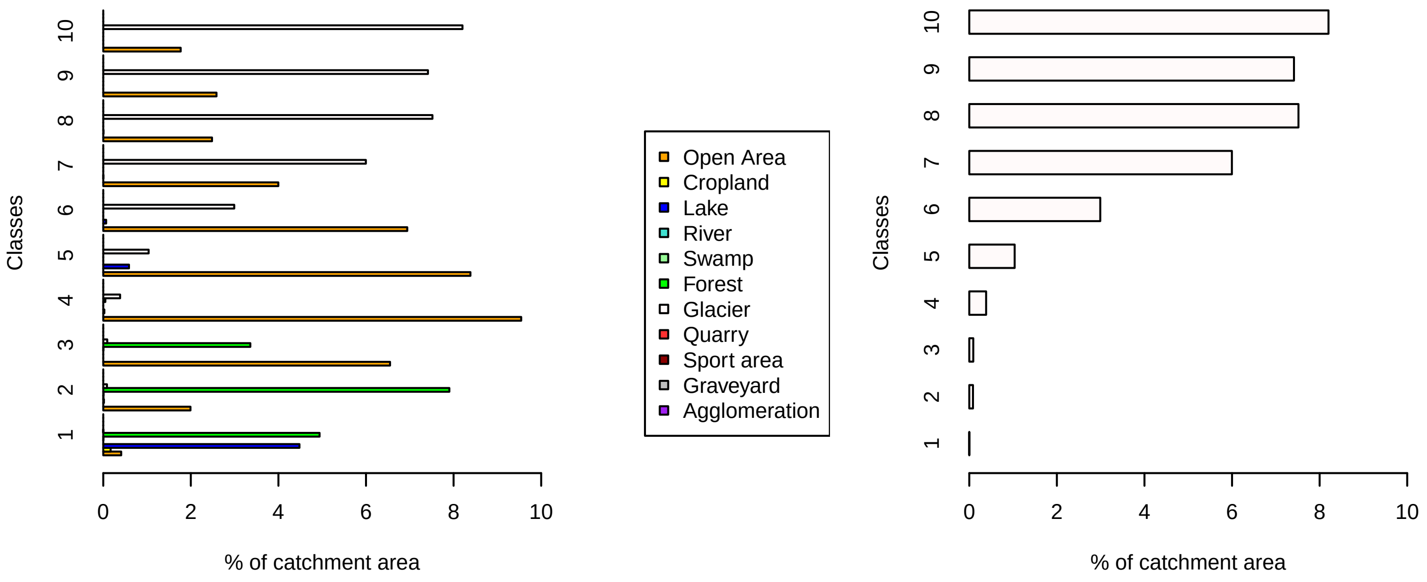


# Proportion of land type in each catchment

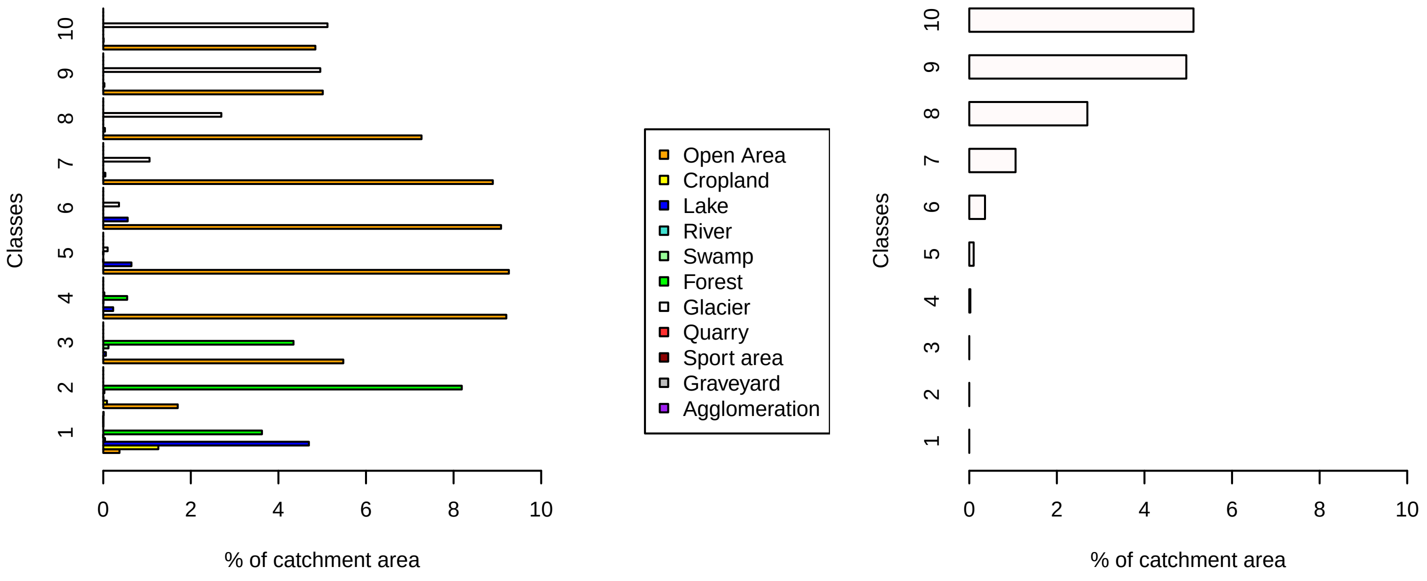
## Catchment: Olden



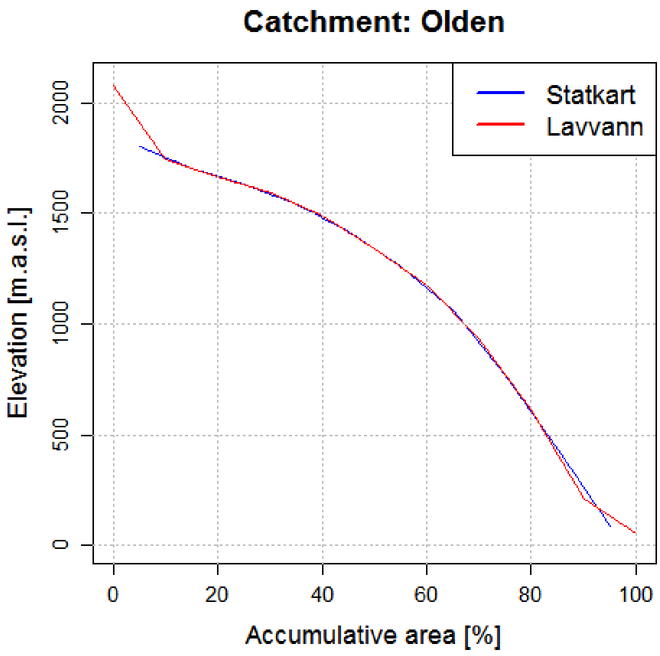
## Catchment: Loen

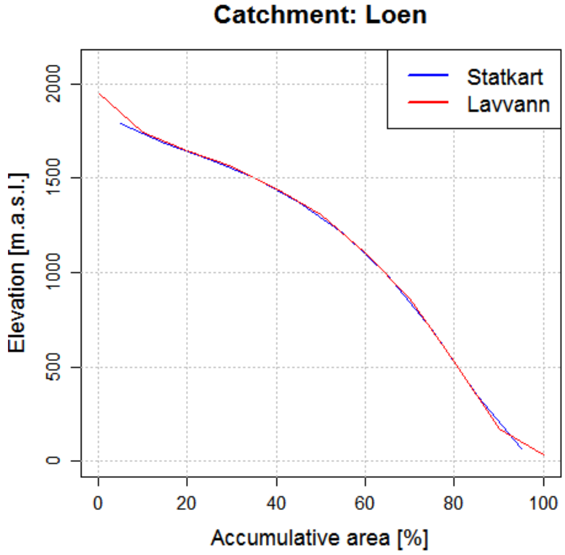


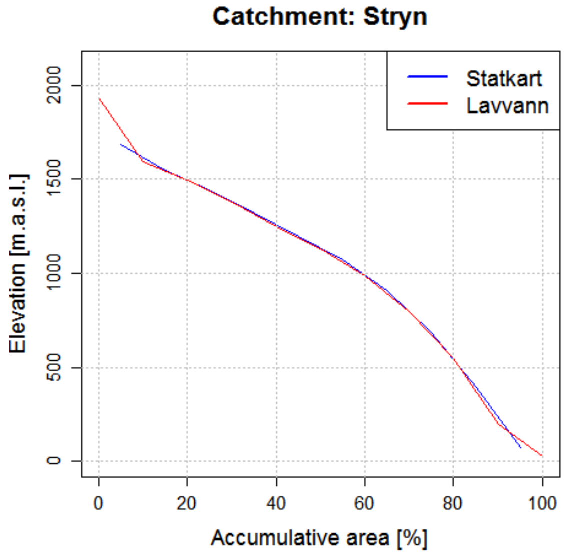
## Catchment: Stryn



## E. HYPSOGRAPHIC CURVES







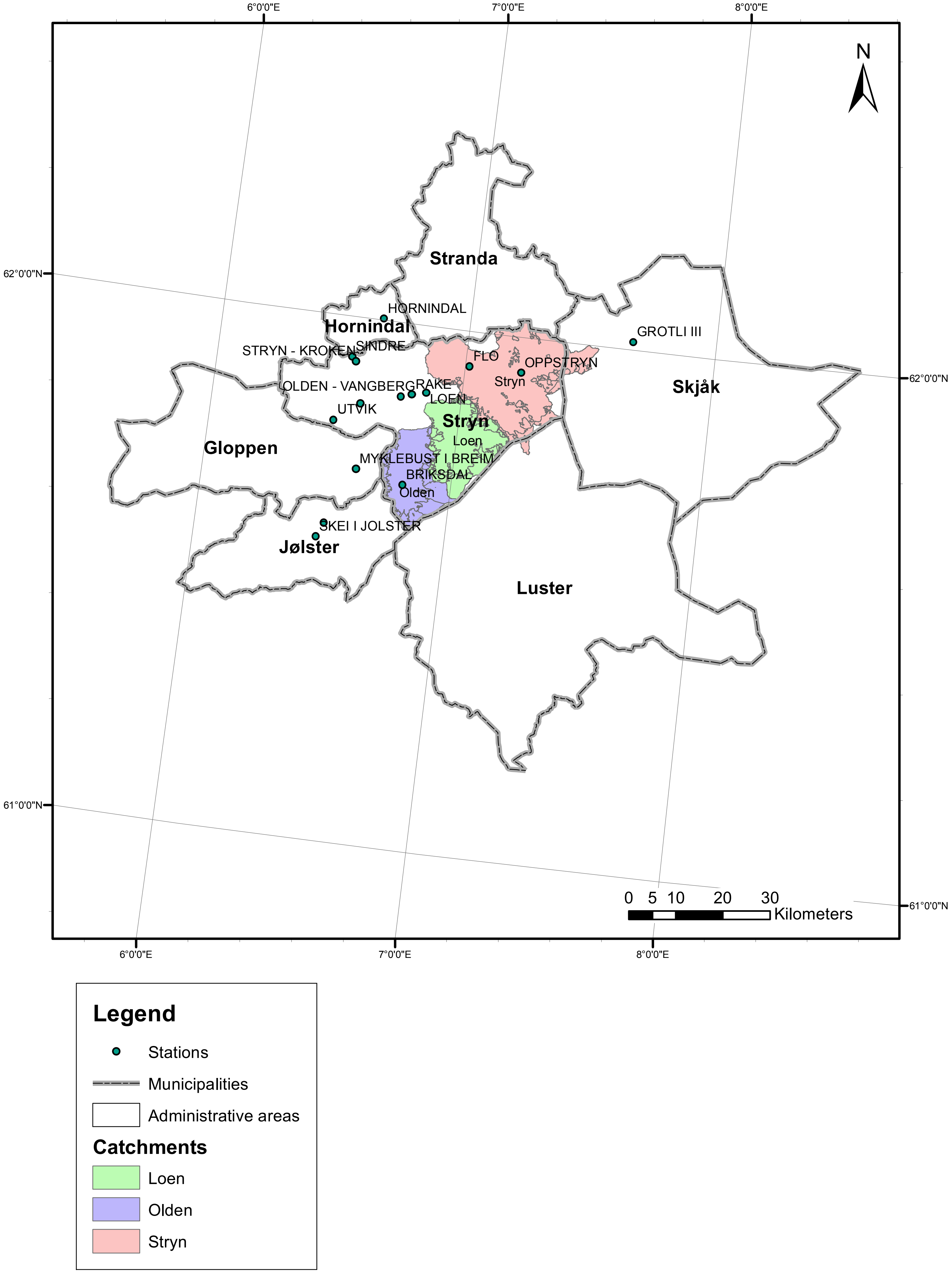
## F. MAP STATIONS

### *a) Precipitation and temperature stations*

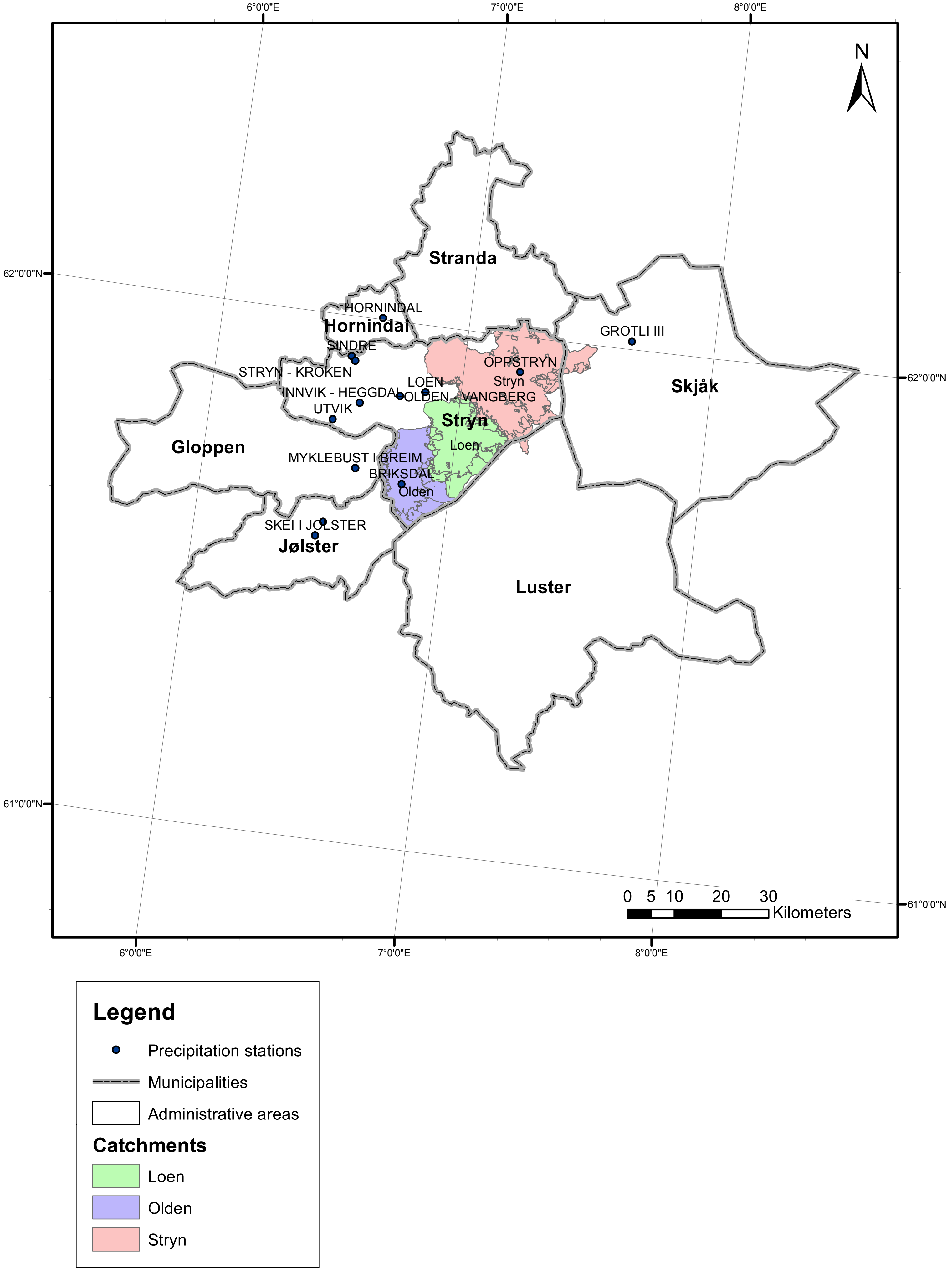
### *b) Precipitation stations*

### *c) Temperature stations*

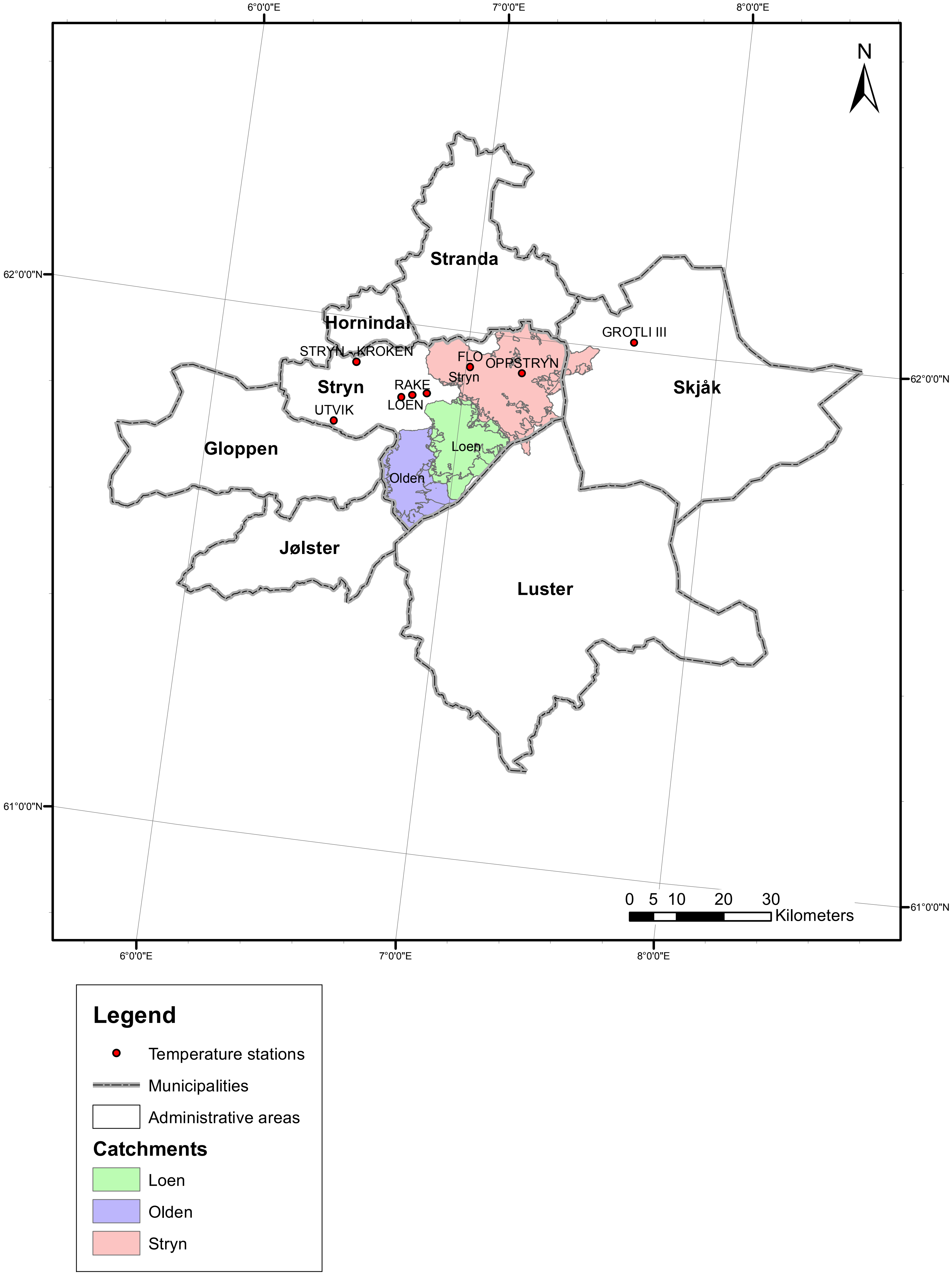
# Catchments area



# Catchments area



# Catchments area



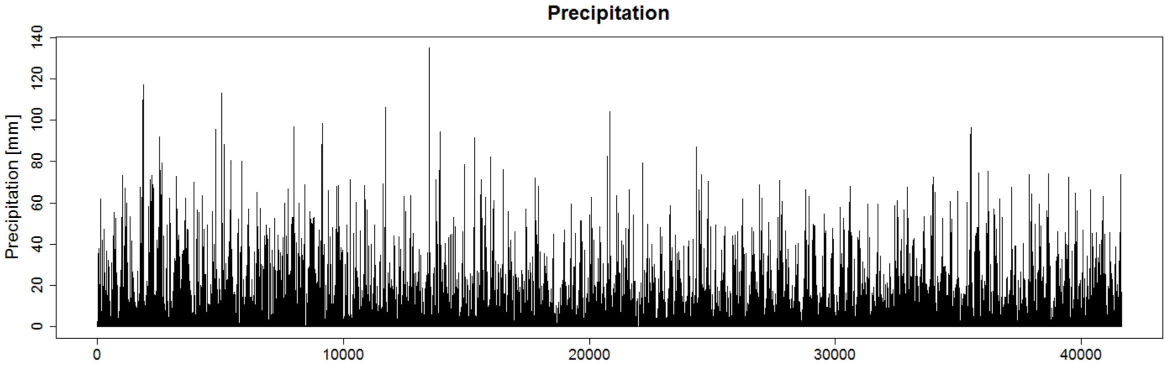
## G. STATIONS

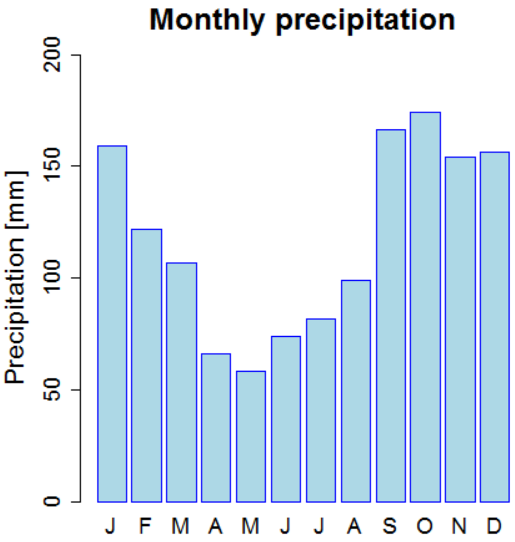
| Stnr | Name | Operates from | Operates until | Altitude | Latitude | Longitude | Municipality | County | T | P |
|---|---|---|---|---|---|---|---|---|---|---|
| 15890 | Grotli III | 01.10.2008 | 31.12.2013 | 872 | 62.02 | 7.66 | Skjåk | Oppland | ✓ | ✓ |
| 57390 | Skei i jolster | 01.07.1969 | 31.12.2013 | 205 | 61.58 | 6.49 | Jølster | S.o.F. |  | ✓ |
| 58120 | Klakegg – Bolset | 01.09.1985 | 30.11.2005 | 187 | 61.60 | 6.51 | Jølster | S.o.F. |  | ✓ |
| 58320 | Myklebust i Breim | 01.01.1900 | 31.12.2013 | 315 | 61.71 | 6.62 | Gloppen | S.o.F. |  | ✓ |
| 58370 | Utvik | 01.06.1962 | 31.01.1969 | 4 | 61.80 | 6.50 | Stryn | S.o.F. | ✓ | ✓ |
| 58390 | Innvik - Heggdal | 17.10.2005 | 31.12.2013 | 70 | 61.84 | 6.60 | Stryn | S.o.F. |  | ✓ |
| 58400 | Innvik | 01.01.1950 | 06.01.2006 | 32 | 61.85 | 6.63 | Stryn | S.o.F. |  | ✓ |
| 58430 | Olden – Vangberg | 01.07.1973 | 31.12.1992 | 78 | 61.86 | 6.76 | Stryn | S.o.F. | ✓ | ✓ |
| 58480 | Briksdal | 01.01.1900 | 31.12.2013 | 40 | 61.69 | 6.81 | Stryn | S.o.F. |  | ✓ |
| 58500 | Loen | 01.04.1971 | 31.03.1988 | 39 | 61.87 | 6.86 | Stryn | S.o.F. | ✓ | ✓ |
| 58530 | Rake | 01.11.1974 | 31.05.1983 | 35 | 61.87 | 6.80 | Stryn | S.o.F. | ✓ |  |
| 58531 | Rake II | 01.11.1974 | 31.05.1983 | 2 | 61.87 | 6.80 | Stryn | S.o.F. | ✓ |  |
| 58532 | Rake III | 01.11.1974 | 30.04.1983 | 62 | 61.87 | 6.80 | Stryn | S.o.F. | ✓ |  |
| 58660 | Flo | 13.05.1983 | 31.08.1988 | 40 | 61.93 | 7.02 | Stryn | S.o.F. | ✓ |  |
| 58700 | Oppstryn | 01.01.1900 | 31.01.1991 | 201 | 61.93 | 7.23 | Stryn | S.o.F. | ✓ | ✓ |
| 58880 | Sindre | 01.01.1957 | 30.06.2005 | 118 | 61.92 | 6.54 | Stryn | S.o.F. |  | ✓ |
| 58900 | Stryn - Kroken | 24.11.1993 | 31.12.2013 | 208 | 61.92 | 6.56 | Stryn | S.o.F. | ✓ | ✓ |
| 58960 | Hornindal | 01.01.1900 | 31.12.2013 | 349 | 62.00 | 6.65 | Hornindal | S.o.F. |  | ✓ |

# H. PRECIPITATION: MISSING DATA

| Station n° | 15890 | 57390 | 58120 | 58320 | 58370 | 58390 | 58400 | 58430 | 58500 | 58700 | 58880 | 58900_P | 58960 | Station average | Normal ratio method | Inverse distance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance to Briksdal | 57674.2 | 21484.3 | 18574.3 | 10476.3 | 20177.2 | 19527.7 | NA | 18738.1 | 20136.9 | 3465.3 | 29279.0 | 28063.4 | 35540.0 | NA | NA | NA |
| Annual precipitation | 723.5 | 1839.9 | 1999.9 | 1549.4 | 1042.1 | 1248.7 | 1111.0 | 1365.5 | 1096.7 | 1059.5 | 1597.5 | 1668.0 | 1792.1 | NA | NA | NA |
| 31.07.1908 | NA | NA | NA | 13.5 | NA | NA | NA | NA | NA | 9.5 | NA | NA | 12.3 | 11.8 | 11.6 | 10.6 |
| 05.06.1912 | NA | NA | NA | 0.0 | NA | NA | NA | NA | NA | 0.0 | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 |
| 29.03.1921 | NA | NA | NA | 0.0 | NA | NA | NA | NA | NA | 0.0 | NA | NA | 1.0 | 0.3 | 0.3 | 0.1 |
| 19.05.1927 | NA | NA | NA | 0.0 | NA | NA | NA | NA | NA | 0.0 | NA | NA | 0.5 | 0.2 | 0.1 | 0.0 |
| 21.05.1927 | NA | NA | NA | 0.0 | NA | NA | NA | NA | NA | 0.0 | NA | NA | 0.3 | 0.1 | 0.1 | 0.0 |
| 09.12.1999 | NA | 2.0 | 2.9 | 2.5 | NA | NA | 3.9 | NA | NA | NA | 2.6 | NA | 0.0 | 2.3 | 2.2 | 2.2 |
| 22.10.2004 | NA | 0.1 | NA | 1.6 | NA | NA | 3.0 | NA | NA | NA | 4.6 | 4.5 | 3.5 | 2.9 | 2.7 | 2.4 |
| 27.10.2004 | NA | 5.4 | NA | 1.3 | NA | NA | 1.2 | NA | NA | NA | 1.1 | 1.6 | 2.0 | 2.1 | 1.8 | 2.2 |
| 03.11.2004 | NA | 0.2 | NA | 0.1 | NA | NA | 0.3 | NA | NA | NA | 0.2 | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 |
| 07.11.2004 | NA | 0.4 | NA | 0.0 | NA | NA | 0.2 | NA | NA | NA | 0.1 | 3.0 | 0.0 | 0.6 | 0.5 | 0.5 |
| 25.11.2004 | NA | 24.5 | NA | 13.0 | NA | NA | 10.0 | NA | NA | NA | 19.6 | 21.8 | 22.1 | 18.5 | 16.1 | 18.5 |
| 08.12.2004 | NA | 12.1 | NA | 28.2 | NA | NA | 9.1 | NA | NA | NA | NA | 20.5 | 13.8 | 16.7 | 15.0 | 21.3 |
| 28.05.2005 | NA | 6.0 | NA | 3.8 | NA | NA | 0.2 | NA | NA | NA | 1.6 | 1.6 | 3.6 | 2.8 | 2.3 | 3.6 |
| 30.05.2005 | NA | 6.0 | NA | 5.8 | NA | NA | 13.0 | NA | NA | NA | 6.6 | 4.8 | 11.8 | 8.0 | 7.6 | 6.5 |
| 04.06.2005 | NA | 4.0 | NA | 0.0 | NA | NA | 3.0 | NA | NA | NA | 6.1 | 1.2 | 5.6 | 3.3 | 3.0 | 2.5 |
| 05.06.2005 | NA | 2.2 | NA | 1.8 | NA | NA | 1.7 | NA | NA | NA | 0.3 | 1.7 | 1.5 | 1.5 | 1.4 | 1.6 |
| 18.06.2005 | NA | 0.3 | NA | 12.2 | NA | NA | 4.0 | NA | NA | NA | 1.5 | 3.1 | 5.7 | 4.5 | 4.2 | 6.3 |
| 19.06.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.0 | NA | NA | NA | 0.1 | 0.0 | 3.5 | 0.6 | 0.5 | 0.4 |
| 24.06.2005 | NA | 14.6 | NA | 7.0 | NA | NA | 2.4 | NA | NA | NA | 3.6 | 4.3 | 6.4 | 6.4 | 5.4 | 7.5 |
| 25.06.2005 | NA | 1.0 | NA | 4.8 | NA | NA | 0.0 | NA | NA | NA | 0.3 | 0.0 | 0.5 | 1.1 | 1.0 | 2.2 |
| 26.06.2005 | NA | 1.2 | NA | 1.8 | NA | NA | 1.1 | NA | NA | NA | 1.3 | 1.0 | 2.4 | 1.5 | 1.3 | 1.6 |
| 27.06.2005 | NA | 7.7 | NA | 4.3 | NA | NA | 1.5 | NA | NA | NA | 2.4 | 1.4 | 4.5 | 3.6 | 3.1 | 4.3 |
| 28.06.2005 | NA | 4.1 | NA | 4.0 | NA | NA | 1.8 | NA | NA | NA | 1.0 | 0.4 | 6.2 | 2.9 | 2.5 | 3.3 |
| 02.08.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.0 | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 05.08.2005 | NA | 31.3 | NA | 20.0 | NA | NA | 8.4 | NA | NA | NA | NA | 15.4 | 12.5 | 17.5 | 15.2 | 20.7 |
| 07.08.2005 | NA | 2.0 | NA | 4.9 | NA | NA | 0.5 | NA | NA | NA | NA | 0.7 | 0.6 | 1.7 | 1.5 | 2.9 |
| 09.08.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.2 | NA | NA | NA | NA | 0.0 | 0.1 | 0.1 | 0.1 | 0.0 |
| 11.08.2005 | NA | 0.0 | NA | 0.6 | NA | NA | 0.2 | NA | NA | NA | NA | 0.0 | 0.9 | 0.3 | 0.3 | 0.4 |
| 14.08.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.2 | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| 16.08.2005 | NA | 9.2 | NA | 3.4 | NA | NA | 6.0 | NA | NA | NA | NA | 4.4 | 5.6 | 5.7 | 5.2 | 5.2 |
| 19.08.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.1 | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 22.08.2005 | NA | 0.0 | NA | 0.0 | NA | NA | 0.0 | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 23.07.2013 | 0.1 | 0.0 | NA | 0.1 | NA | 0.0 | NA | NA | NA | NA | NA | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

## I. PRECIPITATION RECORD

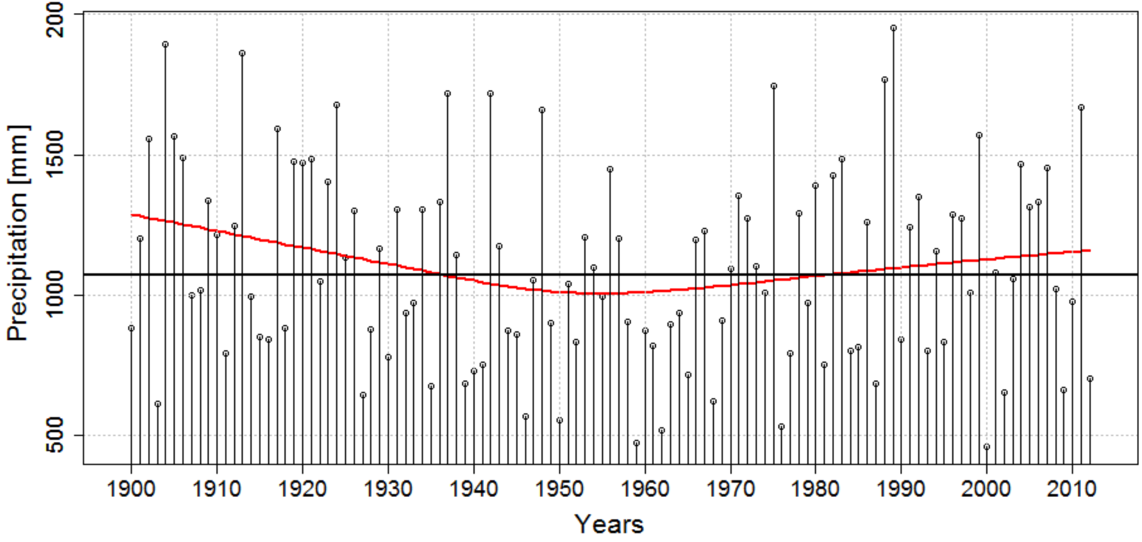




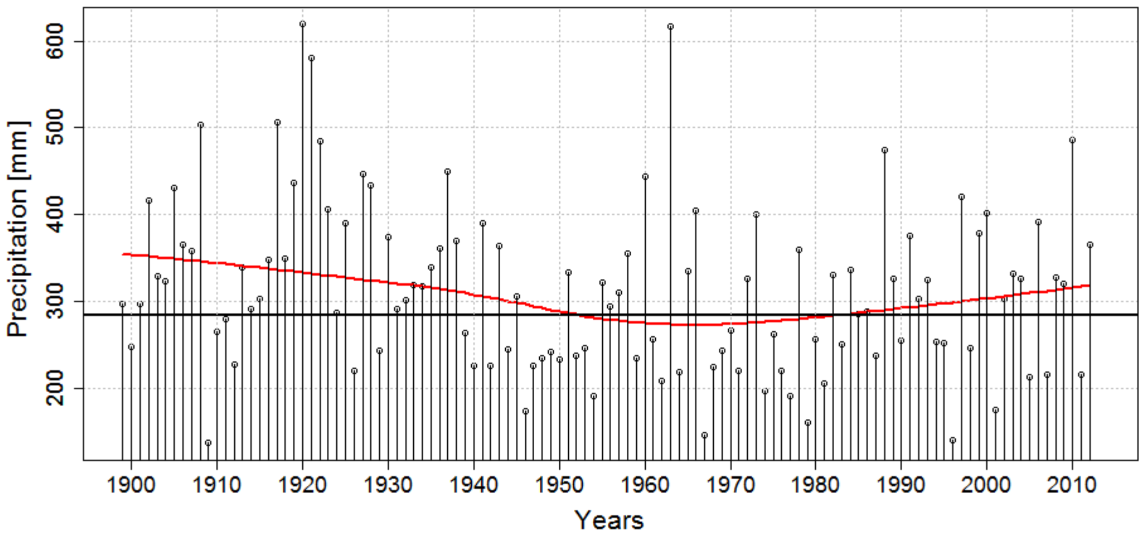
Monthly precipitation over the period of record for Briksdal station

| | Monthly precipitation | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Period | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec. |
| 1900-2012 | 159 | 122 | 106 | 66 | 58 | 74 | 82 | 99 | 167 | 174 | 154 | 156 |
| 1961-1990 | 135 | 91 | 111 | 50 | 48 | 70 | 83 | 88 | 185 | 179 | 158 | 174 |
| 1971-2000 | 166 | 123 | 114 | 65 | 51 | 70 | 75 | 88 | 161 | 166 | 168 | 187 |
| 2001-2012 | 157 | 113 | 108 | 60 | 71 | 70 | 74 | 94 | 180 | 151 | 182 | 167 |

| Period | Annual precipitation |
|---|---|
| 1900-2012 | 1417 |
| 1961-1990 | 1372 |
| 1971-2000 | 1434 |
| 2001-2012 | 1426 |

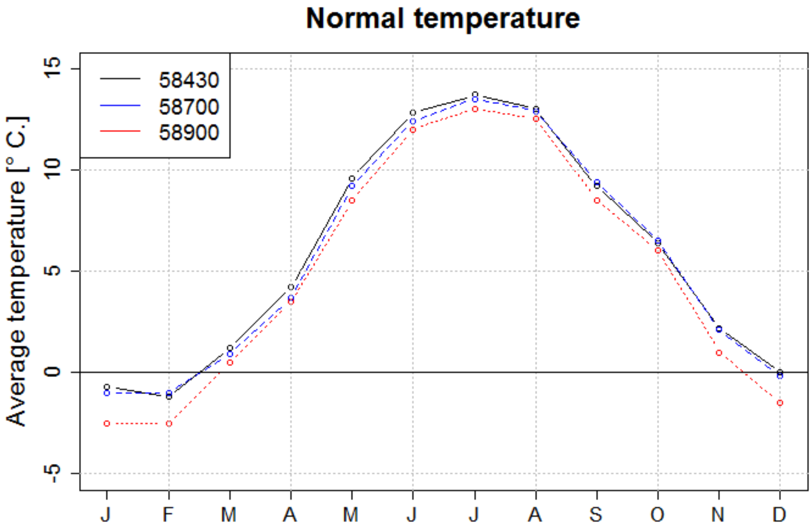


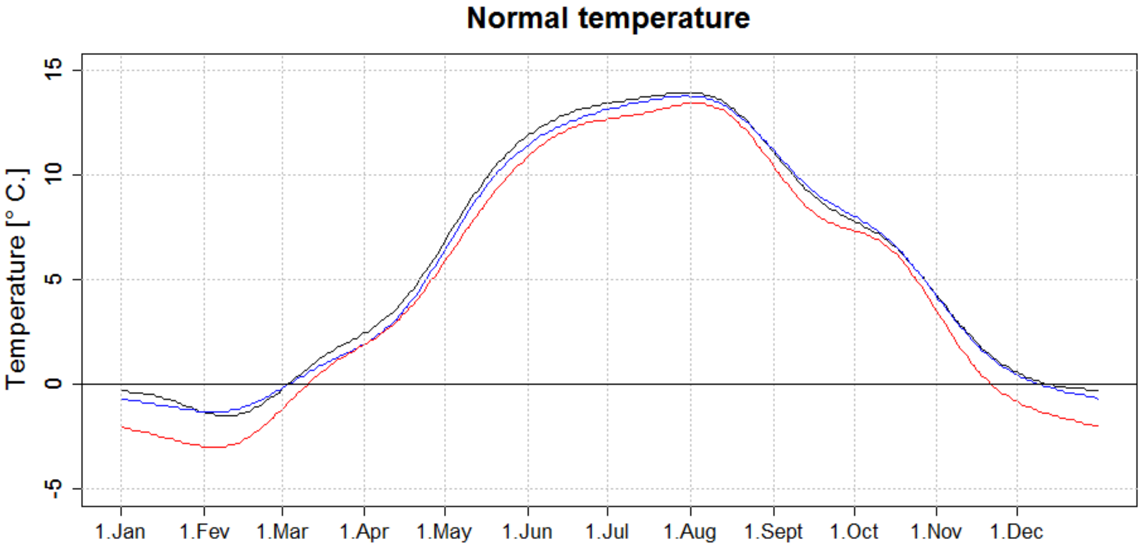
Precipitation in winter



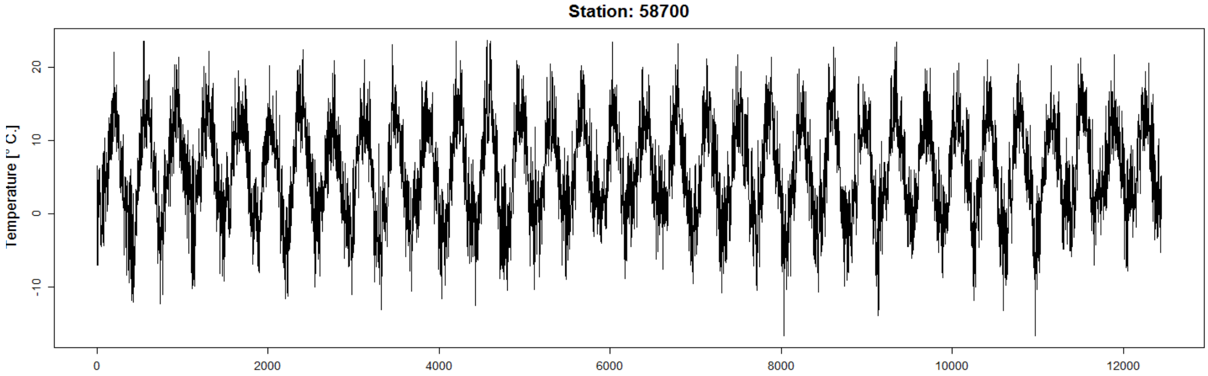
Precipitation in summer

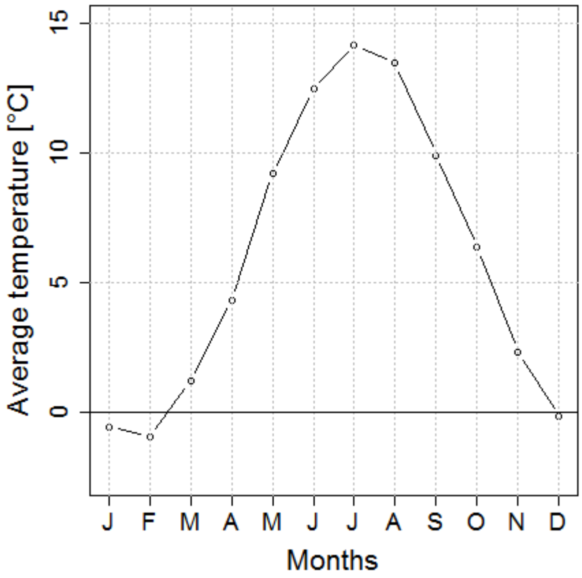
## J. COMPARISON BETWEEN NORMAL TEMPERATURE





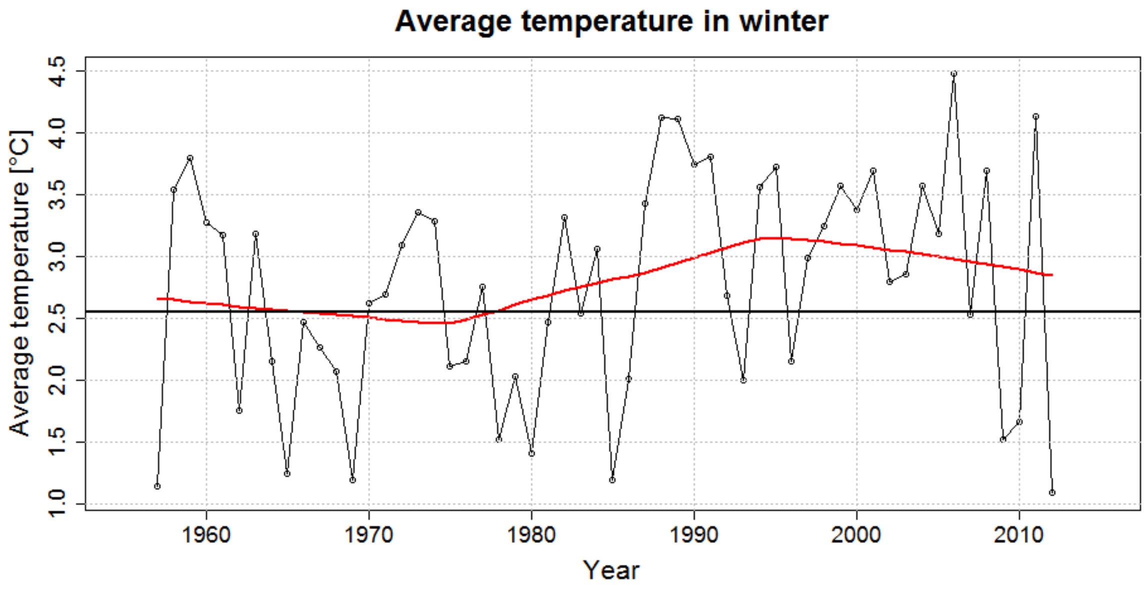
## K. OPPSTRYN TEMPERATURE

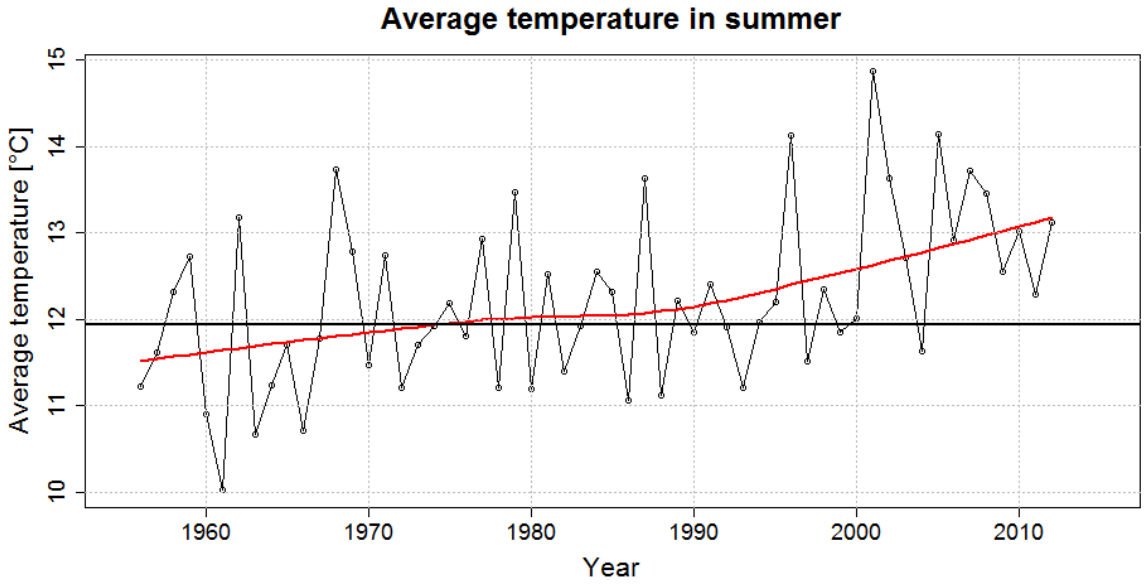




Average temperature over period of record

## L. TEMPERATURE RECORD


Average temperature in winter


Average temperature in summer

## M. EVAPOTRANSPIRATION DATA

| Fordampning | Middel for hele obs.perioden (mm/dag) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dag nr | Januar | Februar | Mars | April | Mai | Juni | Juli | August | September | Oktober | November | Desember |
| 1 | 0.0 | 0.0 | 0.1 | 0.7 | 2.0 | 3.4 | 3.9 | 3.6 | 2.6 | 1.6 | 0.7 | 0.2 |
| 2 | 0.0 | 0.0 | 0.1 | 0.7 | 2.0 | 3.4 | 3.9 | 3.6 | 2.6 | 1.6 | 0.7 | 0.1 |
| 3 | 0.0 | 0.0 | 0.2 | 0.8 | 2.1 | 3.4 | 3.9 | 3.6 | 2.6 | 1.5 | 0.7 | 0.1 |
| 4 | 0.0 | 0.0 | 0.2 | 0.8 | 2.1 | 3.5 | 3.9 | 3.5 | 2.5 | 1.5 | 0.6 | 0.1 |
| 5 | 0.0 | 0.0 | 0.2 | 0.8 | 2.2 | 3.5 | 4.0 | 3.5 | 2.5 | 1.5 | 0.6 | 0.1 |
| 6 | 0.0 | 0.0 | 0.2 | 0.8 | 2.2 | 3.5 | 4.0 | 3.5 | 2.4 | 1.4 | 0.6 | 0.1 |
| 7 | 0.0 | 0.0 | 0.2 | 0.9 | 2.3 | 3.6 | 4.0 | 3.5 | 2.4 | 1.4 | 0.6 | 0.1 |
| 8 | 0.0 | 0.0 | 0.2 | 0.9 | 2.4 | 3.6 | 4.0 | 3.4 | 2.3 | 1.4 | 0.5 | 0.1 |
| 9 | 0.0 | 0.0 | 0.2 | 0.9 | 2.4 | 3.7 | 4.0 | 3.4 | 2.3 | 1.4 | 0.5 | 0.1 |
| 10 | 0.0 | 0.0 | 0.2 | 0.9 | 2.5 | 3.7 | 4.0 | 3.4 | 2.3 | 1.3 | 0.5 | 0.1 |
| 11 | 0.0 | 0.0 | 0.2 | 1.0 | 2.5 | 3.7 | 4.0 | 3.4 | 2.2 | 1.3 | 0.4 | 0.0 |
| 12 | 0.0 | 0.0 | 0.2 | 1.0 | 2.6 | 3.8 | 4.0 | 3.4 | 2.2 | 1.3 | 0.4 | 0.0 |
| 13 | 0.0 | 0.0 | 0.2 | 1.0 | 2.6 | 3.8 | 4.0 | 3.3 | 2.1 | 1.2 | 0.4 | 0.0 |
| 14 | 0.0 | 0.0 | 0.3 | 1.0 | 2.7 | 3.8 | 4.0 | 3.3 | 2.1 | 1.2 | 0.4 | 0.0 |
| 15 | 0.0 | 0.0 | 0.3 | 1.1 | 2.7 | 3.9 | 4.0 | 3.3 | 2.1 | 1.2 | 0.3 | 0.0 |
| 16 | 0.0 | 0.0 | 0.3 | 1.1 | 2.8 | 3.9 | 4.0 | 3.3 | 2.0 | 1.2 | 0.3 | 0.0 |
| 17 | 0.0 | 0.0 | 0.3 | 1.1 | 2.8 | 3.9 | 4.0 | 3.2 | 2.0 | 1.1 | 0.3 | 0.0 |
| 18 | 0.0 | 0.0 | 0.3 | 1.2 | 2.8 | 3.9 | 3.9 | 3.2 | 2.0 | 1.1 | 0.3 | 0.0 |
| 19 | 0.0 | 0.0 | 0.3 | 1.3 | 2.9 | 3.9 | 3.9 | 3.2 | 2.0 | 1.1 | 0.3 | 0.0 |
| 20 | 0.0 | 0.0 | 0.4 | 1.3 | 2.9 | 3.9 | 3.9 | 3.1 | 1.9 | 1.1 | 0.3 | 0.0 |
| 21 | 0.0 | 0.0 | 0.4 | 1.4 | 3.0 | 3.9 | 3.9 | 3.1 | 1.9 | 1.0 | 0.3 | 0.0 |
| 22 | 0.0 | 0.1 | 0.4 | 1.4 | 3.0 | 3.9 | 3.8 | 3.0 | 1.9 | 1.0 | 0.3 | 0.0 |
| 23 | 0.0 | 0.1 | 0.5 | 1.5 | 3.0 | 3.9 | 3.8 | 3.0 | 1.8 | 1.0 | 0.3 | 0.0 |
| 24 | 0.0 | 0.1 | 0.5 | 1.5 | 3.1 | 3.9 | 3.8 | 3.0 | 1.8 | 0.9 | 0.2 | 0.0 |
| 25 | 0.0 | 0.1 | 0.5 | 1.6 | 3.1 | 3.9 | 3.8 | 2.9 | 1.8 | 0.9 | 0.2 | 0.0 |
| 26 | 0.0 | 0.1 | 0.5 | 1.6 | 3.1 | 3.9 | 3.7 | 2.9 | 1.8 | 0.9 | 0.2 | 0.0 |
| 27 | 0.0 | 0.1 | 0.6 | 1.7 | 3.2 | 3.9 | 3.7 | 2.8 | 1.7 | 0.9 | 0.2 | 0.0 |
| 28 | 0.0 | 0.1 | 0.6 | 1.7 | 3.2 | 3.9 | 3.7 | 2.8 | 1.7 | 0.8 | 0.2 | 0.0 |
| 29 | 0.0 | | 0.6 | 1.8 | 3.2 | 3.9 | 3.7 | 2.8 | 1.7 | 0.8 | 0.2 | 0.0 |
| 30 | 0.0 | | 0.6 | 1.9 | 3.3 | 3.9 | 3.7 | 2.7 | 1.6 | 0.8 | 0.2 | 0.0 |
| 31 | 0.0 | | 0.7 | | 3.3 | | 3.6 | 2.7 | | 0.8 | | 0.0 |

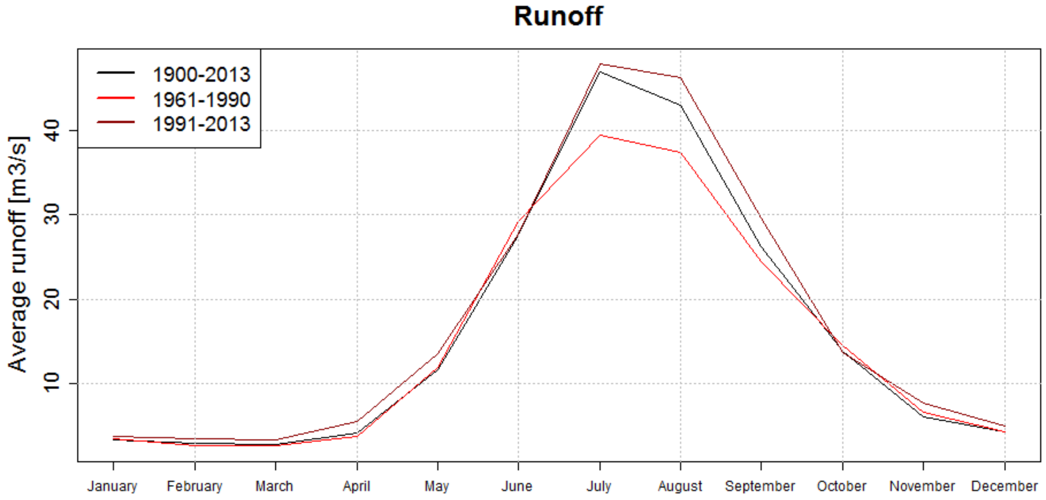
## N. RUNOFF

| Olden | January | February | March | April | May | June | July | August | September | Octobrer | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1900-2013 | 3.99 | 3.44 | 3.18 | 4.01 | 9.93 | 24.67 | 42.54 | 40.52 | 25.94 | 14.38 | 6.87 | 5.00 |
| 1961-1990 | 4.49 | 3.34 | 3.33 | 3.83 | 10.17 | 26.95 | 37.29 | 36.68 | 25.31 | 15.32 | 8.08 | 5.56 |
| 1991-2013 | 3.91 | 3.50 | 3.19 | 4.54 | 10.33 | 24.00 | 44.65 | 44.00 | 28.25 | 12.85 | 7.59 | 5.07 |

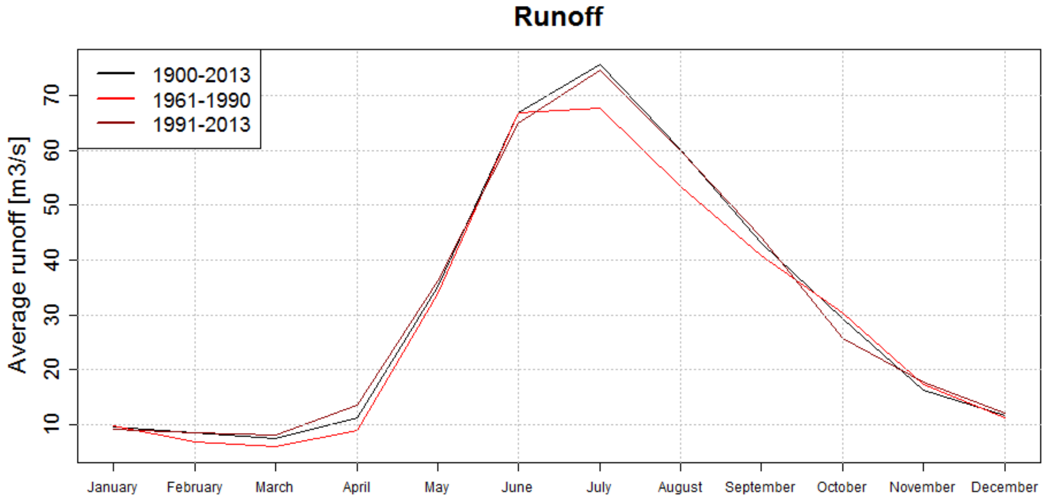
| Loen | January | February | March | April | May | June | July | August | September | Octobrer | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1900-2013 | 3.42 | 2.93 | 2.85 | 4.18 | 11.59 | 27.53 | 46.97 | 43.03 | 26.20 | 13.81 | 6.07 | 4.30 |
| 1961-1990 | 3.53 | 2.63 | 2.67 | 3.70 | 11.94 | 29.16 | 39.41 | 37.44 | 24.47 | 14.46 | 6.66 | 4.31 |
| 1991-2013 | 3.81 | 3.51 | 3.38 | 5.59 | 13.56 | 27.72 | 47.89 | 46.18 | 29.59 | 13.64 | 7.66 | 5.01 |

| Stryn | January | February | March | April | May | June | July | August | September | Octobrer | November | December |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1900-2013 | 9.57 | 8.41 | 7.40 | 11.32 | 35.10 | 66.95 | 75.76 | 60.19 | 43.08 | 29.30 | 16.31 | 11.57 |
| 1961-1990 | 9.75 | 6.70 | 5.90 | 8.82 | 33.87 | 66.84 | 67.71 | 53.54 | 40.79 | 30.26 | 17.39 | 11.30 |
| 1991-2013 | 9.04 | 8.49 | 8.01 | 13.58 | 36.30 | 64.93 | 74.68 | 60.04 | 44.30 | 25.81 | 17.73 | 12.09 |

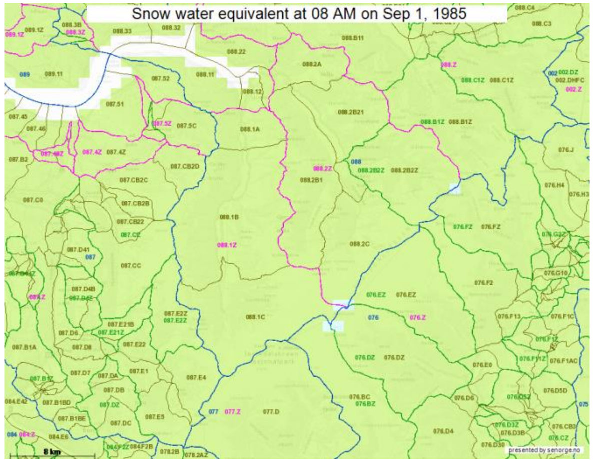
Loen

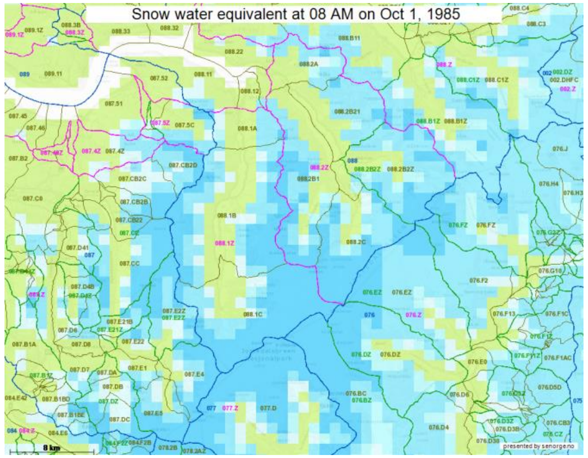

Runoff
1900-2013
1961-1990
1991-2013
Average runoff [m3/s]
10
20
30
40
January
February
March
April
May
June
July
August
September
October
November
December

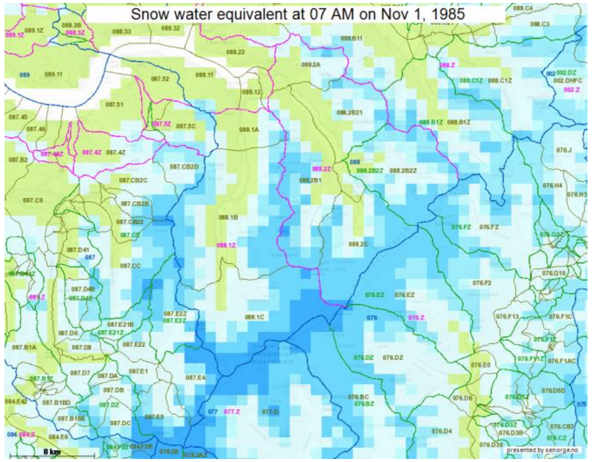
Stryn

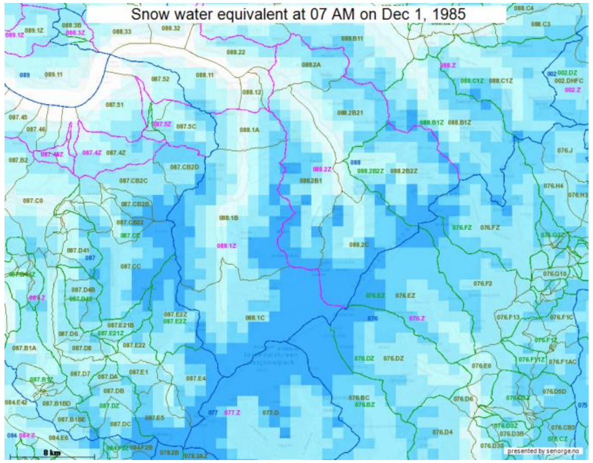

Runoff
1900-2013
1961-1990
1991-2013
Average runoff [m3/s]
10
20
30
40
50
60
70
January
February
March
April
May
June
July
August
September
October
November
December

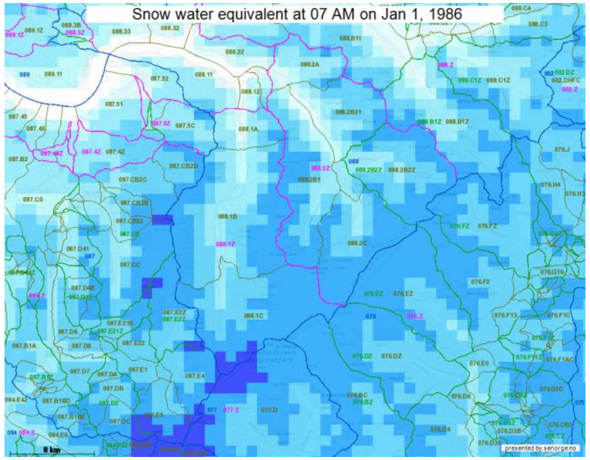
## O. Snow equivalent in 1985-1986

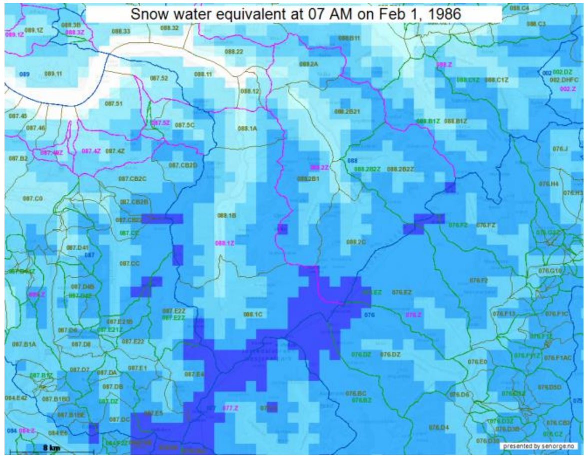

Snow water equivalent at 08 AM on Sep 1, 1985

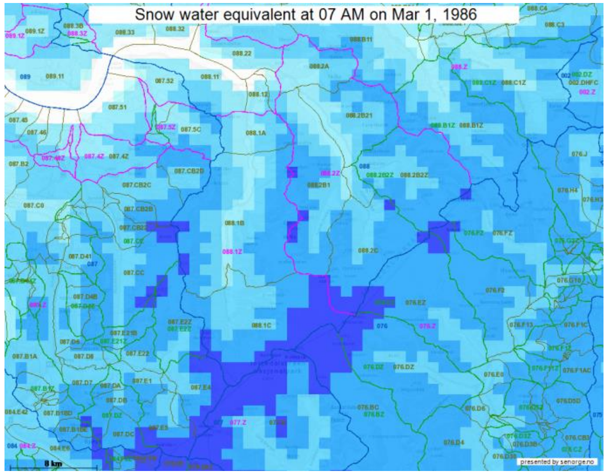

Snow water equivalent at 08 AM on Oct 1, 1985

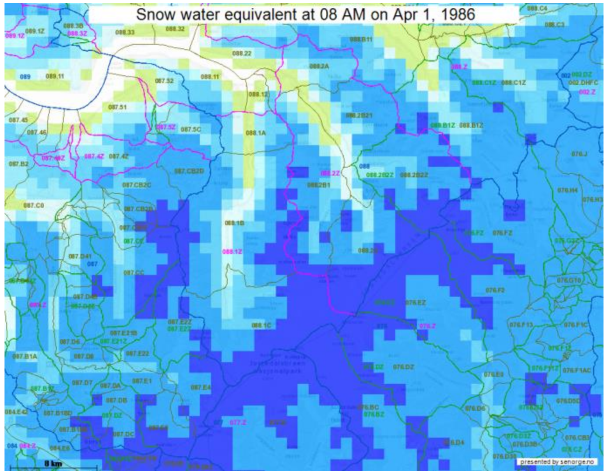

Snow water equivalent at 07 AM on Nov 1, 1985

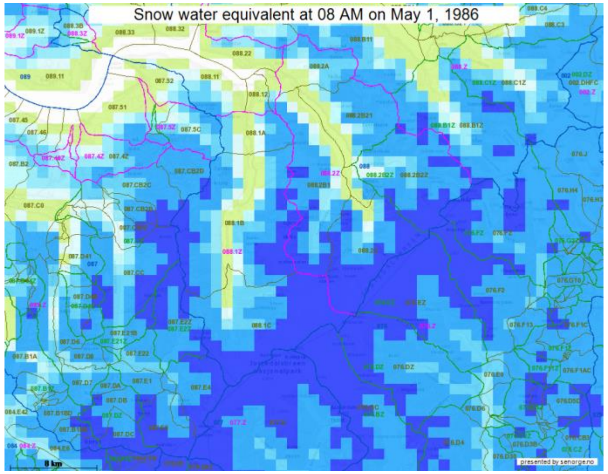

Snow water equivalent at 07 AM on Dec 1, 1985

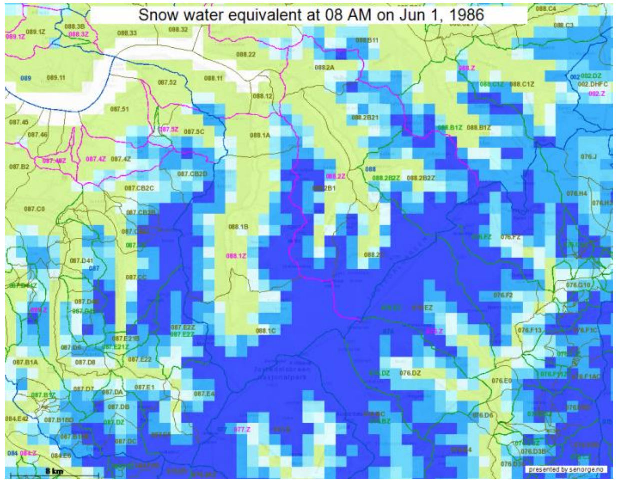

Snow water equivalent at 07 AM on Jan 1, 1986

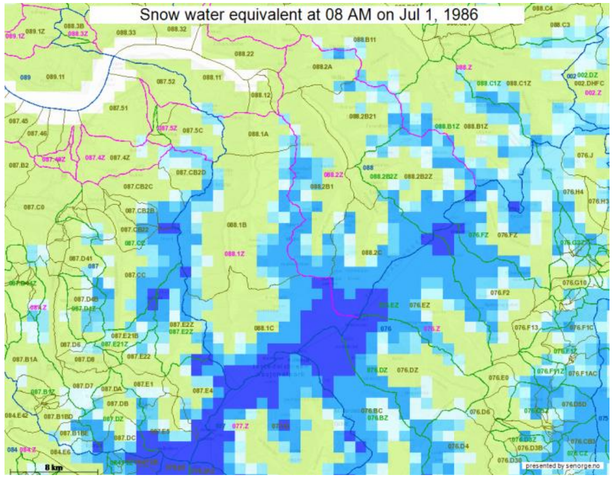

Snow water equivalent at 07 AM on Feb 1, 1986

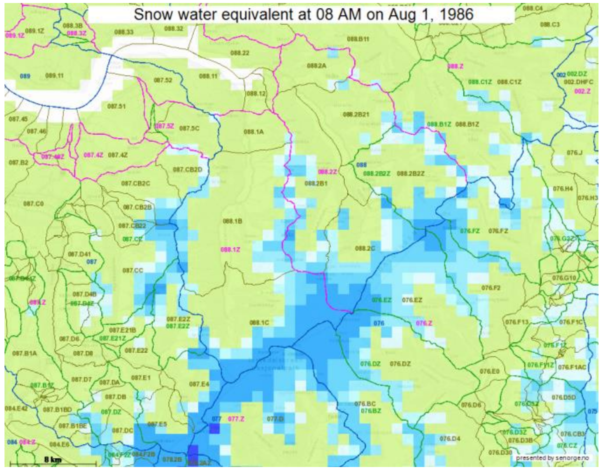

Snow water equivalent at 07 AM on Mar 1, 1986
8 km
presented by senorge.no

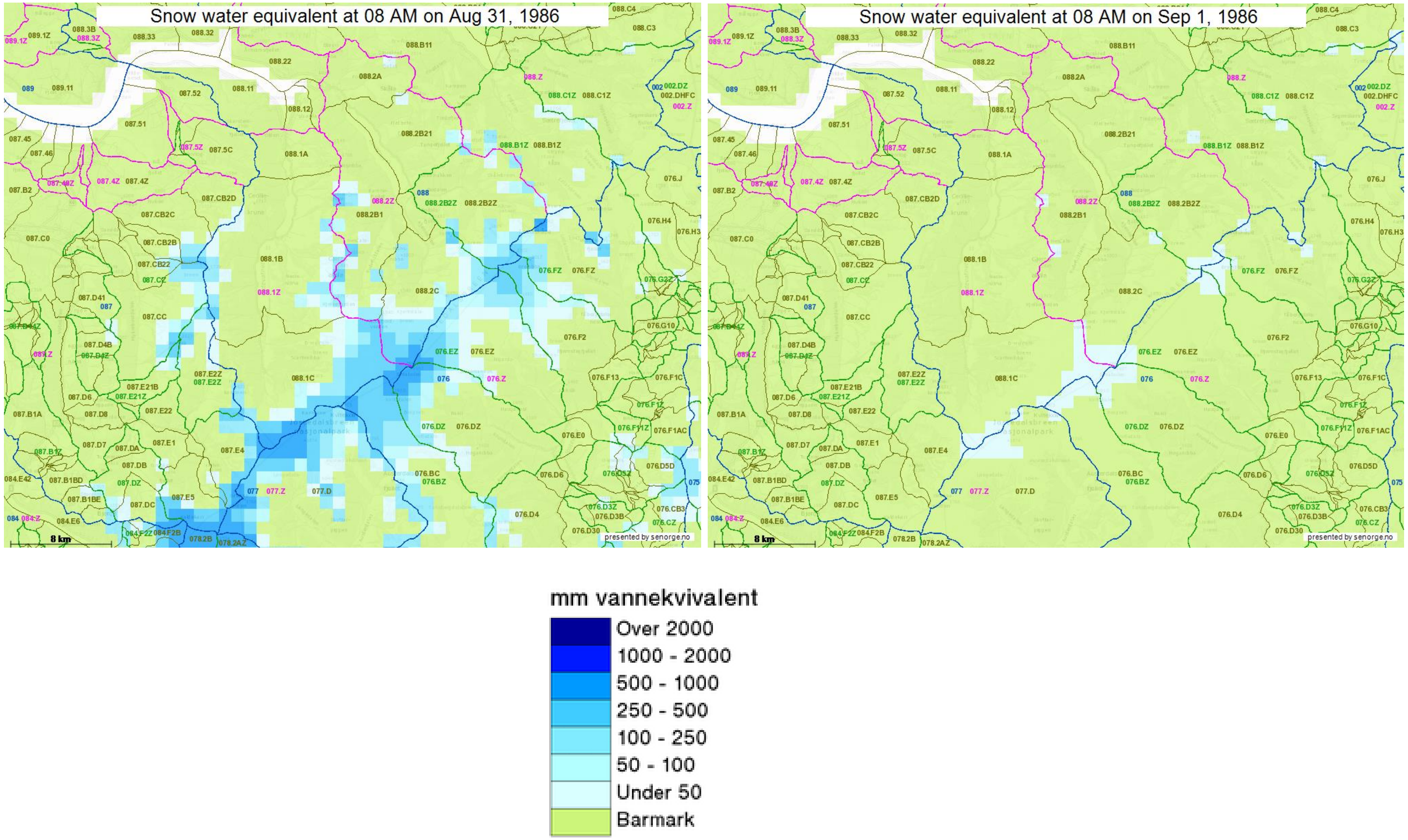

Snow water equivalent at 08 AM on Apr 1, 1986
8 km
presented by senorge.no


Snow water equivalent at 08 AM on May 1, 1986
8 km
presented by senorge.no

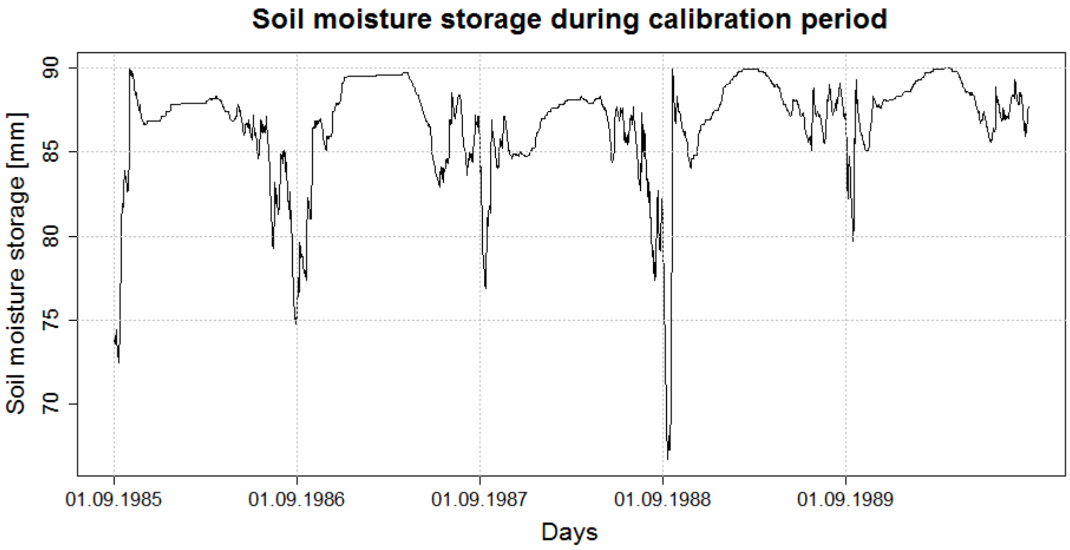

Snow water equivalent at 08 AM on Jun 1, 1986
8 km
presented by senorge.no

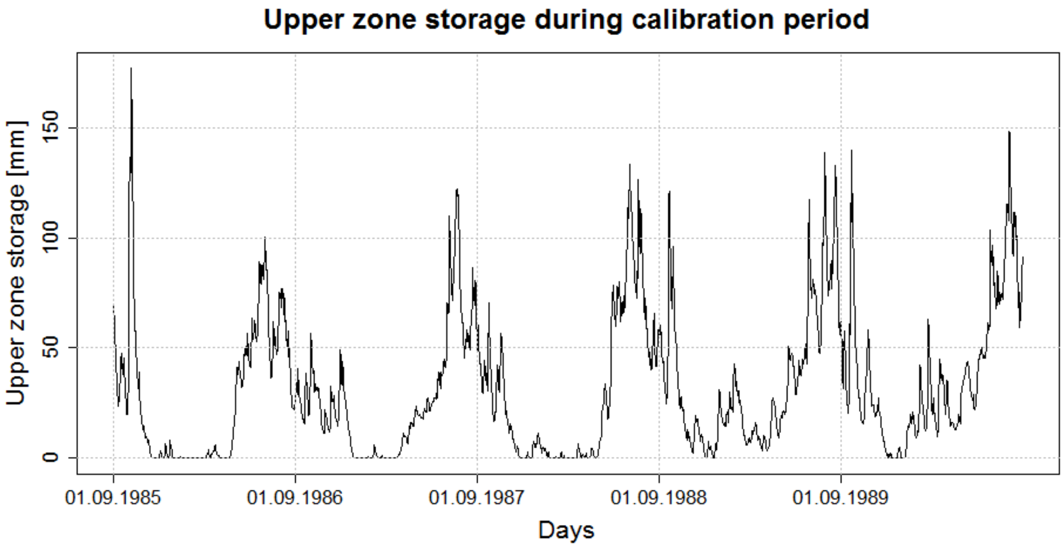

Snow water equivalent at 08 AM on Jul 1, 1986
8 km
presented by senorge.no

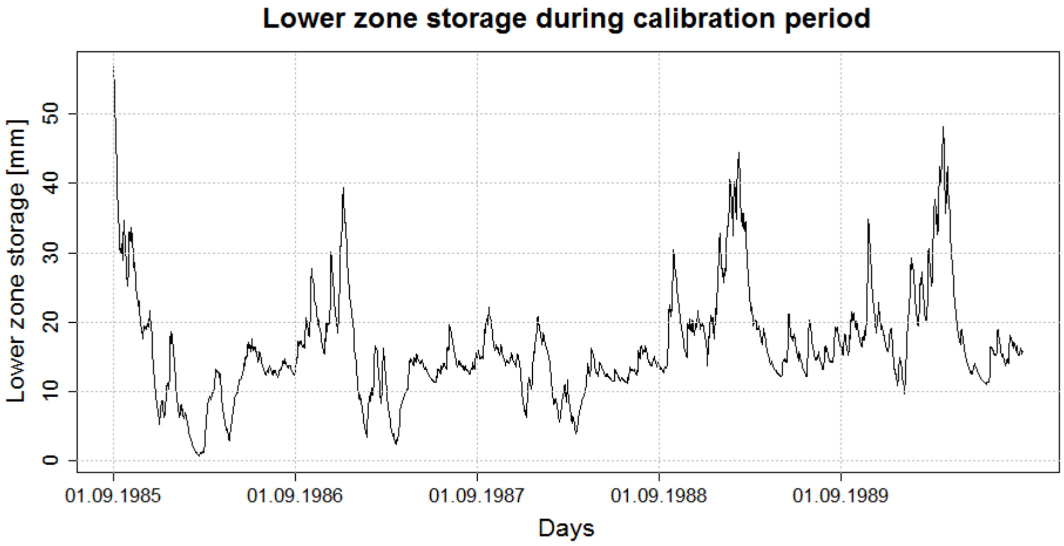

Snow water equivalent at 08 AM on Aug 1, 1986
8 km
presented by senorge.no


Snow water equivalent at 08 AM on Aug 31, 1986
Snow water equivalent at 08 AM on Sep 1, 1986
8 km
presented by senorge.no
mm vannekvivalent
Over 2000
1000 - 2000
500 - 1000
250 - 500
100 - 250
50 - 100
Under 50
Barmark

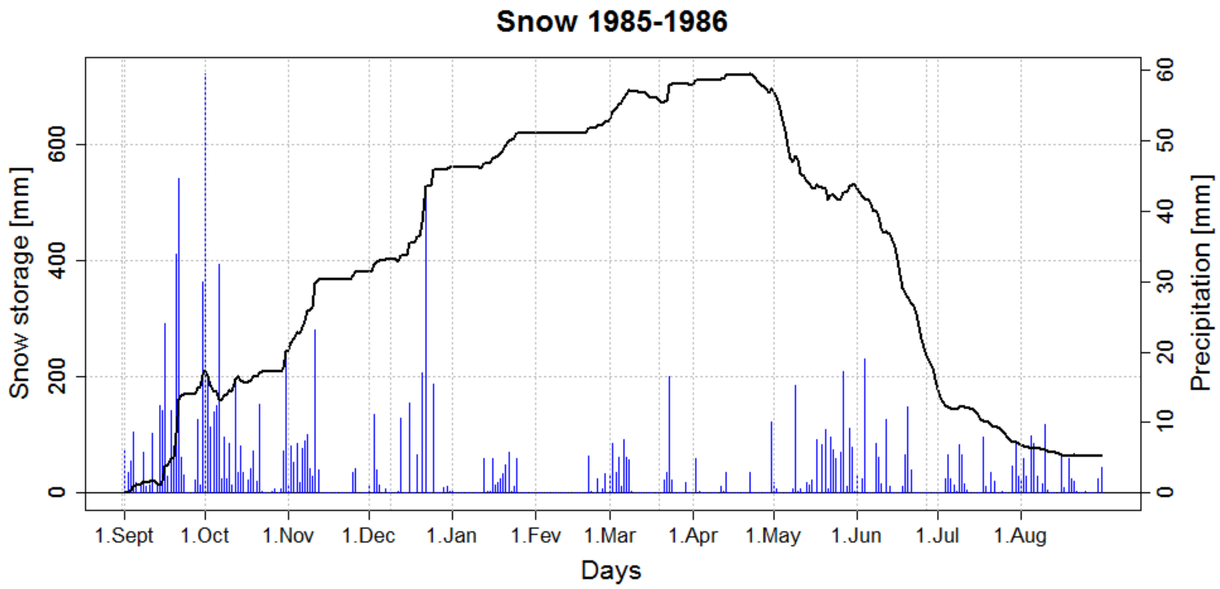
## P. CALIBRATION 1

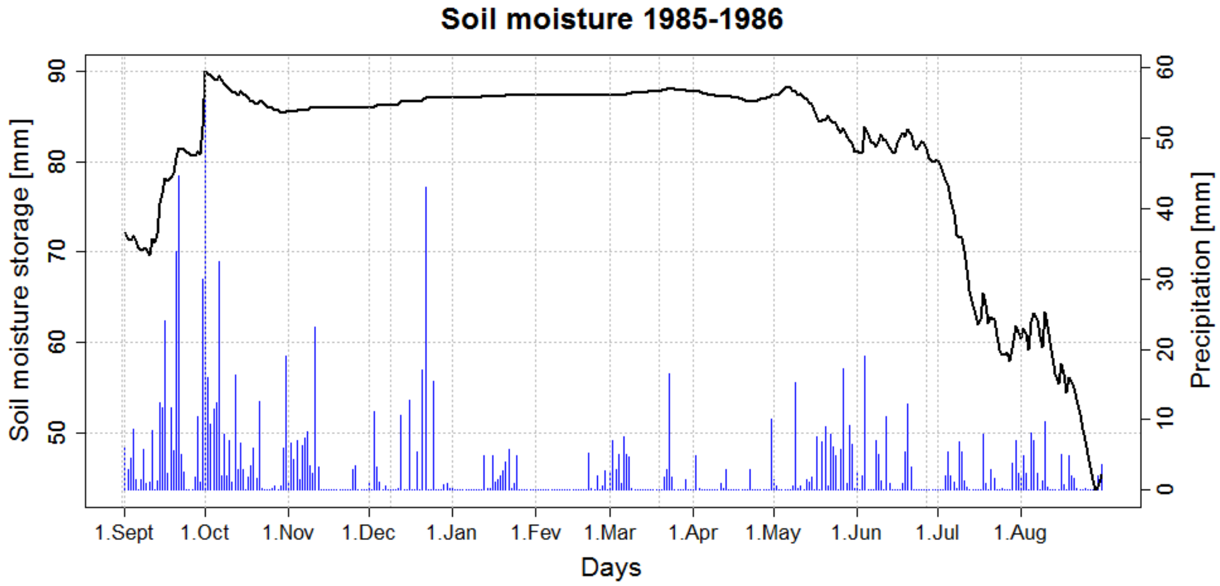




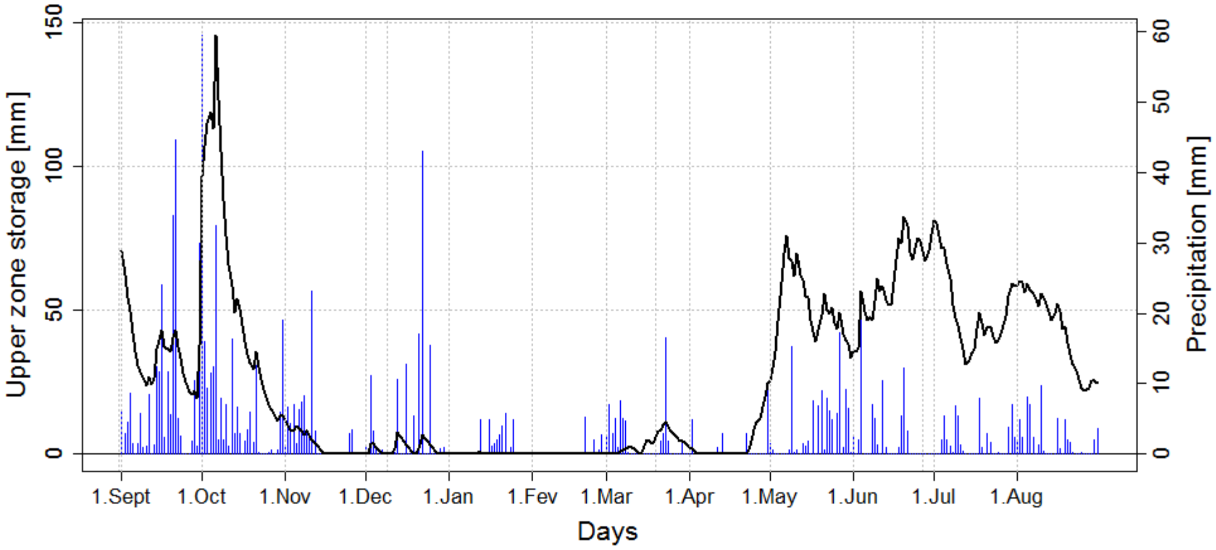


## Q. Calibration 2

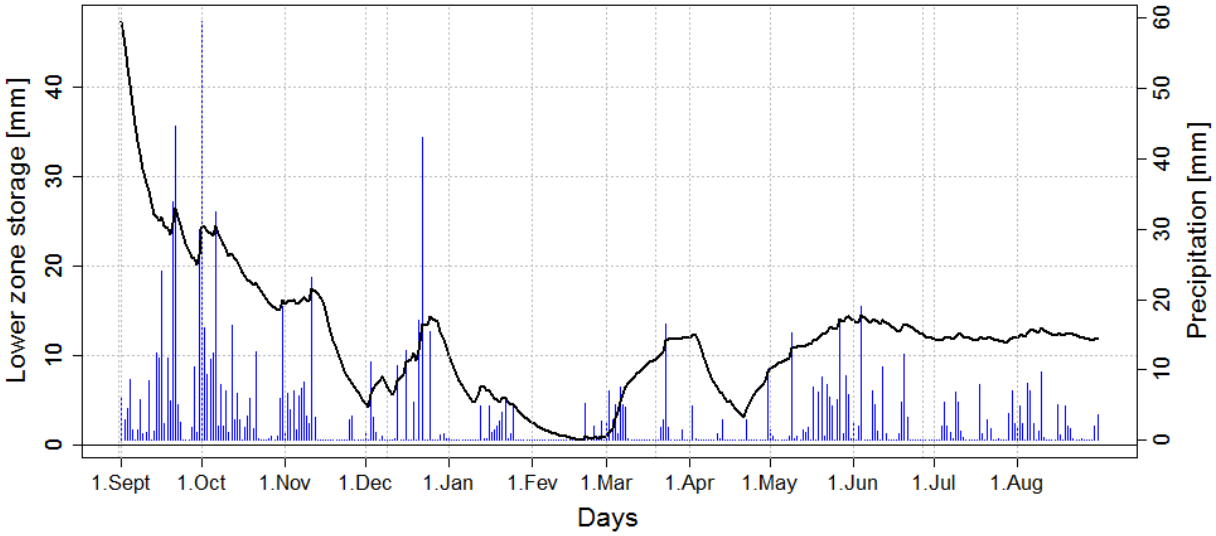

Snow 1985-1986


Soil moisture 1985-1986

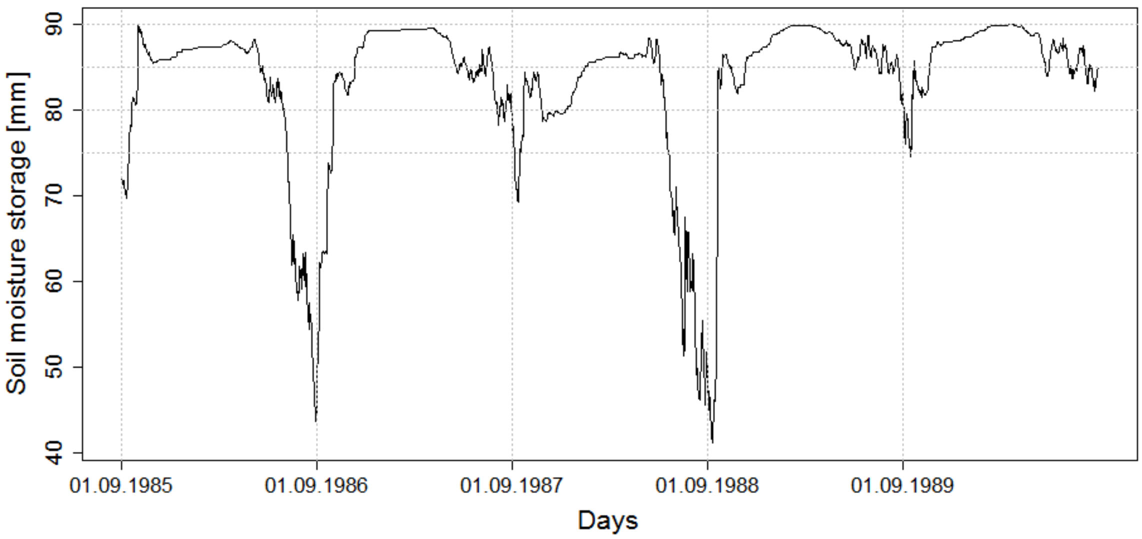
**Upper zone 1985-1986**



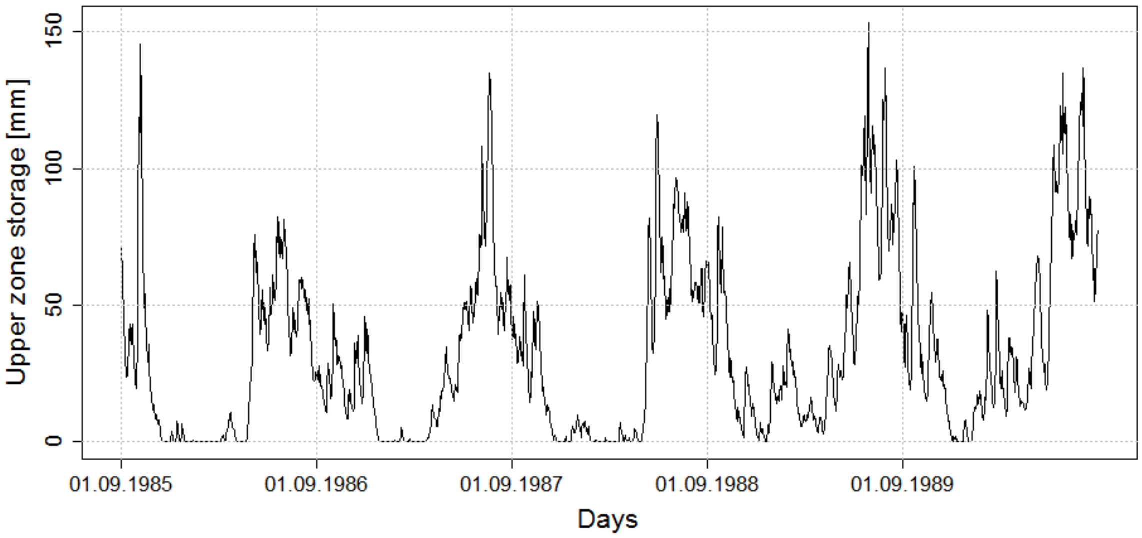
**Lower zone 1985-1986**



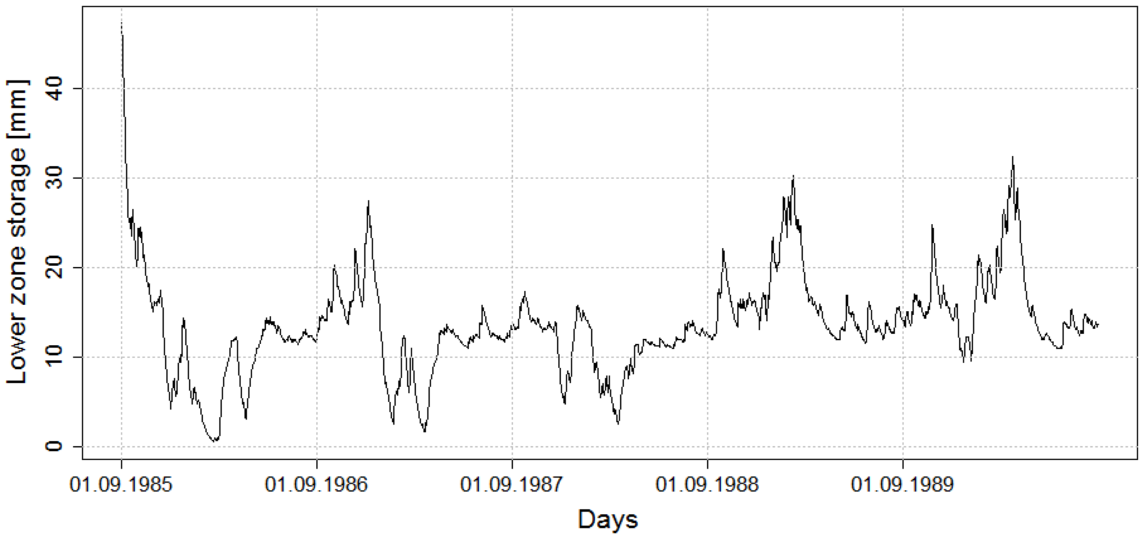
Soil moisture storage during calibration period



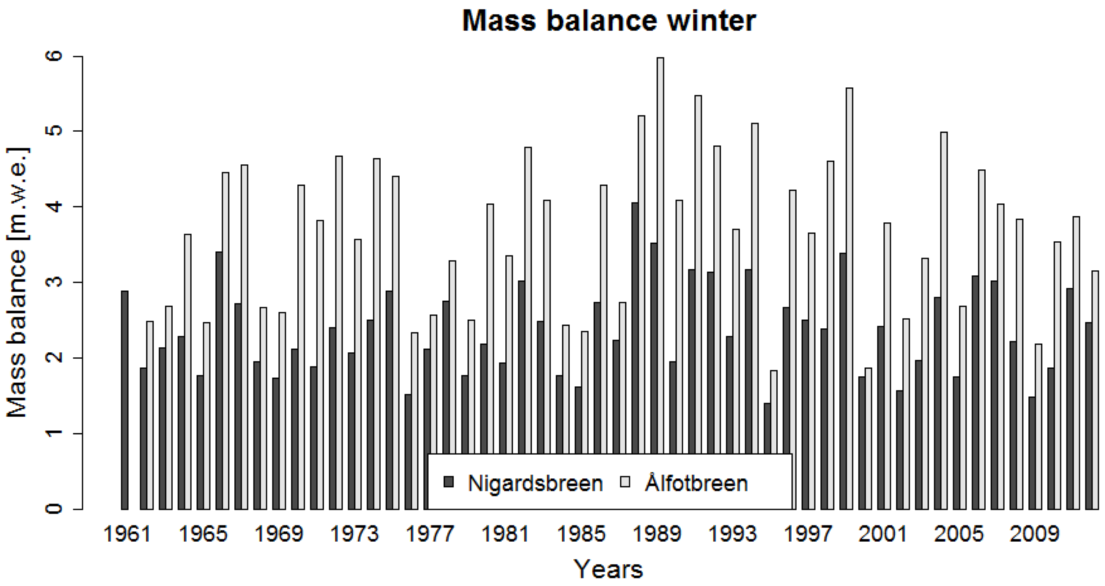
Upper zone storage during calibration period

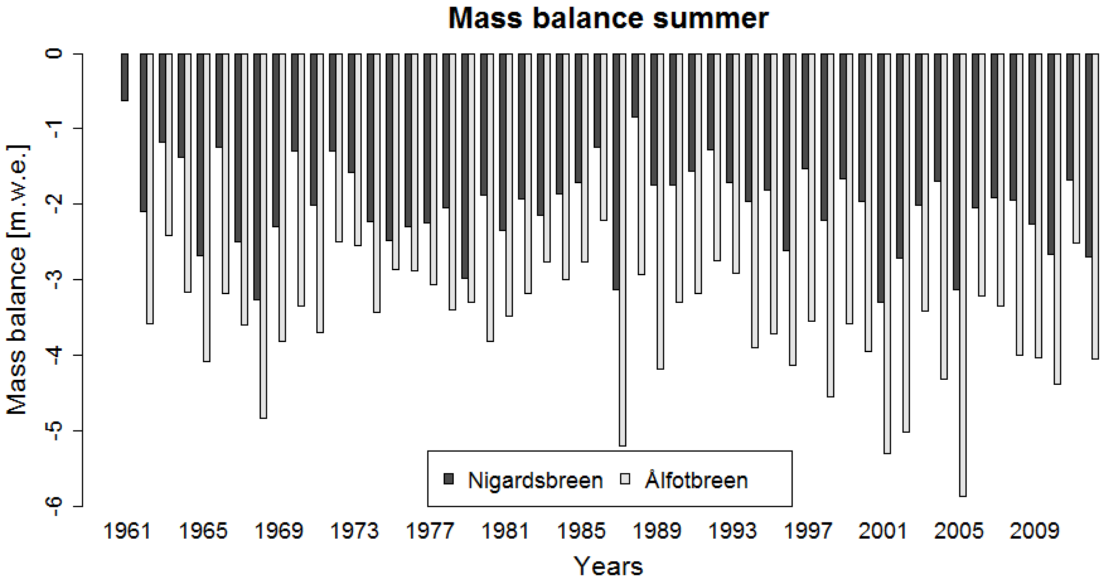


Lower zone storage during calibration period



# R. MASS BALANCES

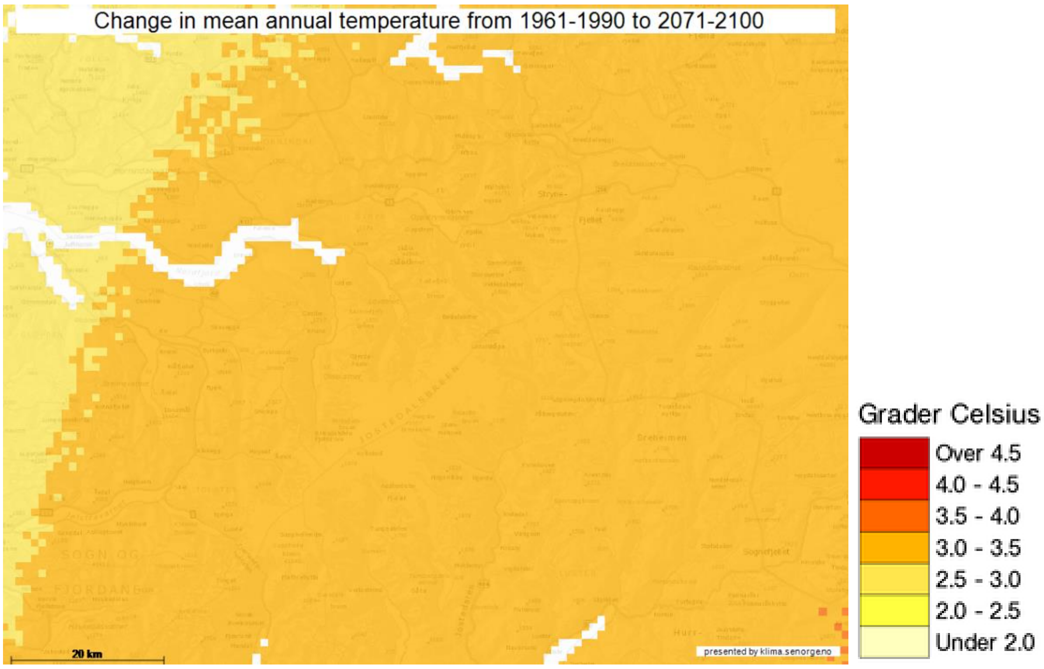




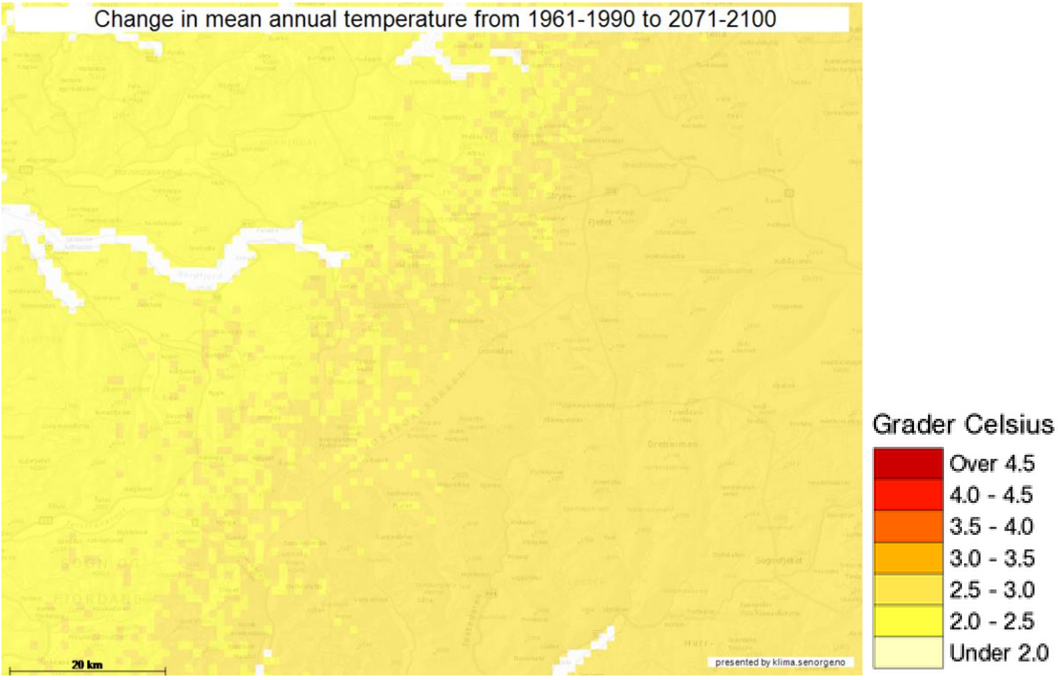
## S. BRIKSDALBREEN EVOLUTION

Briksdalsbreen in 1989 and 2009. The glacier has retreated 0.9 km between 1900 and 2012 Photos: Stefan Winkler and Hinrich Bernard Basemann

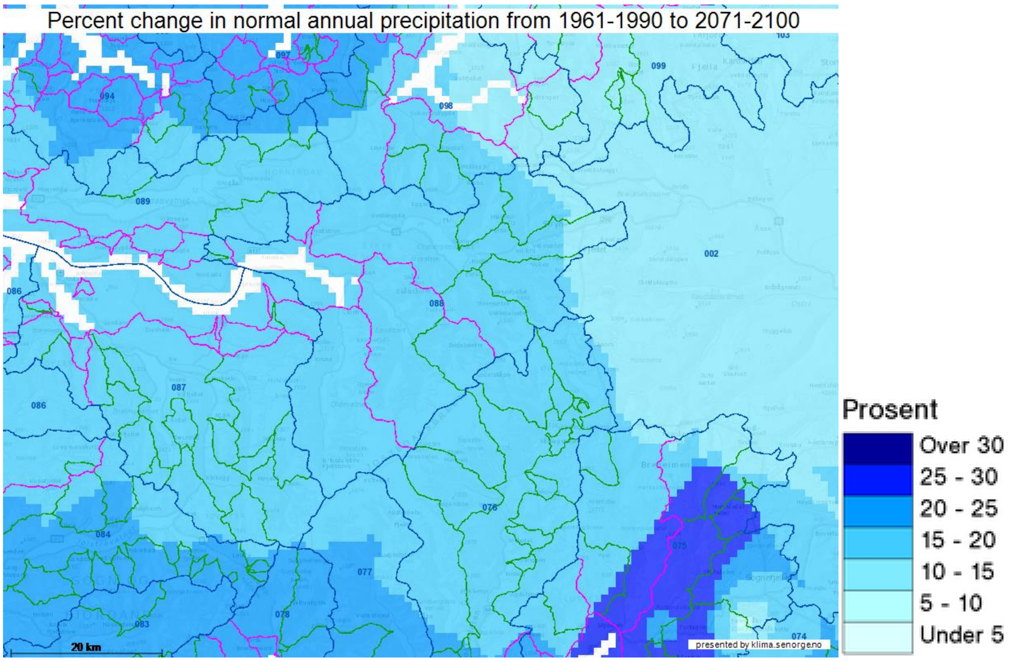
## T. CLIMATE CHANGE: MAP



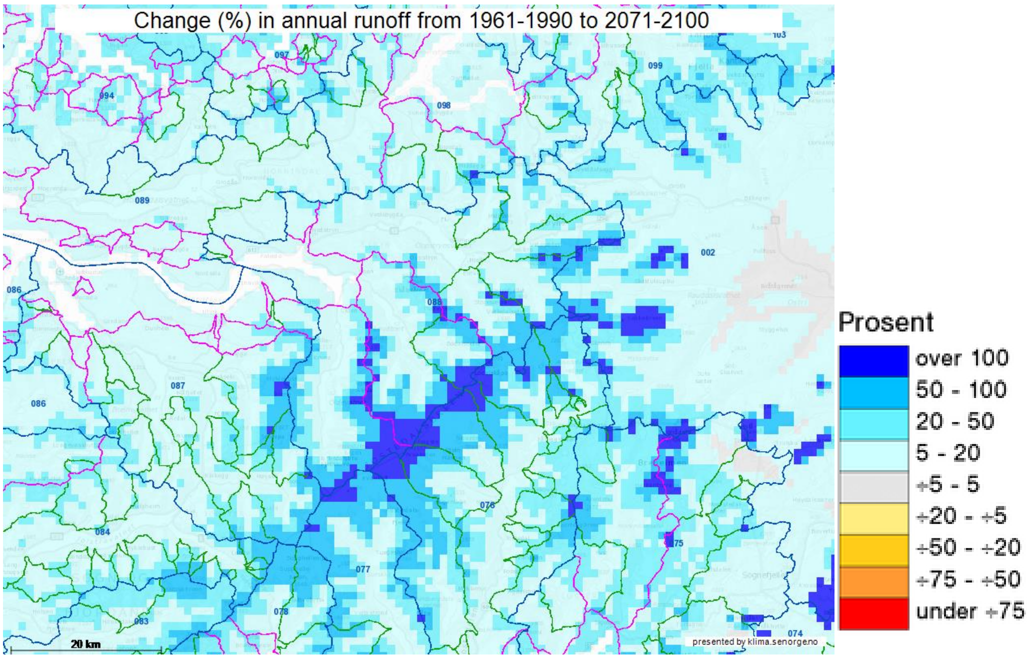
HadM3H, A2



HadM3H, B2

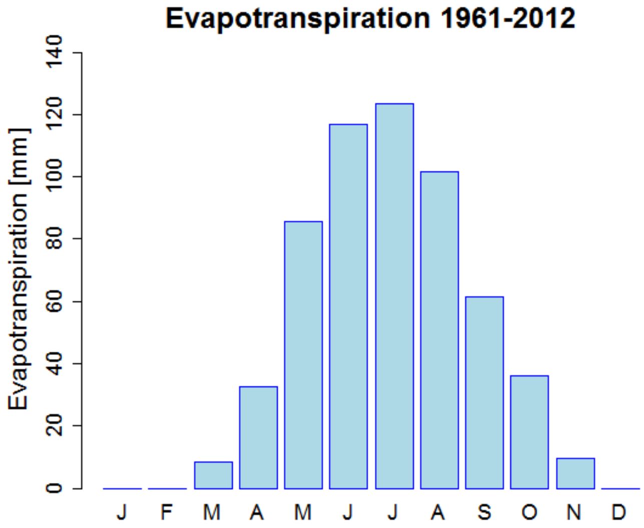


ECHAM4/OPYC3, IPCC SRES scenario B2

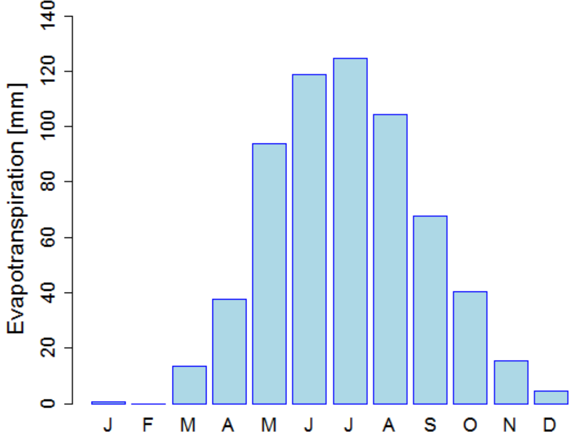


ECHAM4/OPYC3, IPCC SRES scenario B2

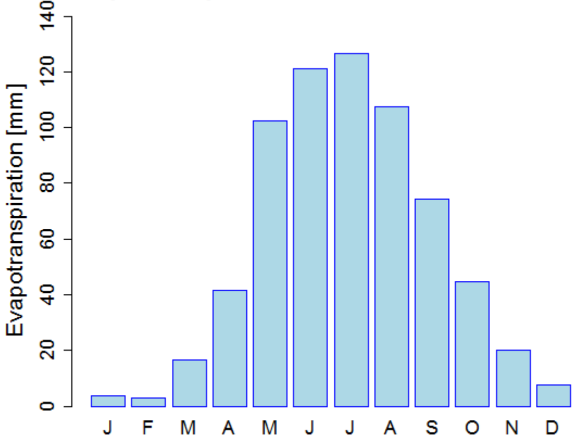
## U. CLIMATE CHANGE: EVAPORATION



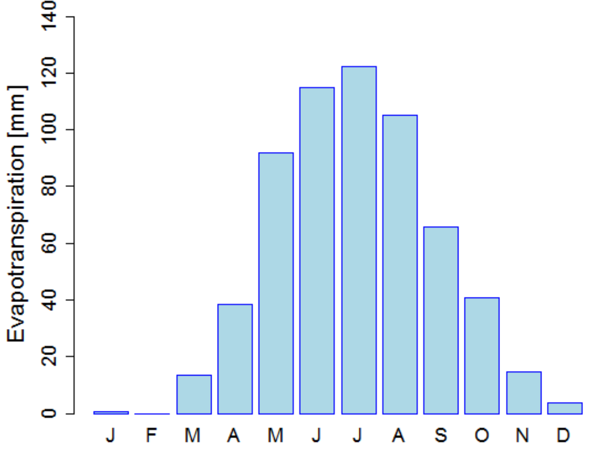
| EPOT | Base | Scenario A2 | | | | Scenario B2 | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months | 1961 | 2016 | | 2071 | | 2016 | | 2071 | |
| | | [mm] | Increase | [mm] | Increase | [mm] | Increase | [mm] | Increase |
| January | 0 | 0.80 | +0.80 | 3.59 | +3.59 | 0.53 | +0.53 | 3.65 | +3.65 |
| February | 0 | 0 | +0.00 | 3.10 | +3.10 | 0 | +0.00 | 2.02 | +2.02 |
| March | 8.33 | 13.47 | +5.14 | 16.47 | +8.13 | 13.32 | +4.99 | 16.59 | +8.25 |
| April | 32.65 | 37.73 | +5.07 | 41.59 | +8.94 | 38.34 | +5.69 | 42.97 | +10.31 |
| May | 85.71 | 93.94 | +8.23 | 102.41 | +16.70 | 91.70 | +5.99 | 97.63 | +11.93 |
| June | 116.93 | 118.79 | +1.86 | 121.07 | +4.14 | 114.91 | -2.03 | 112.82 | -4.12 |
| July | 123.32 | 124.62 | +1.30 | 126.40 | +3.09 | 122.39 | -0.93 | 121.52 | -1.80 |
| August | 101.45 | 104.19 | +2.74 | 107.45 | +5.99 | 105.03 | +3.58 | 108.92 | +7.47 |
| September | 61.45 | 67.67 | +6.23 | 74.13 | +12.68 | 65.63 | +4.18 | 69.79 | +8.35 |
| October | 36.01 | 40.44 | +4.43 | 44.55 | +8.53 | 40.95 | +4.93 | 45.53 | +9.52 |
| November | 9.76 | 15.53 | +5.77 | 19.95 | +10.19 | 14.84 | +5.08 | 18.84 | +9.08 |
| December | 0 | 4.62 | +4.62 | 7.45 | +7.45 | 3.68 | +3.68 | 6.14 | +6.14 |
| Year | 576 | 622 | +46 | 668 | +93 | 611 | +36 | 646 | +71 |



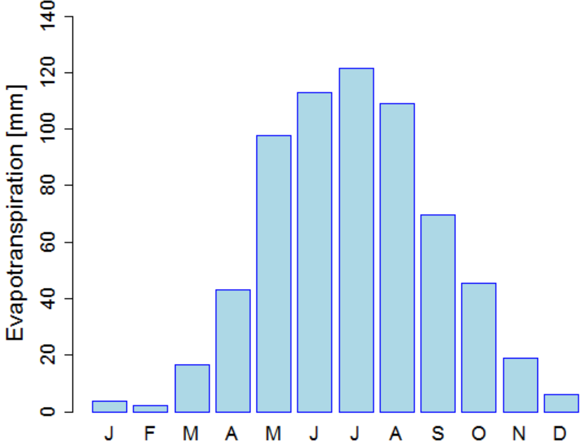
Evapotranspiration 2013-2064: Scenario A2



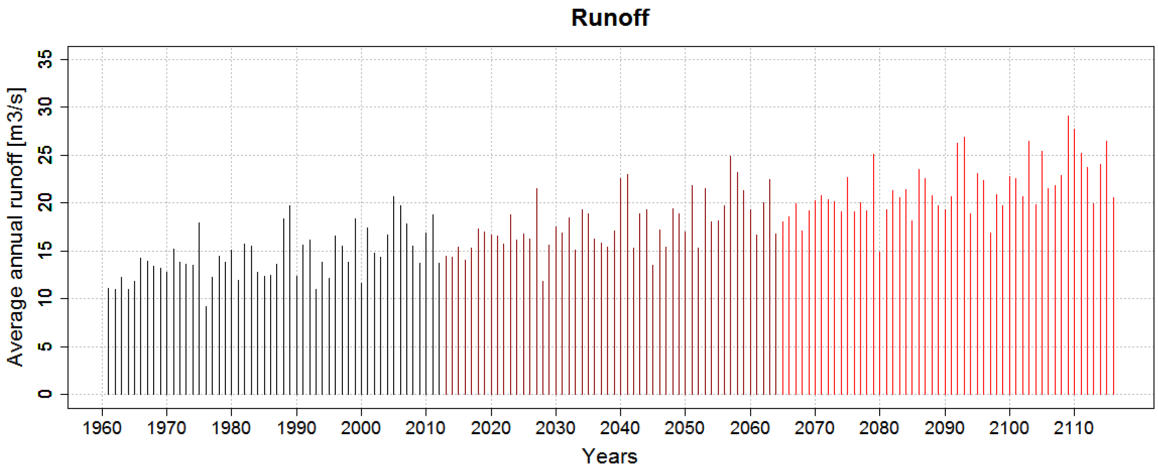
Evapotranspiration 2065-2116: Scenario A2



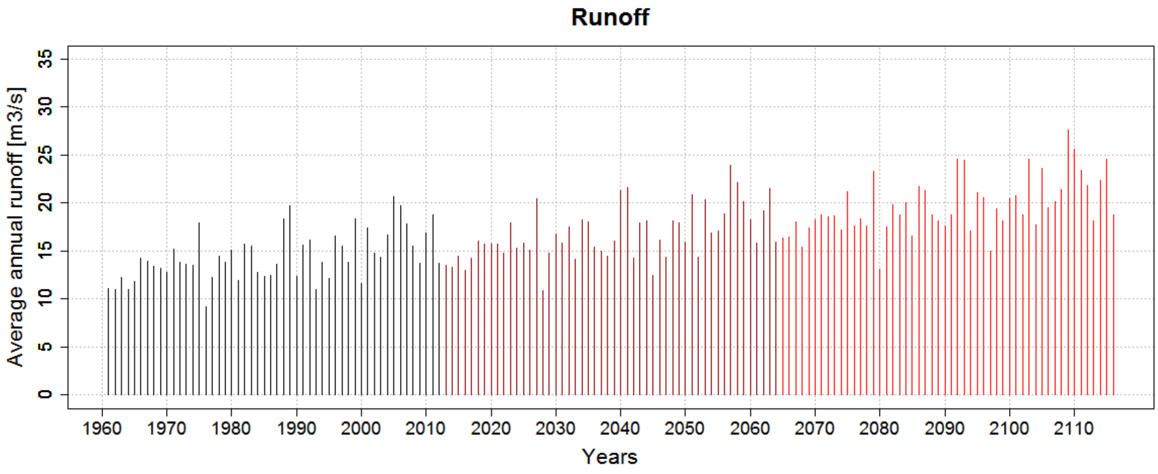
Evapotranspiration 2013-2064: Scenario B2



Evapotranspiration 2065-2116: Scenario B2



Forecast - cal.2 - scenario A2 – runoff



Forecast - cal.2 - scenario B2 – runoff