Institut für Hydrologie

Albert-Ludwigs-Universität Freiburg

Johannes Schneider

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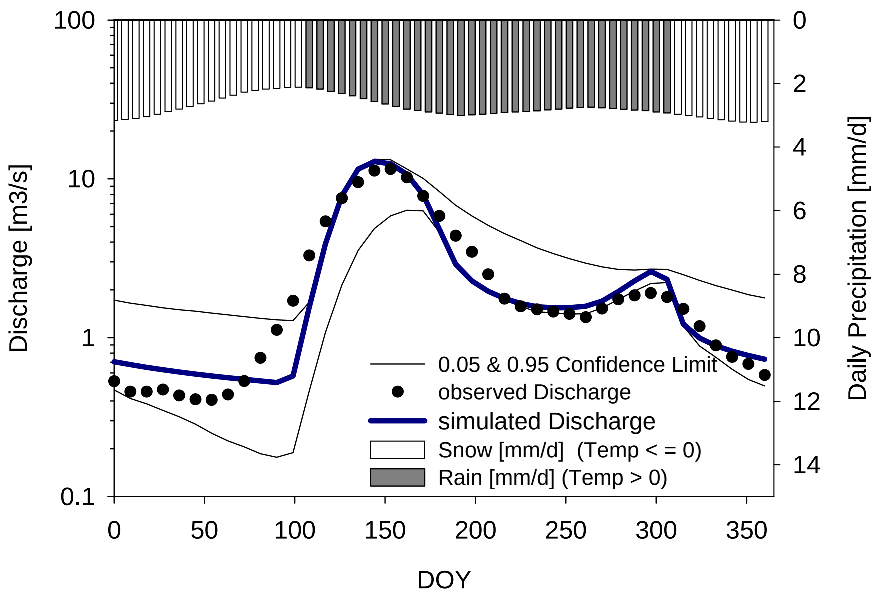


Diplomarbeit unter der Leitung von

Prof. Dr. M. Weiler

Dr. K. Stahl

Freiburg im Breisgau

Dezember 2008

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# List of symbols

| | | |
|---|---|---|
| $a$ | Recession coefficient | [$m^{3-3b}$ $s^{b}$] |
| $a_{1}, a_{2}, a_{3}, a_{4}, a_{5},$ | Recession constants | |
| $AET$ | Actual evapotranspiration | [mm/d; mm/a] |
| $a_{pt}$ | Priestley and Taylor alpha | [-] |
| $b$ | Recession exponent | |
| $C, k, m, p$ | Recession constants | |
| $C_{a}$ | Heat capacity of air | [MJ/kg/°C] |
| $ddf$ | Degree-day-factor | [mm/°C/d] |
| $DR$ | Direct runoff | [% of effective rainfall] |
| $DR_{sm}$ | Direct runoff during snowmelt | [% of effective rainfall] |
| $G$ | Soil heat flux | [Mj/m2/d] |
| $HC$ | Holding capacity | [-] |
| $I$ | System input | [mm] |
| $K, B, C$ | Recession coefficients | [$d^{-1}$] |
| $lnN_{eff}$ | logarithmic Nash-Sutcliffe efficiency | [-] |
| $LWRC$ | Liquid Water Retaining Capacity | [mm] |
| $N_{eff}$ | Nash-Sutcliffe efficiency | [-] |
| $p, q$ | Recession constants | |
| $PET$ | Potential evapotranspiration | [mm/d; mm/a]] |
| $Q$ | Discharge | [mm/a; m3/s] |
| $Q_{0}$ | Discharge at time t = 0 | [$m^{3}$/s] |
| $q_{melt}$ | Snowmelt | [mm/d] |
| $Q_{obs}$ | Observed discharge | [mm/a; m3/s] |
| $Q_{sim}$ | Simulated discharge | [mm/a; m3/s] |
| $Q_{t}$ | Discharge at time t | [$m^{3}$/s] |
| $R_{c}$ | Rainfall correction factor | [-] |
| $refp$ | Temperature modulating factor | [-] |
| $RF$ | Refreezing factor | [-] |
| $RMSE$ | Root mean square error | [-] |
| $Rn$ | Mean monthly net radiation | [Mj/m2/d] |
| $S$ | Storage volume | [$m^{3}$] |
| $s$ | slope of saturation vapor pressure | [kPa/°C] |
| $S_{c}$ | Snowfall correction factor | [-] |
| $SUB$ | Sublimation | [mm/d] |
| $SWE$ | Snow water equivalent | [mm] |
| $t$ | Time (seconds, day) | [s, d] |
| $T$ | Temperature | [°C] |

| | | |
|---|---|---|
| $T_{AIR}$ | Mean daily temperature | [°C] |
| *TH* | Threshold | [-] |
| $T_M$ | Melting temperature | [°C] |
| *Tw* | Drying time | [d] |
| *W* | Ratio of average precipitation | [mm/a] |
| $\lambda$ | Psychrometric constant | [-] |
| $\gamma$ | Latent heat of vaporization | [MJ/kg] |
| *%B* | Length of the period in which the gauging station is covered by ice and snow | |
| *%E* | Length of the period in which discharge data where estimated | |

# List of abbreviations

| | |
|---|---|
| API | Antecedent Precipitation Index |
| BC | British Columbia |
| BTM | Baseline Thematic Mapping |
| CGCM | Canadian Global Climate Model |
| DEM | Digital Elevation Model |
| DOY | Day of Year |
| GCM | Global Climate Model |
| GLUE | Generalized Likelihood Uncertainty Estimation |
| HBV | Hydrologiska Byråns Vattenbalansmodell |
| IHACRES | Identification of Unit Hydrograph and Component flows from Rainfall, Evaporation and Streamflow data |
| m.a.s.l | meter above sea level |
| MCAT | Monte Carlo Analysis Tool |
| MPI | Mountain Pine Beetle |
| PRISM | Parameter-elevation Regressions on Independent Slope Model |

# Summary

Climate has changed since the industrial revolution as a consequence of increasing emissions of greenhouse gases into the atmosphere. As a result of rising temperatures and changes in precipitation, the hydrological regimes will change as well. In British Columbia, Canada, there have been concerns recently that global warming causes an earlier and diluted spring peak flow, and extended summer low flow periods. The proceeding climate change will worsen these effects, so that it is to be expected that low flows will become hazards to ecosystems and water management schemes. Low flows are important for water-supply, the maintenance of quantity and quality of water for irrigation as well as for stream flow ecology and wildlife conservation.

In this thesis a low parameterized water balance model was created which is based on a non-linear transfer-function approach that transforms a distributed effective water input into a characteristic regime at the outlet of the catchment. This input is derived from a gridded 30-year mean monthly precipitation and temperature data, disaggregated to a daily resolution with respect to a simple approach of evapotranspiration and a degree-day snow accumulation and snowmelt model.

The two parameters of the transfer-function routine were calibrated to the characteristic hydrograph of a set of 15 gauged catchments with different, geographical positions, size, elevations, climate and hydrological regimes.

The application of two commonly used delta-changes climate scenarios confirms the expected earlier and diluted spring peak flow for all catchments. The degree of significant changes during summer low flow periods depends on the characteristic catchment delta-changes as well as on the catchment geology.

Whereas catchments dominated by sedimentary rocks and enough effective water input tend to be less sensitive to changes in climatic inputs, catchments dominated by bedrock show more significant changes during low flow periods.

**Keywords:** Low Flows, Rainfall-Runoff-modeling, Recession Analysis, Climate Change, British Columbia

# Zusammenfassung

Seit der industriellen Revolution hat sich das Klima als Konsequenz von steigenden Treibhausgasemissionen verändert. In Folge von ansteigenden Temperaturen und sich verändernden Niederschlägen, verändern sich auch die hydrologischen Abflussregime. In British Columbia, Kanada, wurde beobachtet, dass die globale Erwärmung frühere und abgeschwächtere, durch die Schneeschmelze verursachte, Frühjahrshochwasser und ausgeprägtere Niedrigwasserperioden im Sommer verursacht. Der fortschreitende Klimawandel wird diese Effekte noch verstärken, so dass davon auszugehen ist, dass Niedrigwasserperioden zu einer Gefahr für Ökosysteme und das Wasserressourcen-Management werden. Niedrigwasser sind von besonderer Bedeutung für die Wasserversorgung, die Aufrechterhaltung der Wasserqualität und -quantität für Bewässerung sowie für die Gewässerökologie und den Artenschutz.

Das in dieser Arbeit entwickelte Wasserbilanz-Modell, basierend auf einer nicht-linearen Transferfunktion, transferiert einen effektiven Wasser-Input in ein charakteristisches Abflussregime am Einzugsgebietsauslass. Der Input stammt von mittleren monatlichen Niederschlags- und Temperaturdaten, disaggregiert auf eine tägliche Auflösung unter Beachtung der Verdunstung und eines Tag-Grad Schneeakkumulations- und Schneeschmelzmodelles.

Die beiden Parameter der Transferfunktions-Routine werden anhand einer charakteristischen Abflussgangline für 15 Einzugsgebiete mit unterschiedlichen geographischen Lagen, Einzugsgebietsgrößen und mittleren –höhen und klimatischen und hydrologischen Regimen kalibriert.

Die Anwendung von zwei üblichen Klimaszenarien bestätigt für alle Einzugsgebiete die erwarteten früheren und abgeschwächten Frühjahrshochwasser. Der Grad der Veränderungen während Niedrigwasserbedingungen im Sommer hängt von den einzugsgebiets-charakteristischen Klimaveränderungen sowohl der Einzugsgebietsgeologie ab. Während Einzugsgebiete dominiert von Sedimentgestein und ausreichendem effektivem Wasser-Input dazu tendieren weniger sensitiv auf Klimaveränderungen zu reagieren, zeigen Einzugsgebiete mit großem Anteil an Festgestein größere signifikante Veränderungen während Niedrigwasserperioden.

**Stichworte:** Niedrigwasser, Niederschlags-Abfluss-Modellierung, Rezensionsanalyse, Klimawandel, British Columbia

# 1 Introduction

Low flows as a natural hazard will impact socio-economic aspects, e.g. water supply, reservoir operation, waste load allocation as well as the quality of water and health of aquatic ecosystems (BURN, ET AL. 2008). Therefore it is important to understand the driving factors of low flows and their sensitivity to climate change.

Low flows depend primarily on climate which controls the magnitude of precipitation input, temperature and evapotranspiration. Temperature determines whether the precipitation falls as snow or rain. During winter all precipitation is stored as snow, which causes the typical extended “winter low flow” period of nival runoff regimes (RHODENHUIS, ET AL. 2007). Also temperature is the driving factor of snowmelt. The typical “summer low flows” occurs when the snowmelt peak is passed with decreasing precipitation rates and increasing temperatures and the connected atmospheric demand.

Furthermore catchment characteristics e.g. geology, vegetation, catchment size and elevation lead to different sensitivities to climatic inputs. During deficit periods, soil moisture may be reduced through water uptake of vegetation. Storages may be depleted through outflow to the river depending on factors like fill levels and hydraulic resistances (BURN, ET AL. 2008).

Especially the geology, the storage and aquifer characteristics are responsible for the sensitivity of the catchments to changes in climate inputs (SMAKHTIN 2001). Catchments with productive aquifers (large unconsolidated sedimentary rocks) and continued outflow of the storages may feed and balance low flows (SCIBEK, ET AL., 2007). But catchments with only small and unproductive aquifers (mainly headwater bedrock catchments) tend to be very vulnerable to low flows due to a lack of precipitation and an increasing atmospheric demand (WANDLE, ET AL., 1993).

As a consequence of changing precipitation rates and temperatures, effective rainfall and the resulting runoff will change as well. There is no doubt that a change in climate has taken place during the last century and that it will continue in the future as a consequence of increasing greenhouse gas emissions (IPCC 2007). But beside the climatic changes vegetation and land-use changes are also determining whether low flows will become a hazard or not. The main land use changes in British Columbia are clear cuttings and the rising influence of the Mountain-Pine-Beetle has become epidemic in the last years (RHODENHUIS, ET AL., 2007). In general the consequences are a reduced atmospheric demand, increased rates of snowmelt and modified runoff pathways by which water flows to the stream channel (surface runoff) with effects on erosion and groundwater recharge (MOORE, ET AL., 2005; RHODENHUIS, ET AL., 2007). Still both effects on low flows are possible: higher low flows due to the lower atmospheric demand as well as reduced low flows due to a decreasing recharge and groundwater level (SMAKHTIN, 2001).

Commonly used statistical tools which estimate low flows are usually based on frequency analysis, percentiles of flow duration curves and return periods (QUARDA, ET AL., 2008; SMAKHTIN, 2001). The disadvantage of the statistical tools is that they integrate climate and catchment characteristics. So it is hardly possible to forecast changes in low flows due to changing climatic conditions.

Empirical Rainfall-Runoff models, which describe catchment characteristics without physical background by calibration to gauged discharge data, allow simulating changes in discharge due to changing model inputs, such as precipitation or temperature. Low flows only are fed by groundwater and its outflow depending on the storage volume. The groundwater outflow follows a characteristic recession curve during periods with no input. Therefore recession analysis is well suited to estimate low flows (BAKO, ET AL., 1988).

## Objective and procedure

Objectives of this thesis are to review the current state of research concerning (I) recent and predicted climate change and its impacts on watershed hydrology, focussing on low flows in British Columbia and (II) on recession analysis. In the next step (III) a parsimonious model shall be developed that allows exploring the sensitivity of a catchment´s hydrologic regime with focus to precipitation and snowmelt changes. Vegetation changes will not be taken into account in this work.

The model used here creates a tool which separates climate and catchment characteristics. Consequently it would be possible to change climate inputs, according to commonly used scenarios of global change and to simulate changes in runoff depending on each specific catchment characteristic.

Because the input data are mean monthly precipitation and temperature data and because the model will be calibrated to mean discharge data, this study focuses on mean trends in low flows. It will not be possible to estimate trends in extreme events, like peak flows caused by storm events or droughts caused by lacks of temporal climatic precipitation deficits.

The model will be applied to a set of gauged catchments for different hydro-climatic zones in British Columbia and fitted to summer low flows. The responses with respect to different catchment characteristics will be compared in order to forecast the applicability and to find restrictions.

# 2 Impacts of climate change on watershed hydrology and low flows

## 2.1 Hydro - climate and runoff regimes of British Columbia (BC)

The climate of British Columbia is characterized by the geographical exposure to the Pacific Ocean as well as the North American landmass and its topography (MOORE, ET AL., 2008). As shown in FIGURE 2.1 annual mean temperatures in coastal areas are the highest in BC with an average ranging from 5 °C to 10 °C. Parts of the Fraser Plateau and Okanangan are dominated by extremely high summer temperatures and as a consequence high annual mean temperatures. In the northern part of BC and in high elevations in the Coastal and Rocky Mountains temperatures generally range from -5° to 0° C (RHODENHUIS, ET AL., 2007).

To understand hydro-climate response and runoff regimes, RHODENHUIS, ET AL., (2007) divided British Columbia into seven hydro-climatic regions (FIGURE 2.1). These represent areas with similar patterns of air temperature, precipitation and hydrology.

Coastal regions close to the pacific with mountain terrain are affected by similar storm patterns and orographic uplift with annual precipitation of 1500 - 5000 mm. Regions behind the coastal mountains tend to be drier and therefore may have different reactions on climate change. The Fraser Plateau is situated in high elevations in the rain shadow of the Coastal Mountains western to the Rocky Mountains and is characterized by low precipitation rates. The Columbia Basin will probably be strongly affected by climate change, because of its southern latitude combined with recent declining glaciers (SCHIEFER, ET AL., 2007). The Okanangan region is dominated by a large demand for water evoked by the agriculture and growth of population. The north eastern part of BC has a hydro-climatic regime with a large fraction of rainfall taking place in summer and very low precipitation rates in winter and its mean annual temperature is below zero.

Besides the primarily climate control mechanisms of the mountain ranges in north-south direction, climate variability is also affected by the variability in sea surface temperatures and large scale atmospheric circulation patterns of the pacific ocean (MOORE, ET AL., 2008; RHODENHUIS, ET AL., 2007).

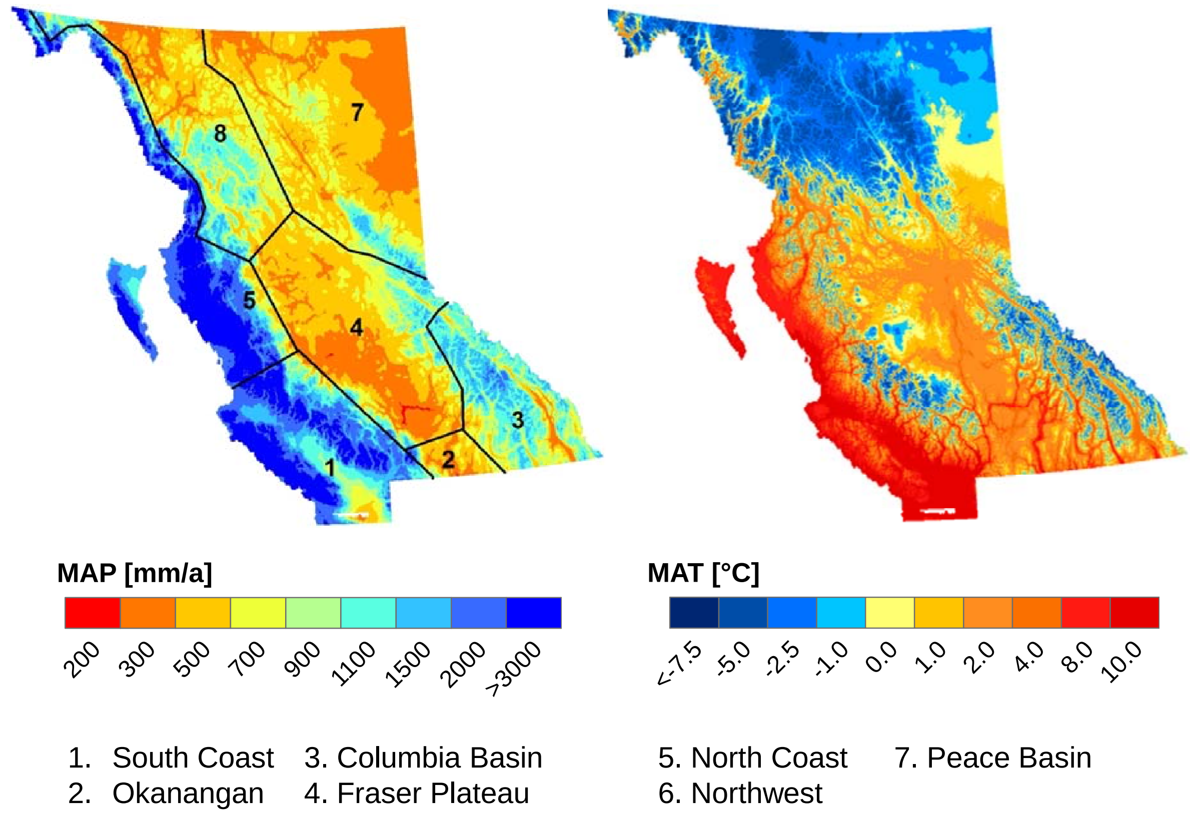


Figure 2.1: Mean Annual Precipitation MAP (left) with simplified hydro-climatic regions according to RHODENHUIS, ET AL., (2007) and Mean Annual Temperature MAT (right) of British Columbia based on the ClimateBC dataset (SPITTLEHOUSE, 2006).

The resulting runoff can be classified into four runoff regimes: pluvial (rainfall), nival (snowfall), hybrid (mixed rainfall and snowfall), and glacial (PIKE (1), ET AL., 2008). The timing of peak and low flows is different in each regime.

Because of lower temperatures in higher elevations runoff regimes in BC are generally either nival or nival/glacial. Especially some of the northern regions, show summer peak flows resulting from summer rains. In lower regions like the Georgia Basin in south West of BC and at the Coast the regimes tend to be pluvial.

**Pluvial**

Pluvial regimes closely follow the seasonal patterns of precipitation and are located in the lowlands and coastal areas. Peak flows tend to be in November and December, low flows in July and August.

As climate change caused changes in precipitation patterns, PIKE (2), ET AL., (2008) expects that an increased number of storm events will result in an increased frequency and magnitude of storm driven peak flows and in drier summers in more low flow conditions.

#### Hybrid

Hybrid regimes have two high flows, one from October to January, one from April to June and low flows in August and September. The snow packs can store a lot of water and damp the response of watersheds to large midwinter rain events. Rain instead of snow will elevate the frequency of winter peak flows and reduce spring peak flow (RHODENHUIS, ET AL., 2007).

#### Nival

Nival Regimes are characterized by peak flows from May to June as a result of snowmelt, and low flows in winter, because precipitation is stored as snowpack.
Due to climate change and warming temperatures, less precipitation will fall as snow and nival regimes tend to become hybrid regimes.

#### Glacial

Glacial runoff regimes have peak flows from May to September and low flow during winter season. As a consequence of climate change peak flows will decrease and occur earlier in the year. The reduction or elimination of the glacial melt-water component in the summer would increase the frequency and duration of low flow days in these systems (PIKE (2), ET AL., 2008).

#### BC´s runoff regimes

As written in the previous sections BC´s runoff regimes are mainly nival dominated with winter low flows. The summer low flow periods in these catchments occur typically when snowmelt starts early and/or over a short period of time (e. g. Tsilcoh River).
The coastal areas with low elevations are pluvial dominated that it is to say that summer is the primary low flow season (Tsitika River).

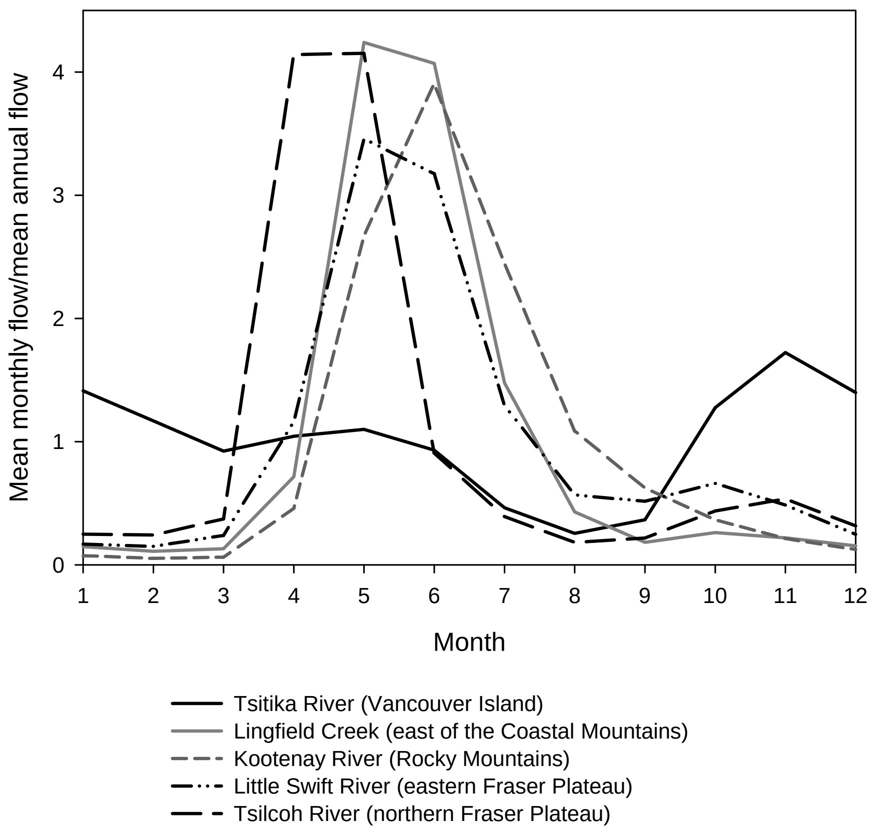


Figure 2.2: BC´s low flow regimes

## 2.2 Recent and projected changes in British Columbia and impacts on streamflow

### Temperature and precipitation

Climate studies generally indicate a rise in air temperature for all seasons (MOORE, ET AL., 2008; RHODENHUIS 2007), but especially in winter seasons, during the past 100 years in British Columbia (PIKE, ET AL., 2008). Seasonal trends of minimum temperature were detected with increases as much as 3.5°C per century in northern BC (MOORE, ET AL., 2008; FIGURE 2.3).

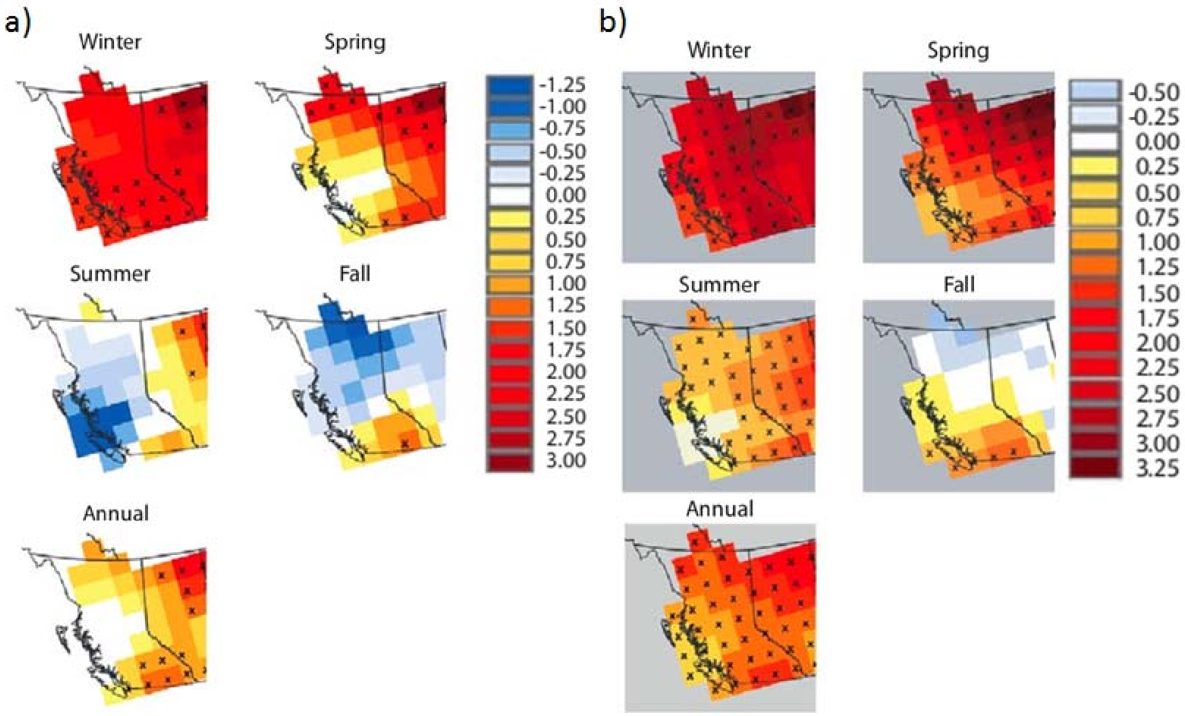


Figure 2.3: Seasonal trends in maximum (a) and minimum (b) temperatures for British Columbia for 1900-2003 [°C over 104 years] (from MOORE, ET AL., 2008).

Furthermore, detailed studies of recent (1900-2004) temperature and precipitation trends in BC (RHODENHUIS, ET AL., 2007; MOORE, ET AL., 2008) reported positive trends especially in daily minimum temperatures, contrasting with daily mean and maximum temperatures (FIGURE 2.3). By comparing the global mean temperature trend of 0.7 °C per century the trend with 1°C per century in BC is slightly steeper.

Registered annual trends in precipitation were also generally positive by around +22 % per century across BC. Trends in winter precipitation tends to increase by around 50% (RHODENHUIS, ET AL., 2007)

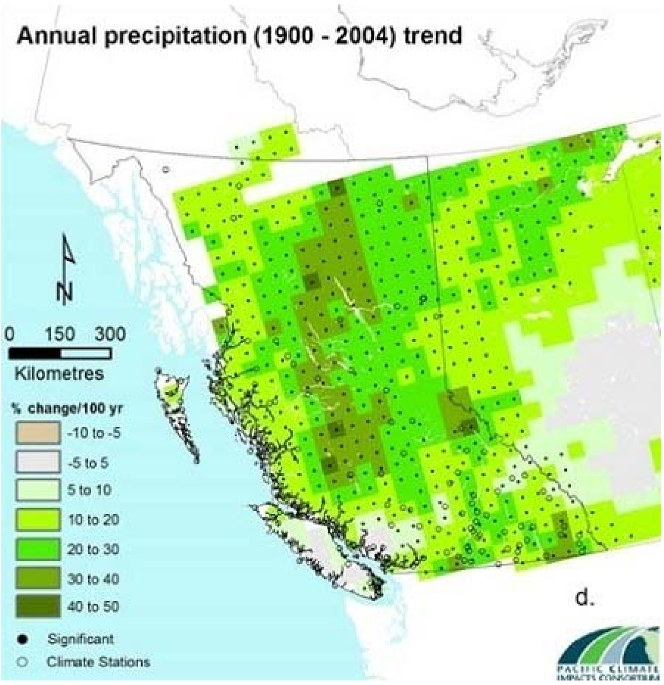


Figure 2.4: Annual trend in precipitation for British Columbia [% change per 100 years] (from RHODENHUIS, ET. AL., 2007)

Table 2.1: Forecasting changes in temperature and precipitation for 2020s, 2050s and 2080 for BC (SPITTELHOUSE, 2007).

| | 2020 | | 2050 | | 2080 | |
|---|---|---|---|---|---|---|
| | **Temp. °C** | **PPT %** | **Temp. °C** | **PPT %** | **Temp. °C** | **PPT %** |
| **Southern BC** | | | | | | |
| Winter | 0 to 2 | -5 to +15 | 1.5 to 3.5 | 0 to + 20 | 2 to 7 | 0 to +25 |
| Summer | 0.5 to 2 | -30 to +5 | 1.5 to 4 | -35 to 0 | 2.5 to 7.5 | -50 to 0 |
| **Central BC** | | | | | | |
| Winter | 0 to 2 | -5 to +15 | 1.5 to 4 | 0 to +30 | 2.6 to 6 | +5 to +40 |
| Summer | 0.5 to 1.5 | -10 to + 5 | 1.8 to 3.5 | -20 to 0 | 2.5 to 6.5 | -20 to +5 |
| **Northern BC** | | | | | | |
| Winter | 0 to 2.5 | 0 to +20 | 1.5 to 5.5 | 0 to +25 | 2.5 to 9 | 0 to + 45 |
| Summer | 0.5 to 1.5 | -10 to +10 | 1.5 to 3.5 | -10 to +15 | 2 to 6 | -15 to +25 |

TABLE 2.1 shows the changes in temperature and precipitation predicted for BC for the 2020s, 2050s and 2080s from seven global climate models and for eight emission scenarios. The data are changes from the Climate Normals from 1960-1990 (delta-changes) expressed as a change in mean temperature or as a percentage change in total precipitation [PPT%] (SPITTELHOUSE, 2007).

PIKE (1), ET AL. (2008) estimates a significant increase of heavy rainfall events during spring (May, June, July 1950-1995). In the second half of last century, ZHANG ET AL. (2000) detect an increase in extreme wet and in extreme dry conditions.

### Increasing atmospheric demand

Due to increasing temperatures, the atmospheric demand will increase as well. Increasing evapotranspiration losses from streams, lakes and reservoirs may have consequences on streamflow and lead to a growing water demand for irrigation. The affected water availability has influences on growth and survival of vegetation and effects increased fire risk (PIKE, ET AL., 2008).

### Snow

Analysing the last half of the $20^{th}$ century, ZHANG, ET AL., (2000) detected declining precipitation trends -especially in winter- and an increasing summer precipitation.

As a consequence of increasing temperatures the proportion of snow to rain is changing and less snow is falling during winter seasons. RHODENHUIS, ET AL., (2007) located declines mostly in central and north coast regions and in higher elevations of the southern Coastal Mountains.

Due to higher temperatures, snowmelt will be accelerated. STEWART, ET AL., (2004) predicted that, assuming a common climate change scenario, spring peak flows for many rivers in north America take place 30-40% earlier for the 21th century as a consequence of earlier snowmelt.

Especially the winter warming (and the increasing winter minimum temperatures) will be responsible for reduced snow packs. The average snow lines will migrate northwards and to higher elevations and will change the flow regime. Nival regimes will become hybrid, hybrid will become pluvial. However PIKE (1), ET AL., (2008) underlined that interactions between increased temperatures and changes to precipitation are complex and not fully understood.

FIGURE 2.5 shows the simulated snow depth at the Upper Pentiction Creek Experimental Watershed under winter 2001/02 temperature and precipitation conditions as well as three climate change scenarios (SPITTELHOUSE, 2007).

A decreasing storage of winter precipitation will reduce the magnitude of spring peak flow and lead to extended summer low flow conditions (PIKE (2), ET AL., 2008). The changes in streamflow regimes due to accelerated snowmelt will have impacts on streamflow ecology, hydroelectric power and water availability.

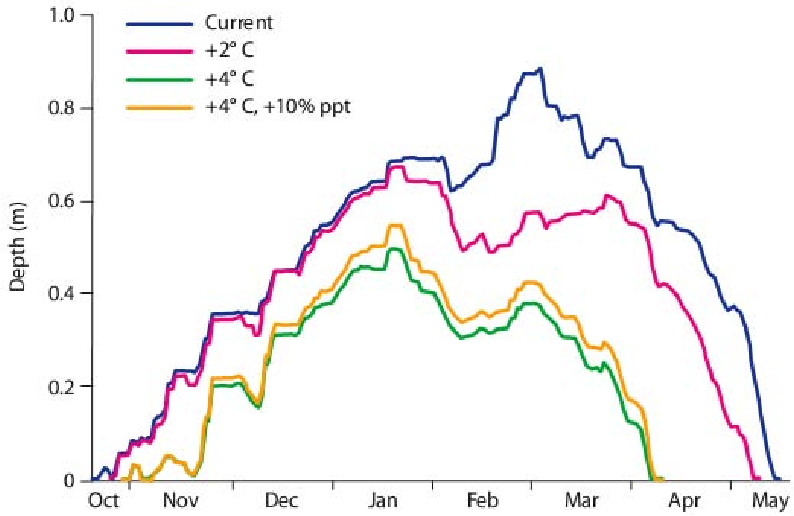


Figure 2.5: Simulated winter snow depth at the Upper Pentiction Creek under current conditions (blue line) and three climate-change scenarios. For 2°C and 4°C warming, with no precipitation change, and one for 4°C warming with a 10% increase in precipitation (Spittelhouse, 2007)

### Glaciers

Over winter seasons glaciers store water and release it during summer. This natural reservoir is very important for a lot of ecosystems and also for power generation. Glaciers are a sensitive indicator of climate change, and at the moment most of them are out of equilibrium with the current climate (PIKE (1), ET AL., 2008).

Glaciers cover about 30.000 km$^2$ or 3% of BC, which -generally show decreasing accumulation conditions in winter and increasing melting conditions in summer. A new equilibrium can only be reached by a large reduction in glacier area and a withdrawal of the glacier terminus. Between 1985 and 1999 a total volume loss of 22.48 +/-5.53 km$^2$ per year of BC glaciers where recorded, using radar and digital terrain models. However, in some regions especially in the north west of BC glacial volumes caused by precipitation increased and a rather cold temperature prevailed (RHODENHUIS, ET AL., 2007).

Future scenarios assume that except for the coldest regions, all glaciers will continue to recede (RHODENHUIS, ET AL., 2007). Glaciers with less than 100 m thickness will disappear in the next 20 years (PIKE (2), ET AL., 2008). A negative glacier mass balance will result at first in increased summer streamflows for some years which will be followed by a larger decrease with more low flow periods when the glacier will eventually have disappeared.

In an analysis of august streamflow in BC a significant negative trend for glacier-fed streams could be observed. This suggests that most glaciers in British Columbia have passed already the initial phase of warming-induced increased runoff (STAHL, ET AL., 2006).

**Runoff**

A detailed study about trends in Canadian streamflow (ZHANG, ET AL., 2001) reported a decreasing annual mean streamflow across southern Canada. Significant decreases were identified in monthly mean streamflow for March and April as well as in late summer and autumn months as a consequence of an earlier spring high-flow season. The decrease in annual mean streamflow may be a result of an increase in mean temperature, associated with an increasing evapotranspiration. But ZHANG, ET AL., (2001) underlined, that without additional detailed regional analysis, it is difficult to attribute exact causes to the trends in some variables.

## 2.3 Processes and driving factors of low flows

SMAKHTIN (2001) distinguishes between drought events and low flows. Droughts as natural events are a result of extended periods with precipitation occurrence below the average and are characterized by several factors like groundwater level, lake storage or soil moisture. Droughts include low flow periods, but a continuous seasonal low flow event does not necessarily constitute a drought. So it is necessary to confine low flows as a seasonal phenomenon and as a integrated component of a flow regime from drought.
This section should gives an overview of driving forces of low flows as well as the related hydrologic risk in British Columbia.

### 2.3.1 Climate variability

The main impacts on runoff and low flows are caused by climate conditions. Climate determines the magnitude and variation of precipitation and temperature and it is the leading variable for evapotranspiration. Low flows are a result of a lack of input into the hydrological system over a long period. This output results from an extended dry-weather period with climatic water deficit (summer low flows) or during periods with temperatures below zero which cause the storage of precipitation as snow (winter low flows) (BURN, ET AL., 2008; EATON, ET AL., 2007).
EATON, ET AL., (2007) estimated low flow periods by a “threshold low-flow” value, which is defined to be 25% of the mean annual streamflow, expressed in mm/month for different

climatic regions in British Columbia. Depending on mean annual precipitation and the proportion of rainfall to snowfall the estimated low flow periods with different durations and intensities occur between June and August after snowmelt peak and between November and March during periods where precipitation is stored as snow.

However, climate varies temporally in different time scales according to circulation patterns (RHODENHUIS, 2007; MOORE, ET AL., 2008) and spatially, especially in mountain regions. Also climate will change according to the climate change scenarios (IPCC, 2007) which will affect variations in low flows.

### 2.3.2 Catchment characteristics

Furthermore low flows are the result of different processes in catchment scale. The catchment characteristics e.g. the type of soil, geology, vegetation, topography and the hydraulic conductivity and extension of the aquifer (BURN, ET AL., 2008; SMAKHTIN, 2001), control how climatic surpluses and deficits propagate through the system and into streamflow. Conceptually a catchment can be described as a series of interconnected reservoirs with components of recharge, storage and discharge. The natural discharge during low flow periods is mostly derived from groundwater storage and the outflow follows a characteristic recession curve.

The geology has a powerful effect on the magnitude and timing of groundwater discharge to streams. Preconditions for continuous low flows are so that the aquifer become seasonally recharged with adequate amounts of soil moisture, the water table is shallow enough to be intersected by the stream and the aquifer's size and hydraulic conductivity must be sufficient to maintain flows throughout the dry season (SMAKHTIN, 2001). Catchments in which surficial geology and aquifers are dominated by sand, gravel and unconsolidated sedimentary rocks may store a large fraction of local precipitation (WANDLE, ET AL., 1993). The linked continued outflow of the storages may feed and balance low flows. SCIBEK, ET AL., (2007) assumed that large alluvial aquifers in southern British Columbia can provide late summer baseflow to rivers after being recharged from the river during the spring freshet.

But catchments in which surficial geology and aquifers are dominated by bedrock (situated mainly in the uplands) have only small capacities to store and transmit water. Therefore precipitation often results in saturation to land surface and thus in rapid runoff (WANDLE, ET AL., 1993). These catchments with small and unproductive aquifers, tend to be very vulnerable to low flows due to a lack of precipitation and an increasing atmospheric demand (WANDLE, ET AL., 1993; SMAKHTIN, 2001).

Lakes and wetlands may additionally have influences on low flows in rivers which have direct hydraulic connection (SMAKHTIN, 2001). Depending on elevation and temperature summer low flows could be influenced by snow- and glaciermelt.

### 2.3.3 Anthropogenic influences on low flows and the Mountain Pine Beetle Epidemic in BC

Besides natural impacts on low flows anthropogenic influences play another role in low flow hydrology. Groundwater abstraction will reduce the phreatic surface, the storage volume and the input into the channel (CLAUSEN, ET AL., 1994). Artificial drainage can lead to more rapid removal from valley bottom storage and to a reduction in the sustainability of lateral drainage during dry weather seasons (SMAKHTIN, 2001). Changes in vegetation will have influences on evapotranspiration. Afforestation may lead to increased interception and increased transpiration losses connected with a decrease in mean flow QUERNER, ET AL., (1997). Generally deforestation causes lower evapotranspiration rates so that the annual water yield increases. Still it is difficult to forecast low flows due to deforestation. The consequences of the lower atmospheric demand are increased rates of snowmelt and modified runoff pathways by which water flows to the stream channel (surface runoff). More surface runoff will presumably result in lowering the groundwater table and thus in reducing low flows (SMAKHTIN, 2001; MOORE, ET AL., 2005) despite the higher annual water yield. Therefore both effects on low flows are possible: higher low flows due to the lower atmospheric demand and reduced low flows due to a decreasing recharge and groundwater level (SMAKHTIN, 2001).

River abstraction, irrigation return flows from agricultural fields and the construction of dams will also have direct impacts on streamflow.

As a special local phenomenon BC suffers under the current Mountain-Pine-Beetle (MPB) epidemic which has caused huge losses of forest since 1994 with large impacts on economy and environment as well as on the quantity and quality of the water (HELIE, ET AL., 2005). The MPB may have influences on the hydrology of forested watersheds such as deforestation or burning. It is to be assumed that the annual water yield increases but late summer and fall low flows will increase as well (RHODENHUIS, ET AL., 2007).

### 2.3.4 Low flow related hazards in BC

Low flows are very important for the socio-economic aspects and the health of aquatic ecosystems. BURN, ET AL., (2008) summarized the impacts of low flows across Canada and concludes the main impacts for BC: Low flows affect hydropower production, municipal water supplies and waste water allocation as well as irrigation, which rely especially on sustained inflow during climatic deficit conditions. Moreover the ecosystems are very damageable especially during summer low flow conditions when the water temperatures are high. The cold-water species such as salmonids for example are very vulnerable due to more extreme low flow conditions. The salmon fishery is an important industry in BC so that any interference might cause serious economic damage for the state.

Thus it is important to understand the processes that affect low flows and their responses to changing climate conditions in order to manage properly the available water resources.

## 2.4 Conclusions

Runoff regimes and low flows are primarily controlled by precipitation and temperature patterns and furthermore by geology and vegetation. The climatic impacts on low flows in British Columbia are often published, detailed studies about the impacts of geology (and aquifer characteristics) on low flows are more rare. But it is to be assumed that large and more productive aquifers are less sensitive to changing climate conditions than small and unproductive aquifers.

The largest impacts of climate change on runoff may be expected in areas where the regime will change (e.g. glacial to nival, nival to hybrid, hybrid to pluvial). Due to an earlier and diluted snowmelt it is to be expected that summer low flow periods are more extended.

But it is not established whether the extended periods are connected with more extreme conditions in mean low flows. The idea is that at the end of the growing season the storages are empty in any case. Thus the impact of climate warming need not result in pronounced mean summer low flow conditions.

It can be assumed that the catchment characteristics and the describing parameters won’t change significantly (except for vegetation) over time. A model that represents the catchment characteristics may simulate changes in runoff due to changing inputs.

# 3 Recession analysis and transfer-function models

In hydrological modelling, there are two different approaches. The first type of models attempts to reflect our physical understanding (physically based). In this case it is possible to make predictions that lie outside of the range of data available in time and space. The second type, which will be analysed in this chapter sustains that all models, despite their physically based theory, are essentially tools for the extrapolation of available data in time (to different periods) and space (to different catchments) (BEVEN, 2001 P. 85). This data based (black box) modelling is thoroughly empirical and usually applied at catchment scale without making much physical argument or theory about processes.
KIRCHNER (2006, 2008) stated the disadvantages of physically based modelling as follows: For physically based models, properties of interest are usually only direct measurable at scales (many orders of magnitude) smaller than the catchment itself. So it is indispensable to 'scale up' microphysics properties of subsurface, so that the behaviour at larger scales will be described by the same governing equations (e.g. Richard equation, Darcy´s Law) with variables (e.g. water flux, volumetric water content, hydraulic potential). But it is currently unclear whether this up-scaling premise is correct or whether effective large-scale governing equations can represent heterogeneous catchment characteristics (KIRCHNER, 2008). The consequences are usually large domains of uncertainty.

In dry periods water is depleted from catchments by evapotranspiration and groundwater/soilwater is discharging into a stream. The decrease of streamflow during these periods is called recession and is reflected in a characteristic streamflow hydrograph by a recession curve (TALLAKSEN, 1995). The type of streamflow recession depends primarily on climate, relief, storage volumes and drainage functions which are influenced by catchment geology and the distance from stream channels to basin boundaries (SMAKHTIN, 2001; TALLAKSEN, 1995). Initially the recession curve is steep as a consequence from the quick response components like overland flow and interflow. It flattens out with deeper subsurface stores influences and can even become nearly constant if discharge is only influenced by groundwater.

In gauged rivers, where discharge depends primarily on the volume of stored water in the subsurface, recession equations easily can be applied to forecast low flows (BAKO, ET AL., 1988) and commonly occur as an integrated part in real-time flood forecasting (TALLAKSEN, 1995).

### 3.1.1 Basic analytical expressions

Most of the recession analyses used by TALLAKSEN (1995) are differentiated from a theoretical point of view, starting with basic flow equations and modelling recession as a reservoir outflow. Modelling recession as an autoregressive process and based on empirical relationships is not described because this is irrelevant for this study.

#### Recession modelling from basic flow equations

The basic differential equation was presented by BOUSSINESQ (1877) and describes a transient outflow of a large unconfined aquifer into the stream bed under idealized conditions which means no evapotranspiration, leakage or recharge. BOUSSINESQ (1904) linearized the differential by making simplifying assumptions which lead to Equation 3.1 and the alternative forms (3.2) or (3.3), where $Q_t$ is discharge at time t, $Q_0$ is discharge at time t = 0. $C$, $a_1$ and $k$ are constants.

$$Q_t = Q_0 exp^{(-\frac{t}{c})} \tag{3.1}$$

$$Q_t = Q_0 exp^{(-a_1 * t)} \tag{3.2}$$

$$Q_t = Q_0 k^t \tag{3.3}$$

First applications of these equations are made by MAILLET (1905) under different boundary conditions, like steady state flows, problems of stability of flow, influence of basin geometry and size and the effects of antecedent precipitation.

HORTON (1933) suggested following nonlinear relationship where $a_2$ and $m$ are constants.

$$Q_t = Q_0 exp\,(-a_2 t^m) \qquad 3.4$$

This equation can be derived by a simple time transformation (HALL, 1968). BOUSSINESQ (1904) presented a solution for the nonlinear differential equation, under conditions that assume negligible vertical flow components and the effect of capillarity above the water table can be neglected (“Depuit-Boussinesq conditions”), a typical curvilinear water table and a zero water level in stream channel (TALLAKSEN, 1995) that leads to following equation with constant $a_3$.

$$Q_t = Q_0(1 + a_3 * t)^{-2} \qquad 3.5$$

WERNER, ET AL., (1951) described the outflow of a confined aquifer, with $Q_t$ as sum of n exponential terms and constants $a_i$ and $b_i$,

$$Q_t = Q_0 * \sum b_i * exp(-a_i * t) \qquad 3.6$$

and for unconfined aquifers, based on theoretical considerations as well as real observations:

$$Q_t = \frac{Q_0}{(1 + a_4 * t)^2} \qquad 3.7$$

**Modelling Recession as reservoir outflow**

TALLAKSEN (1995) underlined that the simple exponential equation does not generally represent the recession flow over a wide range of flows. Also she was in favour of representing the catchment storage by a nonlinear approach or conceptually modelled by more than a single reservoir. Outflow, as given in Equation (3.1) is equivalent to the outflow from a simple linear storage model with no inflow components with storage volume S and parameters $p$=1 and $k$=1/$C$ (Equation 3.8). The outflow of this lumped storage can be characterized by following equation.

$$Q = K * S^p \qquad 3.8$$

To prove the linearity of the storage-discharge relationship, the hydrograph should be plotted semilogarithmically (TALLAKSEN, 1995). A linear relationship can be obtained if the recession curve is a straight line ($p$=1), $p > 1$ result in a concave downward, $p < 1$ in a convex type of curve (MITCHELL, 1972). Typically are results for $p$ <1.

Equation (3.8) with p as a function of $S$ can account for a continually changing relationship between $Q$ and $S$, i.e. with constants $K$ and $q$.

$$Q = K * S^{(1+qS)} \qquad 3.9$$

This storage formulation is chosen in recession analysis from WITTENBERG (1994). The recession progress is commonly formulated in terms of the reservoir outflow, which can be described by the continuity equation.

$$I - Q = {ds}/{dt} \qquad 3.10$$

For nonlinear models and no inflow conditions, the outflow is given by (BRUTSAERT, ET AL., 1977) where $a_5$ is a constant.

$$Q_t = Q_0(1 + a_5 t)^{p/1-p} \qquad 3.11$$

Equation (3.11) equals the expression for $p$=2 in equation (3.5) which shows that the aquifer modelled by (3.5) has the same drainage characteristics as a lumped storage model of second order (Tallaksen, 1995).

### 3.1.2 Application areas

As written previously a quantitative analysis of streamflow recession analysis and the finding of analytic expressions and mathematical models can be traced back to BOUSSINESQ (1877, 1904) and MAILLET (1905).

In this section a short review of selected papers of applied recession analysis and transfer function models will be given.

In TOEBES, ET AL., (1964) different exponential recession curves where tested in catchments in New Zealand and Australia. Best fit for baseflow was obtained with a double exponential type of recession curve. The conclusions are that for practical purposes a characteristic, empirical low water flow curve for each stream is necessary.

CLAUSSEN (1992) modeled streamflow recession in two Danish streams in order to obtain hydraulic parameters. Best fit was obtained also by advancement of the single exponential equation 3.2 to

$$Q_t = B + CK^t \qquad 3.12$$

where K is a constant for each catchment and B and C are constant s within each recession.
WITTENBERG (1994) introduced the following non-linear storage-discharge relationship. By insertion equation 3.8 into the “continuity equation” of a storage without influent conditions (*dS/dt=-Q*) the formula to calculate stream flow recession of a nonlinear storage can be differentiated (a detailed examination to differentiation can be found in Wittenberg (1999) with initial Value $Q_0$, time steps of $\Delta t$ = 1 and parameter values of *a* and *b*:

$$Q_t = Q_0 * \left(1 + \frac{(1-b) * Q_0^{(1-b)}}{a * b} * t\right)^{\frac{1}{b-1}} \qquad 3.13$$

WITTENBERG (1994) applied the recession model in gauged catchments in northwest Germany (e.g. Ferndorf River at Kreuztal) and the Ping Fei Meng region, China. Generally he obtained best fits with values of b around 0.4 for unconfined aquifers which is far away from the results of a linear reservoir model (b = 1). The non-linear approach shows also in many cases better estimations than using the two parallel linear reservoirs.
WITTENBERG (1999) simulated recession curves at more than 80 gauging stations in Germany and used the transfer function model for baseflow separation and to estimate groundwater recharge. This approach was also successfully applied in the Harris River Catchment in south-western Australia to estimate groundwater balances (WITTENBERG, ET AL., 1999).

GRIFFITHS, ET AL., (1997) applied an exponential recession equation with two and three parameters in seven New Zealand basins after singular precipitation events and stated that recession analysis is well applicable for interpolating or extrapolating data, particularly in basins where little is known about water storage behaviour.

The IHACRES model (Identification of Unit Hydrograph and Component flows from Rainfall, Evaporation and Streamflow data) estimates an effective rainfall by considering soil storage and taking temperature as an index of evapotranspiration for longer simulation periods. The total streamflow response is represented as convolution of a generalized linear transfer-function (JAKEMAN, ET AL., 1990). Applied and modified was this model in different climatic zones, e.g. in the uplands of Wales (JAKEMAN, ET AL., 1990), in ungauged catchments in S.E. Australia (POST, ET AL., 1999) and in two Brazilian catchments (LITTLEWOOD, ET AL., 2007).

KIRCHNER (2008) describes catchments in Plynlimon (Wales) where discharge primarily depends on storage volume, with a simple first-order nonlinear equation and a sensitivity function representing the sensitivity of discharge to changes in storage. On one hand discharge can be predicted from precipitation and evapotranspiration series and on the other hand KIRCHNER (2008) doing ‘hydrology backwards’ by inferring precipitation from fluctuations in streamflow.

## 3.2 Conclusions

Low flows are strong connected with baseflow which follows a typical recession curve during periods without any input. Recession analysis is a useful tool in rainfall runoff modelling and is well suited to estimate low flows. The advantage of empirical models like recession analysis is the low parameterization with low demand of physically knowledge.

The reasons for having chosen the non-linear approach are: (I) WITTENBERG (1994, 1999) proofed by his approach the non-linear relationship between storage content and discharge, (II) he obtained successful estimations of streamflow recession in catchments with different characteristics e. g. size, elevation, geology and vegetation.

By using linear approaches to describe streamflow recession maybe the system cannot be described by a single storage and one describing parameter set. Consequently it could be necessary to introduce additional storages, which must be described by different parameter sets.

# 4 Model description

## 4.1 Structure

The approach is to apply a model that transfers a temporal input (precipitation and snowmelt) into a temporal watershed output (hydrograph). The model is based on a transfer-function (WITTENBERG, 1994) which describes stream flow recession during periods of no input.

The long term climatic input is derived from regionalized 400m Climate Normals (1961-1990) of mean monthly precipitation and temperature of the ClimateBC Dataset (SPITTLEHOUSE, 2006).

During periods in which temperatures remains below zero precipitation is accumulated in snow water equivalent (SWE). During periods of positive temperatures effective rainfall, as input into the transfer function, was estimated as the precipitation and additionally snowmelt when the temperature is above zero minus actual evapotranspiration.

All calculations from preprocessing the input data transferring effective rainfall to discharge and finally the sensitivity and uncertainty analysis are written in MATLAB® (MATHWORKS, 1996). The program source codes and used functions are attached in the Appendix (A 1).

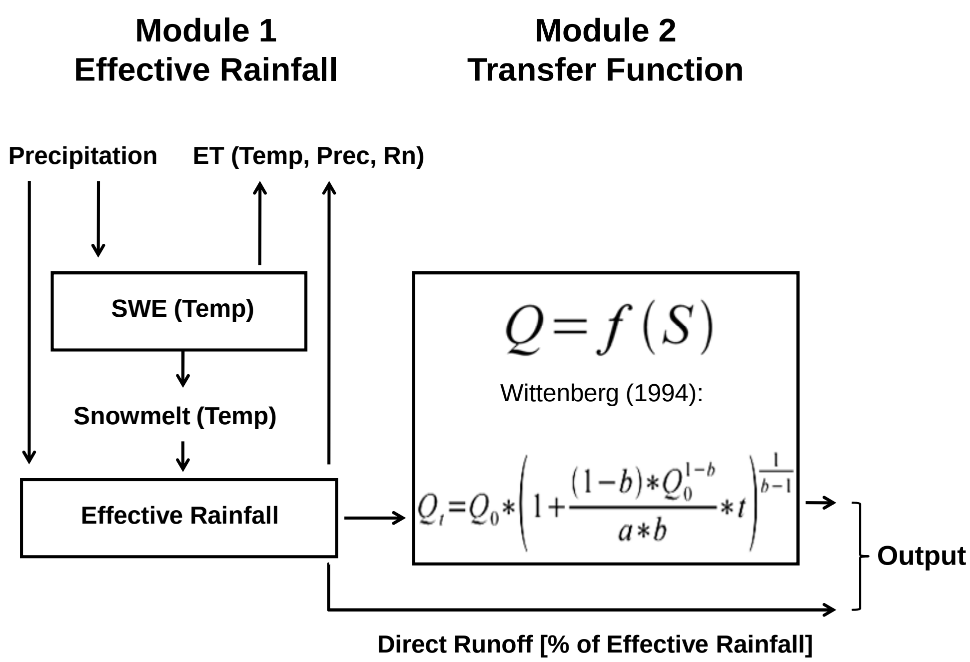


Figure 4.1: Conceptual Model

## 4.2 Module 1 - Effective Rainfall

Monthly precipitation and temperature data are disaggregated into daily values by applying the running average for each 400m grid cell within the watershed. Inactive cells are set to zero. Snow accumulation, snowmelt and evapotranspiration are calculated separately for each active grid cell. The resulting effective rainfall, the mean average of all active cells at every time step, is used as input into the transfer function model.

### 4.2.1 Evapotranspiration

Conforming to the simple approach of the low parameterized transfer function model the evapotranspiration routine should have as few parameters as possible. In this thesis potential evapotranspiration *PET* is calculated by the approach of PRIESTLEY AND TAYLOR (PRIESTLEY, ET AL., 1972). The PRIESTLEY AND TAYLOR method is well suited to estimate *PET*, particularly on a daily basis, under non water-supply limited conditions and was often used in these climatic regions (BLACK, 2008, MCNAUGHTON, ET AL., 1973). It requires only the knowledge of the daily net radiation and air temperature. Mean daily temperature data were taken from ClimateBC dataset (SPITTLEHOUSE, 2006) while the mean monthly net radiation *Rn* [MJ/$m^2$/d] data was derived from the Canadian Ecodistrics Climate Normals (POLE STAR GEOMATICS INC. (PSG), 1997).

**Potential evapotranspiration**

The Priestley and Taylor Method (PRIESTLEY, ET AL., 1972) for calculating daily *PET* [mm/d] replaces the aerodynamic term of Penman-Monteith equation by a dimensionless empirical coefficient α. PRIESTLEY AND TAYLOR (1972) established a “best estimate” of $\alpha_{pt}$=1.26. Such $\alpha_{pt}$ coefficient turned out to be generally constant in landscapes where vegetation cover is almost complete and moisture availability for evaporation is unlimited (ENGSTROM, ET AL., 2002). Under drier or varied vegetation conditions large deviations in α have been reported.

A decreasing of soil moisture depends on different types of vegetation or climatic conditions, which causes that $\alpha_{pt}$ decreases due to the surface restrictions of ET rates. VISVANADHAM, ET AL., (1991) estimated a value of $\alpha_{pt}$ =1.03 in a rainforest, MCNAUGHTON, ET AL., (1973) a value of $\alpha_{pt}$ = 1.05 in a Douglas fir stand (BC-Vancouver Island) and DE BRUIN, ET AL., (1982) α=1.12 for grass.

$$PET = \alpha_{pt} * \frac{1}{\lambda * p_w} * \frac{s * (R_n - G)}{s + \gamma} \qquad 4.1$$

Hereby, λ [MJ/kg] stands for the latent heat of vaporization, *Rn* [MJ/m$^2$/d] for the net Radiation, G [MJ/m$^2$/d] for the soil heat flux (which can be ignored for daily calculations), s [kPa/°C] for the slope of the saturation vapour pressure divided by temperature and γ the psychrometric constant.

The latent heat of vaporization λ as a function of temperature is given by (DINGMAN, 2002 P. 274) through the following relationship:

$$\lambda = 2.5 - 2.63 * 10^{-3} * T \qquad 4.2$$

and the slope *s* of the relationship between saturation vapor pressure and temperature as (DINGMAN, 2002 P. 273):

$$s = 0.611 * exp^{\left(\frac{17.3*T}{T+237.3}\right)} \qquad 4.3$$

The psychrometric constant is not strictly a constant because pressure is a function of elevation and varies slightly over the time at a given location while latent heat varies slightly according to the change of temperature. The decrease of pressure with elevation should be accounted for when estimating γ [kPa/°C] at high elevations (DINGMAN, 2002 P. 274).

$$\gamma = \frac{c_a * P}{0.622 * \lambda} \qquad 4.4$$

*P* stands for the atmospheric pressure [kPa] depending on elevation and λ for the latent heat of vaporization. The heat capacity of air $C_a$ is equal to 1.0*10$^{-3}$ [MJ/kg/°C].

**Actual evapotranspiration**

Calculating actual evapotranspiration *AET* without any additional physically based parameters (e.g. soil moisture deficit, maximum water availability, field capacity, wilting point) is a difficult task.

Concerning the concept of a low parameterized model and the lack of additional data, and the use of mean precipitation and temperature data the approach of TURC (1954) should suffice to reduce PET.

In regions where potential evapotranspiration *PET* exceeds precipitation, actual average evapotranspiration *AET* is limited by the amount of precipitation. In regions with sufficient rainfall during all seasons, evapotranspiration is limited by the available energy so that *AET* is equal to *PET*. TURC (1954) AND PIKE (1964) thus reasoned that mean annual evapotranspiration is determined by the ratio of average precipitation *W[mm/a]* to *PET[mm/a]* and proposed the following relationship:

$$AET = \frac{Prec}{\sqrt{0.9 + (Prec/PET)^2}} \qquad 4.5$$

Because mean monthly precipitation data was disaggregated into daily values, there are no days with no precipitation input. That makes it possible to apply this method at every time step. So that during periods where precipitation [mm/d] exceeded *PET* [mm/d], *AET* [mm/d] was equal to *PET* and during periods where PET exceeded precipitation, *AET* was equal to the mean precipitation (see FIGURE 4.3).

Note that this approach is only suited in cases where mean precipitation series are used with inputs at every day. It is impossible to calculate *AET* for real time series in this way when there are days of no precipitation input. The consequence would be that on those days, evapotranspiration would be zero as well. According to this approach no water can evaporate that was falling as precipitation on the previous day.

**Outlook**

When calculating with real time-series a further development of the evapotranspiration routine is necessary. The following section should demonstrate basically suited simple approaches for estimating actual evapotranspiration.

BUDYKO (1963) described, that actual evapotranspiration depends linearly on the soil moisture content. Indeed, in order to estimate the ‘critical soil moisture’, -the threshold on which *AET* becomes smaller than *PET*-, it is necessary to know about soil moisture parameters. This approach has often been discussed and further developed to describe *AET*. There were introduced empirical factors, to estimate AET (ZHANG, ET. AL., 2008), DONOHUE, ET AL., (2007) proposes to implicate vegetation parameters as well as CALDER, (1992) and CALDER, ET AL., (2003) who introduced for the HYLUC (Hydrological Land Use Change) model additional empirical parameters for different vegetation types.

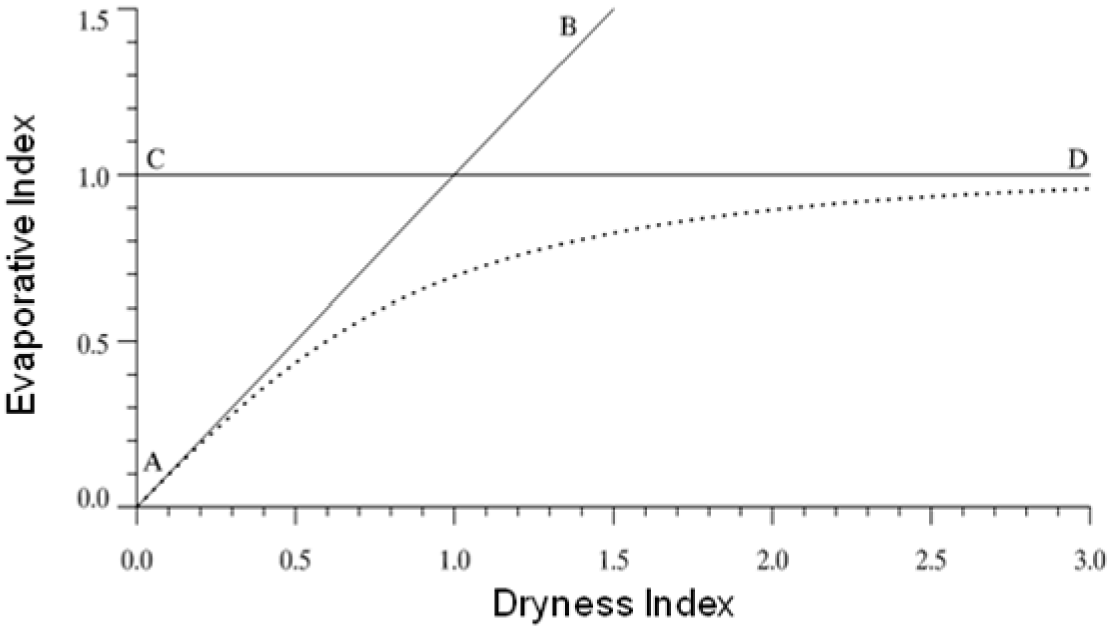


Figure 4.2: The Budyko curve (dotted line) describes the relationship between the dryness index (PET/Prec) and the evaporative index (AET/Prec). Line A-B defines the energy-limit to evapotranspiration, and line C-D defines the Water limit (according to ZHANG, ET AL., (2008)).

Other commonly used approaches to estimate effective rainfall for rainfall-runoff models are based on soil moisture accounting modules without the need of soil parameters. These approaches range from closing the water balance to estimate *AET* to different further developments of the antecedent precipitation index *API*, like the catchment moisture deficit (EVANS, ET AL., 1998) or the catchment wetness index (JAKEMAN, ET AL., 1990). It introduces two calibration parameters: the temperature modulating factor *refp*, and a parameter for drying time *Tw* and a factor to adapt the volume of observed to simulated discharge *v* (WAGENER (1), ET AL., 2004). These methods where successfully applied in different climatic regions (e.g. JAKEMAN, ET AL., 1990; JAKEMAN, ET AL., 1993; LITTLEWOOD, ET AL., 2007).

To calibrate these models it may be useful to estimate actual evapotranspiration by measurements of latent heat fluxes from different test sites in Canada. These Data are available on the Fluxnet Canada Data Information System (FLUXNET CANADA, 2008).

### 4.2.2 Snowmelt

The snow melt routine is based on the empirical degree-day temperature-index approach of the HBV model (e.g. BERGSTRÖM, 1976, SEIBERT, 1997). The temperature-index approaches have been developed because of the difficulty of fulfilling the data requirements of physically based energy-balance approaches and estimates snowmelt for daily or longer time period as a linear function of average air temperature (DINGMAN, 2002 P. 210).
During periods of air temperatures below zero, all precipitation is accumulated in Snow Water Equivalent *SWE* [mm]. In spring, when temperatures become positive, daily snowmelt is given by

$$q_{melt} = ddf(T_{AIR} - T_{M}) \qquad if\ T_{AIR} > T_M \qquad 4.6$$

$$q_{melt} = 0 \qquad if\ T_{AIR} < T_M \qquad 4.7$$

Hereby, $q_{melt}$ stands for the calculated snowmelt [mm/d], *ddf* the degree-day factor [mm/°C/d], $T_{AIR}$ the mean daily Temperature [°C] and $T_M$ the melting temperature [°C].
Additional the HBV model snowmelt module includes the possibility to store water in the snow pack. The amount of water that can be stored in the snow pack, *RLW* (retained liquid water [mm]) is controlled by the holding capacity *HC* [-], a parameter representing the fraction of *SWE* that can be retained in the liquid phase. By the time when *RLW* exceeds the liquid water retaining capacity *LWRC* [mm] which is calculated by *SWE**HC* excess water becomes effective rainfall.

In FIGURE 4.3 it is shown the mean precipitation, the estimated snowmelt, actual evapotranspiration and effective rainfall.

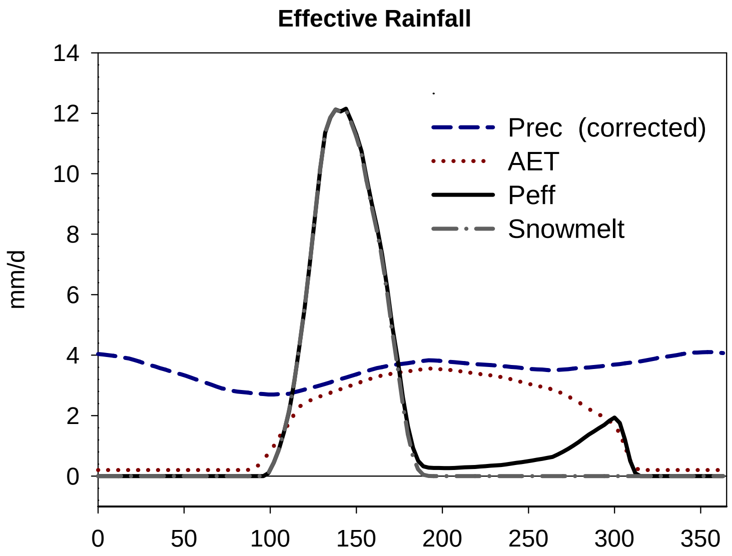


Figure 4.3: Estimated precipitation, snowmelt, evapotranspiration and effective rainfall (Little Swift River Catchment)

### 4.2.3 Parameter estimation

To obtain a better simulation, it is necessary to add some correctors to adapt the effective rainfall and close the water balance within the catchments. Because of the uncertainty of regionalized precipitation as well as in the observed discharge it may be necessary to correct rainfall. Further parameters describe the behaviour of snowmelt, evapotranspiration, and direct runoff components but generally the parameters, are set fixed for every catchment, if they are not parameters for correcting precipitation.

#### Precipitation correction

The regionalized precipitation remains uncertain (more about the used data in referred in chapter 5.1) In order to predict the observed discharge, it is often necessary to use corrected rainfall. In this thesis a rainfall correction factor $R_c$ and a snowfall correction factor $S_c$ are introduced.

#### Snowmelt:

The Degree-Day-Factor *ddf* [mm/°K] determines how much snow melts per day depending on the difference between air temperature $T_{AIR}$ and melting temperature $T_M$. In literature *ddf* values range from 1.8-3.7 mm/°C (U.S. ARMY CORPS OF ENGINEERS, 1998) and 2.0 – 4.0 mm/°C (MOORE, 1993). SEIBERT (1997) used for $T_M$ values from -2.5 to + 2.5°C. Holding

Capacity *HC* is set to 0.1. Refreezing factor *RF* is set to 0.05, but is not sensitive in this thesis because there are no cases of warmer and colder fluctuation periods during the continuous snow cover in the input data.

**Evapotranspiration**

In the evapotranspiration routine only the Priestley and Taylor Coefficient $\alpha_{pt}$ can be adapted. Usually for this work a $\alpha_{pt}$ value of 1.26 is used. Actual evapotranspiration during periods with temperatures below zero *SUB* (Sublimation) is estimated with values till 0.5 mm/d (STORCK ET. AL., 2002). To apply the Priestley and Taylor Equation it is necessary to insert the elevation [m.a.s.l.] in order to calculate atmospheric pressure *p*.

**Direct Runoff**

In some catchments it may be useful to introduce a factor for quick-flow components. The effective rainfall is split into two parts, one of which became direct runoff. The rest is routed through the transfer function module. $DR_{sm}$ [-] describes direct runoff during melting conditions, *DR* [-] for the rest of the year with positive air temperatures.

TABLE 4.1 shows the necessary parameters for describing effective rainfall in MODULE 1. Their values are generally used in this model and the proposed parameter range.

Table 4.1: Used parameters for estimating effective rainfall and their proposed parameter range

| SYMBOL | DESCRIPTION | VALUE (RANGE) | UNIT |
|---|---|---|---|
| *size* | Catchment size | | [km$^2$] |
| *ddf* | Degree-day-factor | 2 (1.8 – 4.0) | [mm/°C/d] |
| $T_m$ | Melting temperature | 0.0 (-2.5 – 2.5) | [°C] |

| | | | |
|---|---|---|---|
| *HC* | Holding capacity | 0.1 | [-] |
| $\alpha_{pt}$ | Priestley and Taylor coefficient | 1.26 | [-] |
| *elev* | Mean basin elevation | | [m a.s.l] |
| *SUB* | Evapotranspiration from snow | 0.5 (0.1 – 0.7) | [mm/d] |
| $DR_{SM}$ | Direct runoff during snow melt peak | 0.0 (0.0 – 0.2) | [-] |
| *DR* | Direct runoff after snow melt peak | 0.0 (0.0 – 0.2) | [-] |
| $R_c$ | Corrected rainfall | 1.0 (0.6 – 1.4) | [-] |
| $S_c$ | Corrected snowfall | 1.0 (0.6 – 1.4) | [-] |

## 4.3 Module 2 - Baseflow recession as nonlinear storage processes according to H. Wittenberg (1994)

### 4.3.1 Recession Description

The nonlinear storage-recession relationship is empirical and theoretical proved (KUBOTA, ET AL., 1995; WITTENBERG, 1994, 1999). It can be described by the following differential equation (WITTENBERG 1999) where *S* is storage, *Q* is discharge and *a* and *b* are constants.

$$S = a * Q^b \qquad 4.8$$

Through insertion of equation 4.8 into continuity equation of storage without inflow conditions (dS/dt=-Q), and differentiation (cf. 3.1.2) WITTENBERG (1994, 1999) obtained following nonlinear function:

$$Q_t = Q_0 * \left(1 + \frac{(1-b) * Q_0^{(1-b)}}{a * b} * t\right)^{\frac{1}{b-1}} \qquad 4.9$$

In catchments with large groundwater storages (WITTENBERG, 1997) in unconsolidated rock aquifers, better results may be obtained through an extended version of Equation 4.9 of a constant baseflow term $Q_1$.

### 4.3.2 Convolution

In MATLAB® effective rainfall is transferred into discharge using equation 4.9 by a convolution command (*conv*) which is based on:

$$Q(t) = \sum u(j)v(t+1-j) \qquad 4.10$$

Hereby vector $u$ is the time series of effective rainfall, vector $v$ the standardized recession of equation 4.9. The following example should demonstrate the principle of equation 4.10:

$$Q(1) = u(1) * v(1)$$
$$Q(2) = u(1) * v(2) + u(2) * v(1)$$
$$Q(3) = u(1) * v(3) + u(2) * v(2) + u(3) * v(1)$$
$$\dots$$
$$Q(n) = u(1) * v(n) + u(2) * v(n-1) + \cdots + u(n) * v(1)$$
$$\dots$$
$$Q(2 * n - 1) = u(n) * v(n)$$

To obtain steady state conditions, a time series of 20 years of effective rainfall is convoluted with equation 4.9 and only the hydrograph of the 20$^{th}$ year is compared with the mean observed discharge.

## 4.4 Model calibration

To avoid sensitivity and uncertainty analysis, the effective rainfall parameters won´t be calibrated by MONTE CARLO Runs. The aim is to use the same set of parameters for every catchment if possible

Only the parameters *a* and *b* of the transfer-function module become calibrated and subjected to sensitivity and uncertainty analysis.

In FIGURE 4.4 different theoretical examples of recession curves with different parameter combinations of *a* and *b* were shown. It is shown how a combination of *a* and *b* produced what a certain type of curve. Exponent *b* gives a curve its shape and it describes whether the curve is convex (b <1) or concave (b>1). Theoretically, if *b* is hold constant, *a* describes the slope of curve. Thus small values of *a* are responsible for steep while large values are associated for flat curves.

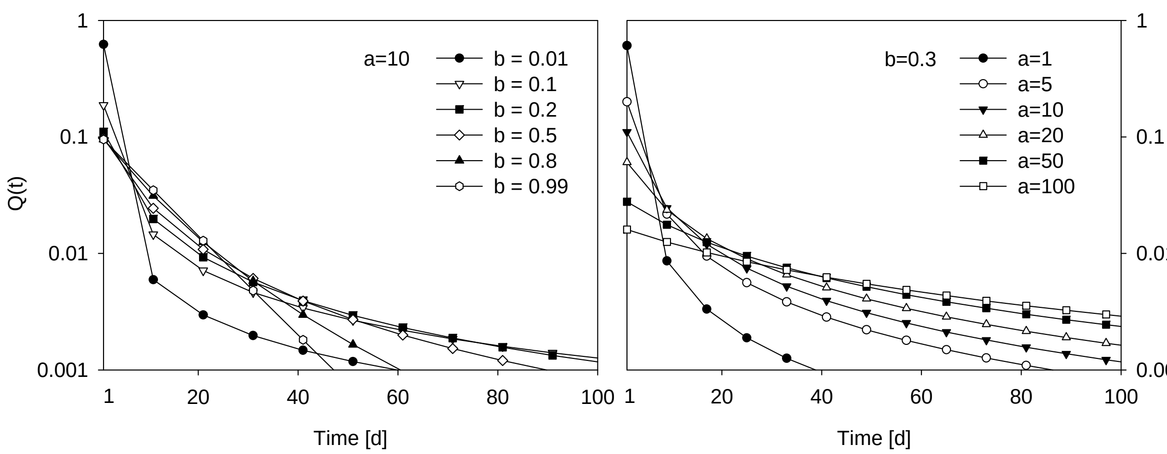


Figure 4.4: Sensitivity of the resulting recession curves of different parameter sets of a and b

To calibrate the transfer-function in WITTENBERG (1994, 1999) exponent *b* is varied systematically and the value of coefficient *a* is stetted fix (obtained by Equation 4.11), so that observed discharge is equal to predicted discharge during the considered period.

$$a = \frac{\sum(Q_{i-1} + Q_i)\Delta t}{2\sum(Q_{i-1}^b - Q_i^b)} \qquad 4.11$$

In this thesis long-term average input data of precipitation (Climate Normals 1961-1990 disaggregated to daily values) are used. The predicted discharge hydrograph (steady state conditions after 20 years) is compared with long-term (normally 20 – 30 years) running average of daily observed streamflow data. Consequently the method of WITTENBERG is unsuitable to calibrate the two parameters because the long-term water balance of observed and predicted discharge should be close to zero.

The MONTE-CARLO approach has been used here in order to find the optimum parameter set. MONTE-CARLO simulations are a common tool used in rainfall-runoff modelling to calibrate parameters (WAGENER (1), ET AL., 2004). A random function varies the parameters in the given ranges and the objective function must lead to the parameter pair that fits best. Usually the parameter range for *a* is from 1 to 100, for *b* from 0 to 1. In catchments where the optimum parameter set clearly can be identified, these parameter ranges are well suited. Usually the best fits were obtained with *b* around 0.2-0.4 and for *a* between 10 and 50. Further analysis' of the MONTE-CARLO parameter samplings like parameter sensitivity and the model-output uncertainty are done by the MONTE-CARLO ANALYSIS TOOL (MCAT) as described by WAGENER (2), ET AL., (2004).

### 4.4.1 Model performance

The efficiency of NASH-SUTCLIFFE (1970) describes the quality of fit for predicted discharge $Q_{sim}$ in relation to the mean average of observed discharge $Q_{obs}$ in every time step.

$$N_{eff} = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2} \quad (-\infty < N_{eff} < 1) \qquad 4.12$$

The values of $N_{eff}$ range from minus infinity to one, the latter value corresponds to a perfect fit. Values below zero indicate that the model deviation is larger than the natural variability and that the model should be refused.

According to the evaluation suggestion of the conventional efficiencies by HENRIKSEN ET AL. 2003 (Table 4.2) can be differentiated in following classifications.

Table 4.2: Evaluation of Nash-Sutcliffe efficiencies (according to Henriksen 2003)

| | Very poor | Poor | Good | Very Good | Excellent |
|---|---|---|---|---|---|
| $N_{eff}$ | < 0.2 | 0.2 - 0.5 | 0.5 - 0.65 | 0.65 – 0.85 | > 0.85 |

Through a logarithmic transformation of the runoff more importance can be attached to the low flow situations (SEIBERT, 1997).

$$lnN_{eff} = 1 - \frac{\sum(ln\,(Q_{obs}) - ln\,(Q_{sim}))^2}{\sum(ln(Q_{obs}) - ln\,(\overline{Q_{obs}}))^2} \quad (-\infty < N_{eff} < 1) \qquad 4.13$$

Another objective function to find the best parameter set used in this work is the Root Mean Square Error (RMSE):

$$RMSE = \sqrt{\frac{1}{N}\sum(Q_{obs} - Q_{sim})^2} \qquad 4.14$$

### 4.4.2 Sensitivity and uncertainty analysis

Sensitivity analysis is a method to find out how changes in model parameters affect the model output. This information can be used to identify parameters that are not important for the reproduction of the system response and helps to analyse the function a=f(b).
Dotty plots are a useful tool to find the optimum set of parameter as well as the sensitivity of each parameter. Note that MCAT is calculating only minimum functions, consequently in FIGURE 4.5 “*1-$N_{eff}$* “ is shown below. That means best fit is close to zero.

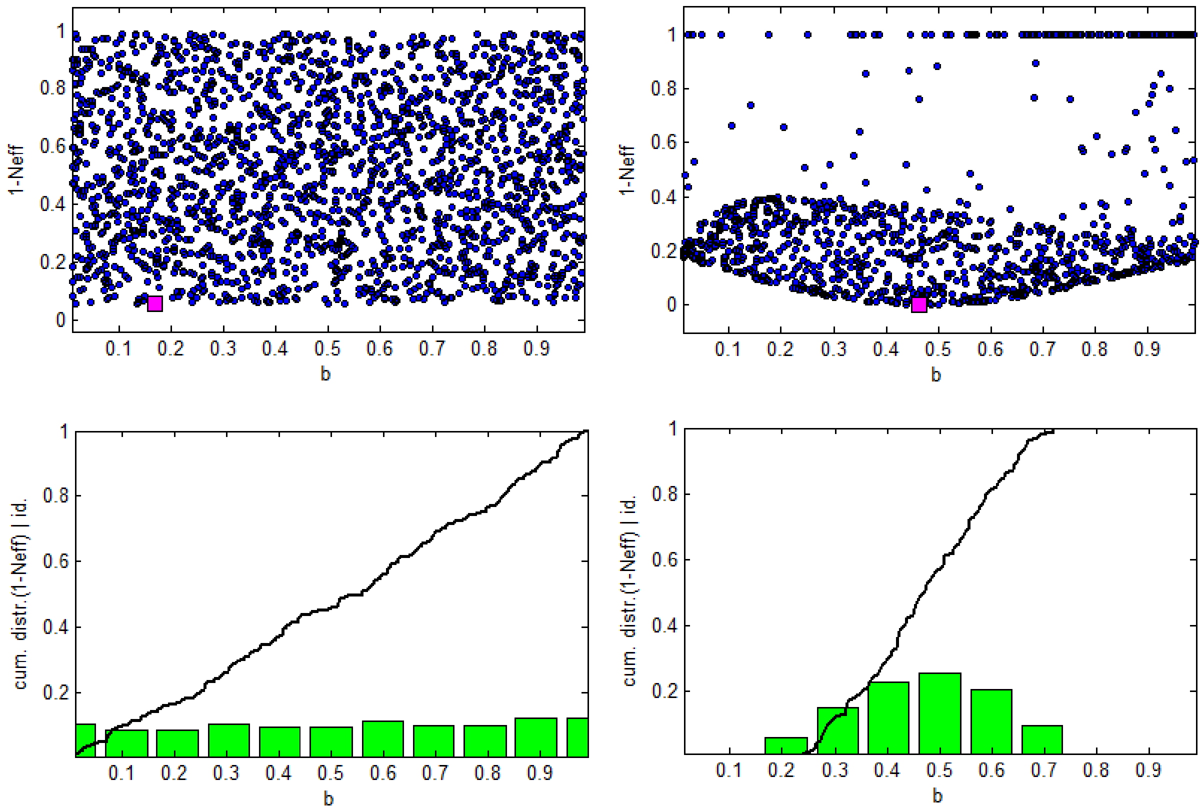


Figure 4.5 Example of well identified parameter (right column) and a poorly identified Parameter (left column). The bottom row shows the cumulative distribution of the best performing 10 % of parameter sets and the corresponding gradients with each segment of the parameter range (Calculated with MCAT (WAGENER (2), ET AL., 2004).

The output uncertainty in this thesis is produced by the MCAT (WAGENER (1), ET AL., 2004) which is based on the Generalized Likelihood Uncertainty Estimation (GLUE) method (BEVEN, ET AL., 1992). The GLUE method is one of the most popular approaches for uncertainty prediction in rainfall-runoff modelling (WAGENER (1), ET AL., 2004; UHLENBROOK, ET AL., 1999).

In GLUE not a single optimum parameter is identified, but instead a population of possible (behavioural) parameter sets can be estimated (WAGENER (2), ET AL., 2004).

The GLUE procedure starts with MONTE-CARLO runs, sampling a large number of random parameter sets. For each point in time a cumulative frequency distribution is generated using the selected objective function (converted to likelihood by normalizing it), while the confidence intervals are calculated using linear interpolation (BEVEN, ET AL., 1992; WAGENER, ET AL., 2007).

To make a difference between behavioural and non-behavioural models as well as in order to give the possibility to compare results and uncertainty estimations independent of the used parameter range, it is necessary to introduce a likelihood threshold (*TH*). All parameter sets which produce an objective function value above this threshold become deleted (WAGENER (1), ET AL., 2004).

The suitable threshold depends on the catchment characteristic. It is not possible to introduce a fixed value, because lower efficiencies will result in smaller uncertainty domains. So the threshold has to be selected depending of the result on each catchment, including most of the samples (WAGENER, 2008). That makes it possible to compare the thresholds of the estimated catchments. In catchments where an identification of clear structures in the parameter - objective function relationship is not possible, the threshold is set to zero (FIGURE 4.6). That proves all models (parameter sets) below zero are non-behavioural according to the theory of the NASH-SUTCLIFFE Efficiency.

Note that, the choice of the modeller of the likelihood function and the threshold between behavioural and non-behavioural models and the connected result of the uncertainty estimation is subjective.

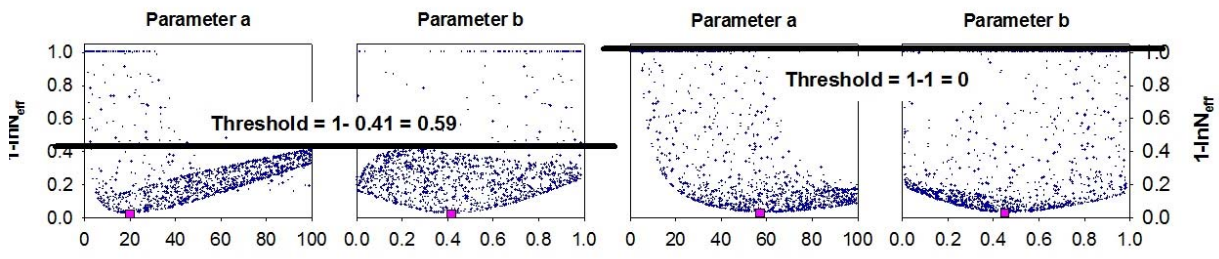


Figure 4.6 Dotty Plots with selected thresholds

In Rainfall-Runoff modelling the performance of the uncertainty estimation method should be generally tested in a similar fashion by verification on independent data in order to split-test model calibration and validation (WAGENER (1), ET AL., 2004). Because of the use of long-term mean average climate and discharge data, and the lack of timeseries for other periods, validation has to be dispensed with.

### 4.4.3 Significance tests

To compare recent and simulated discharge (according to climate change scenario) and uncertainty domains, the KOLMOGOROV-SMIRNOV significance test is used (HAAN, 2002 P. 213 ET SEQ.). The KOLMOGOROV-SMIRNOV test compares the cumulative frequency distributions of values around the best prediction plot *X1* and the simulated discharge *X2* at every time step. The null hypothesis *(h=0)* of this test is that *X1* and *X2* are drawn from the same continuous distribution. The alternative hypothesis *(h=1)* is that they are drawn from different distributions and indicate a failure to reject the null hypothesis at the 5% significance level.

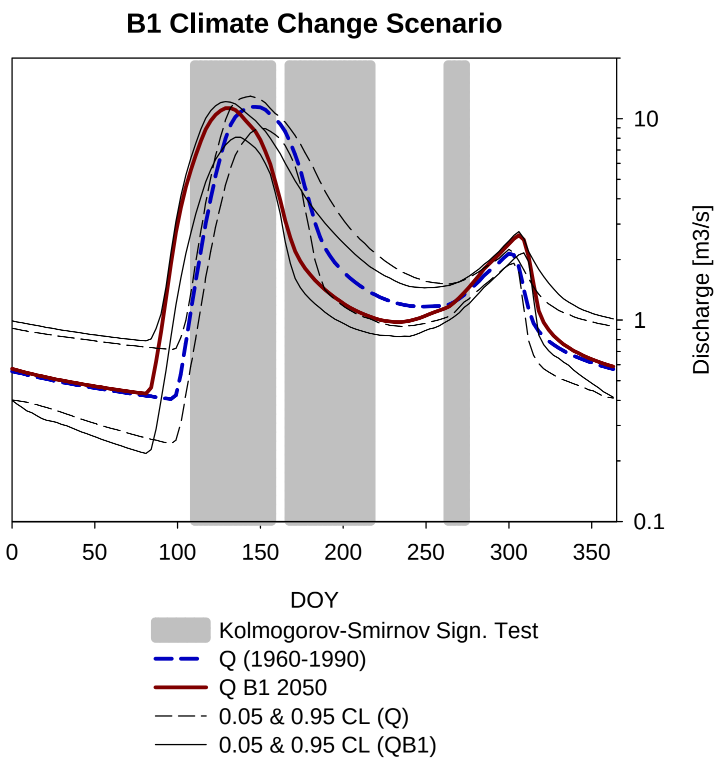


Figure 4.7 Significant changes (grey) of discharge hydrograph calculated by the KOLMOGOROV-SMIRNOV test (Little Swift River).

## 4.5 Conclusions

The aim of a low parameterized model was obtained by renouncing calibration of effective rainfall parameters. Usually the same parameter set will be used (according to values given in literature) for every catchment but it is necessary to introduce factors for correction of precipitation (see chapter 5).

Parameter *a* and *b* of the transfer-function module become calibrated through MONTE-CARLO simulations, choosing randomly selected parameter sets. Uncertainty estimation will be done by the Monte Carlo Analysis tool (WAGENER (2), ET AL., 2004) according to the GLUE method. Uncertainties of the effective rainfall model (parameters and model structure) and uncertainties in climate change scenarios won´t be considered.

The model structure used in this thesis is optimized for calculating mean time series of precipitation and temperature and is calibrated to mean daily discharge hydrographs. By changing the input data according to the climate change scenarios and consistent catchment describing parameters it is possible to forecast changes in mean daily streamflow.

The model structure does not allow calculating with real time series yet because of parts in the MATLAB® code (arguments and remarks concerning precipitation in *if-loops*) and the evapotranspiration routine. So it is e. g. not possible to forecast temporal extreme conditions like droughts or storm induced peak flows.

# 5 Model application

## 5.1 Input data

### Temperature and precipitation

Precipitation and temperature observations are essential to analyse climate and the hydrological response. However, the network of climate stations in BC is 10% smaller than the World Meteorological Organization's minimum and consequently less capable to deliver reasonable and authentic climate data (MILES, M. AND ASSOCIATES, 2003). Most climate observation stations are located in the south of BC and near the roads, but scarce in non-urban areas, small watersheds, in northern regions and higher elevations. Most of the stations are below 200 m, high elevation areas above 1000 m are not well represented (FIGURE 5.1) (RHODENHUIS, ET AL., 2007). So the knowledge of climate changes and variations in temperature, precipitation, glacier cover, snowpack and streamflow in colder and higher elevations regions in BC is not to be relied if absolutely.

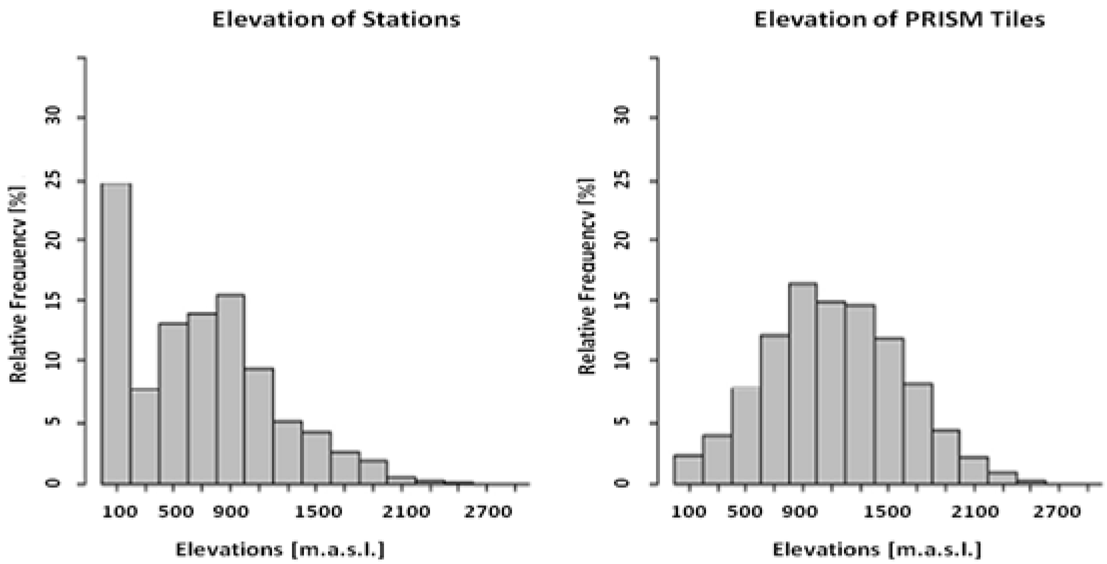


Figure 5.1: Elevation of stations are illustrated as a) relative frequency distribution of observing stations, b) relative frequency distribution of PRISM tiles and Source: PRISM data with Meteorological Service of Canada, Adjusted Historical Canadian Climate Data (RHODENHUIS, ET AL., 2007).

Therefore it is necessary to interpolate climate data between observation stations. The observational networks provides station-based estimates of air temperature and precipitation through interpolation of these point data in relation to topographic influences, called PRISM – Parameter-elevation Regressions on Independent Slope Model (DALY, ET AL., 1994). In comparison to other methods of interpolating PRISM is potentially rather more sophisticated. PRISM is a combination of climatological and statistical concepts and besides the application of a digital elevation model (DEM) to incorporate elevation and slope, PRISM integrates meteorological and climatological expert knowledge (RHODENHUIS, ET AL., 2007). The ClimateBC dataset (SPITTLEHOUSE, 2006) which is used in this thesis for precipitation and temperature input is based on the PRISM data.
Because of the lack of climate stations and the uncertainties of regionalization, especially in higher elevation regions and in the north of BC these data should be considered critically and ought to be corrected if necessary.

#### Global radiation

Global radiation *Rn* needed for the evapotranspiration routine was interpolated using gridded surface interpolation methods, since the density of the climatic station was generally inadequate for using the Thiessen approach to a 1.5 minute raster and to be extrapolated for each ecodistrict (POLE STAR GEOMATICS INC. (PSG), 1997). It should be noted that these ecodistricts have a very low spatial resolution.

#### Discharge

From 20-35 years measured discharge time series, a mean daily discharge, smoothed by a running average, is established to calibrate the model. The flag %B describes the length of the period in which the gauging station is covered by snow and ice, %E the duration of estimated data.

#### Delta-change climate scenario

The established numerous global climate models (GCM) integrate future developments in technology, economic growth and international co-operation and are available for different emission sceneries (IPCC 2007). In this thesis the Canadian Global Climate Model (CGCM) A2 and B1 sceneries (SPITTELHOUSE, 2007) are used to simulate trends in summer low flow. The A2 scenario estimates that emissions continue to increase without significant global efforts to reduce them. The B1 scenario is based on the assumption that the global community will successfully reduce emissions. The data are changes from the Climate Normals of 1960-1990 (delta-changes), expressed as a change in mean temperature or as a percentage change in total precipitation [PPT%], based on the ClimateBC Dataset (SPITTLEHOUSE, 2006).

## 5.2 Study areas

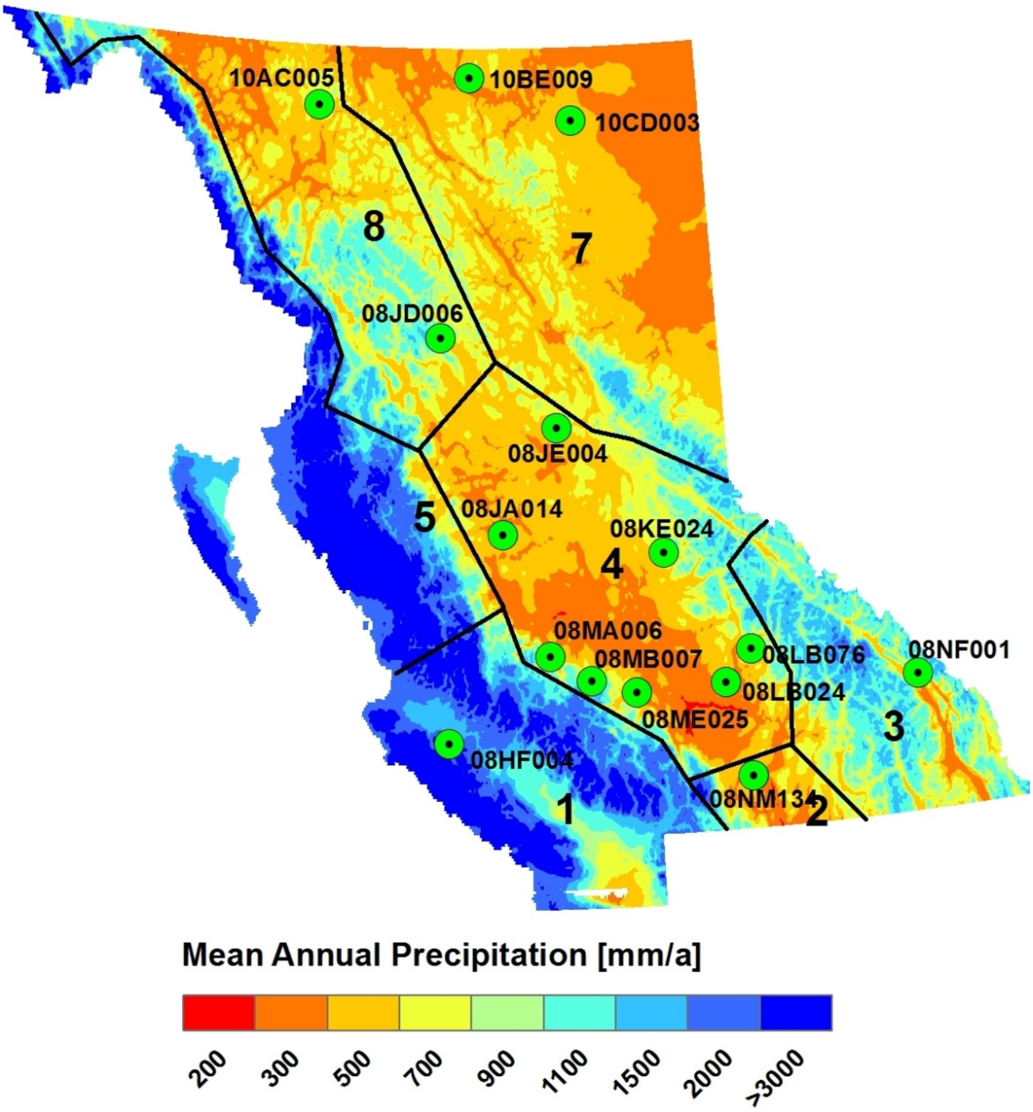


Figure 5.2: Study areas, hydro-climatic zones (RHODENHUIS, ET AL., 2007) and mean annual precipitation of BC ClimateBC Dataset (SPITTLEHOUSE, 2006)

The 15 investigation areas are selected to cover most of the hydro-climatic and vegetation regions of British Columbia. The criteria's for choosing these catchments are a size range from around 100 to 500 square kilometers, a low contingent of wetlands, fresh water bodies, glaciers, and permanent snow. Especially in the north of BC, catchments with these characteristics and a long-term qualitative record of discharge are very rare.

A short overview about climate, hydrological response, geology (BC_geology_alb: MASSEY, N. W. D. ET AL., 2005), vegetation and BTM landuse zones (Baseline Thematic Mapping: PROVINCE OF BRITISH COLUMBIA, 2001) are given in tabulation for every catchment. Detailed maps of topography and the BTM landuse zones are attached in the Appendix (A 2).

Table 5.1: Overview of the most important BTM land use zones in British Columbia (PROVINCE OF BRITISH COLUMBIA, 2001)

| | |
|---|---|
| Alpine | Areas virtually devoid of trees at high elevations. |
| Barren Surfaces | Rock barrens, badlands, sand and gravel flats, dunes and beaches where unvegetated surfaces predominate. |
| Glaciers and Snow | Glaciers and permanent snow. |
| Old Forest | Forest greater than or equal to 140 years old and greater than 6 meters in height. |
| Recently Burned | Areas virtually devoid of trees due to fire within the past 20 years. Forest less than or equal to 15% cover. |
| Recently Logged | Timber harvesting within the past 20 years, or older if tree cover is less than 40% and under 6 meters in height. |
| Shrubs | Naturally occuring shrub cover with less than 50% coverage. This class of ground cover occurs in Northern BC on rich mid-slope positions or along valley bottoms which act as frost pockets. |
| Sub-alpine Avalanche Chutes | Areas below the tree line that are devoid of forest growth due primarily to snow avalanches. Usually herb or shrub covered |
| Wetlands | Wetlands including swamps, marshes, bogs or fens. |
| Young Forest | Forest less than 140 years old and greater than 6 meters in height. |

### 5.2.1 08HF004 - Tsitika River below Catherine Creek

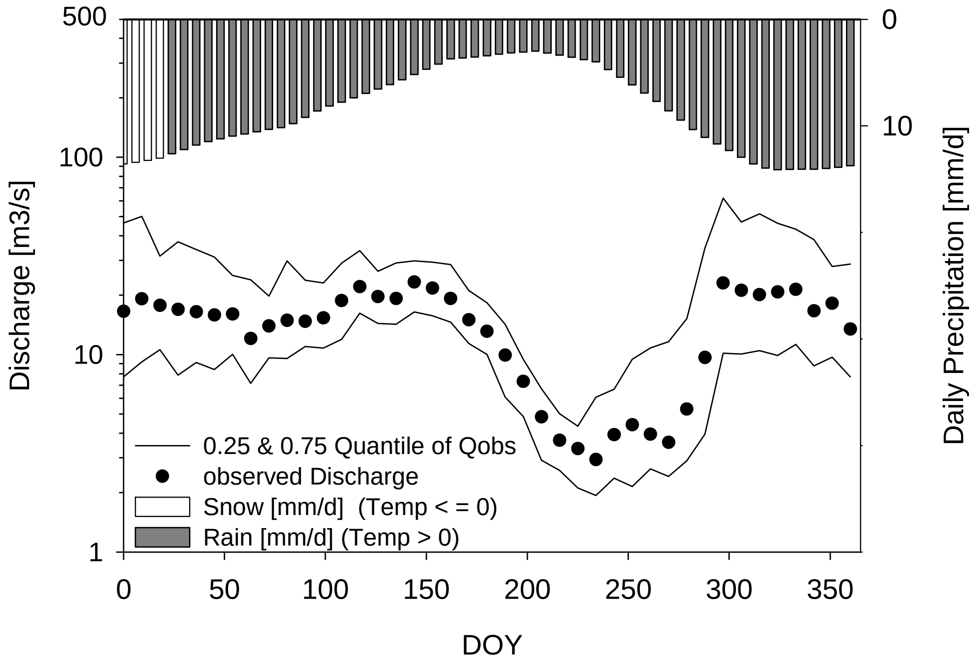


Figure 5.3: Mean discharge (1977-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08HF004)

Table 5.2: Catchment characteristic (08HF004)

| Tsitika River below Catherine Creek | | | |
|---|---|---|---|
| Mean basin elevation [m] | 892 | **Climate** | |
| Basin area [km$^2$] | 360 | Mean annual precipitation* [mm] | 3201 |
| Max discharge [m$^3$/s] | 617 | Mean annual temperature* [°C] | 8.89 |
| Min discharge [m$^3$/s] | 0.829 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 22;1943 | Old forest (Hemlock) | 74% |
| % B (Covered by ice and snow) | 0.59 | Recently logged | 13% |
| % E (Estimated) | 12 | Subalpine avalanche chutes | 6% |
| **Geology (BC_geology_alb)** | | Alpine (Alpine Tundra) | 6% |
| Rock Class: Intrusive rocks, volcanic rocks | | | |
| Rock type: Basaltic volcanic rocks, granodioritic, intrusive rocks | | | |

**ClimateBC Dataset (Spittlehouse, 2006)*

### 5.2.2 08NM134 - Camp Creek at the Mouth near Thirsk

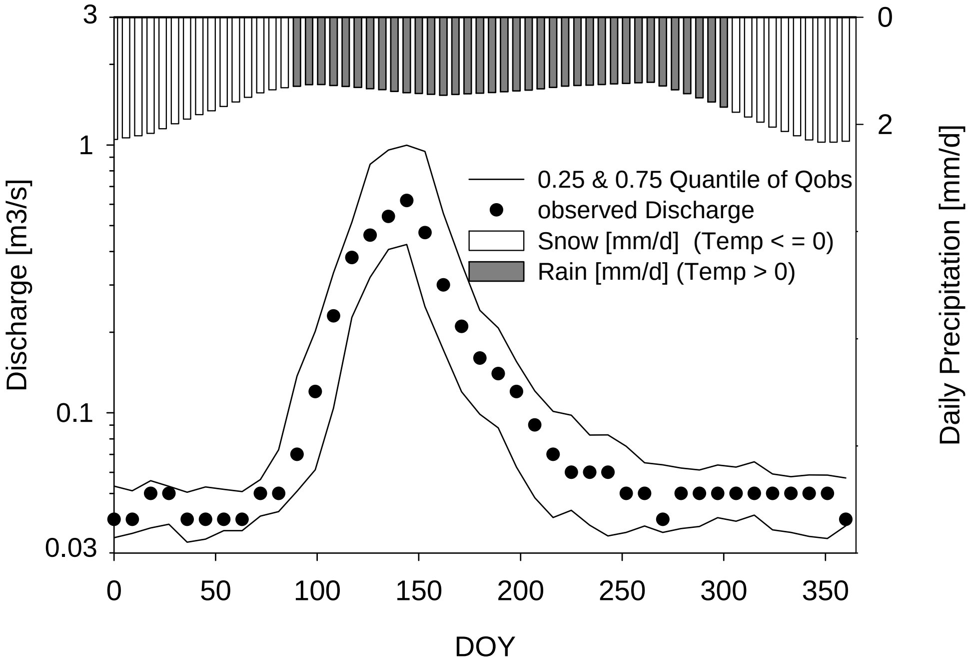


Figure 5.4: Mean discharge (1969-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08NM134)

Table 5.3: Catchment characteristic (08NM134)

| **Camp Creek at the Mouth near Thirsk** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1572 | **Climate** | |
| Basin area [$km^2$] | 33.9 | Mean annual precipitation* [mm] | 584 |
| Max discharge [$m^3/s$] | 3 | Mean annual temperature* [°C] | 2.67 |
| Min discharge [$m^3/s$] | 0.0127 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [$m^3/s$; mm/a] | 0.12;116 | Old forest (Fir, Spruce) | 41% |
| % B (Covered by ice and snow) | 22 | Young forest (Fir, Spruce) | 23% |
| % E (Estimated) | 1 | Recently logged | 35% |
| **Geology (BC_geology_alb)** | | | |
| Rock Class: Intrusive rocks | | | |
| Rock Type: Granite, alkali feldspar, grandodioritic Rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.3 08NF001 – Kootenay River at Kootenay Crossing

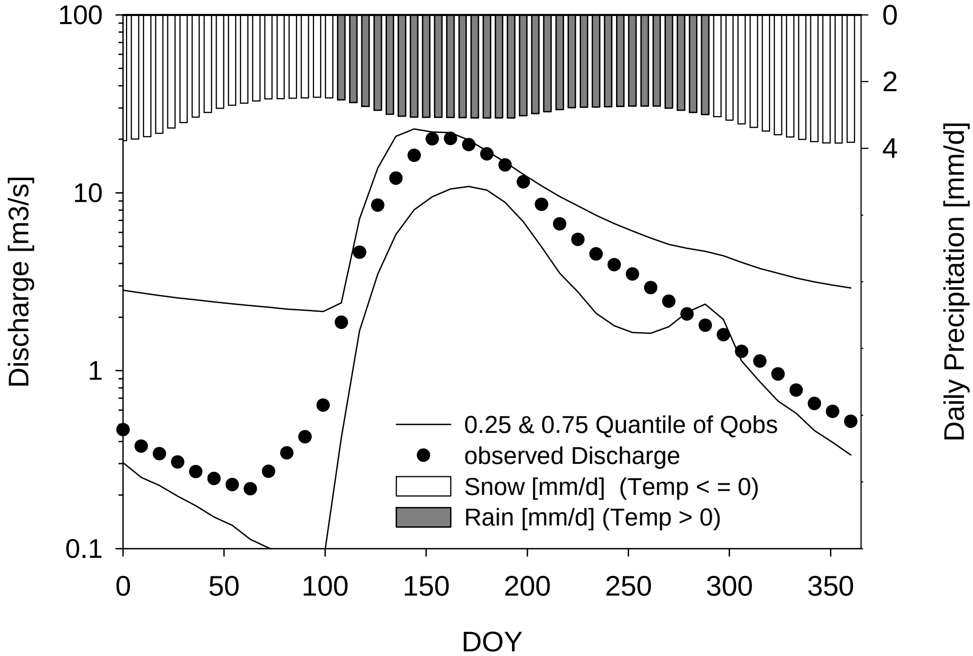


Figure 5.5: Mean Discharge (1969-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08NF001)

Table 5.4: Catchment characteristic (08NF001)

| Kootenay River at Kootenay Crossing | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1861 | **Climate** | |
| Basin area [km$^2$] | 420 | Mean annual precipitation* [mm] | 1112 |
| Max discharge [m$^3$/s] | 53 | Mean annual temperature* [°C] | 0.41 |
| Min discharge [m$^3$/s] | 0 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 4.9;366 | Young forest | 28% |
| % B (Covered by ice and snow) | 24 | Old forest | 26% |
| % E (Estimated) | 14 | Recently logged | 17% |
| **Geology (BC_geology_alb)** | | Alpine | 16% |
| Rock Class: sedimentary rocks | | Subalpine avalanche chutes | 9% |
| Rock Type: mudstone, siltstone, shale fine clastic sedimentary rocks, dolomitic carbonate rocks, undivided sedimentary rocks | | Wetlands/Glaciers/Agriculture | <4% |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.4 08JA014 - Van Tine Creek near the Mouth

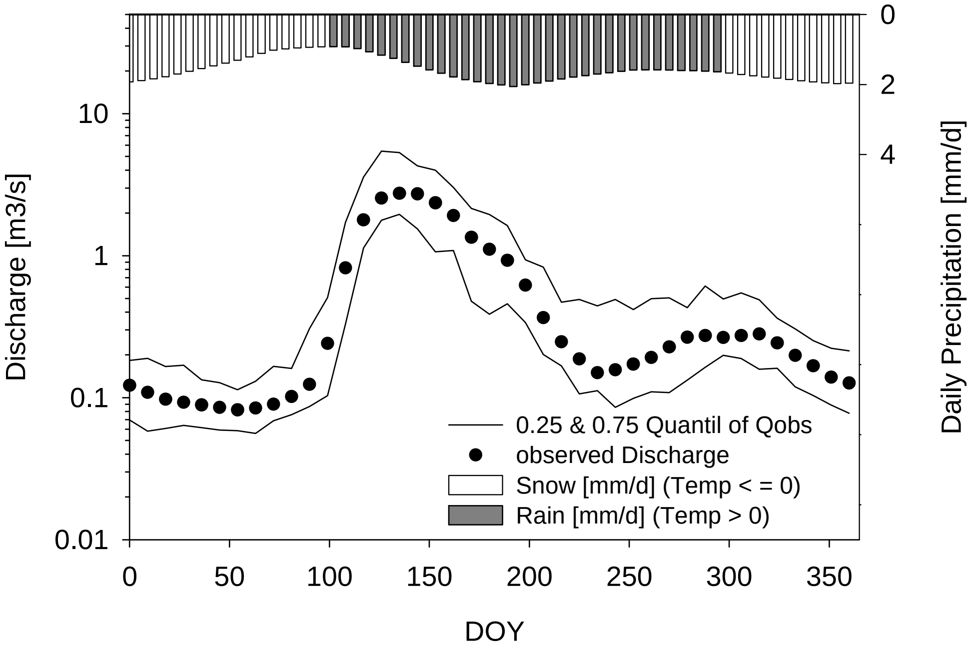


Figure 5.6: Mean discharge (1975-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08JA014)

Table 5.5: Catchment characteristic (08JA014)

| Van Tine Creek Near the Mouth | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1394 | **Climate** | |
| Basin area [km$^2$] | 153 | Mean annual precipitation* [mm] | 582 |
| Max discharge [m$^3$/s] | 24 | Mean annual temperature* [°C] | 1.01 |
| Min discharge [m$^3$/s] | 00.5 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 4.9;366 | Old forest | 66% |
| % B (Covered by ice and snow) | 46 | Young forest | 22% |
| % E (Estimated) | 2 | Recently logged | 6% |
| **Geology (BC_geology_alb)** | | Wetlands | 3% |
| Rock Class: Volcanic rocks, intrusive rocks | | | |
| Rock type: Volcanic rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

## 5.2.5 08JE004 - Tsilcoh River near the Mouth

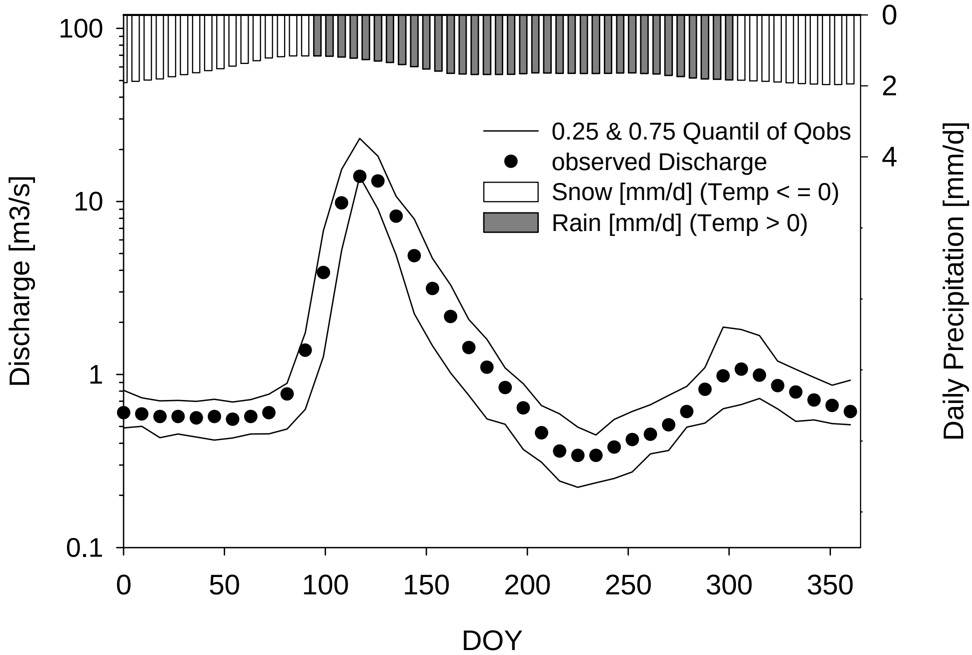


Figure 5.7: Mean discharge (1976-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08JE004)

Table 5.6: Catchment characteristic (08JE004)

| **Tsilcoh River near the Mouth** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1003 | **Climate** | |
| Basin area [km$^2$] | 414 | Mean annual precipitation* [mm] | 592 |
| Max discharge [m$^3$/s] | 42 | Mean annual temperature* [°C] | 1.94 |
| Min discharge [m$^3$/s] | 0.125 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 2.4;183 | Young forest (Spruce) | 60% |
| % B (Covered by ice and snow) | 46 | Old forest (Spruce) | 15% |
| % E (Estimated) | 2 | Recently logged | 12% |
| **Geology (BC_geology_alb)** | | Wetlands | 9% |
| Rock Class: Sedimentary rocks, colcanic rocks | | | |
| Rock Type: undivided sedimentary; rocks, argillite, greywacke, wacke, conglomerate turbidites; basaltic volcanic rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.6 08KE024 - Little Swift River at the Mouth

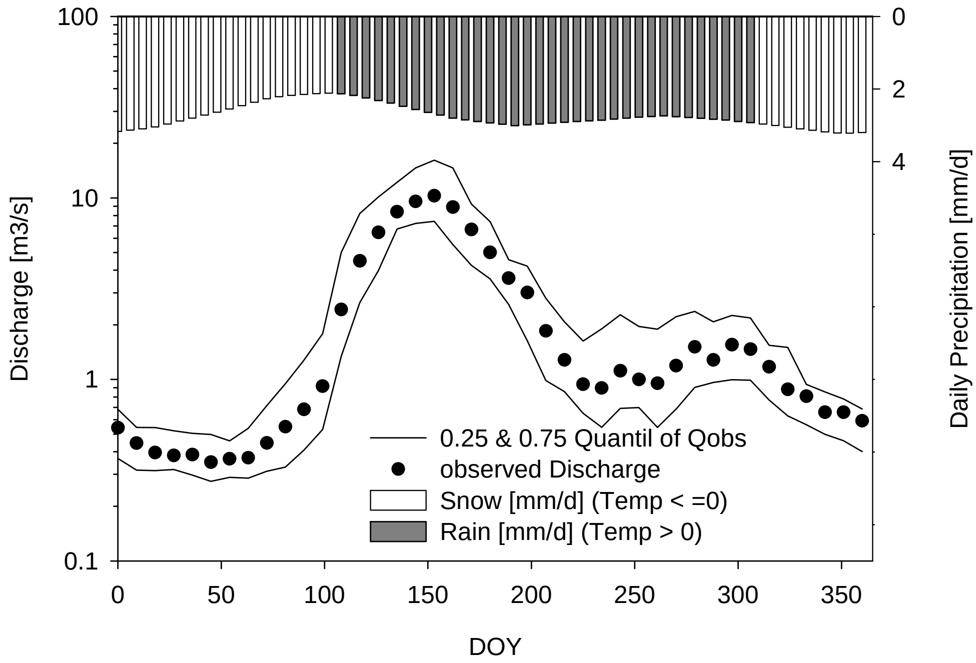


Figure 5.8: Mean discharge (1972-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08KE024)

Table 5.7: Catchment characteristic (08KE024)

| **Little Swift River at the Mouth** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1583 | **Climate** | |
| Basin area [km$^2$] | 133 | Mean annual precipitation* [mm] | 1287 |
| Max discharge [m$^3$/s] | 48 | Mean annual temperature* [°C] | 1.36 |
| Min discharge [m$^3$/s] | 0.109 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 2.8;665 | Old forest (Subalpine Fir) | 78% |
| % B (Covered by ice and snow) | 40 | Recently logged | 15% |
| % E (Estimated) | 6 | Alpine (Alpine Tundra) | 5% |
| **Geology (BC_geology_alb)** | | | |
| Rock Class: Metamorphic rocks | | | |
| Rock Type: Metamorphic rocks, argillite, greywacke, wacke, conglomerate turbidites; basaltic volcanic rocks | | | |

**ClimateBC Dataset (Spittlehouse, 2006)*

### 5.2.7 08LB024 - Fishtrap Creek near the Mouth

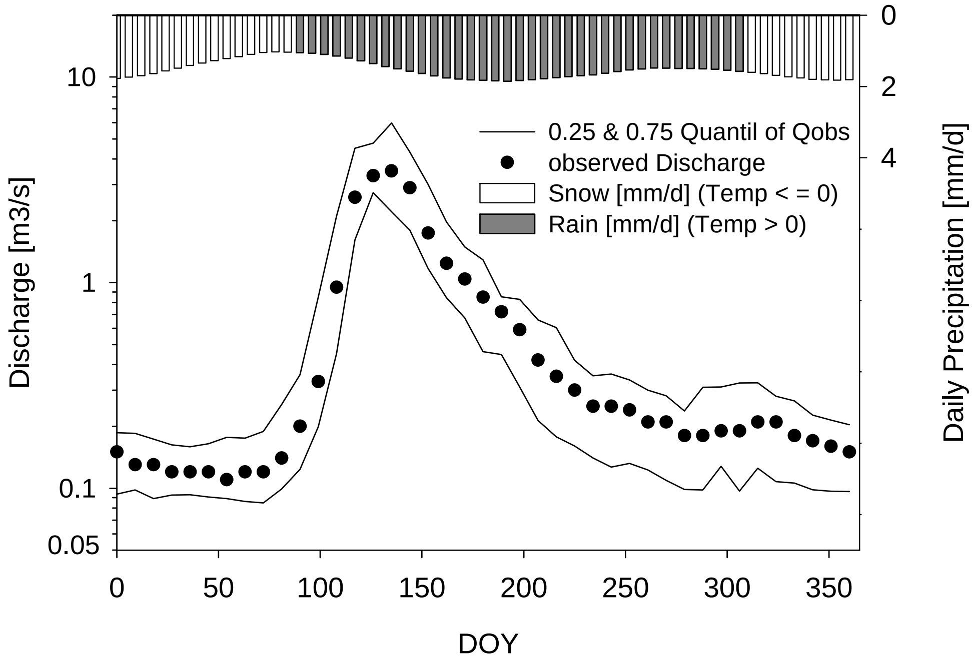


Figure 5.9: Mean discharge (1972-2002), 0.25 & 0.75 quantile and mean daily precipitation* (08LB024)

Table 5.8: Catchment characteristic (08LB024)

| Fishtrap Creek near the Mouth | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1338 | **Climate** | |
| Basin area [km$^2$] | 135 | Mean annual precipitation* [mm] | 563 |
| Max discharge [m$^3$/s] | 14 | Mean annual temperature* [°C] | 3.51 |
| Min discharge [m$^3$/s] | 0.034 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 0.8;179 | Young forest (Spruce, Fir, Cedar) | 56% |
| % B (Covered by ice and snow) | 28 | Old Forest (Spruce, Fir, Cedar) | 21% |
| % E (Estimated) | 8 | Recently logged | 23% |
| **Geology (BC_geology_alb)** | | | |
| Rock Class: Sedimentary rocks | | | |
| Rock Type: mudstone, siltstone, shale fine clastic, sedimentary rocks, turbidites; basaltic volcanic rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.8 08LB076 - Harper Creek near the Mouth

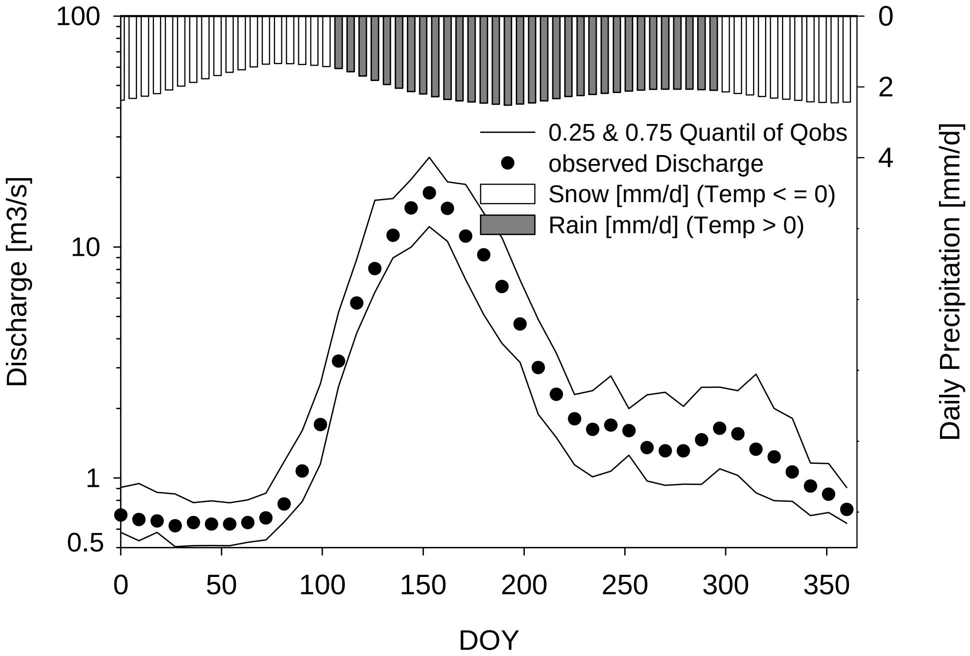


Figure 5.10: Mean discharge (1974-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08LB076)

Table 5.9: Catchment characteristic (08LB076)

| Harper Creek near the Mouth | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1749 | **Climate** | |
| Basin area [km$^2$] | 168 | Mean annual precipitation* [mm] | 757 |
| Max discharge [m$^3$/s] | 55 | Mean annual temperature* [°C] | 0.94 |
| Min discharge [m$^3$/s] | 0.27 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 4.1;773 | Old forest (Fir, Cedar) | 48% |
| % B (Covered by ice and snow) | 25 | Young Forest (Spruce, Fir, Cedar) | 19% |
| % E (Estimated) | 4 | Recently logged | 14% |
| **Geology (BC_geology_alb)** | | Alpine | 12% |
| Rock Class: Intrusive rocks, metamorphic rocks<br>Rock Type: Quartz monzonitic intrusive rocks, paragneis metamorphic rocks | | Burned | 6% |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.9 08MA006 - Lingfield Creek near the Mouth

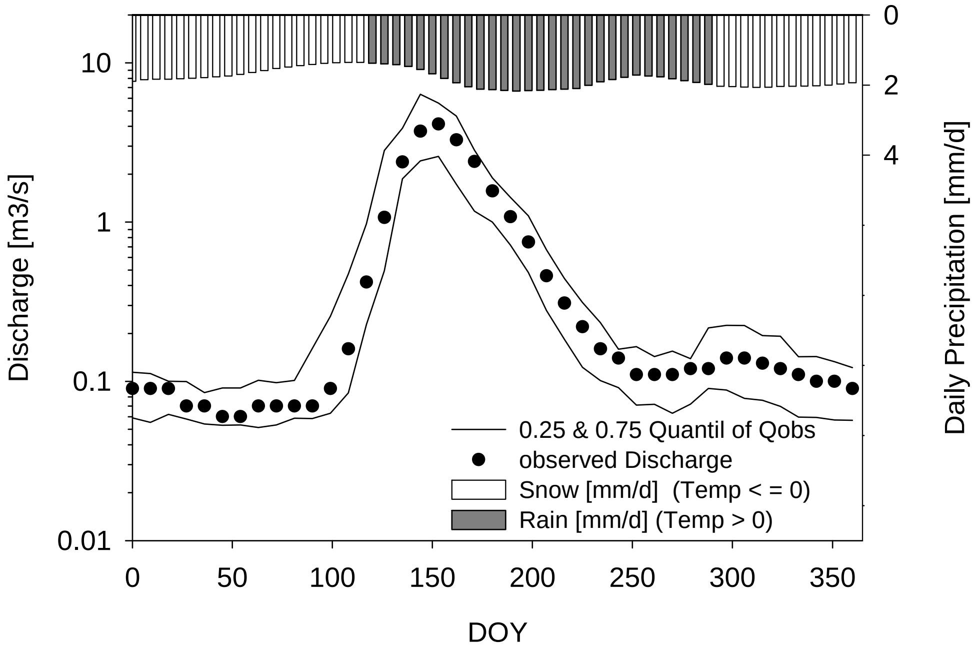


Figure 5.11: Median discharge (1975-2002), 0.25 & 0.75 quantile and mean daily precipitation* (08MA006)

Table 5.10: Catchment characteristic (08MA006)

| Lingfield Creek near the Mouth | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1888 | **Climate** | |
| Basin area [km$^2$] | 98.4 | Mean annual precipitation* [mm] | 667 |
| Max discharge [m$^3$/s] | 15 | Mean annual temperature* [°C] | -0.45 |
| Min discharge [m$^3$/s] | 0.019 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 0.8;246 | Young forest (Fir, Spruce) | 42% |
| % B (Covered by ice and snow) | 45 | Old Forest (Fir, Spruce) | 25% |
| % E (Estimated) | 1 | Alpine (Alpine Tundra) | 19% |
| **Geology (BC_geology_alb)** | | Rangelands (Grassland, Sedges, Shrubs) | 12% |
| Rock Class: Sedimentary rocks | | Wetlands | 1.5% |
| Rock Type: Coarse clastic sedimentary rocks; mudstone, Siltstone, shale fine clastic sedimentary rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.10 08MB007 - Big Creek below Graveyard Creek

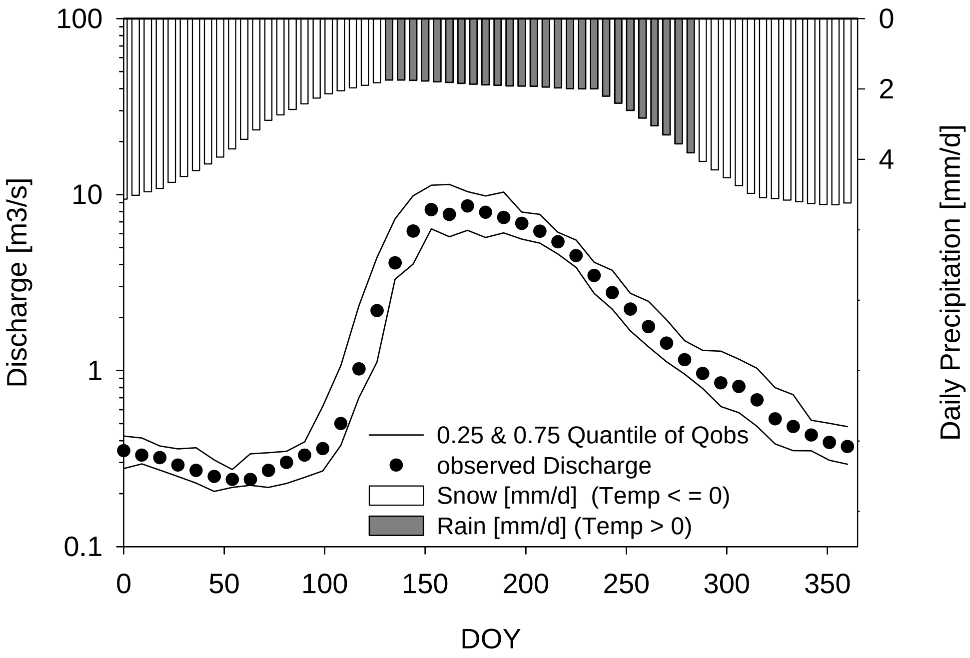


Figure 5.12: Mean discharge (1975-2002), 0.25 & 0.75 quantile and mean daily precipitation* (08MB007)

Table 5.11: Catchment characteristic (08MB007)

| **Big Creek below Graveyard Creek** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 2252 | **Climate** | |
| Basin area [$km^2$] | 232 | Mean annual precipitation* [mm] | 1177 |
| Max discharge [$m^3/s$] | 56 | Mean annual temperature* [°C] | -1.65 |
| Min discharge [$m^3/s$] | 0.099 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [$m^3/s$; mm/a] | 2.8;376 | Alpine (Alpine Tundra) | 63% |
| % B (Covered by ice and snow) | 52 | Old forest (Fir) | 15% |
| % E (Estimated) | 1 | Young forest(Fir) | 7% |
| **Geology (BC_geology_alb)** | | Wetlands | 6% |
| Rock Class: Volcanic rocks(west); sedimentary rocks (east) | | Glaciers and permanent snow | 3% |
| Rock Type: Volcaniclastic rocks; undivided sedimentary rocks | | | |

**ClimateBC Dataset (Spittlehouse, 2006)*

### 5.2.11 08ME025 - Yalakom River above Ore Creek

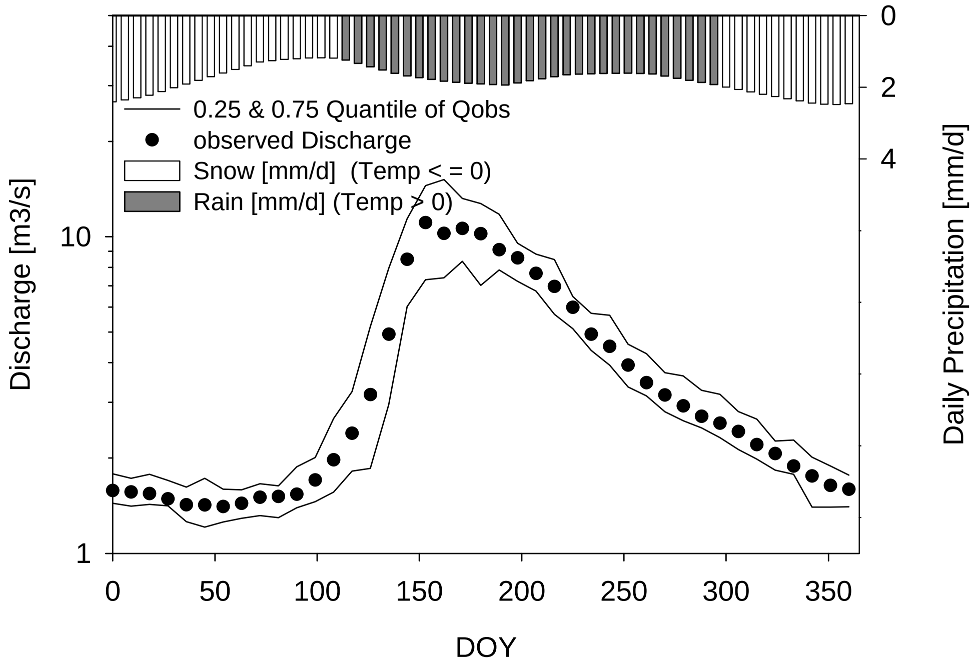


Figure 5.13: Mean discharge (1983-2004), 0.25 & 0.75 quantile and mean daily precipitation* (08ME025)

Table 5.12: Catchment characteristic (08ME025)

| **Yalakom River above Ore Creek** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1922 | **Climate** | |
| Basin area [km$^2$] | 575 | Mean annual precipitation* [mm] | 660 |
| Max discharge [m$^3$/s] | 35 | Mean annual temperature* [°C] | 0.69 |
| Min discharge [m$^3$/s] | 0.656 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 4.3;236 | Old forest (Fir, Spruce) | 41% |
| % B (Covered by ice and snow) | 22 | Young forest (Fir, Spruce) | 23% |
| % E (Estimated) | 5 | Alpine (alpine tundra) | 27% |
| **Geology (BC_geology_alb)** | | Wetlands | 6% |
| Rock Class: Sedimentary rocks, ultramafic rocks, metamorphic rocks | | | |
| Rock Type: undivided sedimentary; rocks, argillite, greywacke, wacke, conglomerate, turbidites; basaltic volcanic rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

## 5.2.12 10BE009 - Teeter Creek near the Mouth

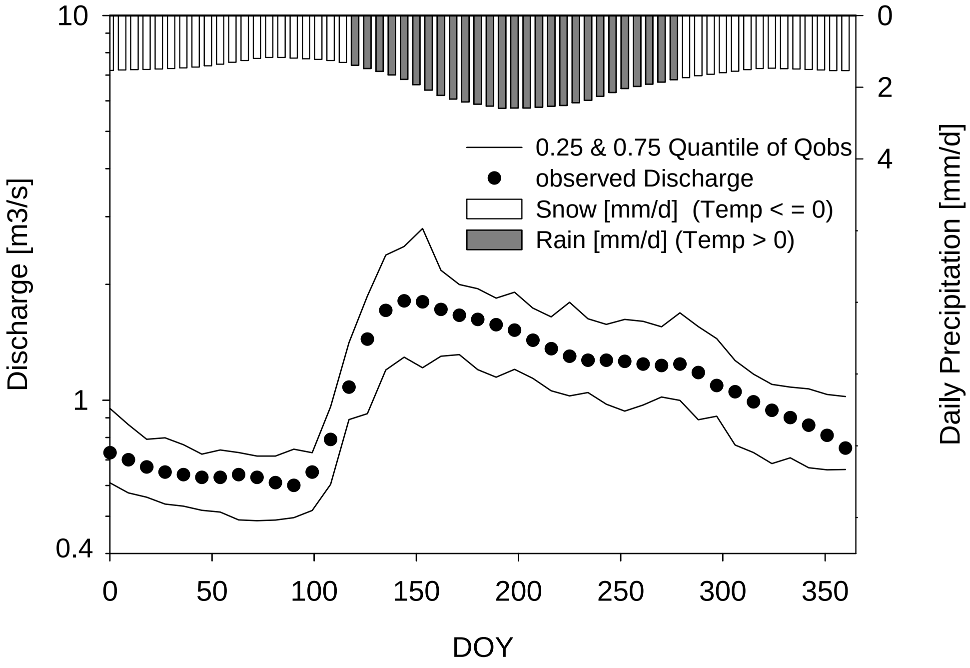


Figure 5.14: Mean discharge (1980-2002), 0.25 & 0.75 quantile and mean daily precipitation* (10BE009)

Table 5.13: Catchment characteristic (10BE009)

| **10BE009** Teeter Creek near the Mouth | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1144 | **Climate** | |
| Basin area [km$^2$] | 211 | Mean annual precipitation* [mm] | 641 |
| Max discharge [m$^3$/s] | 7 | Mean annual temperature* [°C] | -1.44 |
| Min discharge [m$^3$/s] | 0.21 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 1.2;176 | Young forest (Willow, Birch, Spr.) | 43% |
| % B (Covered by ice and snow) | 47 | Alpine (alpine tundra) | 20% |
| % E (Estimated) | 2 | Recently burned | 20% |
| **Geology (BC_geology_alb)** | | Old Forest (Willow, Birch, Spruce) | 14% |
| Rock Class: Sedimentary rocks | | | |
| Rock Type: Limestone, marble, calcareous sedimentary rocks, mudstone/laminate fine clastic sedimentary rocks | | | |

**ClimateBC Dataset (Spittlehouse, 2006)*

### 5.2.13 10CD003 - Raspberry Creek near the Mouth

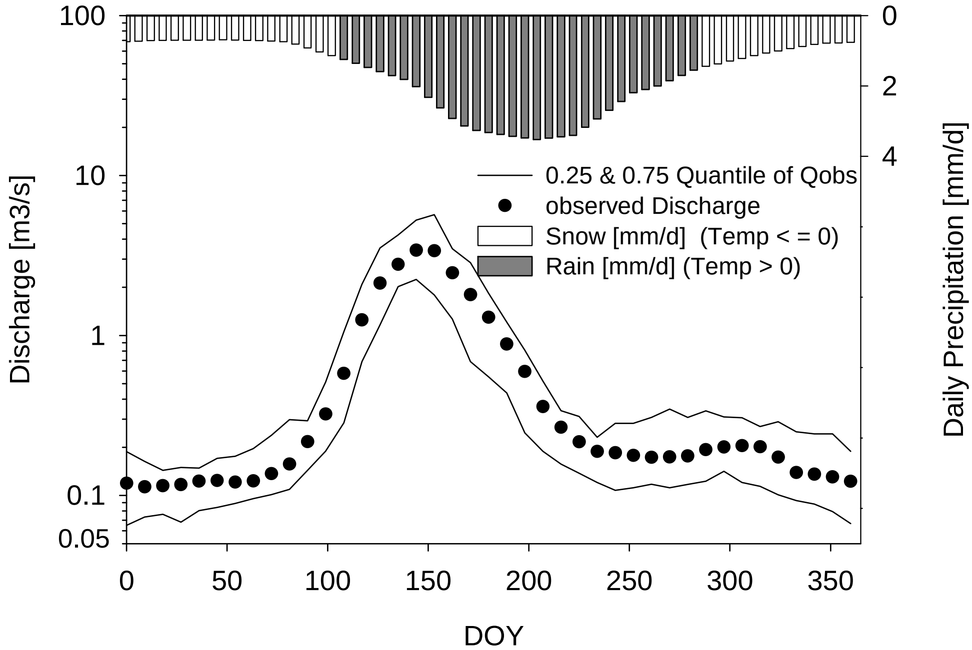


Figure 5.15: Mean discharge (1969-2000), 0.25 & 0.75 quantile and mean daily precipitation* (10CD003)

Table 5.14: Catchment characteristic (10CD003)

| **Raspberry Creek near the Mouth** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 731 | **Climate** | |
| Basin area [km$^2$] | 273 | Mean annual precipitation* [mm] | 617 |
| Max discharge [m$^3$/s] | 61 | Mean annual temperature* [°C] | -0.54 |
| Min discharge [m$^3$/s] | 0.0 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 0.8;87 | Young forest (Boreal Spruce).) | 76% |
| % B (Covered by ice and snow) | 52 | Recently burned | 8% |
| % E (Estimated) | 6 | Shrubs | 6% |
| **Geology (BC_geology_alb)** | | Wetlands | 6% |
| Rock Class: Sedimentary rocks | | | |
| Rock Type: undivided sedimentary rocks, argillite, greywacke, wacke, conglomerate turbidites; basaltic volcanic rocks | | | |

**ClimateBC Dataset (Spittlehouse, 2006)*

### 5.2.14 10AC005 – Cottonwood River above Bass Creek

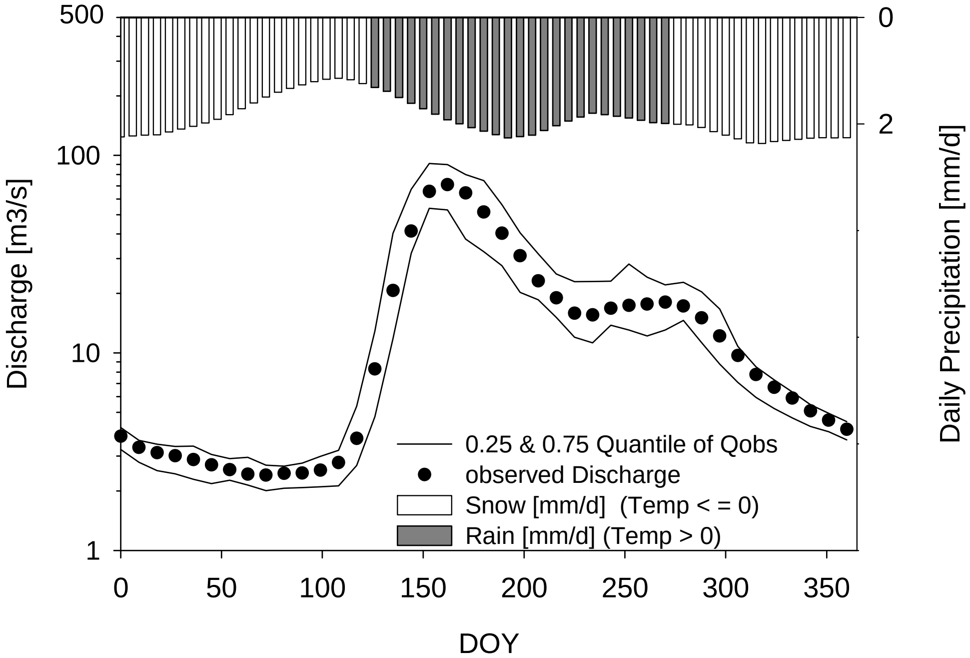


Figure 5.16: Mean discharge (1969-2003), 0.25 & 0.75 quantile and mean daily precipitation* (10AC005)

Table 5.15 : Catchment characteristic (10AC005)

| **Cottonwood River Above Bass Creek** | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1520 | **Climate** | |
| Basin area [km$^2$] | 888 | Mean annual precipitation* [mm/a] | 700 |
| Max discharge [m$^3$/s] | 201 | Mean annual temperature* [°C] | -1.94 |
| Min discharge [m$^3$/s] | 0.435 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [m$^3$/s; mm/a] | 18;648 | Shrubs (alpine tundra) | 28% |
| % B (Covered by ice and snow) | 53 | Alpine (alpine tundra) | 26% |
| % E (Estimated) | 3 | Old forest (Spruce, Willow, Birch) | 20% |
| **Geology (BC_geology_alb)** | | Sub-Alpine avalanche chutes | 16% |
| Rock Class: intrusive rocks, sedimentary rocks | | Young forest (Spr., Willow Birch) | 8 % |
| Rock Type: Granite, intrusive rocks sedimentary rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

### 5.2.15 08JD006 - Driftwood River above Kastberg Creek

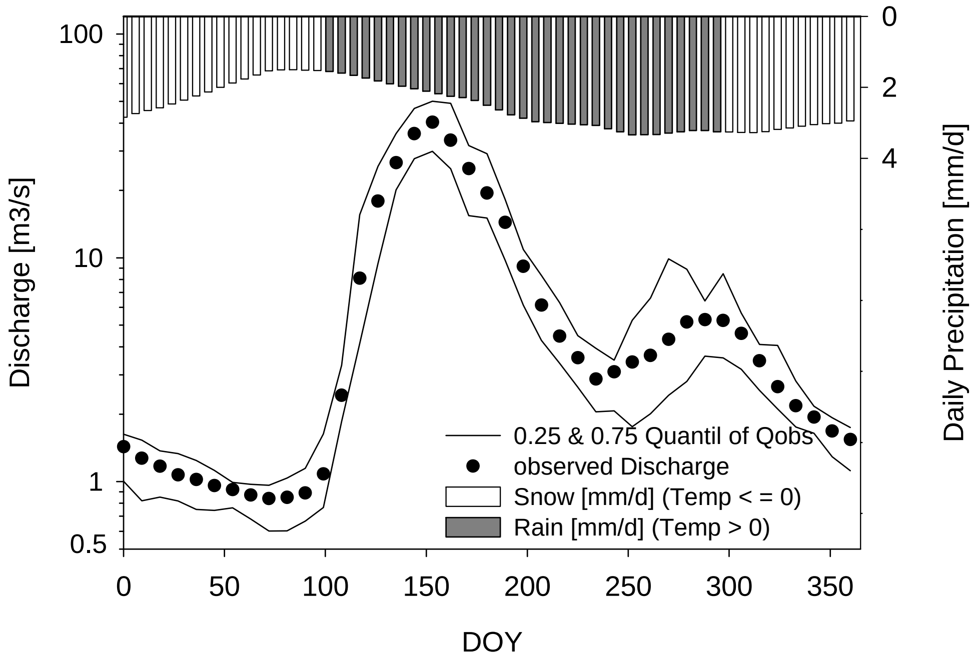


Figure 5.17: Mean discharge (1980-2003), 0.25 & 0.75 quantile and mean daily precipitation* (08JD006)

Table 5.16: Catchment characteristic (08JD006)

| Driftwood River above Kastberg Creek | | | |
|---|---|---|---|
| Mean basin elevation [m] | 1295 | **Climate** | |
| Basin area [$km^2$] | 407 | Mean annual precipitation* [mm] | 939 |
| Max discharge [$m^3$/s] | 94 | Mean annual temperature* [°C] | -0.87 |
| Min discharge [$m^3$/s] | 0.24 | **BTM land use Zones (Vegetation)** | |
| Mean discharge [$m^3$/s; mm/a] | 8.2;638 | Old forest (Fir, Spruce) | 46% |
| % B (Covered by ice and snow) | 24 | Young forest (Fir, Spruce) | 27% |
| % E (Estimated) | 5 | Alpine (alpine tundra) | 11% |
| **Geology (BC_geology_alb)** | | Wetlands | 8% |
| Rock Class: Volcanic rocks, sedimentary rocks | | | |
| Rock Type: Calc-alkaline volcanic rocks, undivided sedimentary rocks | | | |

**ClimateBC Dataset (SPITTLEHOUSE, 2006)*

## 5.3 Results and discussion

### 5.3.1 Calibration and sensitivity analysis

#### Module 1 – Effective rainfall

#### Results

The effective rainfall module does not become calibrated. Neither Monte-Carlo runs nor sensitivity and uncertainty analysis are executed. It was tried to use the same parameter set for every catchment. However sometime it was useful to vary the parameters in a certain range in order to obtain better fittings and to close the water balance. The used parameters for the effective rainfall module are tabulated below.

Table 5.17: Used parameters in Module 1

| | *ddf* | *HC* | $T_m$ | *α* | *SUB* | $DR_{SM}$ | $R_c$ | $S_c$ |
|---|---|---|---|---|---|---|---|---|
| | [mm/°C] | [-] | [°C] | [-] | [mm/d] | [-] | [-] | [-] |
| 08HF004 | 2 | 0.1 | 0 | 1.26 | 0.5 | 0 | 0.95 | 0.95 |
| 08NM134 | 1 | 0.1 | 0 | 1.26 | 0.5 | 0 | 0.75 | 0.75 |
| 08NF001 | 1.5 | 0.1 | 0 | 1.26 | 0.5 | 0 | 0.76 | 0.76 |
| 08JA014 | 1 | 0.1 | -0.5 | 1.26 | 0.5 | 0 | 1 | 1 |
| 08JE004 | 1.5 | 0.1 | 0 | 1.26 | 0.45 | 0 | 0.95 | 0.95 |
| 08KE024 | 2 | 0.1 | -1 | 1.26 | 0.2 | 0 | 1.27 | 1.27 |
| 08LB024 | 2 | 0.1 | 1 | 1.26 | 0.25 | 0 | 1 | 1 |
| 08LB076 | 1.5 | 0.1 | -1 | 1.26 | 0.2 | 0 | 1.9 | 1.9 |
| 08MA006 | 1.5 | 0.1 | -0.5 | 1.26 | 0.5 | 0 | 0.98 | 0.98 |
| 08MB007 | 1 | 0.1 | -1 | 1.26 | 0.5 | 0 | 0.57 | 0.57 |
| 08ME025 | 2 | 0.1 | 0 | 1.26 | 0.4 | 0 | 0.9 | 0.9 |
| 10BE009 | 2 | 0.1 | -0.5 | 1.26 | 0.5 | 0 | 0.92 | 0.92 |
| 10CD003 | 1 | 0.1 | 1 | 1.26 | 0.5 | 0 | 0.99 | 0.99 |
| 10AC005 | 2 | 0.1 | -1 | 0.75 | 0.5 | 0 | 1.8 | 1.3 |
| 08JD006 | 2 | 0.1 | 0 | 1.26 | 0.2 | 0 | 1.2 | 1.3 |

### Discussion

As shown in Figure 5.18 it is difficult to identify clear patterns in the calculated precipitation factors. There is no clear link between the figures and the geographical position or the mean elevation of the catchments.

But in general the precipitation must be reduced, especially in the south west of BC, but also in some catchments in the east and north of BC. It is necessary to operate with positive factors in two catchments in the luv (west) side of the Rocky Mountains (08LB076, 08KE024) as well as in two catchments in the north-west of BC (10AC005, 08JD006).

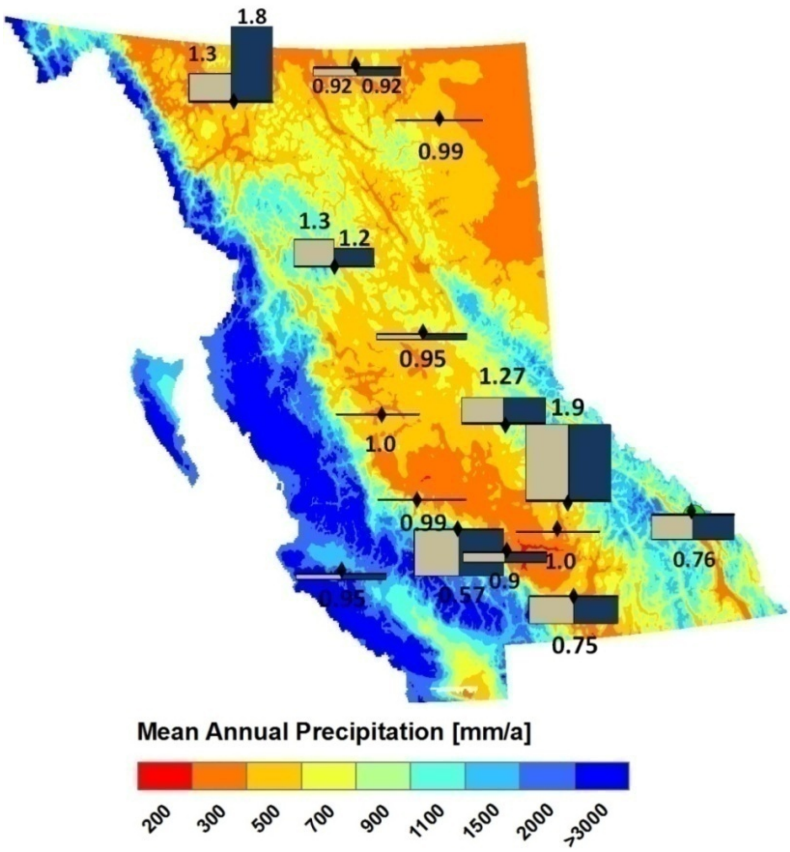


Figure 5.18: Mean annual precipitation and used correction factors (grey: snowfall $S_c$, blue: rainfall $R_c$) for the simulated catchments

The generally negative factors could be a consequence of an underestimated *AET*. But in contrast to e.g. 10AC005 (in the very north-west of BC) the calculated evapotranspiration must be reduced (TABLE 5.17), despite the very high precipitation correction factor.

Generally the estimated *PET*, according to the used Priestley and Taylor alpha $\alpha_{PT}$, of 1.26 is too high (in some catchments with maximum values of 8 mm/d) but in this model *PET* is not sensitive. Using a $\alpha_{PT}$ of 1.05 like MCNAUGHTON, ET AL., (1973) estimated it for a Douglas Fir stand on Vancouver Island the resulting annual *AET* is only around 5 mm less than using the value of 1.26. Nevertheless in further applications, especially when calculating real timeseries a lower value of $\alpha_{PT}$ should be used.

### Module 2 – Transfer-function

### Results

In each catchment 2000 Monte-Carlo runs were carried out to identify the best parameter sets for the transfer-function module. The parameter range is preset under consideration of typical values (WITTENBERG, 1999).

In FIGURE 5.19 and FIGURE 5.20 the objective function (1-lnNeff because MCAT calculates with minimum functions) is shown on the Y-Axis and the parameter range on the X-axis. Best parameter set is shown as a pink square. In Table 5.18 the best parameter sets and their connected Nash-Sutcliffe efficiencies are summarized and in FIGURE 5.21 recession curves are displayed accordingly.

In some catchments, an optimum parameter set of *a* and *b* clearly can be identified (08HF004, 08NM134, 08NF001, 08JA014, 08KE024, 08LB024, 08MA006, 08ME025, 10AC005, 08JD006). In 08MB007, 08JE004 and 08LB076 the best fit was obtained by a value of *b* close to zero compensated with a high parameter *a* in the first two catchments .

At 10BE009 only parameter *a* is sensitive, but with a value of 192 wide out of the range compares to all the other catchments. The very high value of *a* causes a slow recession. In 10CD003 also parameter *a* is the sensitive parameter.

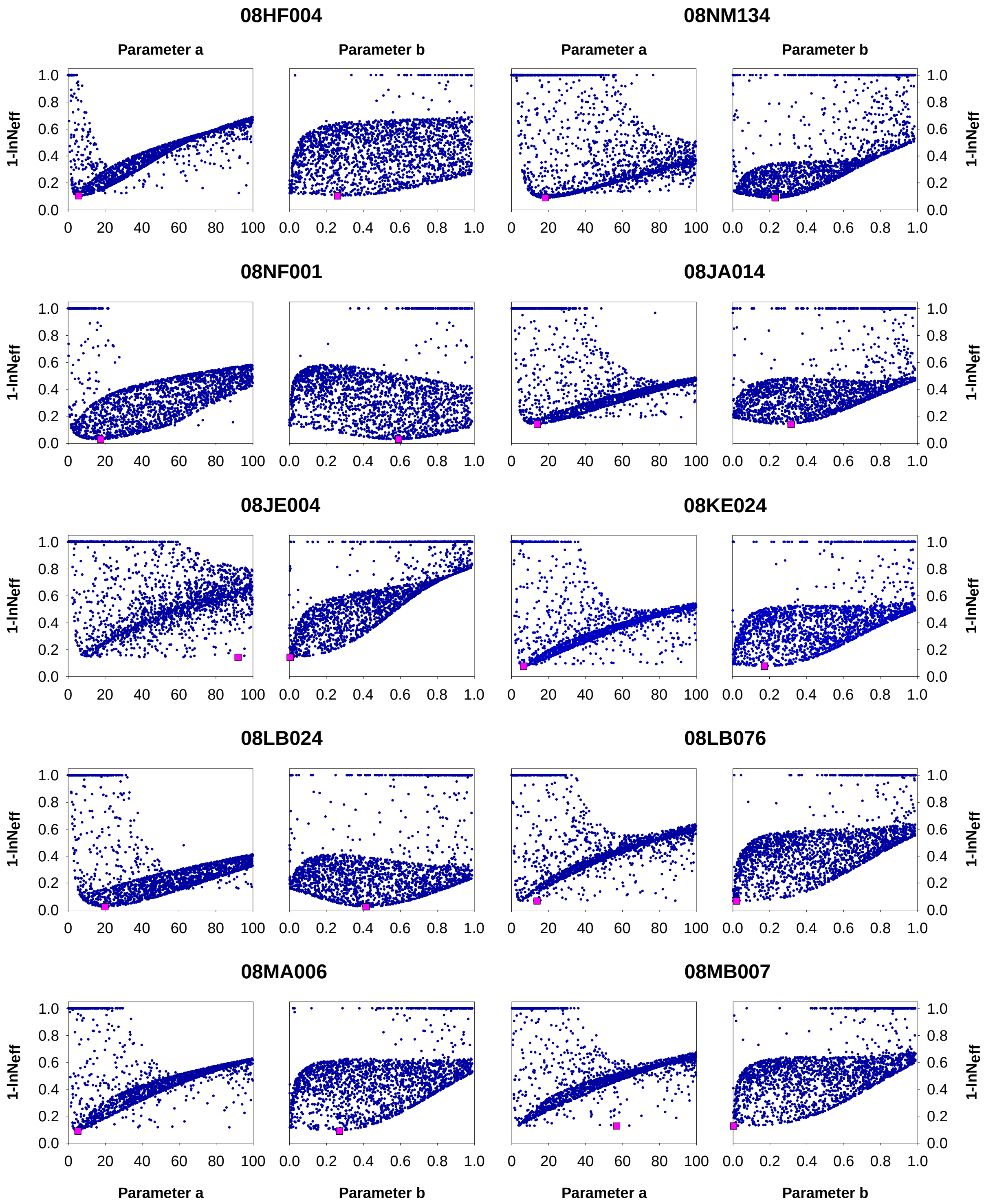


Figure 5.19: Sensitivity analysis of calculated catchments of parameter *a* and *b*

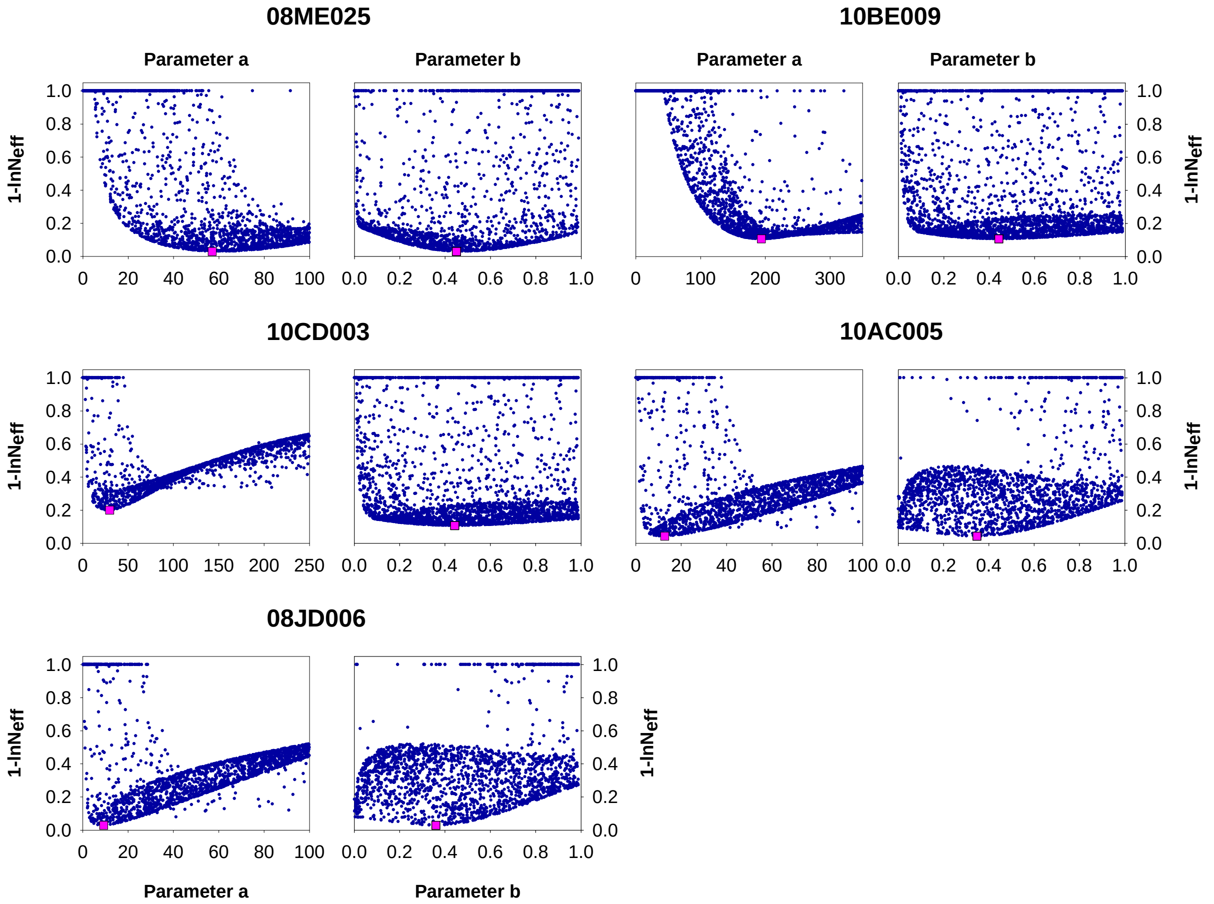


Figure 5.20: Sensitivity analysis of calculated catchments of parameter a and b

Table 5.18: Best parameter set after calibration, objective function and selected threshold *(TH)* for uncertainty analysis

| | *a* | *b* | $lnN_{eff}$ | *TH* | | *a* | *b* | $lnN_{eff}$ | *TH* |
|---|---|---|---|---|---|---|---|---|---|
| 08HF004 | 5.69 | 0.26 | 0.89 | 0.7 | 08MA006 | 5.20 | 0.27 | 0.91 | 0.65 |
| 08NM134 | 18.35 | 0.23 | 0.91 | 0.5 | 08MB007 | 56.75 | $3.0e^{-3}$ | 0.87 | 0.65 |
| 08NF001 | 17.63 | 0.59 | 0.97 | 0.5 | 08ME025 | 57.53 | 0.45 | 0.97 | 0 |
| 08JA014 | 13.96 | 0.14 | 0.84 | 0.5 | 10BE009 | 193.9 | 0.44 | 0.89 | 0 |
| 08JE004 | 92.00 | $5.0e^{-3}$ | 0.86 | 0 | 10CD003 | 21.62 | 0.34 | 0.79 | 0.6 |
| 08KE024 | 6.52 | 0.17 | 0.92 | 0.6 | 10AC005 | 12.74 | 0.35 | 0.96 | 0.5 |
| 08LB024 | 19.91 | 0.41 | 0.98 | 0.4 | 08JD006 | 9.27 | 0.36 | 0.97 | 0.5 |
| 08LB076 | 13.82 | 0.02 | 0.93 | 0.6 | | | | | |

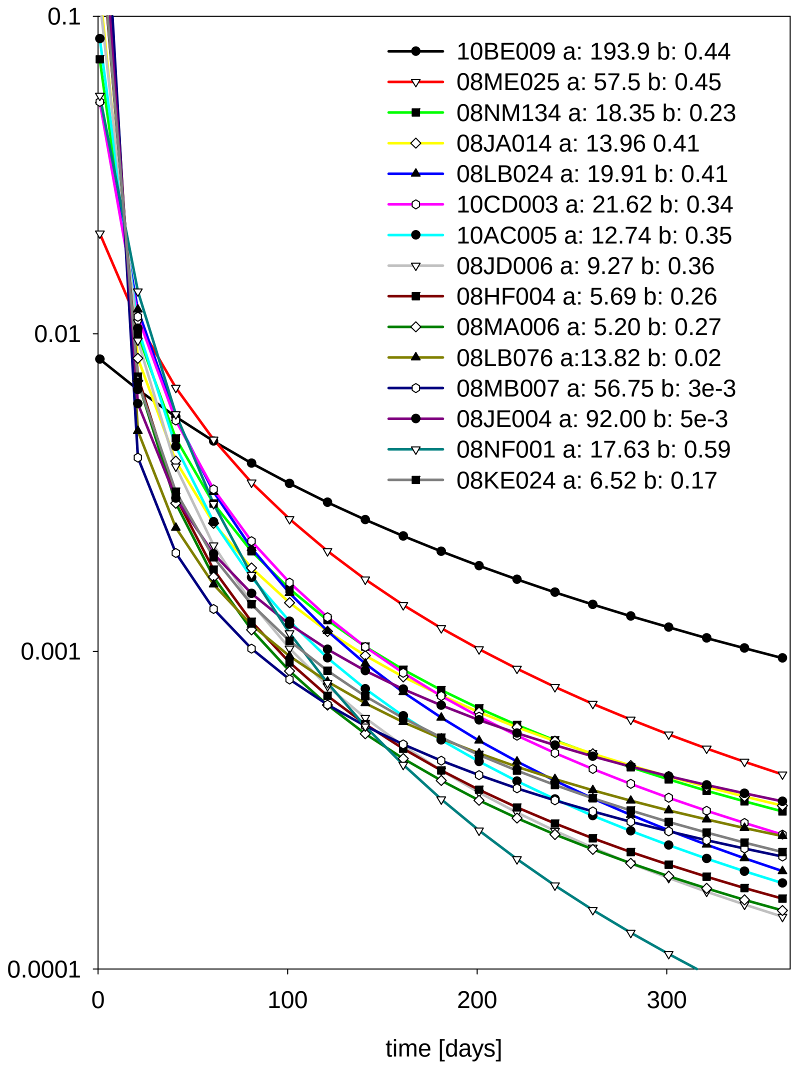


Figure 5.21: Characteristic recession curves of the 15 catchments according to the best parameter sets

## Discussion

It is hardly possible to regionalize the parameters which describe recession with only 15 simulated catchments. But it is apparent, that the recession characteristic depends on the catchments geology. Basically catchments with a large contingent of sedimentary rocks, and assuming that these catchments have more productive aquifers, tend to be described by parameter sets of *a* and *b* which describe a slower reservoir outflow (10BE009, 08ME025). Especially parameter a, which describes the backslide of the recession curve, seems to be the sensitive parameter for reservoir outflow, but can be compensated with extreme values of *b* (08JE004, 08NF001). Catchments which are dominated by bedrock, the function a=f(b) resulting in faster reservoir outflow (e.g. 08KE024, 08LB076, 08NM134 and 08JA014).

### 5.3.2 Observed vs. simulated discharge

#### Results

Usually, it is no problem to obtain good fittings of the snowmelt peak, especially when considering the objective function *RMSE*. The $lnN_{eff}$ tends to overestimate the snowmelt peak (note that discharge is plotted logarithmically in FIGURE 5.22/5.23) but gives better fittings to the low flows. The timing of the beginning of the snowmelt tends to be a little bit too late.

A general phenomenon is that at the end of the growing season before temperatures fall below 0°C (around DOY 260 to 310), discharge is generally overestimated, which extreme in e.g. 08LB076 or 08MA006.

08HF004 is the only catchment in a coastal region (Vancouver Island) with mean monthly temperatures above zero and very high precipitation rates, especially in autumn, winter and spring. The consequences are constant high flows during these seasons and summer low flow conditions (pluvial runoff regime). The summer low flow conditions are well represented by the model.

All other catchments have typical characteristics of mixed or nival runoff regimes. A really good fit to the summer low flows is obtained in the catchments 08JA014 and 08KE024, excepting for variations during the low flows and the fitting of the rest of the year (08JA014).

Catchment 08LB024 tend to represent the low flow well too, except for the overestimated discharge at the end of the growing season.

Catchment 08JD006 shows also a generally well fitting. But it is not possible to reduce the overestimated summer low flows any more in terms of the recession curve and the domain of uncertainty in question (the same problem but more extreme in 08LB024 and 08MA006).

The recession type of 08NF001, 08ME025 and 10BE009 tend to be very flat, with no typical summer low flow conditions. The best fitting was obtained in 08NF001 with a relative high value of parameter *b* (0.59), but the sensitive factor is *a* in 08ME025 (57) and 10BE009 (193).

Catchment 10AC005 is with 888 km$^2$ the largest catchment simulated in this thesis. In this catchment it was necessary to increase precipitation ($R_c$=1.8) and reduce potential evapotranspiration ($\alpha_{pt}$=0.7) considerably in order to obtain a good fitting.

In catchment 10CD003 it is not possible to fit the simulated to the observed discharge hydrograph.

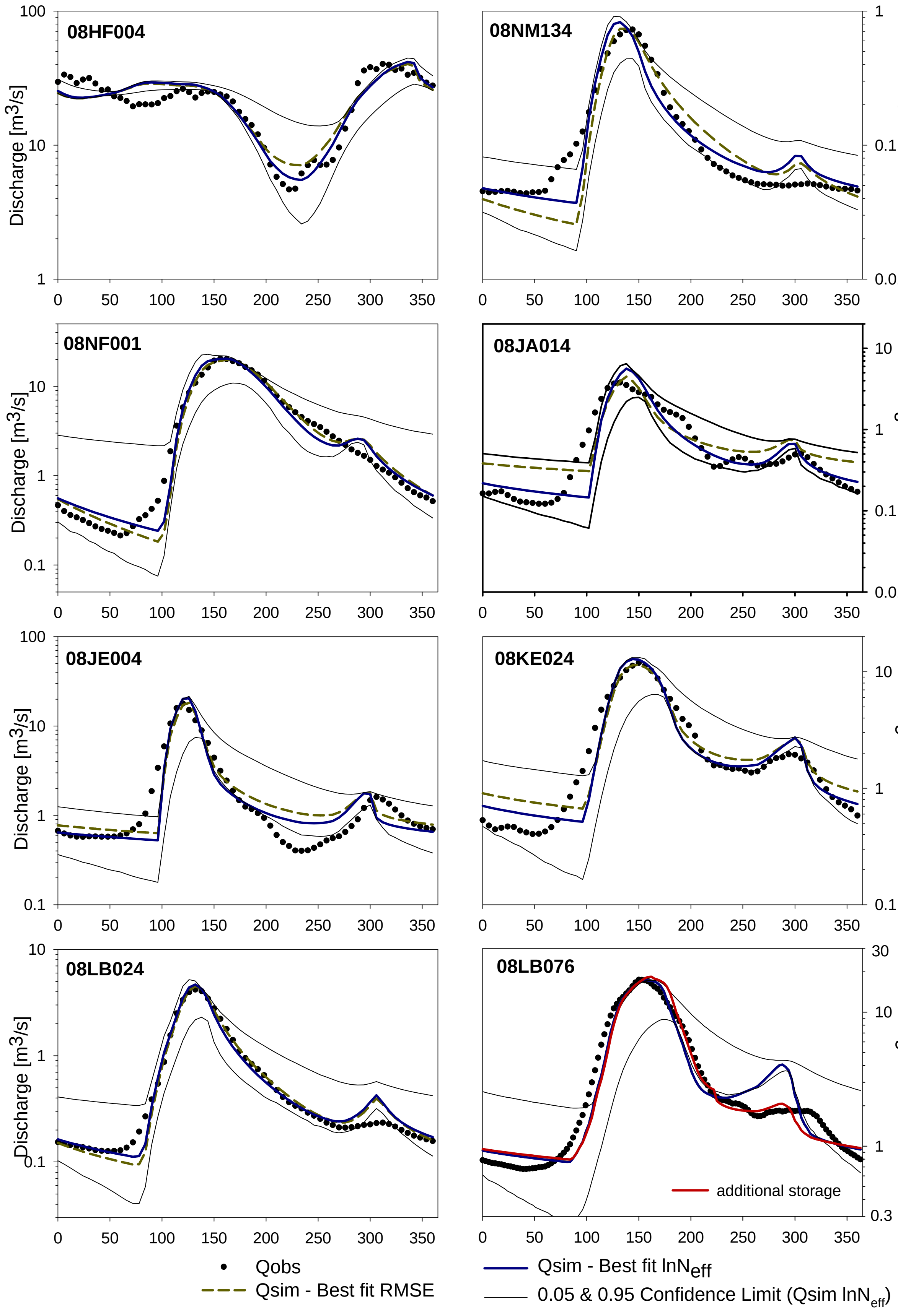


Figure 5.22: Observed vs. simulated hydrograph

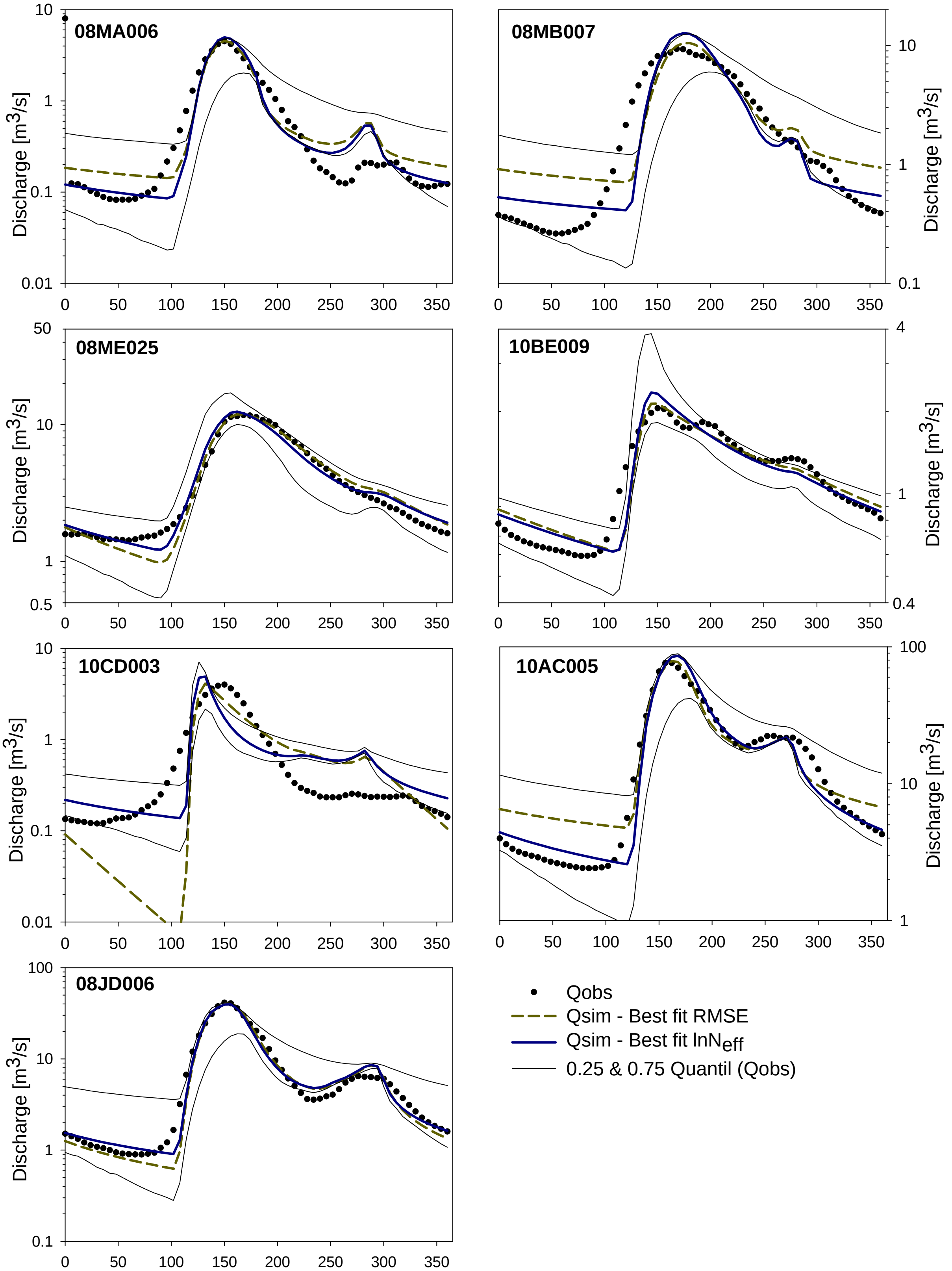


Figure 5.23: Observed vs. simulated hydrograph

## Discussion

The reason why spring peak flow generally starts too late could be a result of uncertainties in the used and disaggregated temperature data controlling the snowmelt.

The overestimation of discharge at the end of the growing season could be a direct response to the increasing effective rainfall, as a consequence of increasing precipitation rates and decreasing temperatures and evapotranspiration.

It is to be assumed, that at the end of the growing season the storages are empty and must be filled first before effective rainfall becomes runoff. The transfer-function model probably cannot consider empty storages at the end of the growing season before temperatures fall below zero.

A “trial version” of an “empty” storage/reservoir, is applied in catchment 08LB076 (FIGURE 5.22). This storage is filled by a percentage amount of effective rainfall (40%) at the end of the growing season and spends the water stored together with the snowmelt of the next year to the effective rainfall. The result is a better fitting at the end of the growing season (red line).

But this storage wasn´t applied generally, because it is neither possible to estimate the correct percentage amount to fill this storage nor to define the correct reservoir outflow. The consequence would be that additional factors have to become calibrated, which would be non-conforming to the aim of this thesis.

To fit the low flows (e.g. by calculating the objective function only for recession periods; $Q_{(t)} < Q_{(t-1)}$) of 08LB024, 08JD006 and 08MA006, an extreme parameter set would be necessary to describe recession, and the consequence would be that simulated discharge of the rest of the year would have been unrealistic.

The reason for these effects could be: (I) the catchment cannot be described by only a single storage with one characteristic recession curve and (II) the produced mean discharge time series does not really represent the characteristic recession of the catchment.

It is improbable that the used input data are responsible for this because during these periods evapotranspiration exceeds precipitation and consequently the effective rainfall is zero anyway, so that there is no further input into the transfer-function.

In 10AC005 it has to be assumed that there must be fast flow components because of the large share of alpine area (25%) and bedrock.

The comparison of the best parameter set for the transfer-function with direct runoff ($DR$ & $DR_{SM}$= 0.25), which is to be excepted of the transfer-function, and without direct runoff components ($DR$ & $DR_{SM}$= 0) defined in the effective rainfall module, leads to a different parameter set, but comparatively good results. The calculation with $DR_{(SM)}$=0 leads to a smaller parameter $a$, than in the other case, which results in a faster reservoir outflow. According to this catchment, the transfer-function in general could be able to implicate fast flow components.

Table 5.19: Parameter set and efficiency by calculating with and without fast runoff components

| | $a$ | $b$ | $lnN_{eff}$ |
|---|---|---|---|
| $DR_{(SM)}$=0 | 12.7 | 0.34 | 0.957 |
| $DR_{(SM)}$=0.25 | 22 | 0.39 | 0.962 |

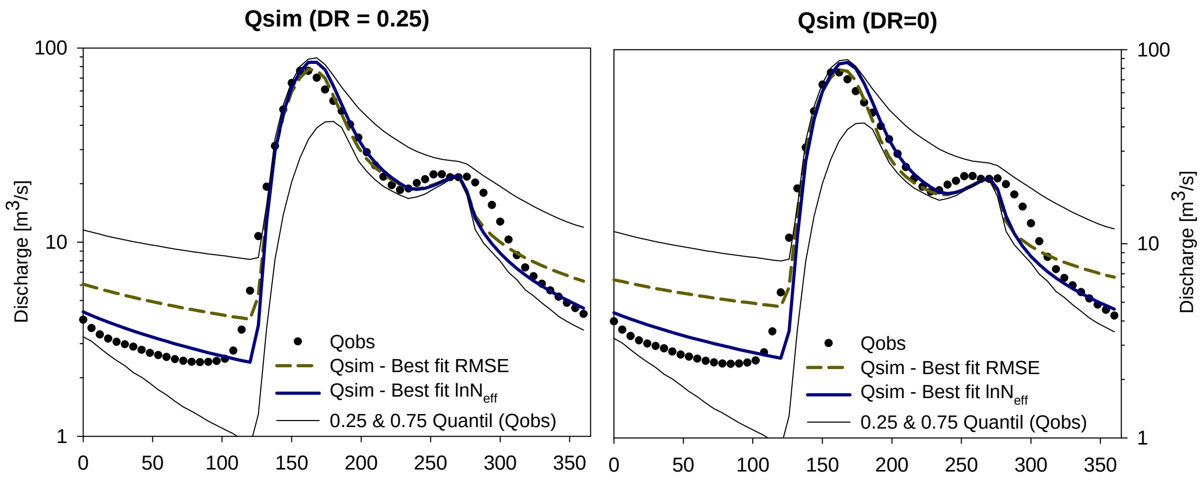


Figure 5.24: Best prediction plot by calculating with (left) and without (right) fast runoff components

Catchment 10CD003 may be an extreme example for the problems of estimating effective rainfall. In this case the used input data and the estimated effective rainfall from these data will be responsible for the bad result. Furthermore no clear optimum parameter set could be identified for this catchment in the sensitivity analysis.

In general, the results of the effective rainfall module seem to be reasonable. The snowmelt routine according to the degree-day approach is a commonly used tool and was often successfully applied. A good fit is to be seen when observing the simulated snow-melt peak in general. The simple approach of the evapotranspiration delivers reasonable results. In this thesis especially the relationship between precipitation and actual evapotranspiration is of particular interest. An overestimated evapotranspiration will lead to higher precipitation correction factors and vice versa.

But there is no doubt that there are also uncertainties in the model-structure which could lead to uncertainties in effective rainfall. For example, the evapotranspiration could be under estimated because generally it is necessary to reduce input precipitation, but in 10AC005 it is necessary to reduce evapotranspiration despite the huge precipitation correction factor.

Furthermore, there are certainly uncertainties in the used effective rainfall parameters. With a systematically calibration of these parameters the fitting in general would be better, but with the result of huge domains of uncertainties. But according to the approach of a parsimonious model, it was avoided to calibrate these parameters systematically by Monte-Carlo runs.

Also the uncertainties and the exigency of correction factors for monthly precipitation input, discussed in the previous sections, as well as the disaggregation to daily values may lead to distorted effective rainfall results. It can be tried to gauge and to balance out the uncertainties in precipitation with the correction factors in terms of the water balance.

The calculated effective rainfall is to be seen critically due to the uncertainties in the used input data, as well as in the model (model-structure and used parameters).

### 5.3.3 Future scenarios

#### Results

The results of the model application are shown in FIGURE 5.25 taking into account the model-structure and identified parameter sets for MODULE 1 and MODULE 2 as well as the modified precipitation and temperature input data (delta-changes according to the A2 CGCM scenario).
It is quite evident that all catchments show significant changes during snowmelt peak. Furthermore, there are generally significant changes at the end of the growing season.
Catchment 08HF004, being the only pluvial affected catchment, shows significant changes only in late autumn, winter and spring season as a consequence of increasing precipitations. All other catchments do not show changes during the winter season.
In 08NF001, 08KE024, 08LB076, 10BE009, 10AC005 and 08JD006 discharge will change significantly during the whole growing season.
In 08NM134, 08JA014 and 08JE004 discharge will not change significantly during the summer low flows. In 08LB024, 08MA006 and 08ME025 the periods with significant changes after having passed the snowmelt peak are longer, but there will be no significant changes at the end of the summer low flows.

#### Discussion

As it was expected in the previous chapters the snowmelt occurs earlier in the year due to higher temperatures, and the snowmelt peak is diluted, because of the shorter duration of temperatures below zero and the changing proportion from snowfall to rainfall.
The significant changes at the end of the growing season could lead to misinterpretations. It has to be assumed that this change does not only result from input changes, but rather from the model uncertainty at the end of the growing season. A positive correction of precipitation, as it is usual during this period due to the climate change scenarios, will lead to a further overestimation of discharge.

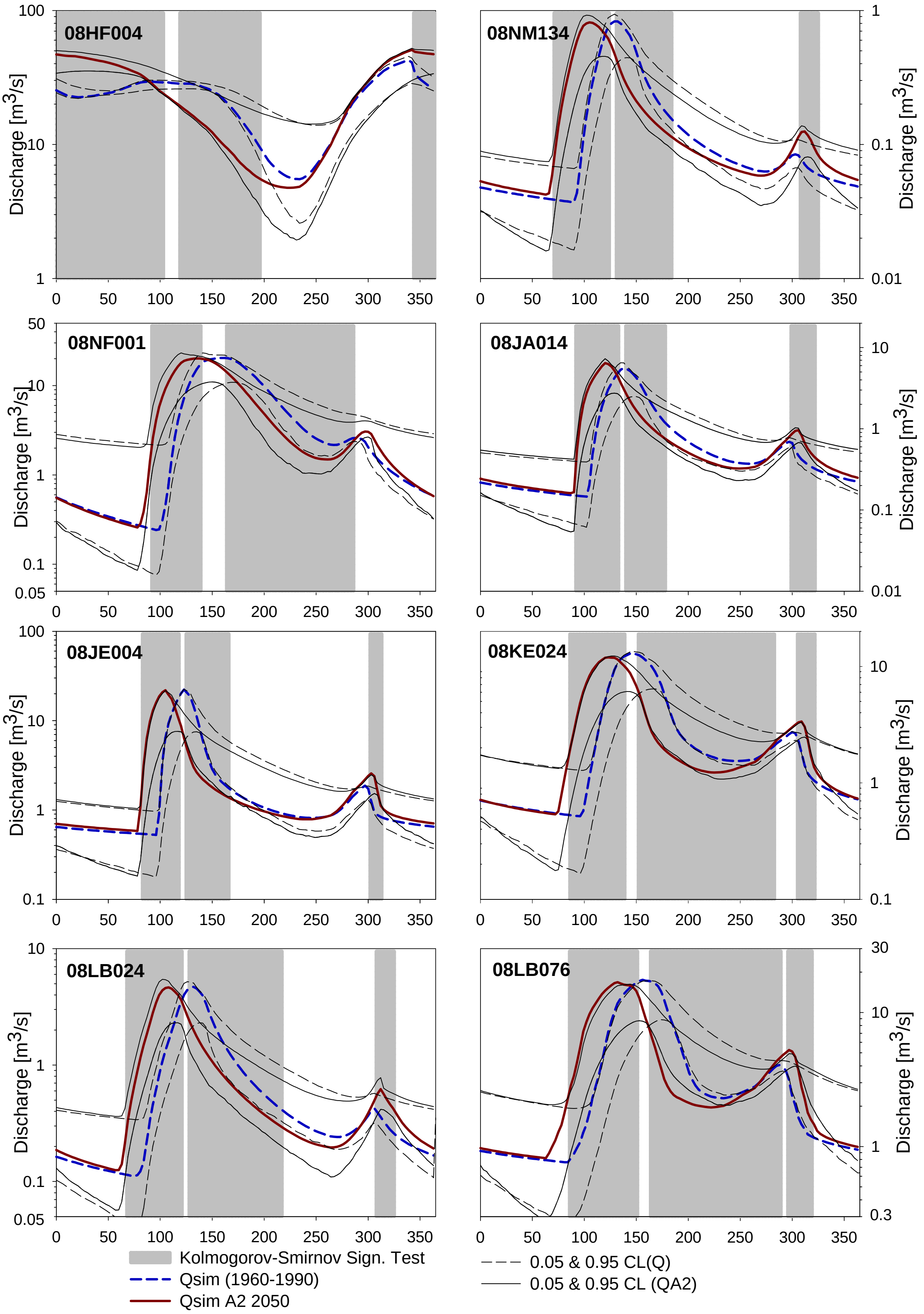


Figure 5.25: Simulated discharge for the period 1960-1990 and the 2050s (CGCM A2 Climate Scenario) with uncertainty domains (0.05 & 0.95 Confidence Limits). Significant changes according to the Kolmogorov-Smirnov Significance test are greyed-out.

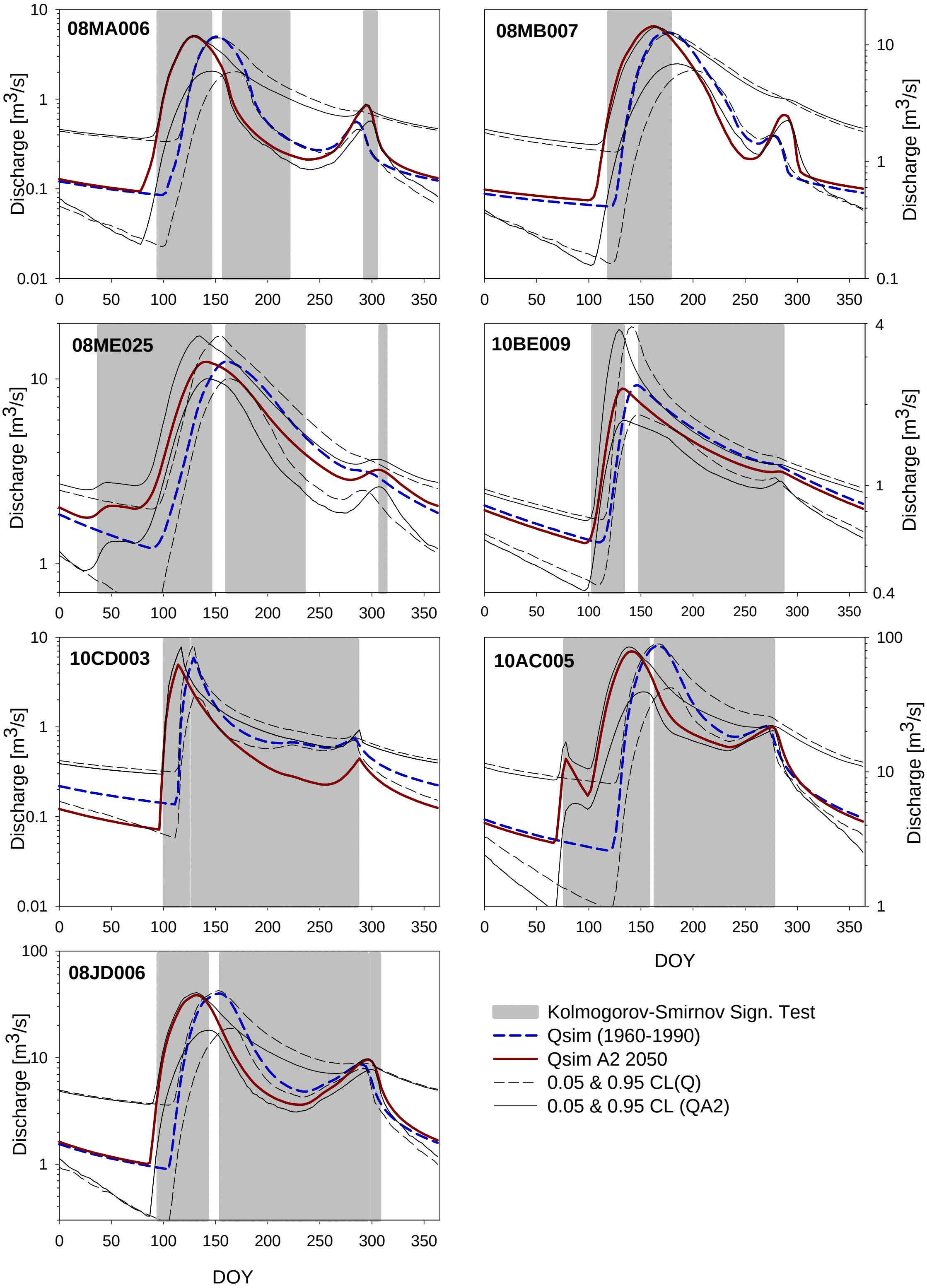


Figure 5.26: Simulated discharge for the period 1960-1990 and the 2050s (CGCM A2 Climate Scenario) with uncertainty domains (0.05 & 0.95 Confidence Limits). Significant changes according to the Kolmogorov-Smirnov Significance test are greyed-out.

The duration of the changes after having passed the snowmelt peak depends on the catchment and the used delta changes. Usually, the delta-changes are in the same dimension, which means that changes during low flow periods primarily depend from catchment characteristic. It depends whether the geology is dominated of unconsolidated sedimentary rocks or bedrocks.

In catchment 08LB076 and 08LB024, the delta-changes are the same, but the very small values of *b* and also a smaller *a* value of catchment 08LB076 describes a larger sensitivity to the input data. This has to be assumed as a consequence of a lower contingent of sedimentary rocks.

In 08JA014 and in 08KE024, there are similar delta-changes. But in 08JA014 there is only a short period with significant changes and in 08KE024 discharge changes during the whole period with temperatures above zero. In both catchments parameter *b* is with 0.14 and 0.17 in the same dimension, but parameter *a* in catchment 08KE024 is smaller than in 08JA014, which describes a larger sensitivity to the input data. However, the rock type is described in both catchments as bedrock. For a further interpretation, detailed data/informations about the aquifers characteresics would be needed.

In the catchments 08MB007 and 08ME025 the periods with significant changes are not very long. That is the result of the high *a* values, which have a low sensitivity to changing input data. These catchments are mainly characterized by sedimentary rocks.

In the catchments, in the north of BC, the periods with significant changes are very extended. In 10AC005 and 08JD006, the parameter set is clearly identified and the fitting is well. The catchment-describing parameters would actually lead to a result e.g. like in 08NM134 or 08MA006 with a lower sensitivity to input changes and resulting in a shorter period with significant changes in discharge. The reasons for the extended periods of low flows probably are a consequence of the sparse available water in the north of BC. Ecpecially the winter precipitation rates are very low, so that there is less spring recharge than in the south of BC, and the available summer precipitation is strongly reduced by the high atmospheric demand.

In 10BE009 and 10CD003, the periods with significant changes are also very long like in 10AC005 and 08JD006. The parameter set for the transfer-function is not clearly identified (especially 10CD003), which makes it difficult to describe the sensitivity of the catchment to changing input data, but it is to be assumed that as a consequence of the geology type of sedimentary rocks, the sensitivity of the recession is low, and the extended low flow periods are the consequence of of the climatic conditions as well.

Despite the different driving factors, the different spatial characteristic of changing temperature and precipitation conditions on the one hand, and the different sensitivity of each catchment on these changes on the other hand,  it is possible to suggest a first pattern where sigificant changes in low flows occur and where they do not.

In the north of BC there are significant changes in discharge according to the climate change scenarios during the whole period with temperatures above zero due to more increasing temperatures than in the south of BC (08JD006, 10AC005, 10BE009, 10CD003) despite the lower catchment sensitivity because of the catchments geology, when assuming that sedimentary rocks are connected with larger and more productive aquifers, than in headwater bedrock catchments.

In the lower and western parts of the Fraser Plateau, the catchments (08JA014, 08JE004, 08MA006, 08MB007, 08ME025 and 08LB024) generally show a lower sensitivity to changing inputs connected with less significant changes in low flow periods (unconsolidated rock) than the catchments in the west side of the Rocky Mountains (bedrock - 08KE024, 08LB076), where discharge changes significantly during these periods according to similar delta-changes.

The results of the model-runs with the delta-changes according to the B1 climate change scenario are shown in the Apendix. In this climate change scenario it is assumed, that greenhouse gas emissions will be reduced and the consequence would be that temperatue will not increase as the A2 scenario predicts. So the results of the simulated discharge in the B1 scenario show the same trend in all catchments but not as extreme as extreme in the A2 scenario.

### 5.3.4 Conclusions

Uncertainties in input data (the Climate Normals and in the climate change scenarios) as well as uncertainties in the model structure of the effective rainfall module and the used parameters are not taken into account in this work. Therefore the estimated effective rainfall is to assessed critically.

The best parameter set for the transfer-function was obtained by applying Monte-Carlo runs. A general pattern where the model delivers good fittings according to catchment characteristics, e.g. geographical position, mean elevation, catchment size, geology or vegetation, cannot be found. So it has to be assumed that problems with a good fitting are the result of (I) incorrectly estimated effective rainfalls (e.g. 10CD003, 10AC005), or (II) that the catchment can´t be described in detail in terms of one single storage and one characteristic recession curve (e.g. 08JE004, 08JD006).

Furthermore, the sensitivity analysis shows that the best parameter set depends on the catchment characteristics above all on whether the geology is dominated by sedimentary rock or bedrock.

Sedimentary rock dominated catchments tend to be characterized by higher values of *a* which are responsible for a slower reservoir outflow and a lower sensitivity to input changes according to the climate change scenarios. In catchments with a large share of bedrock, best fits were usually obtained with lower values of *a*. These lower values are responsible for a faster reservoir outflow and a higher sensitivity to changing inputs.

But that depends strongly on the water available; the catchments in the north of BC are characterized mainly by large sedimentary rock aquifers but also by low precipitation rates especially in winter which causes less spring recharge as in the south of BC and results in significant changes in discharge, despite the lower sensitivity caused by geology to changing inputs.

It can be summarized, that significant changes in summer low flows occur on the one hand mainly in regions where the impacts are evident like in the north of British Columbia. On the other hand especially catchments with a large share of bedrock are sensitive to the impacts of climate change. Catchments with large unconsolidated rock aquifers and enough water available tend to be less sensitive to climate change without any significant changes in summer low flows.

# 6 Final conclusions

The objective of the study was to estimate the impact of climate changes on low flows. The largest impacts on runoff are expected in areas where the runoff regime will change. Furthermore the catchment sensitivity to input changes is relevant whether the low flow periods will be more extended or pronounced. Several studies expected an earlier and diluted spring peak flow, according to global warming and an extended summer low flow period.

The model developed in this thesis is as parameterized as low as possible and orientated to an application as universal as possible. The model structure is optimized to use mean precipitation and temperature data to forecast trends in mean low flows. The fitting of the simulated to the observed hydrographs is in most catchments across BC well, especially the snowmelt-peak and the winter low flow conditions are easily to describe by this model. That confirms the universal application with only few input data and few assumptions. The fitting to the summer low flows is generally more difficult.

The results of the model generally show the expected earlier and diluted spring peak flow according to the CGCM A2 and B1 climate scenario for the 2050s. Significant changes during the summer low flow periods depend on the catchment and climate characteristics.

The results of the sensitivity analysis don´t allow to regionalize parameters to catchment characteristics such as, size, elevation or vegetation, but the parameter set probably depends on the catchments geology. In this thesis the catchments have been differentiated if they are dominated by bedrock or unconsolidated sedimentary rock. The general assumption that catchments dominated by sedimentary rock tend to be connected with larger, more productive aquifers is confirmed when comparing the best parameter sets of different catchments, and the sensitivity of each catchment to changing climatic inputs. These catchments tend to be described by a parameter set with a slower reservoir outflow and less significant changes of discharge during low flow periods than catchments which are mainly dominated by bedrock.

Apart from the geology of the catchments the climatic conditions as well as the delta-changes are also very important for the sensitivity of low flows. In particular the changes in the north of BC are greater than in the south, so that more significant changes could be observed.

The model finds restrictions in (I) the estimation of the correct effective rainfall but also (II) the transfer-function cant represents every catchment in the same way. It has to be assumed that not every catchment can be described with a single storage.

## Outlook

It would be very helpful to validate the model (model-structure and parameter sets) with real time series. To achieve this, it would be necessary to find a new estimation of actual evapotranspiration and to modify parts of the model-structure. Specific empirical approaches with an antecedent precipitation index (JAKEMAN, ET. AL., 1990) or the approaches according to BUDYKO (1963), which describe PET depending on precipitation, are of particular interest to estimate actual evapotranspiration. For both approaches there are studies which integrate vegetation influences on evapotranspiration. The evapotranspiration routine furthermore has the advantage that with real time series estimations of extreme events are possible, and the calibration of real discharge time series could lead to a better description of the specific catchments recession characteristics. Eventually the used mean discharge time series, smoothed by a running average, do not represent the real recession characteristic. It would be interesting, whether the resulting best parameter sets deliver the same results.

To regionalize the parameters it would be necessary to apply to the model for more catchments and furthermore it would be enlightening to find more detailed information about the catchments aquifers.

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# Appendix A

## A 1 Program source codes

### A 1.1 Read me v1 - Low Flow Prediction Model

**Included files and functions to run the model**

- main.m
- MC.m
- modul1.m
- modul2.m
- modul2_mc.m
- quantil.m
- test.m

- **to run MCAT (WAGENER (2), ET AL., 2004):**

- area3.m
- area3legend.m
- bestpred.m
- classp.m
- correlmatrix.m
- dotlhoods.m
- dotty.m
- explore3d.m
- gloue.m (modified)
- idmain.m
- interp_special.m
- linereg.m
- load_spkp_24h.m
- load_sxtp24.m
- loadbmp.m
- magnifyrecttofig.m
- mcat.m
- mcatool.m
- multiobj.m
- norm.dist
- pareto.m
- paretofront.m
- paretopairs.m
- paretounc.m
- parvis.m
- pefilt.m
- pixel.m
- plot_sims.m
- plot_sims_pattern.m
- plot_sims_pattern_v2.m
- plot_sims_trad.m
- plot_sims_pattern.m
- plot_sims_pattern_v2.m
- plot_sims_trad.m
- plot_sims_trad2.m
- postdis.m
- prange.m
- range.m
- runKollatPlots.m
- sensi.m
- sensi2.m
- sensi3.m
- table.m
- time_surface.m
- tpage.m
- uncert.m
- unpad.m
- var.m
- crest.bmp
- logo.bmp
- psu.bmb

**Main Program (*main.m*)**

The main program runs *module1.m* by the given effective rainfall parameters (size, elev, ddf, HC, Tm, $a_{pt}$, sub, drsm, dr, Rc, Sc, feS) and transfers the estimated effective rainfall to m*odule2.m* which is controlled by parameter *a* and *b*. By setting the delta-changes (line 52-69) as it is possible to do the calculations with the CGCM A2 and B1 2050 climate change scenarios instead the Climate Normals from 1960-1990.

**Effective Rainfall (*module1.m)***

To run module1.m the following input data is required:

- prec01.txt to prec12.txt — mean monthly Precipitation data [mm/month] as a MxN *(dim(1),dim(2))* raster file
- temp01.txt to temp12.txt — mean monthly temperature data [°C*10] as a MxN *(dim(1),dim(2))* raster file
- rad.txt — mean daily radiation [MJ/m2/d] as a vector (12,1) including the mean daily radiation for each month
- eS.txt — a vector (122,1) including indices which control whether an additional storage (*eS* - at the end of the growing season) is filled (*I=1*) or not (*I=0)*

By disaggregating monthly values to daily values and applying a running average a 2 year time series of precipitation (*prec*) and temperature (*temp*) in the form of a 3-Dimensional matrix (*dim(1),dim(2),244*) is created. *Dim(1)* and *dim(2)* cover the catchment (400 m grid cells), 244 represents the timesteps for the two-year time series (*prec, temp*) for every grid cell. Inactive cells are set to zero. The model calculations are performed in three day time steps. Thus one year is given as 122 days and two years with 244 days.
*Peff1* describes the effective rainfall for each active grid cell. With Peff2a (*Peff2a(k)=(sum(sum(Peff1(:,:,k))))/cn;*) the mean effective rainfall of the whole catchment is calculated.
The effect of snowfall/SWE storage occurring also from October to December is covered by using only a one year (year two (123:244)) of effective rainfall instead the two year time series for all calculations of *PET, AET, snowmelt, Peff1, Peff2a.* The one-year dataset of effective precipitation is saved as *Peff3.*

When calculating with active direct runoff components (*DR >0*) a direct runoff time series (122:1) is saved as *Q_d.txt*. When calculating without these components the *Q_d* time series is filled by zero´s.

## Transfer-function (m*odule2.m)*

To run m*odule2.m* the following input data is required:

- DOX.txt — a vector (1:2440) which includes the 20 year timeseries as 3 day time steps (0, 3, 6, … , 7317)
- Peff.txt — a vector (1:2440) of the effective rainfall created in MODULE 1[mm/a]
- Q_d.txt — a vector (122:1) which includes direct runoff components [mm/a]
- q_m.txt — a vector (122:1) which includes the observed discharge [m3/s]

*reference* describes the characteristic recession depending on the two transfer-function parameters *a* and *b*. The recession which is standardized to *norm* and becomes convoluted with the 20 year time series of effective rainfall (*Peff*). The 20 year time series is used to obtain steady state conditions after 20 years. *w4 (1:122)* describes the transferred effective rainfall to discharge of year 20 in mm/d.

*Q (1:122)* is the sum of *w4* and direct runoff components *(Qd* - which are excepted from the transfer-function) in m3/a.

Furthermore, *Q* is compared with $Q_{obs}$ by creating plots and objective functions.

**Monte Carlo runs, sensitivity and uncertainty estimation (*MC.m*)**

With *MC.m* the effective rainfall *(Peff)* from m*odule1.m* becomes transferred *n* times into discharge, by running *module2_MC.m* and creating objective functions, according to *n* randomly generated parameter sets of *a* and *b*. *Module2_MC.m* is a simplified version of *modul2.m* and optimized to obtain fast model runs .

To run *MC.m* the following input data is required:

- DOX.txt — a vector (1:2440) which includes the 20 year timeseries as 3 day time steps (0, 3, 6, … , 7317)
- Peff.txt — a vector (1:2440) of the effective rainfall created in MODULE 1[mm/a]
- Q_d.txt — a vector (122:1) which includes direct runoff components [mm/a]
- q_m.txt — a vector (122:1) which includes the observed discharge [m3/s]

The set up for the Monte Carlo Analysis Tool MCAT includes the generated parameter sets (*pars*), the corresponding objective functions (*crit*) and simulated hydrographs (*mct*), the observed discharge (*obs*) and the labelling of different plots.
In MCAT there are a lot of options and graphical demonstrations concerning sensitivity and uncertainty analysis.

To do uncertainty estimation for the climate change scenario the procedure is as follows:

You have to comment line 24 and to uncomment line 25 in *modul2_MC.m* and to select the same threshold in MCAT like in the calculation with no climate change scenario:

```
% Qobs122=Qobs;                    % comment for climate change scenario!
Qobs122=load('Qsimulated.txt'); % uncomment for climate change scenario!
```

Thus it is assumed that it is possible to get a comparable distribution of the uncertainty domain around the simulated discharge as in the calculation with no climate change scenario.

By a modification of *gloue.m* in the MCAT toolbox (see A 1.50) the distributions of the uncertainty domains (between 0.05 and 0.95 confidence limit) is stored as *today.txt* (uncomment when calculating without climate change scenario) or as *A2.txt (B2.txt)* (uncomment when calculating the A2 (B1) scenario) depending on the selected threshold.

Line 85 to 87 in *gloue.m*:

```
save today.txt dist -ascii % uncomment for recent simulation
%save A2.txt dist -ascii   % uncomment for A2 simulation
%save B1.txt dist -ascii   % uncomment for B1 simulation
```

**Mean discharge and Kolmogorov-Smirnov significance test**

The function *quantile.m* creates the mean annual discharge hydrograph from any discharge time series (load '*Qlong.txt*') (no leap years) as well as the median and optional quantiles.

The function *test.m* estimates significant changes (pA2(1,j)=1 and pB1(1,j)=1) between the uncertainty distributions of recent (today.txt) and simulated future (A2.txt and B1.txt) hydrograph according to the Kolmogorov-Smirnov significance test.

## A 1.2 Main Program *(main.m)*

```
Example: 08HF004

clear all
%-------------------------------------------------------------------------
%Main Program of the Low Flow Prediction Model by Johannes
%-------------------------------------------------------------------------



%-------------------------------------------------------------------------
% effective rainfall - parameters
%-------------------------------------------------------------------------

% Catchment characteristic

size=360;        %catchment size [km2]
elev=892;        %mean basin elevation [m]

% Snowmelt

ddf=2;           %degree day factor [mm/°C/d]
HC=.1;           %Holding Capacity [-]
Tm=0;            %melting temperature [°C]

% Evapotranspiration

al=1.05;         %Priestley and Taylor alpha a_pt [-]
sub=0.5;         %winter evaporation [mm/d]

% Direct Runoff

drsm=0;          %direct runoff during snowmelt peak [-]
dr=0;            %direct runoff after snowmelt peak [-]

% Correct Precipitation

Rc=0.91;         %correct rainfall [-]
Sc=0.91;         %correct snowfall [-]

% additional empty storage at the end of growing season

feS=0.0;         %filling empty storage [-]



%-------------------------------------------------------------------------
%Transfer-function parameters
%-------------------------------------------------------------------------

a=5.69;
b=0.26;
```

```
%-------------------------------------------------------------------------
%climate change scenario - [delta change: PPT in %, TT in delta°C]
%-------------------------------------------------------------------------

%no scenario (uncomment for no scenario!)

PPT01=0;PPT02=0;PPT03=0;PPT04=0;PPT05=0;PPT06=0;PPT07=0;PPT08=0;PPT09=0;
PPT10=0;PPT11=0;PPT12=0;TT01=0;TT02=0;TT03=0;TT04=0;TT05=0;TT06=0;TT07=0;
TT08=0;TT09=0;TT10=0;TT11=0;TT12=0;

%A2 (CGCM 2050) - Climate Change Scenario (uncomment for A2 scenario!)

% PPT01=24; PPT02=26; PPT03=6; PPT04=-3; PPT05=-24; PPT06=-8; PPT07=-4;
% PPT08=1; PPT09=-1; PPT10=1; PPT11=12; PPT12=26; TT01=1.65; TT02=1.85;
% TT03=1.95; TT04=1.95; TT05=1.95; TT06=2; TT07=2; TT08=1.9; TT09=1.85;
% TT10=1.8; TT11=1.7; TT12=1.75;
% %
% %B1 (CGCM 2050) - Climate Change Scenario (uncomment for B1 scenario!)
% PPT01=8; PPT02=13; PPT03=10; PPT04=2; PPT05=-20; PPT06=-8; PPT07=-5;
% PPT08=4; PPT09=4; PPT10=-10; PPT11=-1; PPT12=12; TT01=1.2; TT02=1.35;
% TT03=1.45; TT04=1.35; TT05=1.4; TT06=1.4; TT07=1.4; TT08=1.4; TT09=1.4;
% TT10=1.35; TT11=1.2; TT12=1.2;

%-------------------------------------------------------------------------
% effective rainfall
%-------------------------------------------------------------------------

h=waitbar (0,'prepare Peff');

[Peff,Q_d,aPrec_bil,aAET_bil,PREC,ET,aPEFF_bil,PEFF,QD,Bil,MAT,aTemp_bil]=m
odul1(ddf,HC,Tm,al,elev,drsm,dr,sub,Rc,Sc,feS, ...
PPT01,PPT02,PPT03,PPT04,PPT05,PPT06,PPT07,PPT08,PPT09,PPT10,PPT11,PPT12,
...
TT01,TT02,TT03,TT04,TT05,TT06,TT07,TT08,TT09,TT10,TT11,TT12);

waitbar(1/100,h)

close(h);

%-------------------------------------------------------------------------
%Apply transfer-function
%-------------------------------------------------------------------------

h=waitbar (0,'apply transferfunction');

[Q QSIM QOBS NSeff RMSE]=modul2(a,b,size);

waitbar(i/100,h)

close(h);
%-------------------------------------------------------------------------
%Output
%-------------------------------------------------------------------------

sprintf('MAT \t = %5.2f\t[°C] \nMAP \t = %5.2f\t[mm/a] \nET   \t =
%5.2f\t[mm/a] \nPeff \t = %5.2f\t[mm/a] \nQd   \t = %5.2f\t[mm/a]\nBil \t =
%5.2f\t[mm/a] \t [MAP-ET-Peff-Qd]\n\nQsim \t = %5.2f\t[mm/a]\nQobs \t =
%5.2f\t[mm/a]\nNSeff \t = %5.4f\t[-]\nRMSE \t = %5.4f\t[-]',
MAT,PREC,ET,PEFF,QD,Bil,QSIM,QOBS,NSeff,RMSE)
```

### A 1.3 Key sections of m*odule1.m*

```
%-----------------------------------------------------------------------
%PET - Priestley and Taylor
%-----------------------------------------------------------------------

%L - Latent heat of vaporization [MJ/kg]

L=zeros(size(Prec1));
for i=1:dim(1)
    for j=1:dim(2)
        for k=1:244
            if Prec(i,j,k)>0
                L(i,j,k)=2.5-0.00236*Temp(i,j,k);
            elseif Prec(i,j,k)<=0
                L(i,j,k)=0;
            end
        end
    end
end

%S - Slope(saturation vapor pressure and air temperature)

S=zeros(size(Prec1));
for i=1:dim(1)
    for j=1:dim(2)
        for k=1:244
            if Prec(i,j,k)>0
               S(i,j,k)=0.611*exp((17.3*Temp(i,j,k)/ (Temp(i,j,k)+273.3)));
            elseif Prec(i,j,k)<=0
               S(i,j,k)=0;
            end
        end
    end
end


U=zeros(size(Prec1));

%U - psychrometric constant

for i=1:dim(1)
    for j=1:dim(2)
        for k=1:244
            if Prec(i,j,k)>0
                U(i,j,k)=(p*0.001013)/(0.622*L(i,j,k));
            elseif Prec(i,j,k)<=0
                U(i,j,k)=0;
            end
        end
    end
end

%calculate Priestley and Taylor PET

PET=zeros(size(Prec1));
for i=1:dim(1)
    for j=1:dim(2)
        for k=1:244
```

```
            if Prec (i,j,k)>0

PET(i,j,k)=al*1/L(i,j,k)*((S(i,j,k)*radiation(1,1,k))/(S(i,j,k)+U(i,j,k)));
            elseif Prec(i,j,k)<=0
                PET(i,j,k)=0;
            end
        end
    end
end

%AET Turc
AET=zeros(size(Prec1));
for i=1:dim(1)
    for j=1:dim(2)
        for k=1:244
            if Prec (i,j,k)>0 && Temp(i,j,k) > 0

AET(i,j,k)=1*(Prec(i,j,k)/((0.9+(Prec(i,j,k)/PET(i,j,k))^2)^0.5));
            elseif Prec(i,j,k)>0 && Temp (i,j,k) <0
                AET(i,j,k)=1*sub;
            elseif Prec(i,j,k)<=0
                AET(i,j,k)=0;
            end
        end
    end
end


%-----------------------------------------------------------------------
%snow melt & effective rainfall
%-----------------------------------------------------------------------

%parameters - snow melt routine:

% ddf=2.2;  %[mm/°C]
% HC=.1;    %holding capacity of snow cover as a fraction of total water
equivalent
% ds=0.1;   %factor for surface runoff
% dd=0.05;  %factor for surface runoff after snowmelt
% Tm=0;     %melting Temperature
RF=.05; %refreezing factor (Value from HBV)


SWE=zeros(size(Prec));      % Snow Water Equivalent
RLW=zeros(size(Prec));      % Retained liquid Water
Peff1=zeros(size(Prec));    % EFFECTIVE RAINFALL



%apply snow melt routine

SWE(:,:,1)=Prec(:,:,1);

refr=zeros(size(Prec));     % refreezing from retained liquid water (from
HBV)
Qd=zeros(size(Prec));       % direct runoff
melt=zeros(size(Prec));     % snowmelt
LWRC=zeros(size(Prec));     % amount of water which can be retained in the
                               snowpack
```

```
eS=zeros(size(Prec));         % introducing an additional empty storage at
                              end of vegetation phase, which must be filled
SUB=zeros(size(Prec));        % Sum of sublimated water
sm=zeros(size(Prec));         %snowmelt only needed for water balance
for i=1:dim(1)
    for j=1:dim(2)
        for k=2:244
            if Temp(i,j,k)<=0 && Prec(i,j,k)>0
                refr(i,j,k)=RF*ddf*(Tm-Temp(i,j,k));
                if refr(i,j,k)<RLW(i,j,k-1) && RLW(i,j,k-1)>0
                    RLW(i,j,k)=RLW(i,j,k-1)-refr(i,j,k-1);
                    SWE(i,j,k)=SWE(i,j,k-1)+Prec(i,j,k)+refr(i,j,k)-
sub+eS(i,j,k-1);
                    SUB(i,j,k)=sub;
                    Peff1(i,j,k)=0;
                    Qd(i,j,k)=0;
                    eS(i,j,k)=0;
                    AET(i,j,k)=0;
                    sm(i,j,k)=0;
                elseif refr(i,j,k)>=RLW(i,j,k-1) && RLW(i,j,k-1)>0
                    RLW(i,j,k)=0;
                    SWE(i,j,k)=SWE(i,j,k-1)+Prec(i,j,k)+refr(i,j,k)-
sub+eS(i,j,k-1);
                    SUB(i,j,k)=sub;
                    Peff1(i,j,k)=0;
                    Qd(i,j,k)=0;
                    eS(i,j,k)=0;
                    AET(i,j,k)=0;
                    sm(i,j,k)=0;
                elseif RLW(i,j,k-1)==0
                    RLW(i,j,k)=0;
                    SWE(i,j,k)=SWE(i,j,k-1)+Prec(i,j,k)-sub+eS(i,j,k-1);
                    SUB(i,j,k)=sub;
                    Peff1(i,j,k)=0;
                    Qd(i,j,k)=0;
                    eS(i,j,k)=0;
                    AET(i,j,k)=0;
                    sm(i,j,k)=0;
                end
            elseif Temp(i,j,k)<=0 && Prec(i,j,k)==0 %inactive cells
                RLW(i,j,k)=0;
                SWE(i,j,k)=0;
                Peff1(i,j,k)=0;
                Qd(i,j,k)=0;
                eS(i,j,k)=0;
                SUB(i,j,k)=0;
                sm(i,j,k)=0;
            elseif Temp(i,j,k)>0
                melt(i,j,k)=ddf*(Temp(i,j,k)-Tm);
                if melt(i,j,k)<SWE(i,j,k-1) && SWE(i,j,k-1)>0
                    SWE(i,j,k)=SWE(i,j,k-1)-melt(i,j,k);
                    RLW(i,j,k)=RLW(i,j,k-1)+Prec(i,j,k)+melt(i,j,k)-
AET(i,j,k);
                    sm(i,j,k)=0;
                    LWRC(i,j,k)=HC*SWE(i,j,k);
                    Qd(i,j,k)=0;
                    eS(i,j,k)=0;
                    if RLW(i,j,k)>LWRC(i,j,k)
                        Peff1(i,j,k)=(RLW(i,j,k)-LWRC(i,j,k))*(1-drsm);
                        sm(i,j,k)=(RLW(i,j,k)-LWRC(i,j,k))*(1-drsm);
                        Qd(i,j,k)=drsm*(RLW(i,j,k)-LWRC(i,j,k));
                        RLW(i,j,k)=LWRC(i,j,k);
                        eS(i,j,k)=0;
```

```
                    end
                elseif melt(i,j,k)>=SWE(i,j,k-1) && SWE(i,j,k-1)>0
                        Peff1(i,j,k)=(SWE(i,j,k-1)+RLW(i,j,k-
1)+Prec(i,j,k)-AET(i,j,k))*(1-drsm);
                        sm(i,j,k)=(SWE(i,j,k-1)+RLW(i,j,k-1)*(1-drsm));
                        Qd(i,j,k)=drsm*(SWE(i,j,k-1)+RLW(i,j,k-
1)+Prec(i,j,k)-AET(i,j,k));
                        SWE(i,j,k)=0;
                        RLW(i,j,k)=0;
                        eS(i,j,k)=0;
                elseif SWE(i,j,k-1)==0
                        SWE(i,j,k)=0;
                        RLW(i,j,k)=0;
                        if Prec(i,j,k)-AET(i,j,k)>0 && I(k)==0
                            Peff1(i,j,k)=(Prec(i,j,k)-AET(i,j,k))*(1-dr);
                            Qd(i,j,k)=dr*(Prec(i,j,k)-AET(i,j,k));
                            eS(i,j,k)=0;
                            sm(i,j,k)=0;
                        elseif Prec(i,j,k)-AET(i,j,k)>0 && I(k)==1
                            Peff1(i,j,k)=(Prec(i,j,k)-AET(i,j,k))*(1-
dr)*(1-feS);

                            Qd(i,j,k)=dr*(Prec(i,j,k)-AET(i,j,k));
                            eS(i,j,k)=eS(i,j,k-1)+((Prec(i,j,k)-
AET(i,j,k))*feS);
                            sm(i,j,k)=0;
                        elseif Prec(i,j,k)-AET(i,j,k)<=0
                            Peff1(i,j,k)=Prec(i,j,k)-AET(i,j,k);
                            Qd(i,j,k)=0;
                            sm(i,j,k)=0;
                        end
                end
            end
        end
    end
end
%find number of active cells - cn
cellnumbers=find(Prec(:,:,76))>0;
cn=sum(cellnumbers);

%direct runoff time series
Qd2a=zeros(size(Prec));
for k=1:244
    Qd2a(k)=(sum(sum(Qd(:,:,k))))/cn;
end
Q_d(1:122)=Qd2a(123:244);


%--------------------------------------------------------------------------
%effective rainfall time series (20 years)
%--------------------------------------------------------------------------

Peff2a=zeros(1,1,244);

for k=1:244
    Peff2a(k)=(sum(sum(Peff1(:,:,k))))/cn;
end

Peff3(1:122)=Peff2a(123:244);

sum(Peff3);
```

```
    Peff(1:122,1)=Peff3;
    Peff(123:244,1)=Peff3;
    Peff(245:366,1)=Peff3;
    Peff(367:488,1)=Peff3;
    Peff(489:610,1)=Peff3;
    Peff(611:732,1)=Peff3;
    Peff(733:854,1)=Peff3;
    Peff(855:976,1)=Peff3;
    Peff(977:1098,1)=Peff3;
    Peff(1099:1220,1)=Peff3;
    Peff(1221:1342,1)=Peff3;
    Peff(1343:1464,1)=Peff3;
    Peff(1465:1586,1)=Peff3;
    Peff(1587:1708,1)=Peff3;
    Peff(1709:1830,1)=Peff3;
    Peff(1831:1952,1)=Peff3;
    Peff(1953:2074,1)=Peff3;
    Peff(2075:2196,1)=Peff3;
    Peff(2197:2318,1)=Peff3;
    Peff(2319:2440,1)=Peff3;

%---------------------------------------------------------------------------
%write data
%---------------------------------------------------------------------------

save Peff.txt Peff -ascii
save Q_d.txt Q_d -ascii
%---------------------------------------------------------------------------
%Mass Balance
%---------------------------------------------------------------------------
%snowmelt

for k=1:122
    smelt(k)=(sum(sum(sm(:,:,k))))/cn;
end
MELT=transpose(smelt);


%MAP - Mean Annual Precipitation

Prec_bil1=zeros(1,122);

for k=1:122
    Prec_bil1(k)=(sum(sum(Prec(:,:,k))))/cn;
end
aPrec_bil=transpose(Prec_bil1);

PREC=(sum(aPrec_bil))*3;

%MAT - Mean Annual Temperature

Temp_bil1=zeros(1,122);

for k=1:122
    Temp_bil1(k)=(sum(sum(Temp(:,:,k))))/cn;
end
aTemp_bil=transpose(Temp_bil1);

MAT=(sum(aTemp_bil))/122;
```

```
%AET
AET1a(:,:,1:122)=AET(:,:,123:244);
SUB1a(:,:,1:122)=SUB(:,:,123:244);
AET_bil1=zeros(1,122);
SUB_bil=zeros(1,122);
ET_bil=zeros(1,122);

for k=1:122
    AET_bil1(k)=(sum(sum(AET1a(:,:,k))))/cn;
end
for k=1:122
    SUB_bil(k)=(sum(sum(SUB1a(:,:,k))))/cn;
end
AET_an=(sum(AET_bil1))*3;
SUB_an=(sum(SUB_bil))*3;

ET=AET_an+SUB_an;
for k=1:122
     ET_bil(k)=(sum(sum(AET1a(:,:,k))))/cn+(sum(sum(SUB1a(:,:,k))))/cn;
end

aAET_bil=transpose(ET_bil);

%Peff


aPEFF_bil=transpose(Peff3);
PEFF=sum(Peff3)*3;

%SnowMelt&SWE
% for k=123:244
%     snow_bil(k)=(sum(sum(Peff1(:,:,k))))/cn;
% end
% for k=123:244
%     swe_bil(k)=(sum(sum(SWE(:,:,k))))/cn;
% end
%Overlandflow
QD=sum(Q_d)*3;

%Bilanz: N-V
Bil=PREC-ET-PEFF-QD;
```

## A 1.4 Transfer-function *(module2.m)*

```
function [Q QSIM QOBS NSeff RMSE]=modul2(a,b,size)
% size=133;       %catchment size [km2]
% a=12.22;
% b=0.162;
%---------------------------------------------------------------------------
%%%%%TRANSFER-FUNCTION%%%%%%%%%
%---------------------------------------------------------------------------

t=load('DOY.txt');
input=load('Peff.txt');
Qd=load('Q_d.txt');

reference=zeros(122,1);

for i=1:length(t)
   reference(i,1)=1*(1+((1-b)*1^(1-b))/(a*b)*t(i,1))^(1/(b-1));
end

%standardization
sum_reference=sum(reference(:,1));
norm=reference/sum_reference;

%convolution
w=conv(input,norm);

w4(1:122)=w(2319:2440);

%output
Q=w4*size*1000/24/3600+Qd*size*1000/24/3600; %mm/m2/a --> m3/s
Qobs122=load('q_m.txt'); %mean average Discharge
t_122(1:122,1)=t(1:122,1);
%---------------------------------------------------------------------------
%Plot results
%---------------------------------------------------------------------------

plot(t_122,Q,t_122,Qobs122)
xlabel('DOY');
ylabel('Discharge [m3/s]');
legend('Q sim','Q obs');

%---------------------------------------------------------------------------
%Mass Balance
%---------------------------------------------------------------------------

w4_365=w4*3;
Qd_365=Qd*3;
Qobs_mm=3*Qobs122*24*3600/(size*1000); %m3/s-->mm/m2/a

QSIM=sum(w4_365)+sum(Qd_365);
QOBS=sum(Qobs_mm);

%---------------------------------------------------------------------------
%save data
%---------------------------------------------------------------------------

save Qobserved.txt Qobs122 -ascii
```

```
save Qsimulated.txt Q -ascii

%-----------------------------------------------------------------------------
%Objective Functions
%-----------------------------------------------------------------------------

%%%%%%%%%%Nash - Sutcliffe%%%%%%%%%%%%%%

Q_avge=mean(Qobs122);

ae=zeros(122);
ce=zeros(122);
for i=1:122
    ae(i)=(log(Qobs122(i))-log(Q(i)))^2;
    ce(i)=(log(Qobs122(i))-log(Q_avge))^2;

end
SSE=sum(ae);
SSU=sum(ce);
NSeff=1-SSE/SSU;

%%%%%%%%%%%%%%root mean square error%%%%%%%%%%%%%%%%%%%%%%%

fe=zeros(122,1);
ce=0;

for i=1:122
    fe(i)=(Qobs122(i)-Q(i))^2;
    ce=ce+1;
end
RMSE=sqrt(sum(fe)/ce);
```

## A 1.5 Monte Carlo Runs, sensitivity and uncertainty estimation *[MC.m]*

```
clear all
%-----------------------------------------------------------------------------
%Monte Carlo Runs
%-----------------------------------------------------------------------------


n=1000;              % number of Monte Carlo Runs
size=360;           % catchment size

a1=[0.1 100];          % Parameter Range a
b1=[0.001 0.99];       % Parameter Range b


%-----------------------------------------------------------------------------
t=load('DOY.txt');      % 20 year time series (3 day time steps)
input=load('Peff.txt'); % effective rainfall
Qd=load('Q_d.txt');     % direct runoff
Qobs=load('q_m.txt');   % observed discharge

dist_a1=a1(2)-a1(1);
dist_b1=b1(2)-b1(1);
% dist_s1=s1(2)-s1(1);
%-----------------------------------------------------------------------------
```

```
h=waitbar(0,'MC Simulation');

% Run Monte Carlo


RMSE_vec=zeros(n,3);
as=zeros(n,1);
pe=zeros(n,1);
Qsim=zeros(n,122);
for i=1:n
    a=a1(1)+rand(1,1)*dist_a1;
    b=b1(1)+rand(1,1)*dist_b1;
    [RMSE lnNeff peako Q]=modul2_MC(a,b,size,t,input,Qd,Qobs);
    RMSE_vec(i,:)=[a b RMSE];%RMSE
    as(i,:)=lnNeff;
    pe(i,:)=peako;
    Qsim(i,:)=Q;
    waitbar(i/n,h)
end

close(h);

%write data

save RMSE.txt RMSE_vec -ascii

%---------------------------------------------------------------------------
%set up for MCAT (Thorsten Wagener)
%---------------------------------------------------------------------------

pars=[RMSE_vec(:,1) RMSE_vec(:,2)];
crit=[RMSE_vec(:,3) as(:,1)];
vars=pe(:,1);
mct=Qsim(:,:);
    Q_m=load('q_m.txt');
obs=Q_m;
id='Nonlinear Transferfunction model';
pstr=str2mat('a','b');
cstr=str2mat('RMSE','1-lnNeff');
vstr=str2mat('peak output');
dt=1;
t=[];

% start MCAT

mcat(pars,crit,vars,mct,[],obs,id,pstr,cstr,vstr,dt,t);

%---------------------------------------------------------------------------
```

## Modification of MCAT to get the distribution of the 90% Confidence Interval

```
...
create mean and CIs^
    %modified by Johannes to get the distribution (today.txt/A2.txt/B1.txt)
between the 0.95 UCL
    %and the 0.05 LCL --> you can´t change the confidence limits in the
MCAT user interface
    % any more!!! to change manual select an according value in line 87 and
88
    UC=[0.95 0.9 0.85 0.8 0.75 0.7 0.65 0.6 0.55 0.51];
    LC=[0.49 0.45 0.4 0.35 0.3 0.25 0.2 0.15 0.1 0.05];

    pclci_d=zeros(10,ndt);
    pcuci_d=zeros(10,ndt);

    for j=1:10
        for i=1:ndt
        pcsof(i,:)=cumsum(of_matrix_2(i,:))./sum(of_matrix_2(i,:));
        cc=find(pcsof(i,:)<LC(j));pclci_d(j,i)=sq(i,max(cc));
        cc=find(pcsof(i,:)>UC(j));pcuci_d(j,i)=sq(i,min(cc));
        %pclci(i)  =interp1(pcsof(i,:),sq(i,:),gvs.lci);
        %pcuci(i)  =interp1(pcsof(i,:),sq(i,:),gvs.uci);
        mq(i)     =mean(sq(i,:));
        end
    end

    %  pclci_d
    %  save LCI.txt pclci_d -ascii
    % pcuci_d;

    dist(1:10,1:122)=pcuci_d(1:10,1:122);
    dist(11:20,1:122)=pclci_d(1:10,1:122);

    save today.txt dist -ascii % uncomment for recent simulation
    %save A2.txt dist -ascii   % uncomment for A2 simulation
    %save B1.txt dist -ascii   % uncomment for B1 simulation

    pclci=pclci_d(10,:); %0.05 confidence limit (0.1 cl --> pclci_d(9,:)
    pcuci=pcuci_d(1,:);  %0.95 confidence limit (0.9 cl --> pclci_d(2,:)

    %end of modification...
```

# A 2 Study areas (topography and BTM land use zones)

Table A 1: Descriptions BTM (Province of British Columbia, 2001)

| Land use | Definition | Land use | Definition |
|---|---|---|---|
| **Agriculture** | Land based agricultural undifferentiated as to crop (i.e. land is used as the producing medium) | **Fresh Water/Lakes** | Fresh water bodies (lakes, reservoirs and wide portions of major rivers). |
| **Alpine** | Areas virtually devoid of trees at high elevations. | **Recently Logged** | Timber harvesting within the past 20 years, or older if tree cover is less than 40% and under 6 meters in height. |
| **Sub-alpine Avalanche Chutes** | Areas below the tree line that are devoid of forest growth due primarily to snow avalanches. Usually herb or shrub covered | **Selectively Logged** | Areas where the practice of selective logging can be clearly interpreted on the Landsat TM image and TRIM aerial photography. |
| **Barren Surfaces** | Rock barrens, badlands, sand and gravel flats, dunes and beaches where unvegetated surfaces predominate. | **Mining** | Land used now (or in the past and remains unreclaimed) for the surface extraction of minerals or quarry materials |
| **Recently Burned** | Areas virtually devoid of trees due to fire within the past 20 years. Forest less than or equal to 15% cover. | **Rangelands** | Unimproved pasture and grasslands based on cover rather than use. Cover includes drought tolerant grasses, sedges, scattered shrubs to 6 meters in height and less than 35% forest cover. Sparse forest stands are included with their understorey of drought tolerant shrubs and herbs. |
| **Estuaries** | Salt water mud flats and inter tidal areas at the mouth of rivers and creeks where vegetation is influenced by frequent flooding (at least yearly) | **Shrubs** | Naturally occuring shrub cover with less than 50% coverage. Not wetlands, shrub covered logged areas (or other man-made disturbances), alpine, subalpine avalanche chutes or rangelands. This class of ground cover occurs in Northern BC on rich mid-slope positions or along valley bottoms which act as frost pockets. |

| Land use | Definition | Land use | Definition |
|---|---|---|---|
| **Old Forest** | Forest greater than or equal to 140 years old and greater than 6 meters in height. Areas defined as Recently Logged and Selectively Logged land uses are excluded from this class. | **Urban** | All compact settlements including built up areas of cities, towns and villages as well as isolated units away from settlements such as manufacturing plants, rail yards and military camps. In most cases residential use will predominate in these areas. Open space which forms an integral part of the urban agglomeration, e.g. parks, golf courses, etc. are included as urban. |
| **Young Forest** | Forest less than 140 years old and greater than 6 meters in height. Areas defined as Recently Logged and Selectively Logged land uses are excluded from this class. | **Wetlands** | Wetlands including swamps, marshes, bogs or fens. This class excludes lands with evidence or knowledge of haying or grazing in drier years. |
| **Glaciers and Snow** | Glaciers and permanent snow. Depending on the date of imagery, ephemeral snow may be included in this class. | | |

## 1. 08HF004

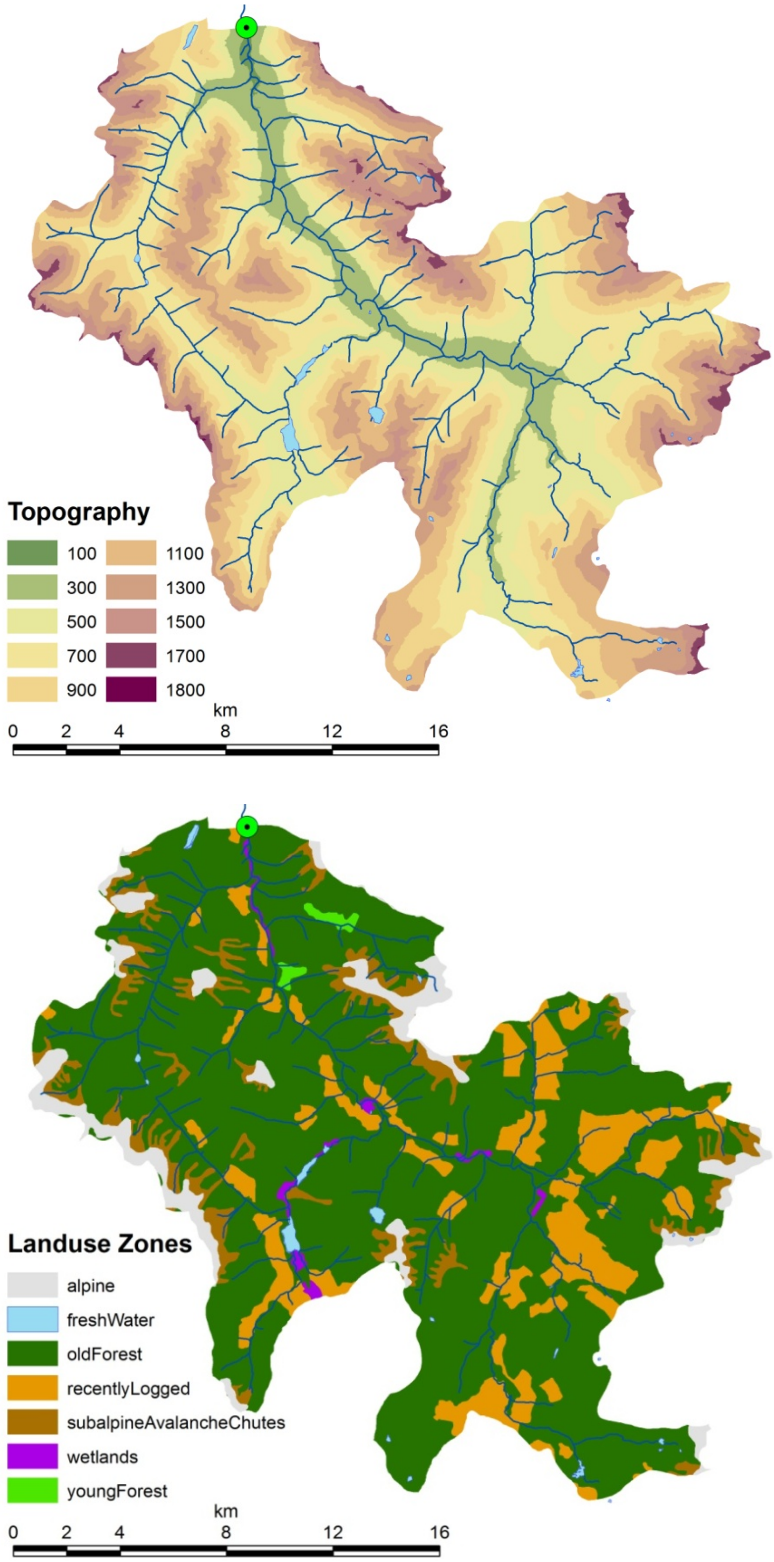



Figure A 1: Topography and BTM land use zones [08HF004]

**2. 08NM134**

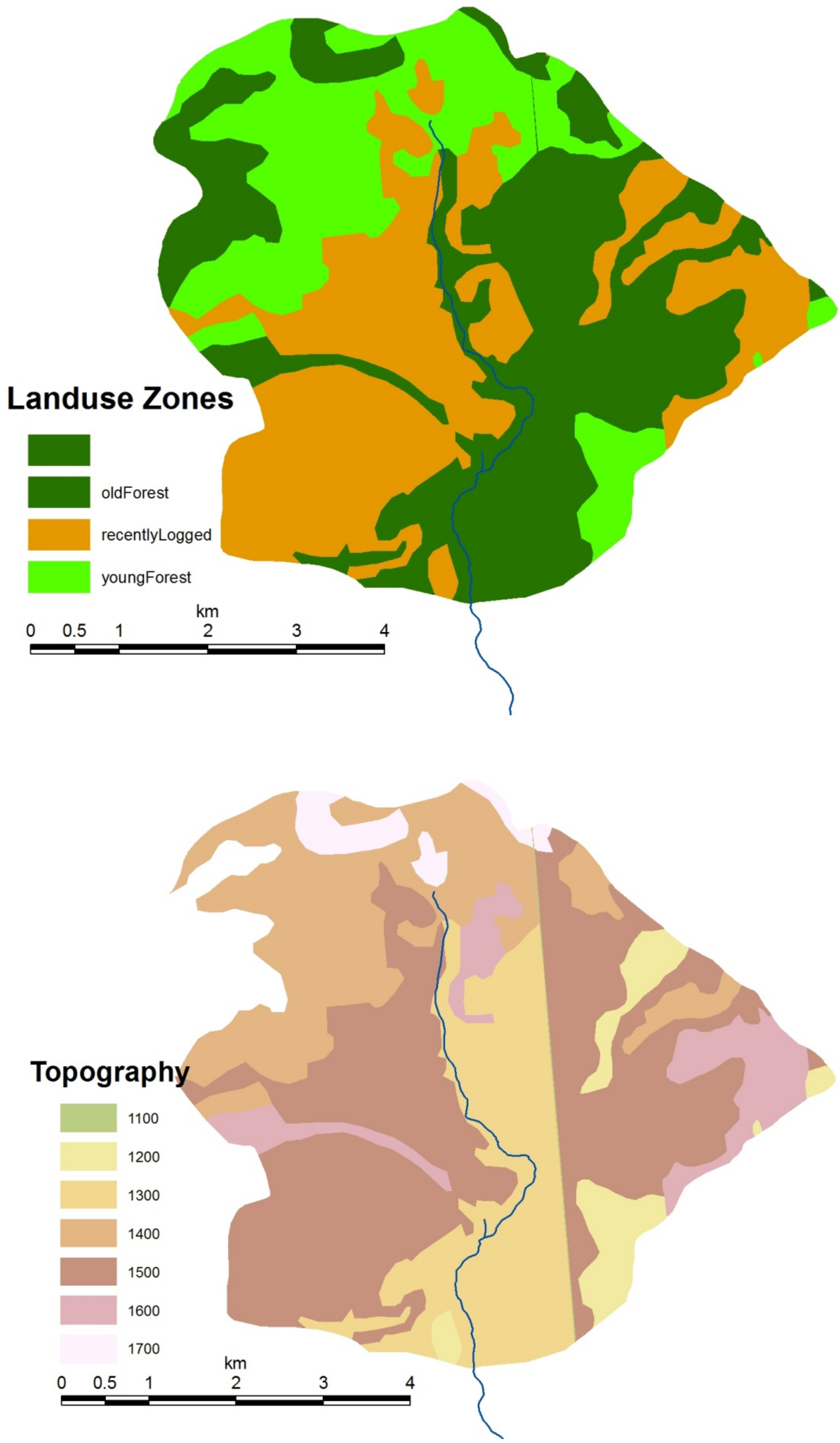
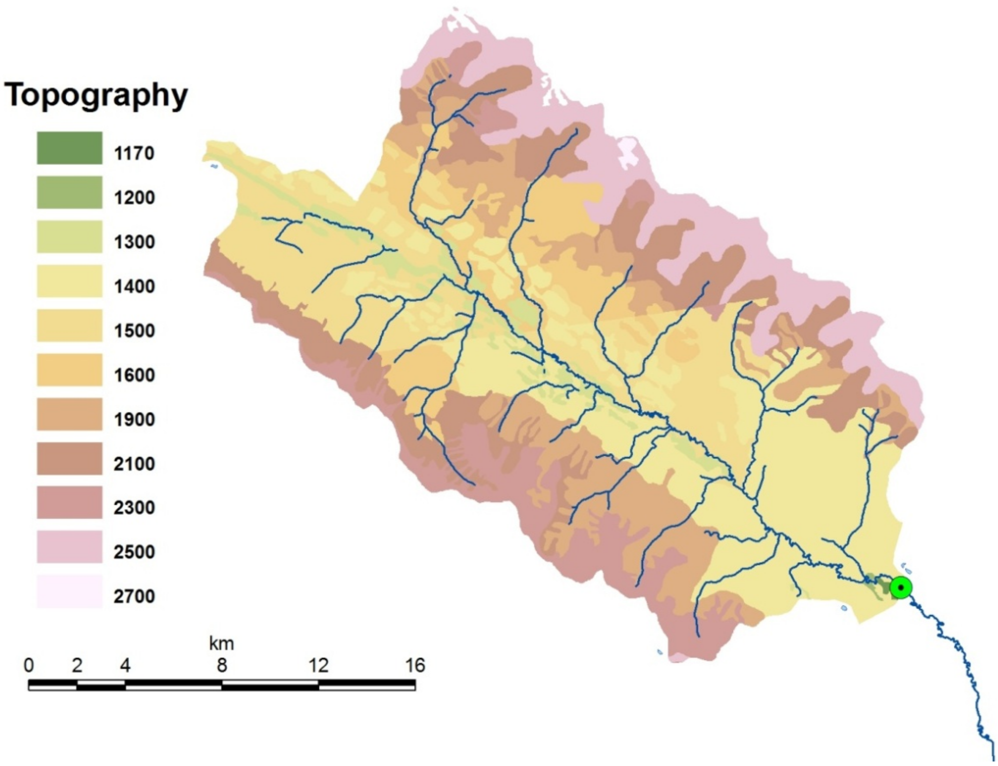



Figure A 2: Topography and BTM land use zones [08NM134]

**3. 08NF001**



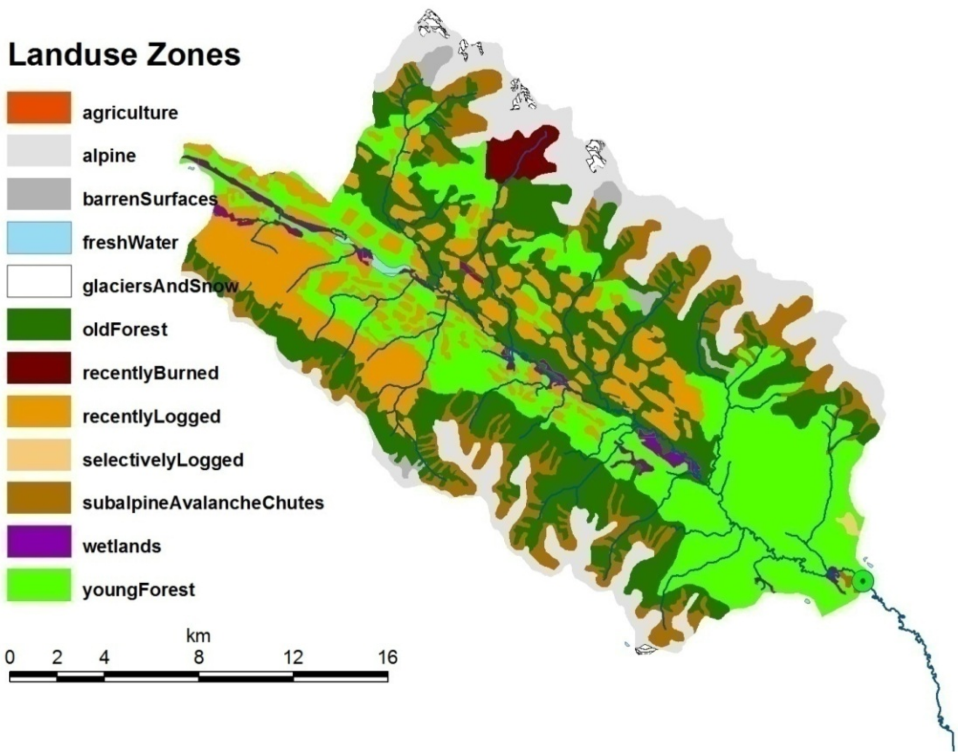
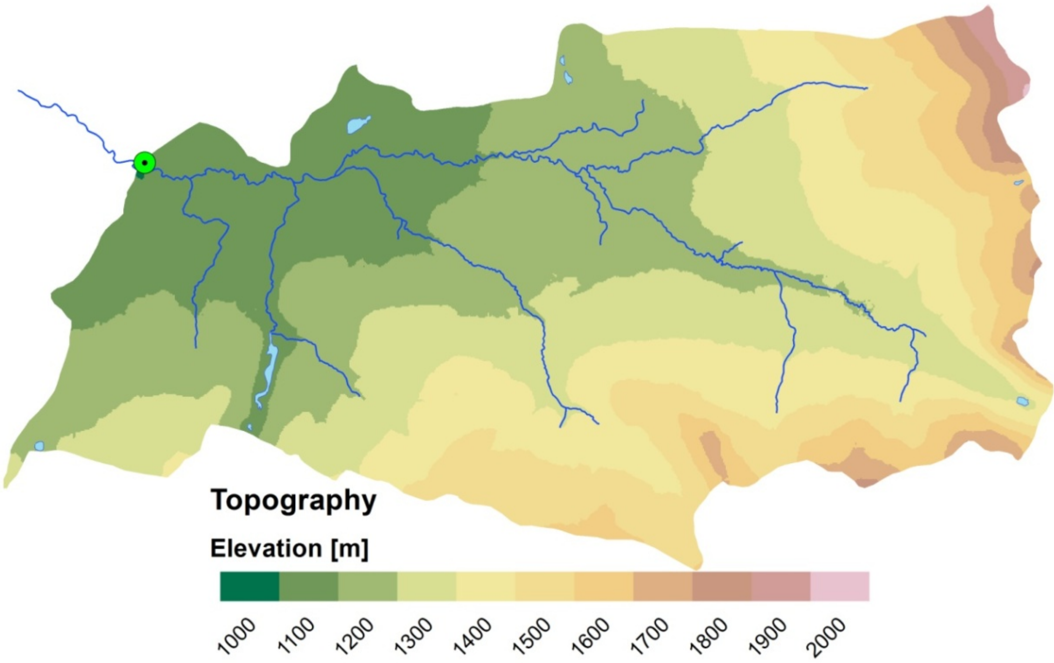




Figure A 3: Topography and BTM land use zones [08NF001]

**4. 08JA014**



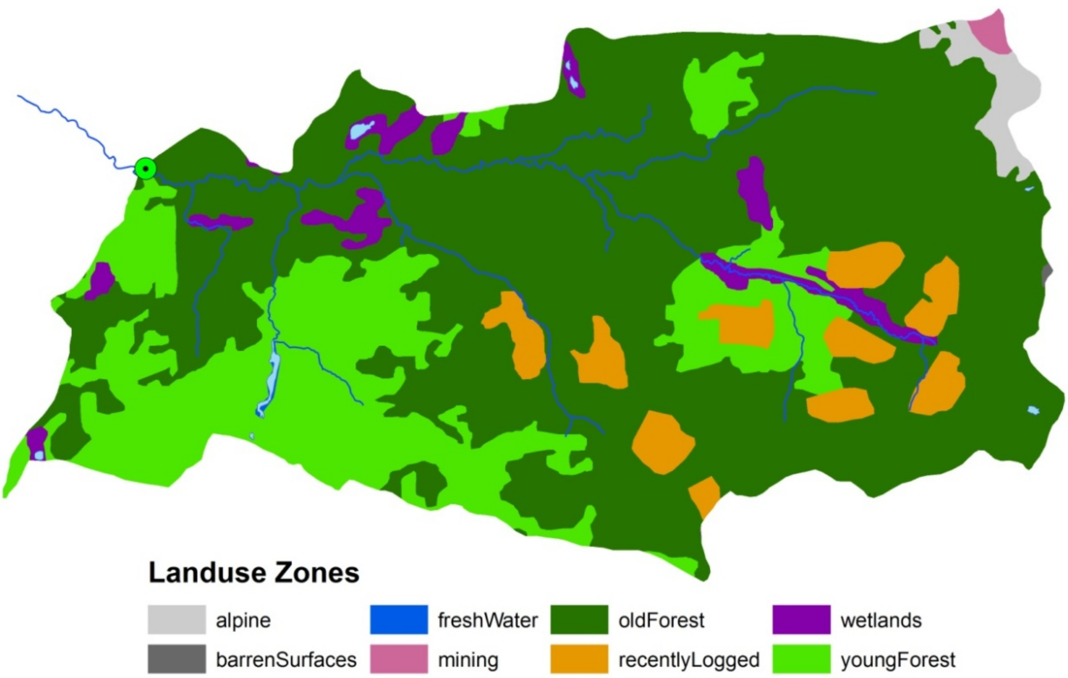
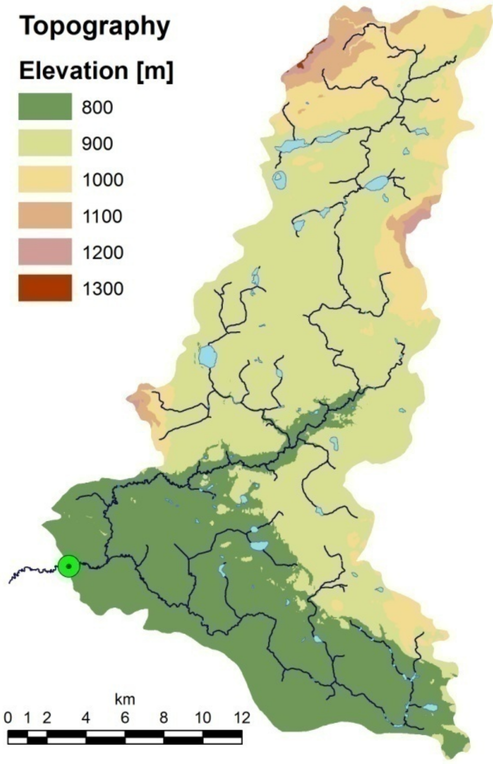




Figure A 4: Topography and BTM land use zones [08JA014]

## 5. 08JE004



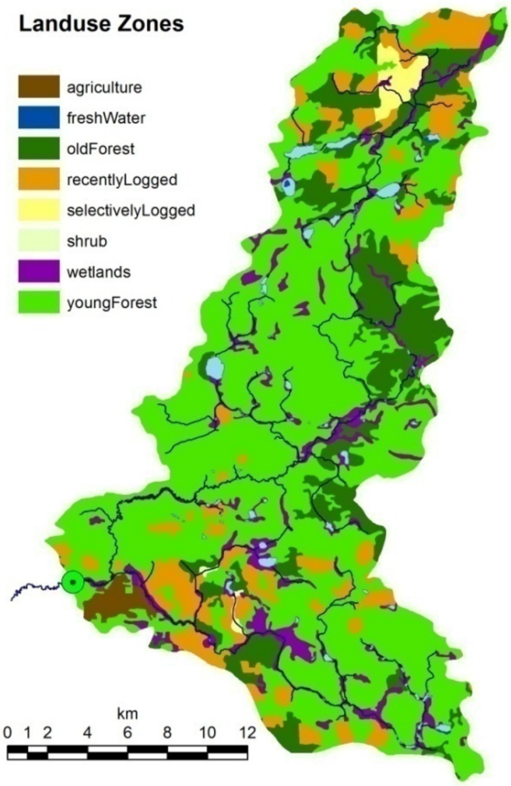
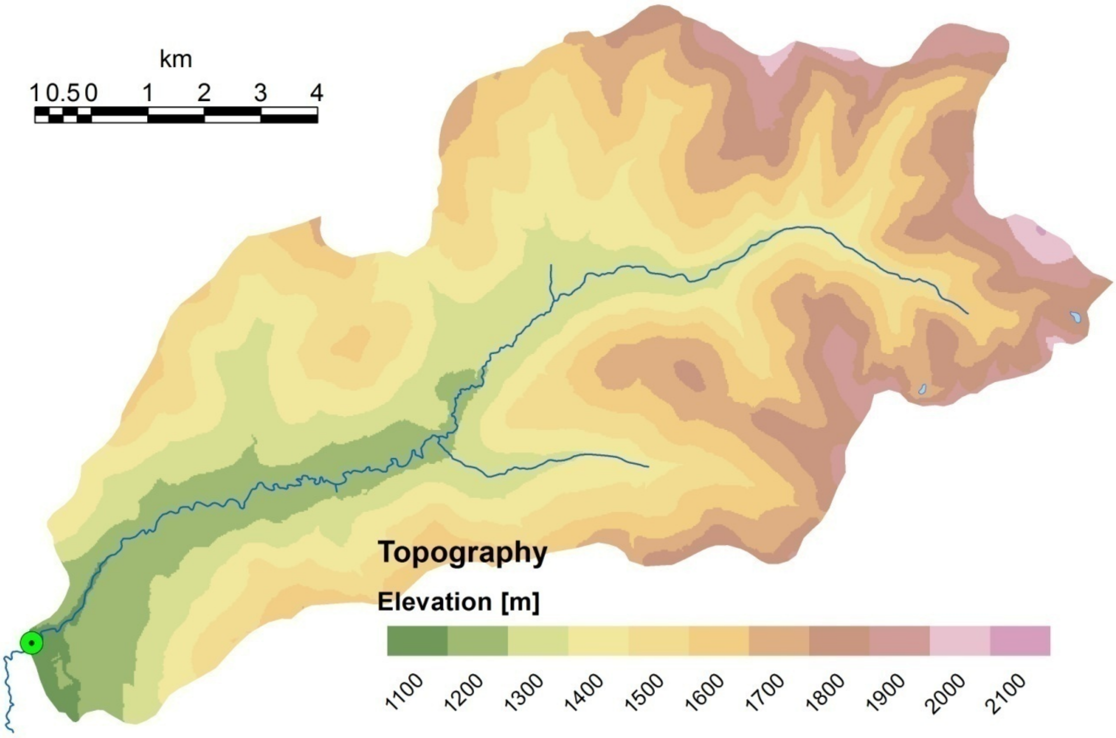




Figure A 5: Topography and BTM land use zones [08JE004]

**6. 08KE024**



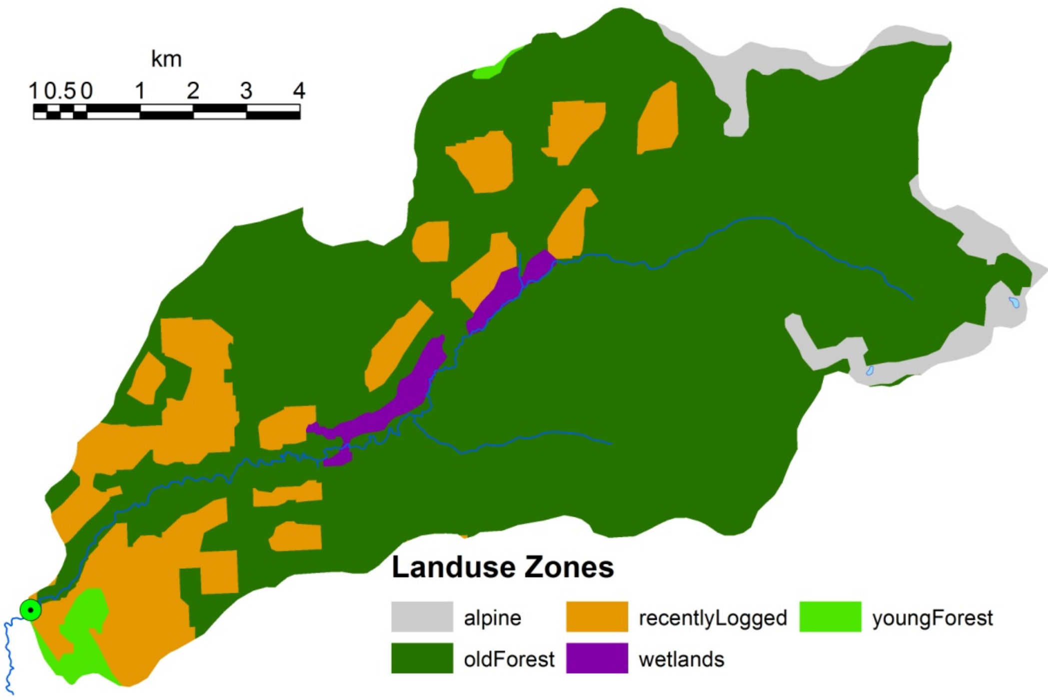
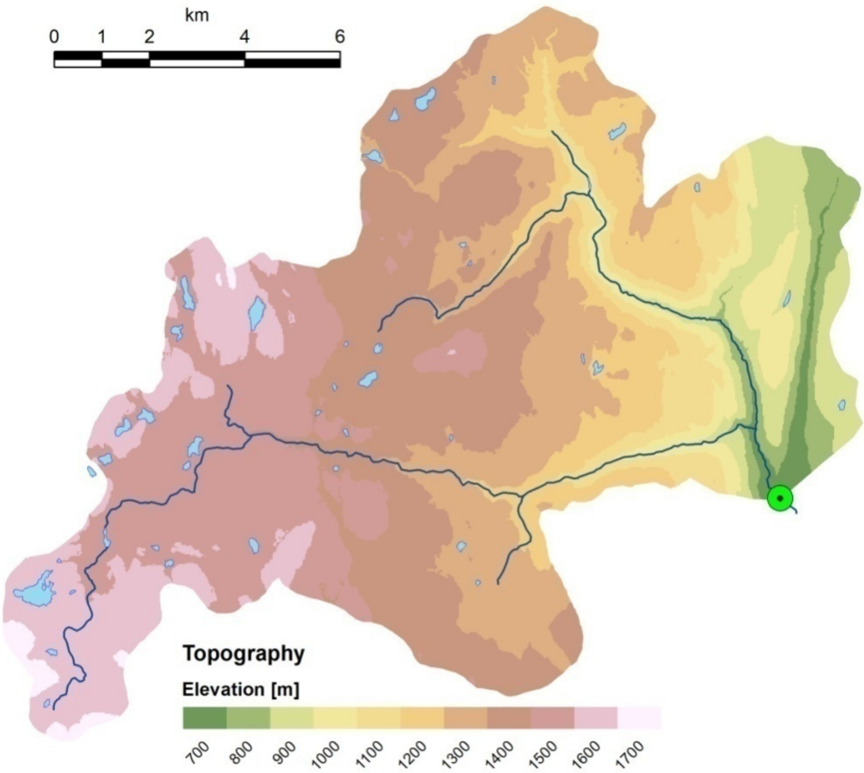




Figure A 6: Topography and BTM land use zones [08KE024]

**7. 08LB024**



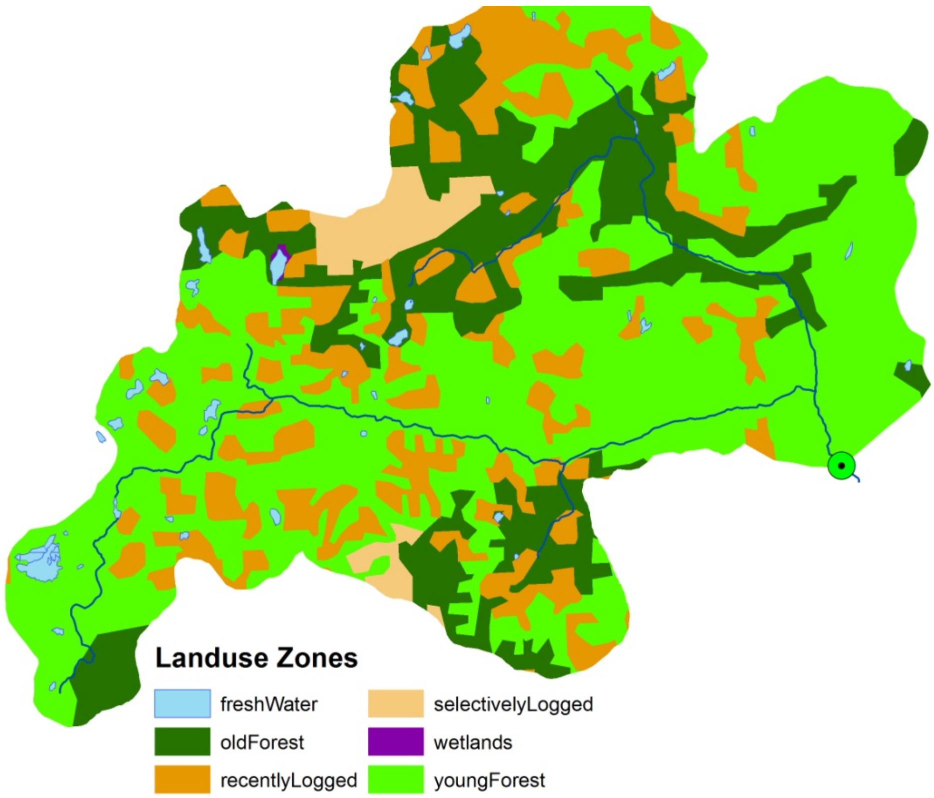




Figure A 7: Topography and BTM land use zones [08LB024]

**8. 08LB076**

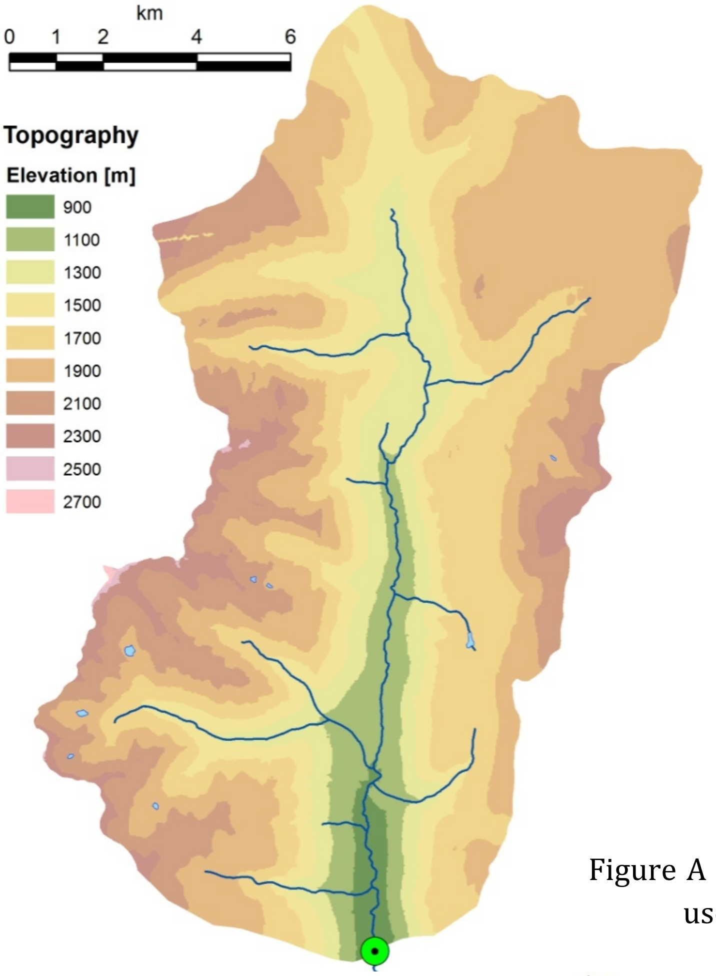
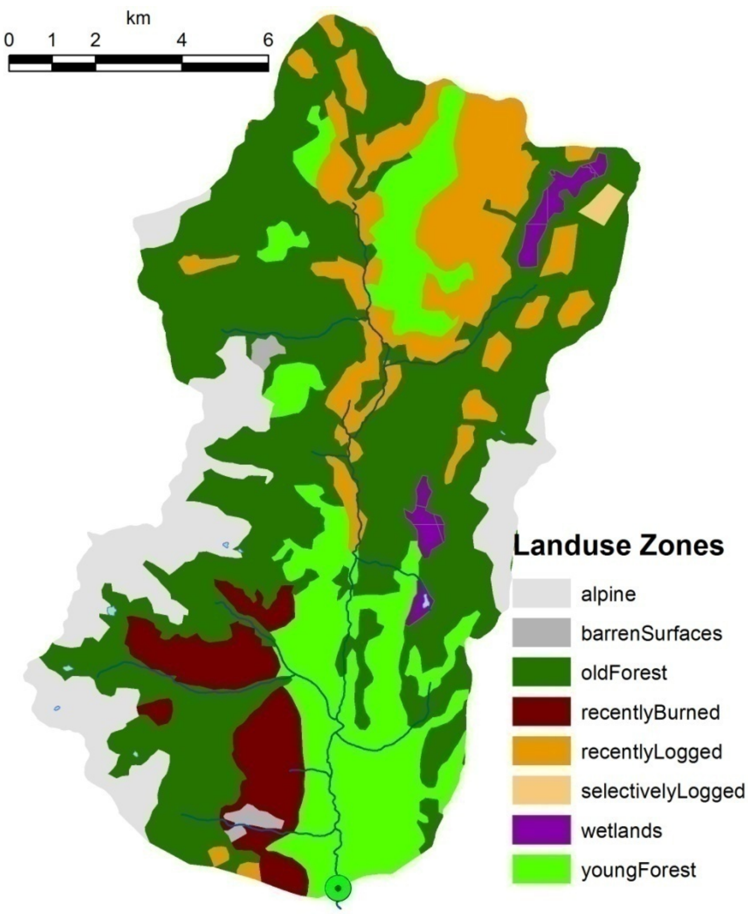



Figure A 8: Topography and BTM land use zones [08LB076]



**9. 08MA006**

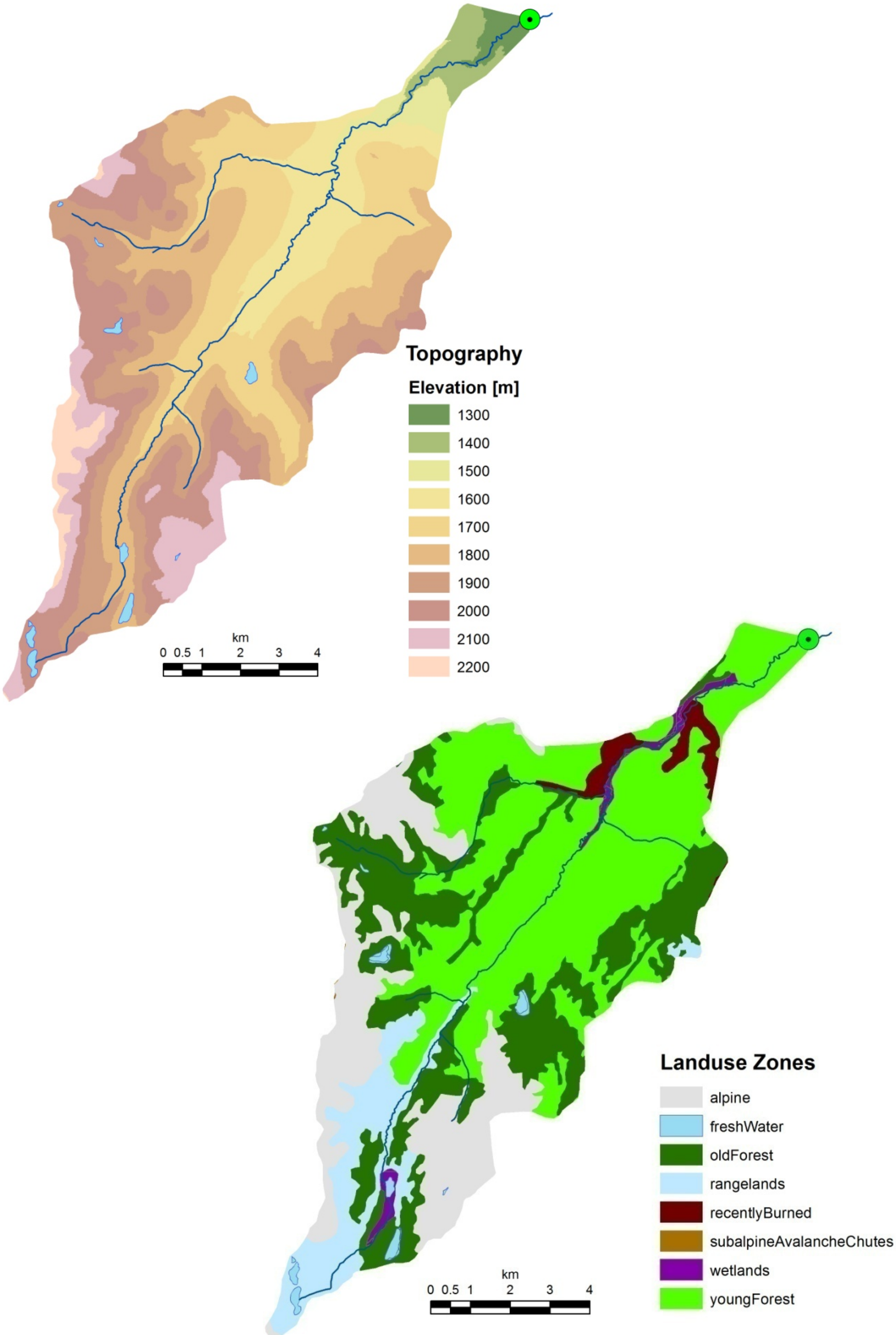
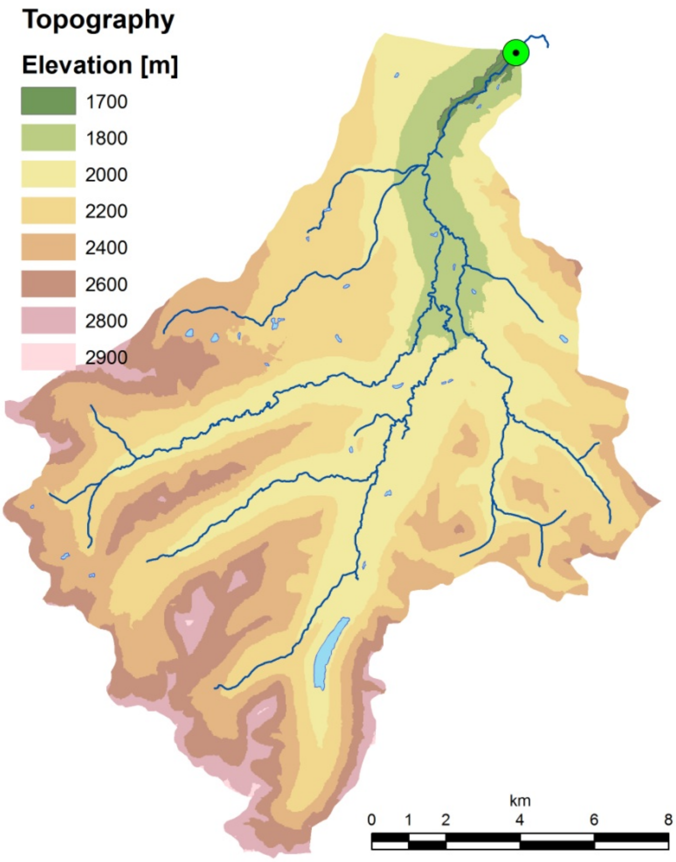



Figure A 9: Topography and BTM land use zones [08MA006]

## 10. 08MB007



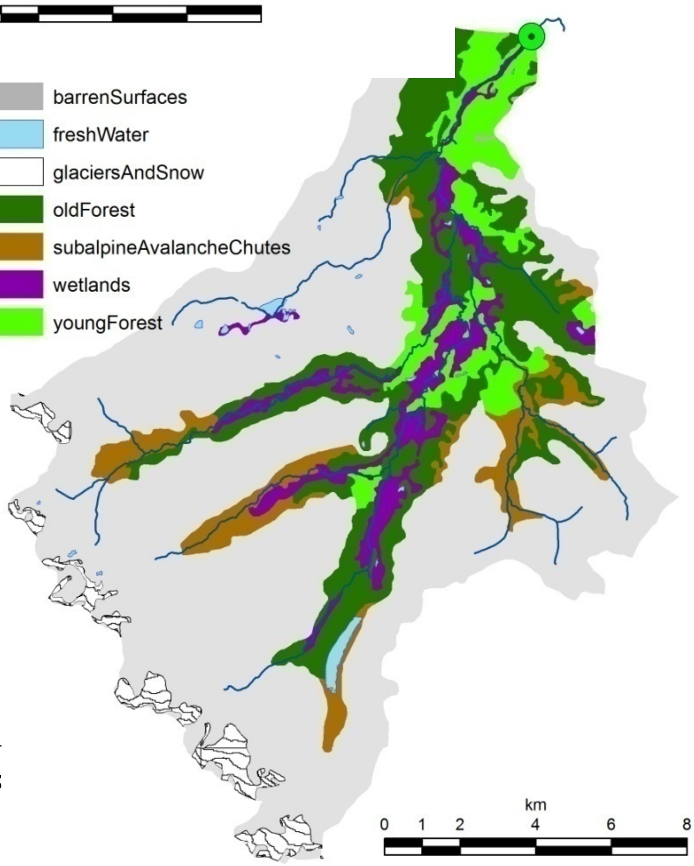




Figure A 10: Topography and BTM land use zones [08MB007]

## 11. 08ME025

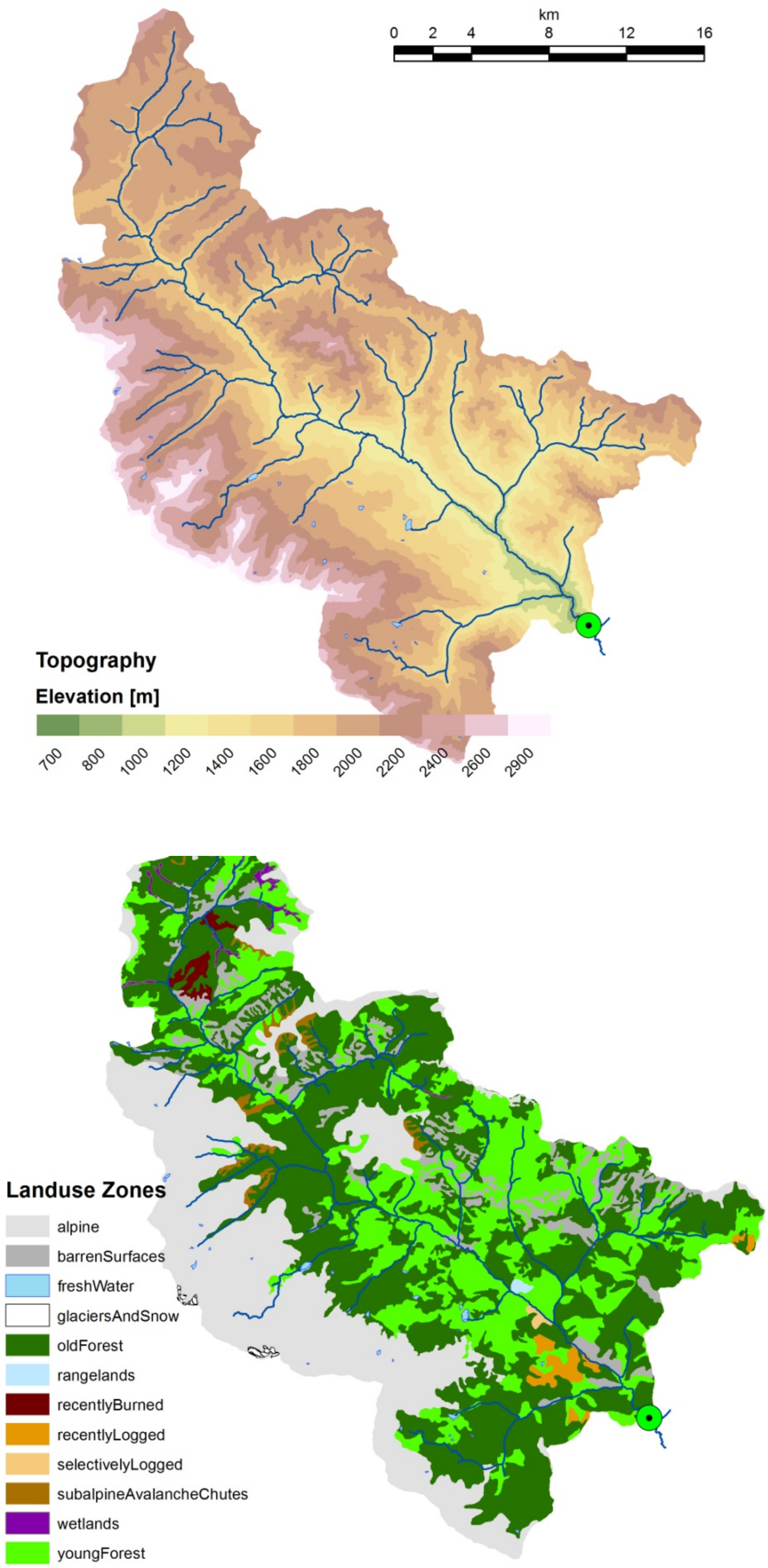



Figure A 11: Topography and BTM land use zones [08ME025]

## 12.10BE009

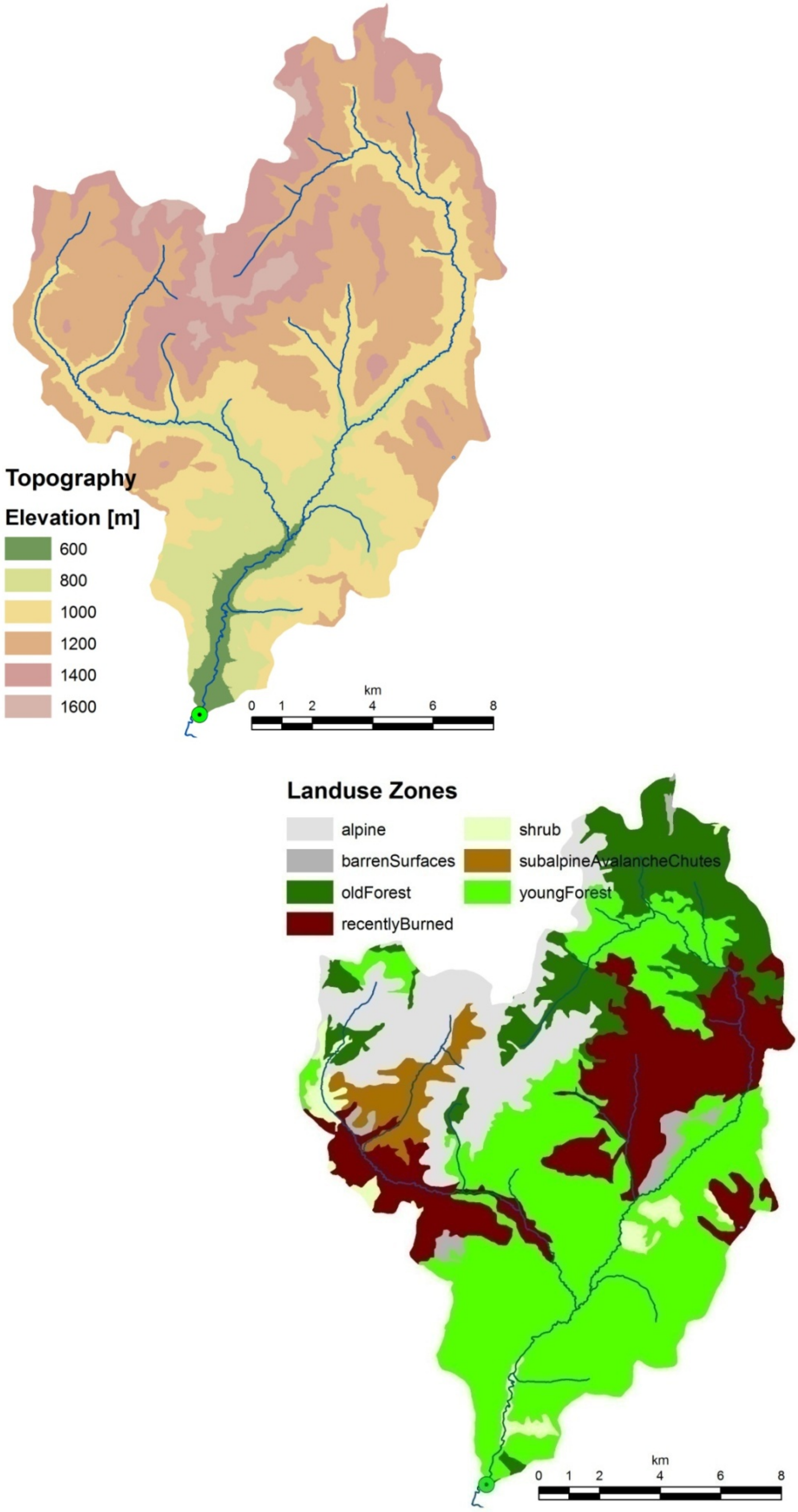



Figure A 12: Topography and BTM land use zones [10BE009]

## 13. 10CD003

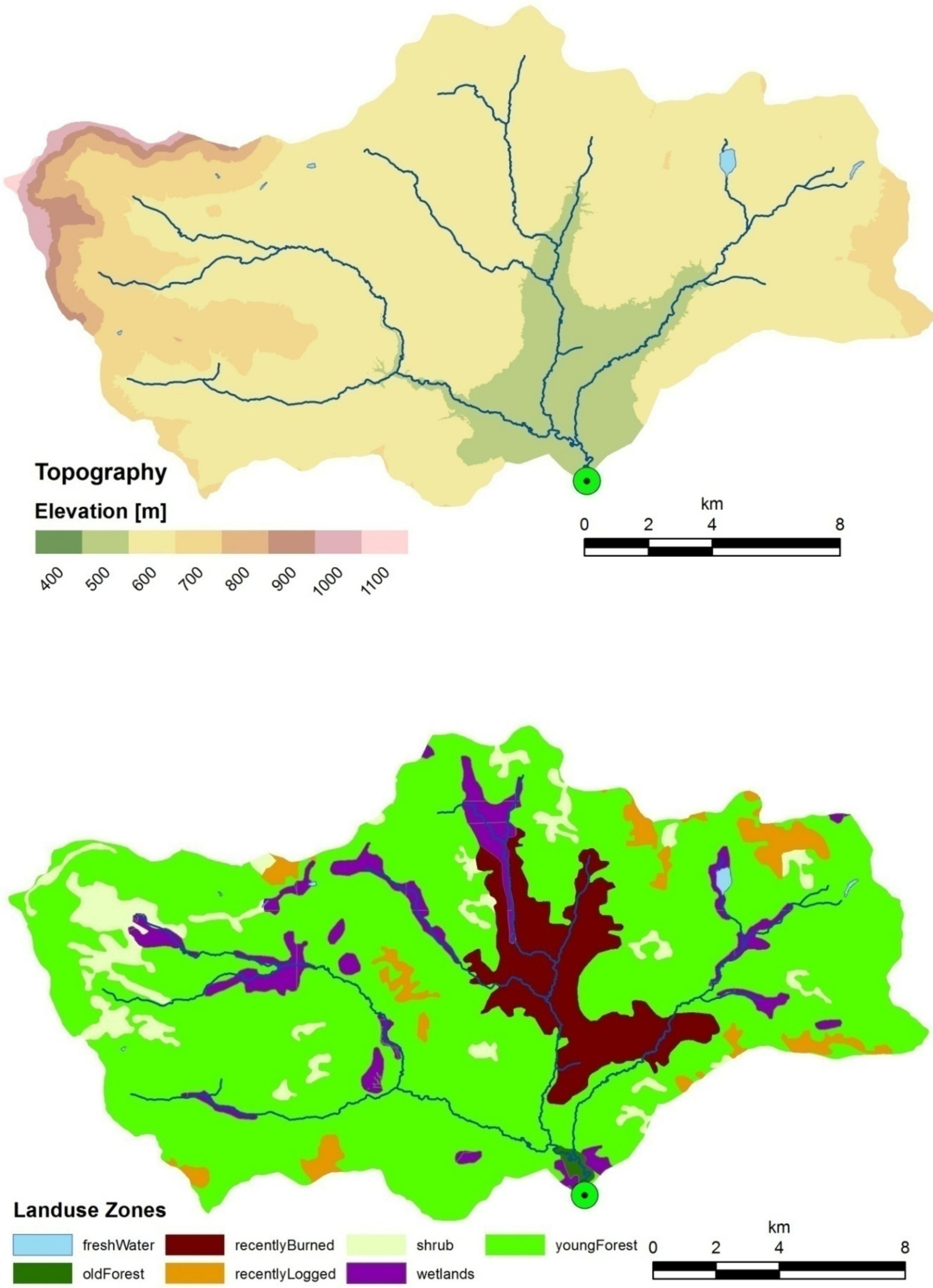
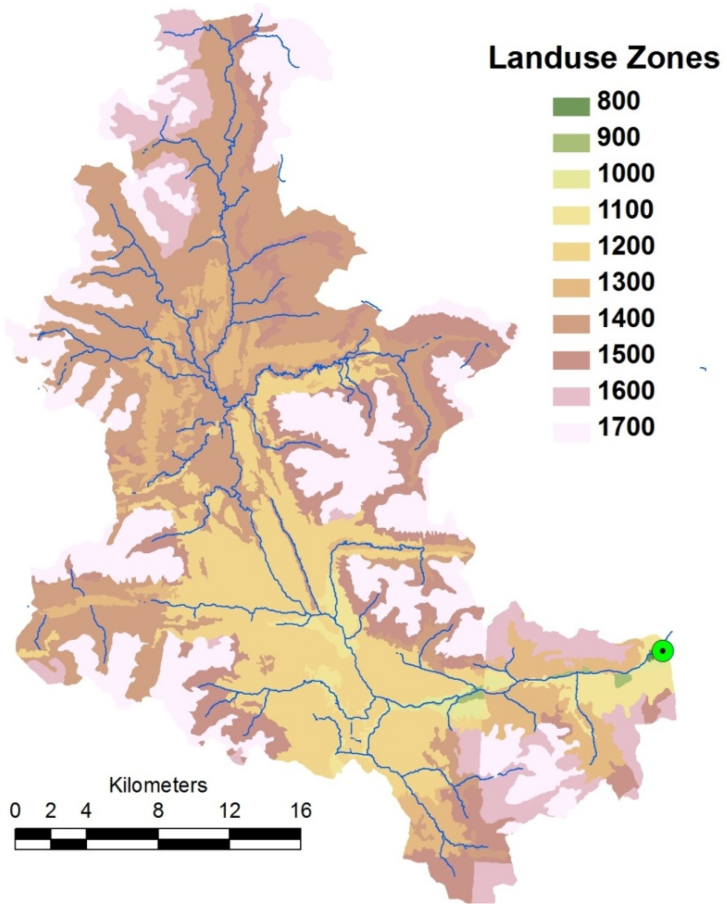



Figure A 13: Topography and BTM land use zones [10CD003]

**14. 10AC005**



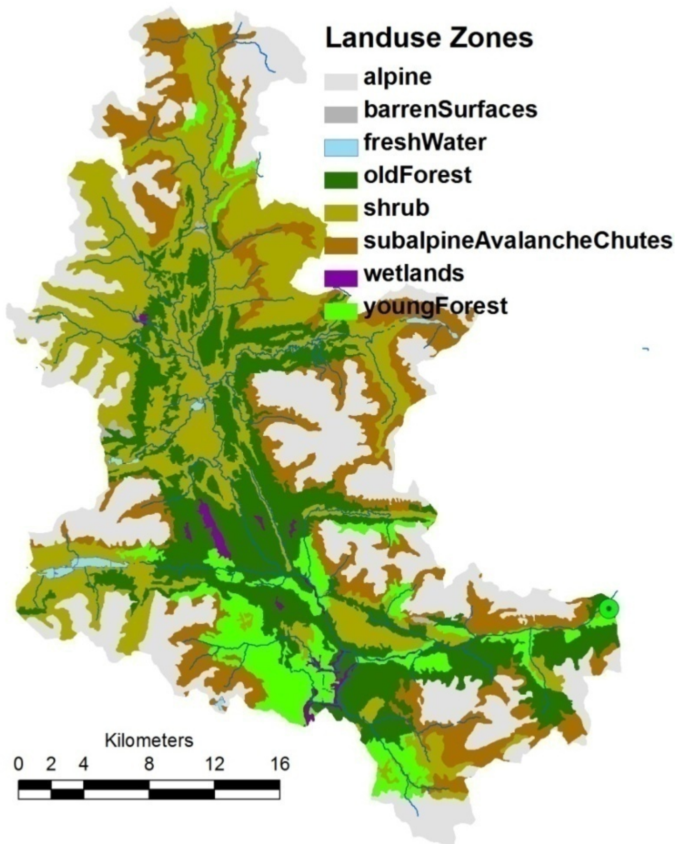
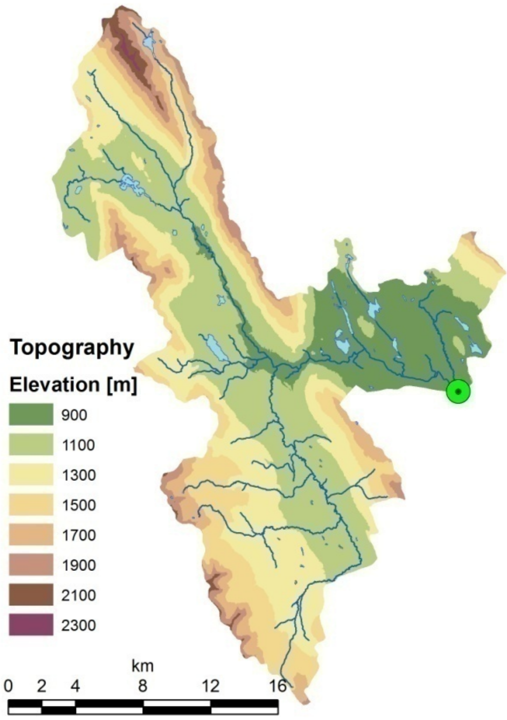




Figure A 14: Topography and BTM land use zones [10AC005]

**15. 08JD006**



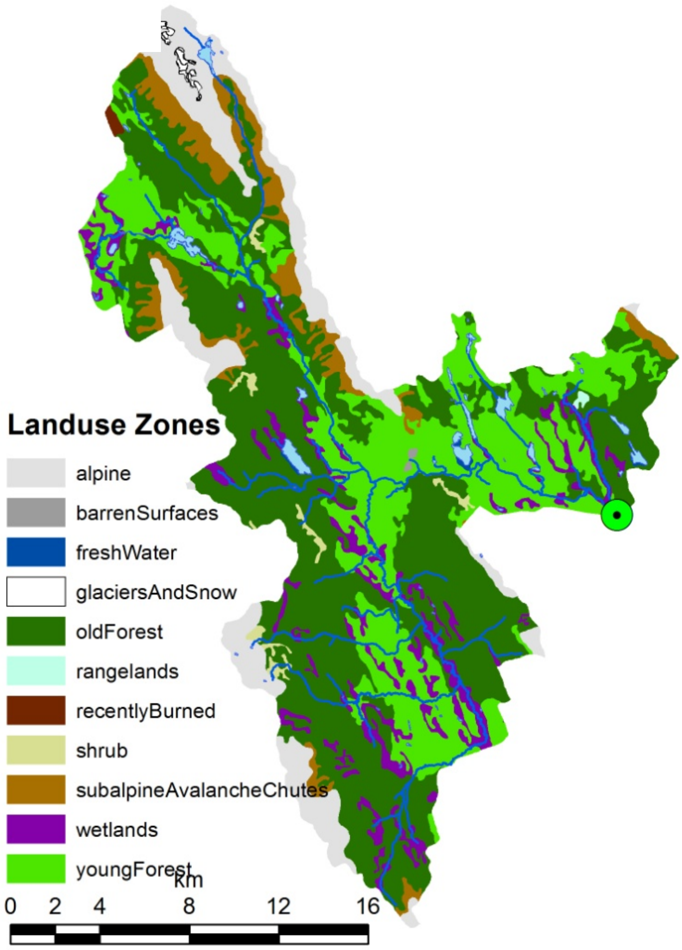




Figure A 15: Topography and BTM land use zones [08JD006]

# A 3 Used delta-changes and resulting water balances

Table A 2: Used delta-changes ClimateBC dataset (SPITTLEHOUSE, 2006)

| **08HF001** | **01** | **02** | **03** | **04** | **05** | **06** | **07** | **08** | **09** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TmeanA2 | 1.65 | 1.85 | 1.95 | 1.95 | 1.95 | 2 | 2 | 1.9 | 1.85 | 1.8 | 1.7 | 1.75 |
| PrecA2 | 24 | 26 | 6 | -3 | -24 | -8 | -4 | 1 | -1 | 1 | 12 | 26 |
| TmeanB1 | 1.2 | 1.35 | 1.45 | 1.35 | 1.4 | 1.4 | 1.4 | 1.4 | 1.4 | 1.35 | 1.2 | 1.2 |
| PrecB1 | 8 | 13 | 10 | 2 | -20 | -8 | -5 | 4 | 4 | -10 | -1 | 12 |
| **08NM134** | | | | | | | | | | | | |
| TmeanA2 | 1.5 | 2.85 | 3.2 | 3.25 | 2.3 | 2 | 2.05 | 1.75 | 1.95 | 1.75 | 1.6 | 1.45 |
| Preca2 | -1 | 7 | 19 | 10 | -17 | -6 | -9 | 2 | 7 | 9 | 27 | 30 |
| TmeanB1 | 1.05 | 2.05 | 2.05 | 2.5 | 1.75 | 1.6 | 1.7 | 1.45 | 1.6 | 1.2 | 0.85 | 1.3 |
| PrecB1 | -6 | 7 | 12 | 2 | -11 | -1 | -8 | 2 | 11 | 2 | 8 | 33 |
| **08NF001** | | | | | | | | | | | | |
| TmeanA2 | 2.35 | 3.45 | 3.25 | 3.4 | 2.85 | 2.25 | 2.1 | 2 | 2.15 | 1.75 | 1.5 | 1.15 |
| PrecA2 | -1 | 5 | 8 | 17 | 1 | -2 | -16 | 5 | -2 | 10 | 17 | 13 |
| TmeanB1 | 1.65 | 2.5 | 4.05 | 1.9 | 1.7 | 1.85 | 1.7 | 1.45 | 1.55 | 1.2 | 0.6 | 1.6 |
| PrecB1 | -3 | 6 | 2 | 8 | 5 | 2 | -13 | 2 | 4 | 5 | 1 | 20 |
| **08JA014** | | | | | | | | | | | | |
| TmeanA2 | 1 | 0.9 | 1.4 | 3.8 | 3.7 | 2.1 | 2.1 | 1.9 | 1.6 | 1.8 | 1.6 | 1.6 |
| PrecA2 | 2 | 15 | 8 | 4 | -16 | -7 | -23 | -8 | 21 | 6 | 18 | 16 |
| TmeanB1 | 1.6 | 2.6 | 2.2 | 1.7 | 2.2 | 1.6 | 1.55 | 1.35 | 1.6 | 1.15 | 0.85 | 1 |
| PrecB1 | -2 | 16 | 0 | -5 | -5 | -1 | -24 | -2 | 9 | -24 | 10 | 9 |
| **08KE024** | | | | | | | | | | | | |
| TmeanA2 | 2.55 | 3.4 | 3.1 | 2.3 | 3.2 | 2.2 | 2.05 | 1.7 | 1.9 | 1.6 | 1.25 | 1.3 |
| PrecA2 | 3 | 13 | 7 | 3 | -9 | -5 | -23 | -5 | 20 | 9 | 17 | 13 |
| TmeanB1 | 1.95 | 2.7 | 2.2 | 1.65 | 2.25 | 1.65 | 1.6 | 1.4 | 1.6 | 1.1 | 0.85 | 1.1 |
| PrecB1 | 1 | 12 | 2 | -7 | 5 | -1 | -23 | -1 | 8 | -19 | 11 | 9 |
| **08MA006** | | | | | | | | | | | | |
| TmeanA2 | 2 | 3.1 | 3.05 | 2.6 | 2.5 | 2 | 2 | 1.7 | 1.9 | 1.7 | 1.4 | 1.5 |
| PrecA2 | 5 | 17 | 13 | 0 | -19 | -6 | -20 | -1 | 13 | 5 | 23 | 23 |
| TmeanB1 | 1.3 | 2.3 | 2.15 | 1.7 | 1.75 | 1.5 | 1.6 | 1.4 | 1.6 | 1.1 | 0.9 | 1.05 |
| PrecB1 | -2 | 13 | 4 | -3 | -8 | -2 | -19 | 0 | 9 | -17 | 10 | 18 |
| **08MB007** | | | | | | | | | | | | |
| TmeanA2 | 1.55 | 2.4 | 2.8 | 2.4 | 2 | 1.85 | 1.95 | 1.65 | 1.9 | 1.7 | 1.6 | 1.7 |
| PrecA2 | 8 | 19 | 19 | -3 | -22 | -5 | -8 | 3 | 5 | 2 | 24 | 30 |
| TmeanB1 | 1 | 2.1 | 2.05 | 1.65 | 1.45 | 1.35 | 1.6 | 1.35 | 1.55 | 1.15 | 0.85 | 1.35 |
| PrecB1 | -2 | 11 | 14 | 1 | -16 | -8 | -8 | 2 | 8 | -7 | 10 | 26 |
| **10BE009** | | | | | | | | | | | | |
| TmeanA2 | 3.45 | 3.6 | 3 | 2.05 | 2.8 | 2.6 | 2.4 | 1.8 | 1.75 | 1.1 | 0.75 | 3.9 |
| PrecA2 | 1 | -2 | -5 | -1 | 16 | 6 | 16 | 5 | 9 | 8 | 7 | 6 |
| TmeanB1 | 2.5 | 2.9 | 1.95 | 1.9 | 2 | 1.9 | 1.8 | 1.55 | 1.45 | 0.85 | 0.85 | 4.25 |
| PrecB1 | -2 | -1 | 1 | -5 | 12 | 2 | 3 | 6 | 12 | 2 | -2 | 3 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **10CD003** | | | | | | | | | | | | |
| TmeanA2 | 3.45 | 3.85 | 3.45 | 1.9 | 3.25 | 2.4 | 2.35 | 1.8 | 1.85 | 1.3 | 0.6 | 2.65 |
| PrecA2 | 6 | 1 | -2 | -3 | 15 | 13 | -3 | -14 | 8 | 13 | 6 | 6 |
| TmeanB1 | 2.45 | 2.9 | 2.45 | 1.65 | 2.5 | 1.8 | 1.9 | 1.5 | 1.55 | 1 | 0.55 | 3.2 |
| PrecB1 | 10 | -2 | 3 | -6 | 18 | 9 | -2 | -14 | 5 | 7 | 1 | 8 |
| **10AC005** | | | | | | | | | | | | |
| TmeanA2 | 3.35 | 4.25 | 3.5 | 3.1 | 4.15 | 2.95 | 2.25 | 1.8 | 1.7 | 1.3 | 1.05 | 1.9 |
| PrecA2 | 6 | 18 | 6 | 2 | 16 | 5 | 2 | 10 | 2 | 1 | 1 | 3 |
| TmeanB1 | 2.6 | 3.4 | 2.85 | 2.8 | 2.65 | 2.45 | 1.65 | 1.55 | 1.35 | 1.15 | 0.85 | 2.55 |
| PrecB1 | 4 | 14 | 8 | 2 | 11 | 8 | 2 | 5 | -1 | 1 | -4 | 15 |
| **08JD006** | | | | | | | | | | | | |
| TmeanA2 | 3.25 | 3.75 | 3.3 | 2.2 | 3.6 | 2.45 | 2.1 | 1.8 | 1.8 | 1.45 | 1 | 1.65 |
| PrecA2 | 6 | 11 | 5 | 6 | 5 | 10 | -13 | -7 | 9 | 2 | 9 | 6 |
| TmeanB1 | 2.6 | 2.75 | 2.3 | 1.85 | 2.45 | 1.85 | 1.7 | 1.4 | 1.55 | 1.1 | 0.8 | 1.5 |
| PrecB1 | 2 | 5 | 7 | -5 | 11 | 13 | 4 | -7 | 0 | -14 | 0 | 11 |

Table A 3: Resulting Water Balances

| | 08HF001 | 08NM134 | 08NF001 | 08JA014 | 08JE004 | 08KE024 | 08LB024 | 08LB076 |
|---|---|---|---|---|---|---|---|---|
| **Resulting Water Balance and Temperature 1960-1990** | | | | | | | | |
| MAT [°C] | 8.89 | 2.67 | 0.41 | 1.01 | 1.94 | 1.36 | 3.51 | 0.94 |
| MAP [mm/a]] | 3041 | 441 | 845 | 582 | 562 | 1287 | 563 | 1438 |
| MAET [mm/a] | 1091 | 300 | 478 | 398 | 379 | 623 | 382 | 676 |
| Qsim | 1949 | 141 | 367 | 183 | 183 | 664 | 181 | 761 |
| Qobs | 1943 | 141 | 366 | 181 | 183 | 666 | 179 | 773 |
| **Resulting Water Balance and Temperature CGCM A2 2050** | | | | | | | | |
| MAT [°C] | 10.75 | 4.9 | 2.75 | 2.96 | 4.14 | 3.56 | 5.65 | 3.14 |
| MAP [mm/a]] | 3346 | 477 | 886 | 595 | 584 | 1332 | 597 | 1525 |
| MAET [mm/a] | 1137 | 324 | 522 | 396 | 391 | 677 | 410 | 744 |
| Qsim | 2208 | 152 | 363 | 198 | 193 | 654 | 187 | 780 |
| **Resulting Water Balance and Temperature CGCM B1 2050** | | | | | | | | |
| MAT [°C] | 10.23 | 4.35 | 2.23 | 2.62 | 3.61 | 3.02 | 5.11 | 2.54 |
| MAP [mm/a]] | 3313 | 465 | 8.75 | 569 | 558 | 1324 | 583 | 1489 |
| MAET [mm/a] | 1125 | 315 | 514 | 390 | 379 | 664 | 401 | 727 |
| Qsim | 2004 | 149 | 361 | 179 | 179 | 659 | 182 | 762 |

| | 08MA006 | 08MB007 | 08ME025 | 10BE009 | 10CD003 | 10AC005 | 08JD006 |
|---|---|---|---|---|---|---|---|
| **Resulting Water Balance and Temperature 1960-1990** | | | | | | | |
| MAT [°C] | -0.45 | -1.65 | 0.69 | -1.44 | -0.54 | -1.94 | 0.87 |
| MAP [mm/a] | 653 | 671 | 594 | 589 | 611 | 1104 | 1164 |
| MAET [mm/a] | 405 | 293 | 356 | 413 | 528 | 454 | 538 |
| Qsim | 248 | 375 | 238 | 176 | 83 | 650 | 626 |
| Qobs | 246 | 376 | 236 | 176 | 87 | 648 | 639 |
| **Resulting Water Balance and Temperature CGCM A2 2050** | | | | | | | |
| MAT [°C] | 1.66 | 0.3 | 3.63 | 1 | 1.86 | 0.66 | 3.24 |
| MAP [mm/a] | 679 | 742 | 641 | 628 | 625 | 1165 | 1205 |
| MAET [mm/a] | 418 | 312 | 387 | 456 | 547 | 581 | 590 |
| Qsim | 261 | 429 | 253 | 172 | 78 | 647 | 615 |
| **Resulting Water Balance and Temperature CGCM B1 2050** | | | | | | | |
| MAT [°C] | 1.07 | -0.2 | 2.2 | 0.55 | 1.41 | 0.21 | 2.7 |
| MAP [mm/a] | 669 | 703 | 619 | 608 | 621 | 1160 | 1172 |
| MAET [mm/a] | 414 | 302 | 370 | 440 | 543 | 501 | 584 |
| Qsim | 255 | 400 | 249 | 168 | 78 | 659 | 588 |

# A 4 CGCM B2 Simulation

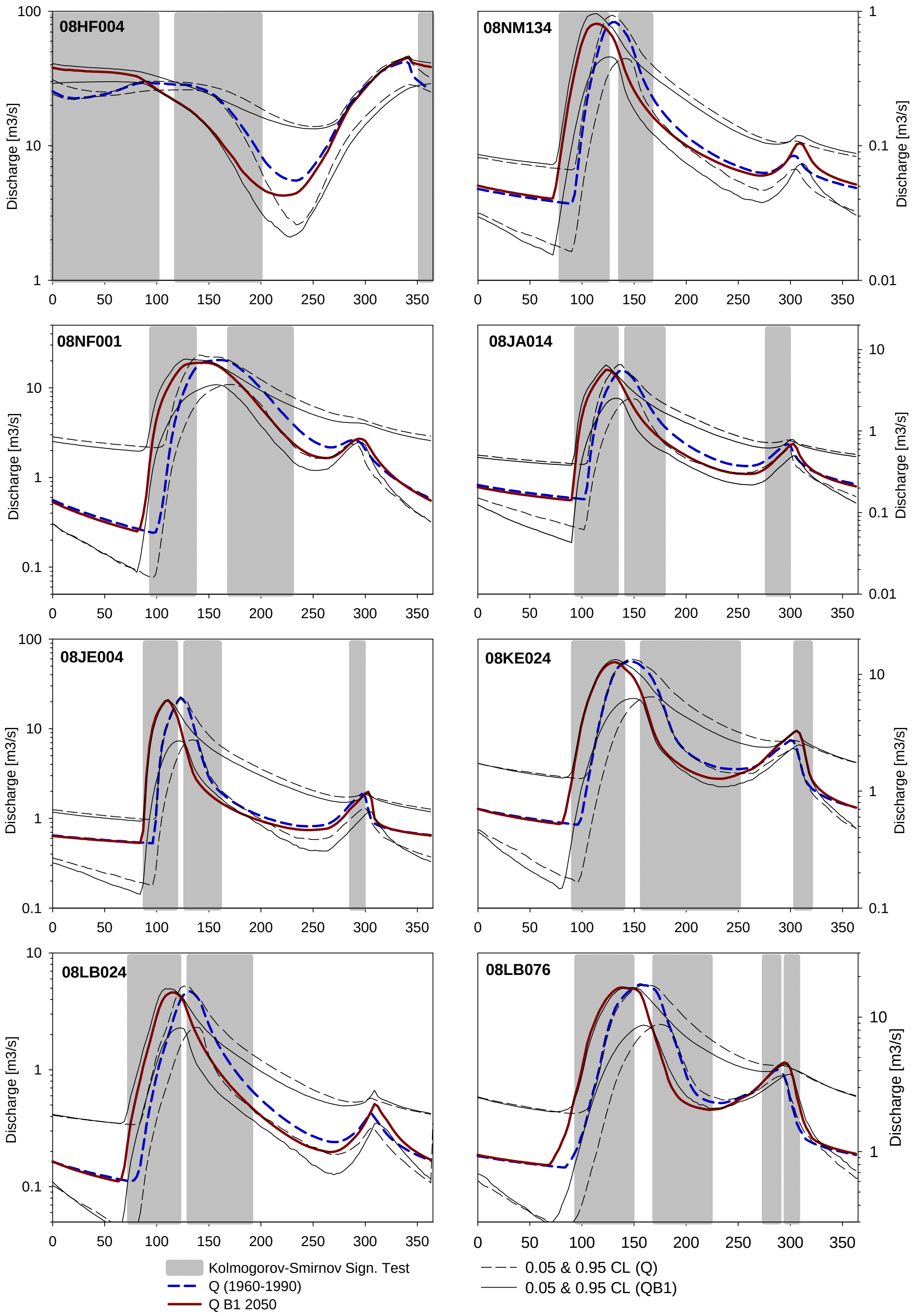



Figure A 16: Simulated discharge for the period 1960-1990 and the 2050s (CGCM B1 Climate Scenario) with uncertainty domains (0.05 & 0.95 Confidence Limits). Significant changes according to the Kolmogorov-Smirnov Significance test are greyed-out.

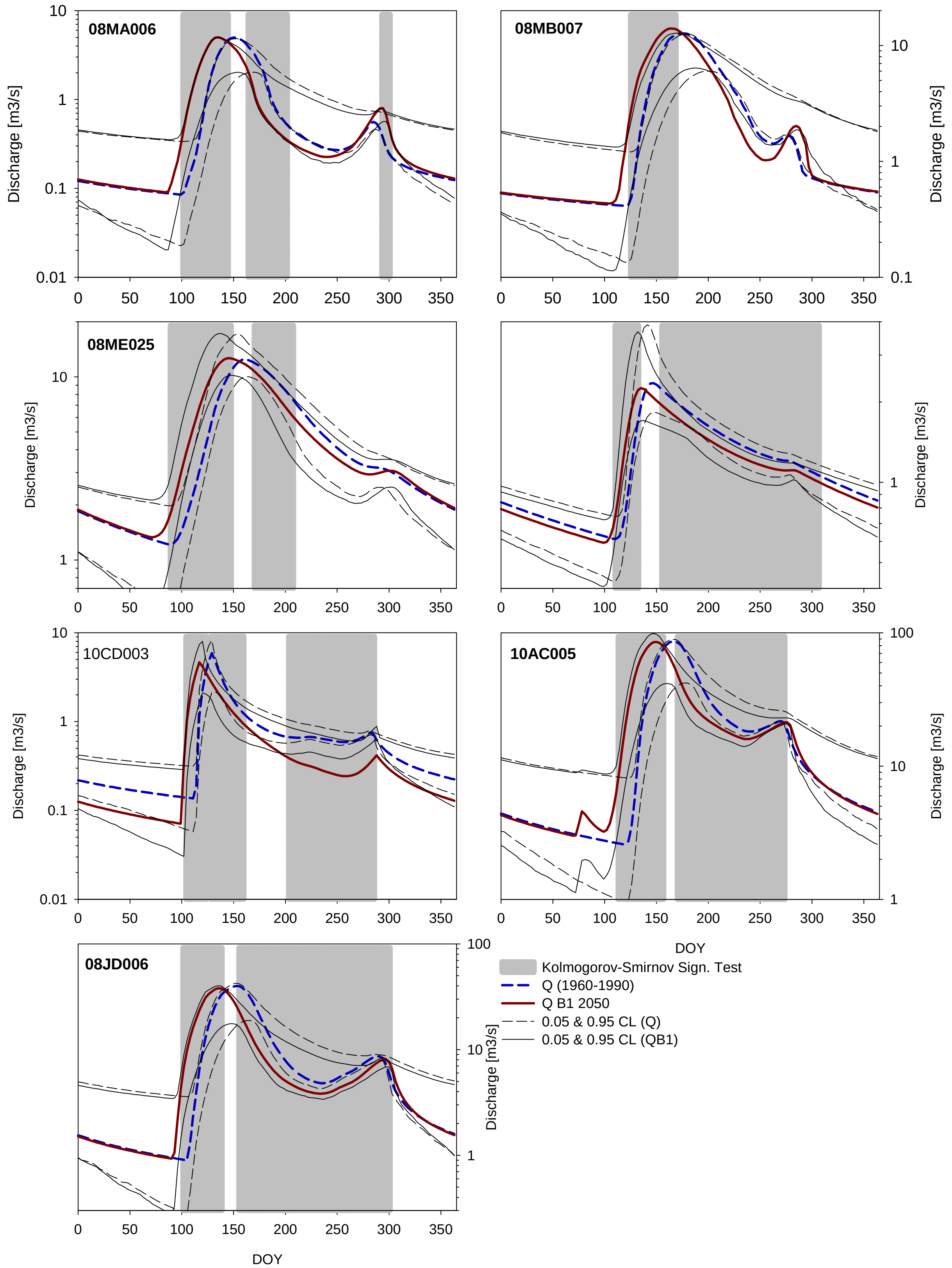



Figure A 17: Simulated discharge for the period 1960-1990 and the 2050s (CGCM B1 Climate Scenario) with uncertainty domains (0.05 & 0.95 Confidence Limits). Significant changes according to the Kolmogorov-Smirnov Significance test are greyed-out.

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# Ehrenwörtliche Erklärung

Hiermit erkläre ich, dass die Arbeit selbstständig und nur unter der Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Freiburg im Breisgau, 29.12.2008

(Johannes Schneider)