

Ludwig-Maximilians-Universität München  
Fakultät für Geowissenschaften  
Department für Geographie

## MASTER THESIS

Environmental Systems and Sustainability –  
Monitoring, Modeling and Management

Submitted in partial fulfillment of the requirements for  
the Master of Science degree

### Climate Change Impacts on the Hydrology and Snowpack of the North Fork Flathead River – Impact Assessment in the transboundary Crown of the Continent Ecosystem (Canada-USA)

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Auswirkungen des Klimawandels  
auf die Hydrologie und die Schneebedeckung des North Fork Flathead River  
– Untersuchung der Klimafolgen in der Grenzregion  
‘Crown of the Continent Ecosystem’ (Kanada-USA)

Presented by:  
Raul R. Wood  
Matriculation Number 8036164  
Email: raulwood@hotmail.de

Submitted: 30.07.2014

Supervisor:  
Prof. Dr. Ralf Ludwig  
Ludwig-Maximilians-Universität München

Co-Supervisor:  
Associate Professor Dr. Greg McDermid  
University of Calgary



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- Raul R. Wood -

## Abstract

To assess the potential changes in hydrology and snowpack in the transboundary North Fork Flathead River, the Water Flow and Balance Simulation Model (WaSiM) is applied. To enable predictions of future hydrology, temperature and precipitation outputs from the coupled GCM-RCM climate model CanESM2/CanRCM4 are used for a delta-change approach. The climate signal for temperature is very pronounced, with a temperature increase of 1.8-2.2°C by 2035 and 3.3-5.1°C by 2075. Precipitation is predicted to increase by 11-35% in 2035 and 13-17% in 2075. Discharge will undergo a shift in both the timing and size of snowmelt, due to snowpack alterations. Portions of winter precipitation will progressively fall as rain instead of snow and winter discharge will increase. As winter snowfall and snowpack accumulation decrease, in response to rising air temperatures, the flow regime will change from a nival-regime to a more complex pluvio-nival-regime. Accumulated snow water equivalent will decrease by -10 - -34% by 2035 and substantially decreases by -40 - -62% by 2075. Total discharge for the North Fork Flathead River near Columbia Falls, Montana will slightly increase by 12-16%.

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## LIST OF ABBREVIATIONS

|         |                                         |
|---------|-----------------------------------------|
| AET     | Real Evapotranspiration                 |
| CanESM2 | Canadian Earth System Model             |
| CanRCM4 | Canadian Regional Climate Model         |
| CCE     | Crown of the Continent Ecosystem        |
| DEM     | Digital Elevation Model                 |
| GCM     | Global Climate Model                    |
| NSE     | Nash-Sutcliffe Efficiency               |
| PET     | Potential Evapotranspiration            |
| PDO     | North Atlantic Oscillation              |
| RCP     | Representative Concentration Pathways   |
| SRES    | Special Report on Emission Scenarios    |
| WaSiM   | Water Flow and Balance Simulation Model |



# 1 INTRODUCTION

In western North America and especially in the Rocky Mountains, winter snow accumulation in alpine watersheds provides most of the streamflow (Lapp et al. 2005). During the melt season, snowmelt contributes considerable to the total discharge and considerable quantities of water are stored in winter (Verbunt et al. 2003). During the last decades, rising temperatures have already decreased snowfall and snowpack accumulation (Day 2009), which is a global phenomenon (Bürger et al. 2011). This is probably also the reason for the decline of streamflow for several rivers in the hydrographic apex of North America (Rood et al. 2005). The Rocky Mountain region near the Canada-United States border, where this study is located, is the origin of headwater streams flowing to the Pacific, Arctic and Atlantic oceans (Rood et al. 2005). This area contains numerous national parks and protected areas with relatively pristine watersheds that allows analysis of hydrologic patterns in an area with minimal human impacts. The transboundary North Fork Flathead River (the study site) forms a low elevation corridor for wide-ranging wildlife to move north and south along the Rockies. It provides critical connectivity for bears, moose, elk, lynx and other species (Sexton 2010). The transboundary Flathead harbors the highest density of grizzly bears in the Lower 48 (The Nature Conservancy 2014). The North Fork Flathead River is considered a regional and range-wide stronghold for native bull trout and nonhybridized westlope cutthroat trout (D'Angelo and Muhlfield 2013, Muhlfield et al. 2014). The British Columbia portion of the valley is largely undeveloped and is still home to the same variety of plants and animals that existed 400 years ago (NCC 2014). Climate change as a result of elevated anthropogenic greenhouse gas concentrations in the atmosphere is likely to shift the spatial and temporal distribution of water resources in river basins throughout the 21<sup>st</sup> century (Chang and Jung 2010). To assess the potential climate change impacts on the hydrology and snowpack in the transboundary North Fork Flathead River, the Water Flow and Balance Simulation Model (WaSiM) is applied. To enable predictions of future hydrology, temperature and precipitation outputs from the coupled GCM-RCM climate model CanESM2/CanRCM4 are used for a delta-change approach. The two Representative Concentration Pathway scenarios RCP4.5 and RCP8.5, from the Fifth-Assessment Report (AR5) of the Intergovernmental Panel on Climate Change, are chosen to describe future climate forcing.

## 2 STUDY AREA: NORTH FORK OF THE FLATHEAD RIVER WATERSHED

The North Fork Flathead River Basin is on the west side of the continental divide in northwestern Montana, USA and southern British Columbia, Canada. The North Fork Flathead River originates in the Canadian Rockies in southern British Columbia and flows south into Montana, and can therefore be called a transboundary watershed. Its basin has a drainage area of approx. 4030 km<sup>2</sup> (1556 mi<sup>2</sup>) upstream from the gaging station, North Fork Flathead River near Columbia Falls, Montana (USGS 12355500, USGS 2014). About 72 percent of the total basin area lies in Montana and 28 percent in British Columbia. The reach of the North Fork is approx. 136 km long and flows south-east along a valley located between the McDonald and Whitefish Range to the west and the Livingstone Range to the east (Fig 1). In Montana, the North Fork forms the western border of Glacier National Park and the eastern border of Flathead National Forest. Only small parts along the stream are privately or state owned properties (Mills et al. 2012).

The topography of the basin is characterized by steep mountainous terrain throughout the basin and glacially formed valleys along the east slope.

The altitude ranges from approx. 966 to close to 3000 m, with the Livingstone Range in the east overtopping the McDonald and Whitefish Range in the west. The North Fork Flathead River basin is a very scarcely populated region with Polebridge as its only community, which is not even connected to the power grid.

The predominant land cover is coniferous forest, which transitions to alpine tundra, bare rock and perennial ice and snow at higher altitudes. The forest in drier areas consists of lodgepole pine, Douglas fir, and western larch, and western hemlock and western cedar in wetter areas (Mills et al. 2012).

Fire is a frequent phenomenon in the North Fork Flathead basin, and recent fires occurred in 1988, 2001, 2003 and 2006 (Fig 2) destroying a substantial part of vegetation. In 2003, several major fires occurred and approx. 63,000 ha of forest burned. Also the Red Bench fire of 1988 (approx. 15,000 ha) and the Moose fire of 2001 (approx. 29,000 ha) burned an extensive part of the forest.

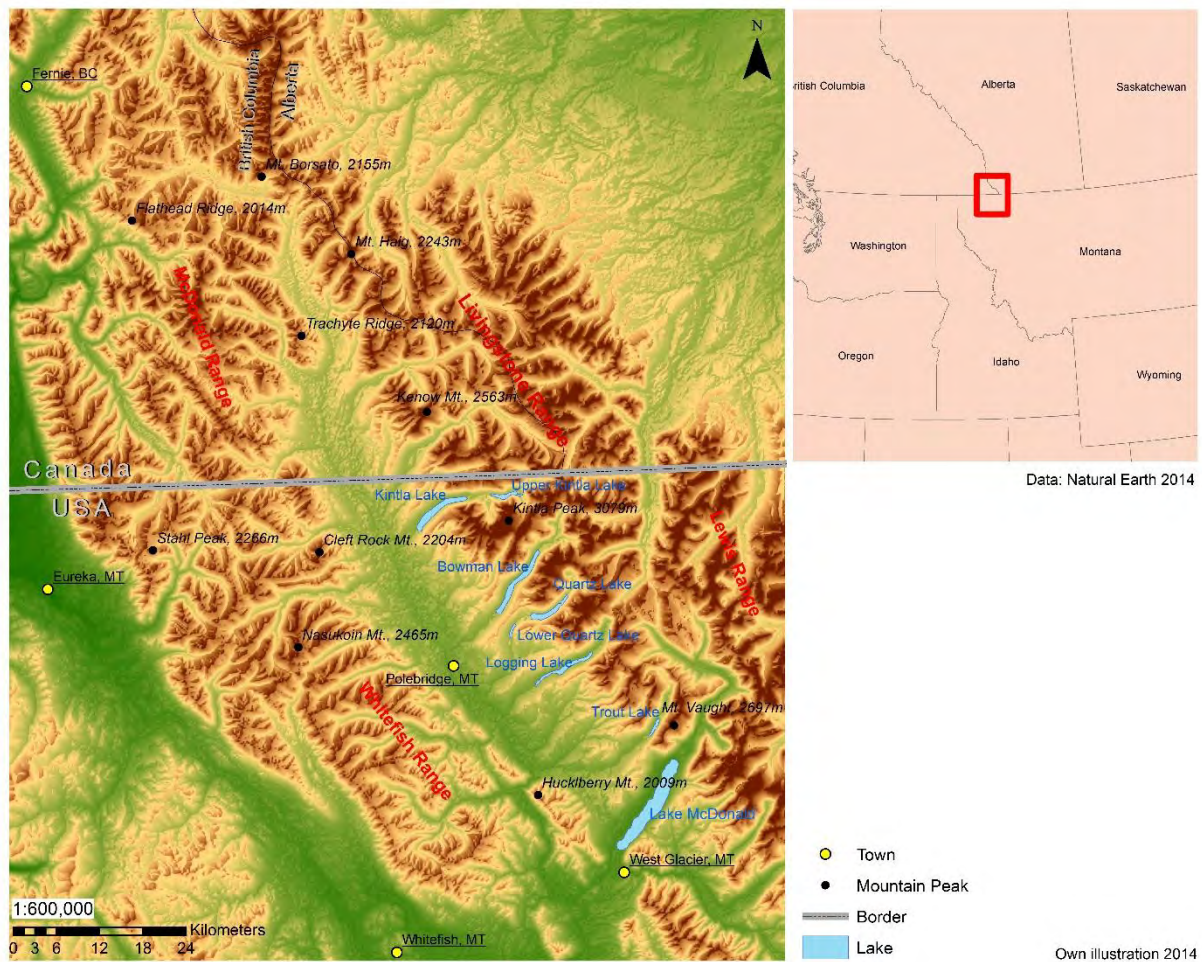


**Fig 1 | Geographic features in the North Fork Flathead River region**

The transboundary Flathead forms a low elevation corridor for wide-ranging wildlife to move north and south along the Rockies. It provides critical connectivity for bears, moose, elk, lynx and other species (Sexton 2010). The transboundary Flathead harbors the highest density of grizzly bears in the Lower 48 (The Nature Conservancy 2014). The North Fork Flathead River is considered a regional and range-wide stronghold for native bull trout and nonhybridized westlope cutthroat trout (D'Angelo and Muhlfield 2013, Muhlfield et al. 2014). The British Columbia portion of the valley is largely undeveloped and is still home to the same variety of plants and animals that existed 400 years ago (NCC 2014).

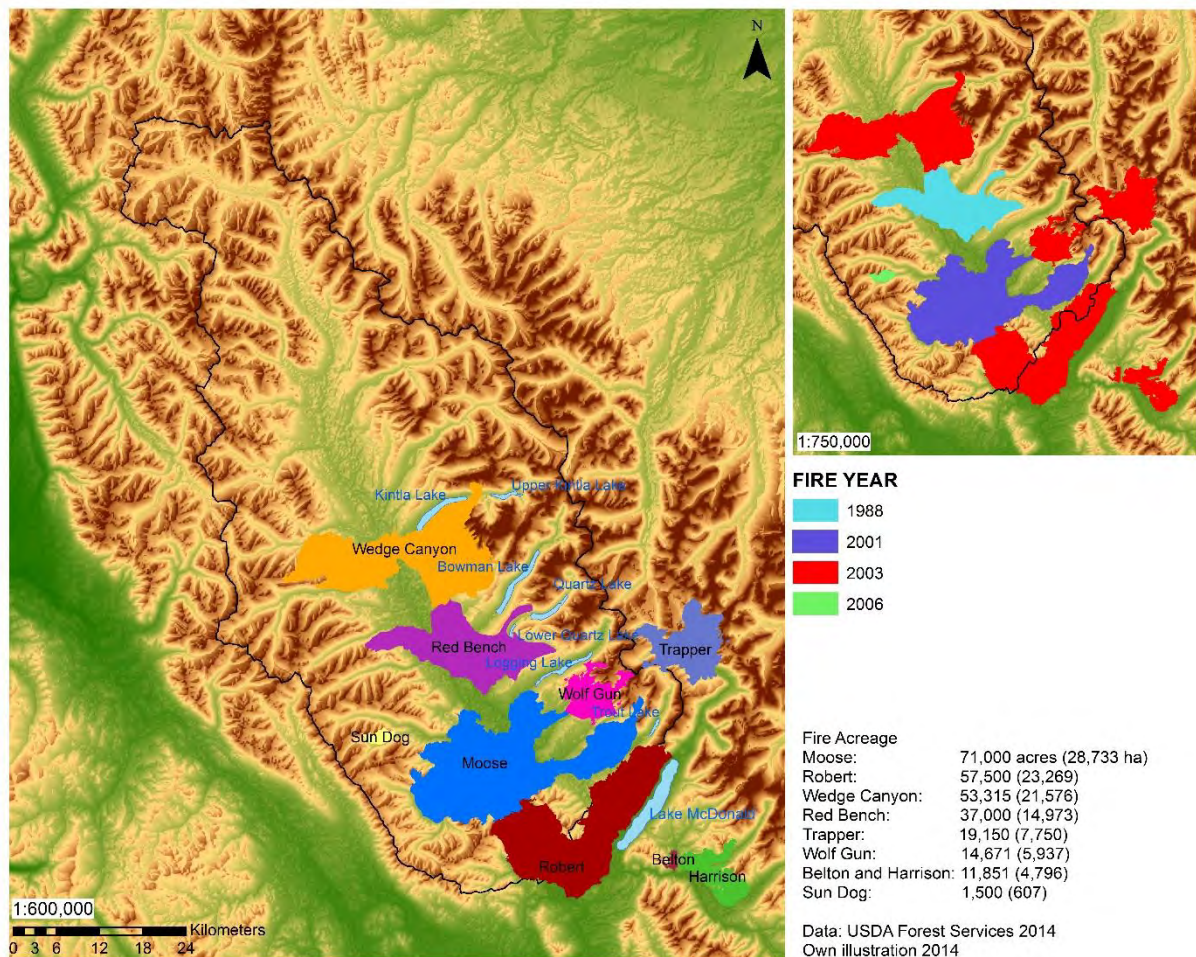


**Fig 2 | Forest Fires in the North Fork Flathead River region**

The climate of the watershed can be considered as a Pacific maritime climate, with warm, dry summers and cold, wet winters (Mills et al. 2012).

Average monthly temperature along the river at Polebridge, MT ranges from  $-6.8^{\circ}\text{C}$  in December to  $16.1^{\circ}\text{C}$  in July. At high altitudes the temperature ranges from  $-8.6^{\circ}\text{C}$  in December to  $12.0^{\circ}\text{C}$  in July. Mean-annual precipitation sums increase with altitude from 509 mm in Polebridge to 1895mm at Flattop Mountain (Fig 3). Basins with a north-south extend seem to be considerable drier, such as towns like Eureka, Fortine, Olney or Polebridge in Montana. Precipitation increases considerable with elevation even within a short distance, e.g. precipitation increases from 384mm in Eureka (774m) within 15 kilometers to 1662mm at Stahl Peak (1838m).

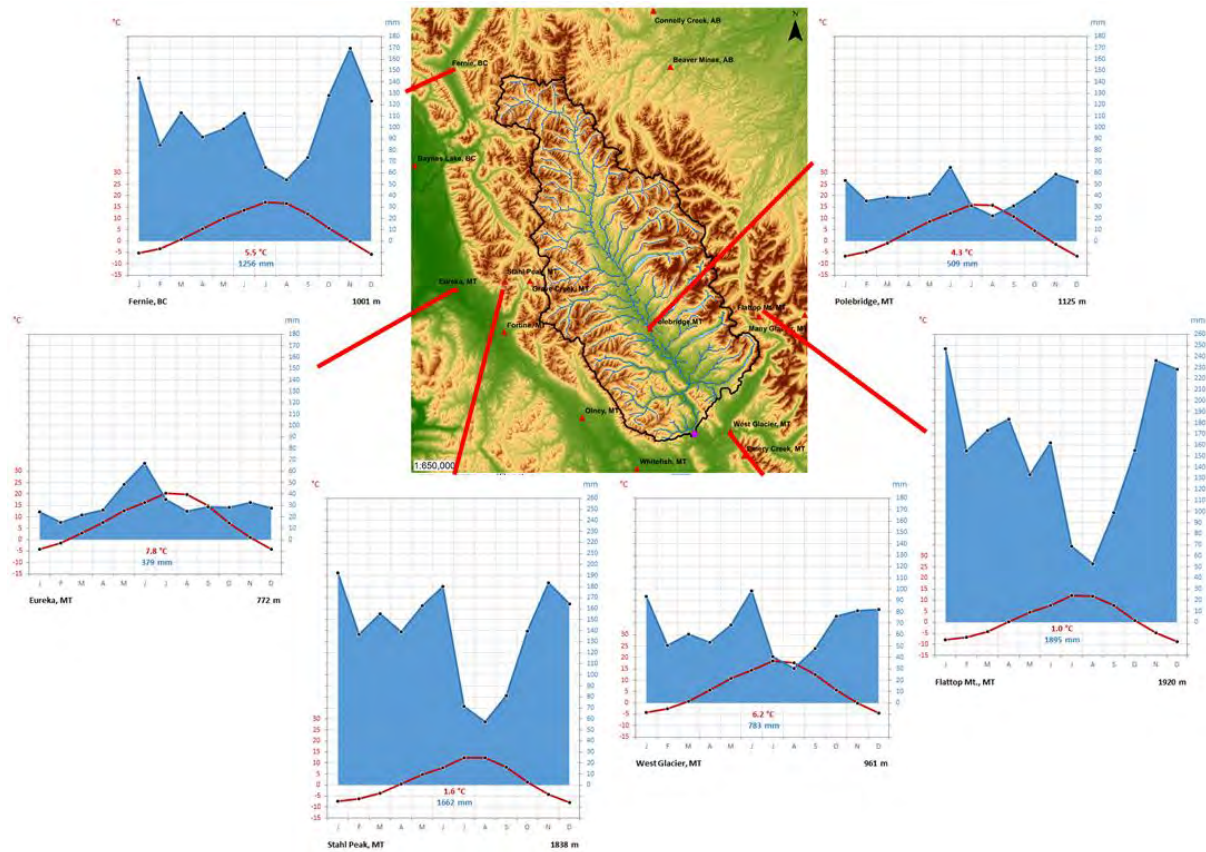


**Fig 3 | Climate in the North Fork Flathead River region**

The North Fork Flathead River itself is a meandering stream that flows in a broad valley from its headwaters in southern British Columbia in south-east direction into Montana. The hydrology of the North Fork is dominated by the accumulation and melting of seasonal snowpack, and can be described as a nival flow regime (Fig 4). With snow melting early April, flow starts increasing. High flows occur during the spring, from May through June, and low flow occurring from late summer through early spring (September-March). The low flow runoff regime is characterized by a uniform flow that fluctuates around 30 m<sup>3</sup>/s. During this season, direct contributions of precipitation and snowmelt are minimal, and contributions of groundwater are high. “Groundwater occurs in talus slopes or fractured bedrock and in the alluvial and glacial till material in the North Fork valley (Mills et al. 2012, p. 6).” Tributaries flow into the North Fork from the west and east. Several tributaries from the east have glacially formed lakes along their stream (Fig 1).

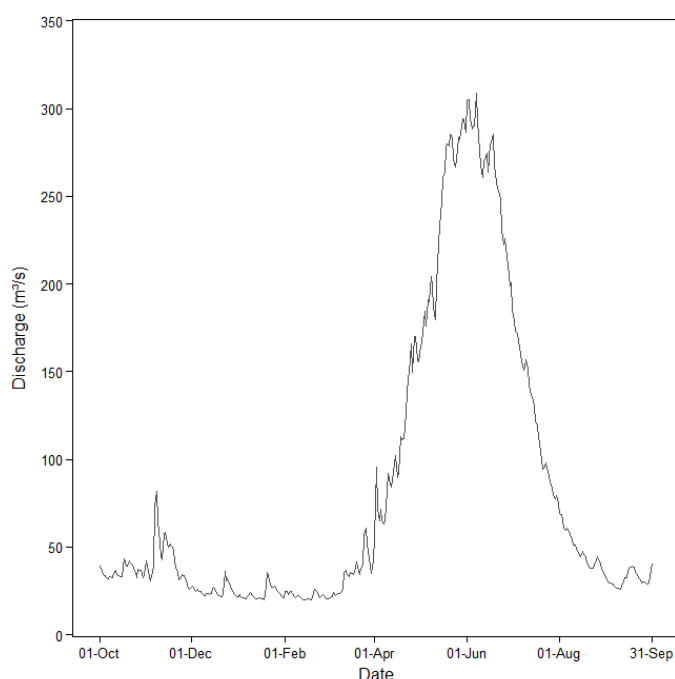


**Fig 4 | Mean daily flow for the North Fork Flathead River near Columbia Falls, MT (1991-2009)**

The Flathead River watershed is a part of the Columbia River system (Fig 5). The Columbia River watershed covers an area of more than 673,394 km<sup>2</sup> (260,000 square miles) including parts of seven states (USA) and British Columbia, Canada (EPA 2014). It is the second largest river in the U.S. in volume of water flow and flows over 1930 km (1200 miles) from its headwaters in the Canadian Rockies to the Pacific Ocean (EPA 2014). Before the water of the Flathead River joins the Columbia River it flows south passing through Flathead Lake and merges into the Clark Fork. Clark Fork flows in north-west direction to Lake Pend Oreille, where it afterwards becomes Pend Oreille River and continues flowing north. The water of Flathead River joins the Columbia River just across the border in British Columbia, at about the same latitude as it originates. By this time, the water has passed through three states (Montana, Idaho and Washington) and twice through British Columbia. Finally the water meets the Pacific Ocean at the state border of Oregon and Washington.

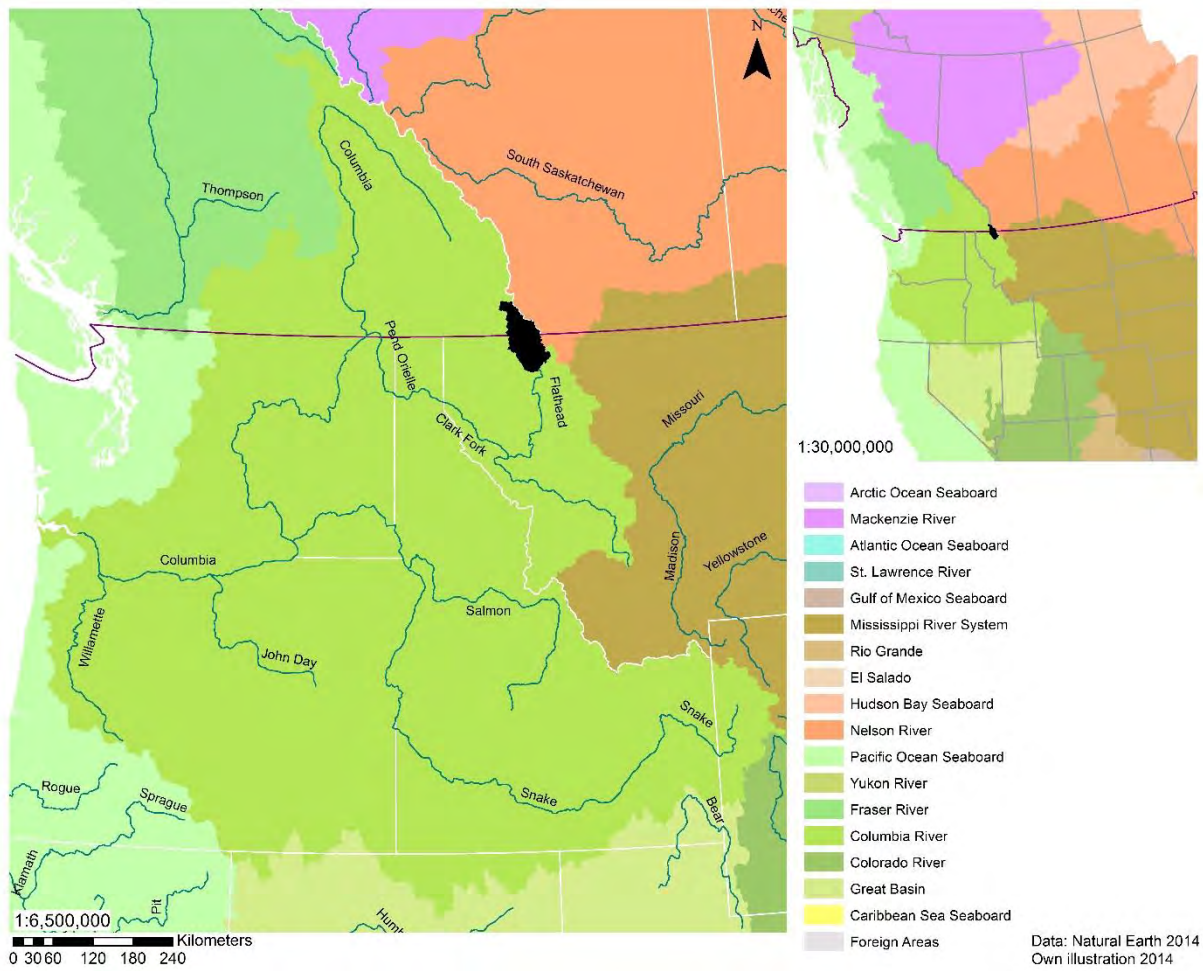


**Fig 5 | Columbia River watershed (North Fork Flathead River watershed in black)**

### 3 HYDROLOGIC MODELING

#### 3.1 BACKGROUND

There are different types of catchment models including empirical, conceptual and physically based models. Empirical models are based on the patterns observed in data, physical based models are based solidly on an understanding of the physical processes and conceptual models pay little attention to the physics of the processes, rather they represent the catchment conceptually, for example as a series of cascading storages for water and the fluxes between them. (Wainwright and Mulligan 2004)

These models may be deterministic models, with a given set of inputs they will always produce the same output, or stochastic models, which represent the variability of events or processes using probability distributions.

Further models may be lumped at the catchment scale, at the subcatchment scale (and thus semi-distributed at the catchment scale) or at the raster grid cell (fully distributed), meaning that data and modeling are aggregated at this scale.

Empirical models incline to be lumped, conceptual models incline to be semi-distributed and physically based models tend to be fully distributed.

(Wainwright and Mulligan 2004)

In general, any model is simply approximating the natural processes and data is in most cases the restrictive factor for setting up complex or physically based models (Cullmann et al. 2011). A model is a hypothesis of the real world's functioning, codified in quantitative terms (Beckers et al. 2009).

Physically based models have the advantage to be used in ungauged catchments, though gaps in parameterization data and process knowledge create model uncertainty and therefore the models are required to be calibrated against gauging station data (Wainwright and Mulligan 2004).

Hydrologic modeling aims at understanding and interpreting catchment specific hydrological behavior (Pushpalatha et al. 2012). The uncertainty related to hydrologic models or their parameterization is considerably less important than uncertainty from GCMs (Velázquez et al. 2013).

“However, hydrological modeling is an important part of the evaluation of the impact of change because it allows us to understand how the hydrological process would react to climate change. (Velázquez et al. 2013)”

### 3.2 THE HYDROLOGICAL MODEL WASIM

The model WaSiM (Water Flow and Balance Simulation Model) was developed by Joerg Schulla at the Eidgenoessische Technische Hochschule (Swiss federal institute of technology). It can be considered as a distributed, deterministic and mainly physical based model. The model consists of several sub models using mainly physically based equations to describe the water flow of a catchment in detail. (Schulla 2013)

According to (Beckers et al. 2009) the model has a high complexity and functionality for forest management and climate change applications.

Jasper et al. (2004) used WaSiM to investigate differential impacts of climate change on the hydrology of two alpine river basins. Kleinn et al. (2005) studied streamflow responses to climate variations and anthropogenic climate change in the Rhine basin. Bürger et al. (2011) estimated future flow of the Columbia River headwaters above Donald, by downscaling four regional climate models of the NARCCAP suite and driving WaSiM.

The model can be run with a variety of spatial and temporal resolutions ranging from centimeters to kilometers and seconds to days (Schulla 2013).

The following components were applied in this implementation of the model:

(1) inverse distance weighting of meteorological input data, combined with elevation-dependent regression, (2) potential evapotranspiration with approaches after (Monteith 1975), (3) snow accumulation and melt

approaches via temperature-index and degree-day-factor without wind consideration, (4) interception model with a bucket approach, (5) single-aquifer groundwater model, including base flow generation by exfiltration of groundwater into river channels, (6) runoff generation and unsaturated zone using the Richards approach.

In this study the model was run with a daily time step and a spatial resolution of 250m. The model was calibrated over the period from 1991-2000, using the climate stations listed in Tab 1 and the USGS gauging station North Fork Flathead River near Columbia Falls, MT (USGS 12355500, (USGS 2014)). The following spatial input data was used: (1) Digital Elevation Model based on the SRTM (Shuttle Radar Topographic Mission) version 4, with an original spatial resolution of 90m, resampled to 250m (CGIAR-CSI 2014), (2) land use data based on the land cover map of the (Crown Managers Partnership 2014), (3) soil types based on the U.S. General Soil Map for Montana (U.S. Department of Agriculture, Natural Resources Conservation Service 2006) extrapolated to the British Columbia, Canada part of the watershed, with an elevation dependent approach, (4) further topographic dependent spatial input data (slope, aspect, river network, subcatchments) was obtained from the DEM using the Topographic Analysis program (TANALYS (Schulla 2013)). The general model structure can be seen in the following figure. For a more detailed description of the single modules and equations used in WaSiM see (Schulla 2013).

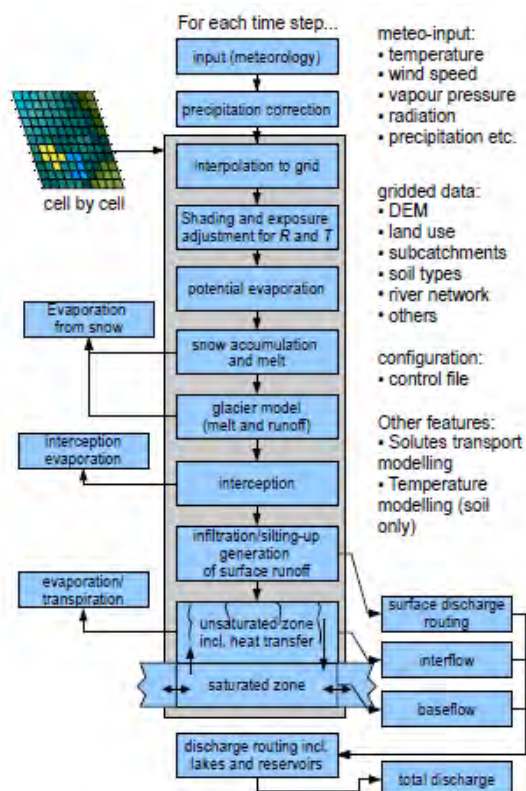


**Fig 6 | Model structure of Wasim (Schulla 2013)**

### 3.3 DATA

#### 3.3.1 Meteorological data

“Reliable surface meteorological data are a basic requirement for hydrological and ecological research at any spatial scale, and is a particularly crucial component of studies of mass and energy transfer over large land surfaces (Thornton et al. 1997).”

WaSiM requires a time series with continuous data over several years. A time series of 20 years or longer is favorable, since it needs to be separated in a calibration and validation period. So the criteria for suitable climate stations are data availability of 20+ consecutive years of data and distance to the watershed. Only 15 climate stations fulfilled these requirements. These 15 climate stations are spread across south-eastern British Columbia, south-western Alberta and north-western Montana (Fig 7). Polebridge, MT is unfortunately the only climate station that is located within the catchment. Further, a limited selection of meteorological variables are routinely measured from the existing networks and therefore all 15 climate stations only measure daily precipitation and temperature (min, max and mean) in a satisfactory way.

The data used in this study was collected from NOAAs National Climate Data Center (NOAA 2014) and climate data from (Government of Canada 2014). Since only temperature and precipitation are being measured widespread, wind speed, solar radiation and relative humidity have to be estimated or extracted from models.

The average height of the climate stations is 1186 m and they range between 772 and 1920 m (Tab 1).

**Tab 1 | List of climate stations**

| Names              | Longitude | Latitude | Elevation [m.asl.] |
|--------------------|-----------|----------|--------------------|
| Baynes Lake, BC    | -115.22   | 49.23    | 792                |
| Beaver Mines, AB   | -114.17   | 49.47    | 1257               |
| Connelly Creek, AB | -114.23   | 49.62    | 1158               |
| Emery Creek, MT    | -113.93   | 48.43    | 1326               |
| Eureka, MT         | -115.07   | 48.90    | 772                |
| Fernie, MT         | -115.07   | 49.48    | 1001               |
| Flattop Mt, MT     | -113.85   | 48.80    | 1920               |
| Fortine, MT        | -114.88   | 48.78    | 926                |
| Grave Creek, MT    | -114.77   | 48.92    | 1311               |
| Many Glacier, MT   | -113.67   | 48.80    | 1494               |
| Olney, MT          | -114.57   | 48.53    | 970                |
| Polebridge, MT     | -114.28   | 48.78    | 1125               |
| Stahl Peak, MT     | -114.87   | 48.92    | 1838               |
| West Glacier, MT   | -113.98   | 48.50    | 961                |
| Whitefish, MT      | -114.40   | 48.48    | 933                |

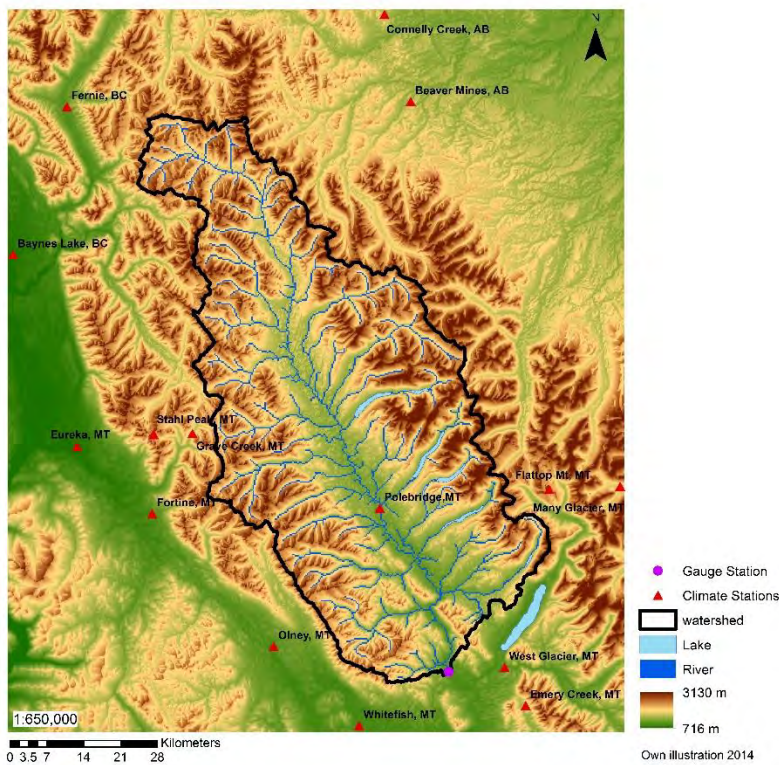


**Fig 7 | Location of climate stations**

All climate stations show a certain amount of days with missing data. The coverage of observed mean temperature ranges between 76-100% with a mean coverage of 94 percent (Tab 2). Data coverage refers to the time span 1990-2012. The average coverage of observed precipitation is 85 percent, which means in average 1259 days or approx. 3 ½ years of data is missing (Tab 3). Data coverage of precipitation ranges between 41 and approx. 100%. Since there is data missing at every location and also partially entire month or years, a second data source for temperature and precipitation needs to be included to fill the data gaps. A second source has been found in the Daymet data (Thornton et al. 2012). Daymet data set provides model-produced gridded daily estimates of weather parameters, based on daily meteorological observations for the entire United States and Mexico, as well as Canada (south of 62 degrees North) for the time 1980 through the latest full calendar year (Thornton et al. 2012). Before the Daymet data set can be utilized to fill the data gaps in the climate station data, both sources of meteorological data (climate station data and Daymet) need to be compared, to guarantee the suitability of Daymet data. As a measure to verify the suitability of Daymet data, yearly mean temperature and yearly mean precipitation was compared. Only years with at least 360 days of data were considered for comparison. The comparison was performed for each climate station. Averaged across all 15 stations, temperature in the Daymet data set was 0.56°C off target.

Mean deltas of yearly mean temperature range between 0.03 °C and -1.43°C and +1.15°C, respectively. Since the data coverage is very high and the satisfactory comparison of single year events (Fig 8), Daymet data can be used for filling the data gaps.

**Tab 2 | Comparison of climate station and Daymet yearly mean temperature**

| Names              | Coverage [%] | Years compared | Ø Tmean [°C]    |        | Delta <sup>1</sup> Tmean [°C] |       |       |
|--------------------|--------------|----------------|-----------------|--------|-------------------------------|-------|-------|
|                    |              |                | CS <sup>2</sup> | Daymet | Min                           | Ø     | Max   |
| Baynes Lake, BC    | 92.6         | 13             | 6.44            | 6.88   | 0.00                          | 0.44  | 1.31  |
| Beaver Mines, AB   | 94.5         | 16             | 4.95            | 4.57   | 0.01                          | -0.38 | -0.95 |
| Connelly Creek, AB | 88.2         | 9              | 4.51            | 3.79   | -0.34                         | -0.72 | -0.99 |
| Emery Creek, MT    | 96.4         | 10             | 3.13            | 4.21   | 0.44                          | 1.08  | 1.48  |
| Eureka, MT         | 99.6         | 19             | 7.83            | 6.89   | -0.14                         | -0.94 | -1.44 |
| Fernie, BC         | 94.6         | 11             | 5.54            | 5.58   | 0.05                          | 0.03  | 0.20  |
| Flattop Mt., MT    | 98.0         | 14             | 1.07            | 1.20   | 0.08                          | 0.12  | 1.55  |
| Fortine, MT        | 91.3         | 15             | 6.53            | 6.61   | -0.06                         | 0.08  | 0.91  |
| Grave Creek, MT    | 92.2         | 13             | 4.01            | 3.65   | 0.01                          | -0.36 | -0.67 |
| Many Glacier, MT   | 96.7         | 11             | 4.26            | 3.00   | -0.98                         | -1.26 | -1.45 |
| Olney, MT          | 97.3         | 15             | 4.75            | 5.90   | 0.49                          | 1.15  | 1.69  |
| Polebridge, MT     | 75.5         | 7              | 3.81            | 4.73   | 0.47                          | 0.91  | 1.24  |
| Stahl Peak, MT     | 97.4         | 15             | 1.48            | 1.02   | -0.08                         | -0.46 | -0.79 |
| West Glacier, MT   | 99.6         | 22             | 6.30            | 6.16   | -0.05                         | -0.14 | -0.49 |
| Whitefish, MT      | 97.2         | 11             | 6.50            | 6.07   | -0.08                         | -0.43 | -0.78 |

<sup>1</sup>Delta: Daymet – Observation, <sup>2</sup>Climate Station

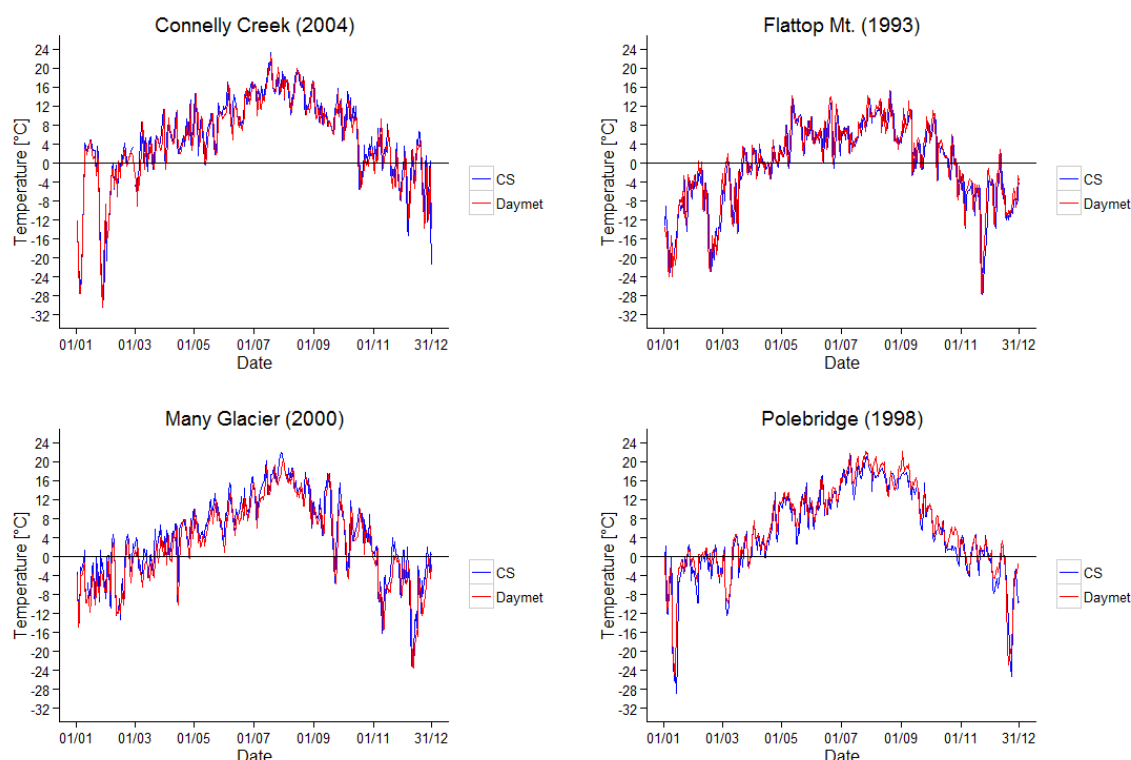


**Fig 8 | Comparison of climate station (CS) and Daymet mean daily temperature (Connelly Creek, Flattop Mt., Many Glacier and Polebridge)**

Since the data coverage for precipitation is considerably lower and the Daymet consistently over- or underestimates precipitation at certain locations, data needs to be corrected. Averaged across all 15 climate stations, the yearly precipitation sums are in average 103 mm off target, which means an average error of 12 percent. The greatest difference between observed and Daymet data is at Fernie, with a mean underestimation of -434 mm of yearly precipitation. This equals a difference of 33 percent. Precipitation for this and five other stations is manually adjusted, by multiplying daily precipitation with a delta factor (Tab 4). Only stations with a constant over or underestimation are considered for correction. The delta factor is calculated for each station separately as a mean delta change factor (observed yearly precipitation / Daymet yearly precipitation), comparable to approaches used in the delta change method in climate change modeling. Again only years with more than 360 days of data are considered for calculating the delta factor.

**Tab 3 | Comparison of climate station and Daymet yearly mean precipitation**

| Name               | Coverage [%] | Years compared | Ø Prcp [mm]     |        | Delta <sup>1</sup> Prcp [mm] |      |      |
|--------------------|--------------|----------------|-----------------|--------|------------------------------|------|------|
|                    |              |                | CS <sup>2</sup> | Daymet | Min                          | Ø    | Max  |
| Baynes Lake, BC    | 92.6         | 11yrs          | 401             | 518    | 0                            | 117  | 182  |
| Beaver Mines, AB   | 95.4         | 19yrs          | 764             | 697    | -6                           | -68  | -212 |
| Connelly Creek, AB | 93.2         | 16yrs          | 585             | 640    | 0                            | 56   | 121  |
| Emery Creek, MT    | 72.7         | 7yrs           | 1064            | 1160   | 26                           | 96   | 203  |
| Eureka, MT         | 99.5         | 19yrs          | 387             | 556    | 73                           | 169  | 347  |
| Fernie, BC         | 94.0         | 7yrs           | 1284            | 859    | -156                         | -424 | -559 |
| Flattop Mt., MT    | 72.8         | 6yrs           | 1836            | 1717   | -25                          | -119 | -265 |
| Fortine, MT        | 90.8         | 12yrs          | 390             | 562    | 103                          | 172  | 307  |
| Grave Creek, MT    | 74.0         | 6yrs           | 1265            | 1203   | 14                           | 62   | -148 |
| Many Glacier, MT   | 73.4         | 6yrs           | 1324            | 1315   | -14                          | -9   | 189  |
| Olney, MT          | 96.8         | 10yrs          | 559             | 593    | -4                           | 34   | 84   |
| Polebridge, MT     | 41.0         | 6yrs           | 583             | 866    | 182                          | 283  | 394  |
| Stahl Peak, MT     | 67.6         | 6yrs           | 1619            | 1621   | 13                           | 3    | 167  |
| West Glacier, MT   | 99.6         | 22yrs          | 769             | 731    | -9                           | -39  | -147 |
| Whitefish, MT      | 98.1         | 18yrs          | 507             | 577    | 2                            | 69   | 172  |

<sup>1</sup>Delta: Daymet – Observation, <sup>2</sup>Climate Station

**Tab 4 | Correction factors for Daymet precipitation data**

| Name               | Years compared | Mean delta <sup>1</sup> [mm] |                       | Correction factor |
|--------------------|----------------|------------------------------|-----------------------|-------------------|
|                    |                | DM <sup>2</sup> -CS          | Corr <sup>3</sup> -CS |                   |
| Baynes Lake, BC    | 11             | +117                         | +3                    | 0.78              |
| Connelly Creek, AB | 15             | +56                          | -2                    | 0.91              |
| Emery Creek, MT    | 7              | +95                          | +3                    | 0.92              |
| Fernie, BC         | 7              | -424                         | +5                    | 1.50              |
| Fortine, MT        | 12             | -172                         | +2                    | 0.69              |
| Polebridge, MT     | 6              | +283                         | -2                    | 0.67              |

<sup>1</sup>delta: Daymet-Observation, <sup>2</sup>DM:Daymet, <sup>3</sup>Corr: Corrected Daymet precipitation

Relative humidity is a meteorological variable that is not routinely measured across a widespread area. So based on the assumption that minimum daily air temperature is a reasonable surrogate for dew-point temperature, relative humidity is estimated. In humid temperate climates, atmospheric water vapor close to the ground often reaches saturation around the time of minimum temperature (Eccel 2012) and the dew point remains relatively constant over the day (Kimball et al. 1997). The relationship of minimum temperature and dew point temperature is however strongly dependent on the climate characteristics of a particular region. But it was assessed that minimum temperature provided good estimates in North America and Europe, and only in arid environments the relationship between minimum and dew point temperature deteriorates (Kimball et al. 1997).

Relative humidity can be expressed as the ratio between actual water vapor  $e_a$  and saturated vapor pressure  $e_s$ , and is therefore a pure function of temperature (Eccel 2012). The actual vapor pressure will be derived from dew point temperature and saturation vapor pressure as a function of mean air temperature (Raes 2012). Equations for mean relative humidity, actual and saturation vapor pressure are presented according to the “FAO ET<sub>0</sub> Calculator (Raes 2012)”.

$$rH_{mean} = \frac{e_a(T_{dew})}{e_s(T_{mean})} \cdot 100$$

Calculating actual vapor pressure  $e_a$ :

$$e_a = 0.6108 \cdot e^{\left[\frac{17.27 \cdot T_{dew}}{T_{dew} + 237.3}\right]}$$

where:  $T_{dew} = T_{min}$  [°C].

Calculating saturation vapor pressure  $e_s$ :

$$e_s = 0.6108 \cdot e^{\left[\frac{17.27 \cdot T}{T + 237.3}\right]}$$

where:  $T = T_{mean}$  [°C].

Global solar radiation is another meteorological variable that is not routinely measured across the catchment and therefore needs to be estimated. It will be derived from the maximum and minimum air temperature by means of the adjusted Hargreaves' radiation formula according to Raes (2012).

$$R_s = k_{RS} \cdot \sqrt{(T_{max} - T_{min})} \cdot R_a$$

where:  $R_s$  = solar radiation [MJ m<sup>-2</sup> d<sup>-1</sup>],  
 $R_a$  = extraterrestrial radiation [MJ m<sup>-2</sup> d<sup>-1</sup>],  
 $T_{max}$  = maximum air temperature [°C],  
 $T_{min}$  = minimum air temperature [°C],  
 $k_{RS}$  = adjusted coefficient (for interior location 0.16, for coastal locations 0.19).

Calculating extraterrestrial radiation  $R_a$ :

$$R_a = \frac{24 \cdot 60 \cdot 60}{\pi} \cdot G_{sc} \cdot d_r \cdot [\omega_s \cdot \sin \varphi \cdot \sin \delta + \cos \varphi \cdot \cos \delta \cdot \sin \omega_s]$$

where:  $R_a$  = extraterrestrial radiation [ $\text{MJ m}^{-2} \text{d}^{-1}$ ],  
 $G_{sc}$  = solar constant ( $0.0820 \text{ MJ m}^{-2} \text{d}^{-1}$ ),  
 $d_r$  = inverse relative distance Earth-Sun,  
 $\omega_s$  = sunset hour angle [rad],  
 $\varphi$  = latitude [rad],  
 $\delta$  = solar declination [rad].

Conversion decimal degree to radians:

$$[rad] = \frac{\pi}{180} \cdot [decimal\ degree]$$

Inverse relative distance Earth-Sun  $d_r$  and solar declination  $\delta$ :

$$d_r = 1 + 0.033 \cdot \cos\left(\frac{2\pi}{365} \cdot J\right)$$

$$\delta = 0.409 \cdot \sin\left(\frac{2\pi}{365} \cdot J - 1.39\right)$$

where:  $J$  = number of the day in the year.

Sunset hour angle  $\omega_s$ :

$$\omega_s = \arccos[-\tan \varphi \tan \delta]$$

where:  $\varphi$  = latitude [rad],  
 $\delta$  = solar declination [rad].

The last missing meteorological variable is daily wind speed. Also this variable is not a frequent component of the meteorological stations in the closer surrounding of the catchment. Therefore, wind speed was extracted from the ECMWF-ERAINT reanalysis data (Environment Canada 2014). A requirement of reanalysis data is its physical coherence, meaning that estimated parameters must be consistent with the laws of physics as well as with observations (Dee et al. 2011) and therefore a good estimate of wind speed. The wind speed was extracted for the 15 locations of the meteorological stations and the time series 1990-2009.

### 3.3.2 Geographic data

Spatially distributed geographic data with a constant pixel resolution (in this study 250m) is necessary for land cover, topography and soil types. The DEM is a crucial part of the modeling, especially in mountainous regions.

The DEM is the basis for deriving topographic dependent data sets, like slope, aspect and curvature, but also important hydrological information, such as flow accumulation, flow direction, river network and subbasin structure can be determined (Schulla 2013).

The greatest difficulty was finding sufficient soil type information for the entire watershed. Especially this data highlighted the challenges of working in a transnational watershed. Most data simply ends at the border and available information at this time for the entire region is very coarse and therefore not recommended to use. For the part of the watershed located in Montana, sufficient soil type information was available. Finding soil type information for the remainder of the watershed located in south-eastern British Columbia was challenging, since this part of the province is only sparsely populated and no major agricultural developments are present. Detailed soil surveys for British Columbia were only available for the western part of the province.

Also soil information for Alberta, Canada ended at the national and provincial border. Soil information in Alberta is widely available, especially because of intensive agricultural activities in southern Alberta. Due to the fact, that there is only soil type information available for the Montana part of the watershed, this information needs to be extrapolated to the remainder of the catchment. As a first step the U.S. general soil map (U.S. Department of Agriculture, Natural Resources Conservation Service 2006) for Montana was generalized to receive the general soil type classes, such as loam, clay, sand, silty-loam and so on, since WaSiM works with these general soil types as an input (Schulla 2013). In WaSiM also more detailed soil classifications could be implemented, but due to the lack of extensive soil information, general soil types are a good approach. As a second step the generalized soil types were analyzed for any patterns. Since the generalizing process only three soil types were left (loam, silty-loam and rock) and a clear pattern with elevation was noticeable. After further analysis the threshold elevation for rock and loam was set to 1800 m. All areas above 1800 m are considered rock and areas below 1800 m loam. Finding a threshold elevation for silty-loam was not successful, but it only exists in the closer surrounding of rivers.

Since this pattern is not stringently applicable to the entire stream, the soil type silty-loam was manually edited for the location in the generalized soil map.

After a visual inspection of the goodness-of-fit of the elevation dependent approach, the soil types loam and rock were extrapolated throughout the remainder of the watershed, and silty-loam was manually added as a soil type along the North Fork Flathead River in the Montana part (Fig 9).

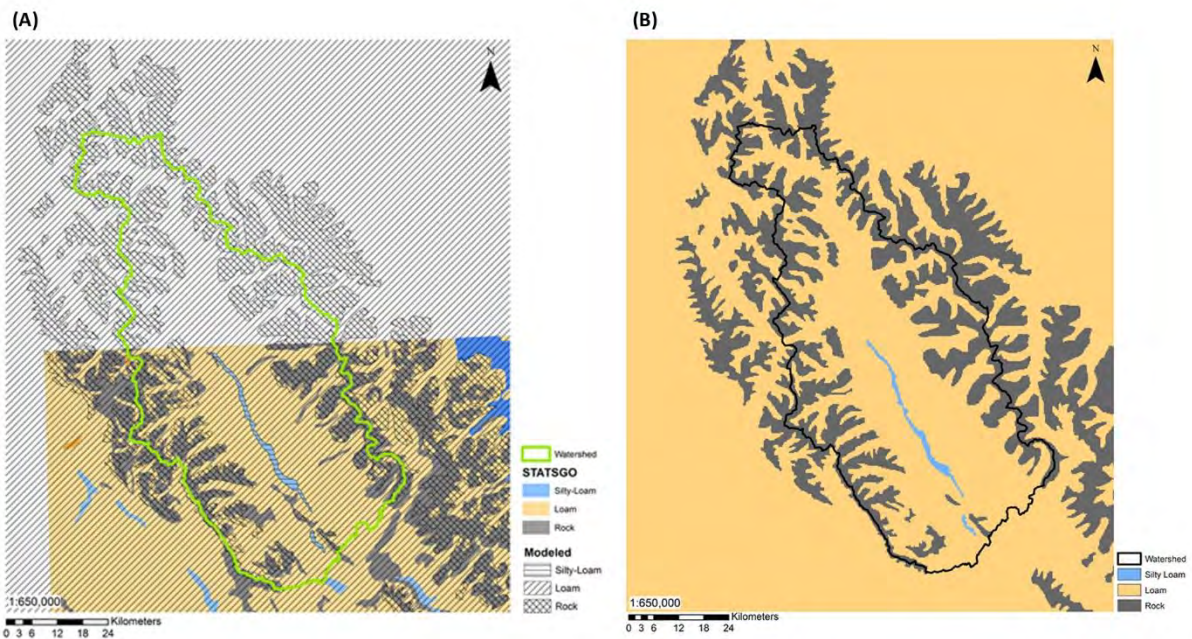


**Fig 9 | Soil input data. (A) Comparison of modeled and STATSGO soil types, (B) Soil type map used in the model**

The land cover mainly consists of extensive coniferous forest, which covers about 74 percent of the catchment. The remaining parts of the watershed are covered by scrub/shrub, no vegetation (barren), grassland, deciduous and mixed forest, water bodies and with less than 1 percent human developments, agriculture and ice/snow (Tab 5). The spatial land cover information is based on the Crown of the Continent land cover map (Crown Managers Partnership 2014).

**Tab 5 | Fraction of land cover in the catchment**

| Land cover type   | Fraction in percent of the watershed |
|-------------------|--------------------------------------|
| Coniferous Forest | 74                                   |
| Scrub/Shrub       | 11                                   |
| Barren            | 6                                    |
| Grassland         | 4                                    |
| Deciduous Forest  | 2                                    |
| Mixed Forest      | 1                                    |
| Water             | 1                                    |
| Developed         | <1                                   |
| Agriculture       | <1                                   |
| Ice/Snow          | <1                                   |

Information about the river network, structure of the subcatchments and further topographic information are derived from the DEM, with the help of the topographic analysis tool (TANALYS). The structure of the subcatchments are defined by pour-points, which are a required input in TANALYS. All areas above the single pour-points that drain into that pour-point form a subcatchment. This allows the modeler to create a unique structure that benefits the study the most. The different structuring of the subcatchments has no effect on the outcome of the model, but the output files are structured according to the subdivided catchments and all hydrologic variables are available on the catchment scale (at the outlet of the catchment) and the subcatchment scale. Subcatchments and river network utilized in this study are shown in Fig 10.



**Fig 10 | River network and subcatchments in the model setup**

### 3.4 CALIBRATION AND VALIDATION

#### 3.4.1 Model Efficiency Criteria

Hydrologists, or any other environmental modeler, evaluates model performance to provide a quantitative estimate of the models ability to reproduce historic and future behavior, and to evaluate improvements to the modeling approach through adjusting model parameter (Krause et al. 2005). Generally, model performance is determined by comparing simulated values and the corresponding observed values (Ritter, A., Muñoz-Carpena, R. 2013). In hydrology there are two general approaches of assessing model performance: (1) Assessing model performance in terms of systematic (e.g. over- or underprediction) and dynamic behavior (e.g. timing, rising limb, falling limb and base flow) through visual inspection of the simulated and observed hydrograph (subjective approach); (2) Assessing model performance using mathematical estimates of the error between the simulated and observed hydrologic variable, such as efficiency criteria (objective approach). Efficiency criteria are defined as mathematical measures of the goodness-of-fit of the simulated and the observed variable. Many efficiency criteria are based on the summation of the error term (e.g. difference of simulated and observed discharge at each time step) normalized by a term of the variability of the observation. To avoid cancelling of errors of opposite sign, the summation of absolute or squared errors is used. (Krause et al. 2005) For addressing model performance evaluation, the use of qualitative and quantitative criteria is recommended, since both approaches capture distinct aspects of model performance (Ritter, A., Muñoz-Carpena, R. 2013). In this study, the coefficient of determination and the Nash-Suttcliffe-Efficiency are used as quantitative criteria according to Krause et al. (2005). The coefficient of determination  $r^2$  is defined as the squared value of the coefficient of correlation according to Bravais-Pearson and can also be expressed as the squared ratio between the covariance and the multiplied standard deviations of the observed and simulated values. It is calculated as:

$$r^2 = \left( \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \right)^2$$

with O observed and P predicted values.

The values of  $r^2$  lie between 0 and 1, whereas 1 means that the distribution of the prediction is equal to the observed time series and a value of zero means that there is no correlation.

The Nash-Sutcliffe-Efficiency (NSE) is a commonly used indicator in hydrologic modeling (Ritter and Muñoz-Carpena 2013). It is defined as one minus the sum of the absolute squared differences between observed and simulated values normalized by the variance of the observed values.

It is calculated as:

$$E = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2}$$

The NSE lies between 1 and  $-\infty$ , whereas 1 indicates perfect fit and efficiency lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.

### 3.4.2 Observed and modeled stream flow

Before calibrating, the observed discharge is briefly characterized.

When looking at the long-term yearly mean discharge for the North Fork Flathead River, near Columbia Falls, Montana from 1960 to 2013 there is no obvious trend evident (Fig 11). The streamflow of the North Fork Flathead River is strongly dependent on the accumulation of snow. It can be considered a nival-flow regime with a dominant maximum flow caused by snowmelt and low flows in summer and winter.

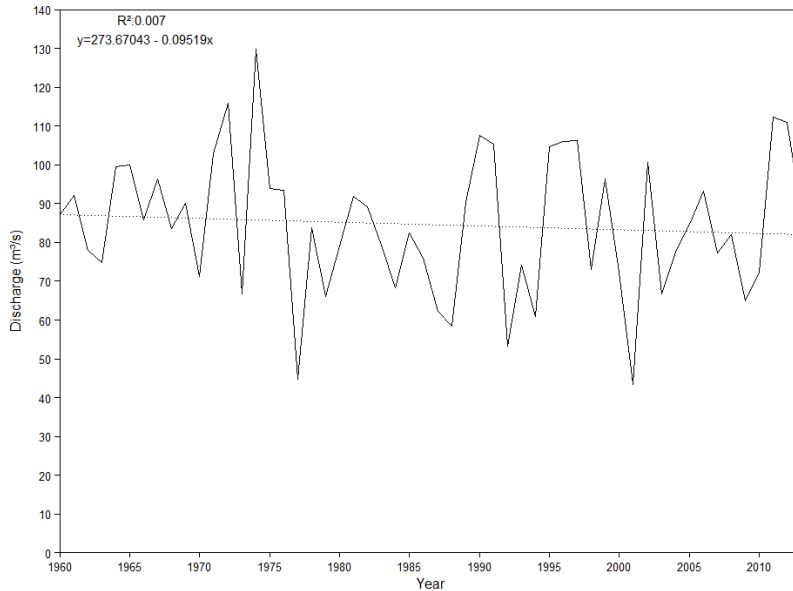


**Fig 11 | Discharge at North Fork Flathead river near Columbia Falls, MT (1960-2013)**  
(dotted line: linear trend 1960-2013)

One of the keys to successful modeling of hydrologic processes in a specific catchment is the calibration itself (Cullmann et al. 2011). In WaSiM calibration is performed manually and gradually. The calibration is executed for the time series 1990-2000, whereby the first year is not being considered when evaluating model performance, since the first year is designated as warm up. A warm up period is necessary, since the WaSiM setup in this study has no initial state as an input, and therefore storages have to be filled first. Optimal parameters are searched by gradually changing single parameters. Every calibration run will be evaluated by calculating the model efficiency criteria (NSE and  $R^2$ ) and comparing Mean Monthly Flow (MMQ) and Mean Flow (MQ) to see if model performance was improved or not. The modeled streamflow will be compared to the observed streamflow at the gauging station. After several calibration runs, if an optimal parameter set is found, the model settings are applied to the validation period 2001-2009 (warm-up: 2000). Validation is necessary to test if the model setup also performs well outside the time series it has been set up for. A parameter set is only considered best if it is applicable in both time series. Until this condition is fulfilled, calibration has to be further executed. Nevertheless, there is not the one ultimate parameter set, since several different parameter sets can lead to the correct output (Wainwright and Mulligan 2004). This is called equifinality.

In WaSiM, only sensitive parameters and parameters that strongly depend on catchment properties should be calibrated (Schulla 2013). When comparing the parameter set before calibration with the observed discharge, several differences in flow regime can be detected (Fig 12). First, the base flow in the low flow season is distinctively below the observed discharge and in summer the river almost dries out. Second, the development of high flows starts too early in the season and the increase of flow until peak flow is influenced by several maxima and minima, which either indicates a strong influence by precipitation events or the snow melt is constantly being interrupted, caused by a low threshold temperature for snow melt. Third, the period of peak flow is divided into two distinct peaks and simulated peak flow declines by the time the observed flow reaches peak flow.

To tackle the differences in snow related hydrologic behavior, the threshold temperature for snow melt, the temperature limit for snow and rain (at which 50 % of the precipitation falls as snow and 50% as rain), the degree day factor and parameters of precipitation correction are calibrated.

To change base flow and overall flow behavior, recession parameters for base, inter- and direct flow as well as soil thickness and recession constant for the saturated hydraulic conductivity with depth are calibrated.

After 44 runs a parameter set was found that represents the observed flow regime. Since the first un-calibrated run, model performance was increased from NSE 0.24 and  $R^2$  0.43 to NSE 0.78 and  $R^2$  0.80. Also mean flow (MQ) was increased from 68.6 to 79.8 m<sup>3</sup>/s, compared to observed MQ 85.3 m<sup>3</sup>/s (Tab 6). The overall model performance was increased and the model represents the observed flow, but the problem with too little base flow is still present.

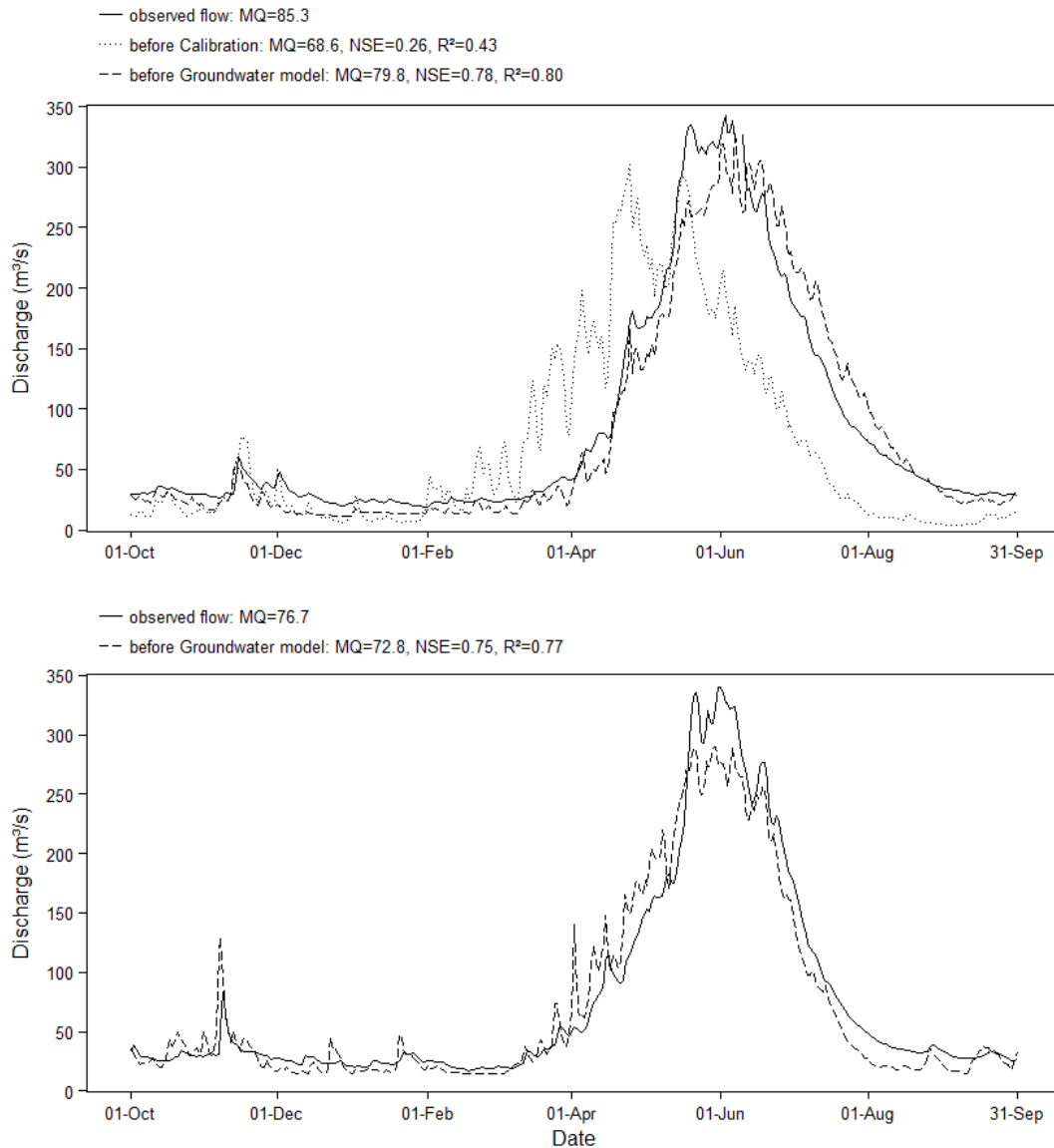


**Fig 12 | Model performance calibration and validation without groundwater module, mean daily discharge (Upper: Calibration (1991-2000), Lower: Validation: (2001-2009))**

**Tab 6 | Mean monthly flow and mean flow in the calibration and validation period**

| Month | Calibration |                |            | Validation |            |
|-------|-------------|----------------|------------|------------|------------|
|       | observed    | not calibrated | calibrated | observed   | calibrated |
| 1     | 22.8        | 10.4           | 14.3       | 25.1       | 22.1       |
| 2     | 23.9        | 35.1           | 16.6       | 20.4       | 16.0       |
| 3     | 31.9        | 87.8           | 23.5       | 32.5       | 34.3       |
| 4     | 104.1       | 206.0          | 86.1       | 93.1       | 122.7      |
| 5     | 269.2       | 224.4          | 229.1      | 241.7      | 239.4      |
| 6     | 271.2       | 134.3          | 278.1      | 258.5      | 227.5      |
| 7     | 121.1       | 42.1           | 158.1      | 91.3       | 69.6       |
| 8     | 50.1        | 8.5            | 57.2       | 36.7       | 21.9       |
| 9     | 30.6        | 8.5            | 24.8       | 29.1       | 24.9       |
| 10    | 31.6        | 17.4           | 25.6       | 29.4       | 31.8       |
| 11    | 36.8        | 35.5           | 27.8       | 36.5       | 42.3       |
| 12    | 27.7        | 14.0           | 13.4       | 24.7       | 20.2       |
| MQ:   | 85.3        | 68.6           | 79.8       | 76.7       | 72.8       |

One can assume that the base flow is influenced by groundwater, since low flow during the snow covered season, where direct contribution of precipitation is very little, is characterized by a homogenous discharge. (Mills et al. 2012; Patton et al. 2003; EPA 2011) confirm the impression of a strong influence of groundwater in low-flow periods. The median observed discharge November through March is between 18-29 m<sup>3</sup>/s, compared to the modeled median discharge of 12-16 m<sup>3</sup>/s (Tab 7). Since the gap between observed and modeled low flow couldn't be bridged by the recession parameters and the increased thickness of the soil layer, a groundwater layer has to be introduced in the WaSiM setup.

**Tab 7 | Median discharge, 10- and 90%-Quantile of observed and modeled discharge (November-March)**

| Month    | observed |        |      | modeled |        |      |
|----------|----------|--------|------|---------|--------|------|
|          | 10%      | median | 90%  | 10%     | median | 90%  |
| November | 15.4     | 23.8   | 74.0 | 6.7     | 15.1   | 58.6 |
| December | 13.2     | 19.0   | 52.0 | 5.8     | 12.0   | 20.6 |
| January  | 13.3     | 20.1   | 36.7 | 6.6     | 11.5   | 35.7 |
| February | 11.3     | 18.1   | 46.3 | 7.1     | 10.9   | 37.5 |
| March    | 15.3     | 28.9   | 52.9 | 7.2     | 15.6   | 45.5 |

In the North Fork Flathead River watershed there are numerous sources for groundwater: (1) Tertiary Rocks, (2) glacial till and (3) alluvial shallow and deep aquifers (LaFave et al. 2004). The shallow alluvial aquifers consist of sand and gravel, and occur at land surface along the floodplains of streams, with a median thickness of approx. 10m (34 ft.) (LaFave et al. 2004). In this study this type of groundwater source is being considered and calibrated. No further information about spatial distribution, aquifer thickness or horizontal and vertical saturated hydraulic conductivity was accessible.

Therefore, a shallow aquifer along the main stem of the stream with a thickness of 10 m is being initialized and other variables are calibrated (Fig 13).

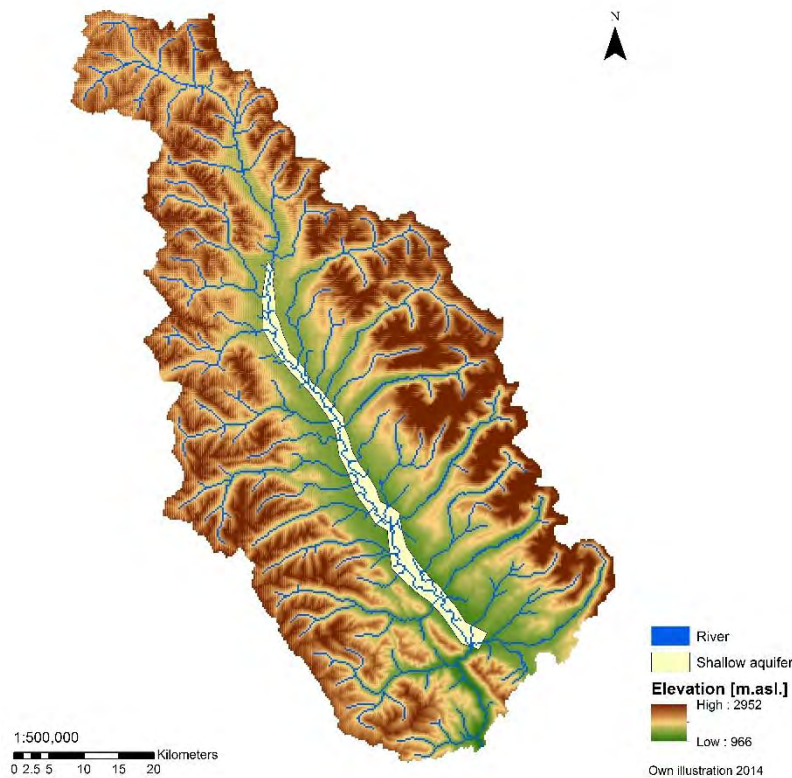
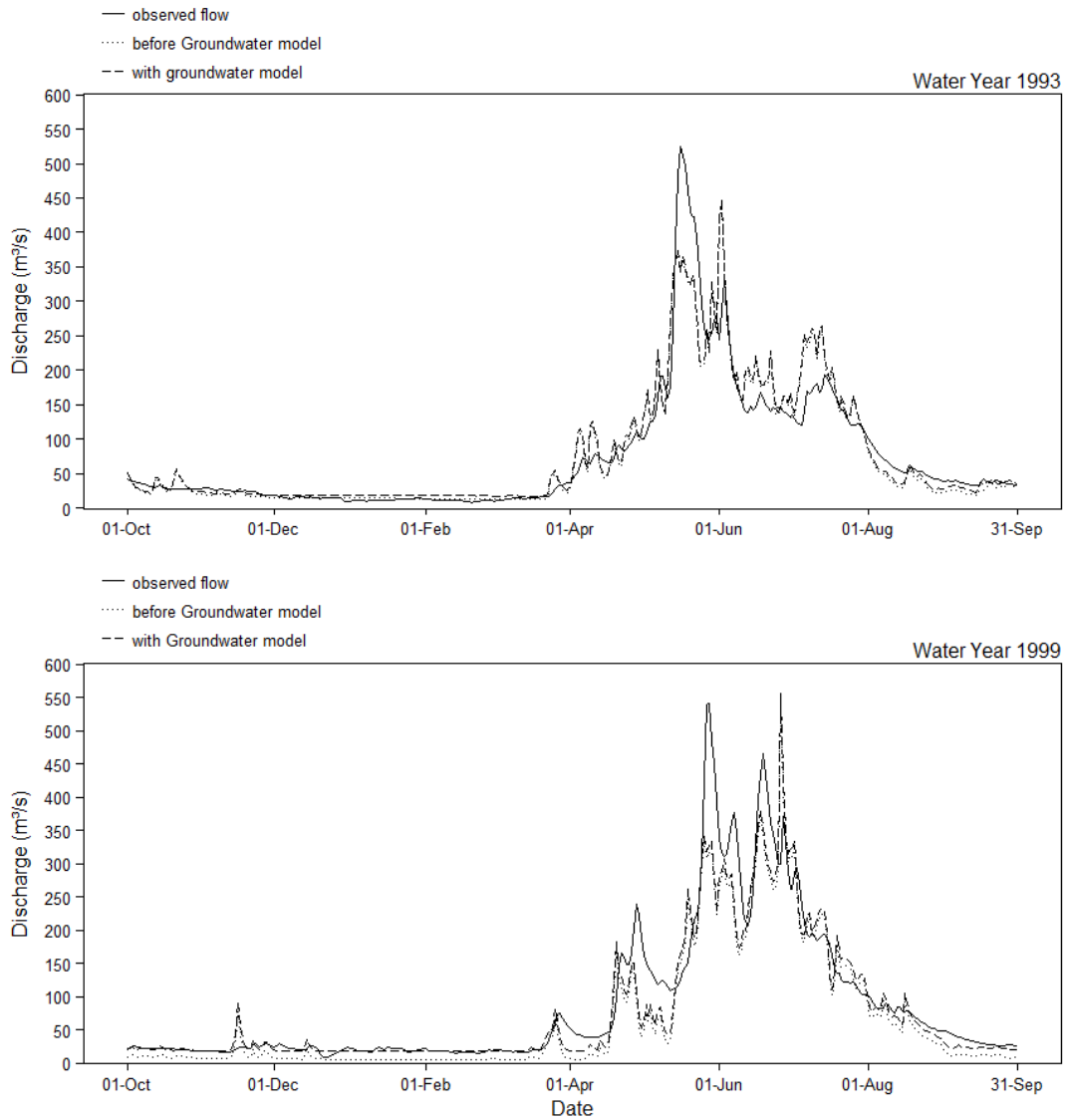


**Fig 13 | Extent of shallow aquifer**

With the introduction of a one layer single shallow aquifer, it was possible to lift the base flow to a comparable level of the observed flow. The low flow periods are now modeled much better. Median low flow with a groundwater layer is now between 19-23 m<sup>3</sup>/s, compared to median observed flow 18-29 m<sup>3</sup>/s (Tab 8). Although base flow was improved, no further improvement of model efficiency criteria was possible. A reason for this could be the low sensitivity of NSE and R<sup>2</sup> for low flow periods (Krause et al. 2005). Nevertheless, the other measures for evaluating the goodness-of-fit were improved. The mean discharge was raised from 79.8 m<sup>3</sup>/s (no groundwater model) to 86.9 m<sup>3</sup>/s (with groundwater model), compared to 85.3 m<sup>3</sup>/s (reference) (Fig 15). This means, that mean flow is only 1.9 percent above observed mean flow, compared to -6.5 percent without groundwater model. Another aspect to consider is, that before including the groundwater module the model always flattened out at the end of the calibration period, meaning that the base flow became considerable less. With enabling the groundwater module with the shallow aquifer, this behavior of the model was suppressed (Fig 14).

**Tab 8 | Median discharge, 10- and 90%-Quantile of observed and modeled discharge with shallow aquifer (November-March)**

| Month    | observed |        |      | modeled |        |      |
|----------|----------|--------|------|---------|--------|------|
|          | 10%      | median | 90%  | 10%     | median | 90%  |
| November | 15.4     | 23.8   | 74.0 | 17.9    | 20.8   | 68.5 |
| December | 13.2     | 19.0   | 52.0 | 17.3    | 19.0   | 30.7 |
| January  | 13.3     | 20.1   | 36.7 | 17.3    | 18.6   | 24.1 |
| February | 11.3     | 18.1   | 46.3 | 17.5    | 18.9   | 30.3 |
| March    | 15.3     | 28.9   | 52.9 | 17.8    | 22.6   | 52.2 |

**Fig 14 | Improvement of base flow at the end of the calibration time series (Water Year 1999)**

Also in the validation period, it was possible to improve the models performance in terms of base flow and mean discharge. Mean discharge was raised from 72.8 m<sup>3</sup>/s (without groundwater) to 79.5 m<sup>3</sup>/s, compared to observed 76.6 m<sup>3</sup>/s (reference), which means a difference of +3.8 percent in mean discharge compared to -5.0 percent without groundwater model.

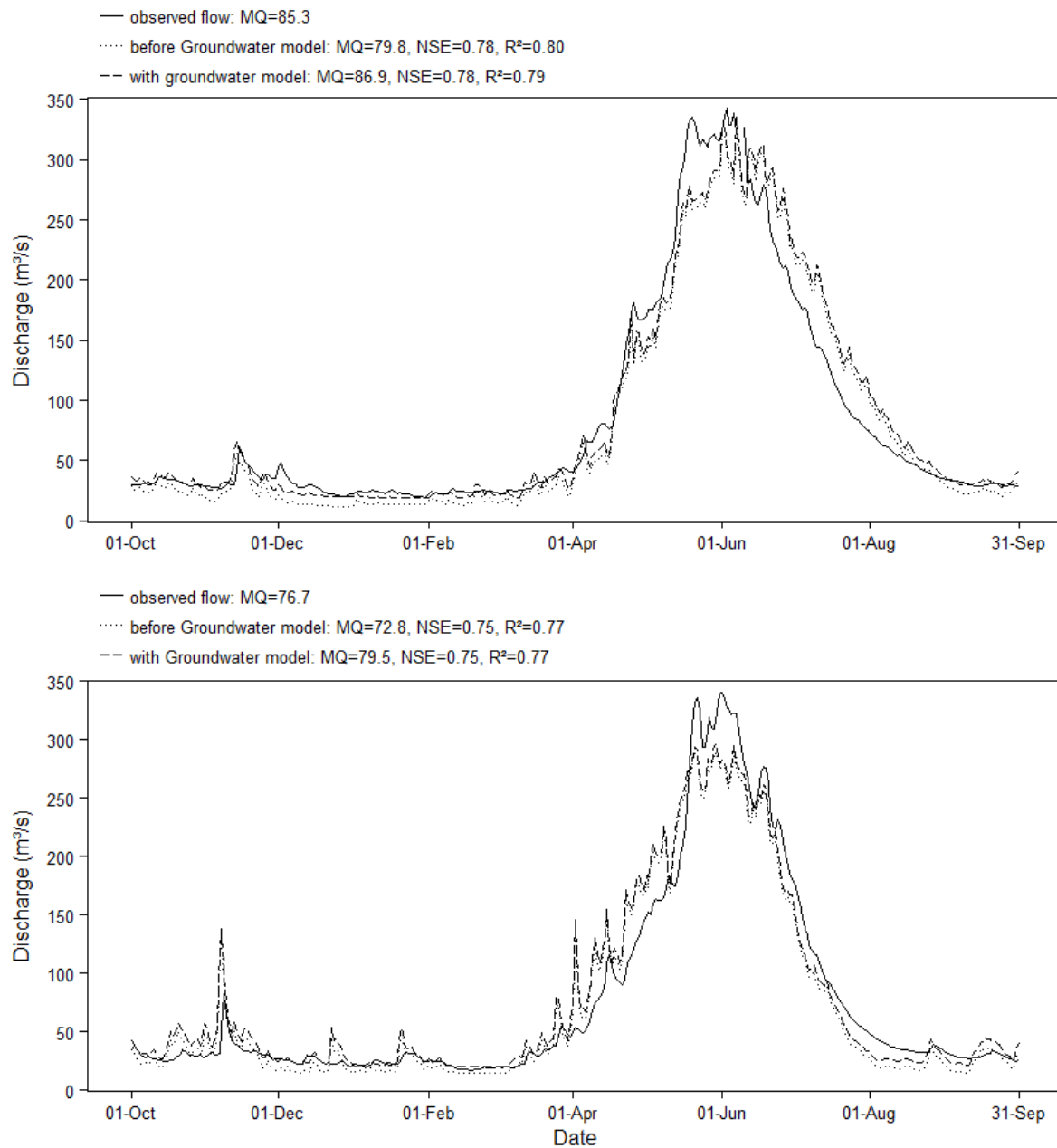


**Fig 15 | Model performance calibration and validation with groundwater module, mean daily discharge (Calibration: 1991-2000, Validation: 2001-2009)**

**Tab 9 | Mean monthly flow and mean flow in the calibration and validation period with groundwater module**

| Month | Calibration |       |         | Validation |       |         |
|-------|-------------|-------|---------|------------|-------|---------|
|       | observed    | no GW | with GW | observed   | no GW | with GW |
| 1     | 22.8        | 14.3  | 19.9    | 25.1       | 22.1  | 27.2    |
| 2     | 23.9        | 16.6  | 22.7    | 20.4       | 16.0  | 21.4    |
| 3     | 31.9        | 23.5  | 30.1    | 32.5       | 34.3  | 40.4    |
| 4     | 104.1       | 86.1  | 93.2    | 93.1       | 122.7 | 129.3   |
| 5     | 269.2       | 229.1 | 235.6   | 241.7      | 239.4 | 245.4   |
| 6     | 271.2       | 278.1 | 284.9   | 258.5      | 227.5 | 233.6   |
| 7     | 121.1       | 158.1 | 164.6   | 91.3       | 69.6  | 75.5    |
| 8     | 50.1        | 57.2  | 63.9    | 36.7       | 21.9  | 28.3    |
| 9     | 30.6        | 24.8  | 32.3    | 29.1       | 24.9  | 32.0    |
| 10    | 31.6        | 25.6  | 33.7    | 29.4       | 31.8  | 39.7    |
| 11    | 36.8        | 27.8  | 36.3    | 36.5       | 42.3  | 50.6    |
| 12    | 27.7        | 13.4  | 22.0    | 24.7       | 20.2  | 28.5    |
| MQ:   | 85.3        | 79.8  | 86.7    | 76.7       | 72.8  | 79.5    |

Another question to discuss in terms of model efficiency, is how to handle outliers. Not considering outliers can improve the model efficiency criteria, in this particular case, the model efficiency criteria in the validation period was improved (Fig 16). Model efficiency in the calibration period was only improved marginal, since only one outlier was not considered.

The performance without outliers was improved, because of the sensitivity of the NSE for high flow values. The outliers that weren't considered were all high flow events, either observed high flow events that were insufficiently represented by the model or modeled high flows, whereas the observed values show distinctively less flow. But in my opinion high flow events have to be considered, even though they might be outliers, because they can give additional information about the model performance. One can see, if this over- or underestimating of high flow events, is a constant situation or if this is the case for only one or two events.

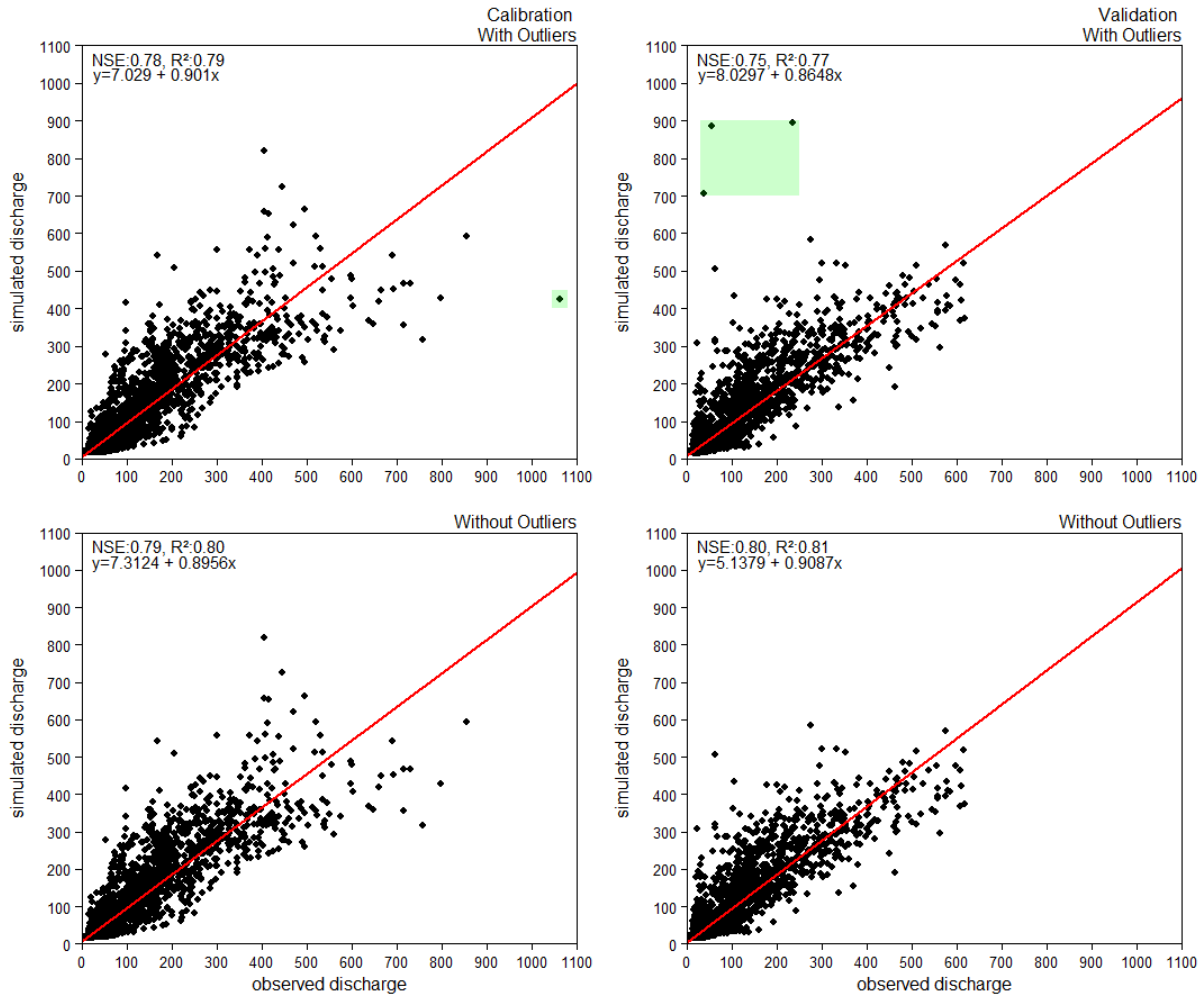


**Fig 16 | Model performance with and without outliers (left: Calibration, right: Validation, green box: Outliers)**

### 3.4.3 Observed and modeled snow cover

An additional approach, to improve model performance is the calibration and validation of a second main driver of the runoff generation. Since the flow regime in the study area is strongly influenced by the accumulation and melting of snow pack, an additional validation of this feature could bring more insight of the catchment specific behavior of snow accumulation and melt. Another reason to validate the model performance in terms of snow cover extent, is the predicted decline in snow cover with rising temperatures (Day 2009; Jasper et al. 2004; Knowles et al. 2006). The model needs to be able to also model the future magnitude and extent of snow cover.

To validate the models performance, modeled and observed snow cover extent are compared. Observed snow cover is derived by applying a maximum likelihood classification to several Landsat images (Tab 10). The Landsat images were classified using several land cover types (rock, forest, barren, snow, water, etc.) and afterward non-snow groups were merged.

This approach was more accurate than only classifying snow and no snow.

The result of the classification, is a map with snow (1) and no snow (0), with the same spatial resolution as the model output (250m).

WaSiM produces daily grids of snow storage, which were used to calculate daily, monthly and mean snow cover extent. A threshold quantity of snow water equivalent (SWE) was set to 40 mm what equals approx. 10 cm of snow depth under the assumption of spring snow with a snow density of 0.4. All areas with more than 40 mm of SWE are considered snow (2) and the remainder as no snow (0).

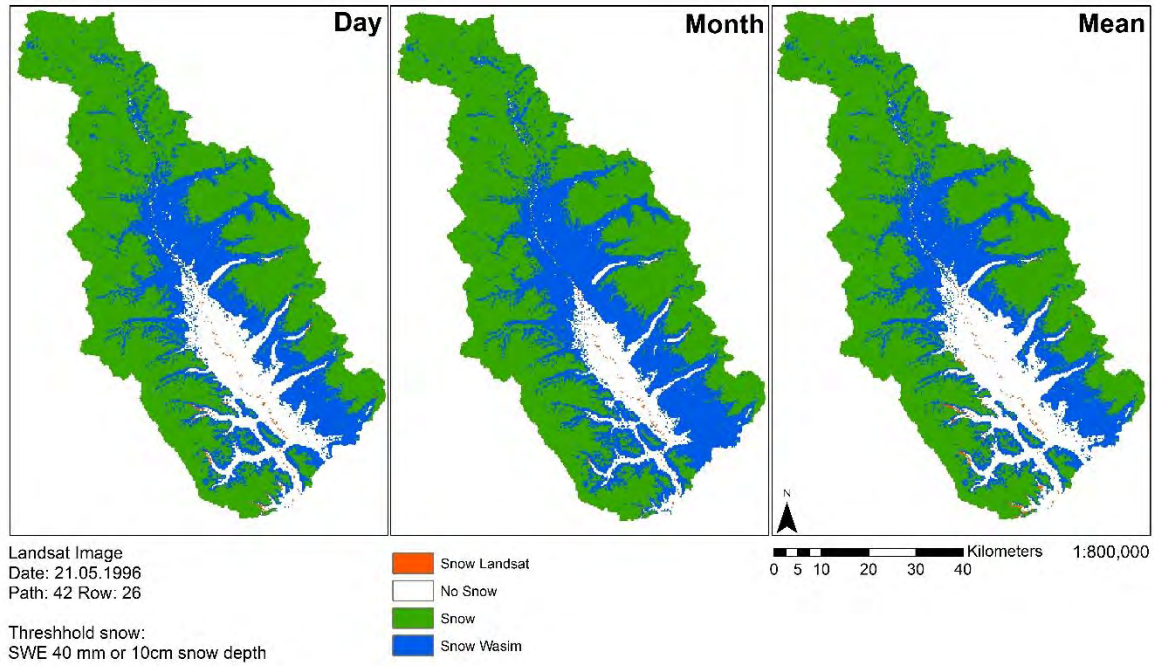
**Tab 10 | Landsat images for snow cover validation**

| Date      | Image-ID              | Path/Row |
|-----------|-----------------------|----------|
| 21.5.1996 | LT50420261996142XXX02 | 42/26    |
| 08.5.1997 | LT50420261997128PAC03 | 42/26    |
| 20.5.1998 | LT50420261998140PAC03 | 41/26    |
| 23.5.1999 | LT50410261999143PAC04 | 41/26    |
| 25.4.2004 | LT50420262004226PAC02 | 42/26    |

To validate the model performance, the Landsat snow cover is subtracted from the WaSiM snow cover (WaSiM – Landsat). In the difference image 0 means that WaSiM correctly modeled no snow, 1 means that snow was correctly modeled, -1 means snow in Landsat and no snow in WaSiM, and 2 means the opposite. All Landsat images are compared to daily WaSiM snow cover from the same day as the Landsat image, monthly snow cover from the same month and year, and the long-term mean monthly snow cover. Evaluation of the goodness-of-fit is performed by visual comparison and the ratio (in percent) between correctly modeled snow and all snow pixels in WaSiM.

First the parameter set (Run 60) from the previous section is validated to see if further calibration of the snow module is advisable. When comparing daily WaSiM snow cover with the Landsat derived snow cover for the 21.5.1996 it is obvious that WaSiM models too much snow in the valleys (Fig 17).

Nevertheless, 69 percent of WaSiM daily snow cover is correctly modeled (Tab 11). This shows that further calibration of snow related parameters would be advisable.

**May 1996****Fig 17 | Modeled and observed snow cover May 1996 (Run 60).**

**Snow Landsat:** Snow in the Landsat image, but no snow in WaSiM; **No Snow:** no snow in both; **Snow:** correctly modeled snow; **Snow WaSiM:** falsely modeled snow.

The temperature limit for snow and rain, and snow melt was further lowered to achieve earlier snow melt and slightly less snow. Temperature limit for snow melt was lowered from 1.5 to 0.7°C and temperature limit for snow and rain was lowered from 1.0 to 0.5°C. With this measure, the snow cover extend has been improved. Comparing daily modeled snow cover and Landsat snow cover in May 1996, model performance was improved from 69 to 79% correctly modeled snow (Tab 11).

**Tab 11 | Model performance snow cover (Run 60 vs Run 62).**

**Ratio between correctly modeled snow pixels and all modeled snow pixels in percent; Run 60: before optimized snow module, Run 62: optimized snow module.**

| Year | Day    |        | Month  |        | Mean   |        |
|------|--------|--------|--------|--------|--------|--------|
|      | Run 60 | Run 62 | Run 60 | Run 62 | Run 60 | Run 62 |
| 1996 | 69     | 79     | 65     | 74     | 70     | 78     |
| 1997 | 63     | 65     | 63     | 66     | 71     | 78     |
| 1998 | 69     | 81     | 69     | 73     | 36     | 41     |
| 1999 | 62     | 72     | 57     | 65     | 59     | 66     |
| 2004 | 65     | 76     | 58     | 66     | 54     | 55     |

Also snow cover extend in the valley is better represented by the optimized snow module parameters (Run 62) (Fig 18). Smaller features, like the Camas Ridge in the south-end of the valley, are also more defined than before optimizing. In years with low snow cover, areas with observed snow cover but no modeled snow increase (Fig 19).

Especially in the south-west part of the watershed snow cover is not being modeled in low snow years. Nevertheless, model performance in terms of snow cover has been increased from 69 to 81% correctly modeled snow. Remaining years compared can be seen in Appendix A.

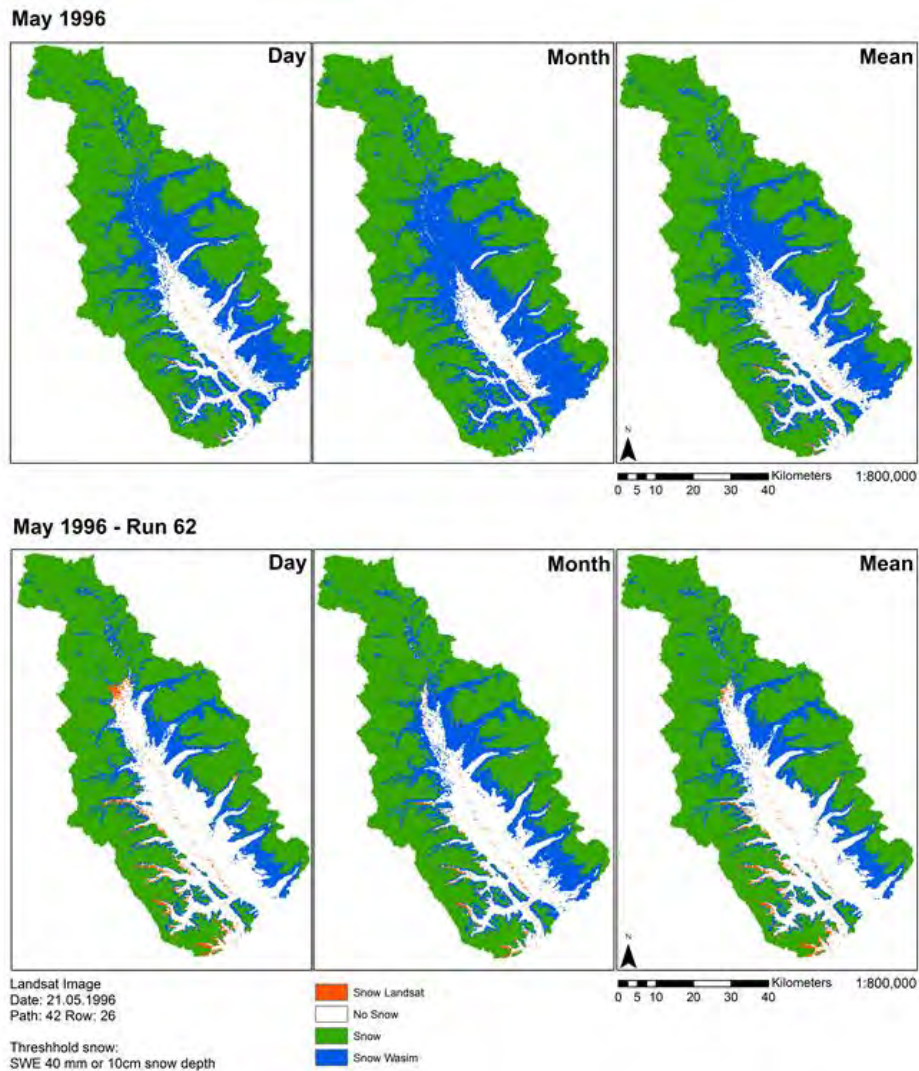


**Fig 18 | Modeled and observed snow cover in May 1996 (Run 60 vs Run 62)**

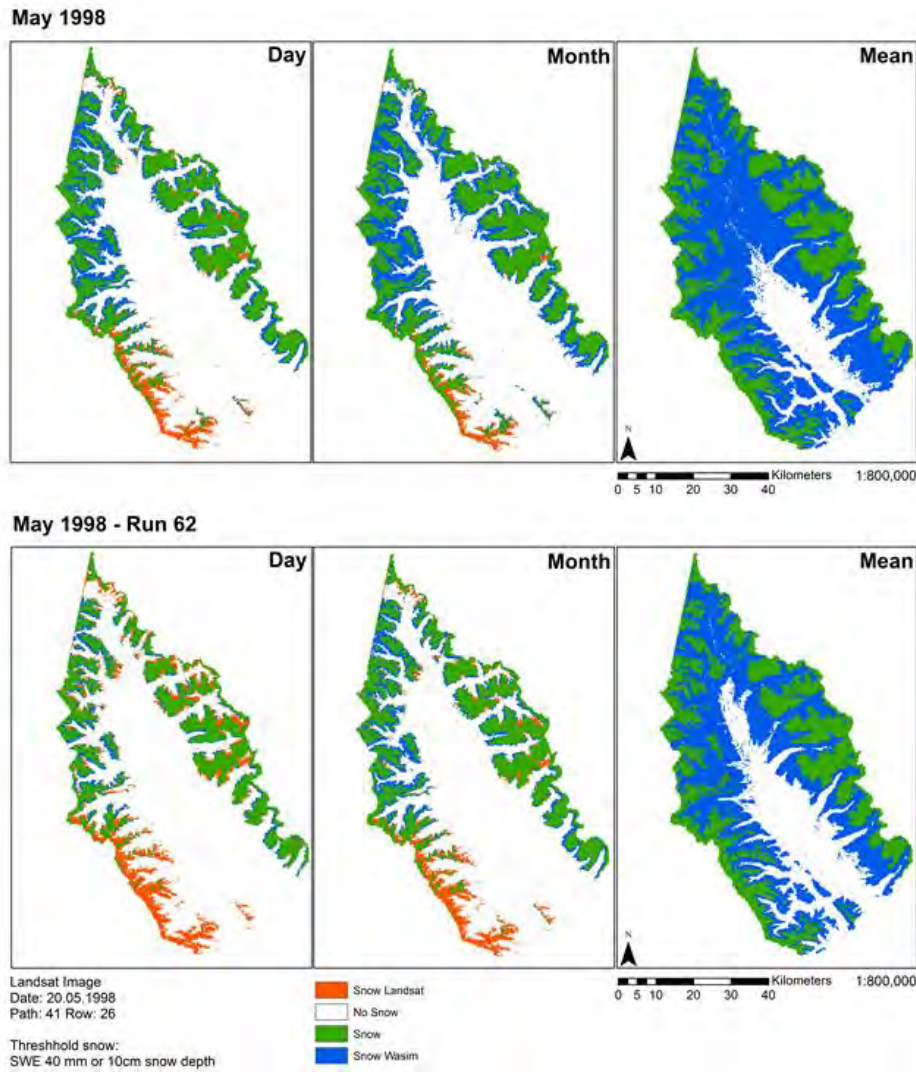


**Fig 19 | Modeled and observed snow cover in May 1998 (Run 60 vs Run 62)**

Before deciding, if the optimized snow parameter set is the best fit for the watershed, the discharge has to be validated. Model performance in terms of flow was improved in the calibration period. NSE and  $R^2$  were raised from 0.78 and 0.79 to 0.81. The swelling and declining of modeled and observed peak flow is now very closely together, which indicates a good model performance in terms of snow melt (Fig 20). But peak flows are lower than the observed and the previous parameter set, which would indicate that the model accumulates too little snow. Overall mean discharge also declined from 85.3 (observed) and 86.9  $\text{m}^3/\text{s}$  respectively (before optimization) to 82.0  $\text{m}^3/\text{s}$ , which is equals a 4% difference in mean discharge compared to observed flow.

When applying the optimized snow parameters to the validation period, model performance could not be improved, instead model performance is distinctively lower than prior snow model optimization. NSE and  $R^2$  dropped from 0.78 and 0.79 to 0.62 and 0.60, respectively. Also the flow regime changed to more rain induced peaks in the snow season (October-April) and earlier snow melt. Further, peak flows are lower and decline earlier.

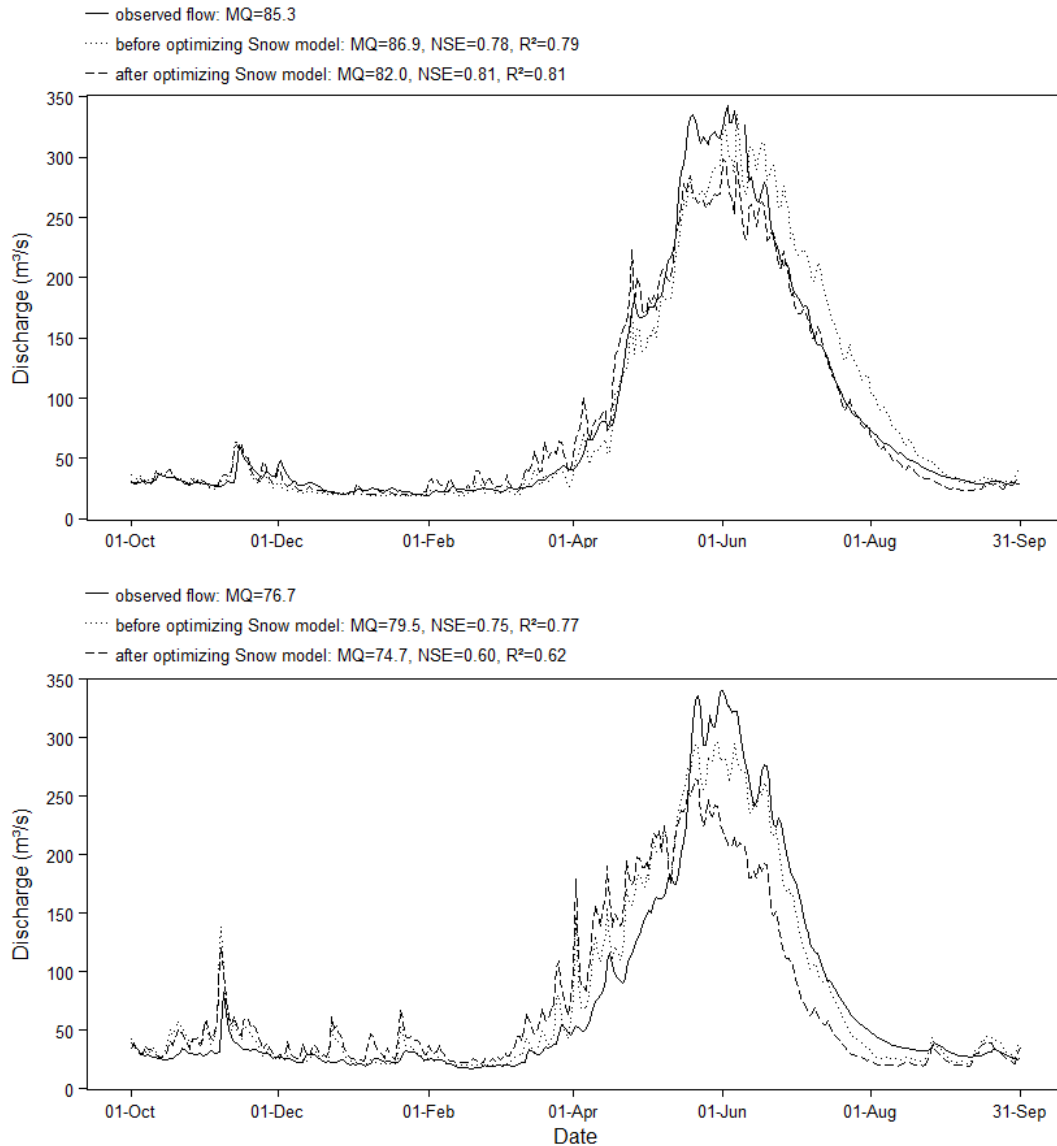


**Fig 20 | Model performance calibration and validation with/without optimized snow module, mean daily discharge (Calibration: 1991-2000, Validation: 2001-2009)**

A possible reason for this drastic change in the flow regime, using the optimized snow module parameters, is a trend in the meteorological input data (Fig 21). Especially temperature has a pronounced linear trend in the input data (1991-2000), with a temperature increase of  $0.82^{\circ}\text{C}$  per decade. The mean temperature in the validation period ( $3.3^{\circ}\text{C}$ ) is  $0.9^{\circ}\text{C}$  higher than in the calibration period ( $2.4^{\circ}\text{C}$ ).

This distinct difference in temperature evokes a strong response of streamflow, when using the parameter set from the optimized snow module. The temperature trend is too strong for the chosen threshold temperatures of snow melt and transition of snow and rain.

This means, that with the given trend the melt and transition temperature are frequently being reached, which for one means more frequent and earlier snow melt, and second more precipitation falling as rain instead of snow. Under the assumption that these parameters for snow melt and transition between rain and snow would be correct (which they clearly aren't), this behavior could be interpreted as a hydrologic response to climate warming. With this strong response, the parameter set of the optimized snow module has to be dismissed, since it is not consistent with the validation period.

This parameter set would only lead to false assumption in the future and the climate signal would influence the model too early and too extreme.

Therefore, the parameter set prior to optimization of the snow module is advisable. The validation of snow cover has shown, that the parameter set before optimization is also capable of realistically modeling snow cover and therefore is a good compromise between good performance of hydrologic behavior and satisfactory performance of the snow model.

Nevertheless, this section has proven that WaSiM is able to model the hydrology under a changing climate and that the catchment is strongly influenced by snow accumulation and melt.

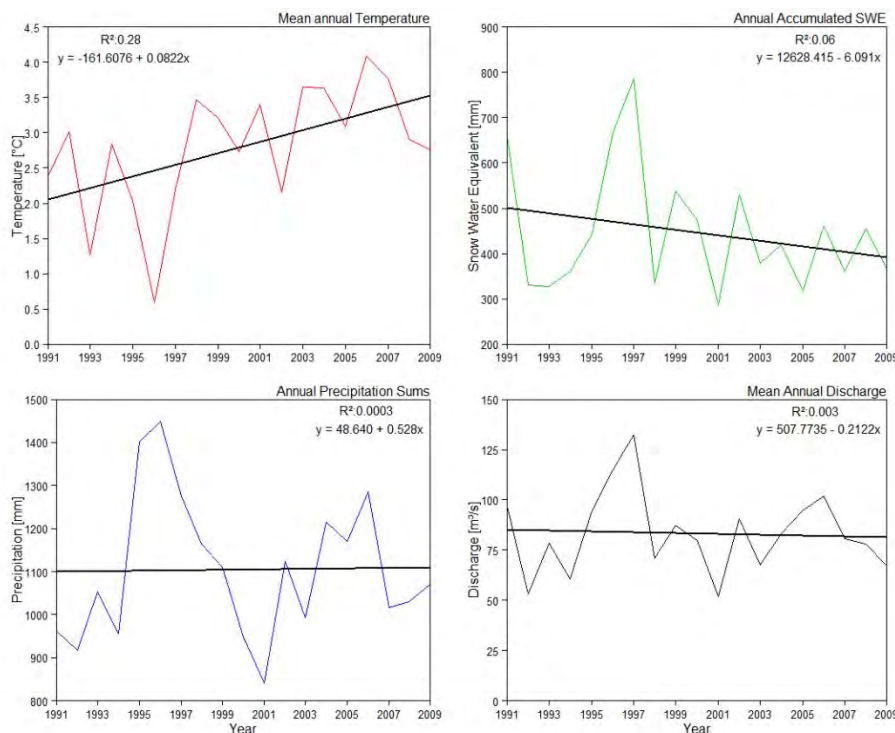


**Fig 21 | Linear trends in temperature, precipitation, SWE and discharge in reference model period (1991-2009)**

Validation with other variables would be advisable, such as observed evapotranspiration. Unfortunately no sufficient observed records of evapotranspiration exist for the watershed and no other satisfactory sources of evapotranspiration rates were accessible. Stations with snow observations would be available outside of the watershed at Akamina Pass, but it is only one point measure that has to be representative for an area of 250x250 m pixel. In my eyes no meaningful findings for the entire watershed will result from the comparison of one snow station and the neighboring pixel.

#### 3.4.4 Best parameter set

After validating several parameter sets, the following parameters will be used to evaluate climate change impacts on the hydrology and snowpack.

**Tab 12 | Best parameters for WaSiM**

|       | Parameter                                                     | best value |
|-------|---------------------------------------------------------------|------------|
|       | Soil model [unsatzon_model]                                   |            |
| QD    | recession parameter for surface direct runoff                 | 30         |
| QI    | recession parameter for interflow                             | 60         |
| DR    | scaling parameter for interflow (drainage density)            | 40         |
| krec  | recession parameter k for base discharge                      | 1.7        |
| Q0    | correction of transmissivities Q0 for base flow               | 40         |
|       | Snow model [snow_model]                                       |            |
| Trans | transient zone for rain-snow                                  | 1.0        |
| T0R   | temperature limit for rain (°C)                               | 1.0        |
| T0    | temperature limit snow melt (°C)                              | 1.5        |
| C0    | degree day factor (mm/d/°C)                                   | 1.2        |
|       | Interpolation temperature, precipitation                      |            |
|       | lower inversion [m.asl.]                                      | 950        |
|       | upper inversion [m.asl.]                                      | 1300       |
|       | precipitation correction [precipitation_correction]           |            |
| a     | a (liquid + snow)                                             | 0.0        |
| b     | b (liquid + snow)                                             | 1.05       |
|       | Groundwater model                                             |            |
|       | initialization of the gw_level [unsatzon_model]               | 3          |
| aq    | aquifer thickness (m) (in input grid)                         | 10         |
| kx    | lateral hydraulic conductivity in x direction (in input grid) | 1.0 e-4    |
| ky    | lateral hydraulic conductivity in y direction (in input grid) | 8.0 e-4    |

## 4 ANALYSIS OF HYDROLOGIC BEHAVIOR IN THE REFERENCE PERIOD

The North Fork Flathead River shows a pronounced annual variability of discharge, which is related to changes in annual precipitation and snowpack. The three consecutive years (1995-97) with mean annual discharge above the long-term mean, also showed precipitation and snowpack above average. All years with negative differences of discharge, showed snowpack below average.

The month December-February are characterized by very uniform low flows, with a small range of values. February is the month with the least variability and in the 19-year time series no days exceeded  $100\text{m}^3/\text{s}$ . Throughout the 19-year time series, the 10%-Quantile of yearly flow is very stable and annual differences are within the range of  $5\text{m}^3/\text{s}$ .

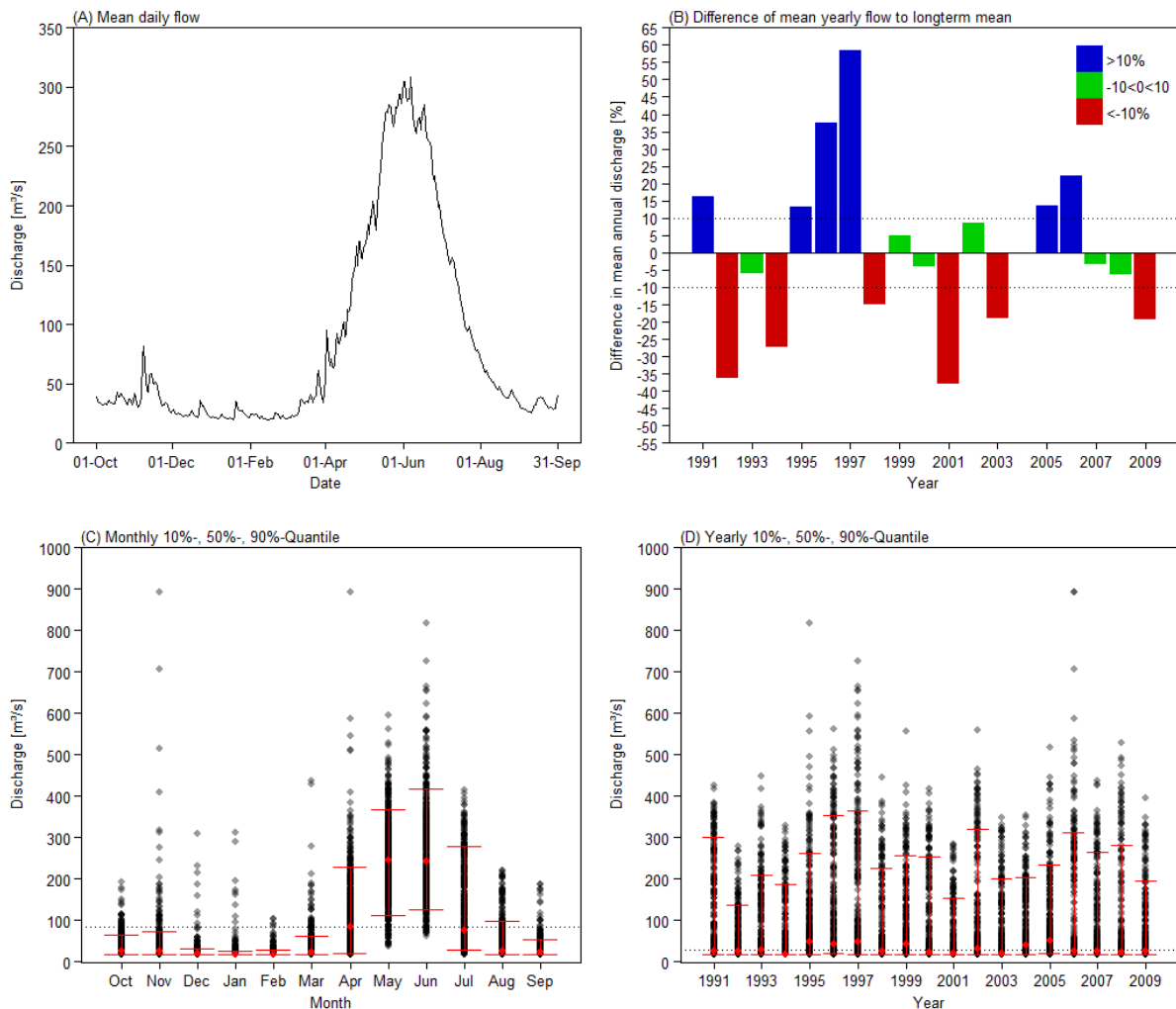


**Fig 22 |** Historic flow at North Fork Flathead River near Columbia Falls, Montana (1991-2009). (A) Mean daily flow; (B) Difference of mean yearly flow to long-term mean flow (in percentage); (C) Mean monthly flow; red lines: 10%- and 90%-quantile, red dot: 50%-quantile, dotted line: mean flow; (D) red lines: 10%- and 90%-quantile, red dot: 50%-quantile, dotted line: median flow

The analysis of the tributaries Sage Creek (flowing in from the east) and Whale Creek (flowing in from the west) show a very similar behavior in flow. Sage and Whale Creek show very little discharge for the period September-February with median flows below  $1\text{ m}^3/\text{s}$ . This flow behavior would indicate, that these tributaries are mainly rain and snow fed, with partial drying out in late summer, fall and winter. The very minimal flows in winter could indicate a frozen over waterbed, which enables direct contributions of precipitation. Contributions from groundwater in these periods is probable existent, but the groundwater model does not cover the tributaries. A model approach, with a groundwater aquifer underlying the entire watershed was not successful, since discharge increased to incredible high amounts. In general, one can say the flow behavior of single tributaries is plausible, since the general flow behavior is in agreement with the validated flow at the gauging station. Nevertheless, additional streamflow data would be necessary for the tributaries, to either prove that contributions of groundwater exist or prove that these tributaries frequently dry out in the low flow seasons. The following figure shows the general flow behavior of Sage Creek (Whale Creek in Appendix B).

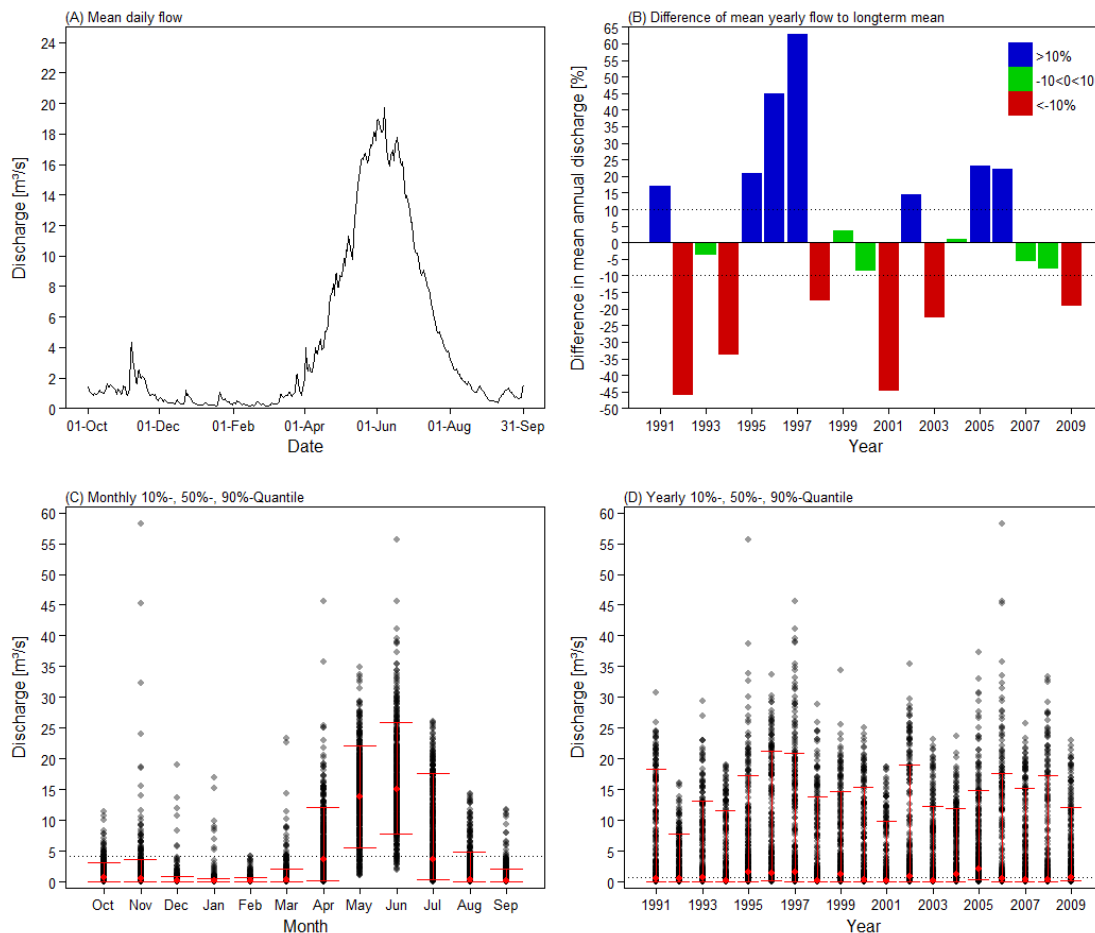


**Fig 23 | Differences in historic flow, Sage Creek (1991-2009).** (A) Mean daily flow; (B) Difference of mean yearly flow to long-term mean flow (in percentage); (C) red lines: 10%- and 90%-quantile, red dot: 50%-quantile, dotted line: mean flow; (D) red lines: 10%- and 90%-quantile, red dot: 50%-quantile, dotted line: median flow

## 5 CLIMATE CHANGE ANALYSIS

### 5.1 GENERAL INFORMATION

#### 5.1.1 Choice of Climate model and scenarios

Raw outputs from General Circulation Model (GCM) simulations are inadequate for assessing hydrologic impacts of climate change at regional scales, because of its coarse spatial resolution (Hay et al. 2000).

Therefore, a coupling of a GCM and a Regional Climate Model (RCM) for dynamical downscaling is chosen for the climate change analysis. The RCM downscales the GCM simulations to a horizontal grid resolution of  $0.22^\circ$  (approx. 25 km) for the North America domain, from GCMs normal horizontal resolution of 300 to 500 km (Wilby et al. 2004).

In this study the model setup CanESM2/CanRCM4, from the Canadian Centre for Climate Modeling and Analysis (Environment Canada 2014), is the basis for the climate change analysis for the Crown of the Continent and the North Fork Flathead River watershed. The Canadian Regional Climate Model 4 (CanRCM4) is nested within the second generation Canadian Earth System Model (CanESM2). This model setup was chosen, on the basis of the most recent versions of GCM and RCM combination. The CanESM2 is also part of the Coupled Model Intercomparison Project (CMIP5).

Further, the two Representative Concentration Pathway (RCP) scenarios RCP4.5 and RCP8.5 were chosen to span a range between the medium-low (RCP4.5) and the extreme scenario (RCP8.5). The RCP scenarios are based on the peak or stabilization value of the radiative forcing by 2100. RCP4.5 scenario is aiming for stabilization at  $4.5 \text{ Wm}^{-2}$  around 2100 and RCP8.5 scenario implies a radiative forcing of  $8.5 \text{ Wm}^{-2}$  by 2100 and further rising beyond this point (Fig 24). When comparing the RCP with the SRES scenarios from IPCC AR4, the RCP4.5 is comparable to the SRES B1 and RCP8.5 is higher than SRES A2 in 2100 and close to A1F1 scenario. (IPCC 2013)

As the baseline period, the time slice 1986-2005 was chosen, because it has the greatest overlap with the observed climate station data (1990-2009).

Also the calibration period, for which the hydrologic model was set up to, is covered by this time slice and therefore should be represented quite well by this period. Representing the near-future the time slice 2026-45 and for the mid-future the time slice 2066-85 was chosen. The twenty year periods centered around the years 2035 (2026-45) and 2075 (2066-85) relative to the historical period 1986-2005.

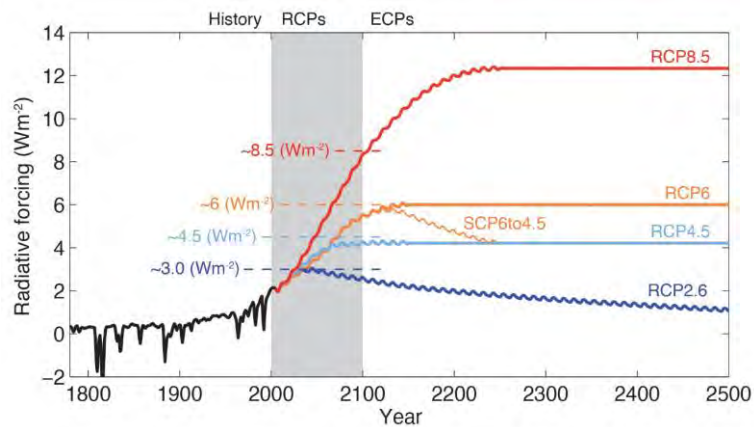


**Fig 24 | Total radiative forcing (anthropogenic plus natural) for RCPs and extended concentration pathways (ECP). (IPCC 2013)**

### 5.1.2 Delta method

In this study, the delta change method is being applied to obtain changes in temperature and precipitation on a local scale. It is a straightforward and popular procedure for rapid impact assessment (Wilby et al. 2004).

The output from the climate model setup was used to calculate the delta change scenarios. The deltas were obtained by calculating the arithmetic differences between the RCM variable derived from a current climate simulation and from a future climate simulation, taken at the same grid location (Hay et al. 2000). This difference or delta is then added to the observed local climate station values of mean daily temperature to obtain the modeled future values. For the change in precipitation a multiplicative change factor is calculated as the ratio between the future and the current climate model simulation (Anandhi et al. 2011). The observed values are then multiplied by the ratio. The deltas are calculated for the monthly averages for mean temperature and precipitation. This approach assumes, that the spatial pattern of the observed climate remains unchanged in the future.

Furthermore rain days and extreme events will stay the same, but the absolute values will change (Wilby et al. 2004). The delta change method removes any biases in simulations relative to observations (Melillo et al. 2014). Deltas are calculated for the entire Crown of the Continent Region and for the location of the 15 climate stations, to obtain climate scenarios for hydrologic modeling of the future response. 190 data points and 12 month were analyzed, which equals a total number of 2280 deltas for each scenario.

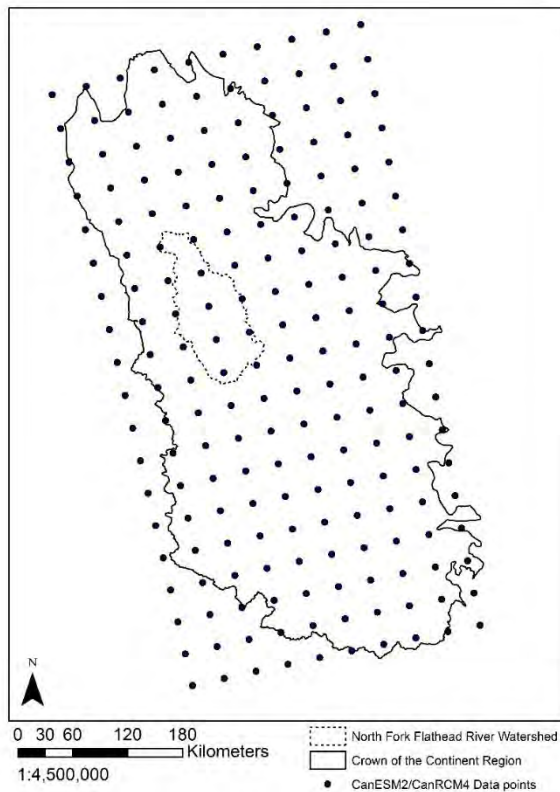


**Fig 25 | Climate model data points (CanRCM4) for delta retrieval**

## 5.2 CLIMATE CHANGE IN THE CROWN OF THE CONTINENT

### 5.2.1 Temperature

The climate model predicts a rapid temperature increase, compared to the reference period 1986-2005 in the Crown of the Continent Region. The two scenarios (RCP4.5, RCP8.5) show a similar signal in the near future (2035), with an increase of 1.8 and 2.1°C (Fig 26). Whereas, by 2075 the temperature increase of the two scenarios is further apart with a warming of 3.1°C (RCP4.5) and 4.9°C (RCP8.5). The temperature increase in the CCE is considerable higher than the global mean temperature change, with almost double the magnitude by 2035. Global temperature rises by approx. 1.0/1.2°C (RCP4.5/RCP8.5) in 2035 and by approx. 1.8/3.0°C in 2075 (IPCC 2013). 20<sup>th</sup> century historic climate change in western Montana has been two to three times higher than global average (Pederson et al. 2010) and therefore confirms a rapid warming, compared to the global average.

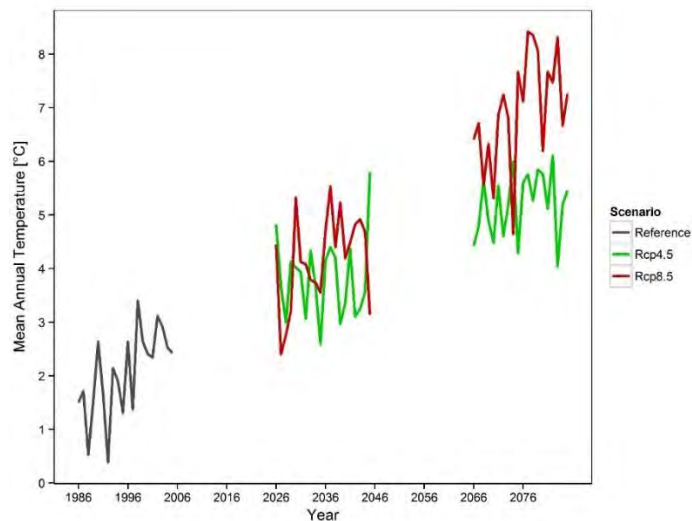


**Fig 26 | Change of mean annual temperature in the CCE**

By 2035, the RCP4.5 scenario predicts a considerable high increase in July, August and September mean temperature, with all 190 data points showing an increase of more than 1.8°C (Fig 27). Also in March approx. 100% of data points show an increase greater than 1.8°C. For October, December, February, May and April approx. 90% of data points show values between 1.0-1.8°C (RCP4.5). 90% of all deltas (190 data points \* 12 month = 2280 deltas) show a temperature increase between 1.0-2.6°C. Whereas, the RCP8.5 scenario predicts, with an agreement of 90%, a temperature increase between 1.0-3.2°C, with the remaining 10% of the data points exceeding 3.2°C by 2035. Especially December, January, March, July and August show a warming greater than 2.1°C. In contrast October, November, February, April, May, June and September show a temperature increase of less than 2.1°C. By 2075, all deltas for the RCP4.5 scenario show a minimum temperature increase of 1.6°C, with 90% of the deltas exceeding 2.2°C warming. The upper 10% of the data shows an increase of more than 4.2°C. January, March, July, August and September show a higher warming than 3.1°C considering their 10%-Quantiles. October, November, April and May show values lower than 3.1°C considering their 90%-Quantiles. In the RCP8.5 scenario, the climate model predicts for all data points within the CCE a temperature change of 2.5°C by 2075. 90% of the data points predict an increase of at least 3.2°C and 10% of the data exceeds 7.1°C until maximum warming of 7.7°C in August. Especially the month July, August and September show an extremely pronounced temperature rise of minimum 5.7°C. Also the snow season October through March shows a delta range of 3.7 – 7.1°C.

Throughout all scenarios and future periods, months July and August show an increase above the scenarios average. Whereas, the majority of deltas in October, April and May show values below the scenarios mean warming. Nevertheless, by 2075 all deltas show a climate warming that exceeds 1.6°C. The temperature change for the entire CCE is summarized in Tab 13.

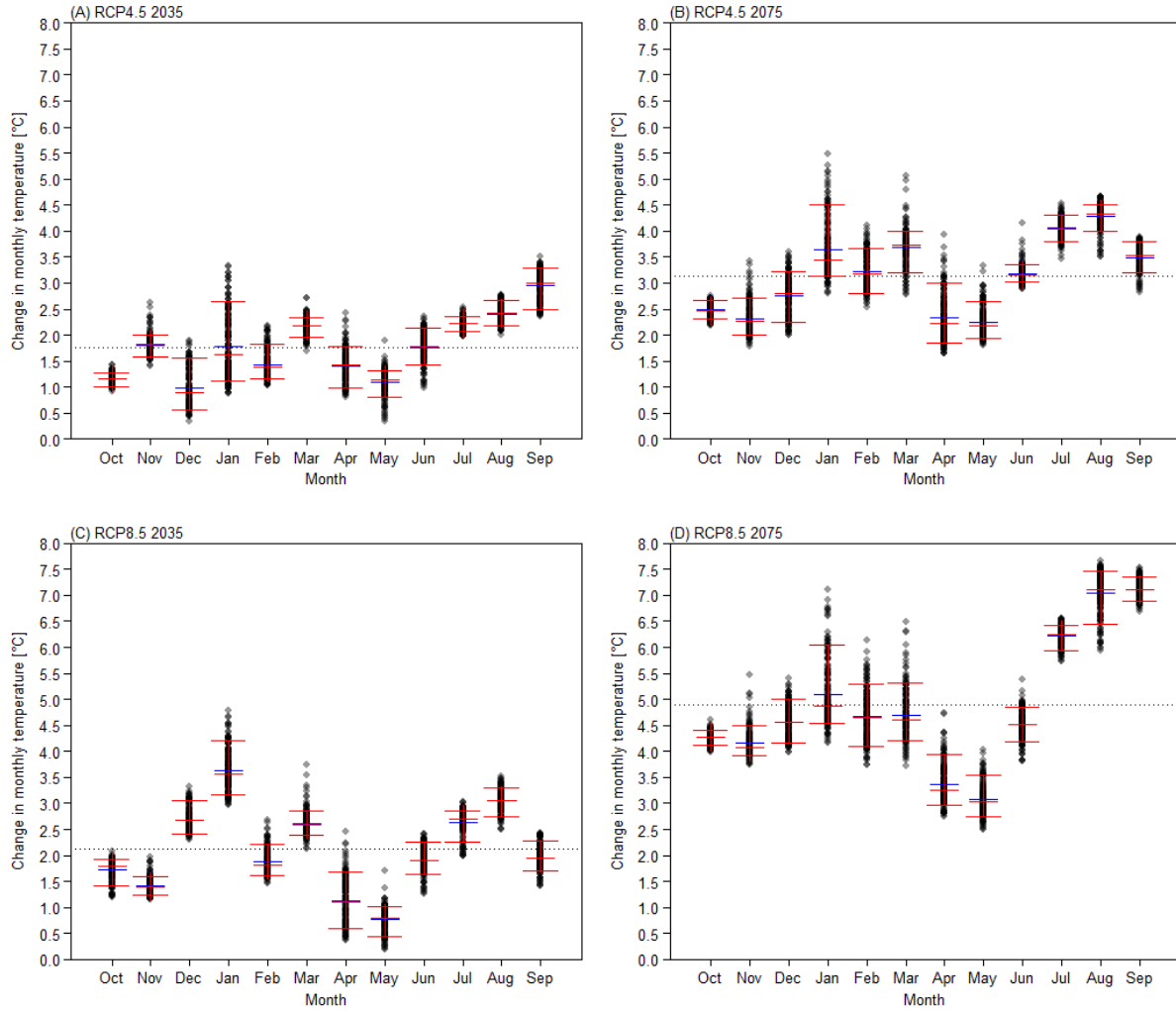


**Fig 27 | Monthly temperature deltas for the CCE. (A)-(D): Red lines: 10%-, 50%- and 90%-quantiles; Blue line: mean monthly change; Dotted line: overall mean temperature change**

**Tab 13 | Change of temperature in the CCE [°C]**

|        |      | Quantile |     |     |     | Min | Max |
|--------|------|----------|-----|-----|-----|-----|-----|
|        | Mean | 10%      | 50% | 90% |     |     |     |
| RCP4.5 | 2035 | 1.8      | 1.0 | 1.7 | 2.6 | 0.3 | 3.5 |
|        | 2075 | 3.1      | 2.2 | 3.2 | 4.2 | 1.6 | 5.5 |
| RCP8.5 | 2035 | 2.1      | 1.0 | 2.0 | 3.2 | 0.2 | 4.8 |
|        | 2075 | 4.9      | 3.2 | 4.6 | 7.1 | 2.5 | 7.7 |

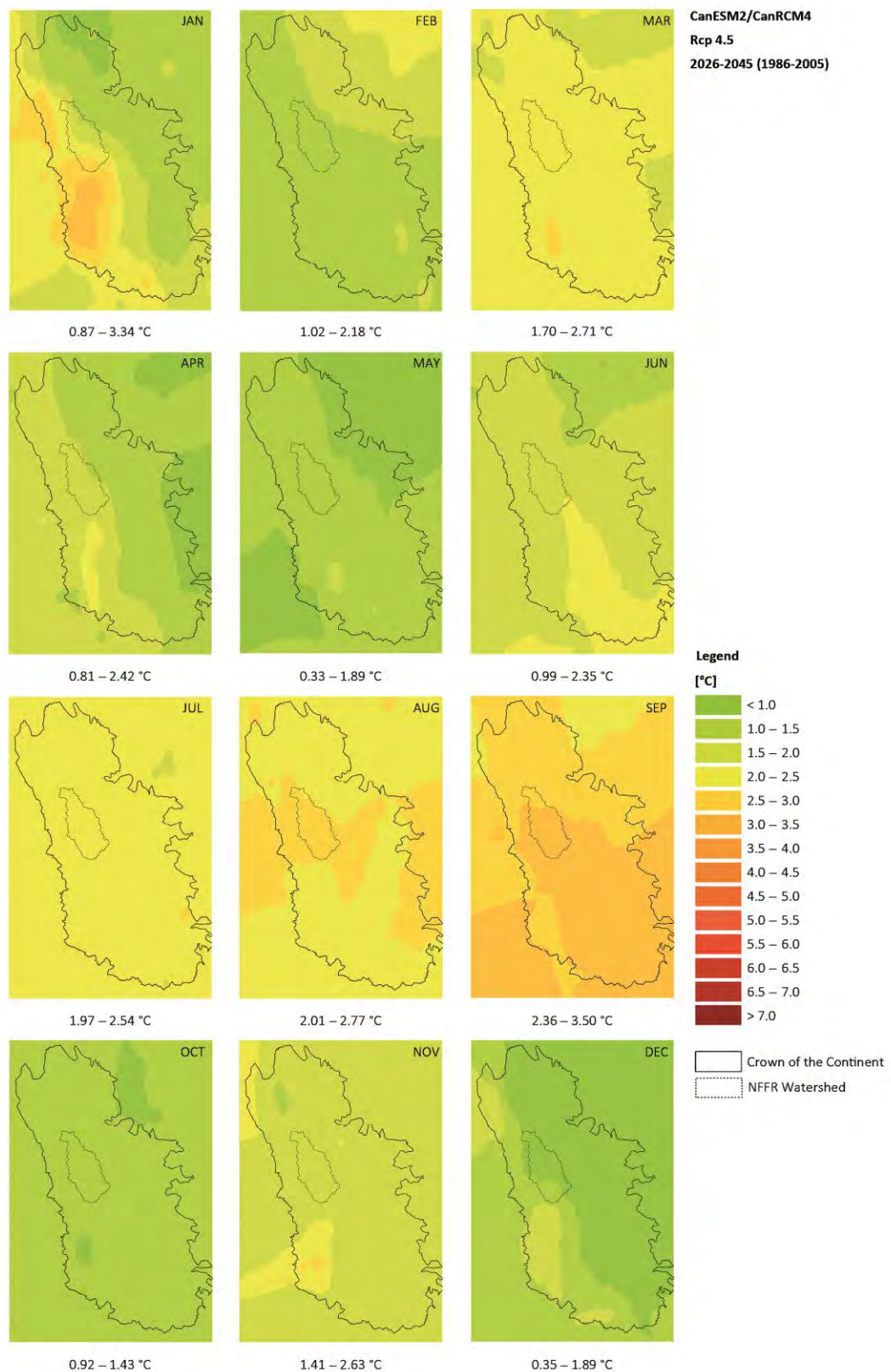


**Fig 28 | Temperature change (°C) in the CCE by 2035 (RCP4.5)**

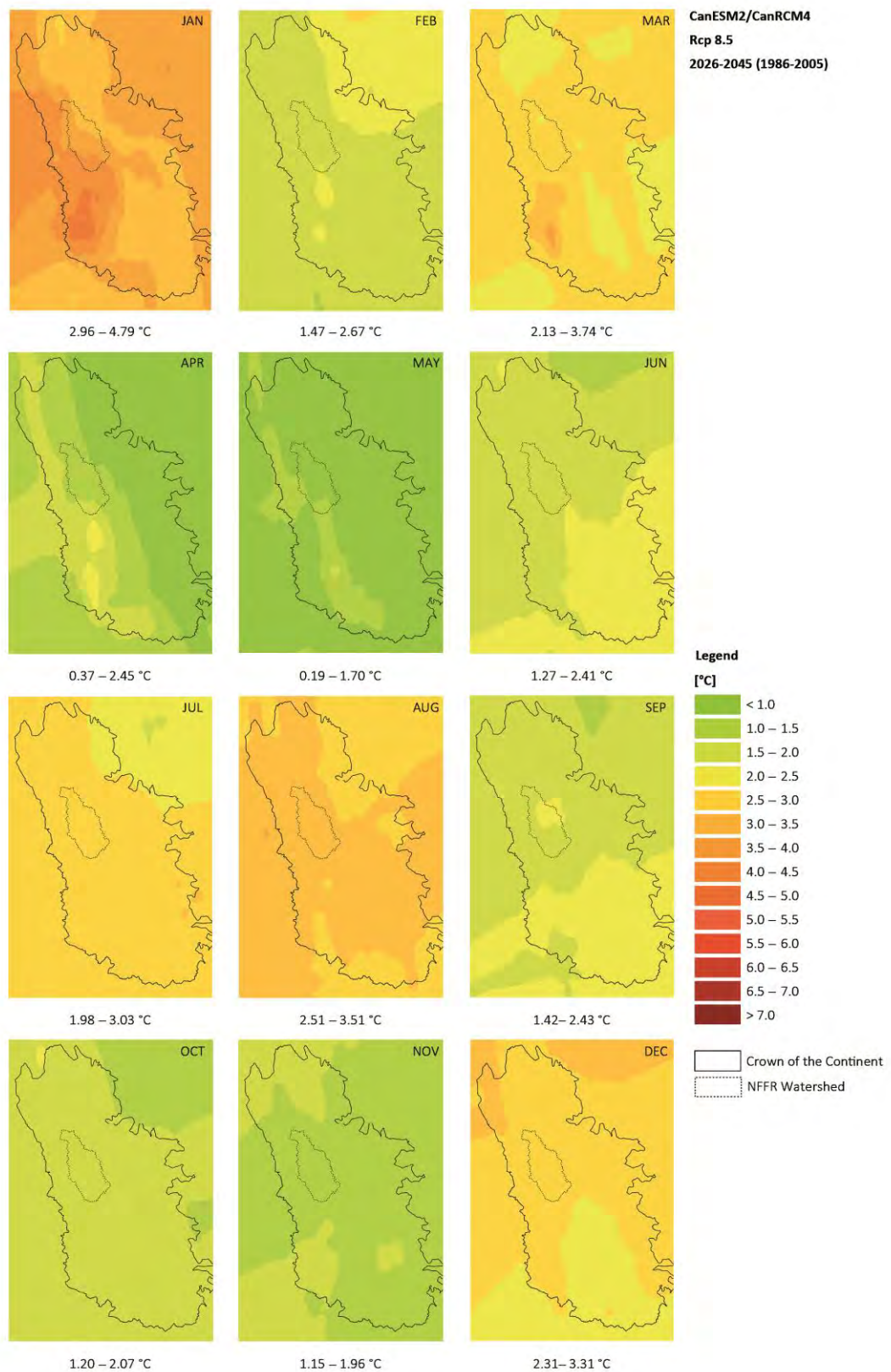


**Fig 29 | Temperature change (°C) in the CCE by 2035 (RCP8.5)**

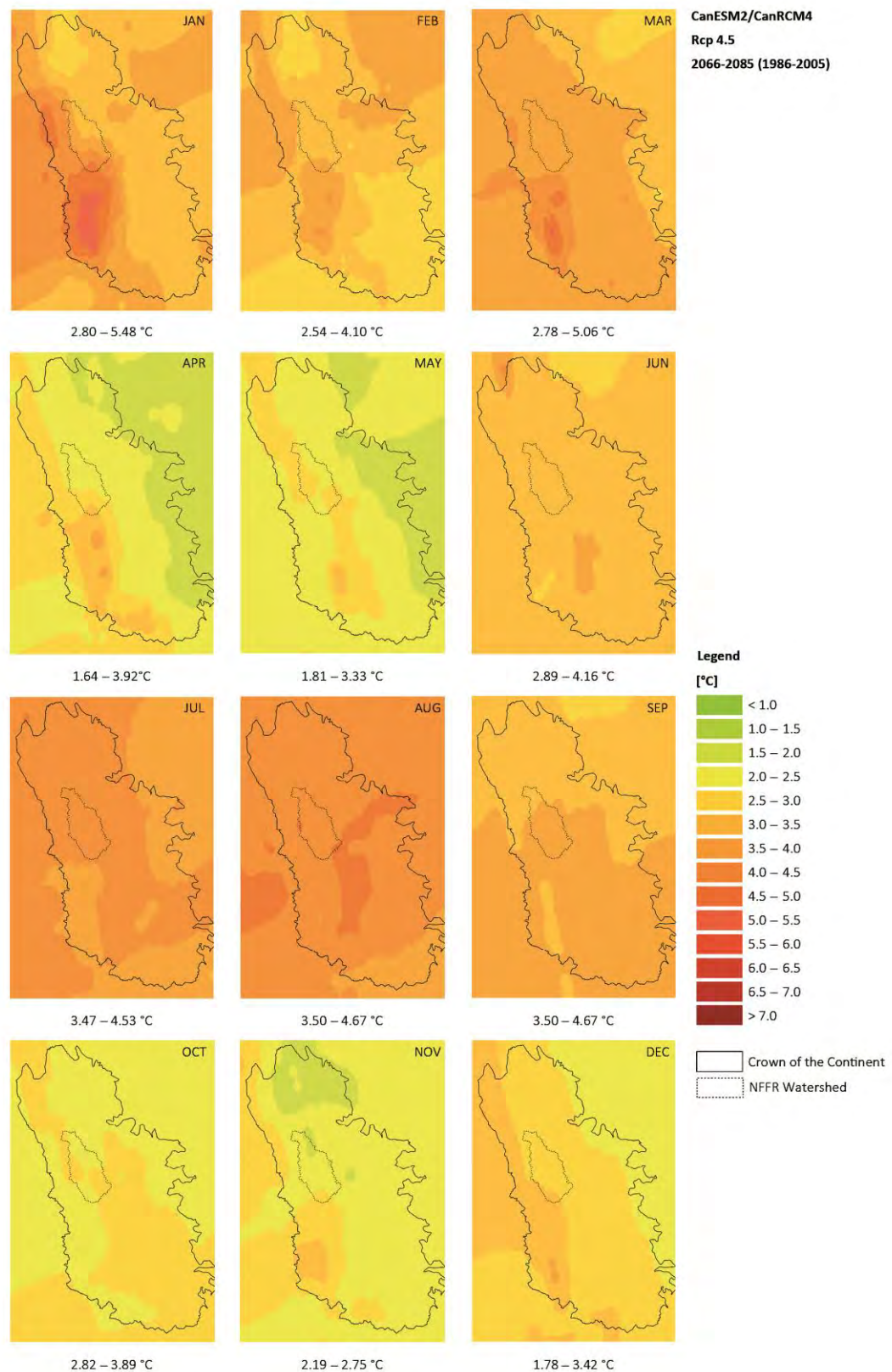


**Fig 30 | Temperature change (°C) in the CCE by 2075 (RCP4.5)**

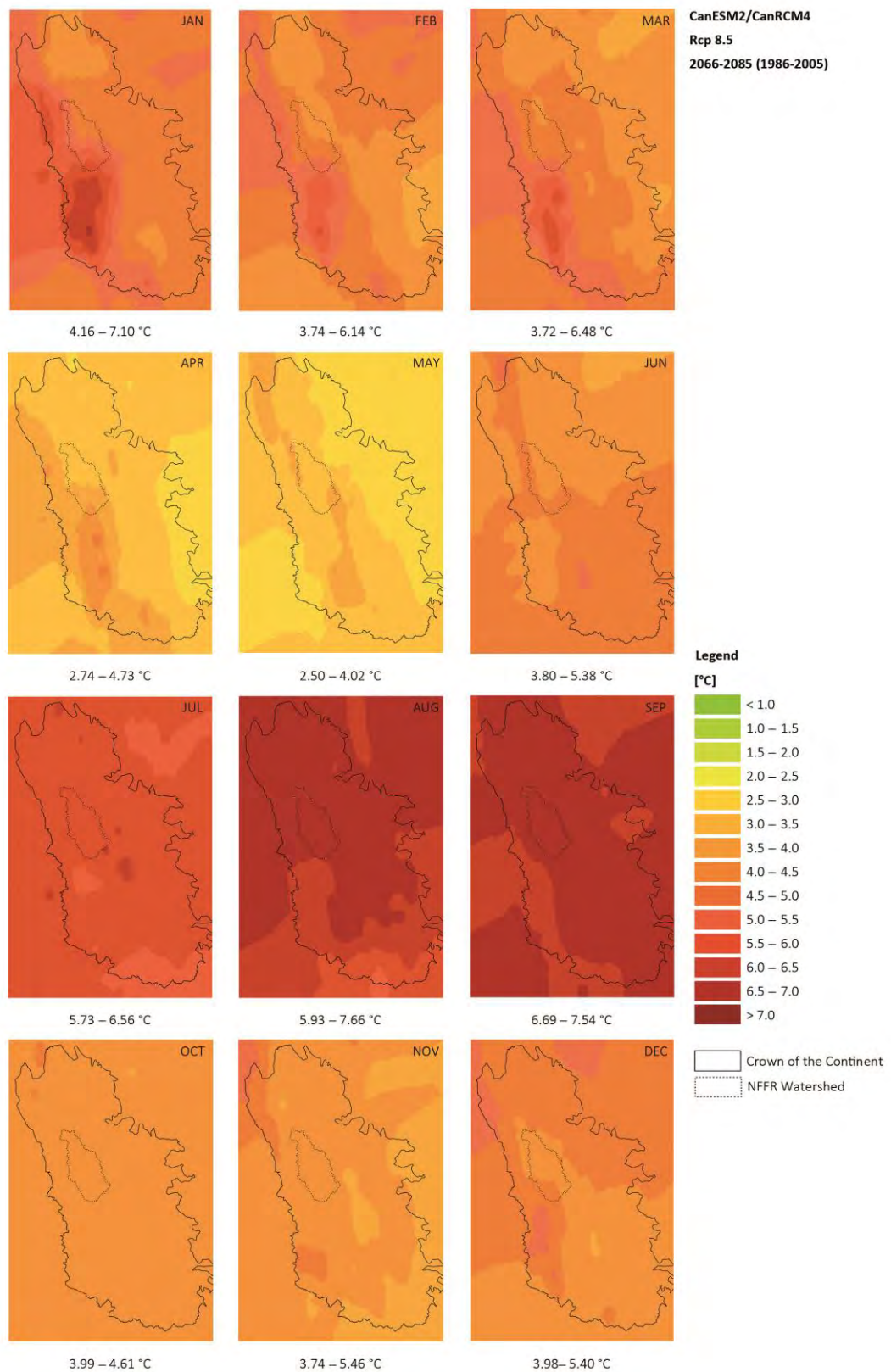


**Fig 31 | Temperature change (°C) in the CCE by 2075 (RCP8.5)**

### 5.2.2 Precipitation

Compared to temperature, the climate trend for precipitation is not as pronounced (Fig 32) and data points show an increase, decrease and no change in monthly precipitation sums. Also the distribution of the two scenarios is closer together. The variability of annual precipitation seems to increase in future. Annual climate model precipitation ranges between 460 and 860 mm in the reference period, whereas in 2026-45 precipitation ranges between approx. 440-1140 mm and in 2066-85 between approx. 600-1140 mm (both RCP8.5).

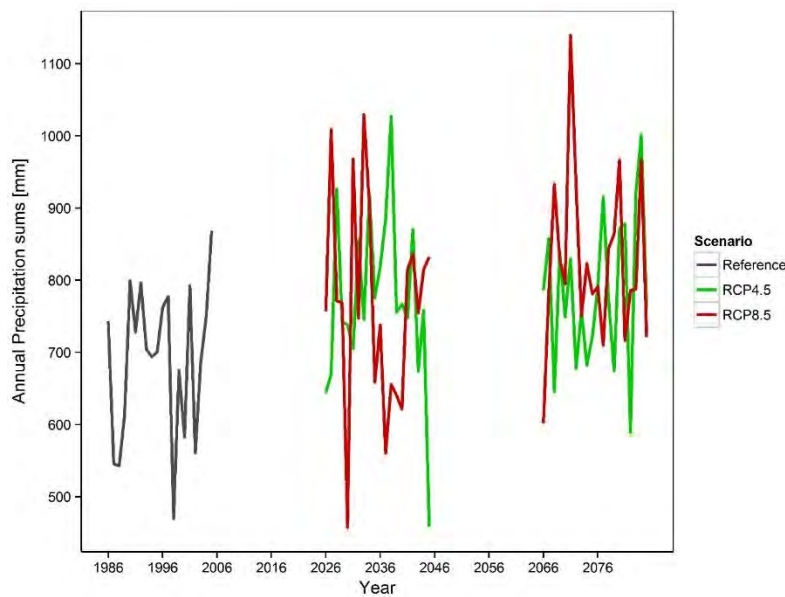


**Fig 32 | Annual precipitation sums in the CCE for 1986-2005, 2026-2045 and 2066-2085 (CanESM2/CanRCM4 output)**

All scenarios predict an increase in precipitation, with the agreement of more than 53% of all deltas (190 data points \* 12 month = 2280 deltas). Less than 14% of all deltas predict a decrease in precipitation. An increase in precipitation is defined as deltas exceeding 10% and deltas below -10% as a decrease.

By 2035, both RCP scenarios agree on February being the month with the strongest decrease in precipitation, with 67% (RCP4.5) and 40% (RCP8.5) of deltas showing values smaller -10%. The RCP4.5 predicts a mean decrease of -16% in February precipitation, whereas the RCP8.5 predicts -6.8%.

Overall mean precipitation is predicted to increase by 14.2% (RCP4.5) and 15.3% (RCP8.5), respectively.

By 2075, there is a higher agreement among the two scenarios. Both scenarios agree in August as the month with the highest agreement in decreasing precipitation amongst deltas. 26% of RCP4.5 deltas predict decreasing August precipitation and 36% in the RCP8.5 scenario. For November, March, April, May and June both scenarios predict an increase in precipitation.

Overall mean precipitation is predicted to increase by 20.2% (RCP4.5) and 27.6% (RCP8.5), respectively.

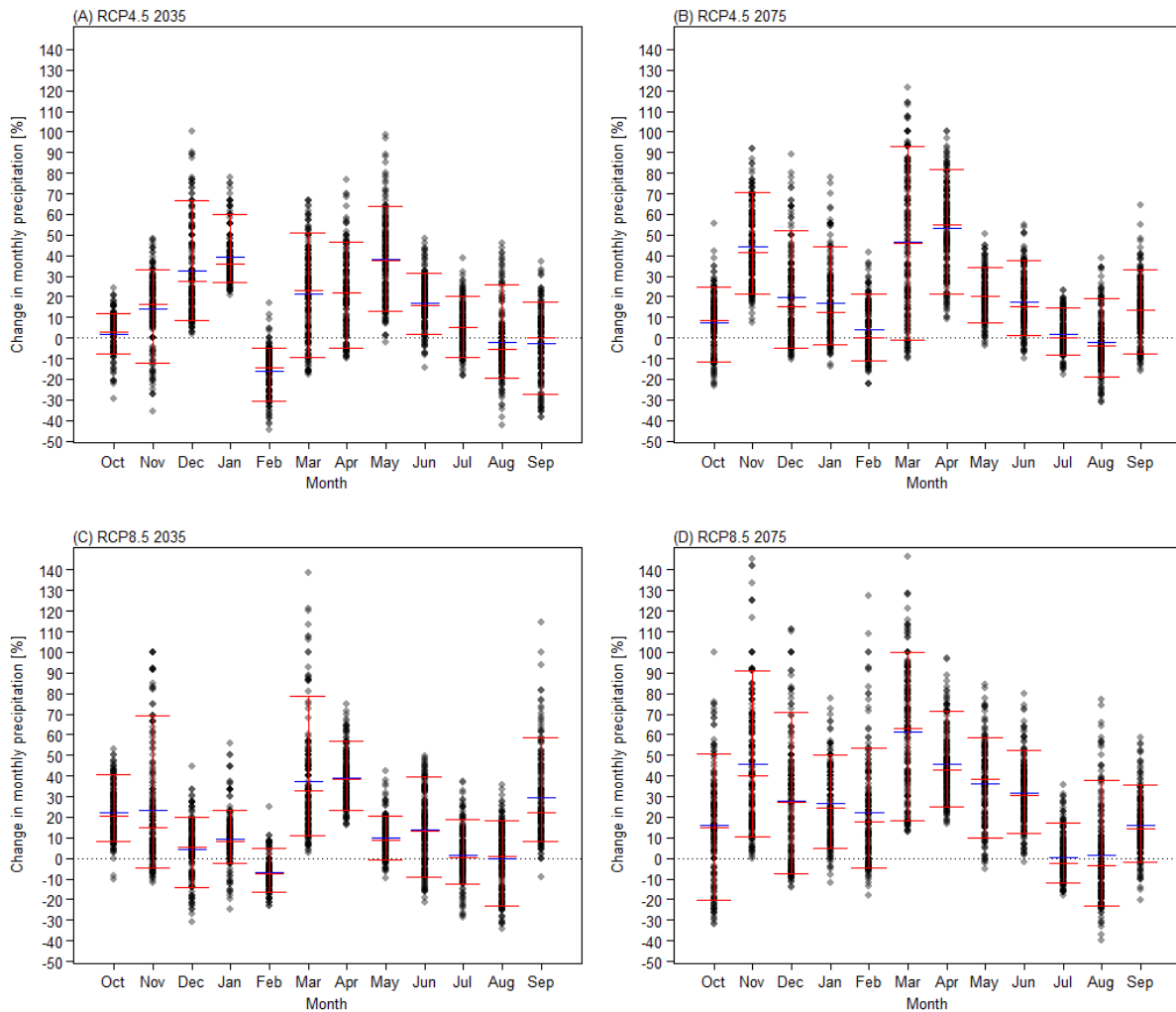


**Fig 33 | Change in monthly precipitation in the CCE. (A)-(D): Red lines: 10%-, 50%- and 90%-quantiles; Blue line: mean**

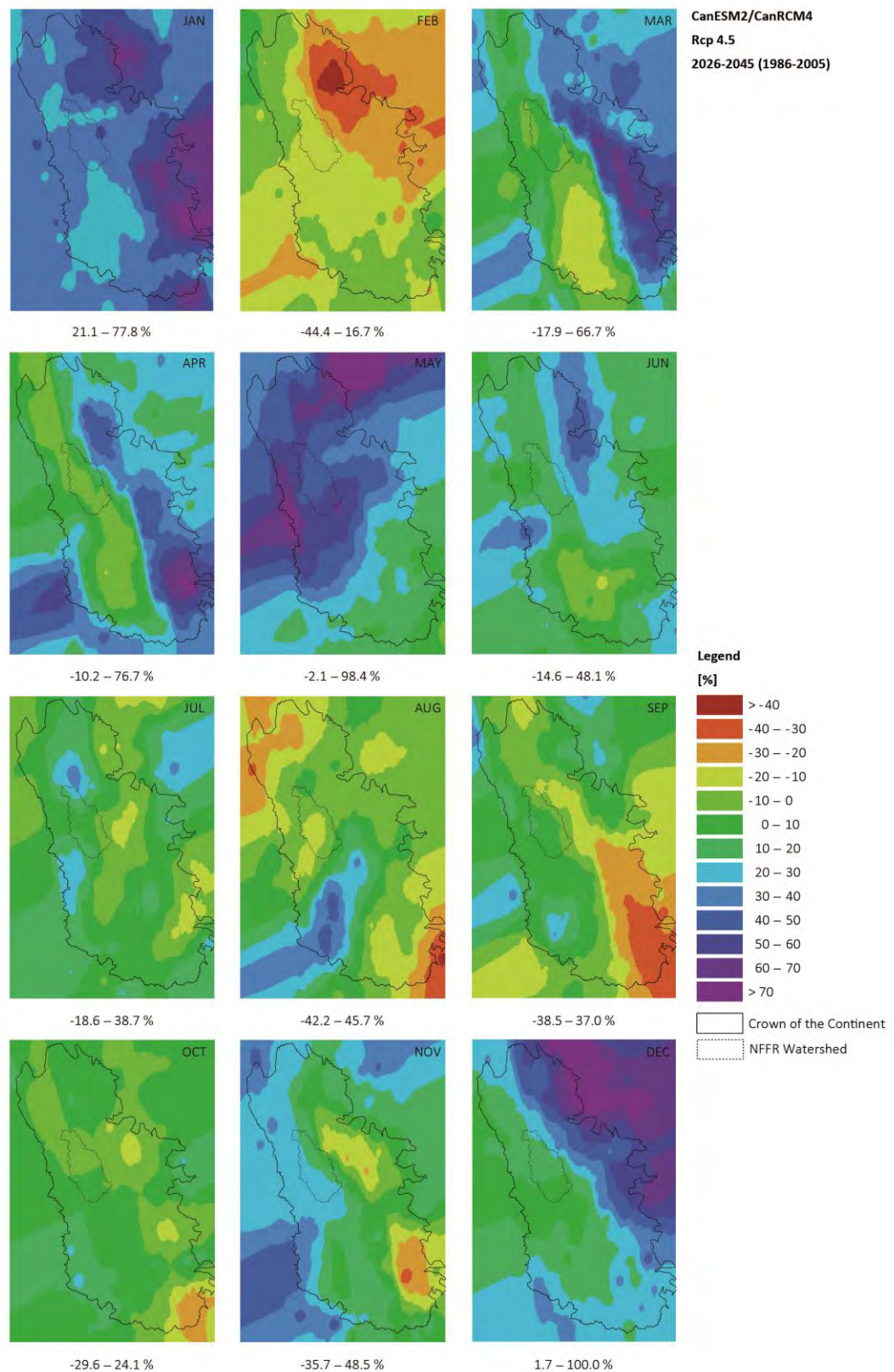


**Fig 34 | Precipitation change (%) in the CCE by 2035 (RCP4.5)**

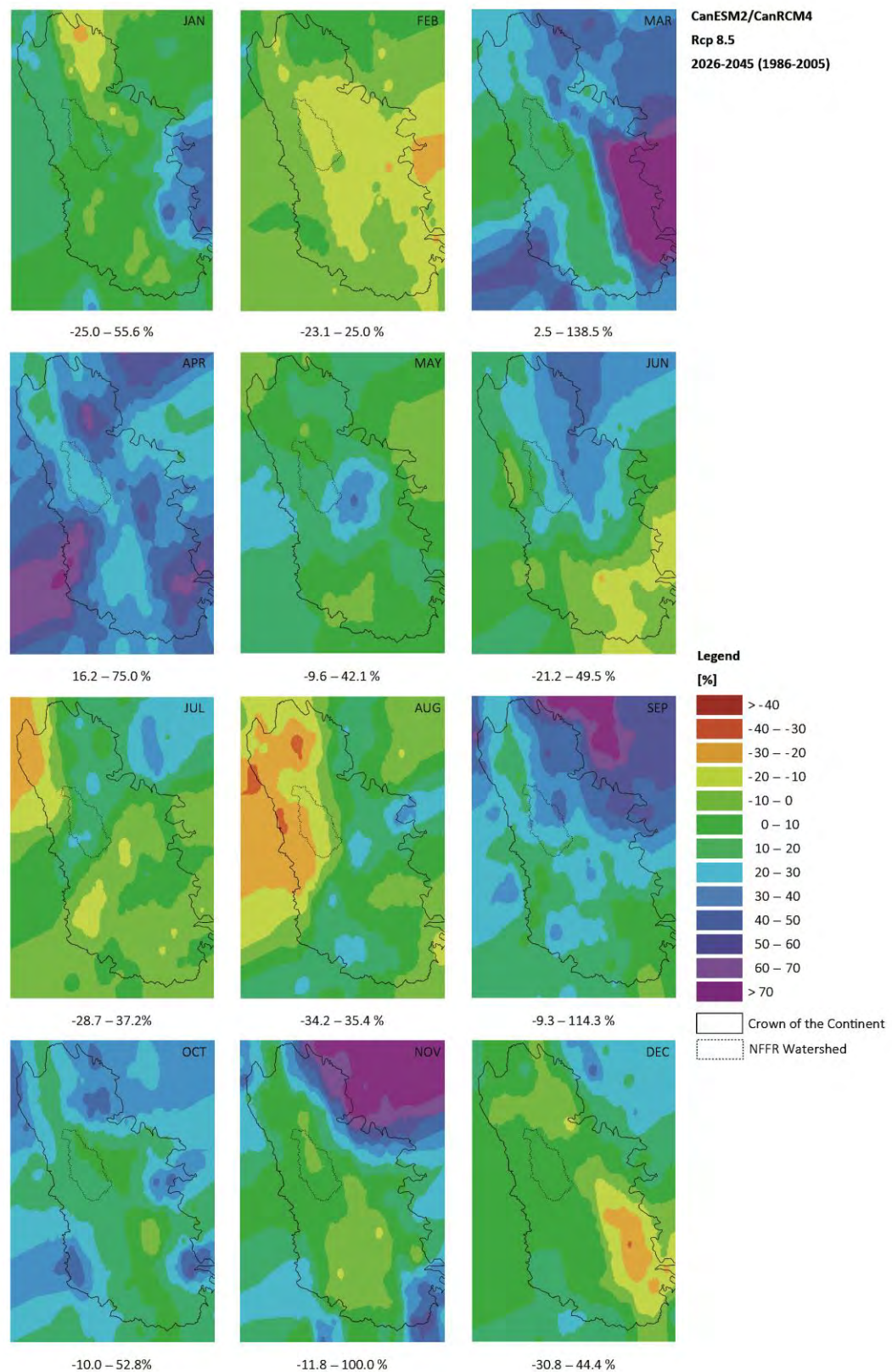


**Fig 35 | Precipitation change (%) in the CCE by 2035 (RCP8.5)**

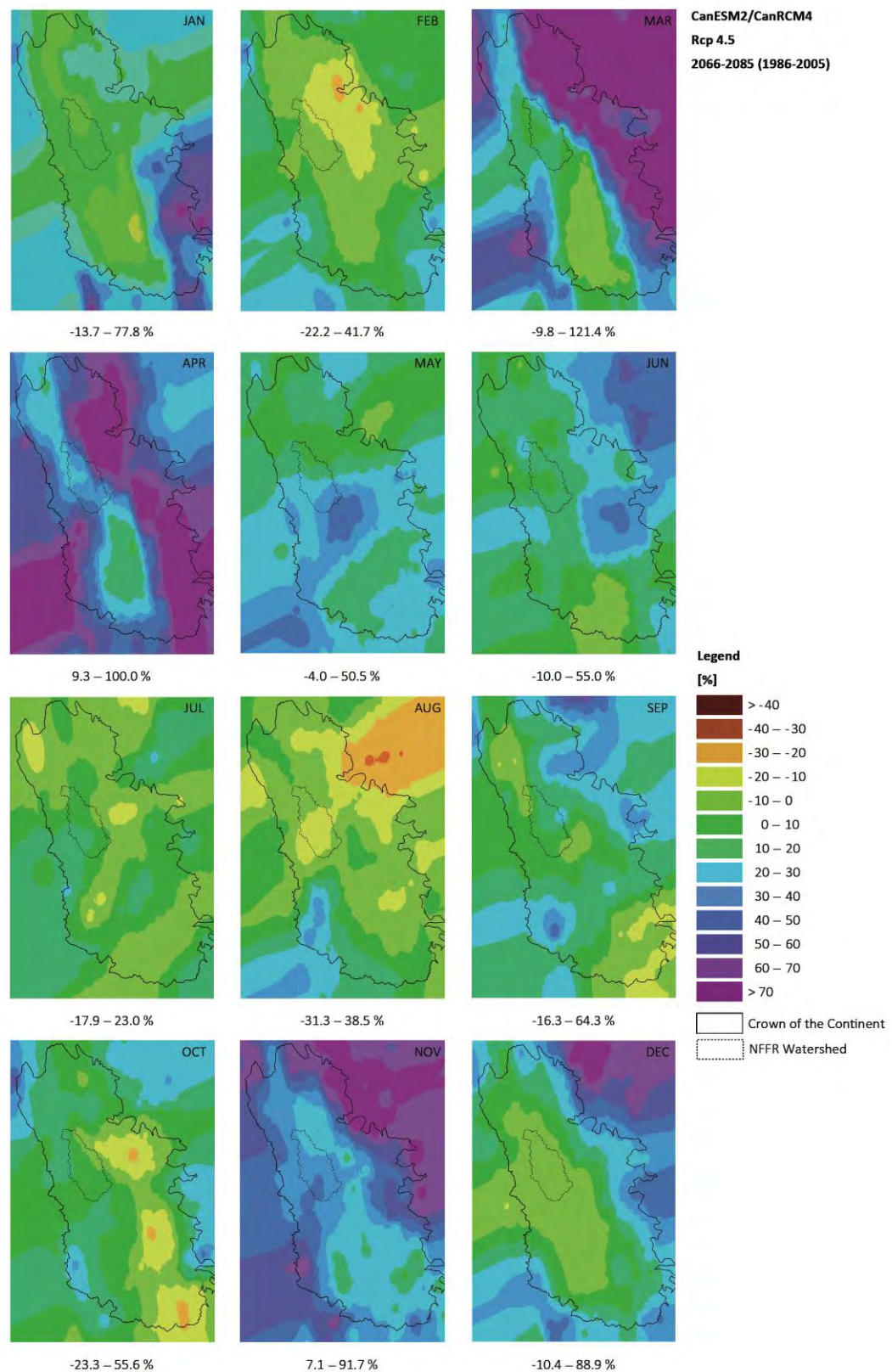


**Fig 36 | Precipitation change (%) in the CCE by 2075 (RCP4.5)**

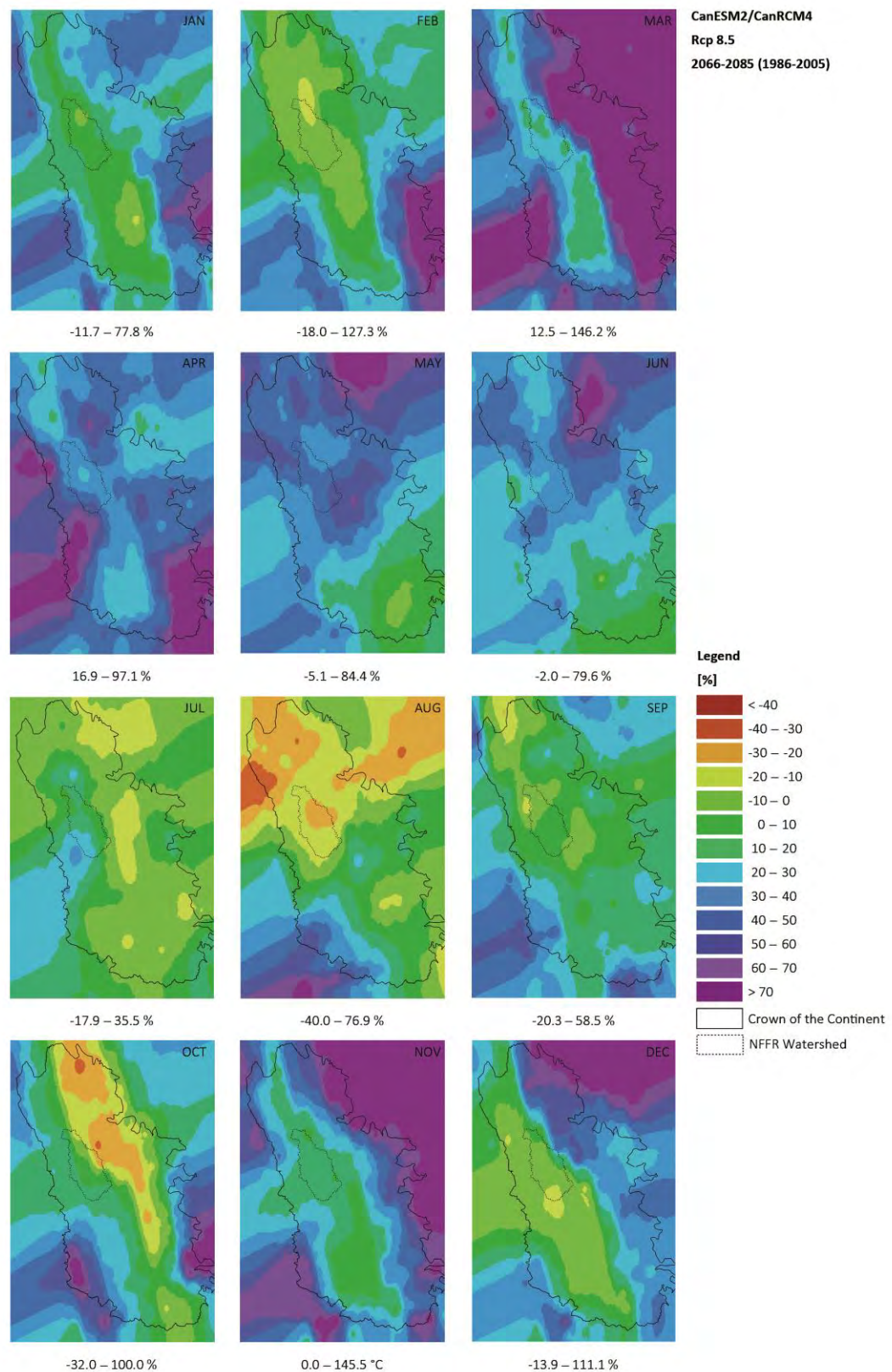


**Fig 37 | Precipitation change (%) in the CCE by 2075 (RCP8.5)**

## 5.3 CLIMATE CHANGE IN THE NORTH FORK FLATHEAD RIVER WATERSHED

### 5.3.1 Historic Trends

Before analyzing the climate change in the watershed, one should see if there is already a trend existent in the reference period. The mean annual temperature in the period 1991-2009 shows an obvious temperature rise with an increase of approx.  $0.8^{\circ}\text{C}$  per decade (Fig 38). The mean temperature of 2001-2009 ( $3.3^{\circ}\text{C}$ ) is  $0.9^{\circ}\text{C}$  higher than the mean temperature of the first half 1991-2000 with  $2.4^{\circ}\text{C}$ , which confirms the presence of a temperature trend. Also Feng and Hu (2007) confirm a strong warming in surface air temperature in the western U.S., during the second half of the twentieth century.

A trend in precipitation is basically not existent, with an increase of only 5mm per decade. The increase of 5mm would account for a change of 0.5% of mean annual precipitation. This is not significant when comparing the 5mm change with a mean annual precipitation of 1105mm.

At first glance, the modeled SWE has a pronounced trend of 60mm decrease per decade, which would account for a loss of 13% SWE per decade, compared to a mean annual accumulated SWE of 447mm. A reason for this pronounced trend, is the existent of three major snow years with SWE beyond 650mm in 1991 (658mm), 1996 (666m) and 1997 (785mm).

Since these events are all in the first third of the time series and no further comparable events occur, this inevitably produces a negative trend.

Although with the documented temperature trend in the watershed and studies of (Day 2009; Knowles et al. 2006) indicate a decrease of snowfall and a shift to more precipitation falling as rain instead of snow. Feng and Hu (2007) write that snow cover in March in North America has been decreasing since the 1950s and that the decline is particularly noticeable in the western United States. Further, the peak snow accumulation and peak snowmelt occurred earlier in the last 50 years. So a decrease in historic SWE is to be expected.

A trend in discharge is basically not existent with a decrease of  $2\text{m}^3/\text{s}$  per decade in the period 1991-2009. When looking at the long term distribution of annual mean discharge from 1960-2013, no trend is visible with a change of  $0.1\text{m}^3/\text{s}$  per decade.

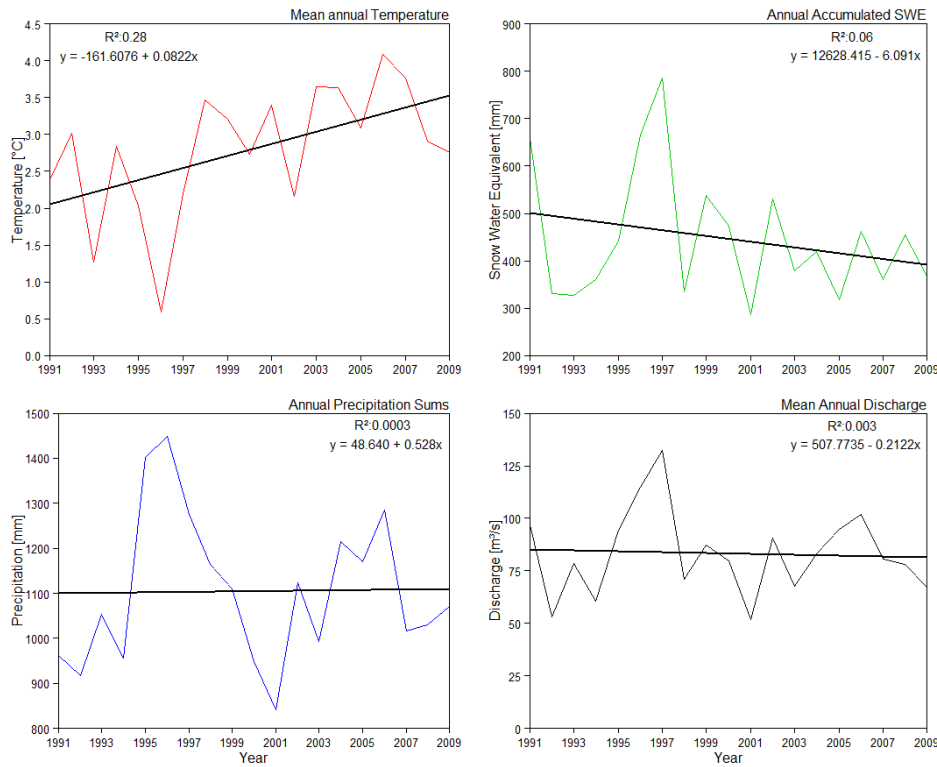


**Fig 38 | Historic Trends in Temperature, Precipitation, SWE and Discharge (1991-2009)**

Looking at the single year differences in temperature confirms the increase in mean annual temperature, with nine out of the last twelve years being above average (Fig 39). The annual precipitation seems to go in cycles, meaning that several years are below average followed by several years above average. Four out of the last seven years showed snow below average and three years can be considered average. The discharge and SWE undergo the biggest changes from year to year with -38 – 58% (discharge) and -36 – 76% (SWE). The year with the lowest and biggest discharge were at the same time the years with the lowest and highest SWE.

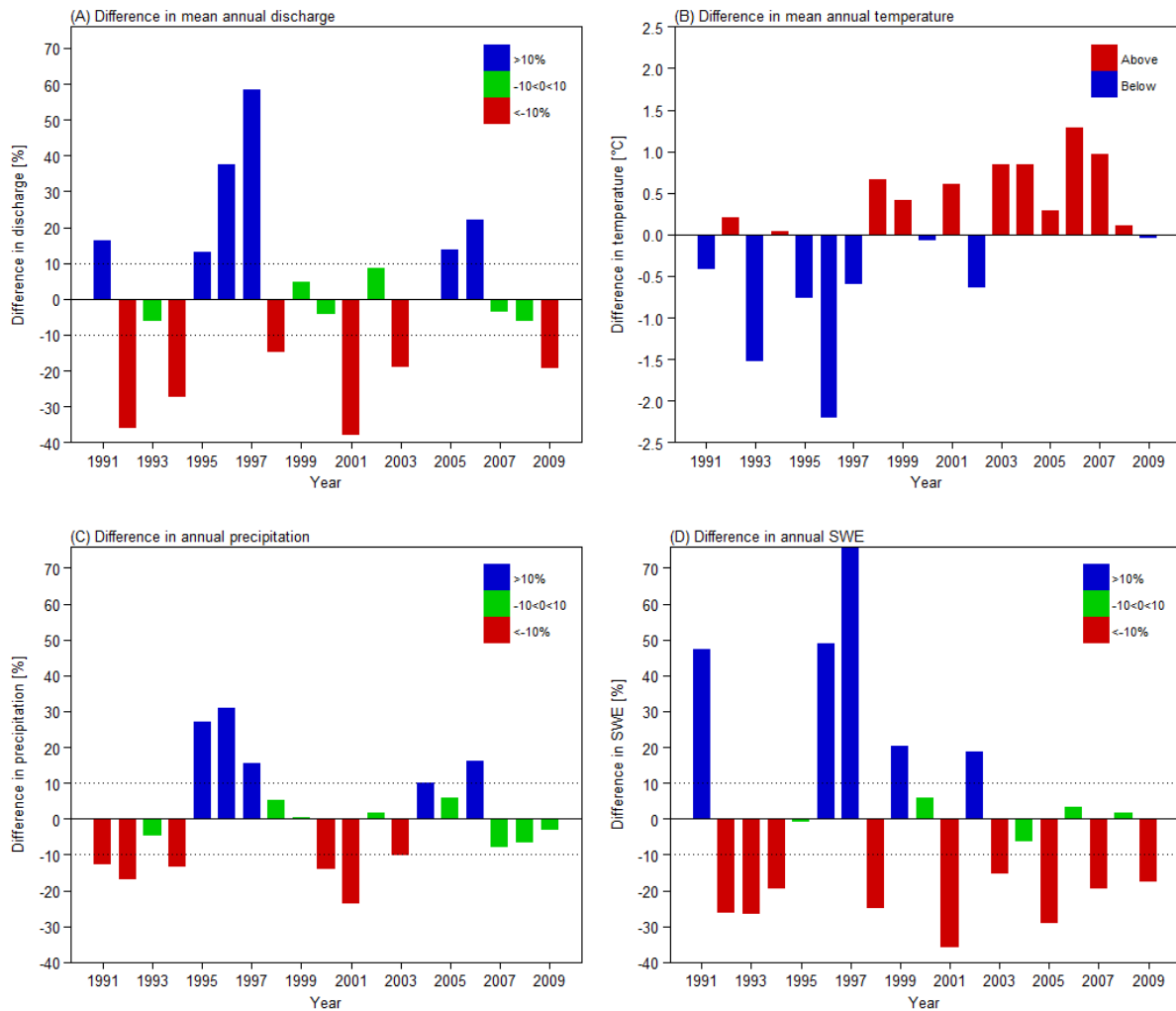


**Fig 39 | Differences in mean annual discharge, temperature, precipitation and SWE (1991-2009)**

Further, the climate model output for the domain of the climate stations should be compared to the observed temperature and precipitation.

Temperature from the climate model shows a clear cold bias, with a difference in mean temperature of 1.9°C in the climate model, compared to a mean climate station temperature of 4.8°C. This bias reflects the undersampling of areal temperature by the climate stations, which basically leads to a warm bias of the station average (Bürger et al. 2011).

Nevertheless, no bias correction is performed, since an advantage of the delta change method is that biases are negligible. Precipitation data shows no obvious bias with mean CanRCM4 precipitation of 886mm compared to a climate station mean of 885mm.

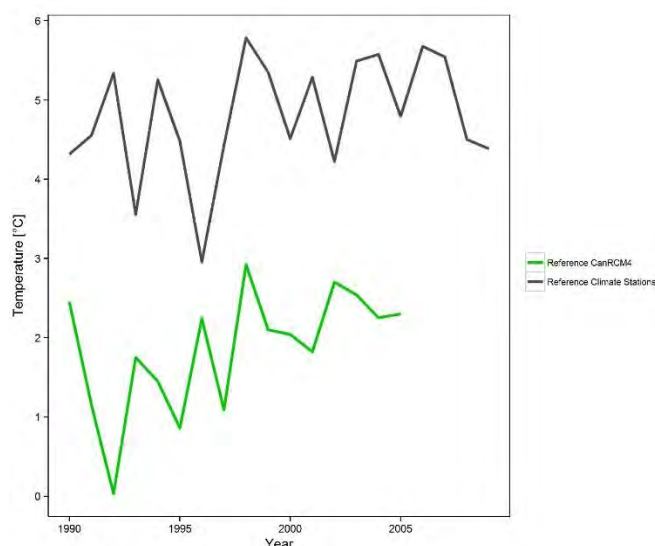


**Fig 40 | Climate model temperature bias. CanRCM4 annual temperature for the domain including the 15 climate stations in comparison to mean climate station temperature.**

### 5.3.2 Temperature

The temperature change for the 15 climate stations, used as the driver for the hydrologic model, show a very similar trend to the CCE. By 2035 temperature will rise by 1.8°C (RCP4.5) and 2.2°C (RCP8.5), with deltas ranging between 0.6-3.2°C (RCP4.5) and 0.7-4.4°C (RCP8.5) (Fig 41). The deltas for the single month are very homogenous across the 15 climate stations, with differences between the deltas of less than 0.5°C in 10 month. By 2075, mean monthly temperature will rise by 3.3°C (RCP4.5) and 5.1°C (RCP8.5), with deltas ranging between 2.0-4.7°C (RCP4.5) and 3.0-7.6°C (RCP8.5). Schnorbus et al. (2014) shows a comparable magnitude of temperature change by 2050 for the Upper Columbia River, with values ranging between the values of 2035 and lower than RCP8.5 by 2075 in this study.

Throughout both scenarios, time slices August and September show the highest increase in temperature. January is also amongst the higher deltas, but it is also the month with the biggest differences between the climate stations (1.8°C). Contrary, May shows the lowest increase in temperature and has a considerable low range with 0.45°C.

The temperature increase will shift mean monthly temperatures upward, with especially summer and winter temperatures undergoing the strongest changes. While in the reference period in the catchment, November through March show mean temperatures below -2.4°C, month with temperatures below zero degrees are declining. By 2035, temperatures are slowly approximating zero degrees with the RCP4.5 scenario still showing 5 month with temperatures below -0.2°C and whereas the RCP8.5 scenario only shows 4 month below -1.5°C.

March is the first month to approximate zero degrees by 2035 and by 2075 March temperatures are already at 1.4°C (RCP4.5) and 2.3°C (RCP8.5), compared to -2.4°C in the reference period. By 2075, the next month to approximate zero degrees is November with -0.7°C in the RCP4.5 scenario and 1.3°C in the RCP8.5, compared to -2.9°C in the reference period. By 2075, the RCP4.5 scenario is showing mean temperatures of -3.9 – 1.4°C for November-March and RCP8.5 shows a range of -2.3 – 2.3°C, compared to -6.8 – -2.4°C in the reference period. The increase of temperature in November-March will have a strong effect on the ratio of snow and rain. Precipitation falling as rain, instead of snow, will increase due to the rising temperatures.

The summer temperatures will undergo the strongest warming, with up to 7.4°C warming in August by 2075. July and August mean temperatures are exceeding 20°C by 2075 in the RCP8.5 scenario. The RCP4.5 is approximating 18°C compared to 13.8 and 13.4°C (July, August) in the reference period. Even though the temperature increase is higher in the summer, the effect on the hydrology won't be as severe as the increase in winter temperature, since the discharge is strongly dependent on snow melt. The RCP4.5 and RCP8.5 scenario are showing very similar mean temperatures for April-June by 2035, with differences between the two scenarios of less than 0.3°C. All monthly temperature deltas for the 15 climate stations can be seen in Appendix C.

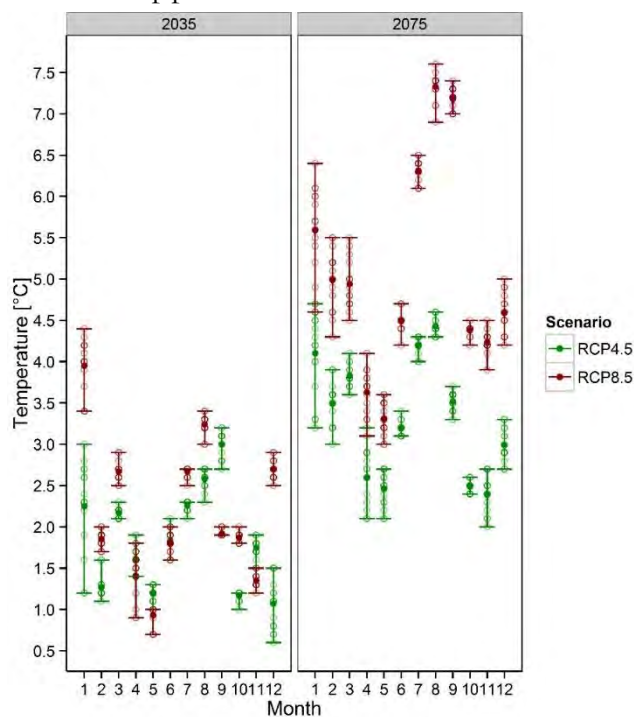


**Fig 41 | Temperature deltas for the 15 climate stations**

The temperature change in the catchment is very homogenous with two observable patterns: (1) lower elevations show a higher increase in temperature; (2) higher altitudes show a slightly less increase in temperature, with the exception of August temperatures by 2075 (Fig 42, Fig 43).

In the reference period, mean temperatures below zero degrees are observable in the period November-March throughout the entire watershed.

At high altitudes, temperatures below zero first occur in October and last in April. With the temperature increase, this pattern will change progressively.

By 2035, lower elevations show values above zero in November and in March, with the majority of valleys along the stream and tributaries.

Temperatures below zero in April only occur in isolated high alpine spots and in October basically no spots exist with mean temperatures below zero.

By 2075, the RCP4.5 scenario predicts negative mean temperatures throughout the entire catchment only for December-February. In November, the valleys still show temperatures above zero, whereas higher elevations show negative values. The temperature pattern of March by 2075, would refer to the pattern of April in the reference period with only negative temperatures at high altitudes. In April, only the RCP4.5 scenario predicts very few isolated high alpine spots with temperatures below zero degrees and both scenarios predict in October no values below zero throughout the entire watershed.

Other patterns observable are, that high mean temperatures are reached earlier and that they last longer throughout September.

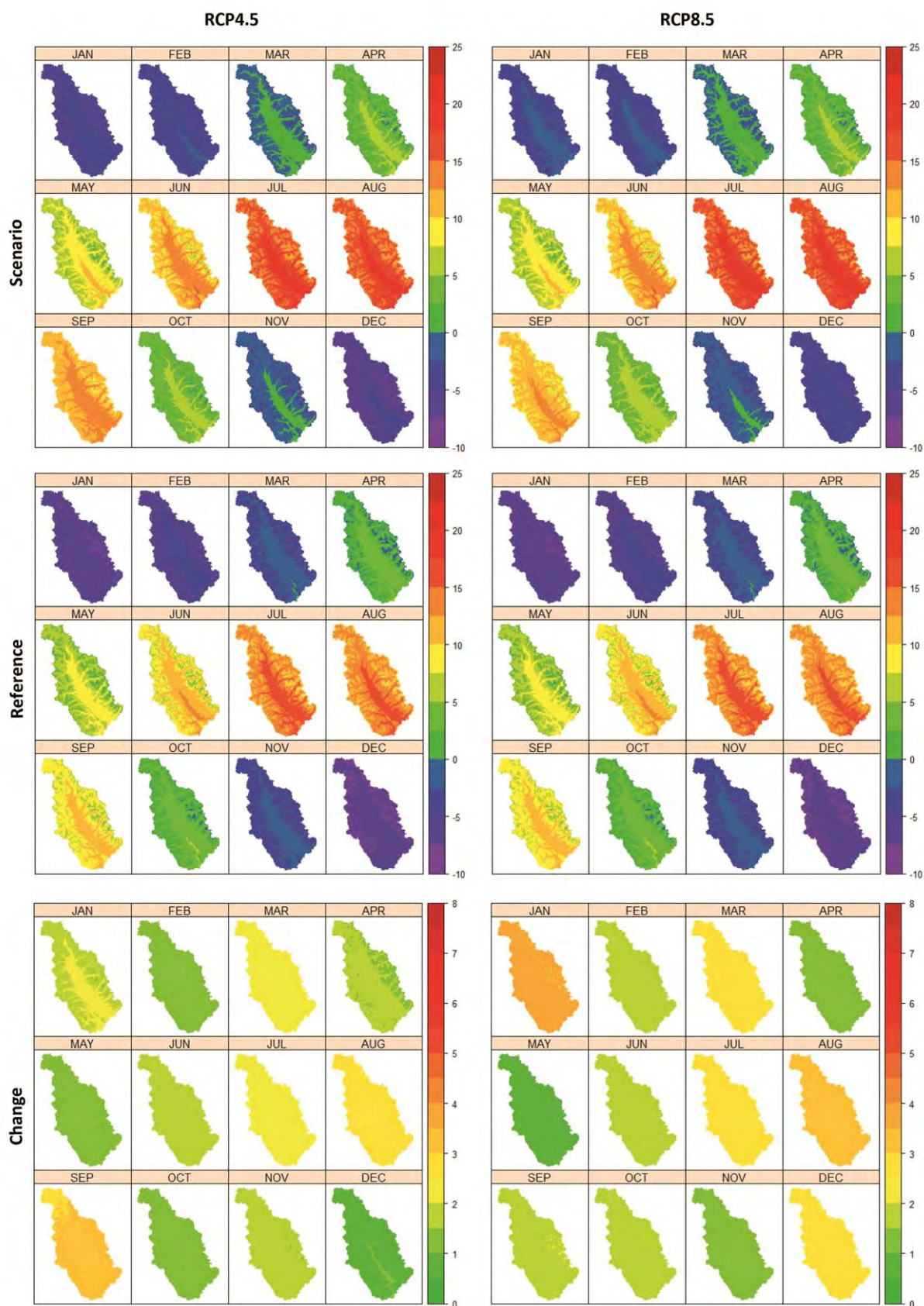


Fig 42 | Temperature change in the catchment by 2035 [°C]. (Scenario – Reference = Change)

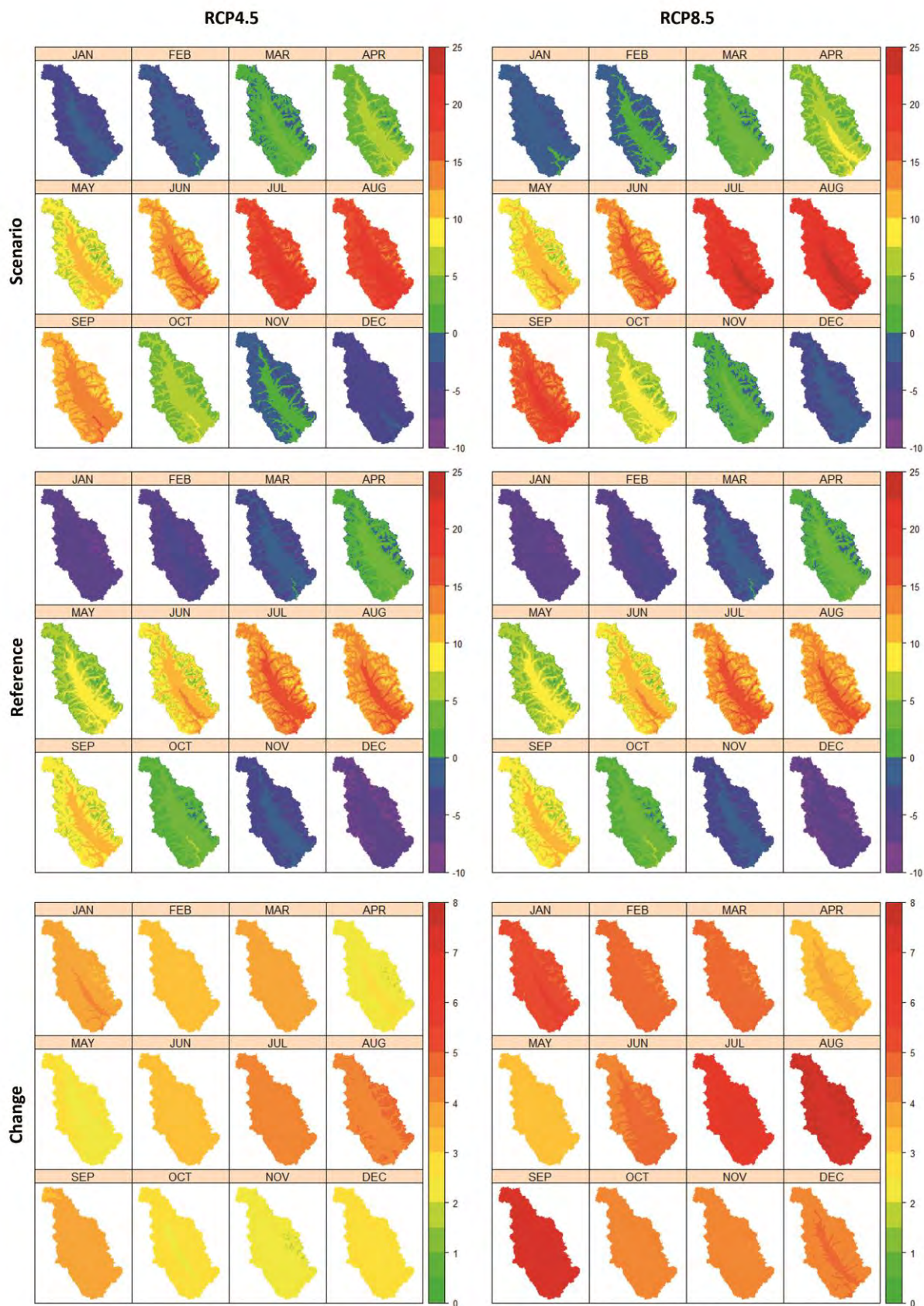


Fig 43 | Temperature change in the catchment by 2075 [°C]. (Scenario – Reference = Change)

### 5.3.3 Precipitation

The following facts are retrieved from the interpolated and elevation dependent regression of the hydrologic model for the catchment, and deltas for the 15 climate stations can be seen in Appendix C.

The climate model predicts increasing annual precipitation sums for the North Fork Flathead River watershed. By 2035, mean annual precipitation will increase by 25% (RCP4.5) and 11% (RCP8.5), with future annual precipitation of 1383mm (RCP4.5) and 1225mm (RCP8.5) averaged over the entire watershed, compared to 1105mm in the reference period. Compared to the precipitation change in the CCE, this means a higher increase for the RCP4.5 and a lower increase for the RCP8.5 scenario. By 2075, the strong increase of precipitation in the RCP4.5 scenario will reduce to an increase of 13% and the RCP8.5 scenario predicts an increase of 17%. Compared to the mean values in the CCE, this means a considerable lower increase in mean annual precipitation.

Looking at the changes of mean monthly precipitation, the RCP4.5 scenario predicts large increases of November, December, January and May precipitation in the catchment by 2035 (Fig 44). The precipitation of these month will change by 35, 24, 51 and 77%. The RCP8.5 scenario predicts comparatively lower increases of precipitation with 3, 3, 10 and 20% for the same months.

By 2035, the RCP8.5 scenario predicts a decrease in February and August precipitation with -10 and -12%, whereas the RCP4.5 shows no change.

By 2075 both scenarios show comparable changes, with the exception of March, May and June where the RCP8.5 predicts a larger change than RCP4.5 and in November the RCP4.5 scenario shows more precipitation.

Especially the months March-June and November will undergo the biggest change with an increase of 11-42% (RCP4.5) and 17-47% (RCP4.5) by 2075.

This pattern is also valid in 2035 with the addition of September and October where precipitation will change by 13-24%.

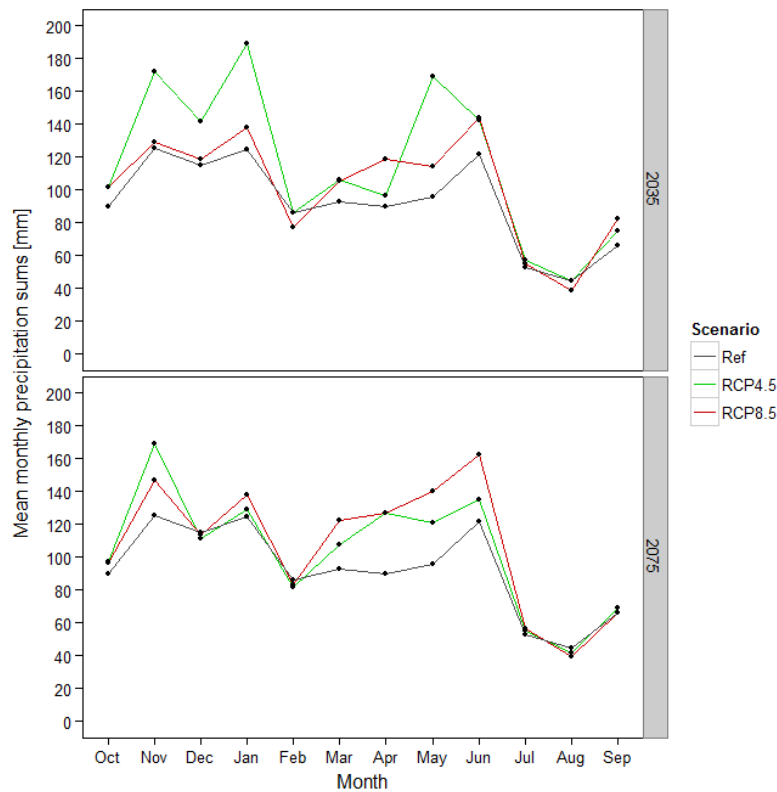


**Fig 44 | Change in mean monthly precipitation in the catchment**

Not only will the amount of precipitation change, but also the type. With the rising temperatures and increasing days above zero degrees Celsius precipitation will progressively fall as rain instead of snow. The amount of possible snow days will reduce considerable in the catchment (Tab 14).

A possible snow day is defined as days with temperatures of 2°C and lower. Two degrees is the upper threshold temperature for precipitation falling as snow defined in the hydrologic model, with 1% of precipitation falling as snow. The fraction of precipitation falling as snow will increase with decreasing temperatures. The transition between 50% snow and 50% rain is reached at a threshold temperature of 1.0°C, and at 0°C and below 100% of precipitation is falling as snow.

In the reference period the number of possible snow days is 172, which will progressively decrease. By 2035, the number of possible snow days is sinking to 147 (RCP4.5) and 139 (RCP8.5), respectively. By 2075, snow days are strikingly reduced to 122 (RCP4.5) and 96 days (RCP8.5). Further, the days eligible for 100% of precipitation falling as snow will be reduced from 140 days in the reference period to 112 days (RCP4.5) and 101 days (RCP8.5) by 2035, and to only 88 and 66 days by 2075 respectively. This drastic change in suitable conditions for snowfall will evoke a strong response to the hydrologic system.

**Tab 14 | Possible days with precipitation falling as snow in the catchment.****20 year mean number of days (Ref: 1991-2009, 2035: 2027-2045, 2075: 2067-2085); T: Temperature.**

|                                                                                                                | Ref | 2035   |        | 2075   |        |
|----------------------------------------------------------------------------------------------------------------|-----|--------|--------|--------|--------|
|                                                                                                                |     | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Number of days with $T \leq 2.0^{\circ}\text{C}$ ;<br>Possible days with $>1\%$ precipitation falling as snow. | 172 | 147    | 139    | 122    | 96     |
| Number of days with $T \leq 1.0^{\circ}$ ;<br>Possible days with $\geq 50\%$ of precipitation falling as snow. | 156 | 130    | 119    | 104    | 81     |
| Number of days with $T \leq 0.0^{\circ}$ ;<br>Possible days with 100% of precipitation falling as snow.        | 140 | 112    | 101    | 88     | 66     |

Looking at the spatial distribution of precipitation in the catchment (Fig 45, Fig 46) two main patterns can be detected: (1) Higher precipitation in the higher elevation ranges in the north-west and east of the catchment; (2) less precipitation in the lower elevation range surrounding Polebridge. Both of these patterns are still valid in the near and mid future. In general the east of the watershed is receiving more precipitation in the future with the exception of February 2035, with 10mm and more decrease. Further, the headwaters of the North Fork Flathead River in British Columbia will receive comparable more precipitation in the future.

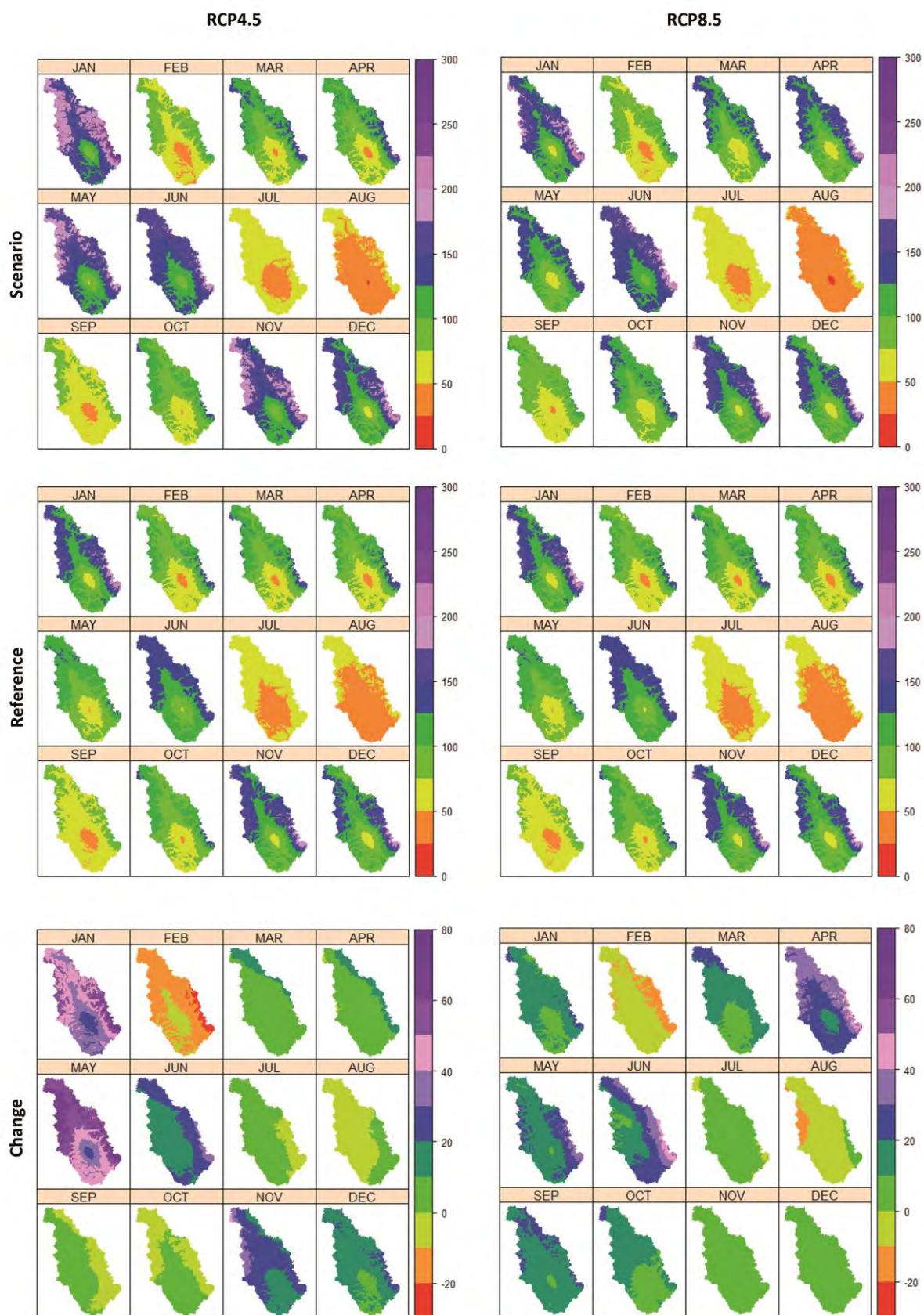


Fig 45 | Precipitation change in the catchment by 2035 [mm]. (Scenario - Reference = Change)

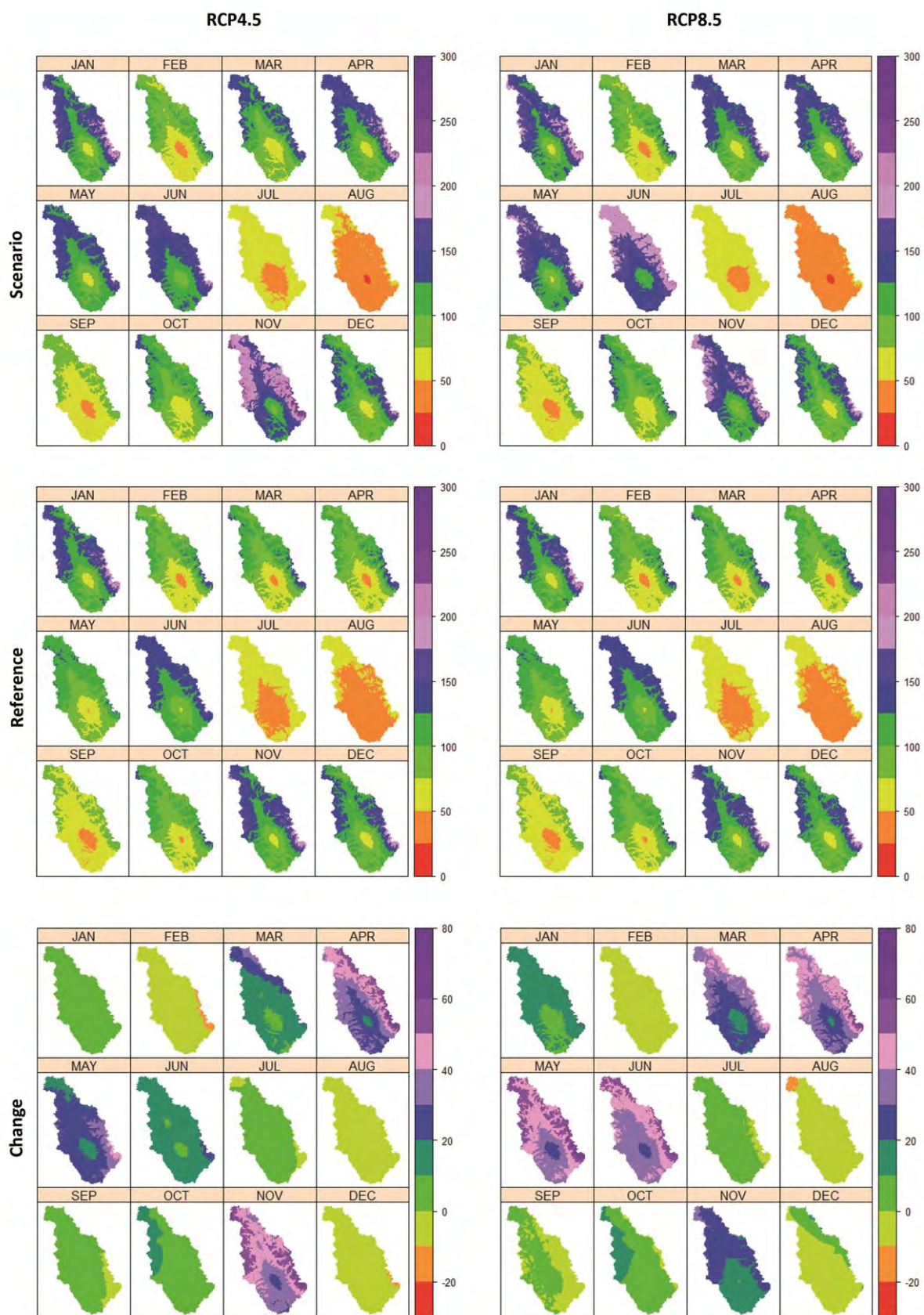


Fig 46 | Precipitation change in the catchment by 2075 [mm]. (Scenario - Reference = Change)

#### 5.3.4 Scenarios for Model input

The climate scenarios for the hydrologic model were obtained by adding the monthly deltas to the daily temperature values, and by multiplying the monthly ratio of change to the daily precipitation values in the observed time series. The climate scenarios were calculated by the delta change approach. Climate variability of the reference period is sustained in the future climate scenarios and changes in inter- or intra-annual variability of extreme events are not considered, due to the delta change approach. The next two figures will show how absolute values of mean annual temperature and mean monthly precipitation will change. All other variables, such as relative humidity, solar radiation and wind speed stay unchanged. The observed time series of 1991-2009 will be the reference period and future scenarios 2035 and 2075 are the reference period plus/multiplied by the delta of RCP4.5 and RCP8.5.

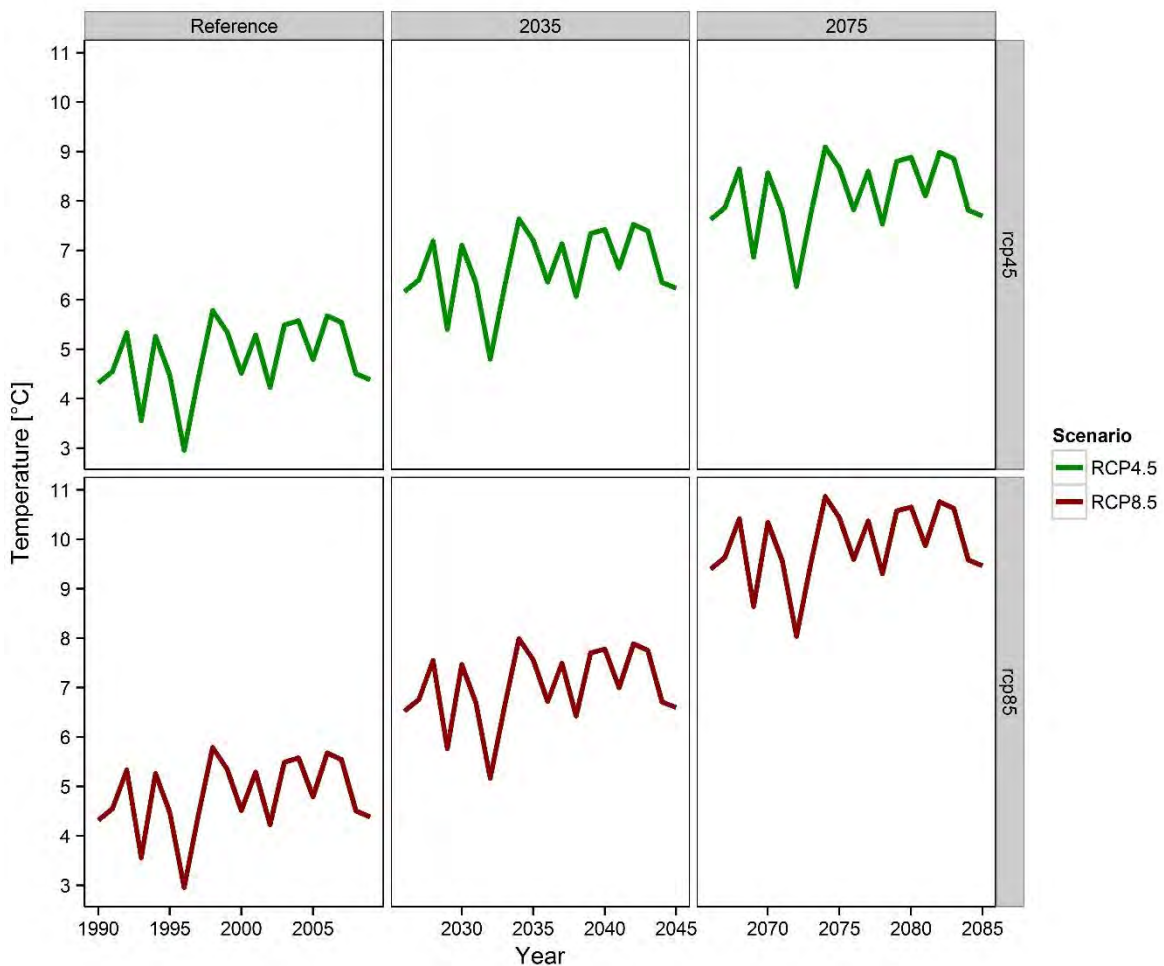


**Fig 47 | Temperature scenarios used for climate change impact assessment (annual mean temperatures)**

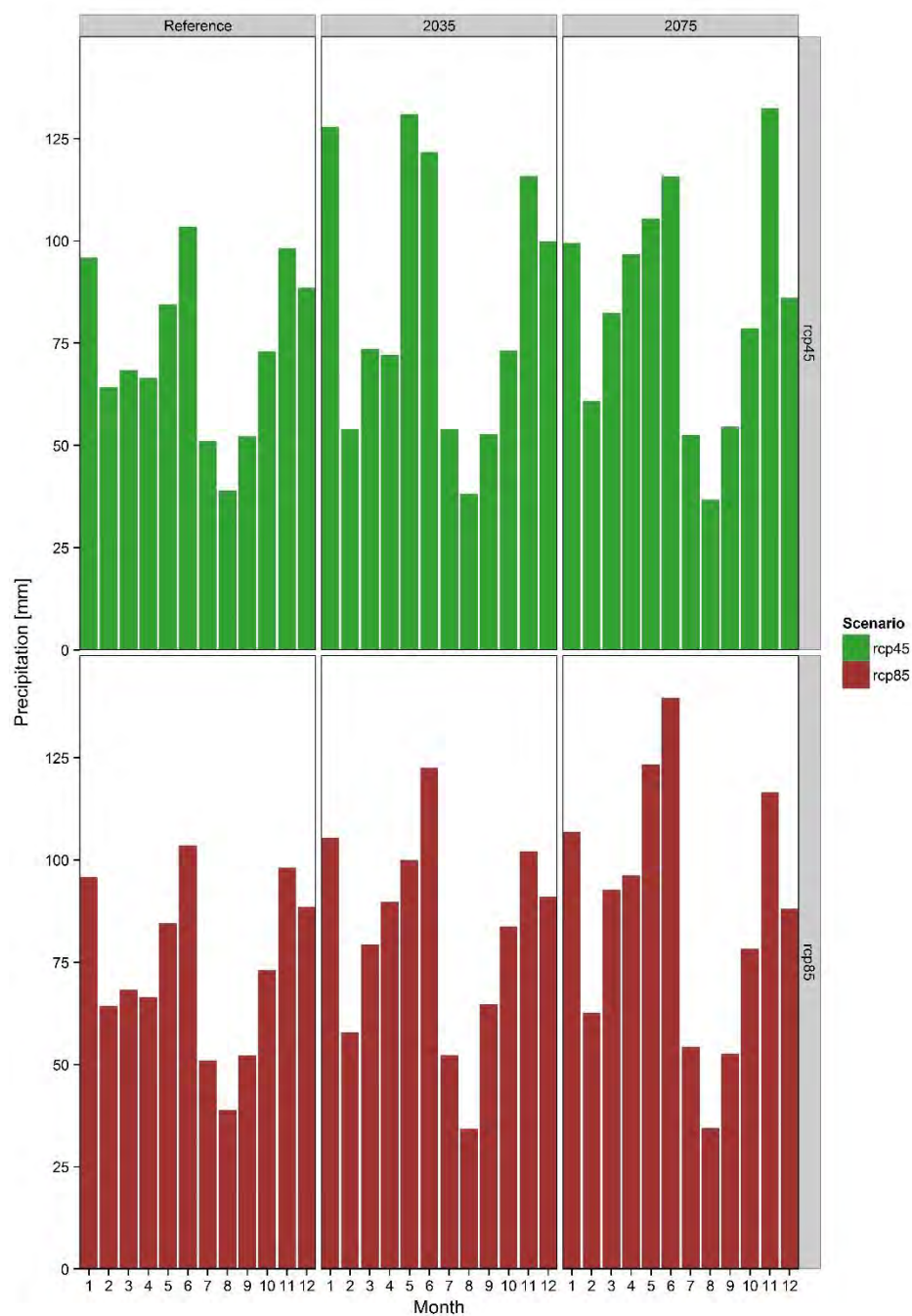


**Fig 48 | Precipitation scenarios used for climate change impact assessment (monthly precipitation sums)**

## 6 CLIMATE CHANGE IMPACTS

### 6.1 SNOWPACK

As documented a strong increase of temperature, with negative mean monthly temperatures progressively approximating zero degrees Celsius, is leading to the declining of snow days. This decline of snow days leads to less precipitation being stored in snowpack and more precipitation falling as rain. The model WaSiM is sensitive to temperature increases, due to the fact that snow-rain partitioning is driven by threshold temperatures for snow and rain. The ratio between rain and snow days is decreasing and therefore precipitation falling as rain is increasing. Calculating the rain/snow ratio (R/S ratio), days with the occurrence of more than 1mm of precipitation are considered rain days, and the occurrence of 1mm of precipitation and temperatures smaller than 1.0°C are considered snow days (days with 50% of precipitation falling as rain).

In the reference period the mean ratio between rain and snow is 0.52, which means that 52% of precipitation days are snow days. Since in this study the rain days basically don't change, due to the delta-change approach, it is obvious that with changing ratios the snow days have to alter. By 2035, the R/S ratio for the RCP4.5 scenario decreases to 0.42 and for the RCP8.5 scenario to 0.38. By 2075, only 32% (RCP4.5) and 25% of rain days are snow days (RCP8.5). Forbes et al. (2011) is noticing a comparable decrease of R/S ratio in the Beaver Creek in southern Alberta. This alteration in R/S ratio is a result of declining snow days and therefore is a result of the temperature increase. In fact, snow days (days with 50% of precipitation falling as rain) are reduced to 82 days (RCP4.5) and 75 days (RCP8.5) by 2035, compared to 99 days in the reference period.

By 2075, snow days are further declining to 66 days (RCP4.5) and 50 days (RCP8.5), respectively. Further, days with 100% snow and days with more than 1% of precipitation falling as snow are declining (Tab 15).

MacDonald et al. (2011) used several GCM outputs to assess the potential impacts of climate change on mountain snowpack in the St. Mary watershed in Montana. This study suggests that all climate scenarios used result in a decrease of R/S ratio and hence the storage of water in the form of snow will decrease.

**Tab 15 | Actual days with precipitation falling as snow in the catchment.**  
**20 year mean number of days (Ref: 1991-2009, 2035: 2027-2045, 2075: 2067-2085); T: Temperature, P: Precipitation.**

|                                                                                                                                     | Ref | 2035   |        | 2075   |        |
|-------------------------------------------------------------------------------------------------------------------------------------|-----|--------|--------|--------|--------|
|                                                                                                                                     |     | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| Number of days with $T \leq 2.0^{\circ}\text{C}$ and $P > 1\text{mm}$ ;<br>Possible days with $>1\%$ precipitation falling as snow. | 172 | 147    | 139    | 122    | 96     |
| Number of days with $T \leq 1.0^{\circ}$ and $P > 1\text{mm}$ ;<br>Possible days with $\geq 50\%$ of precipitation falling as snow. | 156 | 130    | 119    | 104    | 81     |
| Number of days with $T \leq 0.0^{\circ}$ and $P > 1\text{mm}$ ;<br>Possible days with $100\%$ of precipitation falling as snow.     | 140 | 112    | 101    | 88     | 66     |
| Number of days with $T < 1.5^{\circ}$ ;<br>Days without reaching snow melt conditions.                                              | 164 | 138    | 129    | 113    | 89     |

Due to declining snow days and increasing days reaching temperatures for snow melt, the accumulation of snowpack is declining. In addition, the start of accumulation is shifted to later in the season and the end of accumulation is shifted to earlier in the season. In general, precipitation changes between December and February are relatively small (exception RCP4.5 by 2035) and therefore the lack of snow days can't be compensated by considerable increases of winter precipitation.

In the reference period, the snow accumulation starts in early-November and ends with a mean peak SWE of 447mm, in early-April. Start of snow accumulation and snowmelt is defined by exceedance or shortage of 40mm SWE. With the considerable fast decrease of snow days in the catchment, the peak SWE declines to 401mm (RCP4.5) and 296mm (RCP8.5) by 2035, respectively. This corresponds to a relative change of -10% (RCP4.5) and -34% (RCP8.5). The snow accumulation shifts approx. 12 days to later in the season and peaks approx. four weeks earlier. In future, end of snowmelt is reached in early-July (RCP4.5) and late-June (RCP8.5), compared to late-July in the reference period. The persistent increase of temperature is responsible for the further decline in SWE of -40% (RCP4.5) and -62% (RCP8.5) by 2075. In the RCP8.5 scenario, the snow accumulation reaches an early peak and stays relatively constant over an extended period of time. In contrast, the reference period is characterized by a constant accumulation of snow until peak SWE and subsequent rapid decline of snowpack. Since the precipitation increase has only limited capability of compensating the decline, temperature is the driving force of decreasing SWE. MacDonald et al (2011) confirms this statement and further supports the observed trend toward earlier dates for maximum SWE.

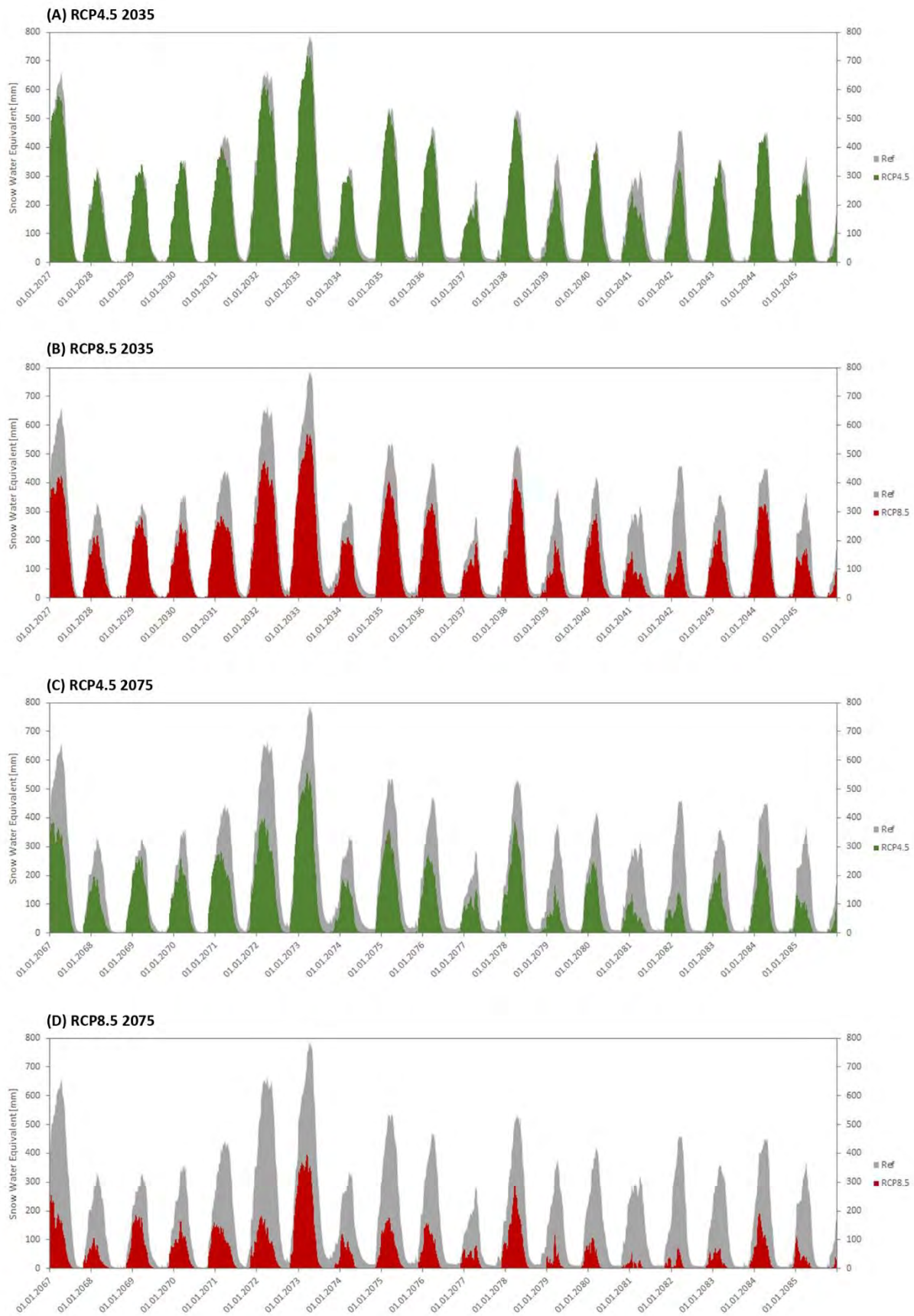


**Fig 49 | Average daily accumulated soil water equivalent in the catchment by 2035 and 2075.**  
 Grey: Reference, Green: RCP4.5 scenario, Red: RCP8.5 scenario.

Due to the fact, that days with SWE exceeding 40mm are declining, the snow cover in the watershed is shrinking. In the reference period on 243 days a SWE of more than 40mm exists. By 2035, days reduced by 13% to 212 days (RCP4.5) and by 17% to 201 days (RCP8.5). Snow days with more than 40mm SWE are further declining by 2075 by 25% to 182 days (RCP4.5) and by 49% to 123 days (RCP8.5). This loss of days takes place especially in the beginning and at the end of the snow season. Hence, the month with the greatest areal snow cover loss is May. By subtracting the future snow cover extent (areas with more than 40mm SWE) from the reference snow cover, the areal snow cover loss can be detected. In future, January is the month with the least loss of areal snow cover with a relative loss of 0% (RCP4.5, 2035) to 22% (RCP8.5, 2075) of January mean snow cover. It is observable, that snow melt will occur progressively earlier in the year and in high alpine regions snow patches late in the season will decrease or diminish entirely. In the reference period snowfields remained throughout the entire year. By November snow covered 70% of the watershed and December through March were basically entirely snow covered. In future, except the RCP4.5 scenario by 2035, snow free areas are increasing throughout the winter season, December through March.

By 2075, in May only 22% of the watershed stay snow covered, whereas in the reference period 84% of the watershed are snow covered. The same pattern is observable in November with 69% of the watershed being snow covered in the reference period and only 10% by 2075 in the RCP8.5 scenario.

The percentage of loss for all month and scenarios can be seen in Appendix D. This loss of areal snow cover does not mean that in these areas snow won't exist anymore, it means that the mean behavior of snow patterns will change to a higher frequency of snow free areas and fragmented snow cover. The snow line in general is progressively moving upslope, in response to the warming and snowpack in the valleys will melt earlier in the season.

Snowpack at lower elevations is in large parts a function of temperature change. As temperature increases, low-elevation areas of the watershed with winter average daily air temperatures near the freezing point in the reference period, will progressively warm above freezing, and change the phase of the precipitation and the rate of snowmelt (MacDonald et al 2011).

This study suggests, that under future climate conditions annual SWE and snow cover extent is decreasing. As temperatures in the lower elevations progressively warm above zero degrees Celsius, the frequency of snow free areas or fragmented snow cover in the lower elevations will increase.

Further, in high alpine regions perennial snow will decline or diminish.

Snowmelt will progressively occur earlier in the season and snow accumulation shifts to later in the season. Days with suitable conditions for snowfall will decline and increasing portions of precipitation will fall as rain.

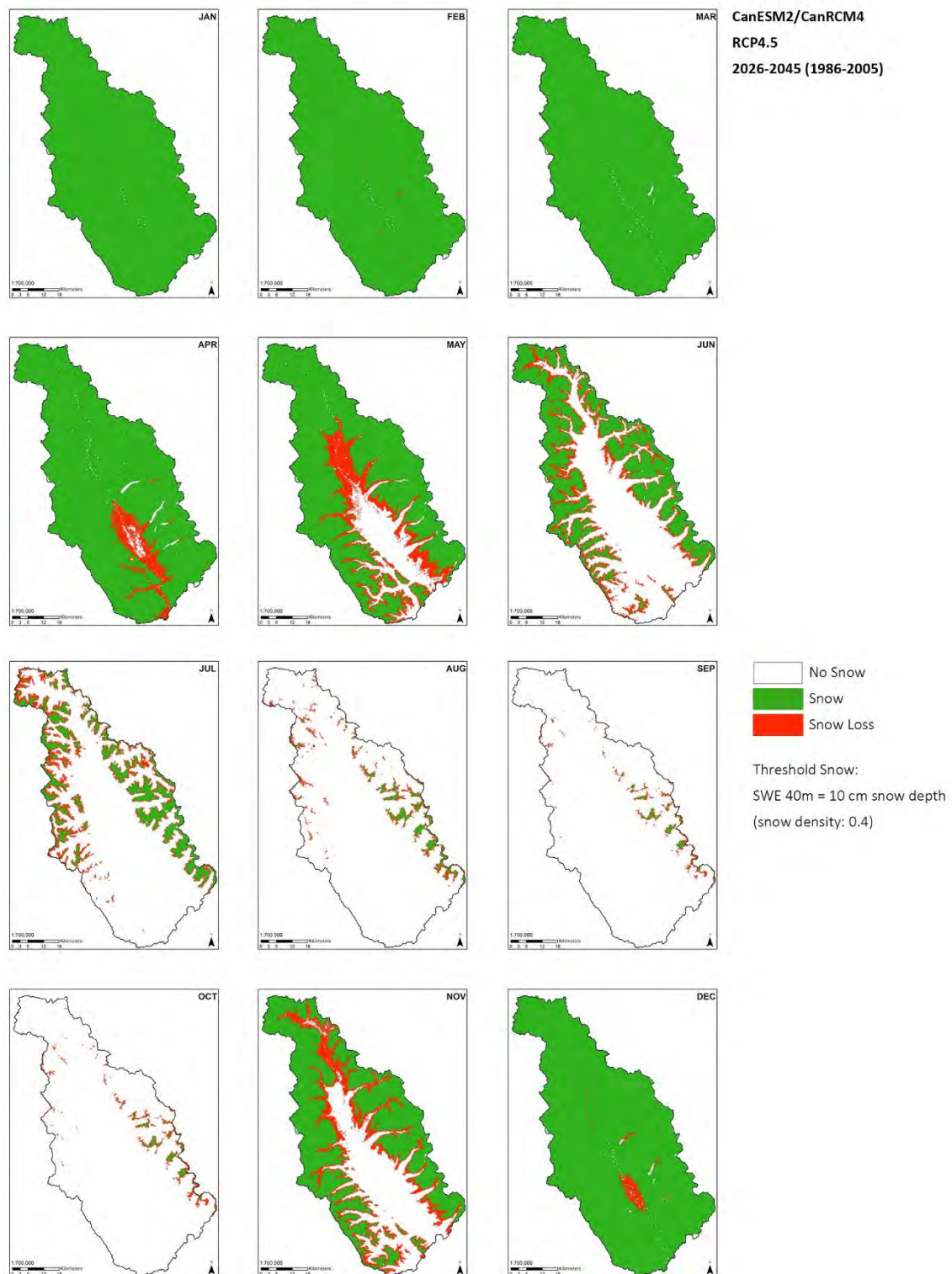


Fig 50 | Change in snow cover by 2035 (RCP4.5)

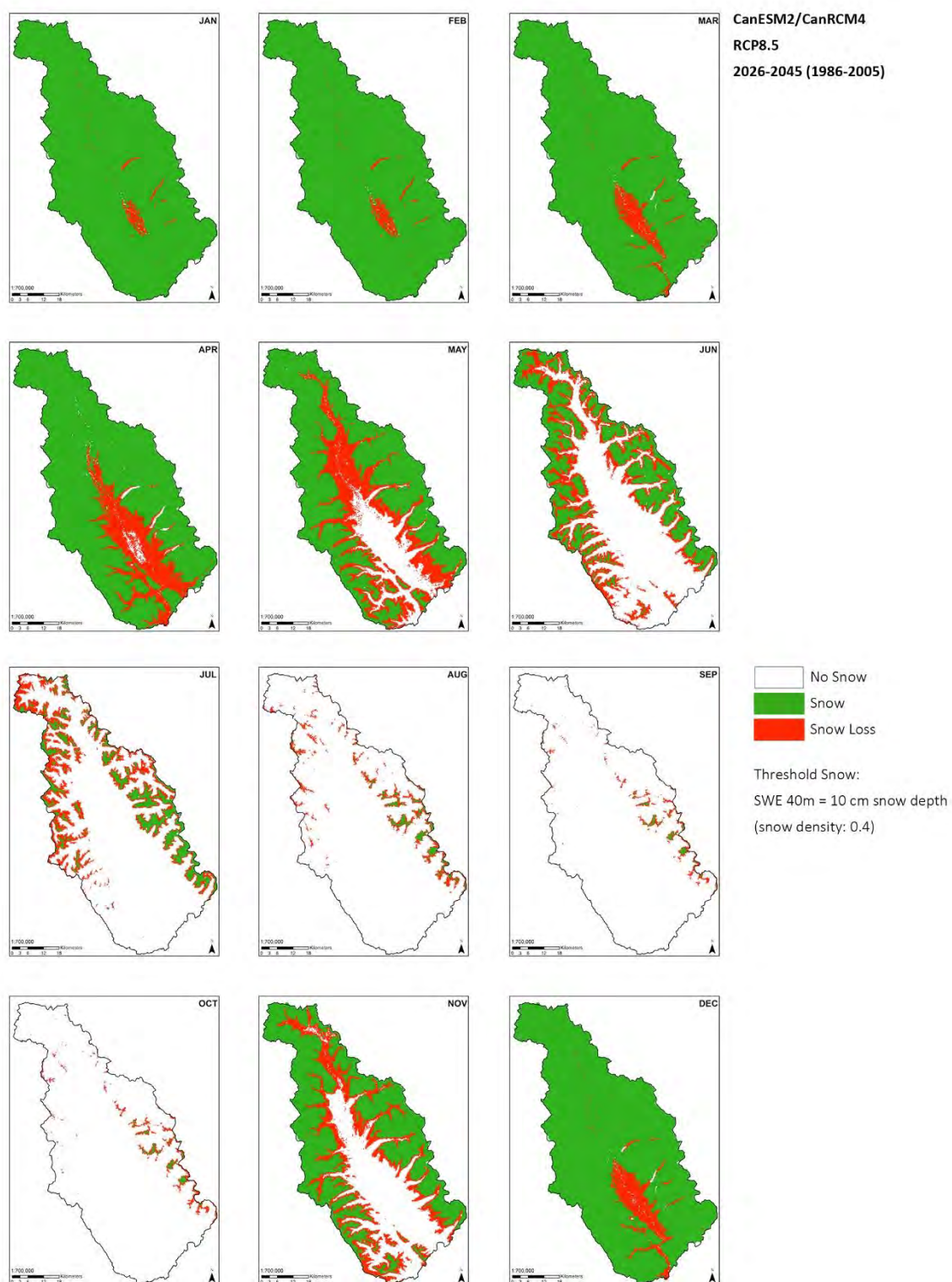


**Fig 51 | Change in snow cover by 2035 (RCP8.5)**

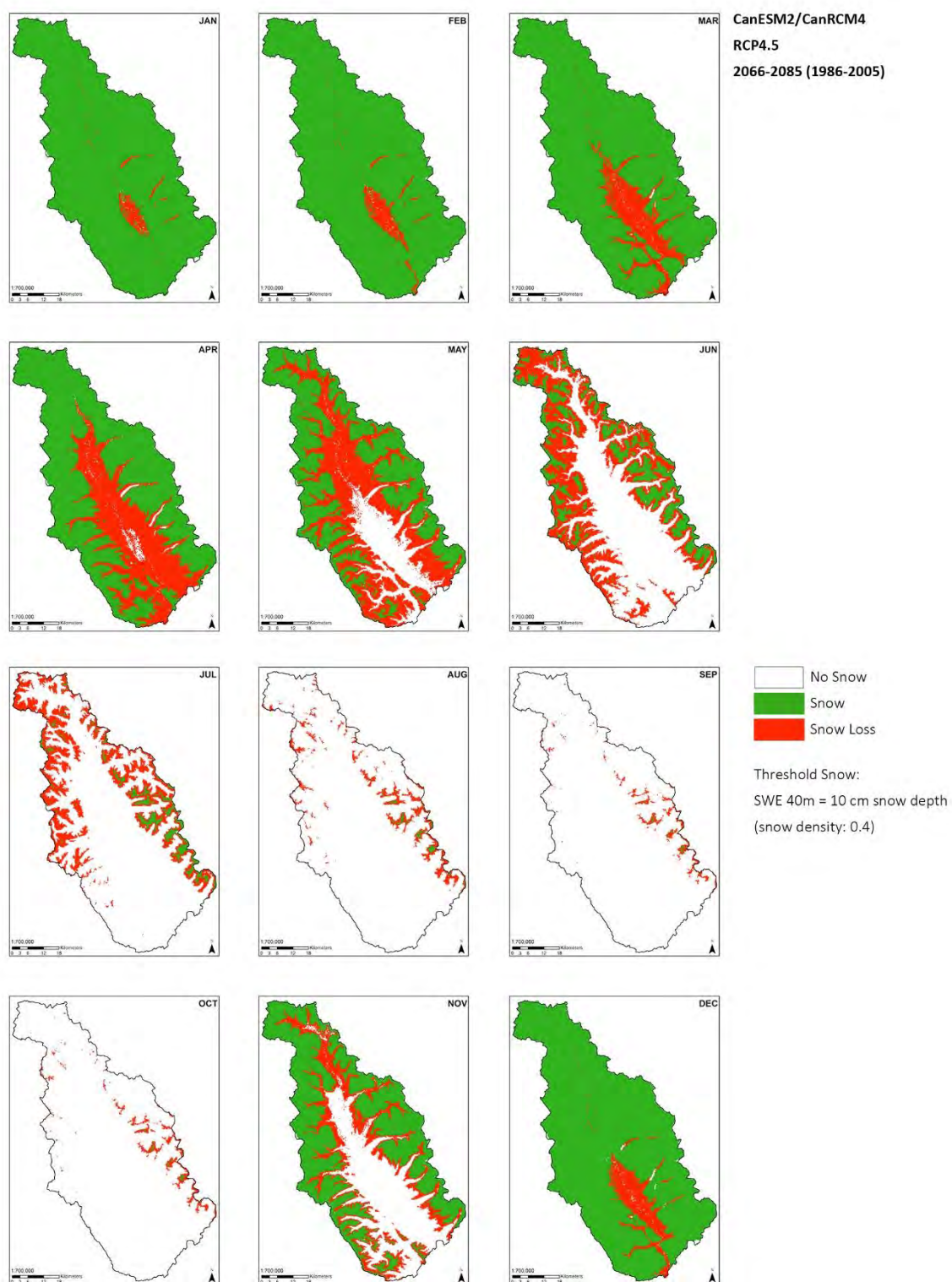


Fig 52 | Change in snow cover by 2075 (RCP4.5)

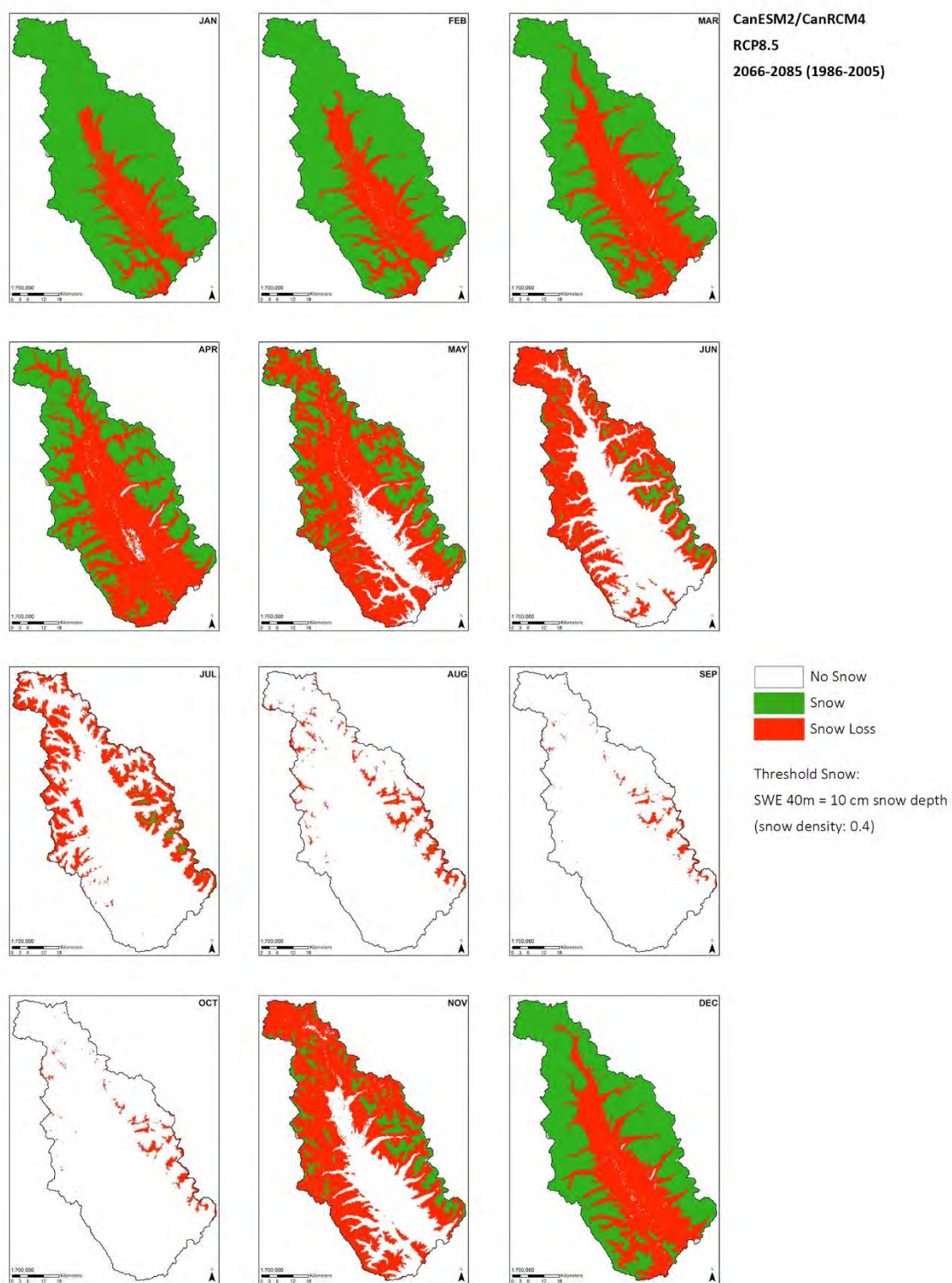


**Fig 53 | Change in snow cover by 2075 (RCP8.5)**

## 6.2 EVAPOTRANSPIRATION

Potential and real evapotranspiration is also undergoing a change in the future, whereby the potential evapotranspiration (PET) has a more pronounced change. Since solar radiation and relative humidity stay unchanged in future, the temperature increase is the main driver for the increase of PET. The greatest differences in PET, occur in the period between May and September and overall yearly PET sums increase between 11% (RCP4.5, 2035) and 32% (RCP8.5, 2075). Real evapotranspiration (AET) is especially changing in the winter (November-March), considering the relative change, due to higher winter temperatures and increasing PET, as well as increasing areas without snow cover. In addition, the soil moisture content is increasing in winter and early spring, leading to more water available for evapotranspiration. The change of 14-28% (RCP4.5) and 25-40% (RCP8.5) by 2075 in winter AET, equals a considerable low absolute change of 2-8mm (RCP4.5) and 4-9mm (RCP8.5). The greatest absolute change in AET can be observed between May and July. For August even a slight decrease is observable, with a maximal decrease of -5% or -4mm (RCP4.5, 2075).

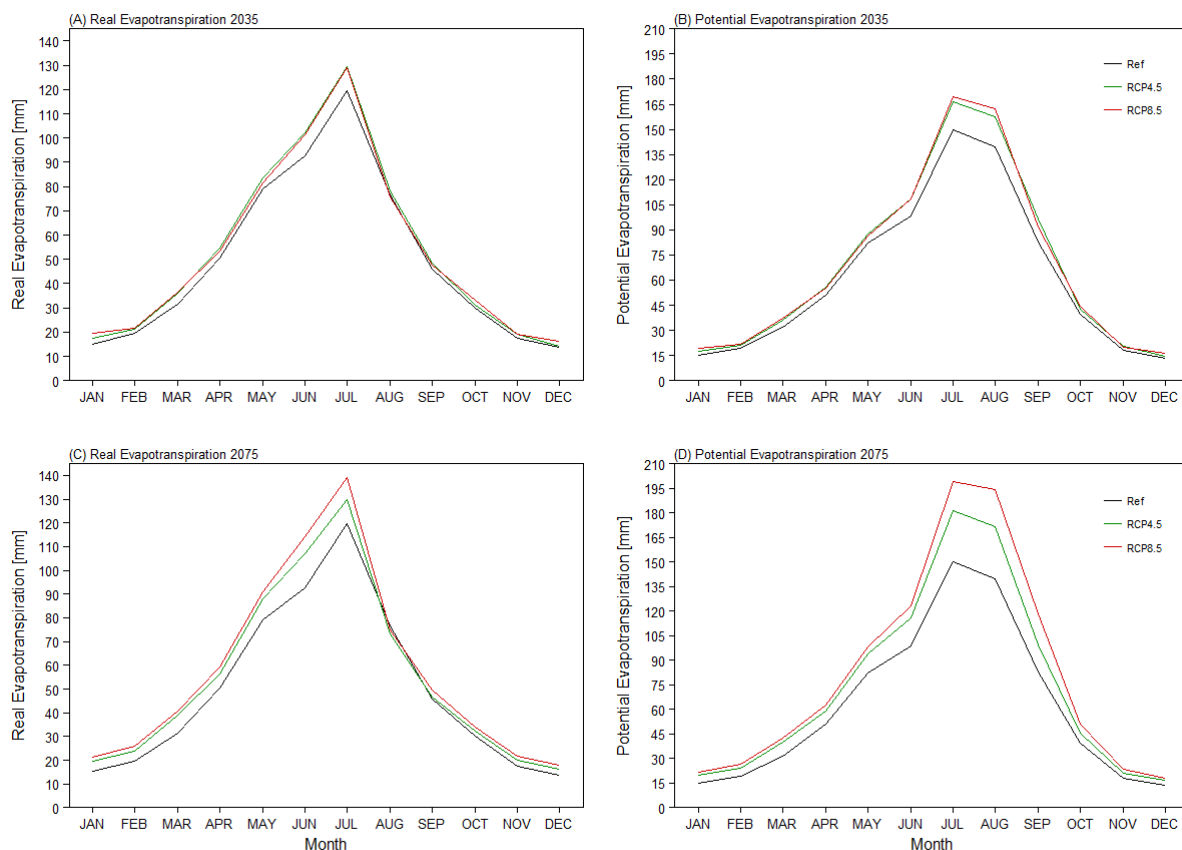


**Fig 54 | Change in real and potential evapotranspiration**

The decrease in AET is better observable in the change maps of mean monthly AET in the catchment (Fig 56, Fig 57). This decline in AET is simulated, despite the increase in PET, indicating an increase in soil moisture deficit. In WaSiM, AET is estimated by reducing the PET by the actual soil moisture, whereby the Richards-Equation is used to model the soil moisture (Schulla 2013). AET is estimated by using the relation between the soil water content and the actual capillary pressure (suction) according to the van Genuchten parameters of the actual soil (Schulla 2013). Indeed the soil moisture content in August decreases in future, compared to the reference period. Jasper et al. (2006) noticed, that the decline in soil moisture is pronounced in forested areas. This confirms the modeled decline in August soil moisture, with the majority of the watershed being covered by forest. Forbes et al. (2011) describes a similar behavior of decreasing soil moisture and AET, indicating that soil moisture will be the limiting factor for AET. The increasing of winter precipitation falling as rain at times when atmospheric water demand is low, results in low PET and AET and subsequent increase of soil moisture content. This behavior can be observed in the period November-April.

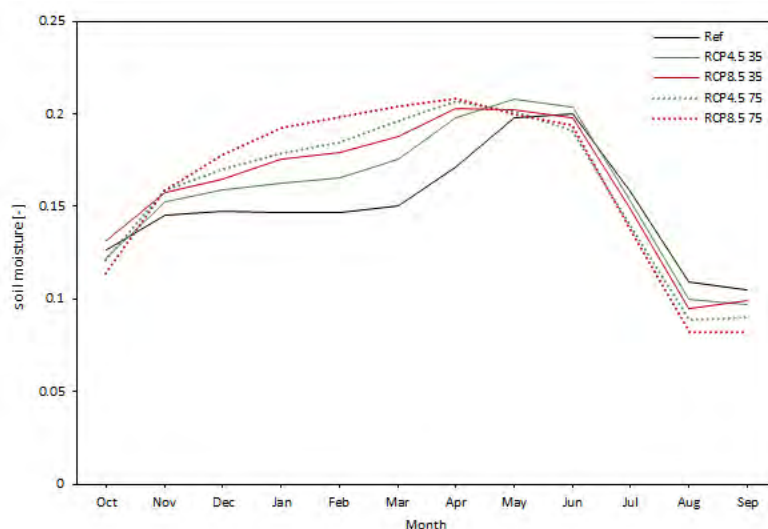


**Fig 55 | Mean monthly soil moisture content.**

**Black: Reference, Green: RCP4.5, Red: RCP8.5, solid: 2035, dotted: 2075**

PET and AET are for the majority of the year (November-June) very close together, with a ratio approximating 1.0 and differences of less than 6 mm in the reference period. The ratio and absolute difference will only change marginal, with a ratio approximating 1.0 and differences less than 10mm. For the period July-October a decrease in the ratio is observable. Especially in August, the ratio between AET and PET is decreasing from 0.6 in the reference period to minimal 0.4 (RCP8.5) by 2075. Jasper et al. (2006) is observing a similar pattern in the Suisse Alps.

This change in the ratio is a result of a stronger increase in PET compared to AET and the fact that AET in August is declining.

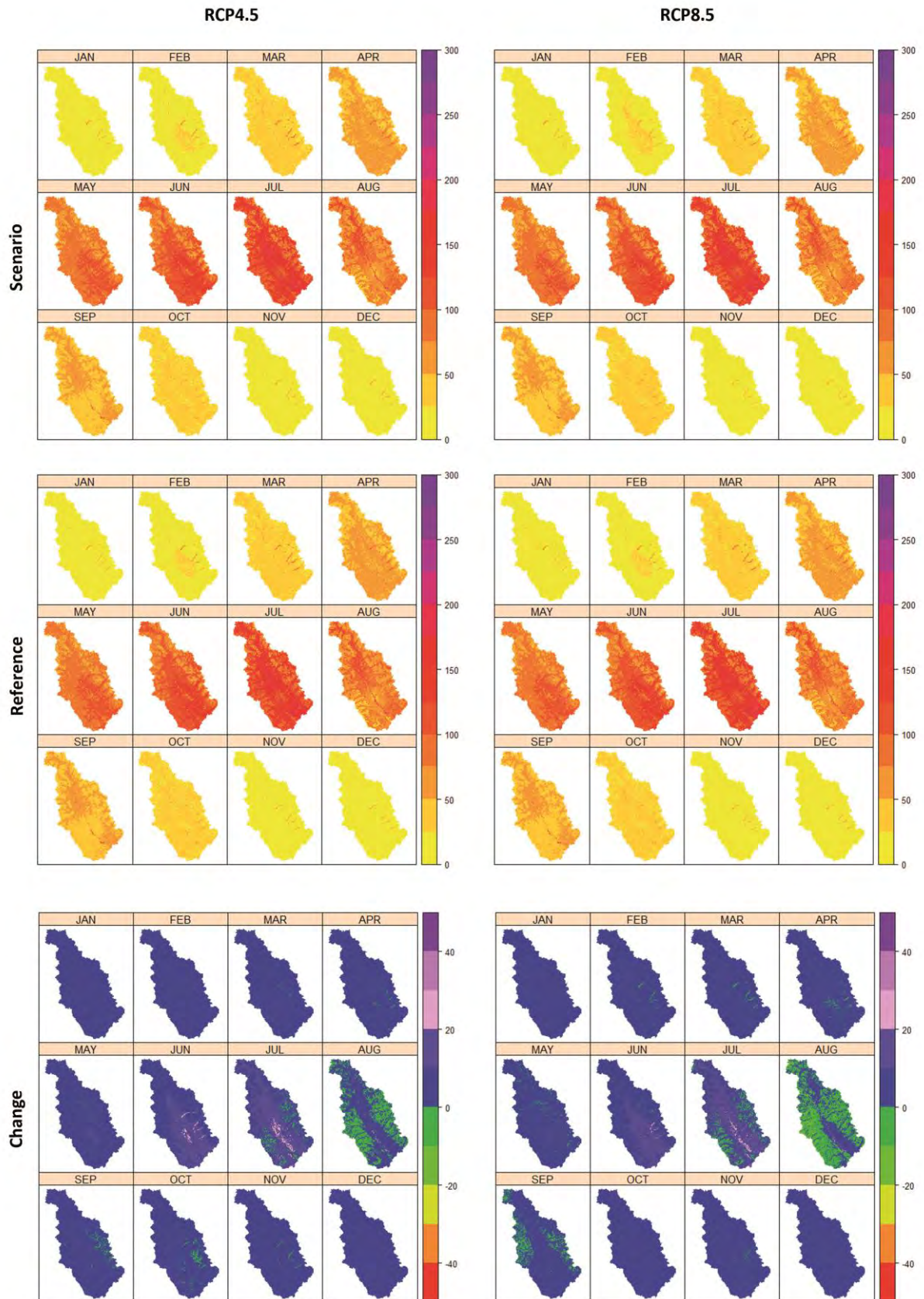


Fig 56 | Change in real evapotranspiration by 2035. (Scenario – Reference = Change)

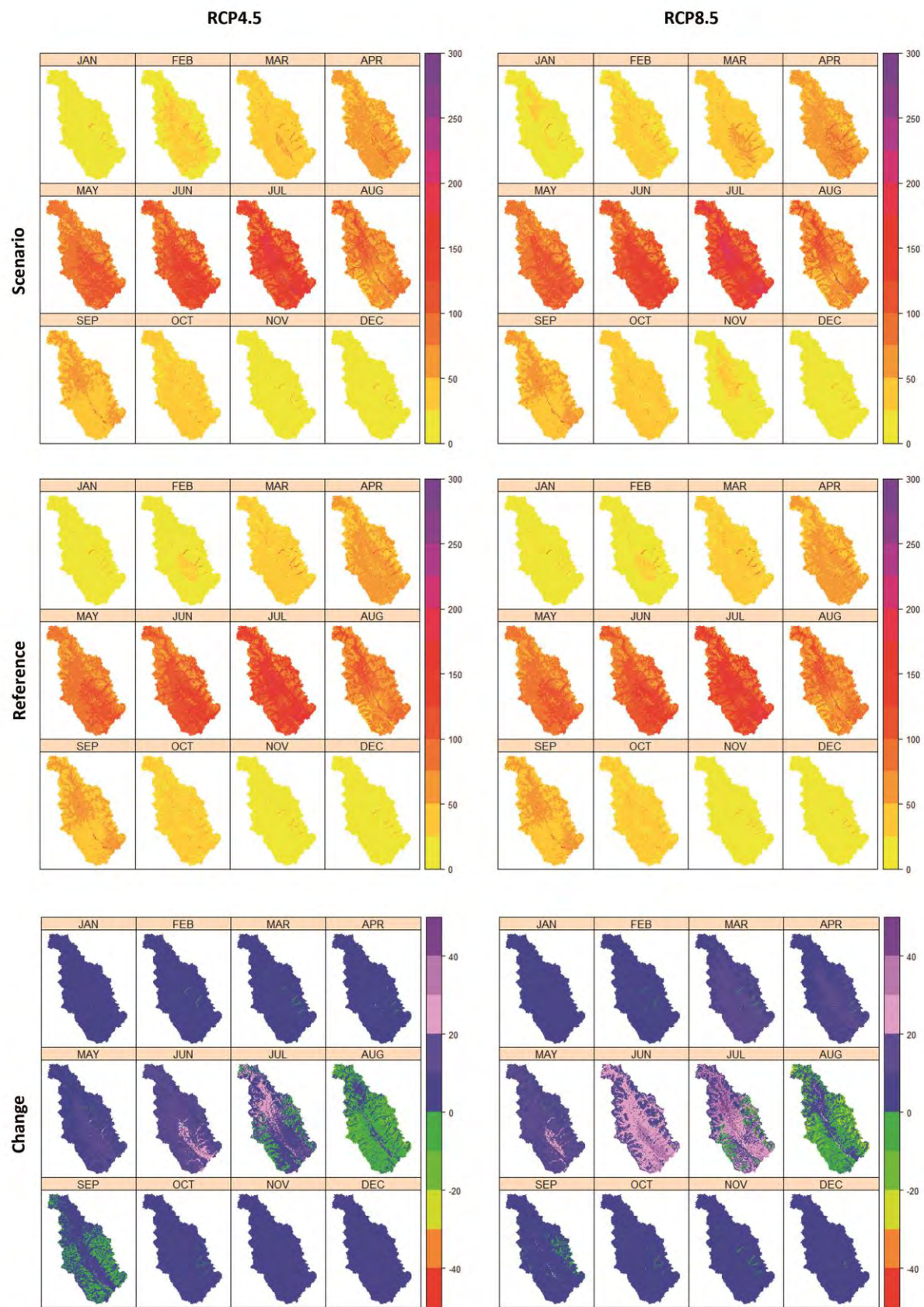


Fig 57 | Change in real evapotranspiration by 2075. (Scenario - Reference = Change)

### 6.3 HYDROLOGY

As discussed in the previous chapter, the climate signal for the North Fork Flathead River watershed is very strong, which evokes a strong response from the system to the new climatic conditions. The high temperature increase in the winter months, leads to a shift to more winter precipitation falling as rain instead of snow. The shift to more liquid precipitation and the higher frequency of freezing and thawing evoke higher discharges in winter and spring. In the reference period, the winter runoff regime is characterized by uniform low flows strongly influenced by groundwater. In the near future (2035) the runoff regime starts to become more heterogeneous, especially in winter and spring, with an even more pronounced heterogeneity by 2075 (Fig 58). The higher temperatures will force snow melt to occur progressively earlier in the season with spring freshet also occurring earlier.

Snow accumulation will peak approx. one month earlier, in beginning March instead of early April. With the end of snow accumulation, discharge starts swelling until peak flows are reached in late May and early June.

By 2035, this behavior is still present, but with diverse quantities.

The RCP8.5 scenario has considerable lower peak flows than in the reference period, with approx.  $255\text{m}^3/\text{s}$  instead of  $305\text{m}^3/\text{s}$ . Further, a first peak is reached in late April, with subsequent reduction of flow caused by a short period of snow accumulation (approx. 2 weeks). The RCP4.5 also shows this small cut, but the period of decreasing flow is shorter and subsequent rising comes earlier. Further, the peak flow of  $331\text{m}^3/\text{s}$  in the RCP4.5 scenario is considerable higher than the RCP8.5 and slightly higher than in the reference period. The higher peak and the more rapid increase of flow, compared to the RCP8.5, is the result of a considerable wet May in the RCP4.5 scenario and more water stored in snowpack.

By 2035 after peak flow, discharge is decreasing more rapid and low flows are reached earlier. Discharge with less than  $40\text{m}^3/\text{s}$  is reached end of July (RCP8.5) and early August (RCP4.5), compared to late August (Reference).

The decrease of August discharge, is a combination of less snowpack and slightly less evapotranspiration. The main driver for the rapid decrease is the retreat of snow. In general, days with flow exceeding  $40\text{ m}^3/\text{s}$  are increasing and days with flow exceeding  $200\text{ m}^3/\text{s}$  are declining (Fig 59). By 2035, days with flow between  $40$  and  $200\text{ m}^3/\text{s}$  are increasing from 120 (reference) to 163 days (RCP4.5) and 245 days (RCP8.5), respectively.

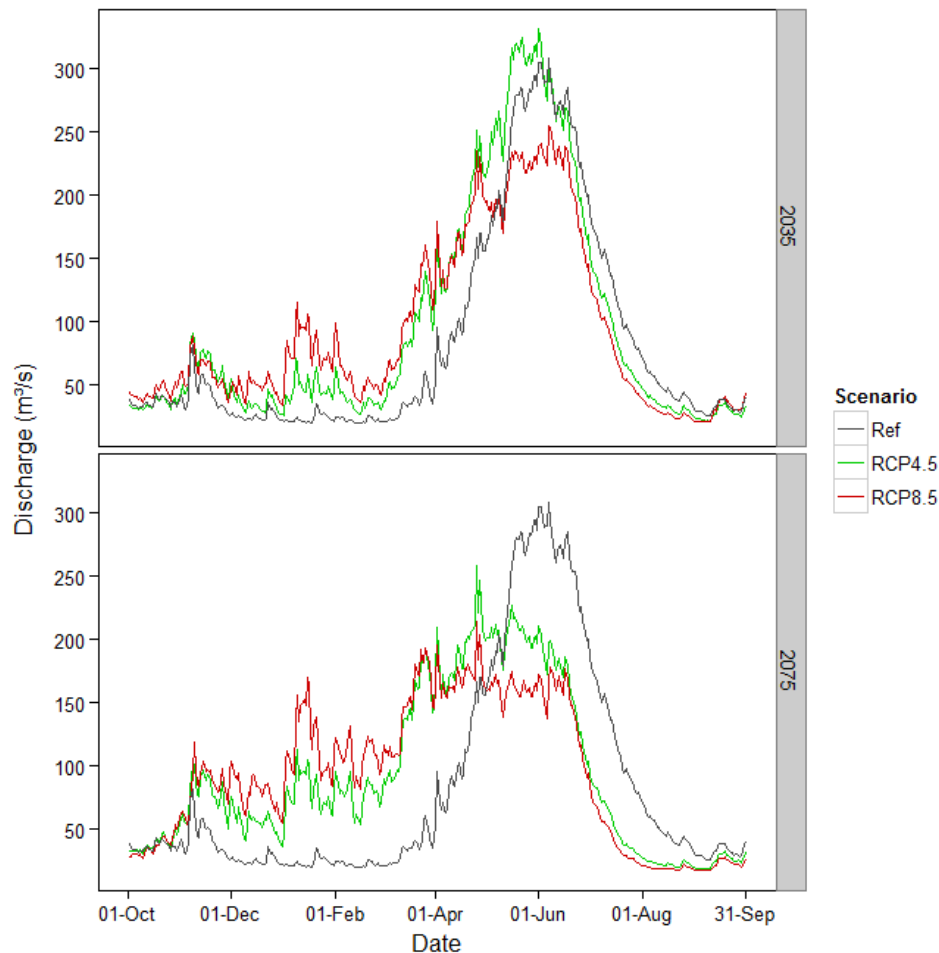


**Fig 58 | Change of mean daily discharge**

By 2075, the flow regime of both scenarios show a strong transformation to more rain dominated flow. The flow between November-June, is becoming very heterogeneous showing several small peaks. Since precipitation in December-February is basically not changing by 2075, the existing precipitation is falling more frequently as rain and the snow cover is frequently undergoing freezing and thawing, which results in contributions to the winter discharge. In contrast, the flow of December-February in the reference period is characterized by uniform flows, indicating that precipitation is stored in snowpack and basically no direct contribution of precipitation and melt water is present.

By 2075, discharge is increasing step wise to the level of high flows around peak flow. First step of increased flow is beginning November until end of December with mean flows of  $66\text{m}^3/\text{s}$  (RCP4.5) and  $84\text{m}^3/\text{s}$  (RCP8.5), compared to low flows of  $33\text{m}^3/\text{s}$  in the reference period. Subsequent flow is increasing to reach the second level of flow in beginning January until beginning March with mean flows of  $80\text{m}^3/\text{s}$  (RCP4.5) and  $113\text{m}^3/\text{s}$  (RCP8.5), compared to low flows of  $23\text{m}^3/\text{s}$  in the reference period.

The first two flow periods of increased flow, occur during the low flow winter season of the reference period, which is characterized by minimal direct contribution of precipitation and mainly groundwater flow.

These periods of increased flow, are strong indicators for the increasing relevance of winter precipitation falling as rain and leading to direct contributions to the discharge. The third period of increased flow, around peak flow in mid-April, ranges from mid-March to mid-June with mean flows of  $190\text{m}^3/\text{s}$  (RCP4.5) and  $166\text{m}^3/\text{s}$  (RCP8.5), compared to  $171\text{m}^3/\text{s}$  in the reference period.

Mean flow of the reference period is comparable, because flow in the reference period exceeds the future flow in early to mid-May. Peak flow by 2075 is reached in both scenarios approx. 43 days earlier by mid-April, instead of early June in the reference period. The peak flow of the RCP4.5 scenario with  $258\text{m}^3/\text{s}$  is considerable higher than the RCP8.5 scenario with  $214\text{m}^3/\text{s}$ , compared to a mean reference peak flow of  $309\text{m}^3/\text{s}$ .

The difference of peak flow in the two scenarios is a result of differences in accumulated snowpack. The RCP4.5 scenario accumulates considerable more snow than the RCP8.5, with 268mm compared to 168mm. Peak flow might be less in future, but high flows are maintained over a longer period.

In general, the flow behavior by 2075 is characterized by an increasing portion of days with flows between  $40\text{-}200\text{m}^3/\text{s}$  and receding days below  $40\text{m}^3/\text{s}$  and above  $200\text{m}^3/\text{s}$ . By 2075, days with flows  $40\text{-}200\text{m}^3/\text{s}$  increase from 120 days (reference) to 234 (RCP4.5) and 264 days (RCP8.5), respectively. Whereas, low flow days with less than  $40\text{m}^3/\text{s}$  recede from 195 days (reference) to 95 days (RCP4.5) and 99 days (RCP8.5), respectively.

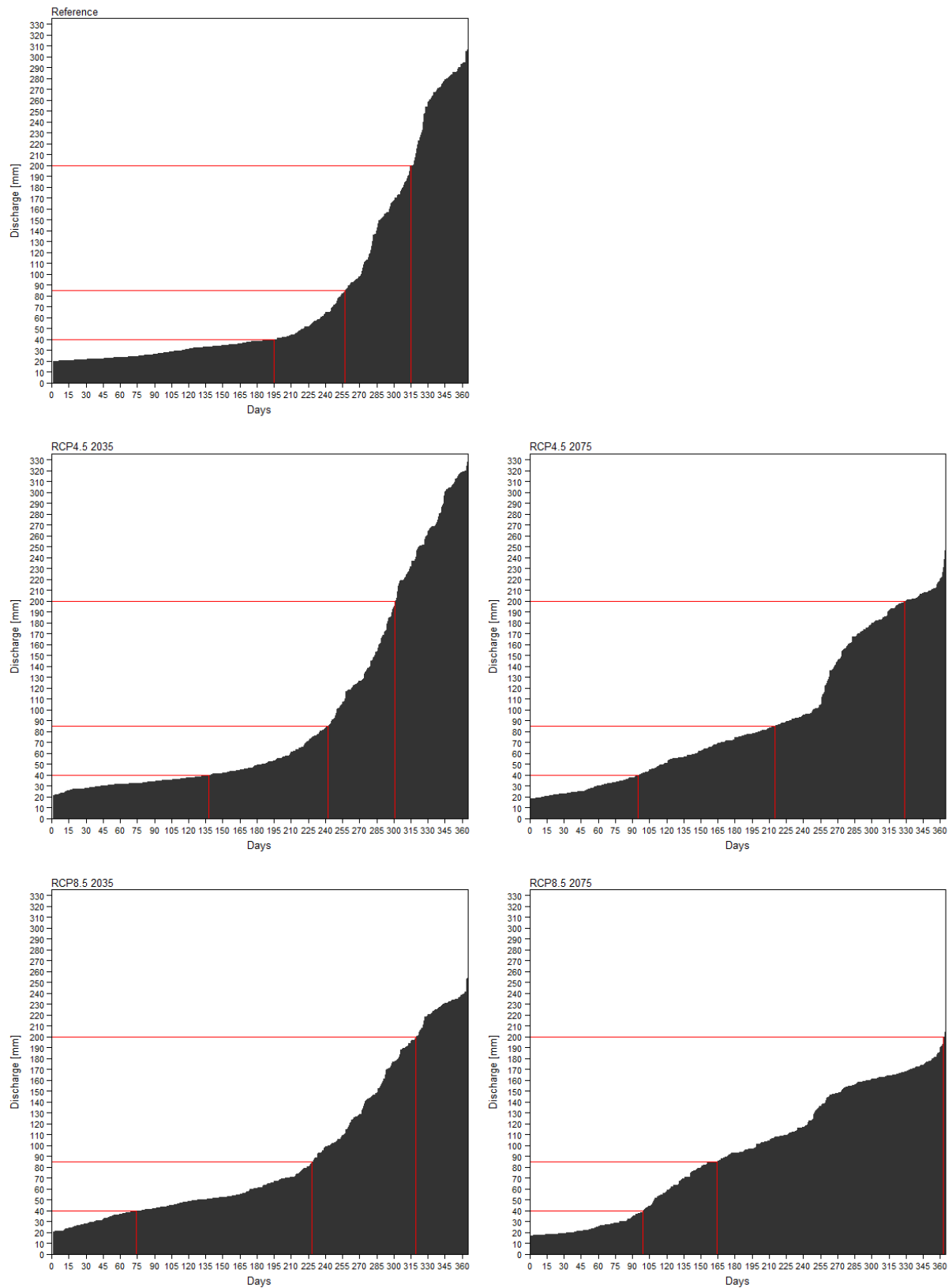


**Fig 59 | Flow-duration curves of the reference and future mean daily discharge. The x-Axis shows the days with exceedance or shortage of a specified discharge; Red lines indicate the days with discharge lower  $40\text{m}^3/\text{s}$ ,  $83.4\text{m}^3/\text{s}$  (reference mean discharge) and  $200\text{m}^3/\text{s}$ .**

What does the change mean for the monthly discharge? All scenarios show an increase in November-April discharge, with changes of mean monthly discharge ranging between 36% and 404% (Fig 60). Especially mean monthly discharge January through March is undergoing serious changes, with already considerable high increases by 2035. The RCP4.5 scenario is showing the least changes with January discharge increasing by 104%, February discharge by 64% and March discharge by 143% by 2035. This means an increase of  $25\text{m}^3/\text{s}$ ,  $14\text{m}^3/\text{s}$  and  $50\text{m}^3/\text{s}$ . By 2075, the RCP4.5 scenario is already showing an increase of January through March discharge of  $58\text{m}^3/\text{s}$  (245%),  $55\text{m}^3/\text{s}$  (247%) and  $101\text{m}^3/\text{s}$  (289%). The RCP8.5 scenario shows even more pronounced changes by 2035, as well as 2075. Summer flow is predicted to become less in future, with especially July and August undergoing a decrease in discharge. Mean July discharge will change by -25% (RCP4.5, 2035) and -65% (RCP8.5, 2075), which equals a change of  $-30\text{m}^3/\text{s}$  and  $-79\text{m}^3/\text{s}$ . August mean flow is undergoing a change of -29% (RCP4.5, 2035) and -59% (RCP8.5, 2075) with mean flows reduced by  $14\text{m}^3/\text{s}$  and  $28\text{m}^3/\text{s}$ . Mean monthly discharge for the reference and future periods can be seen in Appendix D.

The decrease of flow during summertime, together with the higher predicted temperature, will lead to increased stream temperatures (Luo et al. 2013; Jones et al. 2014; Muhlfield et al. 2014).

Overall mean discharge will increase as a result of decreasing low flows by 13-16%, whereas the mean yearly discharge of 2035 and 2075 is very similar. Future long-term mean flow will change to  $97\text{m}^3/\text{s}$  (RCP4.5) and  $93\text{m}^3/\text{s}$  (RCP8.5) by 2035, and to  $93\text{m}^3/\text{s}$  and  $94\text{m}^3/\text{s}$  by 2075, compared to  $83.4\text{m}^3/\text{s}$  in the reference period.

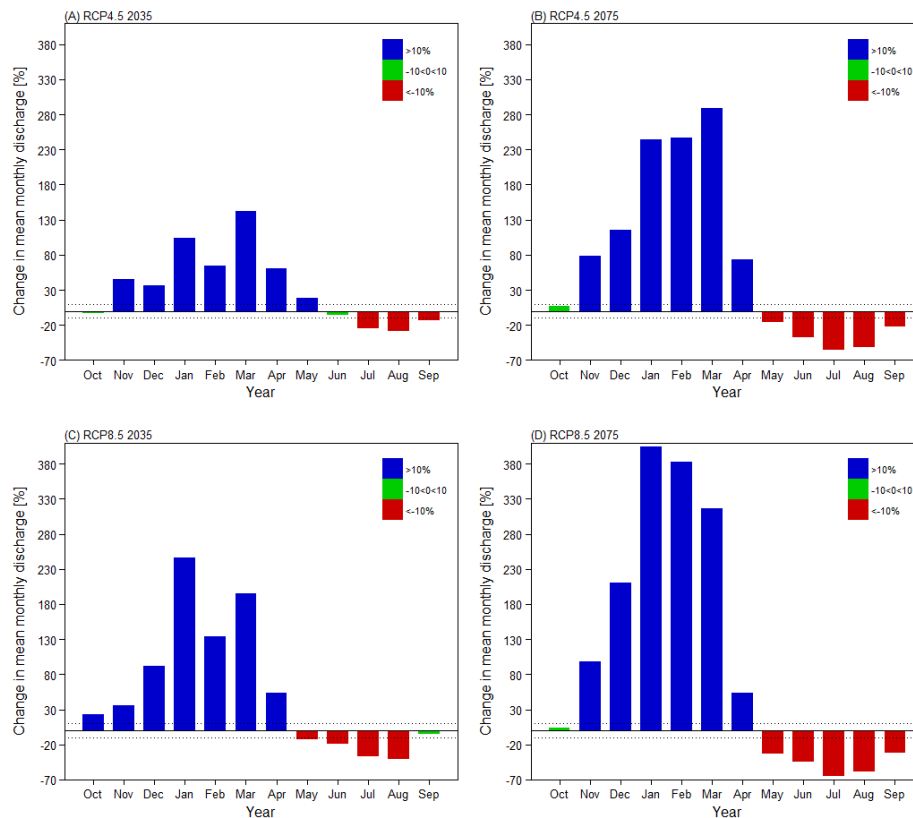


**Fig 60 | Change in mean monthly discharge**

In the reference period the two peak flow month, May and June, are responsible for 50% of total flow and including increasing and decreasing flow before and after high flow season, 73% of total discharge is generated in April-July. Whereas the low flow season from August to March is only generating 27% of total discharge. This strong distribution of only four month bearing three-fourths of the flow and the remaining eight month bearing one-fourth, will change to a two-thirds-one-third (RCP4.5) or 60-40 distribution by 2035 and to approx. 50-50 by 2075. By 2035, the low flow season (August-March) contributes between 32% (RCP4.5) and 40% (RCP8.5) to total flow and by 2075 this part increases to 46% (RCP4.5) and 55% (RCP8.5). This change of distribution, shows that in future higher flows are maintained throughout a broader range of month and that peak flow month are no longer the driving force in terms of total flow. The contribution of each month for all scenario is shown in Appendix D.

The flow in future is more evenly spread over all month, except the summer low flow month (July-October) with decreasing contributions to total flow. Total amount of discharge won't change in future, due to increasing amounts of annual precipitation. Instead an increase of 12-16% is predicted.

This projected change of mean flow behavior of the system is the cumulative effect of different processes: (1) the decreasing influence from snowmelt due to a smaller snowpack; (2) increased amount of winter precipitation falling as rain instead of snow; (3) overall increase of precipitation. All these processes lead to the transformation of a snow-dominated nival-regime, to a more complex rain and snow dominated pluvio-nival regime.

## 7 CONCLUSION AND OUTLOOK

This study shows, that under future climate conditions the hydrologic system of the transboundary North Fork Flathead River will undergo a pronounced change by 2075. The progressive climate warming leads to increasing days with winter daily temperature above freezing and therefore shifting the portion of precipitation falling as snow towards more rain. Days with suitable conditions for snowfall are declining and the slight increase in winter precipitation cannot compensate the loss of accumulated snow water equivalent. The start of the snow season will shift to later in the season and the end of snow season will be reached earlier. In the lower elevations of the catchment, the season with a closed snow cover is declining and the frequency of areas with snow free or fragmented snow cover is increasing. In the reference period, perennial snow in the high alpine regions of the catchment remained throughout the entire season, whereas in future the presence of perennial snow will decline or diminish.

The increasing portion of winter precipitation falling as rain and more days reaching snow melt conditions, lead to an increased contribution to direct flow in the low-flow winter season. Considerable higher discharge in the winter season is the result. Increasing amount of spring precipitation and earlier snow melt leads to a further rising of discharge. In future, peak flows are reached earlier with considerable lower magnitudes due to the shift of both timing and size of snowmelt runoff. Summer discharge is declining, even though real evapotranspiration in August is decreasing, due to increased soil moisture deficit. The reason for decreasing summer flow (July-September), is the lack of water stored in snow with the combination of decreasing or not changing amounts of precipitation.

With the overall increase of annual precipitation the total runoff will rise by 12-16%. Bürger et al. (2011) concluded that the climate change impact on the overall flow is dependent on the choice of climate model. Nevertheless, increasing flow was modeled for a similar climate model family.

In this study, we see the cumulative effects of different processes leading to a shift of a snow-dominated flow regime (nival-regime) to a more complex rain- and snow-dominated flow regime (pluvio-nival-regime).

For a more quantitative statement for the future, further climate models would be recommended to use in the model setup. Nevertheless, with the two scenarios RCP4.5 and RCP8.5 a range between a medium-low and extreme temperature increase was covered. Both of the scenarios predict a strong climate signal for the Crown of the Continent Ecosystem and therefore for the transboundary North Fork Flathead River, which evokes a strong response from the hydrologic system with the documented change in snowpack and shift to a more rain-dominated flow regime. The findings of this study are in general coherent with the literature

In a mountainous watershed with complex terrain, as the study area is, it has to be expected that precipitation in the catchment is underrepresented, due to the fact that only one of the fifteen climate stations is located within the borders of the watershed. Nevertheless, with these and other limitations in data availability, a good model performance was achieved. Further improvements in model performance would be able with additional information about evapotranspiration rates, snowpack, discharge of tributaries, and extent, depth and outflow of groundwater aquifers.

An integration of the study's finding, with other research ongoing in the watershed, like (Muhlfeld et al 2014; Jones et al. 2014), could lead to a better understanding of the impact of a changing hydrology induced by climate change on the ecosystem of a pristine and basically untouched environment. For the coupling of this model setup with stream temperature models on the subcatchment scale, additional discharge records for the tributaries would be necessary, to validate the models performance on the subcatchment scale.

Further continuative studies on the contribution of groundwater in the watershed would be meaningful, since groundwater aquifers seem to affect the streamflow, especially in the low-flow winter period. One can assume, that tributaries flowing into the North Fork Flathead River are likewise effected by groundwater. In this study, the influence of groundwater on the baseflow was encountered by including a single layer aquifer along the mainstem of the river in the model setup. Baseflow conditions were considerable improved, but the aquifers behavior under future conditions was not foreseeable.

Since the streamflow of the Rocky Mountains is controlled by the Pacific Decadal Oscillation (PDO), causing dryness during its positive phase, and wetness during its negative phase (St. Jacques et al. 2010), the influence of PDO in future should be incorporated into further studies.

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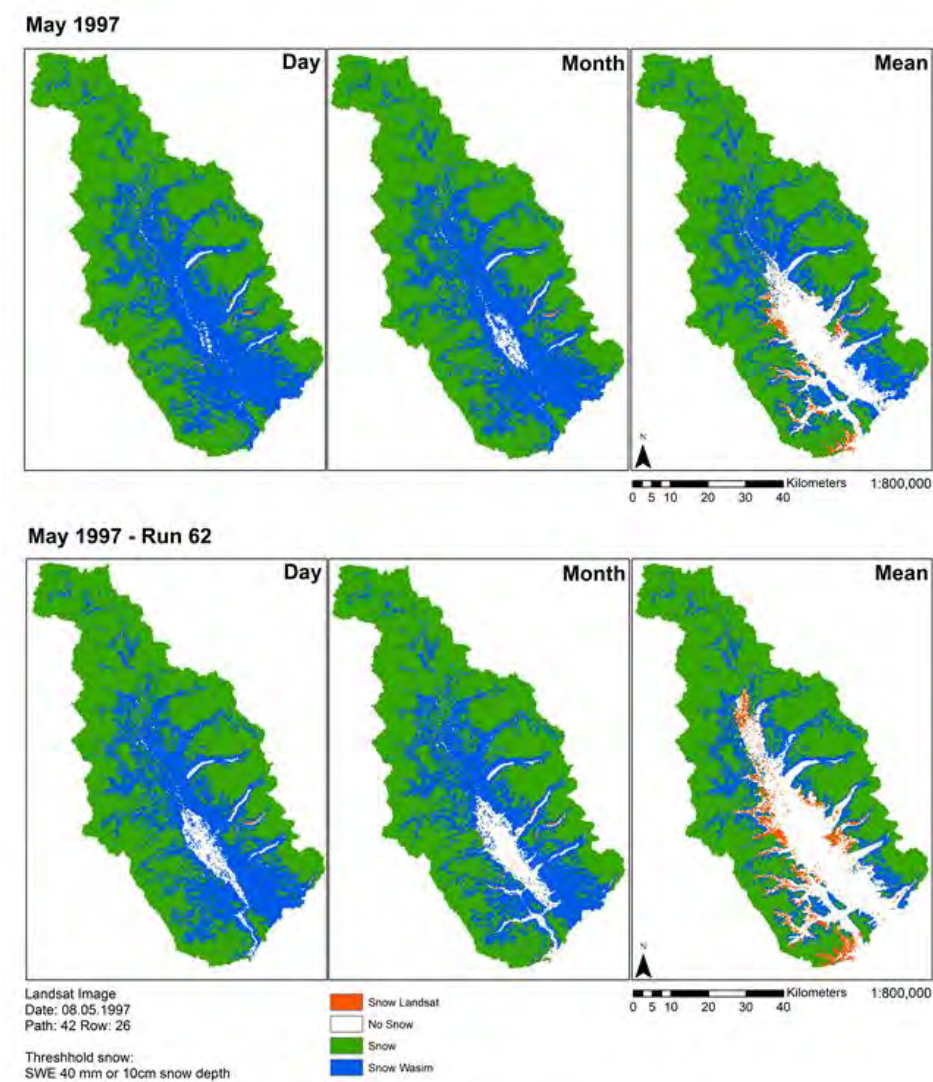
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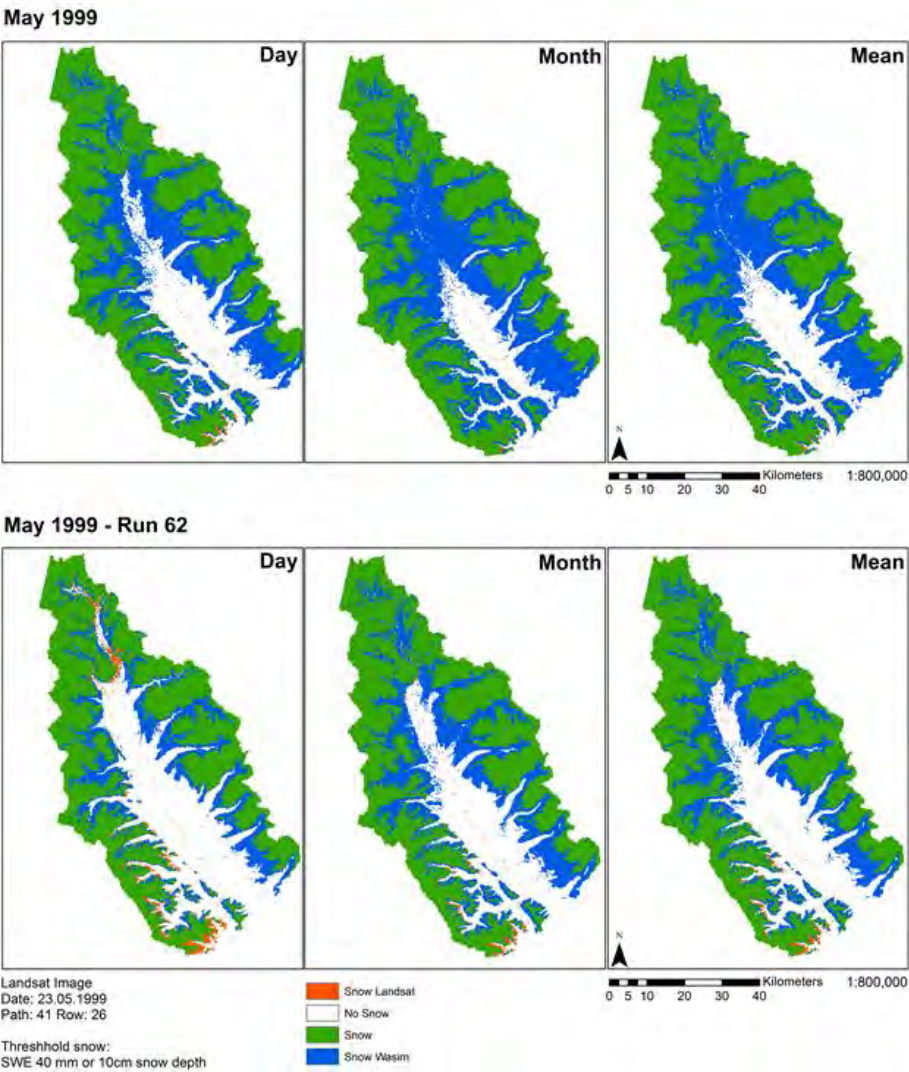
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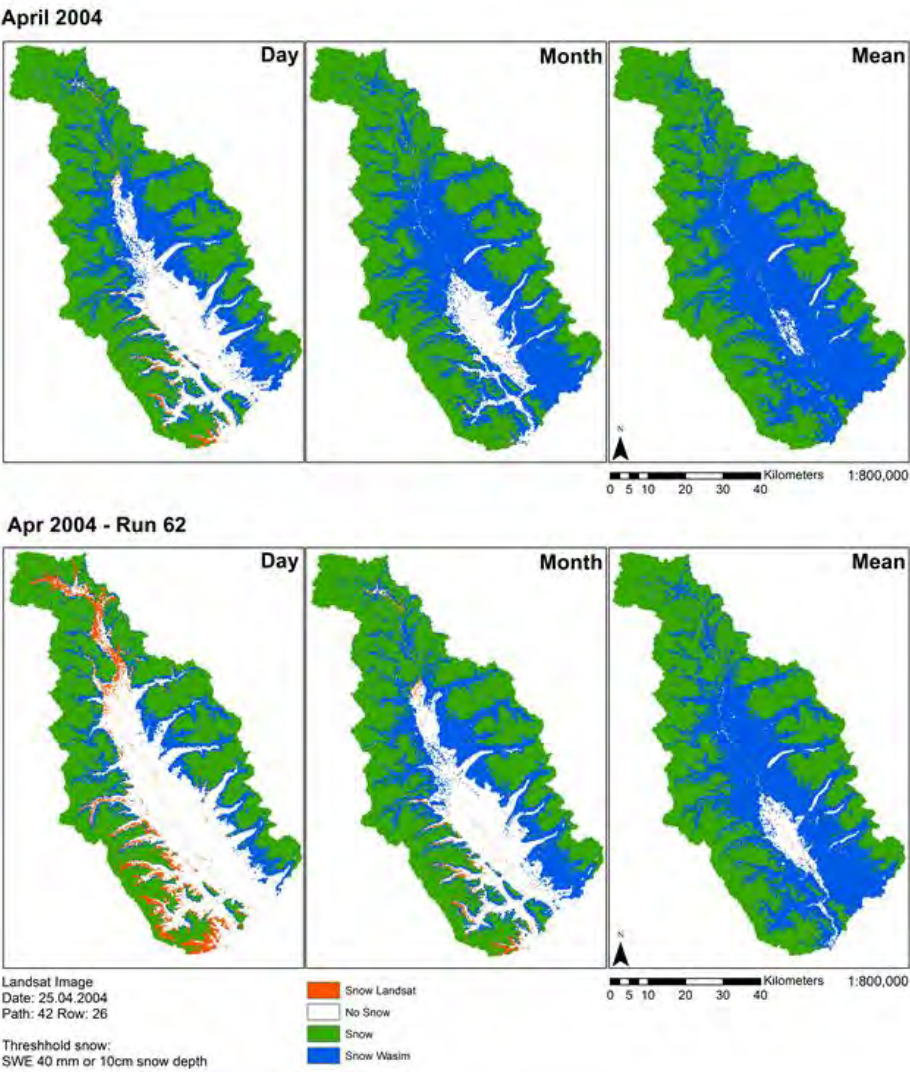
APPENDIX A



Appendix-A 1 | Modeled and observed snow cover in May 1997 (Run 60 vs Run 62)

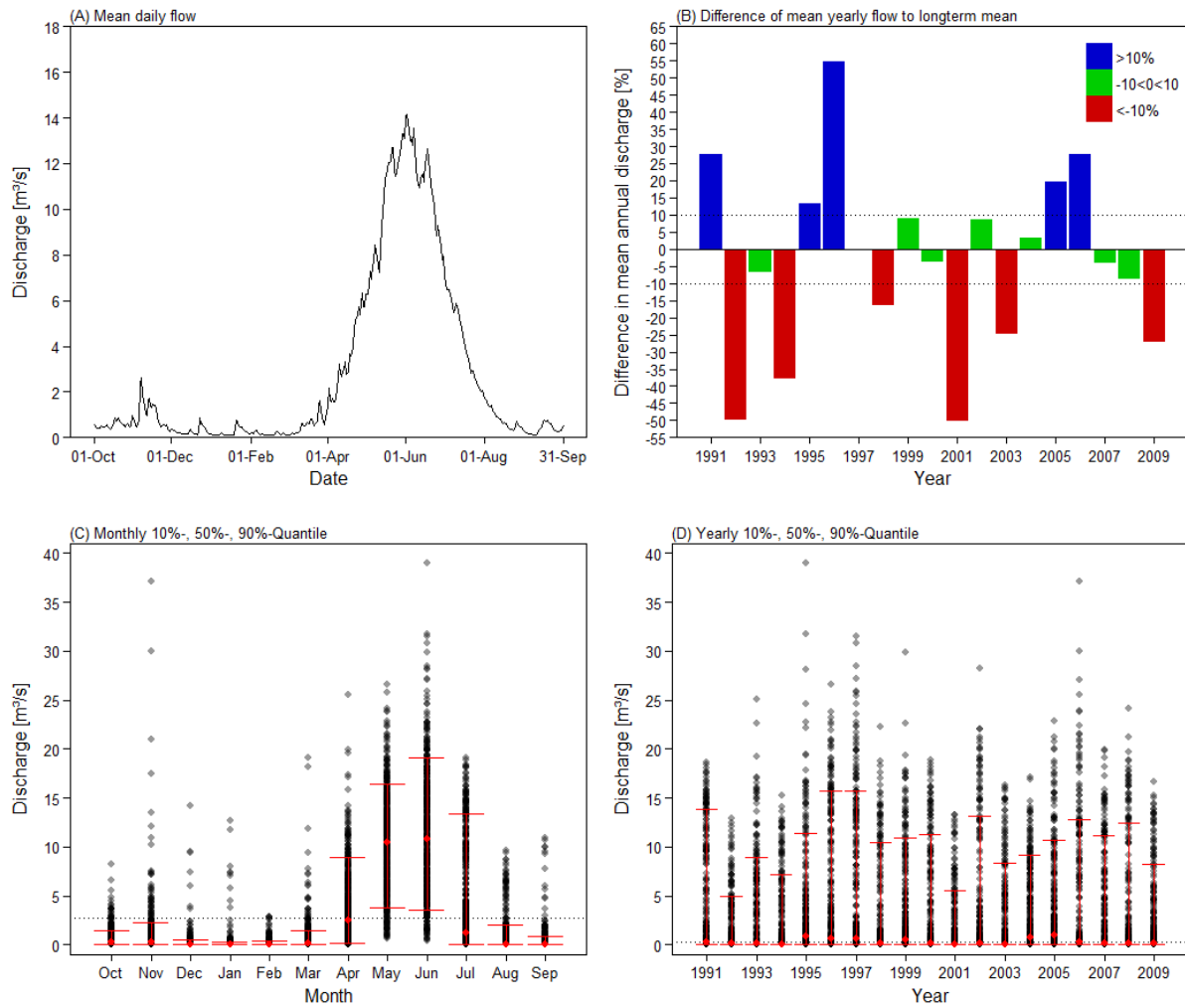


Appendix-A 2 | Modeled and observed snow cover in May 1999 (Run 60 vs Run 62)



Appendix-A 3 | Modeled and observed snow cover in April 2004 (Run 60 vs Run 62)

## APPENDIX B



**Appendix-B 1 | Differences in historic flow, Whale Creek. (A) Mean daily flow; (B) Difference of mean yearly flow to long-term mean flow (in percentage); (C) Monthly flow, red lines: 10%- and 90%-quantile, red dot: median, dotted line: long-term median flow**

## Appendix-B 2 | Differences of historic modeled flow 1991-2009 (January-March)

|      | January           |                   |                        |      |       |                   |   | February          |                   |           |      |      |       |   | March             |                   |           |      |       |       |   |
|------|-------------------|-------------------|------------------------|------|-------|-------------------|---|-------------------|-------------------|-----------|------|------|-------|---|-------------------|-------------------|-----------|------|-------|-------|---|
|      | Mobs <sup>1</sup> | Mean <sup>2</sup> | Quantiles <sup>3</sup> |      |       | Diff <sup>4</sup> |   | Mobs              | Mean              | Quantiles |      |      | Diff  |   | Mobs              | Mean              | Quantiles |      |       | Diff  |   |
|      | m <sup>2</sup> /s | m <sup>3</sup> /s | 0.1                    | 0.5  | 0.9   | %                 |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5  | 0.9  | %     |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5  | 0.9   | %     |   |
| 1991 | 23.6              | 19.3              | 18.5                   | 19.2 | 20.4  | -18.3             | ↓ | 22.1              | 27.3              | 19.7      | 23.4 | 43.8 | 23.5  | ↑ | 35.2              | 21.9              | 18.8      | 19.1 | 29.0  | -37.8 | ↓ |
| 1992 |                   | 18.5              | 17.1                   | 17.2 | 25.0  | -21.8             | ↓ |                   | 19.5              | 17.1      | 17.4 | 26.0 | -11.7 | ↓ |                   | 37.9              | 22.3      | 32.5 | 57.0  | 7.6   | — |
| 1993 |                   | 18.2              | 18.0                   | 18.1 | 18.3  | -23.2             | ↓ |                   | 17.8              | 17.7      | 17.8 | 17.9 | -19.5 | ↓ |                   | 24.1              | 17.6      | 17.7 | 45.8  | -31.4 | ↓ |
| 1994 |                   | 18.7              | 18.4                   | 18.7 | 19.0  | -21.0             | ↓ |                   | 18.2              | 18.1      | 18.2 | 18.3 | -17.7 | ↓ |                   | 29.0              | 18.8      | 21.8 | 51.9  | -17.7 | ↓ |
| 1995 |                   | 18.4              | 17.2                   | 17.3 | 18.8  | -22.2             | ↓ |                   | 38.1              | 17.3      | 23.3 | 89.2 | 72.2  | ↑ |                   | 36.5              | 18.1      | 26.9 | 67.7  | 3.6   | — |
| 1996 |                   | 24.1              | 22.8                   | 24.0 | 25.7  | 2.0               | — |                   | 28.6              | 22.4      | 23.5 | 45.9 | 29.4  | ↑ |                   | 28.4              | 22.1      | 23.2 | 45.0  | -19.3 | ↓ |
| 1997 |                   | 20.6              | 18.3                   | 18.4 | 24.4  | -13.0             | ↓ |                   | 18.6              | 18.0      | 18.2 | 20.0 | -16.0 | ↓ |                   | 38.9              | 17.8      | 18.0 | 87.9  | 10.7  | ↑ |
| 1998 |                   | 20.6              | 20.0                   | 20.5 | 21.1  | -13.0             | ↓ |                   | 19.8              | 19.4      | 19.8 | 20.3 | -10.4 | ↓ |                   | 28.0              | 19.1      | 22.3 | 54.8  | -20.3 | ↓ |
| 1999 |                   | 17.7              | 17.6                   | 17.7 | 17.8  | -25.2             | ↓ |                   | 17.7              | 17.5      | 17.5 | 18.2 | -20.1 | ↓ |                   | 27.1              | 17.5      | 19.6 | 49.6  | -23.0 | ↓ |
| 2000 |                   | 23.5              | 22.3                   | 23.4 | 24.8  | -0.6              | — |                   | 21.6              | 20.9      | 21.4 | 22.6 | -2.4  | — |                   | 30.7              | 20.4      | 23.4 | 50.5  | -12.8 | ↓ |
| 2001 |                   | 17.8              | 17.7                   | 17.7 | 17.9  | -24.7             | ↓ |                   | 17.6              | 17.5      | 17.6 | 17.6 | -20.5 | ↓ |                   | 25.2              | 17.4      | 20.0 | 41.6  | -28.5 | ↓ |
| 2002 |                   | 23.3              | 18.3                   | 18.6 | 36.9  | -1.3              | — |                   | 18.2              | 18.0      | 18.1 | 18.3 | -17.8 | ↓ |                   | 18.0              | 17.7      | 17.8 | 18.3  | -49.0 | ↓ |
| 2003 |                   | 21.4              | 19.4                   | 20.1 | 22.1  | -9.6              | — |                   | 20.3              | 18.7      | 19.1 | 22.7 | -8.2  | — |                   | 39.4              | 18.5      | 25.0 | 78.5  | 12.1  | ↑ |
| 2004 |                   | 18.6              | 18.0                   | 18.2 | 19.7  | -21.1             | ↓ |                   | 18.2              | 17.8      | 17.9 | 19.2 | -17.5 | ↓ |                   | 48.8              | 17.8      | 29.9 | 91.2  | 38.8  | ↑ |
| 2005 |                   | 74.5              | 21.6                   | 22.5 | 181.4 | 215.2             | ↑ |                   | 36.9              | 26.8      | 30.1 | 59.4 | 66.6  | ↑ |                   | 51.7              | 29.2      | 38.3 | 88.3  | 47.0  | ↑ |
| 2006 |                   | 34.0              | 26.8                   | 31.6 | 46.5  | 43.9              | ↑ |                   | 24.5              | 23.2      | 24.5 | 25.9 | 10.7  | ↑ |                   | 27.1              | 22.1      | 23.0 | 40.4  | -23.0 | ↓ |
| 2007 |                   | 21.8              | 21.0                   | 21.6 | 22.8  | -7.9              | — |                   | 20.4              | 20.0      | 20.4 | 20.7 | -8.0  | — |                   | 114.6             | 19.9      | 98.9 | 238.2 | 225.6 | ↑ |
| 2008 |                   | 18.7              | 18.4                   | 18.7 | 19.1  | -20.8             | ↓ |                   | 18.2              | 18.0      | 18.1 | 18.3 | -17.9 | ↓ |                   | 18.4              | 17.7      | 18.0 | 20.0  | -47.6 | ↓ |
| 2009 |                   | 19.5              | 19.1                   | 19.5 | 20.1  | -17.4             | ↓ |                   | 18.9              | 18.6      | 18.8 | 19.3 | -14.7 | ↓ |                   | 22.8              | 18.2      | 18.8 | 38.3  | -35.1 | ↓ |

<sup>1</sup>Long-term monthly mean; <sup>2</sup>Mean monthly flow; <sup>3</sup>Quantiles for each year and Month; <sup>4</sup>Difference mean flow to long-term mean flow, ↑ >10%, — ±10%, <-10%

### Appendix-B 3 | Differences of historic modeled flow 1991-2009 (April-June)

|      | April             |                   |                        |       |       |                   |   | May               |                   |           |       |       |       |   | June              |                   |           |       |       |       |   |
|------|-------------------|-------------------|------------------------|-------|-------|-------------------|---|-------------------|-------------------|-----------|-------|-------|-------|---|-------------------|-------------------|-----------|-------|-------|-------|---|
|      | Mobs <sup>1</sup> | Mean <sup>2</sup> | Quantiles <sup>3</sup> |       |       | Diff <sup>4</sup> |   | Mobs              | Mean              | Quantiles |       |       | Diff  |   | Mobs              | Mean              | Quantiles |       |       | Diff  |   |
|      | m <sup>2</sup> /s | m <sup>3</sup> /s | 0.1                    | 0.5   | 0.9   | %                 |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5   | 0.9   | %     |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5   | 0.9   | %     |   |
| 1991 | 111.2             | 77.5              | 36.4                   | 66.6  | 136.5 | -30.3             | ↓ | 242.6             | 238.3             | 76.2      | 259.8 | 360.2 | -1.8  | — | 259.1             | 318.7             | 232.8     | 328.4 | 381.5 | 23.0  | ↑ |
| 1992 |                   | 99.6              | 20.6                   | 90.2  | 200.8 | -10.5             | ↓ |                   | 170.5             | 114.0     | 162.9 | 256.9 | -29.7 | ↓ |                   | 114.3             | 71.1      | 114.8 | 152.6 | -55.9 | ↓ |
| 1993 |                   | 91.2              | 52.9                   | 98.1  | 124.9 | -18.0             | ↓ |                   | 261.6             | 144.7     | 258.5 | 361.2 | 7.8   | — |                   | 198.2             | 148.7     | 183.8 | 260.3 | -23.5 | ↓ |
| 1994 |                   | 101.6             | 36.1                   | 79.7  | 199.1 | -8.6              | — |                   | 223.1             | 112.2     | 241.4 | 301.8 | -8.0  | — |                   | 183.5             | 143.5     | 173.9 | 246.2 | -29.2 | ↓ |
| 1995 |                   | 55.7              | 33.3                   | 53.1  | 79.8  | -49.9             | ↓ |                   | 171.1             | 114.6     | 152.4 | 254.3 | -29.5 | ↓ |                   | 374.2             | 266.2     | 345.6 | 526.0 | 44.4  | ↑ |
| 1996 |                   | 107.7             | 25.5                   | 114.0 | 167.9 | -3.2              | — |                   | 263.9             | 76.4      | 321.5 | 420.5 | 8.8   | — |                   | 392.2             | 313.5     | 396.0 | 478.3 | 51.4  | ↑ |
| 1997 |                   | 125.7             | 20.3                   | 49.2  | 360.8 | 13.0              | ↑ |                   | 319.6             | 202.3     | 298.4 | 438.8 | 31.7  | ↑ |                   | 479.9             | 319.8     | 480.2 | 654.6 | 85.2  | ↑ |
| 1998 |                   | 93.3              | 32.8                   | 59.5  | 223.6 | -16.1             | ↓ |                   | 271.9             | 200.2     | 270.7 | 378.8 | 12.1  | ↑ |                   | 214.1             | 139.5     | 192.9 | 324.2 | -17.4 | ↓ |
| 1999 |                   | 65.3              | 18.1                   | 34.7  | 144.7 | -41.2             | ↓ |                   | 174.0             | 52.6      | 173.7 | 323.0 | -28.3 | ↓ |                   | 294.6             | 194.8     | 289.7 | 369.1 | 13.7  | ↑ |
| 2000 |                   | 119.9             | 45.4                   | 97.1  | 224.7 | 7.8               | — |                   | 269.8             | 184.4     | 273.1 | 362.2 | 11.2  | ↑ |                   | 276.9             | 204.5     | 284.3 | 346.3 | 6.9   | — |
| 2001 |                   | 69.2              | 18.2                   | 33.1  | 209.2 | -37.8             | ↓ |                   | 188.5             | 111.4     | 174.5 | 275.1 | -22.3 | ↓ |                   | 141.9             | 87.0      | 149.4 | 189.8 | -45.2 | ↓ |
| 2002 |                   | 58.2              | 18.6                   | 42.1  | 116.4 | -47.6             | ↓ |                   | 182.6             | 45.5      | 140.5 | 379.7 | -24.7 | ↓ |                   | 381.1             | 313.8     | 379.7 | 442.2 | 47.1  | ↑ |
| 2003 |                   | 132.9             | 29.4                   | 124.6 | 263.3 | 19.5              | ↑ |                   | 205.2             | 131.7     | 189.7 | 320.5 | -15.4 | ↓ |                   | 215.9             | 142.2     | 212.8 | 306.9 | -16.7 | ↓ |
| 2004 |                   | 183.9             | 118.9                  | 172.8 | 285.1 | 65.4              | ↑ |                   | 217.2             | 139.3     | 225.5 | 291.6 | -10.5 | ↓ |                   | 184.6             | 132.1     | 172.6 | 264.0 | -28.8 | ↓ |
| 2005 |                   | 119.4             | 42.7                   | 103.2 | 221.2 | 7.4               | — |                   | 233.4             | 151.0     | 217.2 | 333.2 | -3.8  | — |                   | 290.3             | 157.9     | 285.8 | 428.5 | 12.0  | ↑ |
| 2006 |                   | 303.0             | 192.1                  | 277.9 | 459.1 | 172.5             | ↑ |                   | 344.2             | 255.3     | 330.6 | 459.6 | 41.9  | ↑ |                   | 241.7             | 102.2     | 245.2 | 378.5 | -6.7  | — |
| 2007 |                   | 166.5             | 61.8                   | 154.1 | 265.2 | 49.7              | ↑ |                   | 299.6             | 231.6     | 309.7 | 347.2 | 23.5  | ↑ |                   | 167.7             | 82.0      | 151.5 | 269.0 | -35.3 | ↓ |
| 2008 |                   | 37.8              | 17.7                   | 22.8  | 80.5  | -66.0             | ↓ |                   | 314.1             | 120.3     | 336.3 | 478.4 | 29.5  | ↑ |                   | 298.6             | 204.8     | 300.4 | 378.2 | 15.2  | ↑ |
| 2009 |                   | 104.5             | 18.5                   | 83.8  | 198.3 | -6.0              | — |                   | 260.7             | 146.1     | 278.8 | 329.5 | 7.5   | — |                   | 154.5             | 98.5      | 146.1 | 221.4 | -40.4 | ↓ |

<sup>1</sup>Long-term monthly mean; <sup>2</sup>Mean monthly flow; <sup>3</sup>Quantiles for each year and Month; <sup>4</sup>Difference mean flow to long-term mean flow, ↑ >10%, — ±10%, <-10%

#### Appendix-B 4 | Differences of historic modeled flow 1991-2009 (July-September)

|      | July              |                   |                        |       |       |                   |   | August            |                   |           |       |       |       |   | September         |                   |           |      |       |       |   |
|------|-------------------|-------------------|------------------------|-------|-------|-------------------|---|-------------------|-------------------|-----------|-------|-------|-------|---|-------------------|-------------------|-----------|------|-------|-------|---|
|      | Mobs <sup>1</sup> | Mean <sup>2</sup> | Quantiles <sup>3</sup> |       |       | Diff <sup>4</sup> |   | Mobs              | Mean              | Quantiles |       |       | Diff  |   | Mobs              | Mean              | Quantiles |      |       | Diff  |   |
|      | m <sup>2</sup> /s | m <sup>3</sup> /s | 0.1                    | 0.5   | 0.9   | %                 |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5   | 0.9   | %     |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5  | 0.9   | %     |   |
| 1991 | 121.0             | 254.8             | 187.9                  | 269.4 | 337.0 | 110.6             | ↑ | 47.0              | 108.9             | 50.7      | 93.2  | 172.5 | 131.6 | ↑ | 31.8              | 26.7              | 20.4      | 25.2 | 34.7  | -16.0 | ↓ |
| 1992 |                   | 50.5              | 27.2                   | 42.3  | 82.5  | -58.2             | ↓ |                   | 20.5              | 18.6      | 20.1  | 23.6  | -56.3 | ↓ |                   | 32.6              | 18.7      | 26.6 | 62.9  | 2.6   | — |
| 1993 |                   | 179.7             | 118.6                  | 166.0 | 257.6 | 48.6              | ↑ |                   | 44.7              | 28.2      | 45.3  | 63.7  | -5.0  | — |                   | 33.2              | 26.0      | 33.0 | 39.4  | 4.5   | — |
| 1994 |                   | 55.5              | 32.7                   | 51.2  | 79.0  | -54.1             | — |                   | 20.4              | 17.3      | 20.1  | 25.0  | -56.6 | ↓ |                   | 17.4              | 16.9      | 17.5 | 17.9  | -45.1 | ↓ |
| 1995 |                   | 183.9             | 97.9                   | 167.0 | 275.9 | 52.0              | ↑ |                   | 65.2              | 39.0      | 68.1  | 90.3  | 38.8  | ↑ |                   | 27.5              | 19.7      | 26.6 | 37.5  | -13.6 | ↓ |
| 1996 |                   | 276.9             | 200.9                  | 280.9 | 366.9 | 128.9             | ↑ |                   | 129.2             | 78.5      | 131.1 | 182.3 | 174.9 | ↑ |                   | 46.5              | 31.1      | 44.2 | 65.7  | 46.2  | ↑ |
| 1997 |                   | 290.0             | 220.4                  | 286.0 | 357.9 | 139.7             | ↑ |                   | 118.5             | 65.6      | 99.6  | 208.5 | 152.1 | ↑ |                   | 62.0              | 48.7      | 60.1 | 77.4  | 95.0  | ↑ |
| 1998 |                   | 73.5              | 44.3                   | 58.3  | 128.0 | -39.3             | ↓ |                   | 37.2              | 25.8      | 31.1  | 62.0  | -20.9 | ↓ |                   | 24.2              | 20.7      | 23.5 | 28.9  | -24.0 | ↓ |
| 1999 |                   | 177.8             | 119.7                  | 162.7 | 229.5 | 47.0              | ↑ |                   | 65.2              | 39.9      | 68.3  | 92.2  | 38.6  | ↑ |                   | 22.9              | 20.2      | 23.0 | 24.6  | -27.9 | ↓ |
| 2000 |                   | 96.1              | 44.8                   | 88.2  | 139.9 | -20.6             | ↓ |                   | 24.6              | 20.1      | 22.2  | 33.1  | -47.7 | ↓ |                   | 28.2              | 20.8      | 25.4 | 34.4  | -11.4 | ↓ |
| 2001 |                   | 34.2              | 21.6                   | 26.2  | 62.8  | -71.7             | ↓ |                   | 20.4              | 19.4      | 20.1  | 21.4  | -56.7 | ↓ |                   | 18.4              | 17.5      | 18.4 | 19.4  | -42.2 | ↓ |
| 2002 |                   | 228.8             | 112.4                  | 249.7 | 336.0 | 89.2              | ↑ |                   | 50.7              | 41.9      | 49.8  | 61.9  | 7.8   | — |                   | 30.6              | 20.2      | 31.2 | 42.9  | -3.8  | — |
| 2003 |                   | 56.5              | 26.6                   | 52.1  | 96.6  | -53.3             | ↓ |                   | 20.7              | 18.8      | 20.1  | 23.5  | -55.9 | ↓ |                   | 18.7              | 17.6      | 18.3 | 19.7  | -41.2 | ↓ |
| 2004 |                   | 73.7              | 30.7                   | 68.2  | 132.9 | -39.1             | ↓ |                   | 56.2              | 22.4      | 27.4  | 146.1 | 19.5  | ↑ |                   | 87.8              | 37.0      | 64.5 | 175.7 | 176.2 | ↑ |
| 2005 |                   | 65.7              | 29.6                   | 59.5  | 108.3 | -45.7             | ↓ |                   | 21.2              | 18.9      | 20.9  | 23.1  | -55.0 | ↓ |                   | 40.5              | 18.0      | 30.6 | 63.5  | 27.6  | ↑ |
| 2006 |                   | 32.2              | 20.0                   | 26.4  | 54.4  | -73.4             | ↓ |                   | 18.5              | 18.1      | 18.4  | 19.0  | -60.7 | ↓ |                   | 18.6              | 17.8      | 18.3 | 20.1  | -41.6 | ↓ |
| 2007 |                   | 36.9              | 20.5                   | 31.6  | 63.1  | -69.5             | ↓ |                   | 17.7              | 17.3      | 17.5  | 18.3  | -62.3 | ↓ |                   | 18.0              | 17.0      | 17.9 | 19.5  | -43.4 | ↓ |
| 2008 |                   | 81.7              | 36.1                   | 63.2  | 174.7 | -32.5             | ↓ |                   | 23.9              | 20.5      | 22.8  | 28.2  | -49.1 | ↓ |                   | 25.3              | 18.5      | 19.2 | 44.0  | -20.4 | ↓ |
| 2009 |                   | 50.2              | 29.1                   | 44.8  | 76.8  | -58.5             | ↓ |                   | 29.6              | 19.7      | 26.1  | 50.4  | -37.1 | ↓ |                   | 24.9              | 17.9      | 19.1 | 43.8  | -21.5 | ↓ |

<sup>1</sup>Long-term monthly mean; <sup>2</sup>Mean monthly flow; <sup>3</sup>Quantiles for each year and Month; <sup>4</sup>Difference mean flow to long-term mean flow, ↑ >10%, — ±10%, <-10%

# Appendix-B 5 | Differences of historic modeled flow 1991-2009 (October-December)

|      | October           |                   |                        |      |       |                   |   | November          |                   |           |      |       |       |   | December          |                   |           |      |       |       |   |
|------|-------------------|-------------------|------------------------|------|-------|-------------------|---|-------------------|-------------------|-----------|------|-------|-------|---|-------------------|-------------------|-----------|------|-------|-------|---|
|      | Mobs <sup>1</sup> | Mean <sup>2</sup> | Quantiles <sup>3</sup> |      |       | Diff <sup>4</sup> |   | Mobs              | Mean              | Quantiles |      |       | Diff  |   | Mobs              | Mean              | Quantiles |      |       | Diff  |   |
|      | m <sup>2</sup> /s | m <sup>3</sup> /s | 0.1                    | 0.5  | 0.9   | %                 |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5  | 0.9   | %     |   | m <sup>3</sup> /s | m <sup>3</sup> /s | 0.1       | 0.5  | 0.9   | %     |   |
| 1991 | 36.2              | 19.3              | 17.3                   | 19.3 | 21.9  | -46.7             | ↓ | 43.1              | 26.2              | 17.2      | 18.6 | 42.2  | -39.1 | ↓ | 25.1              | 18.8              | 17.2      | 17.2 | 22.8  | -24.9 | ↓ |
| 1992 |                   | 33.0              | 23.2                   | 29.8 | 46.8  | -8.7              | — |                   | 21.5              | 19.4      | 20.9 | 25.0  | -50.2 | ↓ |                   | 18.7              | 18.4      | 18.7 | 19.0  | -25.4 | ↓ |
| 1993 |                   | 26.7              | 23.2                   | 26.5 | 30.1  | -26.2             | ↓ |                   | 20.6              | 19.8      | 20.3 | 21.9  | -52.2 | ↓ |                   | 19.3              | 18.9      | 19.2 | 19.8  | -22.8 | ↓ |
| 1994 |                   | 22.5              | 17.1                   | 17.7 | 33.1  | -37.8             | ↓ |                   | 17.6              | 17.4      | 17.5 | 17.9  | -59.1 | ↓ |                   | 17.7              | 17.3      | 17.4 | 18.8  | -29.3 | ↓ |
| 1995 |                   | 57.7              | 26.6                   | 47.2 | 104.3 | 59.3              | ↑ |                   | 69.2              | 29.1      | 50.8 | 148.0 | 60.6  | ↑ |                   | 34.4              | 26.9      | 30.6 | 45.5  | 37.3  | ↑ |
| 1996 |                   | 34.8              | 23.1                   | 31.1 | 51.2  | -3.8              | — |                   | 20.5              | 19.6      | 20.3 | 21.5  | -52.4 | ↓ |                   | 19.0              | 18.7      | 19.0 | 19.3  | -24.1 | ↓ |
| 1997 |                   | 53.1              | 32.5                   | 45.6 | 86.2  | 46.8              | ↑ |                   | 30.4              | 24.7      | 28.0 | 39.1  | -29.5 | ↓ |                   | 22.8              | 21.7      | 22.7 | 24.0  | -9.2  | — |
| 1998 |                   | 21.1              | 18.6                   | 20.8 | 24.0  | -41.7             | ↓ |                   | 26.3              | 18.0      | 20.8 | 37.9  | -38.9 | ↓ |                   | 19.4              | 17.8      | 18.1 | 21.5  | -22.7 | ↓ |
| 1999 |                   | 40.5              | 20.0                   | 36.5 | 62.6  | 12.0              | ↑ |                   | 112.4             | 41.7      | 75.4 | 260.9 | 160.8 | ↑ |                   | 31.5              | 26.0      | 29.8 | 40.2  | 25.8  | ↑ |
| 2000 |                   | 28.6              | 21.1                   | 25.3 | 38.4  | -20.9             | ↓ |                   | 18.8              | 18.3      | 18.7 | 19.6  | -56.4 | ↓ |                   | 18.1              | 17.9      | 18.1 | 18.3  | -27.8 | ↓ |
| 2001 |                   | 27.5              | 17.2                   | 18.8 | 61.0  | -24.1             | ↓ |                   | 40.4              | 21.8      | 34.5 | 69.9  | -6.3  | — |                   | 19.4              | 18.7      | 19.3 | 20.4  | -22.6 | ↓ |
| 2002 |                   | 23.9              | 18.9                   | 22.4 | 29.0  | -34.1             | ↓ |                   | 38.2              | 18.5      | 31.5 | 66.4  | -11.4 | ↓ |                   | 31.1              | 20.4      | 21.6 | 65.3  | 24.0  | ↑ |
| 2003 |                   | 33.2              | 17.3                   | 24.6 | 63.5  | -8.2              | — |                   | 27.6              | 19.4      | 21.6 | 42.9  | -36.0 | ↓ |                   | 18.6              | 18.3      | 18.6 | 19.0  | -25.7 | ↓ |
| 2004 |                   | 40.3              | 30.3                   | 36.9 | 54.8  | 11.3              | ↑ |                   | 39.2              | 27.4      | 31.8 | 66.2  | -9.1  | — |                   | 27.5              | 23.1      | 25.3 | 35.2  | 9.9   | — |
| 2005 |                   | 90.7              | 53.0                   | 80.0 | 147.8 | 150.7             | ↑ |                   | 45.0              | 30.0      | 35.5 | 67.7  | 4.4   | — |                   | 65.4              | 24.9      | 27.0 | 197.4 | 160.9 | ↑ |
| 2006 |                   | 20.4              | 17.2                   | 18.3 | 27.0  | -43.6             | ↓ |                   | 134.1             | 25.3      | 51.2 | 412.7 | 211.0 | ↑ |                   | 25.2              | 23.2      | 24.9 | 27.8  | 0.6   | — |
| 2007 |                   | 42.5              | 28.9                   | 40.9 | 61.1  | 17.5              | ↑ |                   | 32.9              | 22.0      | 25.3 | 58.5  | -23.7 | ↓ |                   | 22.9              | 19.3      | 20.3 | 28.6  | -8.7  | — |
| 2008 |                   | 28.8              | 23.0                   | 26.2 | 38.1  | -20.5             | ↓ |                   | 44.9              | 24.0      | 35.0 | 77.1  | 4.3   | — |                   | 24.3              | 20.5      | 21.9 | 31.2  | -3.2  | — |
| 2009 |                   | 43.0              | 19.0                   | 32.5 | 77.2  | 18.8              | ↑ |                   | 53.1              | 27.7      | 39.6 | 107.3 | 23.2  | ↑ |                   | 22.1              | 20.3      | 21.7 | 24.4  | -12.0 | ↓ |

<sup>1</sup>Long-term monthly mean; <sup>2</sup>Mean monthly flow; <sup>3</sup>Quantiles for each year and Month; <sup>4</sup>Difference mean flow to long-term mean flow, ↑ >10%, — ±10%, <-10%

## APPENDIX C

## Appendix-C 1 | Monthly temperature deltas [°C] for the 15 climate stations (RCP4.5)

|                  | Month   | Baynes Lake, BC | Beaver Mines, AB | Connelly Creek, AB | Emery Creek, MT | Eureka, MT | Fernie, BC | Flattop Mt., MT | Fortune, MT | Grave Creek, MT | Many Glacier, MT | Olney, MT | Polebridge, MT | Stahl Peak, MT | West Glacier, MT | Whitefish, Mt |
|------------------|---------|-----------------|------------------|--------------------|-----------------|------------|------------|-----------------|-------------|-----------------|------------------|-----------|----------------|----------------|------------------|---------------|
|                  |         |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
| 2035 (2026-2045) | RCP 4.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 2.7             | 1.2              | 1.2                | 2.7             | 2.6        | 2.3        | 1.9             | 2.4         | 2.2             | 1.6              | 2.8       | 2.3            | 2.3            | 2.6              | 3.0           |
|                  | 2       | 1.3             | 1.6              | 1.6                | 1.2             | 1.3        | 1.2        | 1.2             | 1.2         | 1.1             | 1.3              | 1.2       | 1.2            | 1.2            | 1.2              | 1.2           |
|                  | 3       | 2.2             | 2.2              | 2.1                | 2.2             | 2.2        | 2.1        | 2.2             | 2.2         | 2.1             | 2.3              | 2.1       | 2.1            | 2.2            | 2.2              | 2.2           |
|                  | 4       | 1.7             | 1.4              | 1.4                | 1.6             | 1.8        | 1.6        | 1.5             | 1.7         | 1.6             | 1.4              | 1.7       | 1.6            | 1.7            | 1.6              | 1.9           |
|                  | 5       | 1.3             | 1.0              | 1.1                | 1.2             | 1.2        | 1.3        | 1.3             | 1.2         | 1.2             | 1.1              | 1.1       | 1.2            | 1.2            | 1.3              | 1.2           |
|                  | 6       | 1.6             | 1.6              | 1.6                | 2.1             | 1.8        | 1.8        | 1.9             | 1.9         | 1.8             | 1.9              | 1.9       | 1.9            | 1.8            | 2.0              | 1.8           |
|                  | 7       | 2.2             | 2.2              | 2.2                | 2.3             | 2.1        | 2.3        | 2.3             | 2.3         | 2.3             | 2.3              | 2.3       | 2.3            | 2.3            | 2.3              | 2.2           |
|                  | 8       | 2.5             | 2.4              | 2.3                | 2.6             | 2.6        | 2.5        | 2.6             | 2.7         | 2.7             | 2.7              | 2.6       | 2.7            | 2.7            | 2.6              | 2.5           |
|                  | 9       | 2.8             | 2.8              | 2.7                | 3.2             | 2.9        | 2.8        | 3.1             | 3.0         | 3.1             | 3.1              | 3.1       | 3.1            | 3.0            | 3.2              | 3.1           |
|                  | 10      | 1.0             | 1.2              | 1.2                | 1.2             | 1.1        | 1.2        | 1.2             | 1.2         | 1.2             | 1.2              | 1.2       | 1.2            | 1.2            | 1.2              | 1.1           |
|                  | 11      | 1.9             | 1.8              | 1.8                | 1.8             | 1.8        | 1.7        | 1.6             | 1.7         | 1.7             | 1.5              | 1.8       | 1.7            | 1.7            | 1.8              | 1.9           |
|                  | 12      | 1.5             | 0.6              | 0.7                | 1.1             | 1.3        | 1.2        | 0.8             | 1.2         | 0.9             | 0.7              | 1.5       | 0.8            | 1.1            | 1.1              | 1.5           |
| 2075 (2066-2085) | RCP 4.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 4.6             | 3.3              | 3.2                | 4.5             | 4.6        | 4.2        | 3.7             | 4.3         | 4.0             | 3.3              | 4.5       | 4.0            | 4.2            | 4.4              | 4.7           |
|                  | 2       | 3.9             | 3.2              | 3.2                | 3.5             | 3.9        | 3.6        | 3.2             | 3.6         | 3.5             | 3.0              | 3.6       | 3.4            | 3.6            | 3.5              | 3.7           |
|                  | 3       | 4.0             | 3.7              | 3.7                | 3.8             | 4.0        | 3.8        | 3.7             | 3.9         | 3.8             | 3.8              | 3.8       | 3.6            | 3.9            | 3.8              | 4.1           |
|                  | 4       | 2.9             | 2.2              | 2.1                | 2.7             | 2.9        | 2.6        | 2.3             | 2.8         | 2.4             | 2.1              | 2.9       | 2.6            | 2.6            | 2.7              | 3.2           |
|                  | 5       | 2.5             | 2.1              | 2.1                | 2.7             | 2.4        | 2.7        | 2.6             | 2.5         | 2.7             | 2.2              | 2.3       | 2.5            | 2.6            | 2.7              | 2.3           |
|                  | 6       | 3.1             | 3.1              | 3.1                | 3.4             | 3.1        | 3.3        | 3.2             | 3.2         | 3.2             | 3.2              | 3.2       | 3.2            | 3.2            | 3.3              | 3.1           |
|                  | 7       | 4.2             | 4.2              | 4.2                | 4.2             | 4.0        | 4.3        | 4.3             | 4.2         | 4.3             | 4.3              | 4.1       | 4.2            | 4.2            | 4.2              | 4.0           |
|                  | 8       | 4.4             | 4.4              | 4.3                | 4.6             | 4.4        | 4.4        | 4.5             | 4.4         | 4.5             | 4.6              | 4.3       | 4.4            | 4.4            | 4.6              | 4.3           |
|                  | 9       | 3.4             | 3.4              | 3.3                | 3.6             | 3.5        | 3.4        | 3.6             | 3.5         | 3.5             | 3.7              | 3.6       | 3.6            | 3.5            | 3.6              | 3.6           |
|                  | 10      | 2.4             | 2.5              | 2.4                | 2.6             | 2.4        | 2.5        | 2.6             | 2.5         | 2.5             | 2.5              | 2.4       | 2.5            | 2.5            | 2.6              | 2.4           |
|                  | 11      | 2.7             | 2.2              | 2.1                | 2.5             | 2.7        | 2.4        | 2.1             | 2.4         | 2.3             | 2.0              | 2.5       | 2.4            | 2.4            | 2.5              | 2.7           |
|                  | 12      | 3.3             | 2.7              | 2.7                | 2.9             | 3.3        | 3.1        | 2.8             | 3.1         | 2.9             | 2.9              | 3.2       | 2.9            | 3.0            | 2.9              | 3.2           |

## Appendix-C 2 | Monthly temperature deltas [°C] for the 15 climate stations (RCP8.5)

|                  | Month   | Baynes Lake, BC | Beaver Mines, AB | Comelly Creek, AB | Emery Creek, MT | Eureka, MT | Fernie, BC | Flattop Mt., MT | Fortine, MT | Grave Creek, MT | Many Glacier, MT | Olney, MT | Polebridge, MT | Stahl Peak, MT | West Glacier, MT | Whitefish, Mt |
|------------------|---------|-----------------|------------------|-------------------|-----------------|------------|------------|-----------------|-------------|-----------------|------------------|-----------|----------------|----------------|------------------|---------------|
|                  |         |                 |                  |                   |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
| 2035 (2026-2045) | RCP 8.5 |                 |                  |                   |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 4.3             | 3.4              | 3.4               | 4.2             | 4.1        | 4.0        | 3.7             | 4.0         | 3.9             | 3.4              | 4.2       | 4.0            | 4.0            | 4.2              | 4.4           |
|                  | 2       | 1.9             | 1.9              | 1.9               | 1.8             | 2.0        | 1.8        | 1.7             | 1.9         | 1.8             | 1.7              | 1.9       | 1.8            | 1.9            | 1.8              | 2.0           |
|                  | 3       | 2.9             | 2.7              | 2.7               | 2.7             | 2.8        | 2.7        | 2.6             | 2.6         | 2.5             | 2.5              | 2.6       | 2.6            | 2.6            | 2.7              | 2.9           |
|                  | 4       | 1.6             | 0.9              | 0.9               | 1.5             | 1.7        | 1.5        | 1.2             | 1.6         | 1.4             | 1.0              | 1.6       | 1.4            | 1.6            | 1.5              | 1.8           |
|                  | 5       | 1.0             | 0.7              | 0.7               | 1.0             | 1.0        | 1.0        | 0.9             | 1.0         | 1.0             | 0.7              | 1.0       | 1.0            | 1.0            | 1.0              | 1.0           |
|                  | 6       | 1.6             | 1.7              | 1.7               | 2.0             | 1.8        | 1.8        | 1.9             | 1.8         | 1.9             | 1.8              | 1.8       | 1.8            | 1.8            | 2.0              | 1.8           |
|                  | 7       | 2.7             | 2.6              | 2.5               | 2.7             | 2.6        | 2.7        | 2.7             | 2.7         | 2.7             | 2.7              | 2.7       | 2.7            | 2.7            | 2.7              | 2.6           |
|                  | 8       | 3.2             | 3.0              | 3.0               | 3.4             | 3.3        | 3.2        | 3.2             | 3.3         | 3.3             | 3.3              | 3.2       | 3.3            | 3.3            | 3.4              | 3.2           |
|                  | 9       | 1.9             | 1.9              | 1.9               | 1.9             | 1.9        | 1.9        | 2.0             | 1.9         | 2.0             | 2.0              | 1.9       | 1.9            | 1.9            | 1.9              | 1.9           |
|                  | 10      | 1.8             | 1.8              | 1.8               | 1.9             | 1.9        | 1.9        | 1.9             | 1.9         | 2.0             | 1.9              | 1.8       | 1.9            | 1.9            | 1.9              | 1.8           |
|                  | 11      | 1.4             | 1.5              | 1.5               | 1.4             | 1.4        | 1.3        | 1.3             | 1.3         | 1.3             | 1.3              | 1.2       | 1.3            | 1.3            | 1.4              | 1.3           |
|                  | 12      | 2.9             | 2.6              | 2.7               | 2.5             | 2.8        | 2.9        | 2.6             | 2.7         | 2.6             | 2.6              | 2.8       | 2.7            | 2.7            | 2.6              | 2.8           |
| 2075 (2066-2085) | RCP 8.5 |                 |                  |                   |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 6.1             | 4.7              | 4.6               | 6.0             | 6.0        | 5.6        | 5.2             | 5.7         | 5.4             | 4.9              | 6.1       | 5.5            | 5.7            | 5.9              | 6.4           |
|                  | 2       | 5.5             | 4.5              | 4.6               | 5.2             | 5.4        | 5.0        | 4.6             | 5.0         | 4.9             | 4.3              | 5.2       | 4.8            | 5.1            | 5.2              | 5.5           |
|                  | 3       | 5.4             | 4.7              | 4.7               | 5.0             | 5.3        | 4.8        | 4.6             | 5.0         | 4.7             | 4.5              | 5.2       | 4.8            | 4.9            | 5.0              | 5.5           |
|                  | 4       | 3.9             | 3.3              | 3.3               | 3.7             | 3.9        | 3.6        | 3.4             | 3.8         | 3.5             | 3.1              | 3.8       | 3.7            | 3.7            | 3.7              | 4.1           |
|                  | 5       | 3.2             | 3.0              | 3.0               | 3.6             | 3.2        | 3.5        | 3.5             | 3.3         | 3.5             | 3.1              | 3.2       | 3.3            | 3.4            | 3.6              | 3.2           |
|                  | 6       | 4.2             | 4.4              | 4.4               | 4.7             | 4.4        | 4.5        | 4.5             | 4.5         | 4.5             | 4.5              | 4.5       | 4.5            | 4.5            | 4.7              | 4.5           |
|                  | 7       | 6.1             | 6.4              | 6.4               | 6.5             | 6.1        | 6.3        | 6.4             | 6.3         | 6.3             | 6.5              | 6.2       | 6.3            | 6.3            | 6.4              | 6.1           |
|                  | 8       | 7.1             | 7.4              | 7.3               | 7.4             | 7.3        | 7.4        | 7.4             | 7.4         | 7.5             | 7.6              | 7.1       | 7.3            | 7.4            | 7.4              | 6.9           |
|                  | 9       | 7.2             | 7.3              | 7.2               | 7.3             | 7.0        | 7.2        | 7.3             | 7.0         | 7.2             | 7.4              | 7.0       | 7.2            | 7.1            | 7.3              | 7.0           |
|                  | 10      | 4.2             | 4.4              | 4.4               | 4.4             | 4.3        | 4.3        | 4.4             | 4.4         | 4.4             | 4.4              | 4.4       | 4.4            | 4.4            | 4.5              | 4.4           |
|                  | 11      | 4.5             | 4.3              | 4.3               | 4.2             | 4.2        | 4.4        | 4.1             | 4.2         | 4.2             | 3.9              | 4.2       | 4.2            | 4.3            | 4.2              | 4.3           |
|                  | 12      | 5.0             | 4.6              | 4.7               | 4.2             | 4.8        | 4.7        | 4.3             | 4.6         | 4.3             | 4.5              | 4.9       | 4.5            | 4.5            | 4.3              | 4.9           |

## Appendix-C 3 | Monthly precipitation deltas [%] for the 15 climate stations (RCP4.5)

|                  | Month   | Baynes Lake, BC | Beaver Mines, AB | Connelly Creek, AB | Emery Creek, MT | Eureka, MT | Fernie, BC | Flattop Mt., MT | Fortine, MT | Grave Creek, MT | Many Glacier, MT | Olney, MT | Polebridge, MT | Stahl Peak, MT | West Glacier, MT | Whitefish, Mt |
|------------------|---------|-----------------|------------------|--------------------|-----------------|------------|------------|-----------------|-------------|-----------------|------------------|-----------|----------------|----------------|------------------|---------------|
|                  |         |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
| 2035 (2026-2045) | RCP 4.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 28.4            | 42.1             | 42.1               | 30.0            | 34.5       | 28.1       | 35.3            | 34.4        | 34.1            | 36.0             | 34.7      | 35.5           | 33.5           | 30.4             | 30.2          |
|                  | 2       | -5.3            | -37.9            | -41.3              | -15.2           | -9.1       | -8.6       | -17.5           | -10.2       | -10.4           | -23.6            | -10.4     | -13.5          | -9.6           | -14.6            | -15.0         |
|                  | 3       | 8.0             | 44.7             | 39.1               | -7.9            | 2.0        | 8.3        | 5.1             | 0.9         | -1.8            | 22.6             | 9.4       | 2.6            | -0.4           | -4.2             | 2.8           |
|                  | 4       | 5.5             | 41.3             | 44.5               | -6.6            | 8.8        | -4.4       | 7.1             | 4.5         | -5.5            | 28.4             | 9.8       | -3.1           | 0.4            | -4.4             | 9.4           |
|                  | 5       | 56.5            | 42.0             | 47.3               | 58.6            | 69.4       | 50.4       | 56.8            | 62.5        | 51.4            | 54.2             | 57.9      | 48.9           | 59.6           | 59.3             | 55.9          |
|                  | 6       | 18.2            | 26.4             | 25.5               | 13.4            | 4.5        | 16.9       | 23.1            | 8.9         | 4.7             | 31.4             | 28.3      | 14.3           | 5.9            | 13.9             | 23.8          |
|                  | 7       | 3.6             | 19.5             | 15.9               | -3.8            | 6.7        | 14.0       | -9.7            | 10.8        | 5.5             | -14.6            | 22.3      | 8.3            | 6.5            | -1.5             | 16.9          |
|                  | 8       | -10.9           | -3.3             | -0.7               | 13.9            | -11.5      | -5.8       | 8.2             | -7.7        | -9.8            | 17.6             | -15.2     | -15.3          | -9.1           | 7.1              | -7.4          |
|                  | 9       | 15.7            | -13.1            | -3.2               | 4.4             | 5.0        | 4.7        | -9.2            | 7.9         | 13.7            | -17.0            | 2.7       | 8.8            | 9.1            | 1.1              | 6.7           |
|                  | 10      | -0.1            | 0.0              | 7.9                | 2.7             | 3.1        | -3.6       | -1.1            | 2.8         | -1.2            | -4.0             | 6.0       | 4.2            | 0.7            | 1.1              | 4.5           |
|                  | 11      | 28.6            | -10.5            | -5.8               | 21.9            | 21.6       | 26.8       | 14.4            | 24.1        | 22.0            | 1.0              | 26.7      | 25.0           | 22.8           | 23.5             | 26.4          |
|                  | 12      | 9.3             | 34.0             | 45.4               | 6.7             | 11.1       | 14.0       | 11.6            | 9.4         | 12.5            | 19.1             | 4.8       | 9.9            | 11.9           | 7.5              | 4.8           |
| 2075 (2066-2085) | RCP 4.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 9.0             | 7.1              | 8.9                | 2.2             | 6.9        | 1.5        | 3.2             | 4.0         | 2.8             | 6.7              | 4.6       | 3.5            | 3.6            | 2.1              | 4.3           |
|                  | 2       | -0.5            | -14.6            | -15.6              | -4.0            | 1.8        | -2.7       | -9.1            | -0.4        | -0.7            | -12.6            | 1.5       | -3.9           | 0.1            | -4.7             | -2.6          |
|                  | 3       | 22.0            | 84.2             | 91.5               | 3.1             | 15.7       | 18.4       | 11.6            | 12.3        | 6.3             | 28.1             | 28.6      | 13.6           | 9.5            | 6.1              | 22.7          |
|                  | 4       | 46.4            | 99.3             | 98.7               | 22.8            | 45.7       | 30.1       | 40.6            | 38.2        | 28.1            | 59.7             | 55.3      | 35.4           | 34.5           | 29.2             | 55.9          |
|                  | 5       | 10.0            | 1.9              | 8.4                | 48.2            | 21.7       | 9.3        | 37.4            | 25.9        | 23.5            | 31.9             | 27.0      | 29.7           | 23.0           | 44.7             | 31.3          |
|                  | 6       | 5.9             | 9.6              | 8.7                | 14.1            | 2.0        | 16.1       | 14.2            | 9.6         | 6.4             | 17.8             | 21.7      | 9.6            | 7.7            | 13.0             | 18.5          |
|                  | 7       | 0.9             | 0.9              | 0.9                | -4.7            | 9.4        | -2.8       | -0.8            | 11.4        | 10.2            | -8.2             | 13.0      | 14.9           | 8.5            | -0.2             | 8.9           |
|                  | 8       | -3.5            | -8.5             | -7.5               | -3.4            | 3.6        | -2.4       | -4.4            | -5.5        | -9.7            | 1.5              | -15.4     | -18.7          | -4.4           | -5.6             | -7.1          |
|                  | 9       | 11.4            | 18.8             | 31.6               | -0.9            | 4.9        | -0.9       | -2.9            | 6.3         | 7.3             | -5.4             | 2.5       | 8.9            | 4.7            | -3.1             | 3.8           |
|                  | 10      | 8.7             | 3.6              | 15.8               | 10.2            | 17.1       | 12.3       | 2.8             | 11.2        | 11.5            | -7.8             | 7.8       | 6.9            | 13.0           | 10.3             | 8.9           |
|                  | 11      | 46.9            | 21.8             | 25.0               | 31.9            | 34.7       | 37.8       | 33.1            | 37.1        | 35.0            | 33.2             | 42.3      | 41.7           | 35.6           | 33.7             | 39.4          |
|                  | 12      | 0.8             | 0.6              | 7.7                | -2.8            | -3.7       | -0.3       | -6.1            | -4.4        | -0.8            | -3.5             | -5.5      | -3.0           | -2.5           | -3.1             | -5.1          |

## Appendix-C 4 | Monthly precipitation deltas [%] for the 15 climate stations (RCP8.5)

|                  | Month   | Baynes Lake, BC | Beaver Mines, AB | Connelly Creek, AB | Emery Creek, MT | Eureka, MT | Fernie, BC | Flattop Mt., MT | Fortine, MT | Grave Creek, MT | Many Glacier, MT | Olney, MT | Polebridge, MT | Stahl Peak, MT | West Glacier, MT | Whitefish, Mt |
|------------------|---------|-----------------|------------------|--------------------|-----------------|------------|------------|-----------------|-------------|-----------------|------------------|-----------|----------------|----------------|------------------|---------------|
|                  |         |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
| 2035 (2026-2045) | RCP 8.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 17.1            | -7.0             | -14.1              | 9.5             | 13.8       | 15.9       | 11.0            | 11.0        | 10.4            | 10.8             | 6.2       | 9.5            | 11.8           | 8.5              | 4.8           |
|                  | 2       | -4.8            | -18.8            | -15.3              | -10.2           | -5.5       | -6.1       | -10.6           | -7.1        | -8.7            | -12.5            | -6.9      | -12.2          | -7.5           | -9.5             | -9.5          |
|                  | 3       | 16.5            | 44.2             | 43.3               | 13.9            | 6.0        | 19.1       | 8.9             | 10.1        | 13.1            | 16.2             | 15.5      | 10.9           | 11.2           | 13.2             | 15.9          |
|                  | 4       | 35.3            | 50.0             | 59.1               | 30.1            | 41.4       | 24.8       | 30.1            | 33.3        | 27.6            | 40.8             | 43.6      | 27.6           | 31.8           | 30.5             | 47.4          |
|                  | 5       | 12.3            | 4.2              | 5.8                | 29.6            | 18.9       | 6.4        | 31.6            | 16.9        | 14.0            | 35.6             | 15.4      | 18.9           | 16.4           | 28.2             | 16.3          |
|                  | 6       | -1.1            | 33.8             | 35.2               | 16.0            | -7.1       | 12.6       | 33.8            | -0.3        | 4.2             | 38.7             | 20.8      | 22.9           | 0.6            | 20.1             | 21.0          |
|                  | 7       | -16.8           | 25.7             | 20.4               | -6.2            | -4.2       | -10.6      | 0.1             | 7.2         | 4.1             | -7.5             | 14.7      | 20.6           | 0.5            | -1.1             | 5.7           |
|                  | 8       | -23.1           | -7.6             | -7.5               | -0.6            | -30.7      | -17.0      | 4.5             | -27.6       | -25.0           | 18.5             | -25.3     | -17.4          | -26.9          | -5.4             | -19.3         |
|                  | 9       | 28.4            | 38.9             | 41.6               | 21.5            | 19.6       | 17.5       | 20.6            | 22.0        | 30.1            | 20.8             | 12.6      | 22.9           | 24.1           | 19.4             | 15.3          |
|                  | 10      | 22.0            | 20.5             | 39.0               | 14.0            | 18.7       | 19.6       | 8.7             | 14.1        | 13.3            | 3.6              | 18.2      | 13.7           | 15.3           | 14.7             | 17.6          |
|                  | 11      | 13.6            | 16.0             | 14.8               | 3.1             | 5.1        | 6.3        | 0.5             | 3.4         | 2.6             | -0.7             | 7.0       | 2.7            | 3.6            | 3.7              | 5.5           |
|                  | 12      | 3.9             | -6.4             | -7.6               | 4.7             | 8.5        | 2.1        | 0.0             | 6.2         | 8.3             | -2.5             | 2.3       | 1.9            | 7.9            | 4.5              | 2.4           |
| 2075 (2066-2085) | RCP 8.5 |                 |                  |                    |                 |            |            |                 |             |                 |                  |           |                |                |                  |               |
|                  | 1       | 23.5            | 21.7             | 30.8               | 7.3             | 17.3       | 12.9       | 8.8             | 12.7        | 8.1             | 14.1             | 13.4      | 8.2            | 11.1           | 7.0              | 8.9           |
|                  | 2       | -4.6            | 4.6              | -3.4               | -3.0            | -1.8       | -4.6       | -4.1            | -1.2        | -3.5            | -1.2             | 1.6       | -8.4           | -2.5           | -2.7             | 2.5           |
|                  | 3       | 40.5            | 88.8             | 78.7               | 21.6            | 39.2       | 26.7       | 26.8            | 30.0        | 25.5            | 51.7             | 40.9      | 24.8           | 27.7           | 23.7             | 41.4          |
|                  | 4       | 60.4            | 52.7             | 59.5               | 40.9            | 59.1       | 34.2       | 38.0            | 49.5        | 37.1            | 45.8             | 61.5      | 39.9           | 43.3           | 42.9             | 63.3          |
|                  | 5       | 52.0            | 34.9             | 39.6               | 54.9            | 39.2       | 47.8       | 56.1            | 35.3        | 45.0            | 55.3             | 37.0      | 44.7           | 42.4           | 53.4             | 40.7          |
|                  | 6       | 33.5            | 42.8             | 37.4               | 32.0            | 16.4       | 42.4       | 39.8            | 21.6        | 28.8            | 41.9             | 43.7      | 33.4           | 25.5           | 35.9             | 39.8          |
|                  | 7       | -1.0            | 0.8              | -0.4               | -2.2            | 9.2        | 9.5        | -5.0            | 16.9        | 15.5            | -14.7            | 34.9      | 20.6           | 11.6           | 1.9              | 24.1          |
|                  | 8       | -22.5           | -18.2            | -18.2              | -0.5            | -9.7       | -23.6      | -5.4            | -8.6        | -17.7           | 5.8              | -10.0     | -17.5          | -13.1          | -7.6             | -10.6         |
|                  | 9       | 15.5            | -1.7             | 4.9                | -2.1            | 7.4        | 3.5        | -3.6            | 5.9         | -0.2            | -9.1             | 2.8       | 6.4            | 1.4            | -2.4             | 6.9           |
|                  | 10      | 20.5            | -24.1            | -16.4              | 16.8            | 20.2       | 14.0       | 0.9             | 15.5        | 15.9            | -15.7            | 15.6      | 6.9            | 17.1           | 16.1             | 19.9          |
|                  | 11      | 36.3            | 22.0             | 34.6               | 17.6            | 22.0       | 22.7       | 12.0            | 18.7        | 18.2            | 15.9             | 19.5      | 13.1           | 19.8           | 16.4             | 21.4          |
|                  | 12      | -9.4            | 53.0             | 53.6               | -7.5            | -6.2       | -4.2       | -2.0            | -6.7        | -5.3            | 13.8             | -9.1      | -8.3           | -5.3           | -7.1             | -11.4         |

## APPENDIX D

**Appendix-D 1 | Area of snow cover lost in percentage. (Reference snow area: Area with SWE >40mm in km<sup>2</sup>; Total area of the catchment: 4030 km<sup>2</sup>)**

|    | Reference snow<br>area [km <sup>2</sup> ] | 2035   |        | 2075   |        |
|----|-------------------------------------------|--------|--------|--------|--------|
|    |                                           | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| 1  | 4029                                      | 0      | 2      | 3      | 22     |
| 2  | 4028                                      | 0      | 2      | 4      | 27     |
| 3  | 4023                                      | 0      | 5      | 13     | 39     |
| 4  | 3974                                      | 7      | 17     | 32     | 56     |
| 5  | 3400                                      | 18     | 30     | 46     | 73     |
| 6  | 2101                                      | 25     | 40     | 64     | 88     |
| 7  | 991                                       | 44     | 61     | 84     | 96     |
| 8  | 255                                       | 57     | 73     | 90     | 98     |
| 9  | 107                                       | 67     | 77     | 93     | 100    |
| 10 | 131                                       | 72     | 79     | 93     | 100    |
| 11 | 2798                                      | 24     | 30     | 29     | 84     |
| 12 | 4019                                      | 2      | 8      | 8      | 39     |

**Appendix-D 2 | Change in mean monthly discharge. (mean discharge, 0.1-, 0.5- and 0.9-quantiles)**

|        |    | Reference |           |       |       | 2035  |           |       |       | 2075  |           |       |       |
|--------|----|-----------|-----------|-------|-------|-------|-----------|-------|-------|-------|-----------|-------|-------|
|        |    | Mean      | Quantiles |       |       | Mean  | Quantiles |       |       | Mean  | Quantiles |       |       |
|        |    |           | 0.1       | 0.5   | 0.9   |       | 0.1       | 0.5   | 0.9   |       | 0.1       | 0.5   | 0.9   |
| RCP4.5 | 1  | 23.6      | 17.6      | 19.1  | 25.7  | 48.2  | 18.5      | 26.3  | 93.7  | 81.6  | 20.1      | 42.8  | 182.9 |
|        | 2  | 22.1      | 17.6      | 18.8  | 27.8  | 36.3  | 18.4      | 24.2  | 68.2  | 76.7  | 23.1      | 47.2  | 169.9 |
|        | 3  | 35.2      | 17.8      | 22.5  | 62.1  | 85.4  | 21.5      | 51.3  | 193.3 | 136.7 | 37.3      | 110.5 | 275.0 |
|        | 4  | 111.2     | 22.0      | 85.7  | 229.1 | 178.9 | 51.0      | 166.2 | 300.6 | 192.7 | 79.7      | 167.9 | 296.9 |
|        | 5  | 242.6     | 112.9     | 244.9 | 366.6 | 287.2 | 149.1     | 267.5 | 456.7 | 204.3 | 81.4      | 189.7 | 357.7 |
|        | 6  | 259.1     | 127.6     | 241.6 | 417.6 | 244.7 | 86.9      | 210.2 | 434.4 | 160.6 | 43.3      | 130.7 | 318.7 |
|        | 7  | 121.0     | 28.4      | 76.2  | 278.2 | 90.5  | 21.1      | 52.0  | 230.0 | 53.3  | 17.3      | 32.2  | 122.9 |
|        | 8  | 47.0      | 18.4      | 26.6  | 97.9  | 33.3  | 16.7      | 20.7  | 60.9  | 22.8  | 15.8      | 17.2  | 34.9  |
|        | 9  | 31.8      | 17.8      | 23.4  | 55.4  | 27.5  | 16.5      | 19.9  | 43.4  | 24.6  | 16.0      | 17.6  | 37.7  |
|        | 10 | 36.2      | 17.8      | 27.4  | 64.9  | 35.2  | 17.4      | 25.6  | 63.0  | 38.9  | 16.9      | 25.1  | 80.1  |
|        | 11 | 43.1      | 18.3      | 27.1  | 74.5  | 62.4  | 18.7      | 38.8  | 123.7 | 76.7  | 19.1      | 47.7  | 159.7 |
|        | 12 | 25.1      | 17.9      | 20.4  | 30.7  | 34.2  | 18.3      | 24.0  | 49.2  | 54.2  | 19.4      | 35.5  | 109.8 |
| RCP8.5 | 1  |           |           |       |       | 82.0  | 20.4      | 40.1  | 188.5 | 119.3 | 28.8      | 77.0  | 257.8 |
|        | 2  |           |           |       |       | 51.6  | 22.3      | 33.5  | 112.8 | 106.8 | 32.4      | 76.0  | 228.5 |
|        | 3  |           |           |       |       | 103.8 | 28.3      | 69.8  | 230.2 | 146.7 | 46.9      | 123.0 | 271.9 |
|        | 4  |           |           |       |       | 171.5 | 58.3      | 153.2 | 283.8 | 171.4 | 72.7      | 145.9 | 268.8 |
|        | 5  |           |           |       |       | 212.5 | 100.1     | 194.3 | 359.5 | 161.2 | 57.6      | 136.0 | 302.0 |
|        | 6  |           |           |       |       | 209.3 | 68.5      | 178.0 | 389.9 | 144.5 | 38.8      | 116.0 | 301.4 |
|        | 7  |           |           |       |       | 76.4  | 19.5      | 46.7  | 189.5 | 42.1  | 16.7      | 26.2  | 89.6  |
|        | 8  |           |           |       |       | 28.0  | 16.3      | 19.2  | 46.7  | 19.2  | 15.6      | 16.7  | 24.0  |
|        | 9  |           |           |       |       | 30.1  | 16.4      | 19.3  | 51.2  | 21.7  | 15.8      | 16.9  | 30.8  |
|        | 10 |           |           |       |       | 44.7  | 17.4      | 30.1  | 91.1  | 37.5  | 16.7      | 22.5  | 81.9  |
|        | 11 |           |           |       |       | 58.6  | 19.3      | 37.8  | 115.2 | 85.3  | 19.9      | 54.4  | 187.4 |
|        | 12 |           |           |       |       | 48.0  | 19.2      | 30.8  | 89.4  | 78.0  | 23.8      | 54.8  | 168.7 |

**Appendix-D 3 | Mean percentage of total flow**

|    | Ref  | 2035   |        | 2075   |        |
|----|------|--------|--------|--------|--------|
|    |      | RCP4.5 | RCP8.5 | RCP4.5 | RCP8.5 |
| 1  | 2.5  | 4.2    | 7.4    | 7.3    | 10.7   |
| 2  | 2.1  | 2.9    | 4.2    | 6.2    | 8.7    |
| 3  | 3.8  | 7.8    | 9.9    | 13.0   | 13.6   |
| 4  | 11.3 | 15.5   | 15.4   | 17.1   | 15.0   |
| 5  | 25.6 | 25.6   | 19.8   | 18.6   | 14.3   |
| 6  | 25.0 | 19.9   | 17.8   | 12.4   | 12.2   |
| 7  | 11.5 | 7.4    | 6.6    | 4.7    | 3.8    |
| 8  | 4.5  | 2.8    | 2.5    | 2.1    | 1.8    |
| 9  | 3.2  | 2.4    | 2.7    | 2.2    | 2.0    |
| 10 | 3.8  | 3.1    | 4.1    | 3.6    | 3.4    |
| 11 | 4.3  | 5.3    | 5.2    | 6.7    | 7.3    |
| 12 | 2.6  | 3.0    | 4.4    | 5.0    | 7.1    |

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## STATEMENT ON PLAGIARISM

I hereby declare, that I completed the present thesis independently, without help from others and without using resources apart from those quoted. Those parts of the thesis that were taken in one way or another from external sources are quoted in every case, this also refers to figures.

Munich, July 30 2014

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Raul R. Wood

## PLAGIATSERKLÄRUNG

Ich erkläre hiermit, dass ich diese Arbeit selbstständig verfasst und keine anderen Hilfsmittel als die angegebenen benützt habe. Die Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen sind, sind in jedem einzelnen Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht. Diese Versicherung bezieht sich auch auf die bildlichen Darstellungen.

München, den 30.07.2014

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Raul R. Wood