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GEO - 511: MASTER THESIS

Evaluation of precipitation data for modeling runoff in alpine regions

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Declaration of Authorship

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Signed: ________________________________

Date: ________________________________

Abstract

This thesis evaluates a gridded disaggregated hourly precipitation dataset, RdisaggH, for Switzerland. It is a product derived from rain-gauge observations and weather radar data, and developed by MeteoSwiss. In this study, this RdisaggH precipitation dataset is compared with a gridded data from rain gauge stations (Meteo dataset). The evaluation is based upon the results obtained after running both these two precipitation datasets into a hydrological model called PREVAH (PREecipitation-Runoff-EVApotranspiration HRU Model) which is a semi-distributed hydrological modelling system. The model was run for five catchments in Switzerland. Each catchment had different topographic characteristics with varying features in terms of altitude, slope, aspect and terrain. Out of these five catchments, three alpine catchments were chosen.

The results showed that RdisaggH simulated runoff obtained from PREVAH produced good results for catchments larger than $100km^2$ as opposed to those below $50km^2$. The larger catchments at higher elevation also simulated more realistic runoffs than the ones at lower elevation. RdisaggH dataset also managed to capture the seasonal variability of these larger catchment better than the Meteo dataset. In all catchments, RdisaggH simulated runoff overestimated the recession period to a varying degree for high precipitation events such as that of 21^{st} and 22^{nd} August 2005, and 8^{th} and $9th$ August 2007. RdisaggH simulated runoff also captured these flood events better than the Meteo simulated runoff in larger catchment with an exception of Weisse Lutschine where it overestimated the peak.

Acknowledgements

I would like to express my sincere appreciation to Dr. Daniel Viviroli and Dr. Tracy Ewen for their supervision and guidance in helping me pursue this topic. I am grateful to Dr. Viviroli for providing me with all the resources to learn PREVAH and having the patience to answer all my questions. Dr. Ewen guided me throughout the writing and analyzing process of this thesis which is the product of the innumerable meetings and fruitful discussions that I have had with both of them.

Thank you to Prof. Jan Seibert for his unabated support throughout the course of my Master's degree. I am also grateful to Dr. Nans Addor, Dr. Maria Staudinger and Marc Vis who provided me with the technical backstopping, particularly with R and helping me learn about NetCDF data extraction and downscaling techniques.

An earnest thanks to the Federal Office of Meteorology and Climatology (MeteoSwiss) for providing me with an hourly precipitation RdisaggH dataset.

The German Federal Ministry of Education and Research (BMBF) also deserves a special mention for appreciation for giving me the 2014 Green Talents award. With its three month research stay scholarship, I was able to continue my work at the Chair of Hydrology in Albert-Ludwigs-University of Freiburg, Germany. Again, I would like to express my thanks to PD Dr. Kerstin Stahl for hosting me and for giving me her constructive comments. A large part of my work in this thesis was accomplished while being in Freiburg, and I would like to thank my colleagues Benedikt Heudorfer and Daphne Freudiger who were always there to help me with my impromptu queries and issues.

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Finally, I would like to express my deepest gratitude to my family who have always inspired and supported me throughout this journey.

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Abbreviations

ANETZ	Automatic Meteorological Network of 72 Stations (Built: 1975 to 1989)
ASCII	**A**merican **S**tandard **C**ode for **I**nformation **I**nterchange
FOEN	**F**ederal **O**ffice of the **E**nvironment, Switzerland
m.a.s.l	**M**eters **A**bove **S**ea **L**evel
MeteoSwiss	Federal Office of Meteorology and Climatology, Switzerland
NASS	MeteoSwiss C-band radar product with spatial and temporal resolution of $1km$ and 5
NetCDF	**N**etwork **C**ommon **D**ata **F**ormat
NSE	**N**ash **S**utcliffe **E**fficiency
PREVAH	**P**recipitation **R**unoff **E**vapotranspiration **HRU** **M**odel
RdisaggH	**R**adar **D**isaggregated **H**ourly data
RMSD	**R**oot **M**ean **S**quare **D**ifference
r2	**C**oefficient of **D**etermination
WMO	**W**orld **M**eteorological **O**rganization

Dedicated to my family...

Chapter 1

Introduction

1.1 Background

The hydrological cycle plays an important role in the global climate system, which is essential for all life on earth. Each year vast quantities of water evaporate from the oceans and further fall as precipitation, accumulating in the mountain cryosphere. The accumulated snow and ice or the glaciers in the mountains do not run down immediately but act as water storage bodies and regulate a flow of freshwater downstream throughout the year. The volume of water flowing down depends upon the melt rate which is primarily determined by air temperature, precipitation and incoming shortwave radiation.

Understanding the melt and runoff from these mountain catchments is very important information for hydrological studies and modelling future scenarios. However, depending upon the remoteness, ruggedness and rigidity of mountain topography, it may not always be possible to collect necessary in-situ temperature and precipitation data which are essential meteorological information to drive the hydrological models. In such cases, observations of temperature and precipitation from the nearest meteorological station are used, which are sometimes quite far from the catchment and often at lower elevation. Although temperature data can be extrapolated using a lapse rate calculation, extrapolation of precipitation often leads to large errors, due to the high spatial variability of precipitation in mountainous regions. Additional spatial information on precipitation however can be obtained from climate models, climate reanalysis and remote sensing data. Using either gridded meteorological data or dataset products derived from observations and either climate model/climate reanalysis or radar satellite data have the potential to better capture the high spatial variability in precipitation in these regions, further leading to improved runoff prediction.

1.2 Significance of the research

In the context of the European alpine region, there are several different precipitation data products available. Some of these products are even freely available online. It is still unclear which of these products yield better results in hydrological modeling and research still needs to be done to evaluate which precipitation products and datasets give better results when modeling runoff in different types of catchments, and whether their output differs according to altitude, slope, aspect or terrain topography. The results of such evaluation will help to gain information on the quality of one of such datasets and also in further understanding the response of different alpine catchment hydrology to the effects of climate change.

1.3 Research questions

New precipitation datasets can lead to more realistic runoff output than rain gauges or weather radar data and better represent extreme precipitation events. The objective of this thesis, is to carry out an evaluation of a new precipitation dataset for modeling runoff in Swiss alpine catchments. In particular, this thesis will address the following research questions:

1. How do the results of two different types of precipitation datasets, an hourly precipitation RdisaggH (a gridded precipitation dataset based on radar and rain gauges), and gridded data from raingauge stations, compare?

2. How do different types of catchments respond to these different types of input data? Do topographic characteristics like altitude, slope, aspect and terrain influence the performance of the model output?

3. Does RdisaggH dataset lead to more realistic runoff for extreme precipitation events?

1.4 Thesis outline

This thesis comprises of seven chapters. The current chapter gives an introduction to the thesis. Chapter 2 and Chapter 3 describe about the study areas and information of datasets used in this thesis. The latter chapter also provides a detail information about the composition of an hourly precipitation RdisaggH dataset and the observed dataset. Chapter 4 explains the detail methodology of research in this thesis while Chapter 5 shows all the output results obtained from simulation of the hydrological model. This also includes assessment of both the precipitation datasets and performance of the model during their calibration and validation period. In Chapter 6, the results are discussed thoroughly in detail to answer the above mentioned research questions and finally, Chapter 7 presents the concluding remarks from this thesis.

Chapter 2

Study sites

All hydrological catchments in Switzerland are defined by their hydrological regime where the term ”regime” refers to the seasonal characteristics of runoff volume of the catchment. The regime for each catchment depend on the region (Alpine, Jura and Central Plateau, and Southern Alpine), the altitude and glaciation, and whether the runoff is contributed by melting ice (glacial), snowmelt (nival) or rain (pluvial)[1].

On these basis, there are 16 different hydrological discharge regimes defined in Switzerland [Aschwanden and Weingartner, 1985]. These discharge regimes capture the ratio of average monthly discharge to the mean annual runoff flow characteristics of all the catchments within Switzerland.

For the purpose of this thesis, a total of five catchments in Switzerland were chosen to represent the different Swiss alpine hydro-climatic regions and the hydrological regimes that exist in these regions. All five catchments and their boundary information is illustrated in figure 2.1. These catchments are listed in table 2.1 along with their respective characteristics such as area, altitude range and their mean, hydrological regime and the percentage of glaciated area in the catchment.

2.1 Allenbach

Allenbach is a small alpine catchment located in Adelboden in Switzerland. It has an area of 28.8 km^2 with mean elevation 1576 $m.a.s.l.$ It is defined by nival alpin hydrological regime and it is the smallest catchment among all the five catchments in this study. The peak runoff in Allenbach is particularly dominated by snowmelt in the spring season.

[1] `http://tinyurl.com/jlmhkga` [Accessed:04.12.2016]

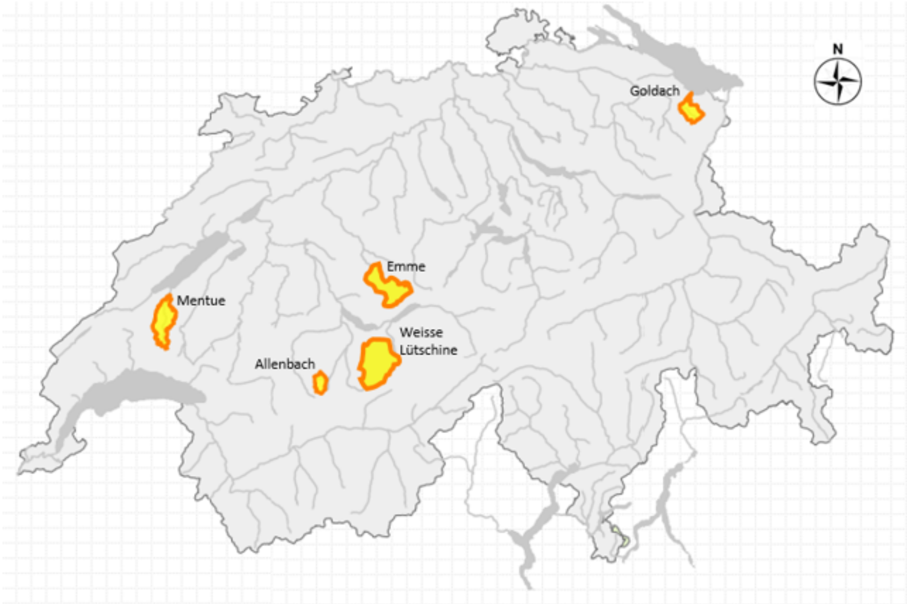


FIGURE 2.1: The chosen five catchments and their boundary in Switzerland[2]

2.2 Mentue

Mentue is a relatively big catchment situated in Yvonand, La Mauguettaz between the Jura and the midland plateau regions of Switzerland. It has an area of 105 km^2 with a mean elevation of 589 $m.a.s.l.$ It has the characteristics of pluvial jurassien hydrological regime, such that the peak runoff is dominated by the precipitation event. Here snowmelt has a very small contribution to the runoff and almost all precipitation flows directly into the rivers year round[3].

2.3 Weisse Lutschine

Weisse Lutschine is the largest alpine catchment of investigation for this thesis in Zweilutschinen. It has an area of 164 km^2 with mean elevation of 1410 $m.a.s.l.$ It is the only glaciated catchment in this study and is thus defined by a-glacio-nival hydrological regime. The peak runoff in such alpine catchment is dictated by both the seasonal snowmelt and the glacial ice melt during spring and summer seasons.

[3]`http://tinyurl.com/jlmhkga` [Accessed:04.12.2016]

2.4 Goldach

Goldach, the second smallest catchment in this investigation is located in Goldach, Bleiche, which is in the midland plateau region of north-eastern Switzerland. It has an area of 49.8 km^2 and a mean elevation of 616 $m.a.s.l.$ It represents the characteristics of pluvial suprieur hydrological regime where peak runoff is dominated by the seasonal precipitation events. Again, the snowmelt does not play any significant role in the runoff.

2.5 Emme

Emme is the second largest alpine catchment in this study with an area of 124 km^2 and mean elevation of 967 $m.a.s.l.$ Located at Eggiwil, Heidbel in the prealpine region of Switzerland, it is defined by nivo-pluvial pralpin hydrological regime. This means that the peak runoff in this catchment is influenced by both the seasonal snowmelt and precipitation events.

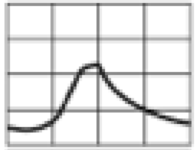
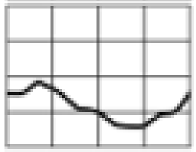
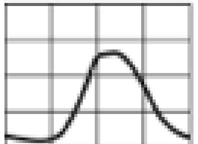
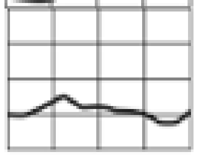
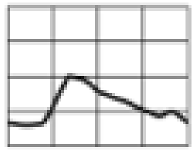
Catchment	**Location (X/Y)**	**Area (km2)**	**Glacier (%)**	**Mean Altitude (m.a.s.l.)**	**Altitude Range (m.a.s.l.)**	**Hydrological Regime**	**Regime Plot**
Allenbach [- Adelboden]	608710/ 148300	28.8	0	1576	1297 - 1856	nival alpin	
Mentue [- Yvonand, La Mauguettaz]	545440/ 180875	105	0	589	449 - 679	pluvial jurassien	
Weisse Lutschine [- Zweilutschinen]	635310/ 164550	164	17.6	1410	650 - 2170	a-glacio-nival	
Goldach [- Goldach, Bleiche]	753190/ 261590	49.8	0	616	399 - 833	pluvial suprieur	
Emme [- Eggiwil, Heidbel]	627910/ 191180	124	0	967	745 - 1189	nivo-pluvial pralpin	

Table 2.1: Characteristic features of selected catchments. The hydrological regimes and plots are based upon the definitions given by Aschwanden and Weingartner [Aschwanden and Weingartner, 1985] for Swiss Alps

Chapter 3

Data

The evaluation in this thesis was based on several available datasets for various catchments in Switzerland. The primary precipitation dataset was the Radar Disaggregated Hourly (RdisaggH) dataset developed by the Federal Office of Meteorology and Climatology (MeteoSwiss) [MeteoSwiss and Frei, 2013]. An observed precipitation dataset from high-resolution rain-gauge network of MeteoSwiss and the observed runoff dataset from the Federal Office of the Environment (FOEN) were also used to evaluate the results[1].

3.1 RdisaggH data

RdisaggH is an experimental hourly gridded precipitation dataset developed by MeteoSwiss combining information from rain-gauge measurements data (RhiresD) and radar data (NASS)[MeteoSwiss and Frei, 2013]. This dataset extends over a period of May 2003 - 2010 covering the entire territory of Switzerland at a $2km \times 2km$ spatial grid resolution and an hourly temporal scale. It is indexed according to the Swiss Coordinate System and made available in Network Common Data Form (NetCDF) format.

MeteoSwiss developed RdisaggH data in a two-step process. For hourly precipitation fields for day D, first, the relative bias of NASS with respect to RhiresD was calculated which extended from 06:00 UTC to 06:00 UTC the following dayMeteoSwiss and Frei [2013]. This bias was determined one by one for each grid point. Secondly, this obtained relative bias was then used to correct the radar field of hour 'H' in day 'D'[MeteoSwiss and Frei, 2013]. This step is similar to simple temporal disaggregation of the daily

[1] `http://tinyurl.com/7mv6m9h` [Accessed:03.11.2016]

precipitation totals into hourly dataset according to the evolution of radar composite separately at each gridpoint[Wüest et al., 2009].

The disaggregation process have the advantage of high accuracy at the daily time scale from the rain-gauge analysis and high temporal resolution from the radar composite[Wüest et al., 2009]. However, it does not capture the spatial resolution from the radar composite. In this disaggregation process, the daily precipitation total is distributed into hourly time frame. The following equation calculates the disaggregated hourly precipitation P at position x and time $(h)t_i$ [Wüest et al., 2009]:

$$P(\vec{x}, t_i) = \frac{E(\vec{x}, t_i)}{\sum_{t_i} E(\vec{x}, t_i)} P_d(\vec{x}); 1 < t_i < 24 \tag{3.1}$$

where, E= hourly precipitation estimate from the radar aggregates P_d= daily precipitation sum from the interporlated rain-gauge data

Figures 3.1, 3.2, 3.3 and 3.4 show the precipitation distribution from RdisaggH dataset in all of Switzerland at different time slices. The visualization was made using the Panoply tool that is available freely online by the Goddard Institute for Space Studies (GISS, National Aeronautics and Space Administration (NASA).

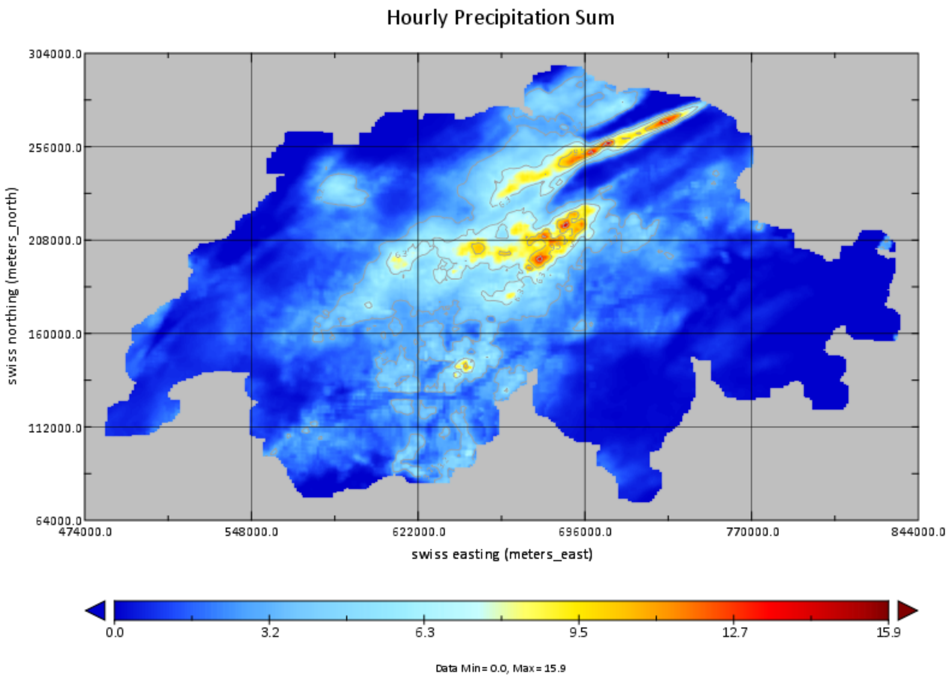


Figure 3.1: Precipitation distribution from RdisaggH dataset across Switzerland at 18:00, 21 August 2005

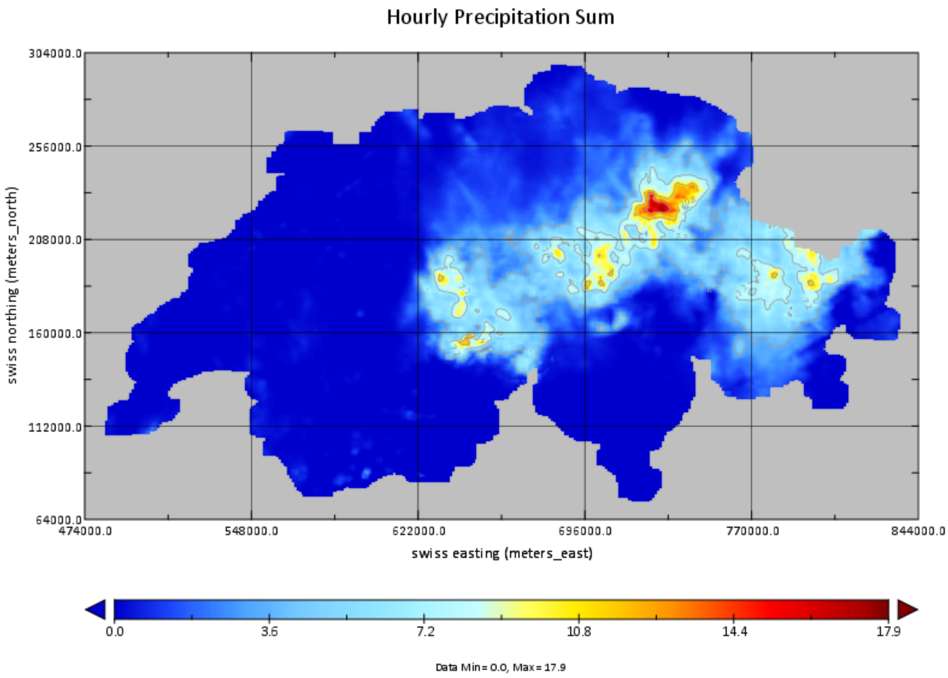


FIGURE 3.2: Precipitation distribution from RdisaggH dataset across Switzerland at 18:00, 22 August 2005

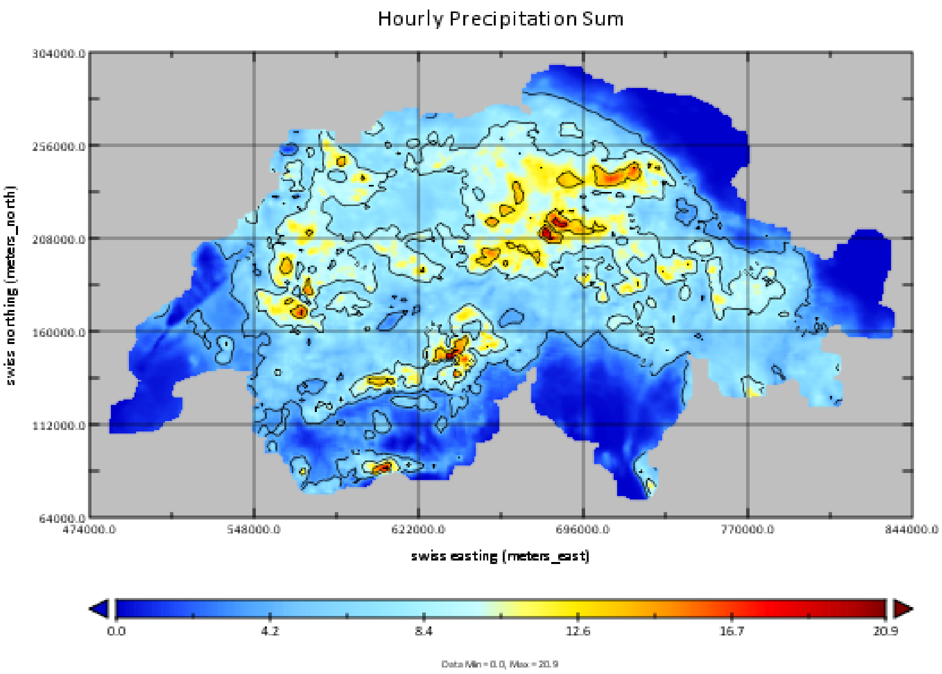


FIGURE 3.3: Precipitation distribution from RdisaggH dataset across Switzerland at 18:00, 8 August 2007

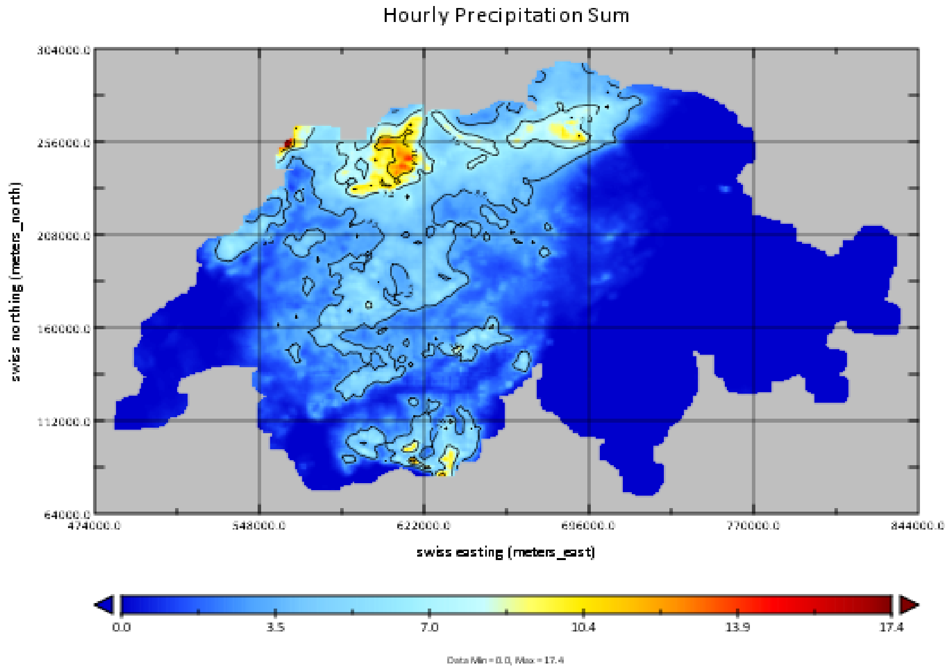


FIGURE 3.4: Precipitation distribution from RdisaggH dataset across Switzerland at 06:00, 9 August 2007

3.1.1 Rhires-D

RhiresD is a rain-gauge observations data obtained at various stations in Switzerland. It is derived from approximately 450 network of both automated and manual rain-gauge stations covering the entire periphery of Switzerland[Wüest et al., 2009]. These stations provide daily precipitation totals and are maintained by the Federal Institute of Meteorology and Climatology or MeteoSwiss. Although these rain-gauges provide accurate but spotty precipitation estimates, it is the accuracy aspect of data that has been exploited in the RdisaggH dataset [Wüest et al., 2009].

Among these stations, 72 rain-gauges stations belong to ANETZ network which provided temporal resolution of 10 minutes. These higher temporal resolution were used later to evaluate the newly derived RdisaggH dataset [Wüest et al., 2009]. This was at the time when RdisaggH dataset was developed. ANETZ has since been renewed to SwissMetNet project consisting of more than 260 automated weather stations[2].

While most of the rain-gauge are manual Hellman type gauges with $200cm^2$ orifice placed $1.5m$ above the ground, there are also automatic tipping bucket gauges for approximately 70 stations [MeteoSwiss and Frei, 2013]

[2] `http://tinyurl.com/hw6loh8` [Accessed: 03.11.2016]

3.1.2 NASS

There are three C-band radars: Albis (925 m.a.s.l.), La Dole (1675 m.a.s.l.) and Monte Lema (1625 m.a.s.l.) stationed near Northern, Western and Southern borders of Switzerland[Germann et al., 2006]. They have an average spatial resolution of few kilometers and 5 minutes time sampling intervals [MeteoSwiss and Frei, 2013][Wüest et al., 2009]. NASS is basically an hourly precipitation composite of these three radars taking 12 measurements per hour[MeteoSwiss and Frei, 2013].

These three radars measure 20 elevations between $-0.3°$ and $45°$[Wüest et al., 2009]. Given the complex mountainous topography of Switzerland, they run into some errors whose source lie in the elevation, orographic sheilding and shadows, and pulse volume factors [Wüest et al., 2009][Germann et al., 2006]. For example: an overestimation of precipitation due to bright band effect on melting layer of snow as the reflectivity of a melting water coating on snow is several times higher than that of th snow [Wüest et al., 2009][Germann et al., 2006].

3.2 Observed Data

The hydrological model PREVAH uses meteorological input data consisting of precipitation, temperature, sunshine duration, cloud cover, relative humidity and wind speed [Viviroli et al., 2009][Liechti et al., 2013]. For the purpose of this thesis, the dataset was acquired for the period of 1 May 2003 to 31 December 2010 at 500 m spatial grid resolution. This dataset was also used as an input data files for running the hydrological model. The original data was acquired from MeteoSwiss of Switzerland. These station values are then interpolated and averaged for different altitude zones or elevation bands by the WINMET tool in PREVAH [Viviroli et al., 2009]. The elevation bands are normally 100 m for small basins [Gurtz et al., 1999].

PREVAH also requires an observed runoff data for the same time period at an hourly time step with units in m^3s^{-1} for its calibration and validation [Viviroli et al., 2009]. This dataset was acquired from the Federal Office of Environment (FOEN) of Switzerland at an average hourly runoff scale with units in m^3s^{-1}.

Chapter 4

Methods

4.1 Hydrological Modeling

Any model is a simple representation of our understanding of the system i.e. how we perceive the system and its processes [Wagener, 2011]. A system could be represented by a set of variables providing information of that system. Then certain parameters are considered which set their properties. Based on the relationships between the processes within the system, a mathematical equation is formulated to represent the model. Such equations will have an input components like precipitation or temperature, state variables like soil moisture, parameters like hydraulic conductivity and the resulting model output like runoff [Wagener, 2011].

A hydrological model in this sense, is a simplified representation of hydrological cycle in a complex terrestrial environment that helps us to understand not just the hydrological system but also predict its future evolution [Wagener, 2011]. Such models provide a quantitative overview to better understand the hydrological variables, their interactions and feedback mechanisms [Seibert and Vis, 2012]. Thus, hydrological model is an important tool that provide crucial information to scientist, policy makers and other stakeholders to help in the planning, problem solving and decision making processes [Viviroli et al., 2009].

4.1.1 Classification

A hydrological model can be classified in several ways. According to the extent of physical principles that are applied in model structure, they are defined under two categories as illustrated in figure 4.1 a) deterministic and b) stochastic. While a deterministic model is based on historic data set, the stochastic model is based on synthetic data with random and uncertain outputs. The deterministic model can be further classified to: i) data-driven (black box models), ii)conceptual (lumped or grey box models) and iii) physically based (distributed or white box models) models [Wagener, 2011] [Refsgaard and Knudsen, 1996].

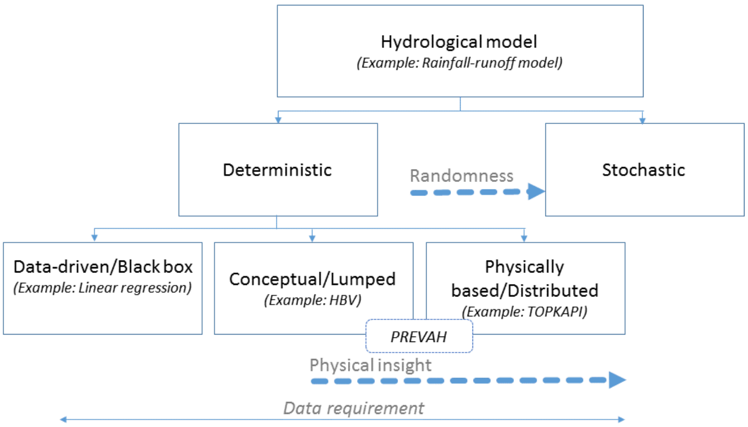


FIGURE 4.1: Classification of hydrological models based on physical processes [Wagener, 2011][Refsgaard and Knudsen, 1996]

4.2 PREVAH

4.2.1 Introduction

The Precipitation Runoff Evapotranspiration HRU Model (PREVAH) is a semi-distributed hydrological model that implements a conceptual process-oriented approach with spatially distributed hydrological response units [Viviroli et al., 2009] [Viviroli et al., 2007b]. This model was develop to understand the spatial and temporal variability of hydrological processes in rugged and rigid catchments with alpine topography. So, the model has a powerful conceptual base to describe the runoff generation processes particularly in high alpine environment [Viviroli et al., 2009]. Based on the hydrological characteristics and other information such as elevation, aspect, land use and soil type of the catchment, PREVAH also uses hydrological response unit (HRU) module to discretize the spatial units by making its clusters [Gurtz et al., 1999] [Bosshard et al., 2013] [Liechti et al., 2013]. The snow and glacier melt module in the model is based on degree-day factor with aspect and slope correction [Bosshard et al., 2013], and the evapotranspiration parameterization module is based upon Penmann-Monteith equation.

As mentioned above, PREVAH is process-oriented in its structure just like the HBV model structure [Viviroli et al., 2009]. It is a conceptual, semi-distributed model requiring six meteorological input data: precipitation, air temperature, sunshine duration, cloud cover/global radiation, relative humidity/water vapor pressure and wind speed at an hourly or daily time step and $500m \times 500m$ spatial resolution [Viviroli et al., 2009] [Bosshard et al., 2013] [Liechti et al., 2013].

4.2.2 Modules and tuneable model parameters

PREVAH also comes with additional set of tools that are designed to help in preprocessing of the required data such as physiogeographical, meteorological and hydrological data [Zappa et al., 2003]. Apart from being able to describe the alpine runoff regimes, PREVAH can also provide continuous simulation of runoff for both low flow and high flood events[Zappa et al., 2003]. The soil moisture accounting and evapotranspiration scheme, the interception module, the combined temperature-radiation modules for snow and ice melt, glacier storage modules for firn, snow and ice melt along ground water modules are all incorporated in PREVAH to better represent the hydrological processes in alpine catchments [Viviroli et al., 2009]. These modules and schemes can be divided into six groups at the model core of PREVAH as illustrated by the flow chart in figure 4.2 along with their inputs and corresponding outputs. Figure 4.3 shows the schematic of the PREVAH model structure.

At the model core of PREVAH, the 'water balance adjustment' module could be controlled by tuning two precipitation parameters to addresss the total runoff volume error of the model along with a series of systematic errors in the modeling chain [Viviroli et al., 2009]. These two parameters are: precipitation adjustment for rain [%](PKOR) and precipitation adjustment for snow [%](SNOKOR).

A transition temperature range of rain and snow [$°C$] (TTRANS) is specified along with threshold temperature for rain and snow [$°C$](TGR) which splits precipitation into liquid (rain) and solid (snow) fractions [Viviroli et al., 2009].

A degree day approach introduced by Hock is used for modeling 'snow melt' module with PREVAH due to its high efficiency that incorporates a seasonal cycle between minimum temperature melt factor for snow [$mmd^{-1}K^{-1}$] and maximum temperature melt factor for snow [$mmd^{-1}K^{-1}$] [Viviroli et al., 2009] [Hock, 1999].

Similarly, glaciated catchments use 'glacier' module which incorporates a constant temperature melt factor for ice [$mmd^{-1}K^{-1}$] (ICETMF) and a constant radiation melt

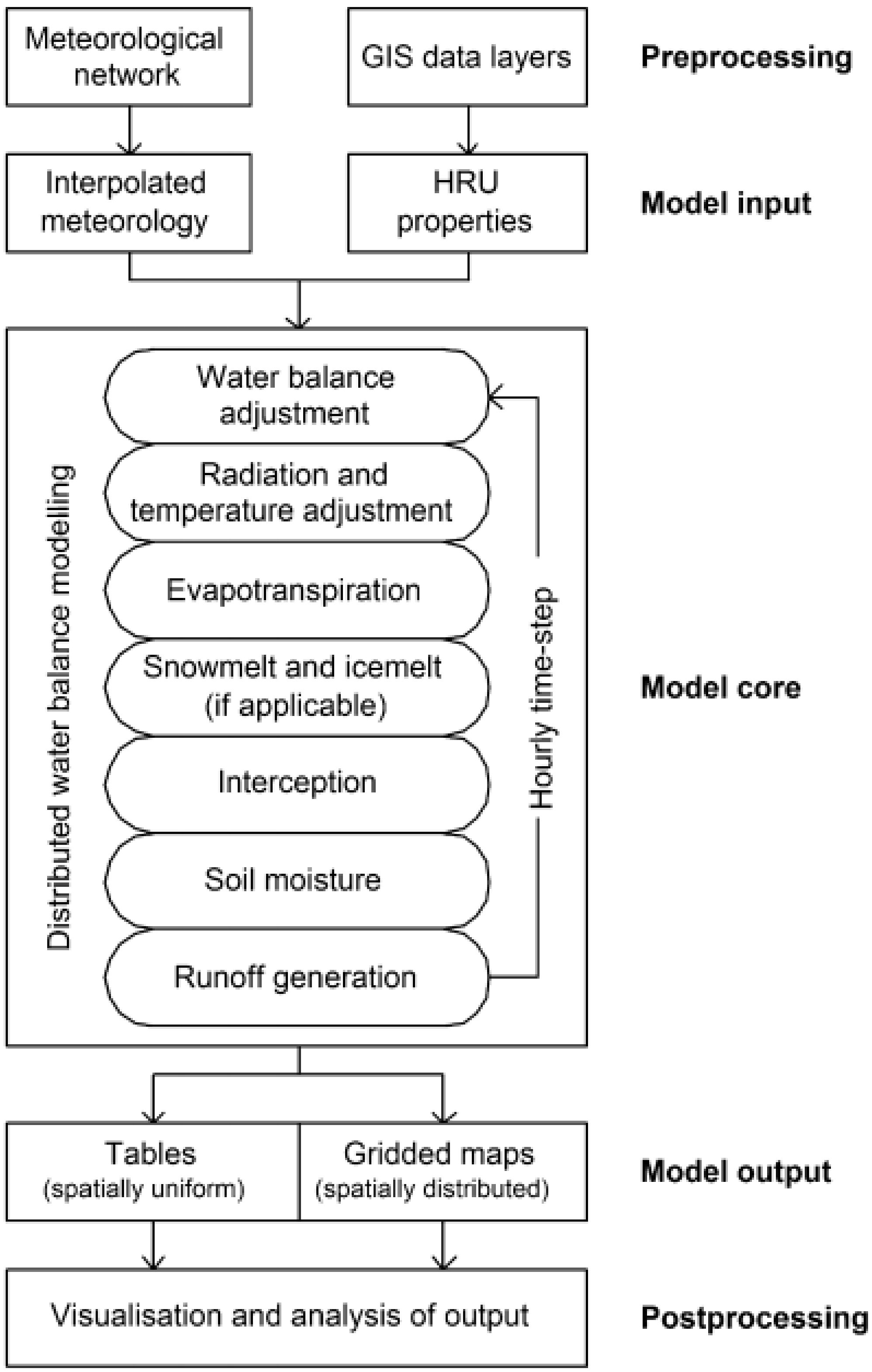


FIGURE 4.2: PREVAH flow chart [Viviroli et al., 2009]

factor for ice $[mmh^{-1}K^{-1}W^{-1}m^2]$ (ICERMF) [Viviroli et al., 2009]. A variable degree-day method is used to calculate the snow melt on glaciers.

The coefficient for non-linearity parameter for infiltration module [-] (BETA) is the only tuneable parameter used in the 'soil moisture' module. The BETA coefficient controls infiltration as a function of actual soil moisture [Viviroli et al., 2009]. So larger the value of BETA, the more delayed infiltration response to precipitation [Viviroli et al., 2009].

The 'runoff generation' module is based on HBV model concept [Bergstrom, 1976] [Lindstrom et al., 1997] [Viviroli et al., 2009]. Here, the storage time for surface runoff (K0H[h]) and interflow (K1H [h]) govern the runoff generation in the soil's unsaturated zone while the combination of two linear groundwater reservoirs produces a quick (CG1H [h]) and a delayed (K2H [h]) baseflows in two distinct storage times [Viviroli et al., 2009] [Schwarze et al., 1999]. The surface runoff is defined by storage threshold (SGR [mm]) [Viviroli et al., 2009]. A significant difference in the runoff generation of PREVAH is that it is based on spatially distribution of the catchment rather than a lump representation like in the HBV model [Gurtz et al., 1999].

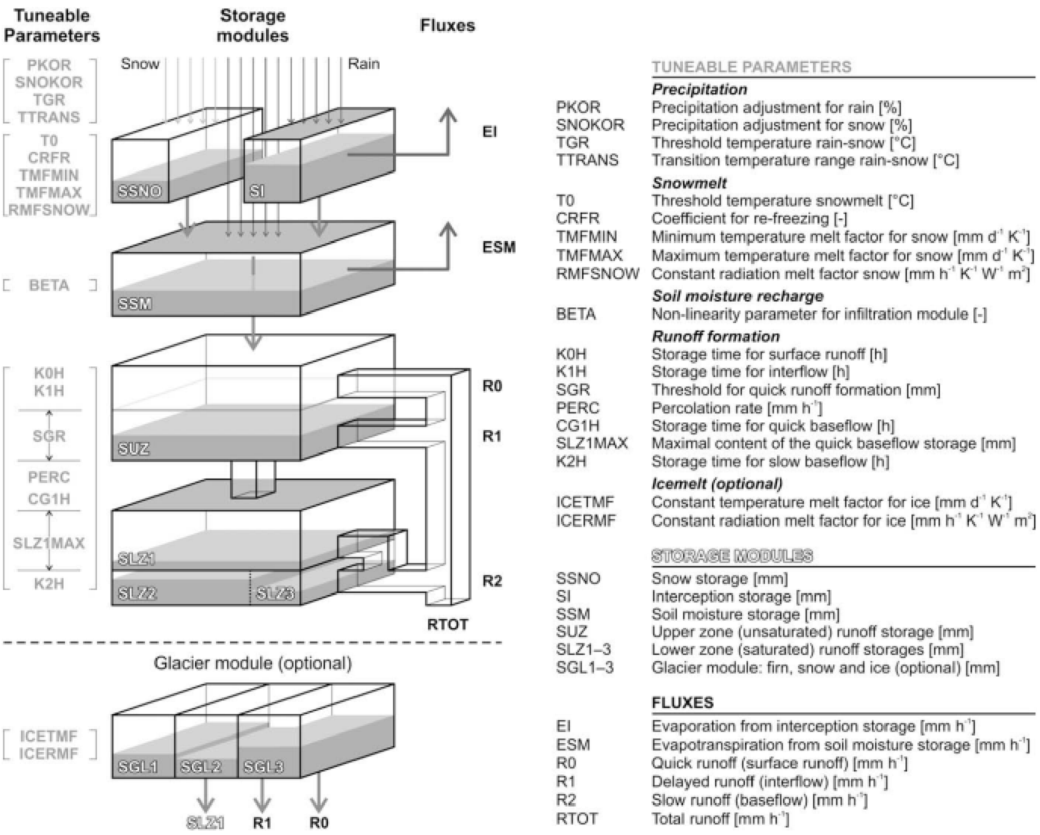


FIGURE 4.3: PREVAH model structure schematic [Viviroli et al., 2009]

4.2.3 Input data

As shown in figure 4.4 PREVAH requires three types of input data for its model run. These are:

i) Physiographical information for the HRUs

These are ASCII-formatted table listing the physiographical properties for parameterization of each HRU along with a map to locate the individual HRU positions for spatially distributed output [Viviroli et al., 2009].

ii) Meteorological input

PREVAH requires high temporal resolution (hourly or daily time step) meteorological input data such as air temperature, precipitation, relative humidity/ water vapour pressure, global radiation, wind speed and sunshine duration for its model run [Viviroli et al., 2009]. The WINMET tool in PREVAH interpolates and aggregates the station value data into an ASCII formatted table lists as mentioned before in Chapter 3: Observed data.

iii) Control file

This is the configuration file with all the tuneable model parameters that controls the individual sub-models of PREVAH as shown in figure 4.3. In addition, it also contains site-specific information necessary for the modeling like the number of HRUs, elevation zones, initial storage contents, time-step and application time-frame, output options and calibration settings [Viviroli et al., 2009].

4.3 Calibration and Validation

The characteristics of catchments vary from one to the other. Any hydrological model has to be adjusted to the conditions of that specific catchment by tweaking its parameters. This process of adjusting the parameters to the closest possible agreement between the observed and the simulated hydrograph is referred as the model calibration.

With PREVAH, this can be attained using a number of tuneable parameters grouped together in pairs that relate to similar processes [Viviroli et al., 2009]. Thus the parameters are treated pair-wise instead of all at once and this is again, also illustrated in figure 4.3 [Viviroli et al., 2009].

The observed runoff from gauging stations and the simulated flow by the model are compared with the help of an objective function by determining the model efficiency.

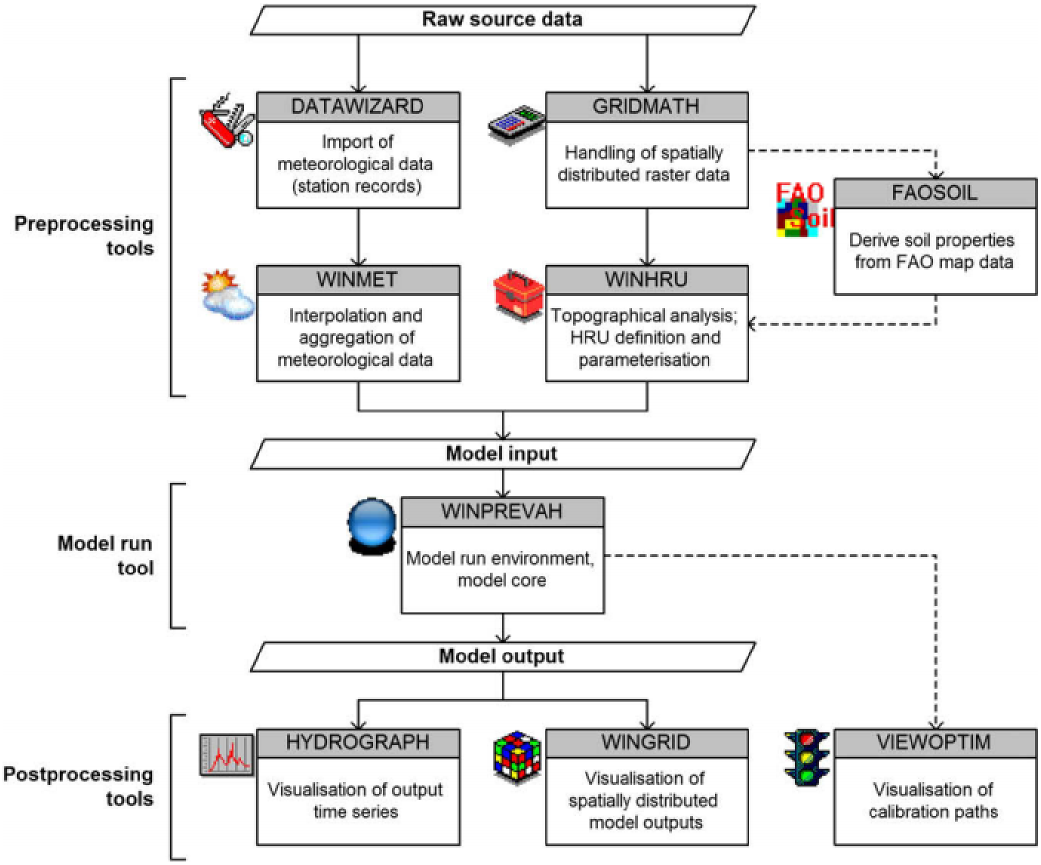


FIGURE 4.4: PREVAH's pre-processing, model run and post-processing [Viviroli et al., 2009]

However, a single aggregate measure of model performance could be lead to information loss particularly if one is using a complicated model [?]. To resolve this issue and extract maximum information PREVAH uses multiple objective functions combining three standard efficiency scores with three different temporal ranges: linear, logarithmic Nash-Sutcliffe efficiency and volumetric deviation [Viviroli et al., 2009] [Viviroli et al., 2007c] [Viviroli et al., 2007d]. These efficiency scores give a qualitative measure of the model performance for both the calibration and the validation model runs.

The standard procedure for model calibration and validation dictates that the data sets to be used for simulation be divided into two non-overlapping time period for each catchment [Viviroli et al., 2007a]. In the Master's thesis research, the time period from May 2003 to December 2006 was used for model calibration in which the year 2003 was employed just for warming up the model. The remaining years: 2004, 2005, 2006 were the actual years applied for the model calibration. PREVAH was calibrated separately each time for every catchment and for both data set i.e. RdisaggH data and observed data as mentioned in Chapter 3, hereafter referred as Meteo data. Similarly, the time period from January 2007 to December 2010 was used for the model validation. Validation runs were performed for all the calibrated files before their full simulation runs.

In both the model calibration and validation processes, the measure for comparison is through the efficiency scores of the model run. Of the three objective functions mentioned above, the linear Nash-Sutcliffe efficiency is only used for comparison in this thesis.

4.4 Data Extraction and Preprocessing

As already mentioned in Chapter 3, PREVAH requires six meteorological input data consisting of precipitation, temperature, sunshine duration, cloud cover, relative humidity and wind speed to run its model.

For the purpose of this thesis, first, PREVAH was run using all these Meteo data set obtained from MeteoSwiss for the period of May 2003 to December 2010. Then, the precipitation input data was changed by simply replacing it with the RdisaggH data set for the same period of time. The rest of the meteorological input data remained the same. The results were two separate simulated runoff output 'Q' for each catchment.

The hourly precipitation RdisaggH were provided by MeteoSwiss at 2 km grid resolution for the entire extent of Switzerland in NetCDF data package. The NetCDF data were packaged separately for each year in accordance to four dimensions - latitudes, longitudes, hourly time steps and the precipitation values belonging to its respective coordinates at a given time step. The NetCDF file size were still huge despite being packaged for just a year because they contained hourly precipitation values for the entire extent of Switzerland.

In order to prepare the data for running PREVAH, first, these precipitation values had to be extracted from NetCDF package for each catchment of interest. This requires catchment boundary information to clip the data set. This could be done using the respective catchment boundary shapefile in ArcGIS or simply by using grid cell based elevation band data of the catchment. In this thesis, the elevation band gridded data of the catchment was used to clip the catchment boundary and extract the respective precipitation values from the NetCDF package. This extracted precipitation values were still in $2km * 2km$ grid resolution and was thus downscaled to $500m * 500m$ grid resolution using bilinear interpolation method. The resulting precipitation values were then arranged in ASCII formatted table using both R programming language script and the Microsoft Excel. The figure 4.5 below illustrates the complete work flow processes of the methodology of this thesis.

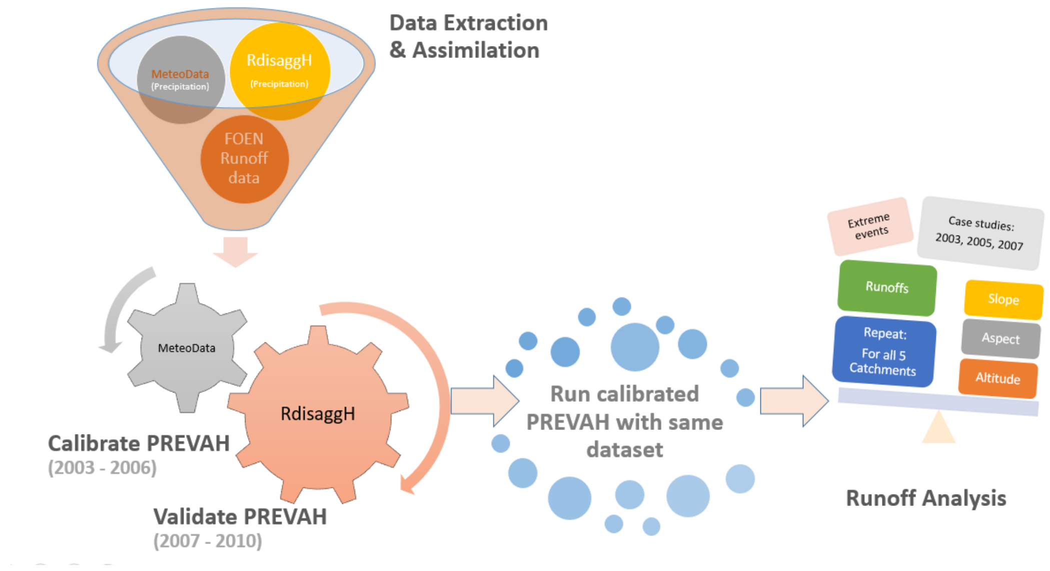


FIGURE 4.5: Steps and processes

Chapter 5

Results

5.1 Evaluation of precipitation datasets: Meteo and RdisaggH

There were two different datasets used as precipitation inputs to run the PREVAH model. Both these datasets were generated following different methods already mentioned in Chapter 3. However, in order to analyze the model output from these datasets, it is also necessary to know how these datasets compared and varied with each other at their given hourly time step. For this, coefficient of determination (r^2) and root mean square difference (RMSD) were calculated for Meteo and RdisaggH precipitation input datasets for the entire time period of evaluation Chapter 4. The resulting r^2 and RMSD values are thus summarized in table 5.1.

The total precipitation sums for both Meteo and RdisaggH datasets were also calculated along with the total sums for all the four seasons: winter (DJF), spring (MAM), summer (JJA) and autumn (SON), for the time period of May 2003 to December 2010. It should be noted here that the precipitation values for December 2010 is not included as they fall in the winter season for the following year. Table 5.2 shows the precipitation sums for different seasons for all the five catchments along with the total sum for the entire time series excluding December 2010.

Time Period		Allenbach		Mentue		Weisse Lutschine		Goldach		Emme	
		r2	*RMSD*	*r2*	*RMSD*	*r2*	*RMSD*	*r2*	*RMSD*	*r2*	*RMSD*
2003-2010		0.20	0.65	0.26	0.47	0.32	0.63	0.23	0.58	0.37	0.56
2003	*Jan-Dec*	0.54	0.53	0.58	0.3	0.33	0.63	0.59	0.45	0.37	0.58
	JJA	0.53	0.74	0.47	0.38	0.23	0.82	0.50	0.59	0.27	0.8
	August	0.61	0.51	0.58	0.43	0.11	0.65	0.47	0.35	0.50	0.55
2005	*Jan-Dec*	0.60	0.39	0.51	0.31	0.36	0.62	0.65	0.36	0.45	0.56
	JJA	0.61	0.59	0.34	0.42	0.41	0.86	0.65	0.6	0.44	0.9
	August	0.65	0.69	0.62	0.27	0.50	1.04	0.56	0.84	0.45	1.16
2007	*Jan-Dec*	0.09	0.75	0.28	0.52	0.44	0.68	0.07	0.59	0.51	0.57
	JJA	0.05	1.22	0.24	0.83	0.43	1.03	0.07	0.88	0.52	0.85
	August	0.06	1.17	0.30	0.95	0.40	1.15	0.12	0.99	0.51	0.77

TABLE 5.1: The coefficient of determination (r^2) and RMSD values between Meteo and RdisaggH precipitation input datasets

	Total (2003-2010) [mm]	**Winter (Dec-Feb) [mm]**	**Spring (Mar-May) [mm]**	**Summer (Jun-Aug) [mm]**	**Autumn (Sept-Nov) [mm]**
Allenbach:					
Meteo	8892	1425	1908	3731	1829
RdisaggH	11847	2145	2895	4642	2165
Mentue:					
Meteo	8680	1553	2173	2734	2220
RdisaggH	7609	1531	1853	2428	1796
Weisse Lutschine:					
Meteo	9910	2126	2331	3461	1991
RdisaggH	14361	2438	3675	5409	2838
Goldach:					
Meteo	7591	1090	1706	2951	1845
RdisaggH	9933	1402	2413	3911	2207
Emme:					
Meteo	9714	1531	2458	3855	1870
RdisaggH	12532	1918	3197	5068	2349

Table 5.2: Precipitation sums for Meteo and RdisaggH datasets along with seasonal sums for all five catchments for the entire evaluation period (May 2003 - Nov. 2010)

5.1.1 Allenbach

In the Allenbach catchment, r^2 between Meteo and RdisaggH precipitation input datasets for the entire period of evaluation (May 2003 to December 2010) is 0.2 while RMSD is 0.65 as shown in table 5.1. This shows a significant difference between the two precipitation input datasets. The precipitation totals for Allenbach catchment for the entire evaluation period for both Meteo and RdisaggH precipitation datasets are given under column 'Total (2003-2010)', and row 'Allenbach' in table 5.2. The Meteo precipitation total is $8892mm$ and falls short of the RdisaggH precipitation total by 24.9%. Here, the RdisaggH precipitation total is $11847mm$. The difference is more significant in spring followed by summer and then winter. This means that RdisaggH dataset presents significantly higher precipitation values in those seasons. This can also be illustrated through figure 5.1 which shows the long term monthly mean for both precipitation input datasets from 2004 to 2010. It is worth mentioning here that table 5.2 gives the general sense of the total precipitation for the two datasets for the entire time period of evaluation where the RdisaggH precipitation total exceeds that of Meteo precipitation total by 24.9%. However, table 5.3 shows that RdisaggH precipitation total has exceeded Meteo precipitation total by 52.2% in 2007 while remaining much the same in 2005. Table 5.3 shows that in 2007, RdisaggH dataset captured unusually high precipitation for both winter and summer seasons.

For the calculation of long term monthly means shown in figure 5.1, the year 2003 was excluded as it had four months of missing RdisaggH precipitation data. As already mentioned in Chapter 3, the time series of RdisaggH precipitation data starts from 6:00 am of May 1, 2003. The consistent difference in monthly mean from January to August in figure 5.1 explains the large difference in precipitation sums during Winter, Spring and Summer seasons in table 5.2.

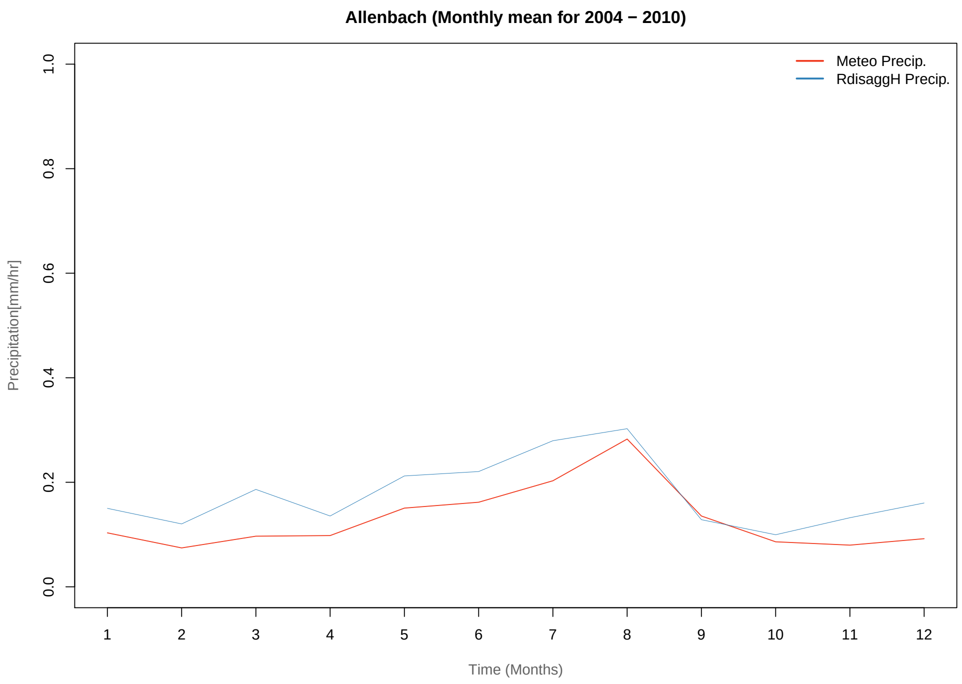


FIGURE 5.1: Allenbach: Long term monthly mean for Meteo and RdisaggH precipitation datasets (2004 - 2010)

The r^2 and RMSD values in table 5.1 increases to 0.54 and 0.53 respectively for 2003 (May - Dec) and then to 0.60 and 0.39 for 2005 (Jan - Dec).The r^2 values improves slightly more to 0.61 and 0.65 for the month of August in 2003 and 2005 respectively. However, RMSD values deteriorates from 0.51 in August 2003 to 0.69 in August 2005. Both r^2 and RMSD values deteriorates considerably to 0.09 and 0.75 respectively in 2007 suggesting higher differences in the two precipitation input datasets. Again, this is obvious from the illustration in figure 5.11 where one can clearly see a sort of a thick clutter on the top axis of the plot from 2007 upto 2010. While there are also some high variations for 2003, 2004, 2005 and 2006, they don't appear so crammed across the horizontal axis. Table 5.3 shows extremely large difference in precipitation sums in 2007 for the two datasets while 2005 shows a close match among the three years. Based on the references betweeen table 5.3 and table 5.1, it is evident that RMSD does a better job in capturing the goodness of fit between these two datasets.

	Precip. Total [mm]	Winter (Dec-Feb) [mm]	Spring (Mar-May) [mm]	Summer (Jun-Aug) [mm]	Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	807.02	NA	124.87	386.23	295.92
RdisaggH	969.01	NA	136.94	499.08	332.91
2005					
Meteo	1352.43	355.17	264.63	525.94	206.69
RdisaggH	1378.56	291.94	292.44	576.33	217.85
2007					
Meteo	892.9	124.09	197.01	427.44	144.36
RdisaggH	1868.92	394.46	431.81	810.69	231.96

Table 5.3: Allenbach: Precipitation sums for Meter and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

5.1.2 Mentue

The r^2 and RMSD between Meteo and RdisaggH precipitation input datasets for time period - May 2003 to December 2010 is 0.26 and 0.47 respectively according to table 5.1 for the Mentue catchment. This again suggests that there is a significant difference between the two precipitation input datasets. However, contrary to Allenbach catchment, table 5.2 shows that the Meteo precipitation total is actually higher than RdisaggH precipitation total by 12.33% in Mentue catchment. The Meteo precipitation total is 8680mm while that of RdisaggH precipitation total is 7609mm. In fact, Mentue is the only catchment which has higher Meteo precipitation sums than the RdisaggH precipitation sums. This is true not just for the total sums of the entire time period of evaluation i.e. 2003 to 2010 but also for the low flow period of 2003 and high flow periods of 2005 and 2007 according to figure 5.4. The difference in the precipitation sums for the years 2003, 2005 and 2007 are however significantly very low when compared to the difference in other catchments. This is perhaps the reason why Mentue yields the best RMSD values for the entire period of evaluation 2003 to 2010, as well as for 2003, 2005 and 2007. Mentue shows the best goodness of fit value of 0.27 for August 2005 and worst value of 0.95 for August 2007.

Figure 5.2 illustrates the difference in long term monthly mean from 2004 to 2010 for both precipitation datasets. Here, the years - 2006, 2008, 2009 and 2010 show particularly higher precipitation values for Meteo precipitation dataset suggesting large differences between the two datasets as also shown on top horizontal axis in figure 5.16. The difference in values for 2003, 2005 and 2007 do not appear so significantly large although the 2005 do show some hourly points with higher values for Meteo dataset. This is further attested by the RMSD values in table 5.1. The RMSD values for the years 2003 (May

	Precip. Total [mm]	Winter (Dec-Feb) [mm]	Spring (Mar-May) [mm]	Summer (Jun-Aug) [mm]	Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	566.26	NA	75.83	216.09	274.34
RdisaggH	553.54	NA	70.96	211.72	270.86
2005					
Meteo	854.25	164.85	254.96	225.74	208.7
RdisaggH	837.95	155.38	252.65	223.15	206.7
2007					
Meteo	1227.42	232.56	281.49	565.41	147.96
RdisaggH	1191.42	254.1	266.35	519.01	151.96

TABLE 5.4: Mentue: Precipitation sums for Meter and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

- Dec) and 2005 (Jan - Dec) are 0.3 and 0.31 respectively while that for the year 2007 (Jan - Dec) is 0.52. There is a small improvement in RMSD value with 0.27 for the month of August in 2005. However August 2003 shows RMSD 0.43 and August 2007 shows RMSD 0.95.

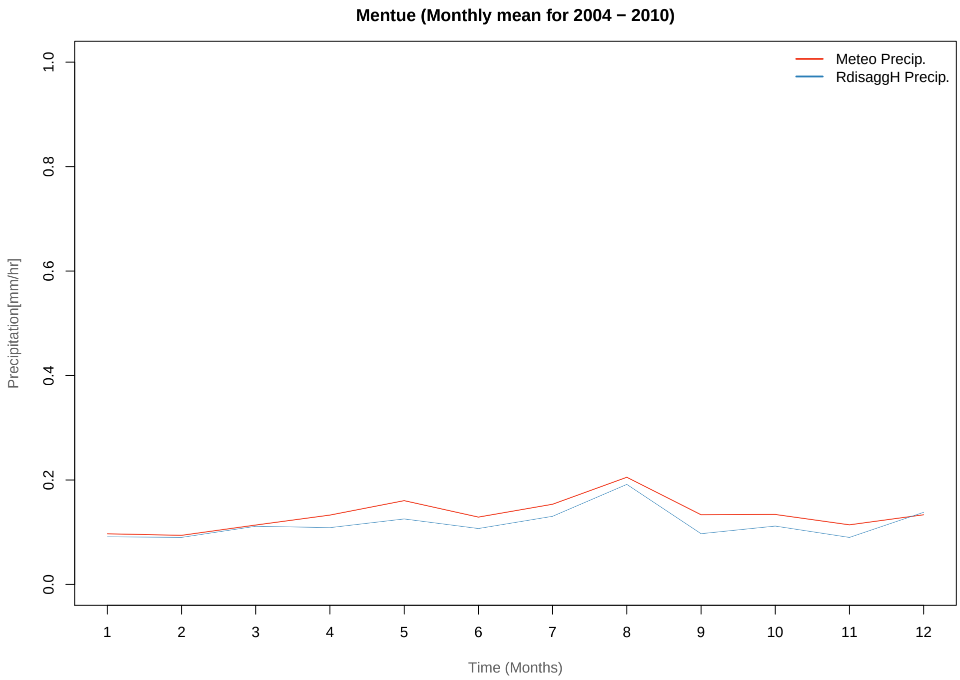


FIGURE 5.2: Mentue: Long term monthly mean for Meteo and RdisaggH precipitation datasets (2004 - 2010)

5.1.3 Weisse Lutschine

For Weisse Lutschine catchment, the r^2 and RMSD for the time period - May 2003 to December 2010 is 0.32 and 0.63 as shown in table 5.1. Both the values shows that the difference between the two precipitation input datasets is significant. Based on evaluation of just the RMSD values, it is slightly better than Allenbach but not that of Mentue or Goldash or Emme. The RdisaggH precipitation dataset shows exceptionally higher hourly values in Weisse Lutschine similar to Allenbach. This is also obvious from figure 5.3. The RdisaggH precipitation total exceeds the Meteo precipitation total by 30.99%. Table 5.2 shows that the Meteo precipitation total for Weisse Lutschine is only 9910mm for the entire evaluation period while the RdisaggH precipitation total is 14361mm. The difference is particularly significant in spring and summer seasons followed by autumn season. However, table 5.5 shows that the difference in precipitation sums is significantly small for 2003 and 2005. However in 2007, RdisaggH precipitation sum grossly exceeds the Meteo precipitation sum by 40.6%. It should be noted here that even though Weisse Lutschine is a glacier catchment. The relatively higher precipitation values in Weisse Lutschine in comparison to other catchments could be due to: a) its higher elevation whereby higher rain-gauge stations could collect more precipitation, as more precipitation falls in higher catchments, b) larger catchment area of 164km^2.

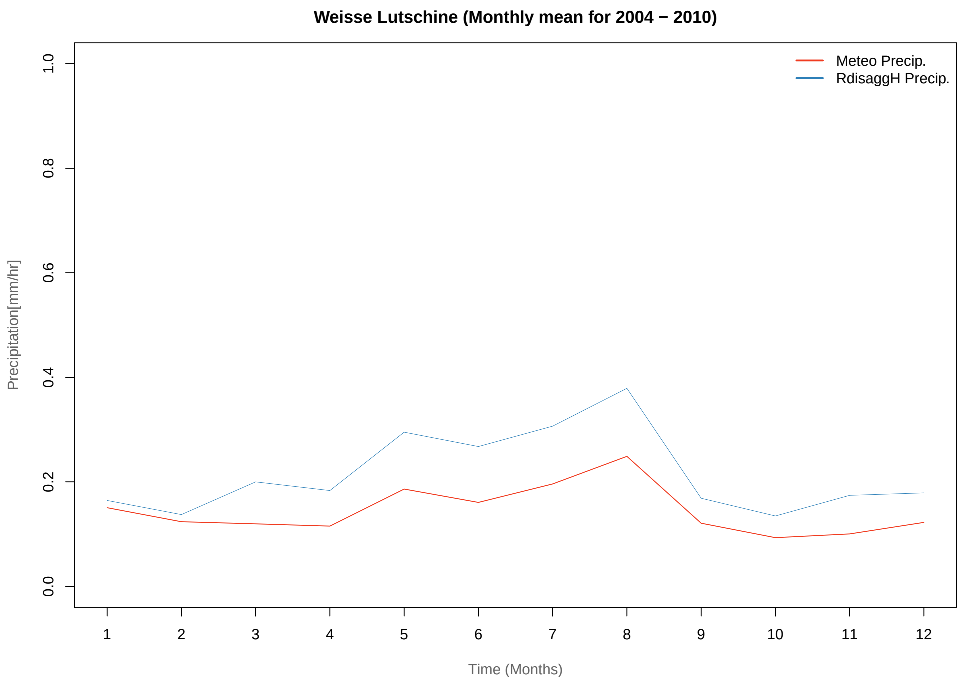


FIGURE 5.3: Weisse Lutschine: Long term monthly mean for Meteo and RdisaggH precipitation datasets (2004 - 2010)

	Precip. Total [mm]	Winter (Dec-Feb) [mm]	Spring (Mar-May) [mm]	Summer (Jun-Aug) [mm]	Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	883.73	NA	157.44	335.42	390.87
RdisaggH	1073.18	NA	173.56	490.92	408.59
2005					
Meteo	1715.23	607.39	378.44	511.66	217.74
RdisaggH	1768.45	386.25	417.35	730.14	234.71
2007					
Meteo	1306.62	218.53	323.85	620.08	114.16
RdisaggH	2200.52	338.78	570.31	952.99	338.44

Table 5.5: Weisse Lutschine: Precipitation sums for Meter and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Both r^2 and RMSD values do not show much improvement for the years 2003 (May - Dec), 2005 (Jan - Dec) and 2007 (Jan - Dec) suggesting that the difference in two datasets is consistent with RdisaggH precipitation dataset having more high values. This is also seen in figure 5.3 of long term monthly means for 2004 to 2010 where RdisaggH dataset exceeds the Meteo dataset during spring and summer seasons.

5.1.4 Goldach

For the Goldach catchment, table 5.1 shows that the r^2 and RMSD value for the time period: May 2003 to December 2010 is 0.23 and 0.58 respectively suggesting a weak correlation between the Meteo and RdisaggH precipitation datasets. Here, the RdisaggH precipitation dataset has higher values compared to Meteo precipitation dataset. This is also evident from table 5.2 which shows the precipitation totals for Meteo dataset to be $7591mm$ while that of RdisaggH dataset is $9933mm$ for the entire evaluation time period. The precipitation total for RdisaggH is greater than that of Meteo dataset by 23.5%. The summer followed by spring and autumn seasons show the highest difference between the two datasets. This is evident from figure 5.4 as well. However, like in the case of Weisse Lutschine, table 5.6 suggest that difference in precipitation sums is actually significantly small for 2003 and 2005 but in 2007, RdisaggH precipitation sum exceeds the Meteo precipitation sum by 30.3%.

In table 5.1, if the two datasets are to be evaluated based on the r^2 values, it improves significantly for the years 2003 (May - Dec), 2005 (Jan - Dec) while it deteriorates drastically for the year 2007 (Jan - Dec). Here, RMSD values gives a slightly different picture. RMSD values also suggest consecutively better goodness of fit for the years 2003 (May - Dec), 2005 (Jan - Dec) and the worst for 2007 (Jan - Dec). However, if one

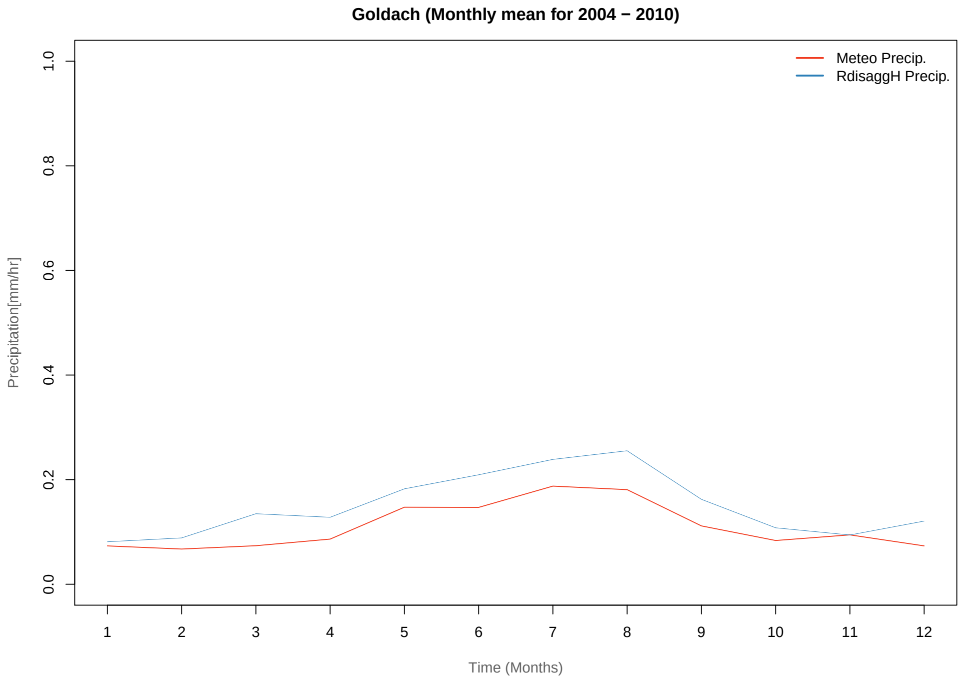


FIGURE 5.4: Goldach: Long term monthly mean for Meteo and RdisaggH precipitation datasets (2004 - 2010)

	Precip. Total [mm]	**Winter (Dec-Feb) [mm]**	**Spring (Mar-May) [mm]**	**Summer (Jun-Aug) [mm]**	**Autumn (Sept-Nov) [mm]**
2003 (May-Nov)					
Meteo	781.46	NA	119.69	290.97	370.8
RdisaggH	751.23	NA	115.48	284.34	351.41
2005					
Meteo	1279.28	218.19	349.52	541.83	169.74
RdisaggH	1205.18	166.74	338.63	533.81	166
2007					
Meteo	855.14	171.21	122.7	411.12	150.11
RdisaggH	1227.29	201.69	260.61	501.43	263.56

TABLE 5.6: Goldach: Precipitation sums for Meter and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

is to evaluate the month of August for 2003 and 2007, these values seem to be inversely correlated. August of 2005 and 2007 give the worst RMSD values of 0.84 and 0.99 while August, 2003 gives the best RMSD value of 0.35 for Goldach.

5.1.5 Emme

Albeit with small margin, the Emme catchment has the best coefficient of determination value for the time period - May 2003 to December 2010 between the Meteo and RdisaggH precipitation input datasets with r^2 value of 0.37. The same cannot be said with its RMSD results but it is second best to Mentue nonetheless with RMSD value of 0.56. Table 5.2 shows the precipitation total for Meteo dataset to be $9714mm$ while that of RdisaggH dataset to be $12532mm$ which is 22.4% higher. Like in Goldach, the difference in seasonal precipitation sum between the two datasets in Emme also show the highest difference in summer followed by spring and autumn seasons. Again, table 5.7 shows that the difference between the two precipitation datasets is significantly low in 2003 and 2005 while in 2007, the RdisaggH precipitation sums exceeds that of Meteo precipitation sums by 23.4%.

The r^2 values improve significantly for 2005 (Jan - Dec) to 0.45 and 2007 (Jan - Dec) to 0.51. The r^2 value for 2003 (May - Dec) remains more or less the same as that to the value drawn for the entire evaluation period which is 0.37. The RMSD values remain more or less the same between 0.56 and 0.57 for all these three years. However, the summer seasons of all 2003, 2005 and 2007 give poor RMSD values of 0.8, 0.9 and 0.85 respectively while r^2 values remain more or less the same as the yearly r^2 values.

Figure 5.5 illustrates the long term monthly means between the two datasets from 2004 to 2010. Similarly the top axis in figure 5.31 shows that the hourly time step values are consistently higher from 2008 to 2010 as they lie above the horizontal line thus suggesting higher RdisaggH values. 2003 shows hourly values with a lot of high variation in their magnitudes. This explains the r^2 value of 0.37 for 2003 (May - Dec) as compared to the year 2007 (Jan - Dec) in table 5.1. However, it should also be noted here that r^2 value for 2003 is based on hourly values from May to December for both datasets and that it misses out on four months of hourly data. Therefore comparing the r^2 value of 2003 with other years could potentially be erroneous in addition to its statistical limitations. However in this case, it is evident from table 5.2 that the winter season gets the least precipitation and the question is actually how much precipitation is missed in the months of March and April in spring of 2003. This is also true for all the previous catchments.

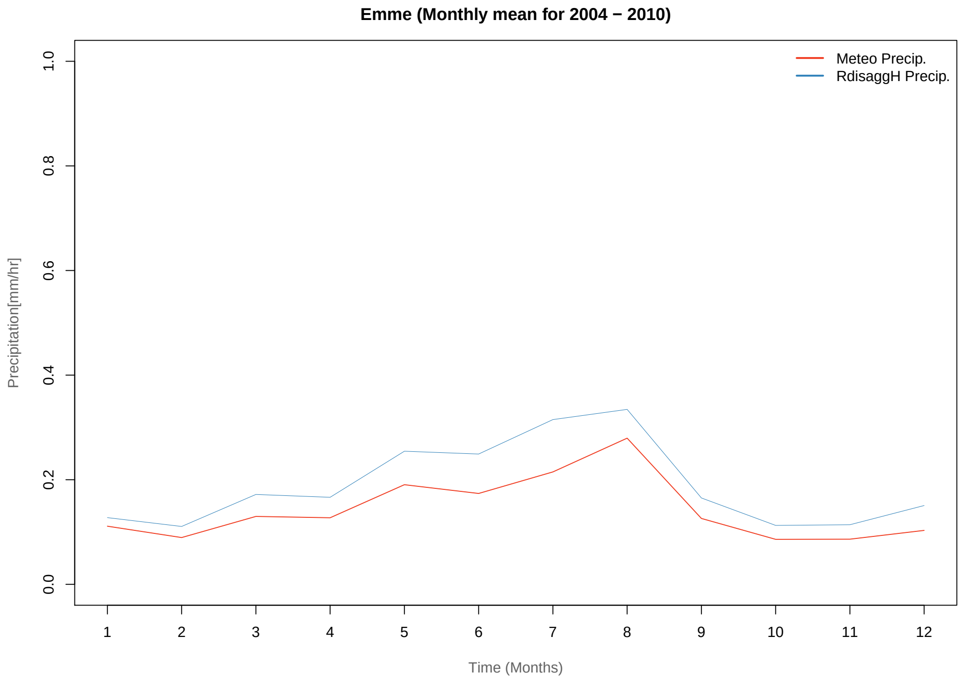


FIGURE 5.5: Emme: Long term monthly mean for Meteo and RdisaggH precipitation datasets (2004 - 2010)

	Precip. Total [mm]	**Winter (Dec-Feb) [mm]**	**Spring (Mar-May) [mm]**	**Summer (Jun-Aug) [mm]**	**Autumn (Sept-Nov) [mm]**
2003 (May-Nov)					
Meteo	906.21	NA	148.4	405.5	352.31
RdisaggH	924.99	NA	138.21	430.21	356.57
2005					
Meteo	1596.67	307.1	370.55	680.33	238.69
RdisaggH	1618.22	244.39	399.64	716.47	257.72
2007					
Meteo	1509.1	237.2	388.19	728.01	155.7
RdisaggH	1970.63	289.37	540.43	885.26	255.57

TABLE 5.7: Emme: Precipitation sums for Meter and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

		Allenbach	Mentue	Weisse Lutschine	Goldach	Emme
Meteo Data:						
Calibration	ELN:	0.399	0.58	0.836	0.424	0.715
(2003-2006)	Score:	0.213	0.471	0.837	0.249	0.665
Validation	ELN:	-0.264	-0.916	0.768	-0.183	0.089
(2007-2010)	Score:	0	0	0.74	0	0
Full Simulation	ELN:	0.132	0.066	0.788	0.062	0.5
(2003-2010)	Score:	0	0	0.768	0	0.358
RdisaggH Data:						
Calibration	ELN:	0.468	0.74	0.76	0.367	0.77
(2003-2006)	Score:	0.312	0.7	0.729	0.167	0.743
Validation	ELN:	-0.099	0.528	0.814	0.268	0.638
(2007-2010)	Score:	0	0.397	0.805	0.026	0.555
Full Simulation	ELN:	0.318	0.616	0.84	0.349	0.712
(2003-2010)	Score:	0.097	0.522	0.844	0.141	0.66

Table 5.8: Linear scores and Nash-Sutcliffe efficiency for all five catchments during their respective calibration, validation and full simulation period of model runs

5.2 Model performance for calibration and validation period

The hydrological model PREVAH was calibrated for all five catchments of investigation using the time series of observed runoff dataset obtained from their respective river guaging stations. A time period of May 2003 to December 2006 was chosen for the model calibration while January 2007 to December 2010 was used for its validation. This has already been explained in Chapter 4. The model efficiency scores computed during the model runs for calibration, validation and full simulation are actually the linear scores that analyze the quality of the model run with respect to the linear efficiency score E_2^{lin} which is the Nash-Sutcliffe efficiency (NSE) measure. The ELN values given in table 5.8 are thus the NSE and the scores below them are the linear scores. Both these values are computed by PREVAH individually for calibration, validation and full simulation model runs for each catchment, first using RdisaggH dataset and then with Meteo dataset. This section shall only focus on the NSE and linear scores of calibration and validation runs of the two datasets.

5.2.1 Allenbach

According to table 5.8, the RdisaggH precipitation input dataset performs slightly better in comparison to the Meteo dataset for the Allenbach catchment. This is true for all the model runs which include calibration for the period of 2003 to 2006, validation for the period of 2007 to 2010 and the full simulation for the entire time series of 2003 to 2010. Both the NSE and linear scores are higher for RdisaggH dataset. If the NSE and linear scores are to be compared among the calibration, validation and full simulation runs in both precipitation datasets for Allenbach catchment, the calibration runs have the best NSE and linear scores. The validation runs shows the worst scores for both precipitation datasets. In fact, for Meteo dataset, the NSE is -0.264 and the linear score is 0 while for RdisaggH dataset, the NSE is -0.099 and the linear score is 0.

Figure 5.6 illustrates the calibration and validation simulated runoff outputs for both the RdisaggH and Meteo precipitation input datasets and compares them with the observed runoff dataset. Here, by calibration and validation simulated runoff output, it means that this is not a full simulation runoff output but a combined simulated runoff output of calibration and validation runs. Thus, for each of the two simulated runoff output dataset, it combines the simulated output from calibration run from 2003 to 2006 with the simulated output from validation run which is from 2007 to 2010. Thus, the final simulated runoff output time series consists from 2003 to 2010 but containing the results from both the calibration and validation runs. This is true for all the calibration and validation plots that will follow hence after in this section.

Here, the simulated runoff output (RdisaggH Q) from RdisaggH precipitation dataset performs slightly better in representing the variability in runoff peaks particularly for 2004 and 2006. The simulated runoff output from both the Meteo and RdisaggH datasets grossly underestimate a lot of peak events between 2007 and 2010 suggesting a weak validation which is also shown by their scores in table 5.8.

5.2.2 Mentue

The Mentue catchment shows some improvement in their NSE and linear scores for both Meteo and RdisaggH datasets unlike the Allenbach catchment. As shown in table 5.8, during the calibration run, the RdisaggH dataset gives higher NSE of 0.74 with linear score 0.7 than the Meteo dataset which gives NSE of 0.58 with linear score 0.471. Similarly during the validation run, the RdisaggH dataset again surpasses the Meteo dataset's performance with NSE 0.528 and linear score 0.397. The NSE and linear score for Meteo data is -0.916 and 0 respectively which is very poor.

Figure 5.7 shows the calibration and validation of simulated runoff outputs for both the RdisaggH and Meteo precipitation input datasets and compares them with the observed runoff dataset. This figure also illustrates that during the calibration run from 2003 to 2006, the simulated runoff output from RdisaggH dataset represents the peak

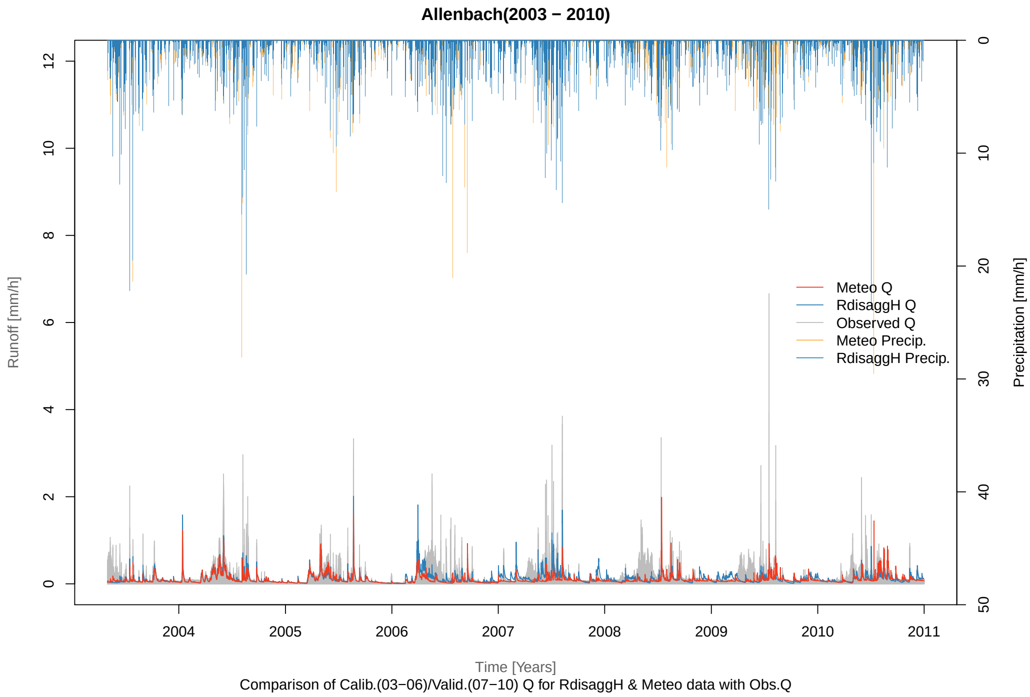


FIGURE 5.6: Allenbach: Calibration and Validation plot for time period May 2003 - December 2010

flood events slightly better than the Meteo dataset. This is particularly evident in the years 2004 and 2006. However, if one looks into the validation run from 2007 to 2010, the simulated runoff output from Meteo dataset consistently overestimates the peak events, particularly during the winters of 2008, 2009 and 2010 thus explaining its poor performances in both calibration and validation runs.

5.2.3 Weisse Lutschine

The Weisse Lutschine catchment shows the best NSE and linear scores for both Meteo and RdisaggH datasets among all the catchments of investigation. During the calibration run, the Meteo dataset gives higher NSE of 0.836 with linear score of 0.837 than the RdisaggH dataset. The RdisaggH dataset gives NSE of 0.76 with linear score of 0.729. However, during the validation run, the RdisaggH dataset surpasses the Meteo dataset's performance with NSE 0.814 and linear score 0.805. The NSE and linear score for Meteo dataset falls short to 0.768 and 0.74 respectively. This can also be seen in figure 5.8 where the simulated runoff output from the calibration run for Meteo dataset is agreeing well with the observed runoff dataset in the years 2004, 2005 and 2006. However, this is not true for the years 2007, 2008, 2009 and 2010 which are the validation period. During the entire validation period, it is the RdisaggH dataset that is in better agreement with

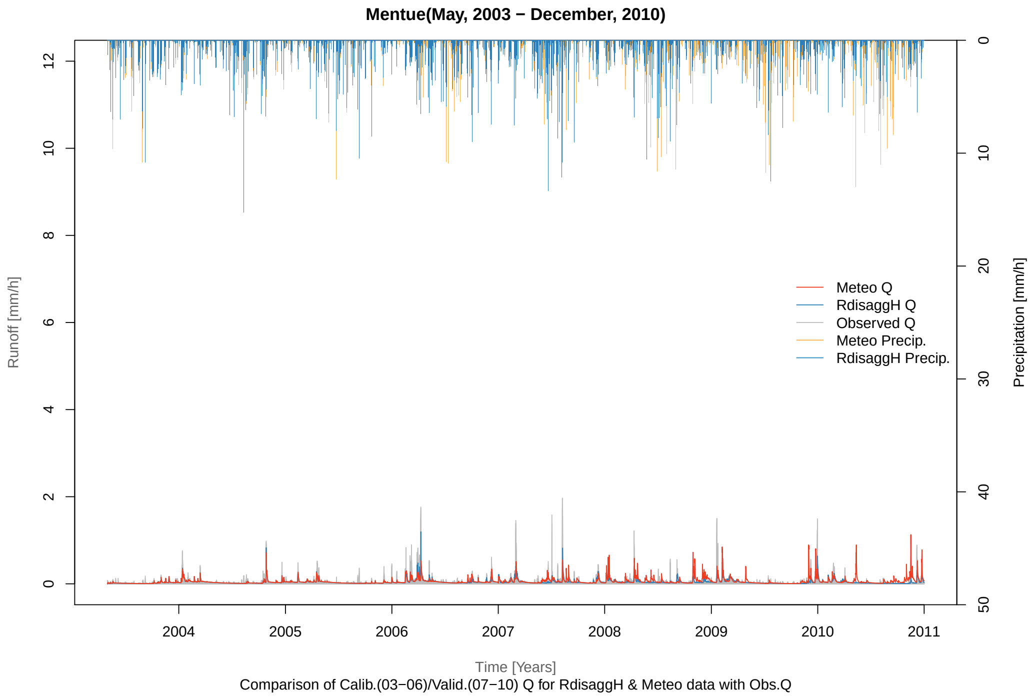


FIGURE 5.7: Mentue: Calibration and Validation plot for time period May 2003 - December 2010

the observed runoff dataset. During the validation run, the simulated runoff output for Meteo dataset underestimates the peaks particularly during the melt season.

5.2.4 Goldach

The Goldach catchment shows poor NSE and linear scores for both Meteo and RdisaggH datasets when compared to the rest of the four catchments of investigation. During the calibration run, the Meteo dataset gives higher NSE of 0.424 with linear score 0.249. On the other hand, the RdisaggH dataset gives relatively low NSE of 0.367 with linear score of 0.167. For the calibration run, the RdisaggH dataset gives the poorest NSE and linear score in Goldach when compared with the other four catchments. During the validation run, the RdisaggH dataset performs little better than the Meteo dataset with NSE 0.268 and linear score 0.026. The NSE and linear score for Meteo dataset is -0.183 and 0 respectively.

Figure 5.9 shows simulated runoff outputs from the calibration run for Meteo dataset corresponding slightly better than the RdisaggH dataset when compared with the observed runoff dataset. However, during the validation run, the runoff output of Meteo dataset completely fails to capture many peak events particularly during 2007, 2009 and 2010 while the runoff output of RdisaggH dataset somewhat captures these events. This

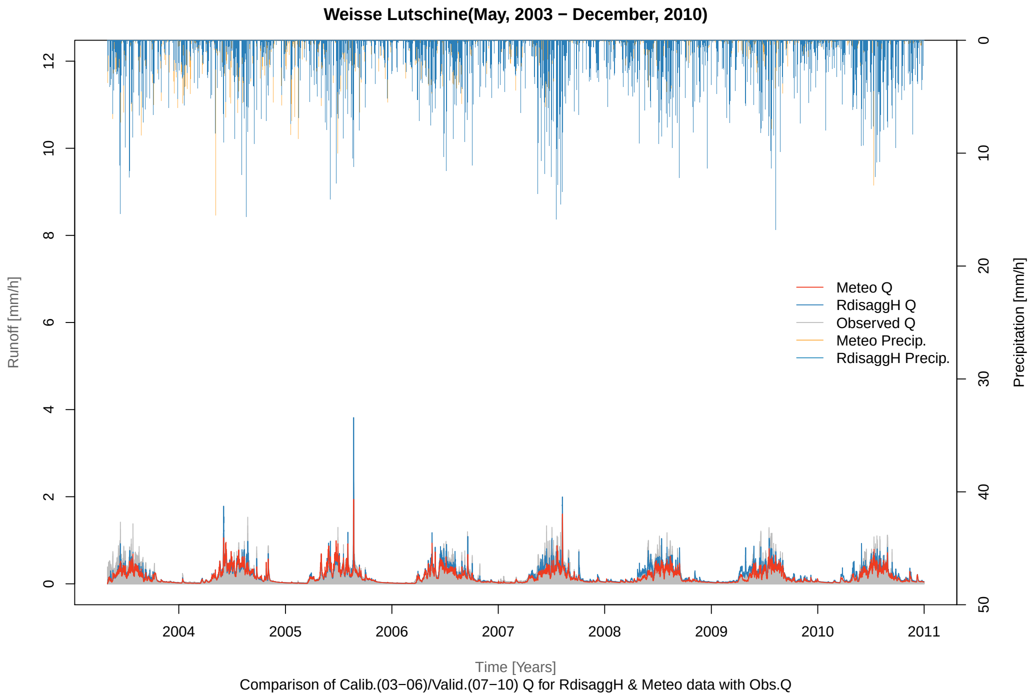


FIGURE 5.8: Weisse Lutschine: Calibration and Validation plot for time period May 2003 - December 2010

could be the reason why RdisaggH dataset gives slightly better NSE and linear score during the validation run.

5.2.5 Emme

The Emme catchment shows second best NSE and linear scores for both Meteo and RdisaggH datasets among all the catchments of investigation. During the calibration run, the RdisaggH dataset gives higher NSE of 0.77 with linear score of 0.743 than the Meteo dataset, which gives NSE 0.715 with linear score 0.665. In the validation run, the RdisaggH dataset performs relatively better with NSE 0.638 and linear score 0.555 than the Meteo dataset. The NSE and linear score for Meteo dataset is 0.089 and 0 respectively. Figure 5.10 illustrates this point very well. In figure 5.10, during the calibration run from 2003 to 2006, the simulated runoff output from both Meteo and RdisaggH datasets represent the peak runoff events in more or less the same manner. Hence both these datasets give higher NSE and linear scores during the calibration period. However, in the validation run from 2007 to 2010, the simulated runoff output for Meteo dataset consistently underestimates and misses the peak events, particularly during the winters of 2008, 2009 and 2010, thus resulting in very poor NSE and linear score.

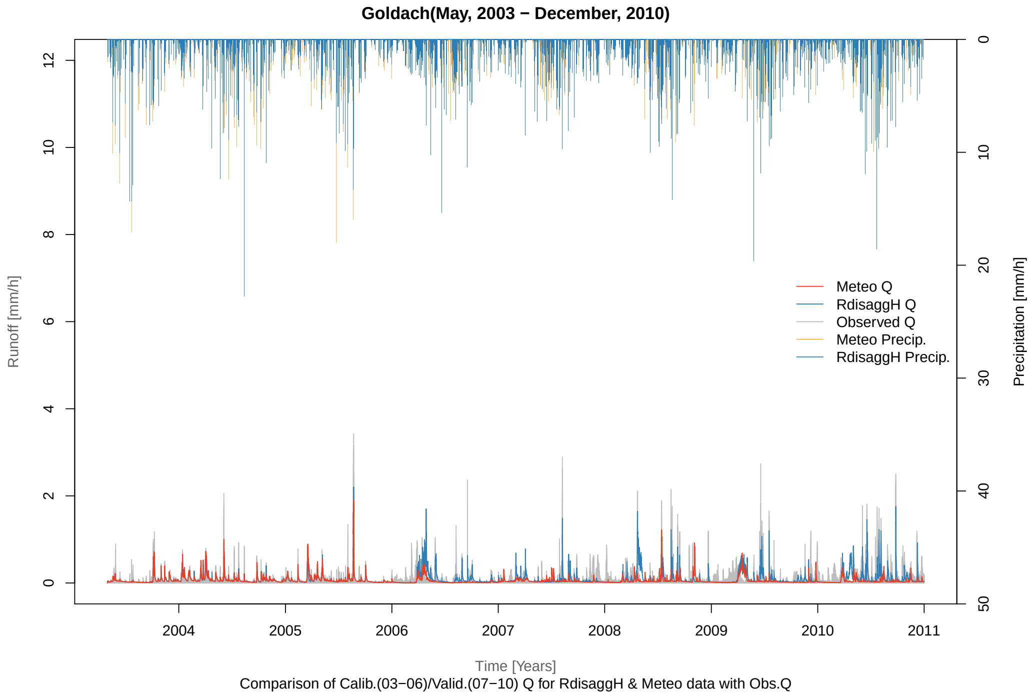


FIGURE 5.9: Goldach: Calibration and Validation plot for time period May 2003 - December 2010

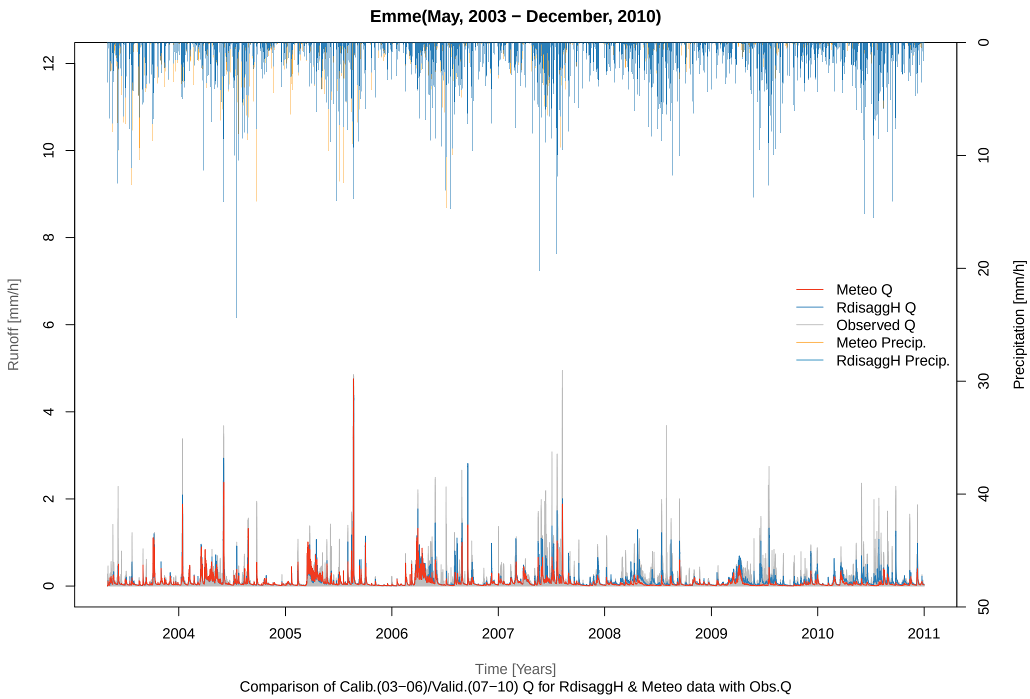


FIGURE 5.10: Emme: Calibration and Validation plot for time period May 2003 - December 2010

5.3 Outputs of PREVAH full simulations for Meteo and RdisaggH datasets

After the calibration and validation runs, full simulation runs were performed using PREVAH model for each of the five catchments using both Meteo and RdisaggH precipitation input datasets. The outputs were two simulated runoffs from two datasets at hourly time steps for every catchment. This section presents these two simulated model outputs along with the observed runoff dataset.

Similar to table 5.2, the total runoff sums from both the simulated runoffs along with the observed runoff were calculated for the entire period of evaluation. The resulting values are summarized in table 5.9. In addition, the total sums for all four seasons: winter (DJF), spring (MAM), summer (JJA) and autumn (SON) for the time period of May 2003 to December 2010 were also calculated. Just like in the case of precipitation sums, the runoff values for December 2010 were not included as they fall in the winter season of the following year. For each catchment, a separate table is created to show the runoff sums for 2003, 2005 and 2007, along with their respective seasonal sums.

5.3.1 Allenbach

According to table 5.8, the simulated runoff from the RdisaggH precipitation dataset shows higher NSE 0.318 with linear score of 0.097 while that of the Meteo precipitation dataset shows relatively low NSE 0.132 with linear score 0 for the Allenbach catchment. These values were given by PREVAH during its simulation runs. The NSE values in this case suggest that the RdisaggH precipitation dataset performs better than the Meteo precipitation dataset during the full simulation for Allenbach catchment. This is further attested in table 5.9 where the total sum of runoff for 2003 - 2010 time period shows that RdisaggH simulated runoff sum of 8509 comes the closest to the observed runoff sum of 9767 than the Meteo simulated sum of 7682. Figure 5.11 here shows that Meteo simulate runoff completely fail to capture peak flood events of 2006, 2007 and 2009 while that of 2008 and 2010 is also not particularly impressive. The NSE obtained from the RdisaggH simulated runoff for Allenbach is the lowest NSE value among all catchments for RdisaggH precipitation dataset.

Table 5.11 shows the coefficient of determination r^2 and NSE between these two simulated runoffs with the observed runoff. The RdisaggH simulated runoff correlates better with $r^2 = 0.34$ than the Meteo simulated runoff with $r^2 = 0.22$ for the entire period of the time series. It should be noted here that the NSE values mentioned in table 5.8 were calculated by PREVAH. PREVAH shows NSE values for the entire period of simulation

	Q Total (2003-2010) [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
Allenbach					
Meteo	7682	1084	1846	2856	1895
RdisaggH	8509	1369	2544	2987	1608
Observed	9767	991	4108	3301	1367
Mentue					
Meteo	3764	1246	1079	556	884
RdisaggH	3024	1057	1013	429	525
Observed	3109	1061	1048	484	516
Weisse Lutschine					
Meteo	10096	557	1919	5735	1885
RdisaggH	11844	654	2477	6523	2190
Observed	11628	502	2324	6906	1896
Goldach					
Meteo	4289	677	1502	1128	982
RdisaggH	5737	639	2303	1616	1179
Observed	6282	1219	1969	1745	1350
Emme					
Meteo	5759	789	2464	1590	915
RdisaggH	7623	1032	2928	2427	1236
Observed	7758	934	3030	2664	1131

Table 5.9: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for all five catchments for the entire evaluation period (May 2003 - Nov. 2010)

	Q Total [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	607	NA	66	258	282
RdisaggH	538	NA	24	232	281
Observed	666	NA	225	240	200
2005					
Meteo	1342	141	453	499	249
RdisaggH	1130	73	447	421	189
Observed	1035	49	512	359	114
2007					
Meteo	711	135	153	263	159
RdisaggH	1386	298	332	573	183
Observed	1363	153	460	583	166

Table 5.10: Allenbach: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Time Period		Allenbach			
		Meteo Q Vs. Obs Q		**RdisaggH Q Vs. Obs Q**	
		r2	*NSE*	*r2*	*NSE*
2003-2010		0.22	0.13	0.342	0.29
2003	*Jan-Dec*	0.11	0.03	0.02	-0.23
	JJA	0.34	0.31	0.23	0.18
	August	0.55	0.31	0.52	0.29
2005	*Jan-Dec*	0.736	0.67	0.75	0.75
	JJA	0.70	0.53	0.68	0.67
	August	0.75	0.53	0.72	0.68
2007	*Jan-Dec*	0.27	0.01	0.39	0.35
	JJA	0.33	-0.05	0.55	0.55
	August	0.538	0.28	0.6036	0.54

TABLE 5.11: The coefficient of determination (r^2) values between observed runoff and simulated runoffs from both Meteo and RdisaggH precipitation datasets for Allenbach

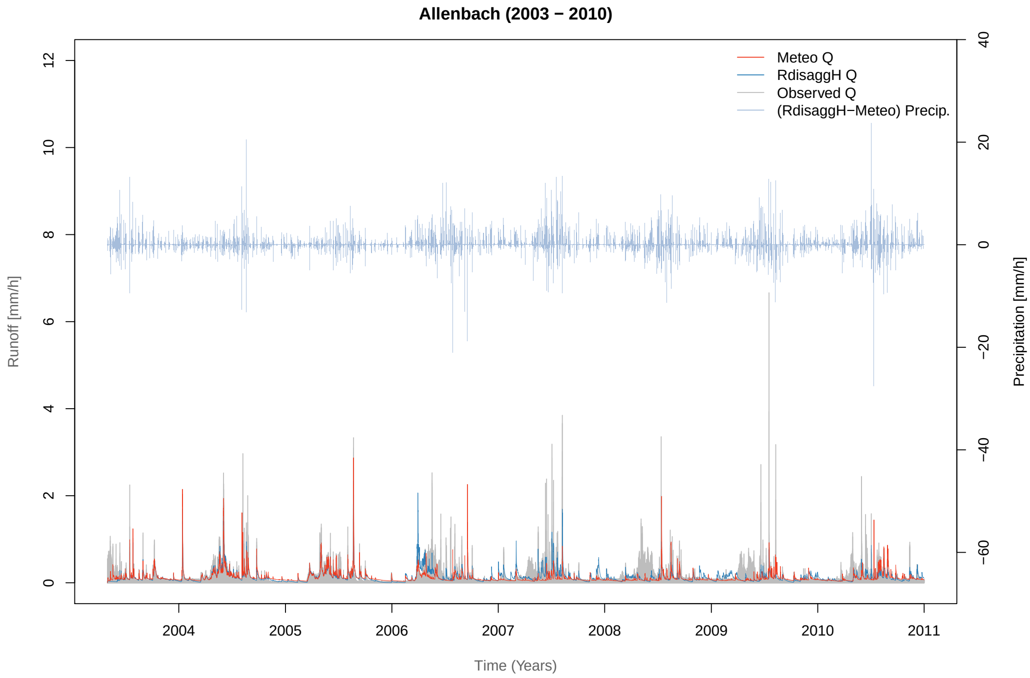


FIGURE 5.11: Allenbach: Full simulation plot for time period May 2003 - December 2010

as well as for individual year of simulation. However, since NSE values for JJA and August were not calculated by PREVAH, this was done using R and thus presented in table 5.11 were calculated in R. All the values presented in table 5.11 were calculated in R. So, the NSE values for 2003 - 2010 may not exactly be the same but slightly higher for PREVAH. This is because PREVAH tries to maximise the NSE score [Viviroli et al., 2007a].

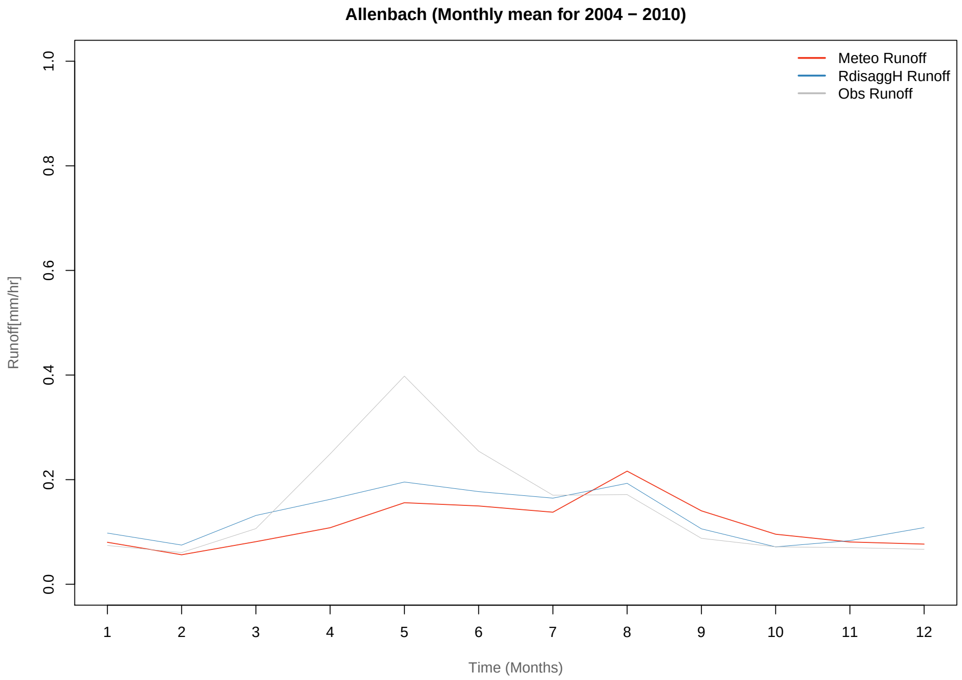


FIGURE 5.12: Allenbach: Long term monthly mean comparison of observed runoff with Meteo and RdisaggH simulated runoffs for 2004 - 2010

5.3.1.1 Case study: 2003

For the year of 2003, the RdisaggH simulated runoff shows poor linear correlation with $r^2 = 0.02$ as well as poor NSE of -0.23 while that of Meteo simulated runoff shows $r^2 = 0.11$ and $NSE = 0.03$. The poor r^2 and NSE values maybe due to the fact that both datasets underestimate much of the peak events in May 2003 as shown in figure 5.11 and figure 5.13. This is also seen in table 5.10 where the observed runoff sum for May in spring is $225mm$ while that from Meteo simulated runoff sum for the same period is $66mm$ and that from RdisaggH simulated runoff sum is $24mm$. However, both datasets capture the low intensity flow very well with a bit of an overestimation in recession and this is why the r^2 and NSE values are far better at 0.55, 0.31 and 0.52, 0.29 for August as shown in table 5.11.

For August as well as for the entire period of 2003, the Meteo simulated runoff captures the flow slightly better than the RdisaggH simulated runoff.

5.3.1.2 Case study: 2005

For the year 2005, the RdisaggH simulated runoff shows $r^2 = 0.75$ and $NSE = 0.75$ while that of Meteo simulated runoff gives $r^2 = 0.73$ and $NSE = 0.67$. However, during

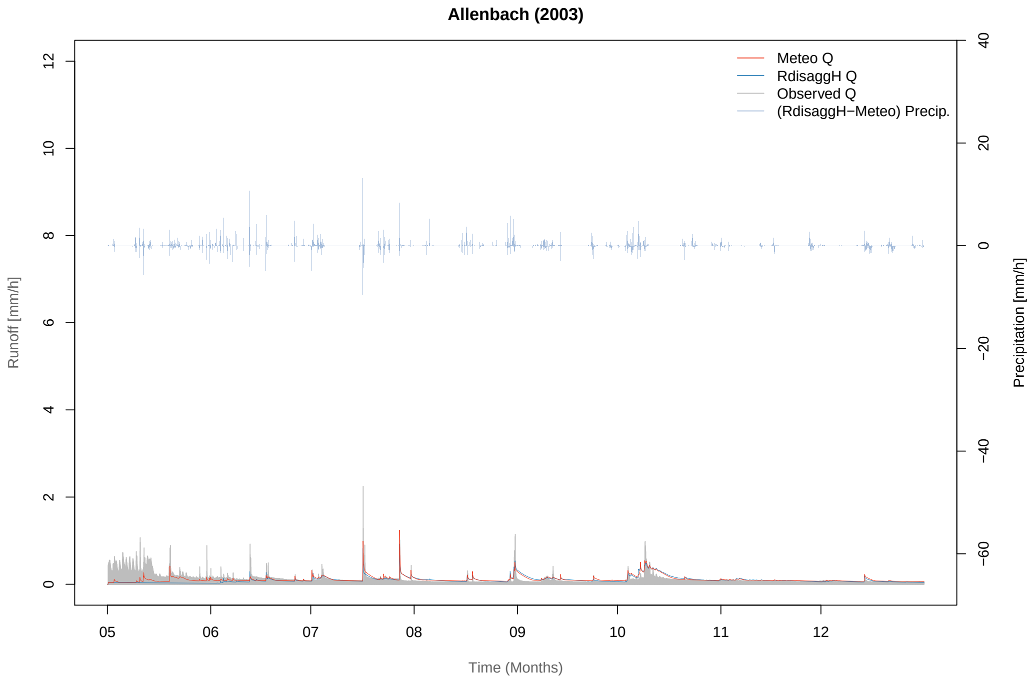


Figure 5.13: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2003, Allenbach

the summer season (JJA), the Meteo simulated runoff shows better correlation with the observed runoff than RdisaggH simulated runoff with $r^2 = 0.70$ to $r^2 = 0.68$. But NSE values shows better goodness of fit for RdisaggH simulated runoff with $NSE = 0.67$ to $NSE = 0.53$ for Meteo simulated runoff. If one inspects the hydrograph shown in figure 5.14 closely, then it is obvious that while both Meteo and RdisaggH simulated runoff overestimates the low intensity flows and recessions in summer season (JJA). Meteo simulated runoff also exceeds the overestimation when compared with RdisaggH simulated runoff but it captures the high peak runoffs relatively well while RdisaggH simulated runoff completely underestimates the high peak runoffs.

Further, figure A.2 plots the monthly means of all the three runoffs. The observed monthly mean illustrates the hydrological regime of the catchment which is well reproduced by both the simulated runoffs.

Thus, it can be inferred that both these two datasets corresponds to the hydrological regime of the catchment showing good r^2 and NSE and tries to capture high flood events to a certain extent. However, RdisaggH dataset does a better job in reproducing the extreme peak events with $NSE = 0.68$ to $NSE = 0.53$ for the month of August as shown in table 5.11 and figure 5.14.

It is worth mentioning here that Switzerland suffered a historic flooding event on 21^{st} and 22^{nd} August, 2005. These events were well reproduced by both the datasets. The peaks of this flood event from all the runoffs can be seen in figure 5.11 and figure 5.14. According to table 5.10, for 2005, the Meteo simulated runoff sum is significantly higher than the observed runoff sum. Looking at it from seasonal perspective, it gives higher runoff sums for spring, summer and autumn. The RdisaggH simulated runoff sum is in between the two, suggesting that RdisaggH dataset may actually be producing a more realistic results if we compare the total runoff output. It is thus also misleading to evaluate the simulated runoff datasets based on r^2 values which in this case suggest the opposite.

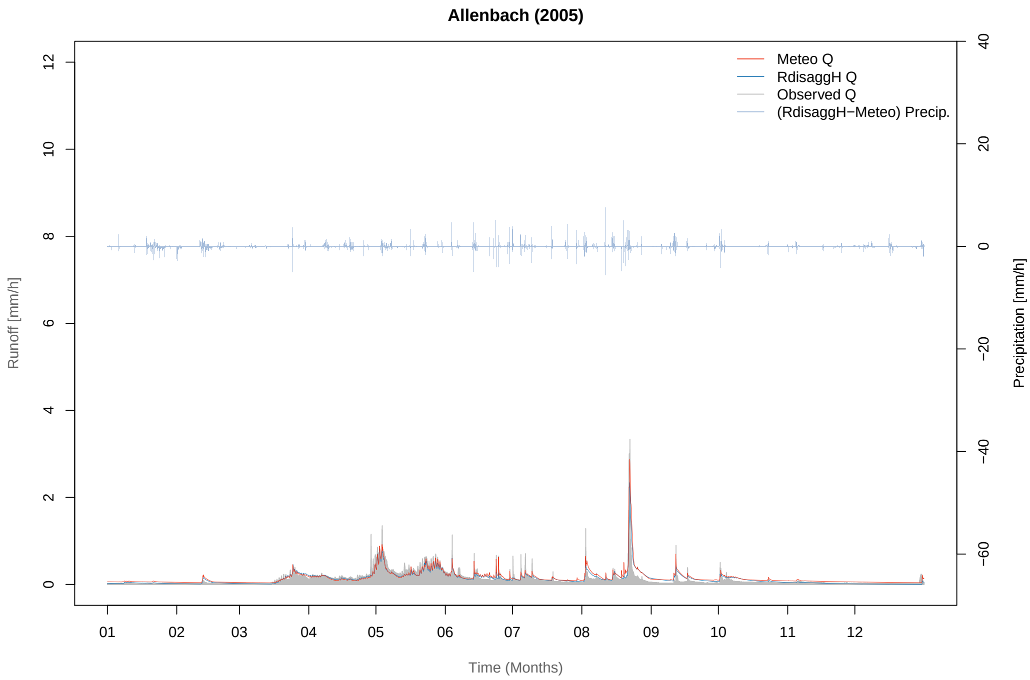


FIGURE 5.14: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2005, Allenbach

5.3.1.3 Case study: 2007

For 2007, the RdisaggH simulated runoff against the observed runoff gives relatively poor results with $r^2 = 0.39$ and $NSE = 0.35$ while that of Meteo simulated runoff gives $r^2 = 0.27$ and $NSE = 0.01$. Both r^2 and NSE remain relatively very high for the summer season (JJA) as well as for the month of August for RdisaggH simulated runoff as shown in table 5.11. During JJA, the $r^2 = 0.55$ and $NSE = 0.55$while for August, $r^2 = 0.6$ and $NSE = 0.54$. Similarly, for Meteo simulated runoff, $r^2 = 0.33$ and $NSE = -0.05$ for JJA while for August $r^2 = 0.28$ and $NSE = 0.28$.

The poor correlation of Meteo simulated runoff could be explained based on figure 5.11 and figure 5.15 where one can see the Meteo simulated runoff missing out to reproduce almost all low intensity peak events and also underestimating high peak events in spring and summer seasons as compared to the RdisaggH simulated runoff. The monthly mean plot of all the runoffs in figure A.4 shows the poor performance of Meteo simulated runoff to represent the hydrological regime of the catchment in 2007. If one simply compares the total runoff sums for 2007 as shown in table 5.10, it is evident that the total sum of RdisaggH runoff comes closer to observed runoff than the Meteo runoff. This is also true for summer season (Jun - Aug).

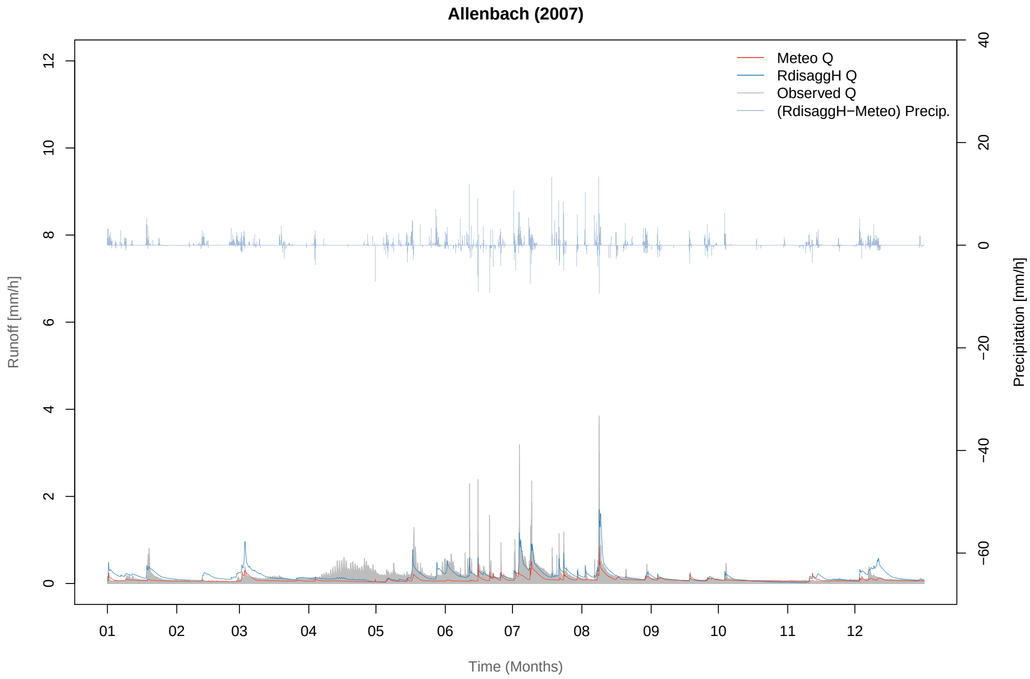


FIGURE 5.15: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2007, Allenbach

5.3.2 Mentue

In table 5.8, the simulated runoff for the RdisaggH precipitation dataset shows exceptionally higher $NSE = 0.616$ with linear score 0.522 while that of the Meteo precipitation dataset shows $NSE = 0.066$ with linear score 0. This means that the RdisaggH precipitation dataset performs really well for Mentue catchment. According to the table 5.9, the Meteo simulated runoff aggregates to $3764mm$ while that of RdisaggH simulated runoff sums to $3024mm$ and observed runoff totals to $3109mm$. This means that the RdisaggH simulated runoff gives more realistic total output of the catchment than the Meteo simulated runoff from PREVAH model. However it is worth to mention here that out of five catchments of investigation, Mentue is the only catchment where Meteo datasets yields both higher precipitation sums (Table 5.2) and runoff sums (Table 5.9) for the total time period 2003 to 2010 as well as for the individual year 2003 (Table 5.12). Also, based on these tables, the Meteo simulated runoff shows higher total value than RdisaggH simulated runoff total or that from observed runoff total for autumn and winter seasons.

The r^2 and NSE for both Meteo and RdisaggH simulated runoffs against observed runoff as shown in table 5.13 also indicate that RdisaggH dataset does a better job in reproducing the runoff output for the entire period of evaluation. According to table 5.13, for Meteo simulated runoff, $r^2 = 0.33$ and $NSE = 0.07$ while that of RdisaggH simulated runoff against the observed runoff, $r^2 = 0.61$ and $NSE = 0.61$. Figure 5.16 shows how the observed and two simulated runoffs compare with each other. Here, the Meteo simulated runoff misses a lot of peak events and yet consistently over-estimate peak events particularly during 2007, 2008, 2009 and 2010.

5.3.2.1 Case study: 2003

Figure 5.16 suggests that 2003 was a dry spell. Despite having a really good NSE for the total time period of evaluation, in 2003 the RdisaggH simulated runoff shows a weak $r^2 = 0.47$ and $NSE = 0.26$ while the Meteo simulated runoff gives $r^2 = 0.48$ and $NSE = -0.11$.

For JJA, Meteo simulated runoff do not correlate well with the observed runoff with equally poor $r^2 = 0.04$ and $NSE = -0.11$. For August, both r^2 and NSE values remains poor with 0.03 and -0.18. Table 5.12 shows that for the spring and summer seasons, the observed runoff totals correlate well with the Meteo simulated runoff totals. However, if one considers total sum for the entire year of 2003 (excluding the first four months with no data), then the RdisaggH simulated runoff value comes closer to the total

	Q Total [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	127	NA	18	23	83
RdisaggH	97	NA	12	21	63
Observed	100	NA	20	28	51
2005					
Meteo	312	119	113	27	33
RdisaggH	318	111	130	41	35
Observed	323	110	130	38	44
2007					
Meteo	555	160	101	207	86
RdisaggH	504	157	127	147	72
Observed	556	160	136	188	71

Table 5.12: Mentue: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Time Period		**Mentue**			
		Meteo Q Vs. Obs Q		**RdisaggH Q Vs. Obs Q**	
		r2	*NSE*	r^2	*NSE*
2003-2010		0.33	0.07	0.61	0.61
2003	*Jan-Dec*	0.48	-0.11	0.47	0.26
	JJA	0.04	-0.11	0.03	-0.13
	August	0.03	-0.18	0.05	-0.17
2005	*Jan-Dec*	0.65	0.64	0.65	0.64
	JJA	0.07	-0.67	0.07	-0.17
	August	0.001	-1.96	0.004	-0.23
2007	*Jan-Dec*	0.41	0.39	0.56	0.54
	JJA	0.31	0.29	0.49	0.44
	August	0.34	0.31	0.51	0.47

Table 5.13: The coefficient of determination (r^2) values between observed runoff and simulated runoffs from both Meteo and RdisaggH precipitation datasets for Mentue

sum of observed simulation. While the r^2 value for RdisaggH simulated runoff against observed runoff is slightly low, NSE for RdisaggH simulated runoff is higher than the Meteo simulated runoff. This could be due to imperceptibly small over-estimation of Meteo simulated runoff during recession at some low peak events in autumn and first month (i.e. December) of the winter period as shown in figure 5.18. Table 5.12 shows that while the observed runoff sum for 2003 is $51mm$, the RdisaggH runoff sum is $63mm$ and the Meteo runoff sum is $83mm$. On the other hand, the RdisaggH simulated runoff shows a significant drop in summer period. In fact it is even worse for JJA with $r^2 = 0.03$ and $NSE = -0.13$ while that for Meteo simulated runoff is $r^2 = 0.04$ and $NSE = -0.11$. This is because both simulated runoff do not capture the infinitesimally low peak flows

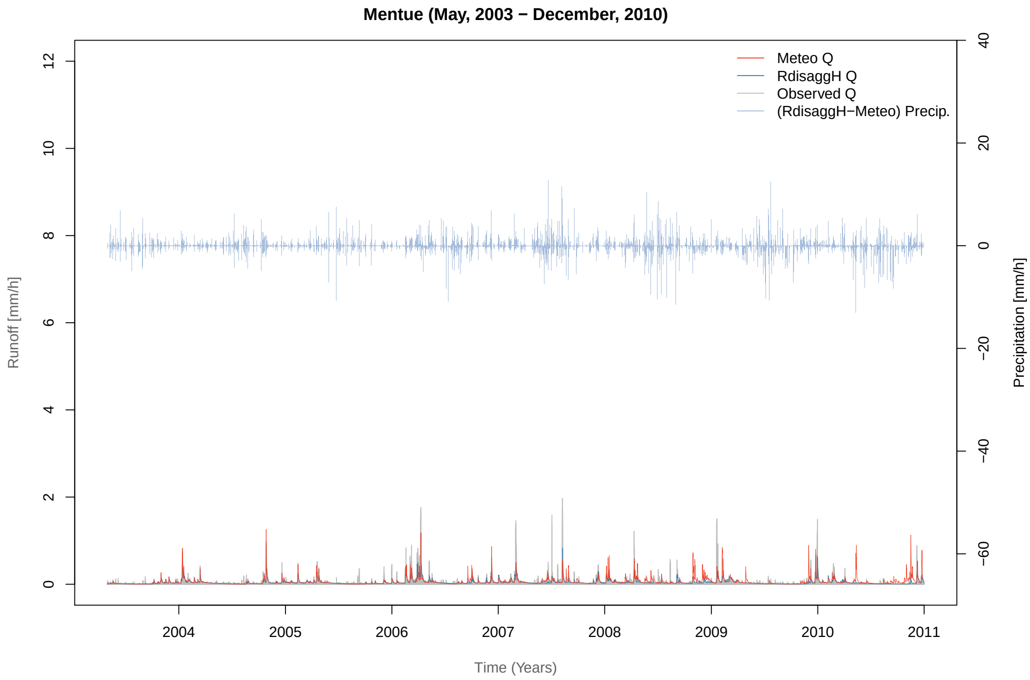


FIGURE 5.16: Mentue: Full simulation plot for time period May 2003 - December 2010

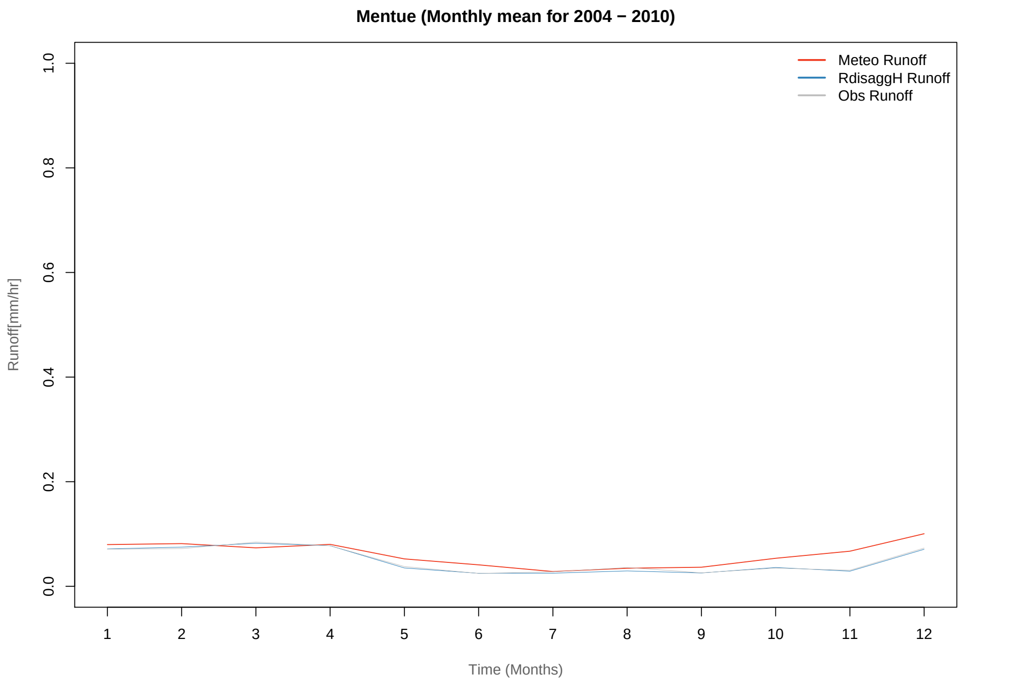


FIGURE 5.17: Mentue: Long term monthly mean comparison of observed runoff with Meteo and RdisaggH simulated runoffs for 2004 - 2010

in summer season.

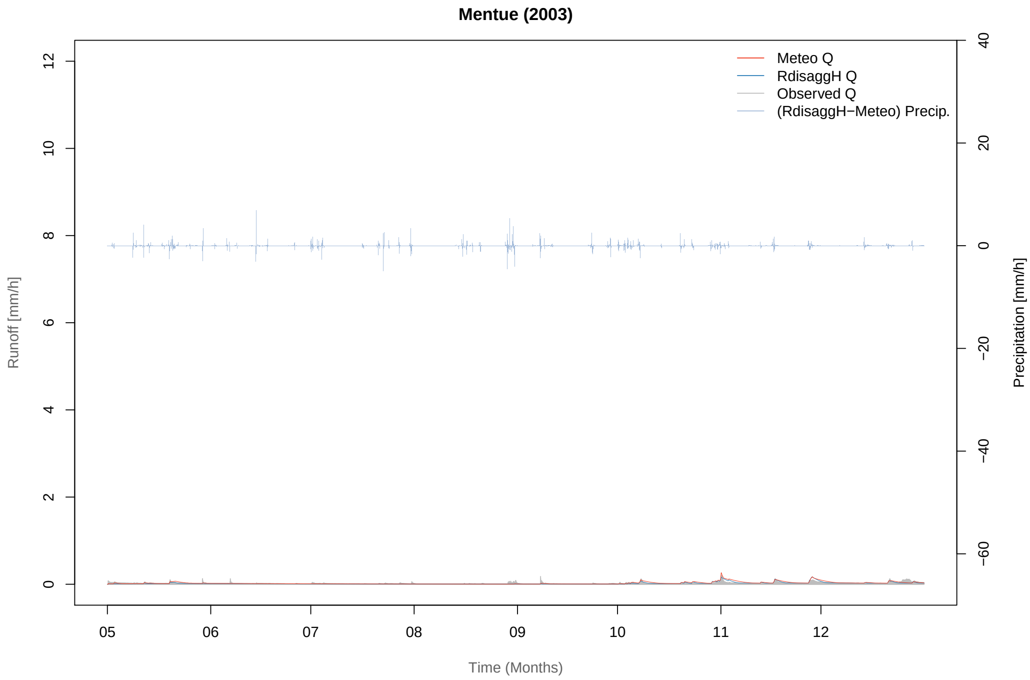


Figure 5.18: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2003, Mentue

5.3.2.2 Case study: 2005

In 2005, both the RdisaggH simulated runoff and the Meteo simulated runoff against the observed runoff give coincidentally the same $r^2 = 0.65$ and $NSE = 0.64$ values. The monthly mean plot for 2005 in figure A.6 also shows almost identical hydrological regimes from the two simulated runoffs that correspond well with the observed runoff. Table 5.12 also show almost similar aggregates of $312mm$, $318mm$ and $323mm$ for Meteo, RdisaggH simulated runoffs and the observed runoff respectively.

During JJA summer season, the r^2 and NSE for both datasets drop significantly to $r^2 = 0.07$ and $NSE = -0.67$ for Meteo simulated runoff and $r^2 = 0.07$ and $NSE = -0.17$ for RdisaggH simulated runoff. Both the r^2 and NSE values get worse for August with $r^2 = 0.001$ and $NSE = -1.96$ for Meteo simulated runoff and $r^2 = 0.004$ and $NSE = -0.23$ for RdisaggH simulated runoff. This is because both the simulated runoffs missed out almost all the infinitesimally low peak flows events as shown in figure 5.19. The r^2 and NSE obtained for August 2005 are the worst in comparison to the values obtained for 2003 and 2007 as shown in table 5.13.

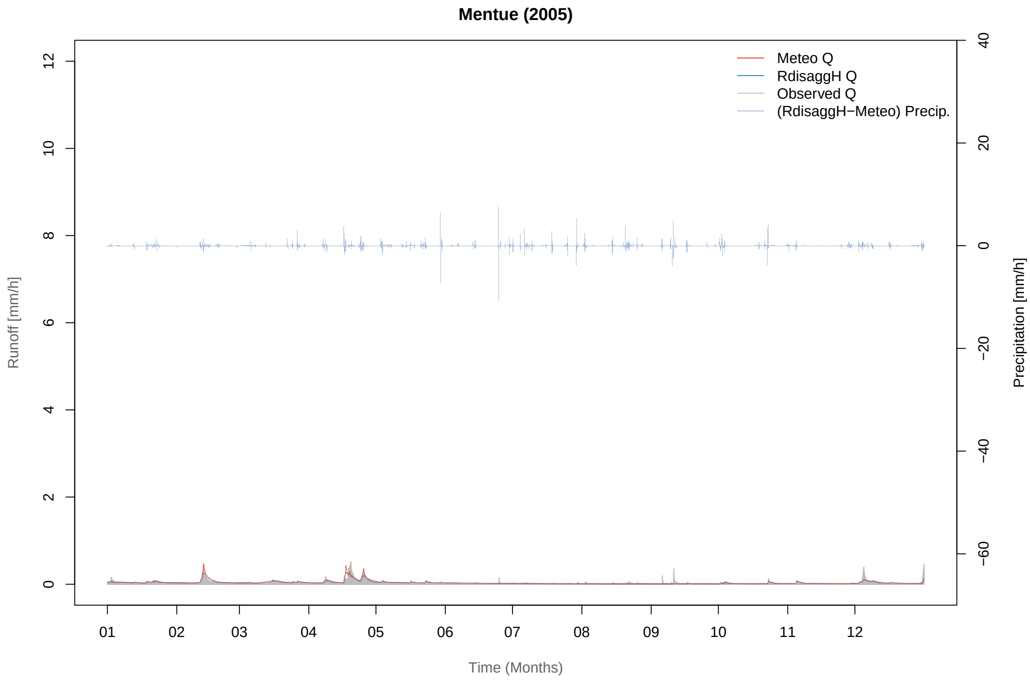


FIGURE 5.19: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2005, Mentue

5.3.2.3 Case study: 2007

For 2007, the RdisaggH simulated runoff gives a relatively better values with $r^2 = 0.56$ and $NSE = 0.54$ while that of Meteo simulated runoff gives $r^2 = 0.41$ and $NSE = 0.39$. Both r^2 and NSE remains high for RdisaggH simulated runoff for the summer season - JJA and as well as for the month of August. For RdisaggH simulated runoff during JJA, $r^2 = 0.49$ and $NSE = 0.44$ while for August, $r^2 = 0.51$ and $NSE = 0.47$. Similarly, for Meteo simulated runoff during the summer season - JJA, the $r^2 = 0.31$ and $NSE = 0.29$ while for August, $r^2 = 0.34$ and $NSE = 0.31$. Both r^2 and NSE have shown significant improvement for summer season and also for the month of August in 2007 when compared to same period in 2003 and 2005. Based on figure 5.16 and figure 5.20 this maybe because in 2007 both the simulated outputs have captured the peak events to some degree. The relative weak correlation of Meteo simulated runoff maybe because of its consistent over-estimation of peak events particularly in June and over-estimation of recessions in August peak events. This is not so much the case with RdisaggH simulated runoff as it is obvious from figure A.8. However, having said this, the sum of Meteo runoff for 2007 is $555mm$ which is very close to $556mm$ i.e. the sum of observed runoff for 2007. The sum of RdisaggH simulated runoff is $504mm$ as given in table 5.12.

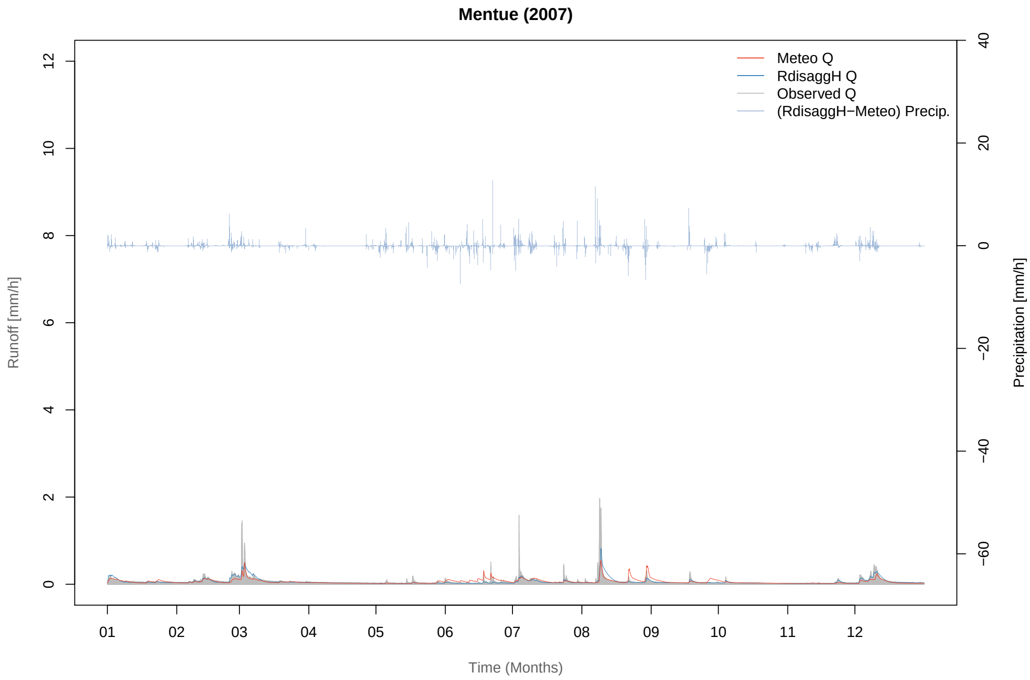


FIGURE 5.20: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2007, Mentue

5.3.3 Weisse Lutschine

Table 5.8 shows that for Weisse Lutschine catchment, the simulated runoff output for the RdisaggH precipitation input dataset give the highest NSE 0.84 with linear score 0.84. Among the five catchments the Meteo precipitation input dataset for Weisse Lutschine also gives the highest NSE 0.78 with linear score 0.76. Thus, in comparison to all the five catchments, Weisse Lutschine has the best NSE for both Meteo and RdisaggH precipitation datasets with the latter dataset doing relatively better than the previous one.

Table 5.15 shows the r^2 and NSE values between these two simulated runoffs against the observed runoff. Again, both the Meteo simulated runoff and the RdisaggH simulated runoff give the best r^2 of 0.79 and 0.82 respectively for the entire time series period. Figure 5.21 shows that while both simulated runoffs correspond well with the observed runoff, the Meteo simulated runoff underestimates the summer peak events from 2006 to 2010. Here the RdisaggH simulated runoff shows a better correlation with the observed runoff. If one simply looks at the runoff sums for each year i.e. 2003, 2005 and 2007 in table 5.14, one finds that the annual Meteo runoff aggregates are either far below the annual observed runoff totals or over it.

	Q Total [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	985	NA	90	687	206
RdisaggH	1032	NA	89	720	221
Observed	1450	NA	230	984	234
2005					
Meteo	1482	69	359	814	241
RdisaggH	1426	70	316	808	231
Observed	1400	58	303	818	221
2007					
Meteo	1261	93	264	714	189
RdisaggH	1598	98	350	895	255
Observed	1679	112	354	985	228

TABLE 5.14: Weisse Lutschine: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Time Period		**Weisse Lutschine**			
		Meteo Vs. Obs		**RdisaggH Vs. Obs**	
		r^2	*NSE*	r^2	*NSE*
2003-2010		0.79	0.76	0.82	0.82
2003	*Jan-Dec*	0.78	0.57	0.81	0.64
	JJA	0.55	-0.45	0.63	-0.16
	August	0.59	-0.39	0.77	0.03
2005	*Jan-Dec*	0.88	0.88	0.9	0.85
	JJA	0.75	0.74	0.9	0.64
	August	0.81	0.81	0.93	0.63
2007	*Jan-Dec*	0.75	0.68	0.84	0.84
	JJA	0.35	-0.38	0.57	0.29
	August	0.53	0.13	0.66	0.02

TABLE 5.15: The coefficient of determination (r^2) values between observed runoff and simulated runoffs from both Meteo and RdisaggH precipitation datasets for Weisse Lutschine

5.3.3.1 Case study: 2003

For 2003, the RdisaggH simulated runoff shows one of the best goodness of fit with $r^2 = 0.81$ and $NSE = 0.64$ while that of Meteo simulated runoff gives $r^2 = 0.78$ and $NSE = 0.57$. For JJA, $r^2 = 0.55$ and $NSE = -0.45$ for Meteo simulated runoff and $r^2 = 0.0.63$ and $NSE = -0.16$ for RdisaggH simulated runoff. This is perhaps because while both the simulated runoffs capture the variation of diurnal cycles well but they also consistently miss the magnitude with large underestimation of this melt season as shown in figure 5.23. RdisaggH simulated runoff shows some improvement for the month

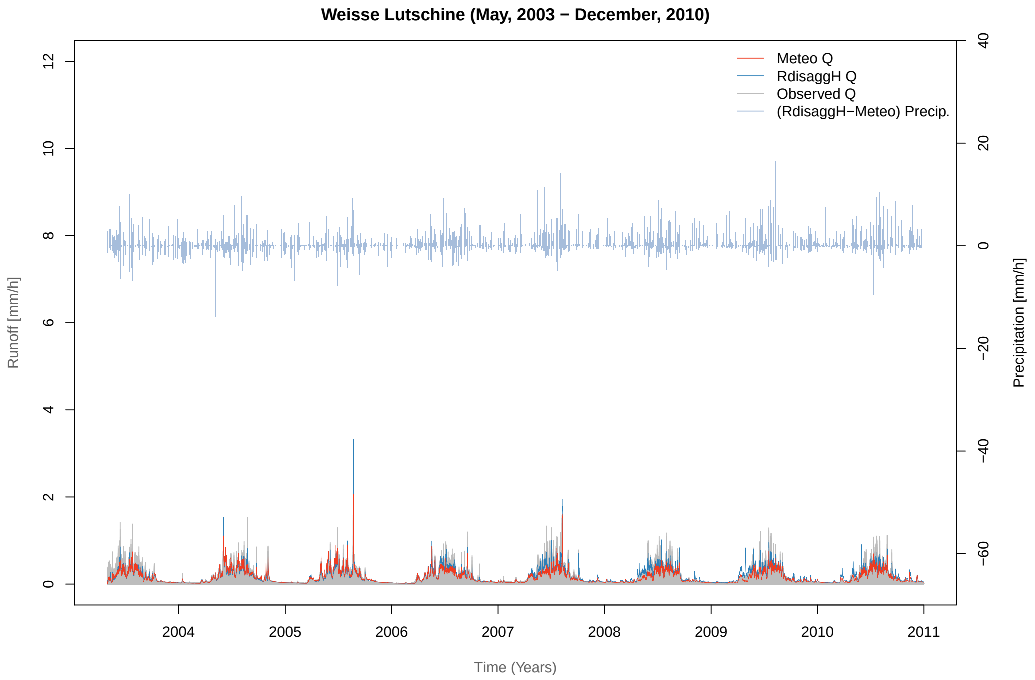


FIGURE 5.21: Weisse Lutschine: Full simulation plot for time period May 2003 - December 2010

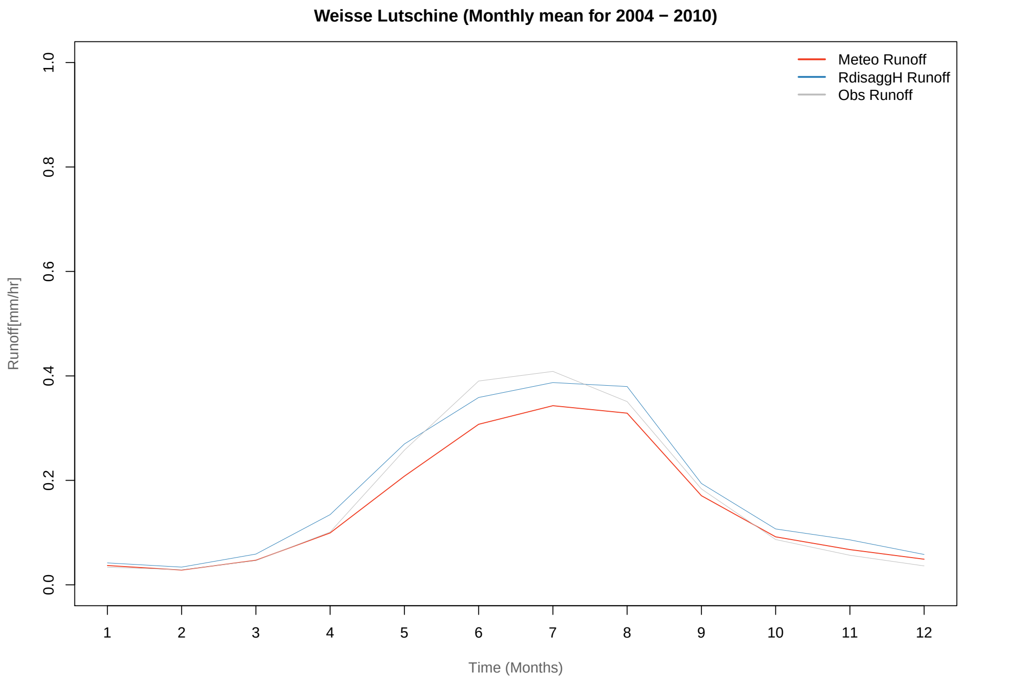


FIGURE 5.22: Weisse Lutschine: Long term monthly mean comparison of observed runoff with Meteo and RdisaggH simulated runoffs for 2004 - 2010

of August with $r^2 = 0.77$ and $NSE = 0.03$ as it captures some peak events better than the Meteo simulated runoff with $r^2 = 0.59$ and $NSE = -0.39$ which is also shown in figure 5.23. Both r^2 and NSE values are provided in table 5.15.

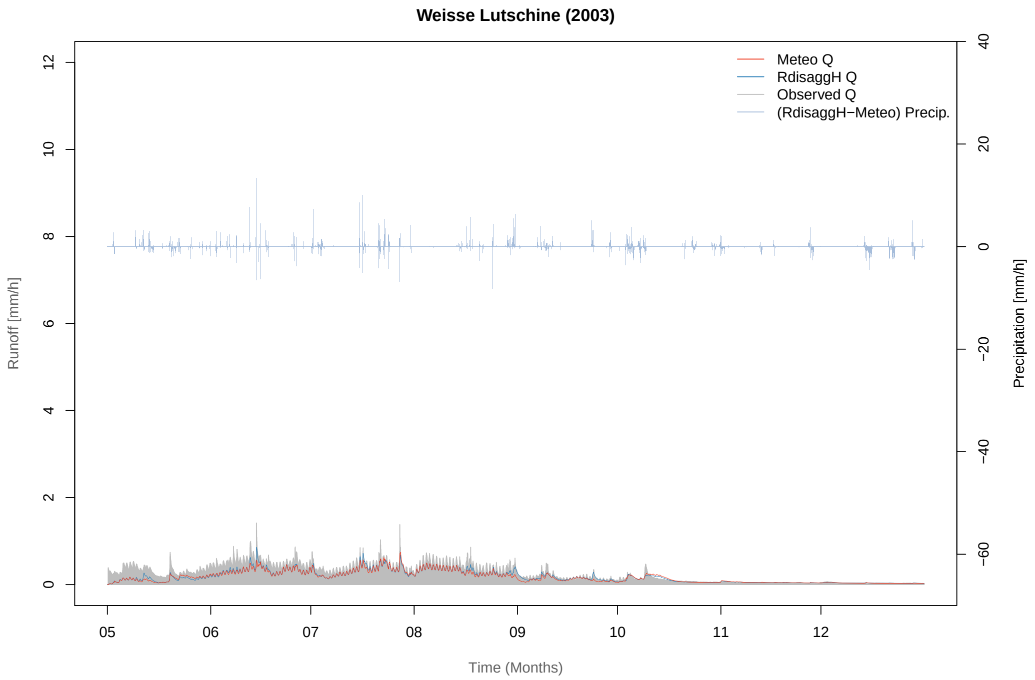


Figure 5.23: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2003, Weisse Lutschine

5.3.3.2 Case study: 2005

For 2005, the RdisaggH simulated runoff gives the highest $r^2 = 0.9$ and $NSE = 0.85$ while that of Meteo simulated runoff gives $r^2 = 0.88$ and $NSE = 0.88$. These values are higher for both r^2 and NSE when compared to the values for the entire time series period as shown in table 5.15. During JJA, $r^2 = 0.9$ and $NSE = 0.64$, and in August $r^2 = 0.93$ and $NSE = 0.63$ for RdisaggH simulated runoff. Similarly, for Meteo simulated runoff during JJA, $r^2 = 0.75$ and $NSE = 0.74$ and in August $r^2 = 0.81$ and $NSE = 0.81$ respectively. Here, both simulated runoffs capture the historic flood event of 21^{st} and 22^{nd} August very well. However the RdisaggH simulate runoff might seem to have slightly overestimated the flood event but it captures the recession better than the Meteo simulated runoff. This is illustrated in figure 5.24 and can also be inferred from figure A.10. According to table 5.14, both the Meteo and RdisaggH datasets seem to get a little higher annual runoff aggregates when compared to the observed total in 2005. However, in the summer season (JJA), the runoff aggregates are almost the same as the observed runoff sum.

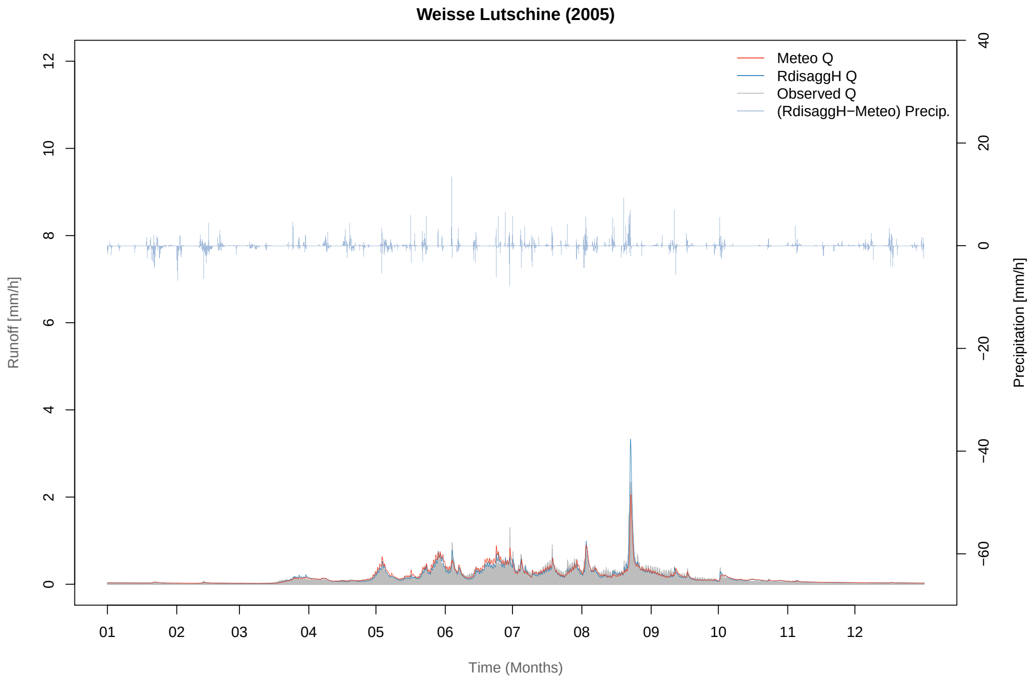


FIGURE 5.24: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2005, Weisse Lutschine

5.3.3.3 Case study: 2007

For 2007, the RdisaggH simulated runoff gives $r^2 = 0.84$ and $NSE = 0.84$ while for JJA, it gives $r^2 = 0.57$ and $NSE = 0.29$. For August, it gives $r^2 = 0.66$ and $NSE = 0.02$. Similarly, the Meteo simulated runoff gives $r^2 = 0.75$ and $NSE = 0.68$ for 2007, $r^2 = 0.35$ and $NSE = -0.38$ for JJA, and finally $r^2 = 0.53$ and $NSE = 0.13$ for August. The weak r^2 and NSE for Meteo dataset for JJA could be due to its gross underestimation of diurnal cycle in June. The Meteo dataset also shows a small precipitation total of $620.08mm$ for summer season as opposed to $952.99mm$ for RdisaggH dataset presented in table 5.5 and illustrated in figure 5.25 which then leads to underestimation of peak runoff. This can be further explained from table 5.14 where the runoff sums for summer season of 2007 is $714mm, 895mmand985mm$ for Meteo, RdisaggH and observed runoffs. So, the runoff from Meteo dataset is missing 27.5% of water from the observed total in the summer season of 2007. The annual sum of 2007 shows that the Meteo runoff sum is 24.8% short of the observed runoff. It should be noted here that all runoff sums in this catchment takes into account of the glacier melt as well. The hydrological regime of this catchment is well represented in figure A.12.

The Meteo simulated runoff also captures the magnitude of the peak flood event of 8^{th} and 9^{th} of August fairly well albeit with overestimated recession time whereas RdisaggH simulated runoff completely overestimate the peak as well as its recession time interval. This could be the reason for slightly better NSE value of Meteo simulated runoff for the August time period.

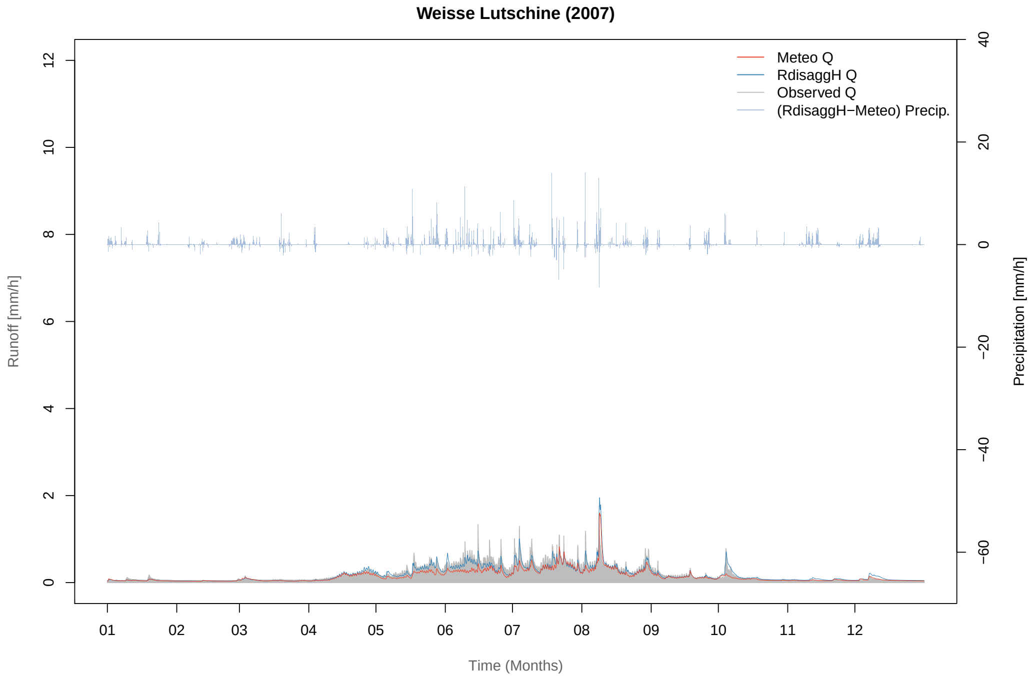


FIGURE 5.25: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2007, Weisse Lutschine

5.3.4 Goldach

Table 5.8 shows that in Goldach catchment, the simulated runoff from the Meteo precipitation input dataset gives the lowest NSE of 0.06 with linear score 0 while the simulated runoff for the RdisaggH precipitation dataset give NSE 0.34 with linear score 0.14 respectively. For the RdisaggH precipitation dataset, this NSE with linear score value obtain in Goldach is the second lowest in comparison to the other five catchments. If one looks into the total runoff sum from both the datasets and compares them with the observed runoff total from 2003 to 2010 as shown in table 5.9, the runoff totals for simulated Meteo and RdisaggH, and observed are $4289mm, 5737mmand6282mm$ respectively. Here, the Meteo runoff sum is short by 31.7% to the observed runoff sum while RdisaggH runoff sum is short by only 8.6%. This could also explain the poor NSE of Meteo simulated runoff.

The r^2 as well as NSE between the two simulated runoffs with the observed runoff is shown in table 5.17 for the Goldach catchment. For the entire time series period, the r^2 of the Meteo simulated runoff and the RdisaggH simulated output runoff against the observed runoff are $r^2 = 0.17$ and $r^2 = 0.43$. The relatively better performance of RdisaggH simulated runoff is probably because it captures the peak events from 2006 to 2010 to some extent unlike the Meteo simulated runoff. Meteo simulated runoff misses some really high peak events of 2006, 2007, 2009 and 2010. This is illustrated in figure 5.26. Figure 5.27 shows monthly mean of RdisaggH simulated runoff for 2004 to 2010 compared to the same of Meteo simulated runoff and observed runoff. Here the RdisaggH monthly mean shows overestimation for spring season while fitting closely with the observed monthly mean during much of the summer and autumn period.

5.3.4.1 Case study: 2003

Although the r^2 and NSE for 2003 to 2010 in both datasets came out to be extremely poor, it is not the same for the year 2003. According to table 5.17, both the Meteo and the RdisaggH simulated runoffs show extremely good correlation with $r^2 = 0.77$ and $NSE = 0.72$ and $r^2 = 0.71$ and $NSE = 0.71$ respectively for 2003. However r^2 and NSE values get worse for summer season (JJA) and also for August for both simulated runoffs. The r^2 and NSE are worse for the RdisaggH simulated runoff with $r^2 = 0.27$ and $NSE = 0.2$ for JJA and $r^2 = 0.01$ and $NSE = -0.007$ for August. For Meteo simulated runoff $r^2 = 0.45$ and $NSE = 0.32$ for JJA and $r^2 = 0.48$ and $NSE = -0.77$ for August.

As illustrated in figure 5.28, both the simulated runoffs fails to capture the low intensity peak flows in August. The relatively better although still worse NSE score for RdisaggH

	Q Total [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	337	NA	48	78	205
RdisaggH	243	NA	37	48	153
Observed	255	NA	39	50	159
2005					
Meteo	914	156	331	290	136
RdisaggH	681	117	232	235	96
Observed	692	137	253	200	102
2007					
Meteo	381	73	109	126	72
RdisaggH	638	99	234	159	145
Observed	616	116	143	144	213

TABLE 5.16: Goldach: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Time Period		**Goldach**			
		Meteo Q Vs. Obs Q		**RdisaggH Q Vs. Obs Q**	
		r^2	*NSE*	r^2	*NSE*
2003-2010		0.17	0.09	0.43	0.36
2003	*Jan-Dec*	0.77	0.72	0.71	0.71
	JJA	0.45	0.32	0.27	0.2
	August	0.48	-0.77	0.01	-0.007
2005	*Jan-Dec*	0.73	0.68	0.61	0.59
	JJA	0.73	0.7	0.62	0.6
	August	0.72	0.69	0.59	0.57
2007	*Jan-Dec*	0.01	-0.1	0.29	0.23
	JJA	0.02	-0.01	0.66	0.66
	August	0.23	0.01	0.67	0.66

TABLE 5.17: The coefficient of determination (r^2) values between observed runoff and simulated runoffs from both Meteo and RdisaggH precipitation datasets for Goldach

simulated runoff is due to the fact that even though it doesn't capture the low intensity peak flows, it captures the rest of the flow sequence while Meteo simulated runoff misses the low intensity peak flows and yet at the same time consistently overestimate the rest of the flow sequence. This is why in 2003, there is higher runoff total of $337mm$ for Meteo simulated runoff whereas observed runoff total is only $255mm$ as shown in table 5.16.

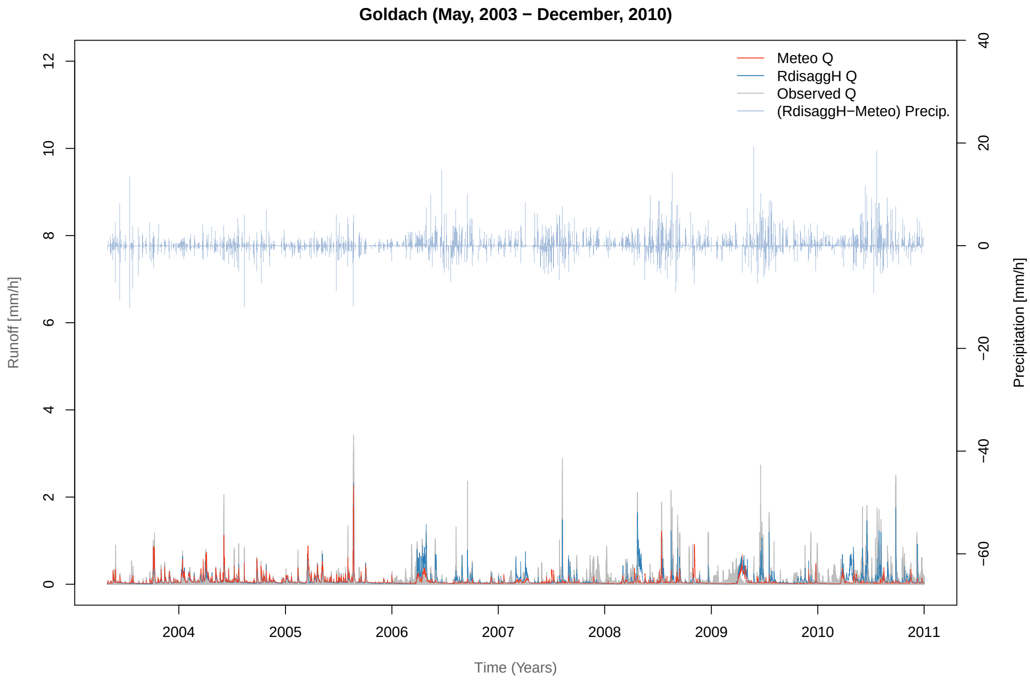


FIGURE 5.26: Goldach: Full simulation plot for time period May 2003 - December 2010

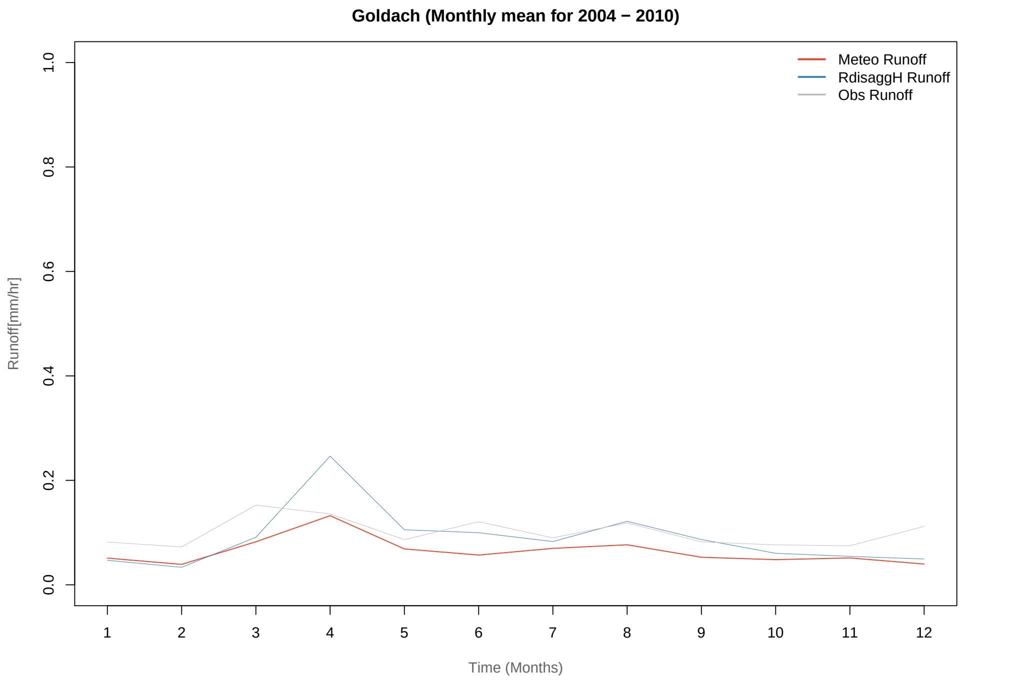


FIGURE 5.27: Goldach: Long term monthly mean comparison of observed runoff with Meteo and RdisaggH simulated runoffs for 2004 - 2010

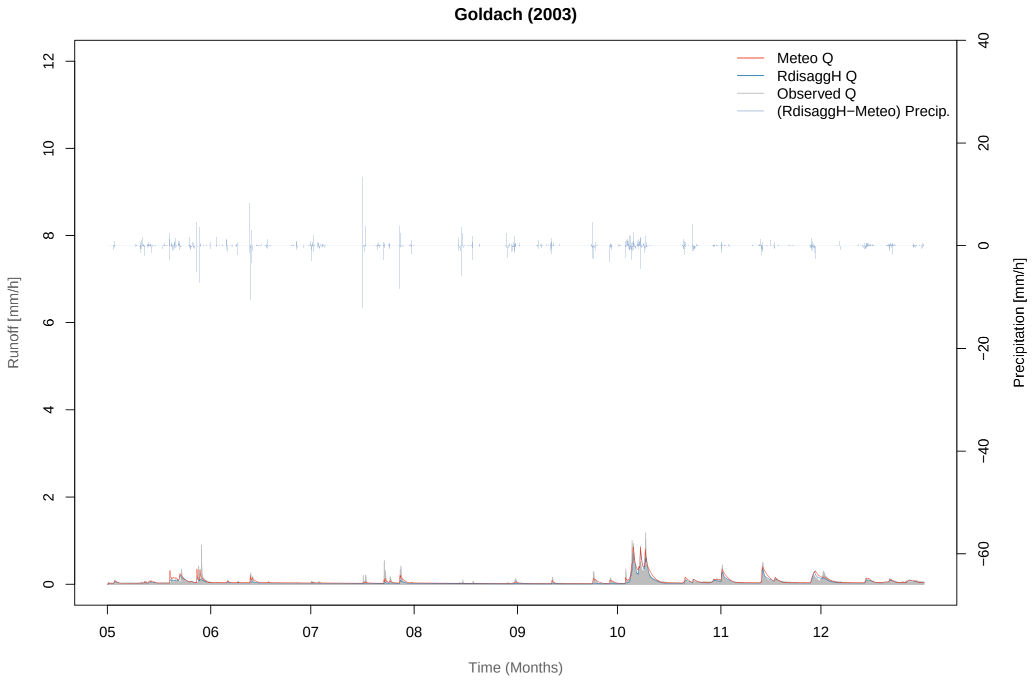


FIGURE 5.28: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2003, Goldach

5.3.4.2 Case study: 2005

Again, for 2005, the Meteo and RdisaggH simulated runoffs are relatively good. For 2005, the $r^2 = 0.73$ and $NSE = 0.68$ for Meteo simulated runoff and $r^2 = 0.61$ and $NSE = 0.59$ for RdisaggH simulated runoff when compared against the observed runoff. For summer season (JJA), the Meteo simulated runoff, $r^2 = 0.73$ and $NSE = 0.7$ and for August $r^2 = 0.72$ and $NSE = 0.69$. Likewise, for JJA, the RdisaggH simulated runoff $r^2 = 0.62$ and $NSE = 0.6$ and for August, $r^2 = 0.59$ and $NSE = 0.57$. Figure 5.29 shows the Meteo simulated runoff captures the magnitude of the peak events in 2005 very well. Thus Meteo simulated runoff has higher NSE for JJA and August than the RdisaggH simulated runoff. However, table 5.16 suggests that the simulated runoff sums of Meteo and RdisaggH datasets, and that of observed runoff sum are $914mm, 681mmand692mm$ respectively. So, based on this table and the figure 5.29, it may be implied there may be significantly small but consistent over-estimation is the Meteo simulated runoff. This can be again seen in figure 5.29 that while Meteo simulated runoff captures the magnitude of the peak flow events very well, it also over estimates the recession by considerable time length. In addition, figure A.14 show how well both the simulated runoffs capture the hydrological regime of the catchment for 2005. Both Meteo and RdisaggH simulated runoff remain the same as observed runoff for the rest of the low flow sequence.

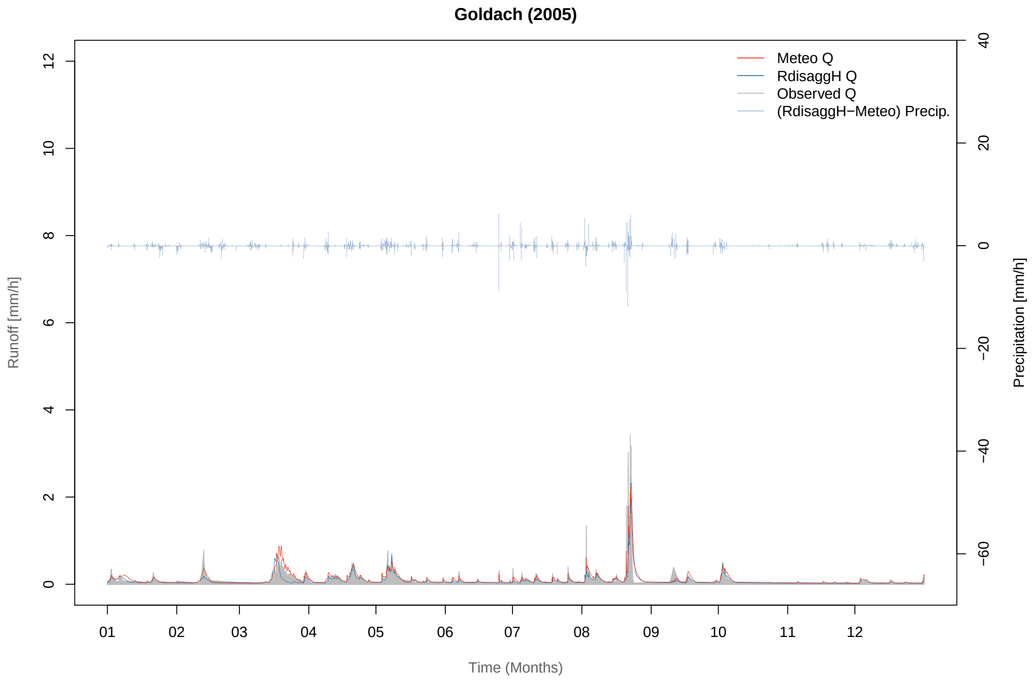


FIGURE 5.29: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2005, Goldach

5.3.4.3 Case study: 2007

For 2007, based on table 5.17 the Meteo simulated runoff shows the poorest r^2 and NSE values specially when compared to that of 2005. For Meteo simulate runoff, the $r^2 = 0.01$ and $NSE = -0.1$ as it is not able to capture most of the peak events as illustrated in figure 5.30. The $r^2 = 0.29$ and $NSE = 0.23$ for the RdisaggH simulated runoff. While the r^2 and NSE for the Meteo simulated runoff does not show any improvement for JJA, there seem to be a considerable boost in r^2 and NSE for the RdisaggH simulated runoff with $r^2 = 0.66$ and $NSE = 0.66$. For August, $r^2 = 0.67$ and $NSE = 0.66$ for RdisaggH simulated runoff while $r^2 = 0.23$ and $NSE = 0.01$ for Meteo simulated runoff. This exceptional performance of RdisaggH simulated runoff is because it captures the peak flood events of JJA and particularly of 8^{th} and 9^{th} August very well where as Meteo simulated runoff completely misses this event Again, the monthly mean plot shown in figure A.16 also illustrates a good fit between RdisaggH simulated runoff and the observed runoff.

5.3.5 Emme

Finally, according to table 5.8, the simulated runoff from the Meteo precipitation input dataset give NSE 0.5 with linear score of 0.35 for Emme catchment. The simulated

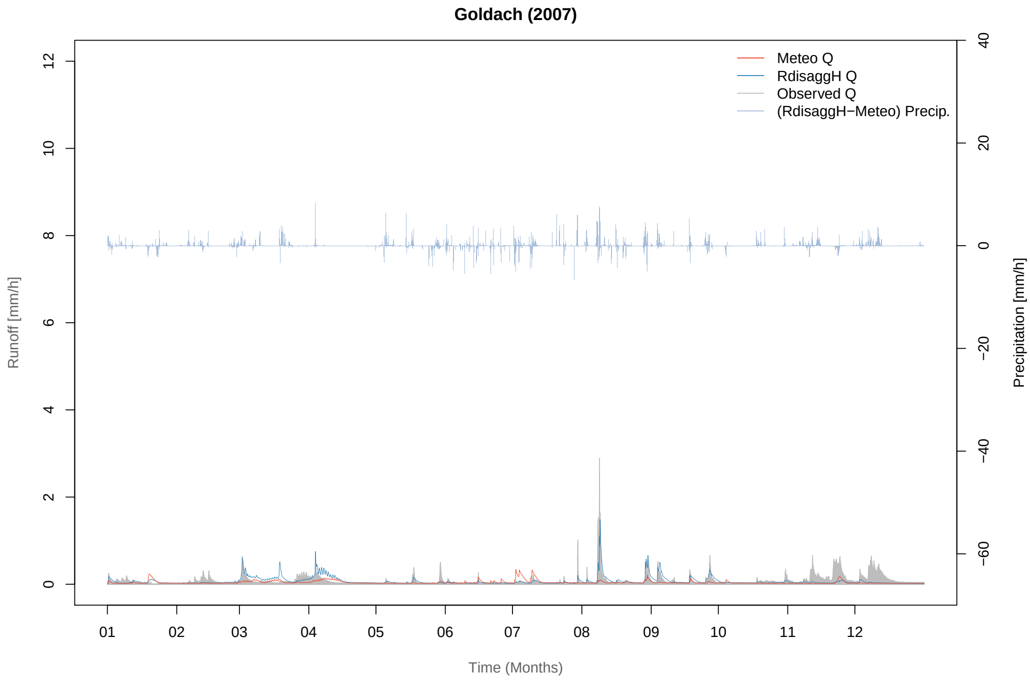


FIGURE 5.30: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2007, Goldach

runoff for the RdisaggH precipitation input dataset give $NSE = 0.71$ with linear score 0.66 respectively. Based on the NSE and linear score values obtained for Emme, one can say that the RdisaggH precipitation input dataset performs better in comparison to the Meteo precipitation input data.

Table 5.19 shows the r^2 and again NSE values of two simulated runoffs for the Emme catchment. For the entire time series period of 2003 to 2010, $r^2 = 0.52$ and $r^2 = 0.7$. The performance of RdisaggH simulated runoff exceeds that of Meteo simulated runoff as the former simulation captures the peak events from 2007 to 2010 shown in figure 5.31. Table 5.18 shows more or less similar runoff total with difference less than 10% for all three years thus giving some clue for the moderate or good r^2 and NSE values.

5.3.5.1 Case study: 2003

For 2003, based on table 5.19, both the Meteo and the RdisaggH simulated runoffs show moderately weak correlation with $r^2 = 0.47$; $NSE = 0.47$ and $r^2 = 0.51$; $NSE = 0.51$ respectively. However r^2 values remain more or less the same for JJA but improves extremely well for August for both simulation runs. In August, $r^2 = 0.81$ for Meteo simulated runoff and $r^2 = 0.78$ for RdisaggH simulated runoff. On the other hand NSE

	Q Total [mm]	Q Winter (Dec-Feb) [mm]	Q Spring (Mar-May) [mm]	Q Summer (Jun-Aug) [mm]	Q Autumn (Sept-Nov) [mm]
2003 (May-Nov)					
Meteo	397	NA	65	111	219
RdisaggH	386	NA	60	124	200
Observed	393	NA	99	130	160
2005					
Meteo	1125	74	567	357	127
RdisaggH	1023	75	435	374	140
Observed	988	83	434	373	98
2007					
Meteo	917	162	273	404	77
RdisaggH	1235	188	379	530	137
Observed	1173	165	353	547	108

TABLE 5.18: Emme: Runoff sums for observed, Meteo and RdisaggH datasets along with seasonal sums for the years 2003, 2005 and 2007

Time Period		Emme			
		Meteo Q Vs. Obs Q		**RdisaggH Q Vs. Obs Q**	
		r^2	*NSE*	r^2	*NSE*
2003-2010		0.52	0.5	0.70	0.7
2003	*Jan-Dec*	0.47	0.47	0.51	0.51
	JJA	0.43	0.32	0.51	0.39
	August	0.81	0.64	0.78	0.57
2005	*Jan-Dec*	0.78	0.78	0.82	0.82
	JJA	0.84	0.83	0.86	0.85
	August	0.84	0.84	0.86	0.86
2007	*Jan-Dec*	0.58	0.52	0.68	0.67
	JJA	0.56	0.5	0.65	0.64
	August	0.74	0.71	0.65	0.64

TABLE 5.19: The coefficient of determination (r^2) values between observed runoff and simulated runoffs from both Meteo and RdisaggH precipitation datasets for Emme

decreases moderately to $NSE = 0.32$ abd $NSE = 0.39$ for JJA and then increases to $NSE = 0.64$ and $NSE = 0.57$ for August.

The significantly high value in August especially for r^2 and also for NSE might be because 2003 was a year of dry spell with extremely low flow in August except with a small peak event on 31^{st} of August. This were fairly well captured by both the simulated runoffs as illustrated in figure 5.33 thus resulting in high r^2. Hence the high values.

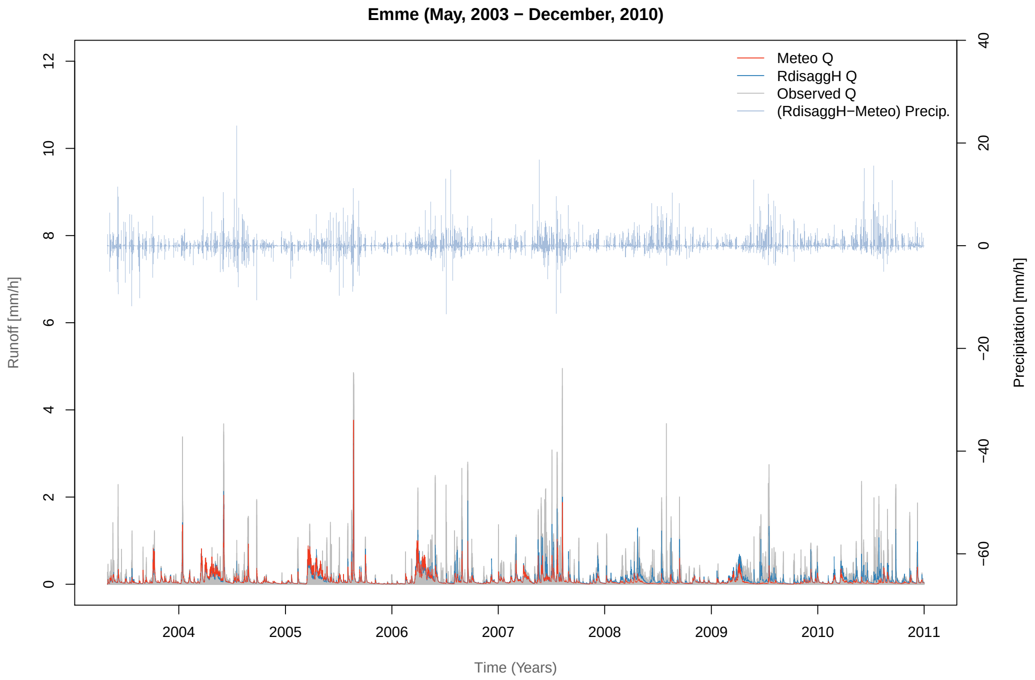


FIGURE 5.31: Emme: Full simulation plot for time period May 2003 - December 2010

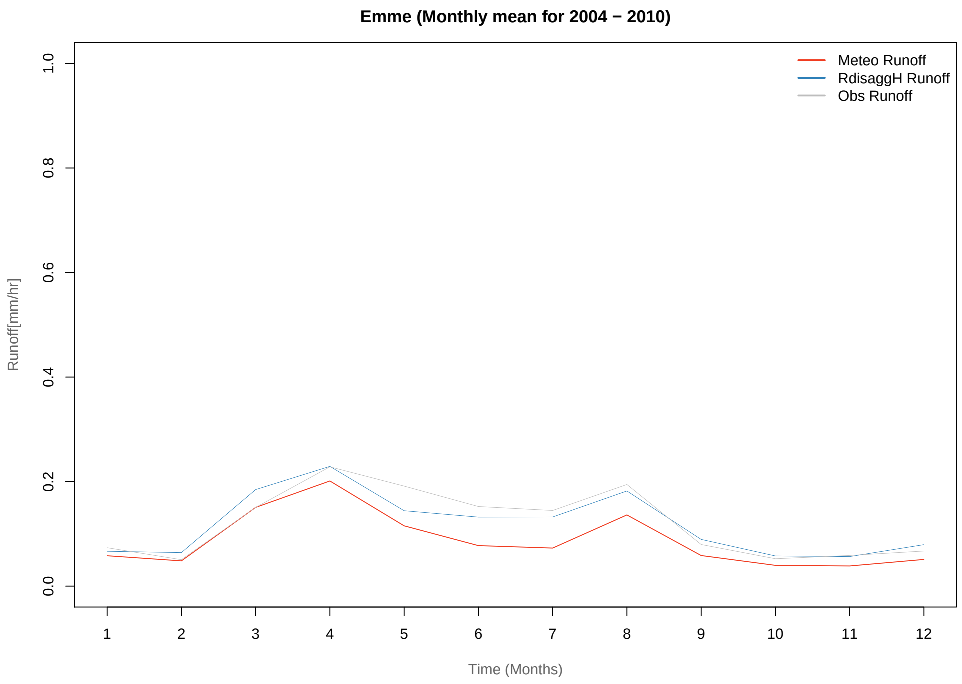


FIGURE 5.32: Emme: Long term monthly mean comparison of observed runoff with Meteo and RdisaggH simulated runoffs for 2004 - 2010

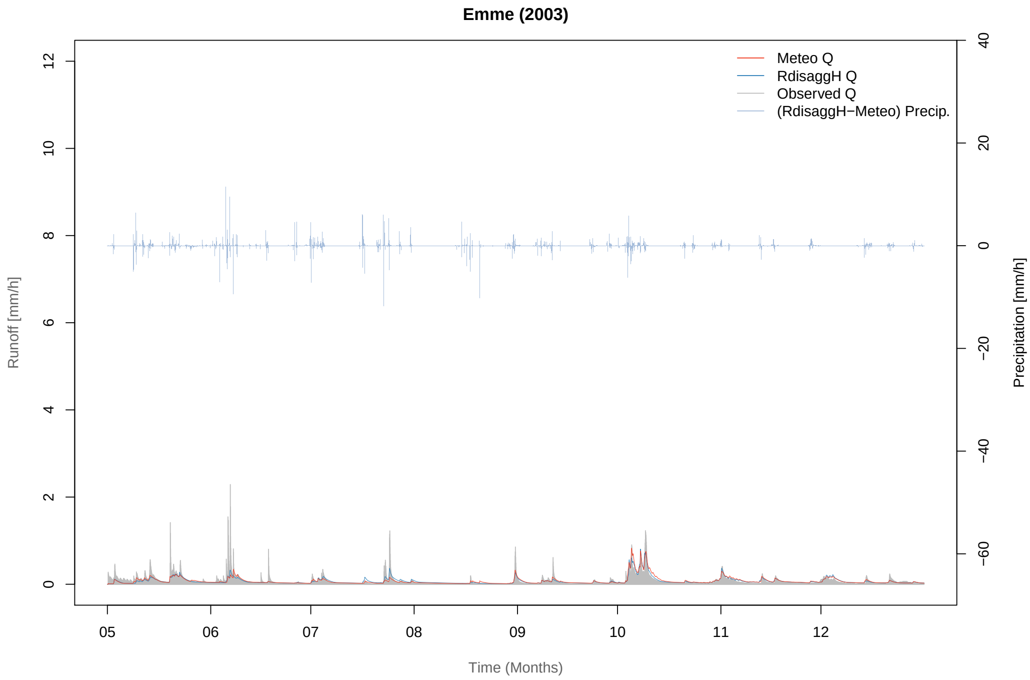


FIGURE 5.33: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2003, Emme

5.3.5.2 Case study: 2005

Table 5.19 shows that the Meteo and RdisaggH simulated runoffs produce extremely good results with $r^2 = 0.78$; $NSE = 0.78$ and $r^2 = 0.82$; $NSE = 0.82$ respectively. Similarly for JJA, the Meteo simulated runoff gives $r^2 = 0.84$; $NSE = 0.83$ while the RdisaggH simulated runoff gives $r^2 = 0.86$; $NSE = 0.85$. Again, for August, the Meteo simulated runoff gives $r^2 = 0.84$; $NSE = 0.84$ while the RdisaggH simulate runoff gives $r^2 = 0.86$; $NSE = 0.86$. These high r^2 and NSE values of 2005 show that both the Meteo and RdisaggH simulated runoffs reproduce the peak flood events and their respective recessions very well. This is particularly true if one looks at the historic flood events of 21^{st} and 22^{nd} August. This is also inferred from figure 5.34 and its monthly mean plot figure A.18. A close inspection also show RdisaggH simulated runoff reproducing the diurnal cycle of snow melt very well during late March and early April. However, it goes on to underestimate the diurnal variation of snow melt in the later half of April and early May while Meteo simulated runoff produces a better results for the same period of time.

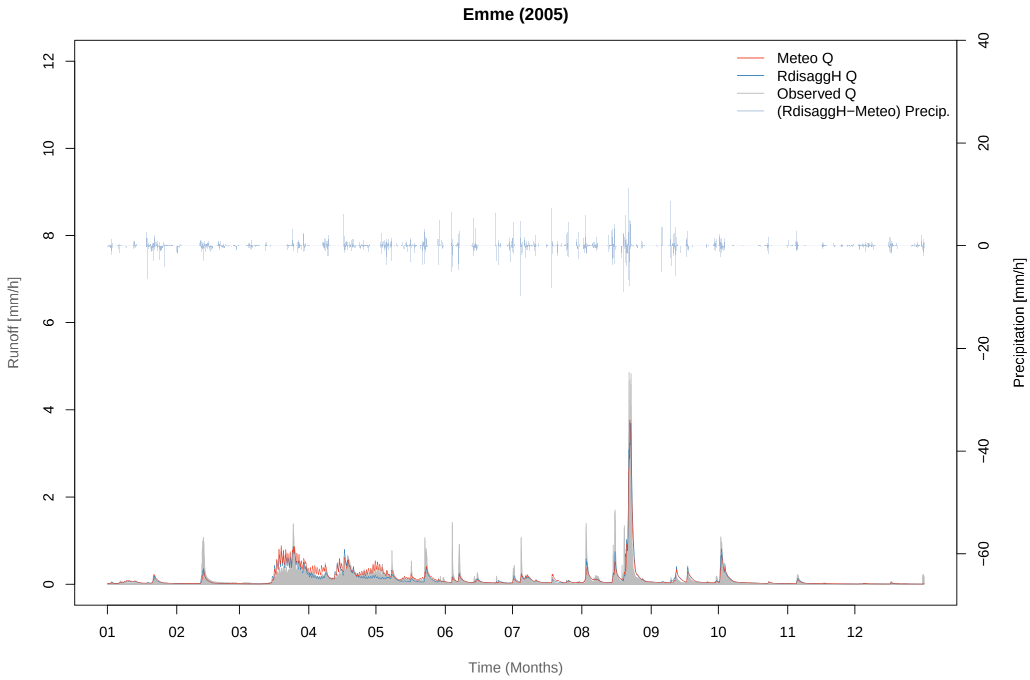


FIGURE 5.34: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2005, Emme

5.3.5.3 Case study: 2007

For 2007, the Meteo simulated runoff shows a moderate score of $r^2 = 0.58$; $NSE = 0.52$. The RdisaggH simulated runoff shows $r^2 = 0.68$; $NSE = 0.67$. The r^2 and NSE for both the Meteo and RdisaggH simulated runoffs with the observed runoff do not show any improvement for JJA, and August. Although the r^2 and NSE for the Meteo simulated runoff increases to 0.74 and 0.71 respectively for August. For RdisaggH simulated runoff, $r^2 = 0.65$; $NSE = 0.64$ for August as well as for JJA as shown in table 5.19. Figure 5.35 shows that both these data captures the flood events of August very well, particularly the severe flooding of 9^{th} and 10^{th} August. Figure A.20 shows the hydrological regime of the catchment for 2007 and how the two simulated datasets compared.

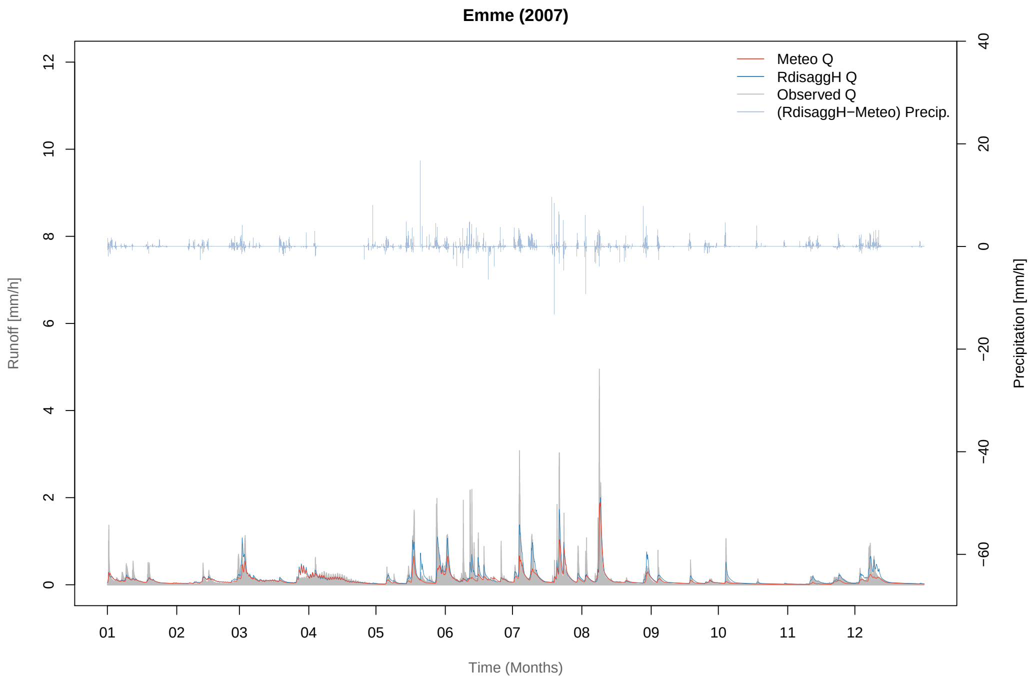


FIGURE 5.35: A hydrograph comparing simulated runoffs for RdisaggH and Meteo precipitation datasets with observed runoff for 2007, Emme

Chapter 6

Discussions

6.1 Comparison of precipitation datasets

A simple comparison of the precipitation sums between the Meteo and RdisaggH precipitation datasets based on table B.2 and table B.3 show higher precipitation aggregates for RdisaggH dataset in all the catchments except Mentue for time periods: 2003 (excluding Goldach), 2005 (excluding Goldach), 2007 and 2003 - 2010. These tables are just the summary of all the tables already presented in Chapter 5.

For all the catchments and for all time period of evaluation, the difference in precipitation sums between the two datasets are the highest either in spring or summer season. RdisaggH precipitation sums are found to be higher in all catchments particularly during these seasons except for Mentue (all time period) and Goldach (2003 and 2005). Both these catchments lie at a low elevation of mean 589$m.a.s.l.$ and 616$m.a.s.l.$ respectively.

Although Mentue is relative large in area (105km^2), it has the lowest mean elevation of 589 $m.a.s.l.$ with relatively dry spring and summer as shown in table 2.1. Such hydrological regime naturally leads to low precipitation totals. In fact table 5.1 shows that Mentue has the best RMSD score among all the other catchments for time periods: 2003, 2005, 2007 and 2003 - 2010. However this could also be the case simply because as this catchment is naturally dry in spring and summer, and the frequency of precipitation events are far too less and low, the magnitude of their difference would be very far too small to yield lowest r^2 value.

Table 5.1 shows that for time period: 2003 - 2010, Allenbach followed by Goldach and Mentue have the lowest r^2 between the Meteo and RdisaggH precipitation datasets. RMSD values given in table 5.1 also shows the highest value suggesting the worst match for Allenbach but Mentue actually gives the best RMSD score (lowest value) between the two precipitation datasets.

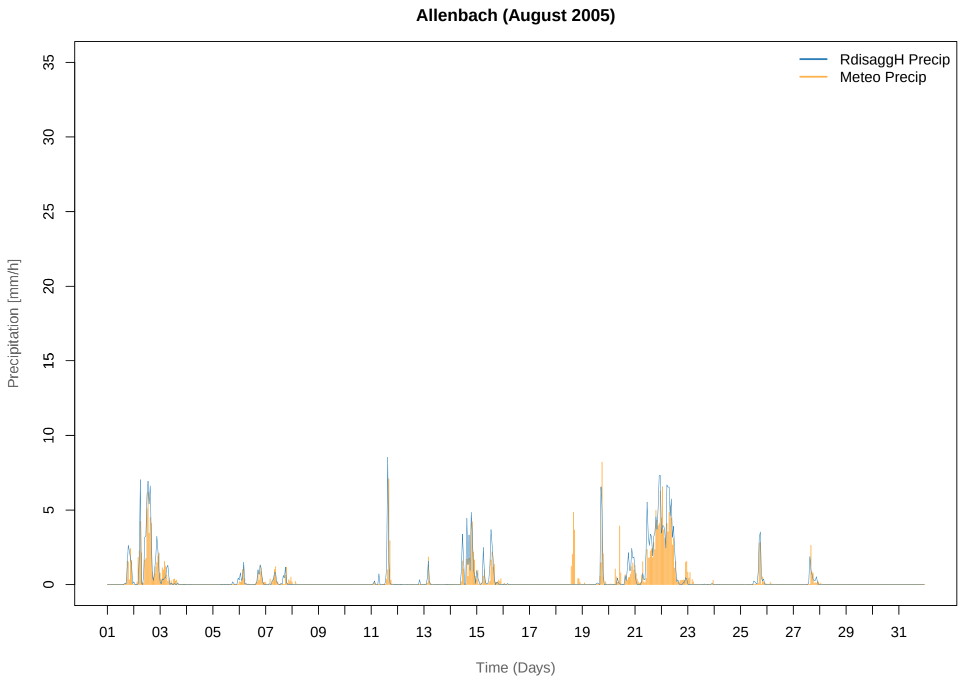


Figure 6.1: Allenbach: Precipitation August 2005

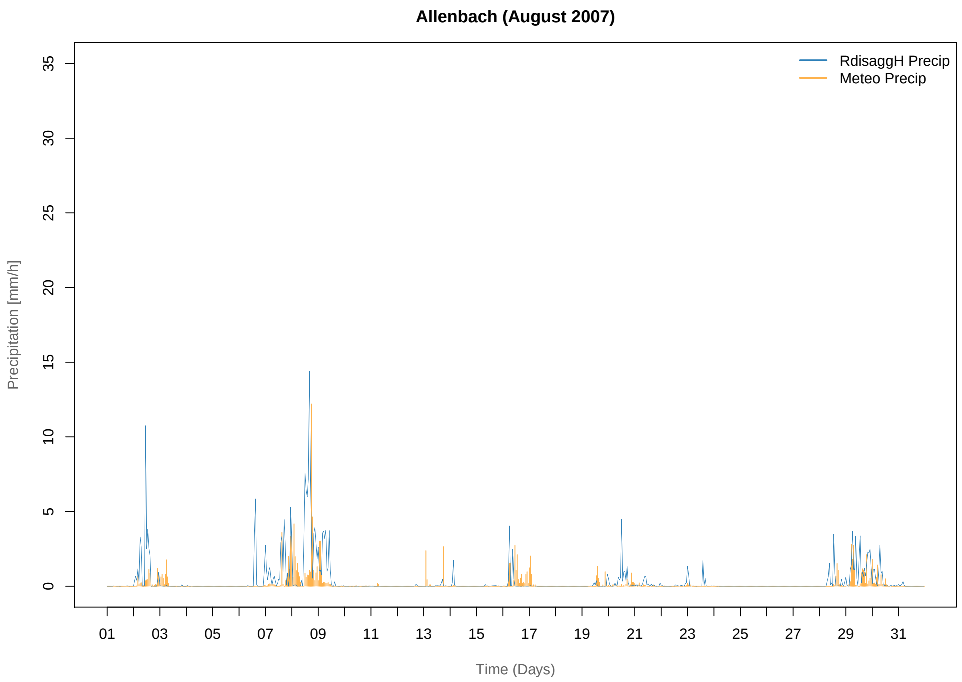


Figure 6.2: Allenbach: Precipitation August 2007

The evaluation of RMSD shows that Allenbach followed by Weisse Lutschine and Goldach show the highest values thus suggesting the worst fit. So, for time period: 2003 - 2010, Allenbach gives the worst fit between the two datasets while Mentue shows the best fit based on RMSD evaluation and Emme if r^2 evaluation is considered.

If long term monthly mean precipitation for time period 2004 - 2010 are to be compared for Allenbach (figure 5.1), Mentue (figure 5.2), Weisse Lutschine (figure 5.3), Goldach (figure 5.4) and Emme (figure 5.5), the largest discrepancies between the Meteo and RdisaggH precipitation datasets are seen in plots for Allenbach followed by Weisse Lutschine while Mentue shows the minimum discrepancy. In figure 5.1, the Meteo precipitation dataset seem to miss out a seasonal event in spring which is captured by the RdisaggH precipitation dataset and this may perhaps be the reason for its worst RMSD and lowest r^2 [Juarez et al., 2008].

For time period: 2003 - 2010, Weisse Lutschine and Emme have relatively higher correlation of good fit but the RMSD values suggest the opposite particularly for Weisse Lutschine. One reason for this could be that both the precipitation datasets in these two catchments captures the seasonal cycle very well but there are also large discrepancies between the two datasets with RdisaggH dataset clearly overestimating the other particularly in spring and summer seasons. This is also clearly evident from figure 5.3 and figure 5.5. So in case of Weisse Lutschine, it would be misleading to assume a high goodness of fit between two datasets based on r^2 value. So for the purpose of the intercomparison between these two precipitation datasets, the RMSD based evaluation seem more sound than the r^2.

Generally, the low r^2 value or large RMSD value suggest large discrepancies among the two datasets at each hourly time step. However, it would be erroneous to draw conclusions for the catchments based on these results because the same evaluation methods but just for 2003, 2005 or 2007 or simply summer season or month of August time period would give different statistical values, as it is evident from table 5.1.

For example, in Allenbach, for 2003: $r^2 = 0.54$ and $RMSD = 0.53$, for 2005: $r^2 = 0.6$ and $RMSD = 0.39$ but then for 2007: $r^2 = 0.09$ and $RMSD = 0.75$. So, while the two datasets matches the best in 2005 as also illustrated from figure A.1, they also show worst correlation in 2007 as shown in figure A.3.

Similarly, in Weisse Lutschine which is a glaciated catchment, for 2003: $r^2 = 0.33$ and $RMSD = 0.63$, for 2005: $r^2 = 0.36$ and $RMSD = 0.62$ but for 2007: $r^2 = 0.44$ and $RMSD = 0.68$. Here, while the r^2 shows gradual increase in goodness of fit, RMSD paints the opposite picture. On comparing figure A.9 and figure A.11, the RMSD results look more plausible.

Both Allenbach and Weisse Lutschine are mountainous catchments situated in the Bernese Alps. It is interesting to note that both precipitation datasets show bad RMSD values for time period: 2003 - 2010. However their RMSD improves quite significantly for 2003 and 2005 and then deteriorates to worse value for 2007. While RdisaggH dataset has some inherent inaccuracy issues particularly in high mountainous regions caused by the topographic shielding of radar beans by the mountains[MeteoSwiss and Frei, 2013], and which could explain the poor RMSD for 2003-2010 and 2007 time period, the improved values in 2003 and 2005 are then difficult to interpret. RdisaggH dataset also has other inherent issues such as having an overall small positive bias with a systematic underestimation of high precipitation intensities and an overestimation of low intensities [MeteoSwiss and Frei, 2013] [Girons Lopez et al., 2015].

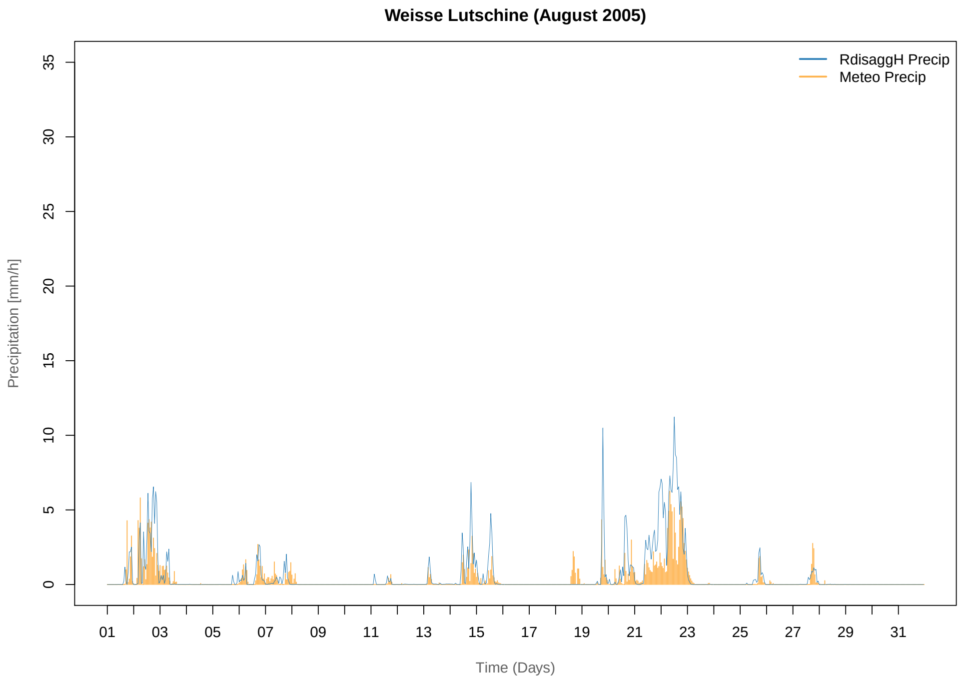


FIGURE 6.3: Weisse Lutschine: Precipitation August 2005

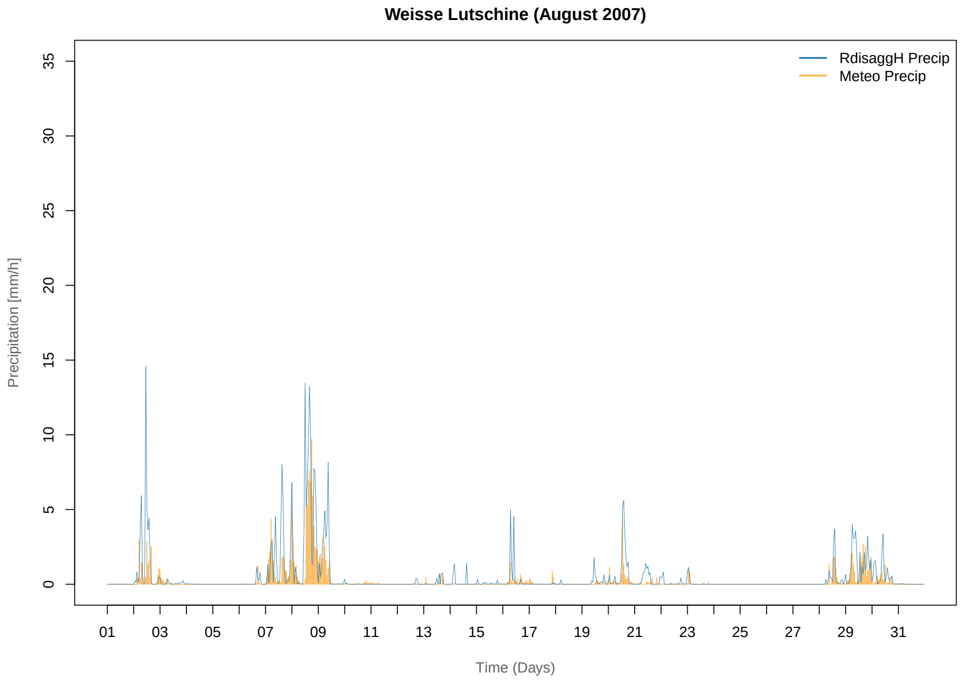


FIGURE 6.4: Weisse Lutschine: Precipitation August 2007

While both 2005 and 2007 had severe flood events, the values remained more or less the same for their summer period. So why are the two datasets correlating so well for 2005 while not for 2007 when both years had similar high precipitation events? This maybe due to an error in spatial precipitation estimation from rain gauge measurement such as errors in measurements themselves or an error in estimation of the spatial and temporal precipitation variability[McMillan et al., 2012]. Here, the rain gauge density and the elevation of their locations in relation to the size of the catchments may also be an issue. The minimum density of rain gauges required for mountainous catchment is four stations per $1000km^2$ [WMO 2008]. Allenbach has one manual precipitation station at an elevation of $1467m.a.s.l.$ which should suffice the WMO standard. Similarly, Weisse Lutschine also has two manual precipitation stations at elevations: $1645m.a.s.l.$ and $2061m.a.s.l.$ [MeteoSwiss, 2015]. A further analysis on assessing the processes of the preparing these gridded dataset may thus be required which unfortunately is beyond the scope this thesis.

Mentue has relatively the best RMSD value and moderate r^2 for time period: 2003 - 2010. However on further assessment for 2003: $r^2 = 0.58$ and $RMSD = 0.3$, for 2005: $r^2 = 0.51$ and $RMSD = 0.31$ but for 2007: $r^2 = 0.28$ and $RMSD = 0.52$. Both precipitation datasets correlate very well for dry period of 2003 and then also for 2005 as shown in figure A.5 but deteriorated in 2007 as illustrated in figure A.7. In comparison between the years 2003, 2005 and 2007, the year 2007 always has the worse RMSD value for all catchments except Emme.

Allenbach and Goldach are two of the smallest catchments with areas less than $50km^2$ while Mentue, Weisse Lutschine and Emme have areas greater than $100km^2$. Studies from [Wood et al., 2000] and [Goodrich et al., 1995] have shown that uncertainties related to precipitation interpolation drastically escalates with increase in the resolution of the interpolation because of the higher precipitation variability when averaging over smaller areas [Girons Lopez et al., 2015]. This seems to be the plausible explanation for poor RMSD and r^2 values for Allenbach. In addition to this, for Meteo dataset which is also interpolated from rain gauge measurement data during preprocessing of PREVAH, it seems that the rain gauge station located at $1467m.a.s.l.$ in Allenbach catchment which $389m$ below its highest point missed most of the high intensity precipitation events of both 2005 and 2007 as shown in figure 6.1 and figure 6.2 respectively. This is also the same for Weisse Lutschine as shown in figure 6.3 and figure 6.4 but not the case with Mentue as shown in figure 6.5 and figure 6.6. The discrepancies in these two datasets is probably unavailability of rain gauges in high elevations of Allenbach and also in Weisse Lutschine that Meteo dataset missed the correct estimation of spatial precipitation intensities [Girons Lopez et al., 2015]

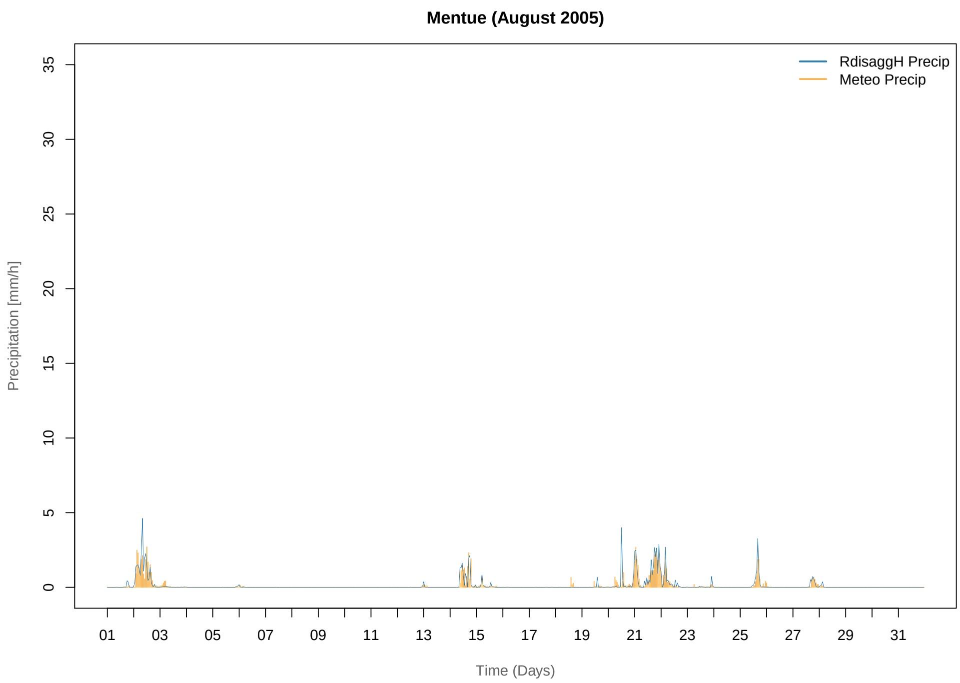


Figure 6.5: Mentue: Precipitation August 2005

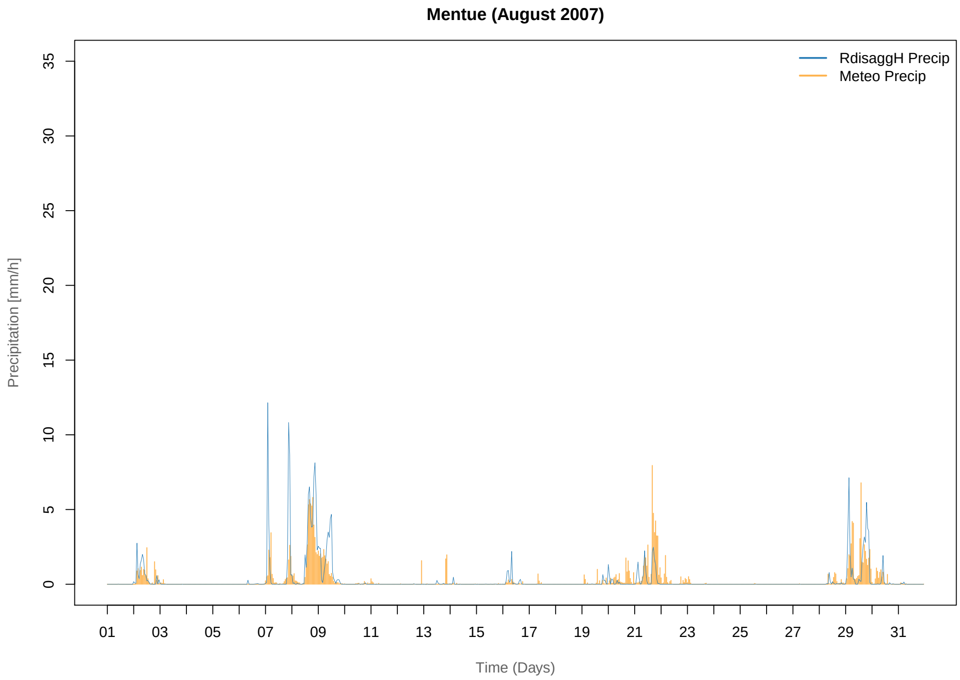


FIGURE 6.6: Mentue: Precipitation August 2007

6.2 Comparison of calibration and validation runs for Meteo and RdisaggH datasets

Table 5.8 summarizes all the NSE and linear scores during calibration and validation process of PREVAH for all five catchments.

The table 5.8 also shows that Weisse Lutschine, Emme and Mentue give the highest NSE values of 0.8, 0.71 and 0.58 respectively for Meteo precipitation dataset during their calibration run. Weisse Lutschine and Emme also give the highest NSE values of 0.76 and 0.08 during its validation run. So it can be inferred that Weisse Lutschine and Emme shows the best NSE for both calibration and validation in PREVAH model using Meteo precipitation dataset while Goldach and Allenbach perform the worst with very low NSE values.

In case of RdisaggH precipitation dataset Emme, Weisse Lutschine and Mentue give the highest NSE values of 0.77, 0.76 and 0.74 respectively during their calibration run. However in the validation run, Weisse Lutschine, Emme and Mentue give the highest NSE values of 0.81, 0.63 and 0.52. Goldach and Allenbach give the lowest NSE values.

When compared within the same dataset, Weisse Lutschine and Emme gives the best NSE for both precipitation datasets. However, when the NSE in selected catchments of these two datasets are compared against each other, the RdisaggH dataset shows a good performance with higher NSE values, particularly in the validation runs. The meteo precipitation dataset gives negative NSE values for all catchments except for Weisse Lutschine.

6.3 Evaluation of the full simulated runoffs from PREVAH with the observed runoff

The comparison of runoff sums between the Meteo and RdisaggH simulated datasets based on table 5.9 and also in table B.2, B.3 show higher runoff aggregates for RdisaggH dataset in all the catchments except Mentue for time period: 2003 - 2010. Mentue also had higher Meteo precipitation sum than RdisaggH precipitation sum. So it is only plausible for this catchment to have higher runoff sum for Meteo precipitation dataset. This suggests that there may be an overestimation in interpolation of Meteo dataset for Mentue.

The total runoff sums for time period: 2003 - 2010, for both Meteo and RdisaggH simulated runoffs fall short of the total runoff sum of the observed runoff in all the catchments except for Mentue and Weisse Lutschine as shown in table 5.9. Between the Meteo and RdisggH simulated runoffs, the RdisaggH simulated runoff estimate better total runoff sum than the Meteo simulated runoff except for Mentue. In Mentue, the Meteo simulated runoff exceeds the observed runoff by 21%. In Weisse Lutschine, the RdisaggH simulated runoff exceeds the observed runoff by merely a 1.8%.

The combined evaluation of table 5.11, 5.13, 5.15, 5.17 and 5.19 show that for time period: 2003 - 2010, Weisse Lutschine has the best coefficient of determination ($r^2 = 0.79$ and $r^2 = 0.82$), and $NSE = 0.76$ and $NSE = 0.82$ for both the simulated runoff datasets against the observed runoff dataset followed by Emme.

For Meteo simulated runoff, Goldach and Allenbach give the worst $r^2 = 0.17$ and $r^2 = 0.22$ while for RdisaggH simulated runoff, Mentue and Goldach give the worst $NSE = 0.07$ and $NSE = 0.09$ for time period: 2003 - 2010.

Within each catchment, if the two r^2 and NSE are compared, the RdisaggH simulated runoff correlates better with the observed runoff giving higher values for all five catchment for time period: 2003 - 2010. As mentioned earlier, Weisse Lutschine followed by Emme and Mentue produce the top three r^2 and NSE values for the RdisaggH simulated runoff in this time period.

Based on the r^2 and NSE, it can be said that the RdisaggH dataset gives a better results in PREVAH model for alpine catchments for the entire time period of evaluation.

6.3.1 Case study: 2003

The r^2 and NSE evaluations of all five catchments show that Weisse Lutschine has the highest values of $r^2 = 0.78; NSE = 0.57$ and $r^2 = 0.81; NSE = 0.64$ for Meteo and RdisaggH simulated runoff against the observed runoff respectively in 2003 (See figure 5.15). This is followed by Goldach (See figure 5.17) with $r^2 = 0.77; NSE = 0.72$ and $r^2 = 0.71; NSE = 0.71$, and then Emme (See figure 5.19) with $r^2 = 0.47; NSE = 0.47$ and $r^2 = 0.51; NSE = 0.51$ respectively. Allenbach has the lowest value with $r^2 = 0.02; NSE = -0.23$ for RdisaggH simulated runoff while Mentue has the lowest value with $r^2 = 0.48; NSE = -0.11$ for Meteo simulated runoff. It should be noted that NSE values are standard practice in runoff comparison and has been given preference over r^2.

2003 was a low flow period and both r^2 and NSE for RdisaggH simulated runoff decreased for all catchments except Goldach. r^2 and NSE for Meteo simulated runoff with observed runoff also decreased for all catchments except Goldach (See figure 5.17) and Mentue (See figure 5.13). Goldach shows a significant improvement of r^2 and NSE for 2003 for both simulated runoffs when both r^2 and NSE are compared with the same for time period: 2003 - 2010. On the other hand Mentue shows relatively moderate improvement in r^2 but only for the Meteo simulated runoff correlation. However, its NSE values decrease for both simulated runoff.

The r^2 and NSE for both the Meteo and RdisaggH simulated runoffs decreases for the summer season (JJA) of 2003 for all the catchments except Allenbach where they increase to $r^2 = 0.34; NSE = 0.31$ and $r^2 = 0.23; NSE = 0.18$ respectively (See figure 5.11). Allenbach is the smallest catchment of investigation in this thesis. Mentue and Goldach catchments have the lowest mean elevation of $589 m.a.s.l.$ and $616 m.a.s.l.$ respectively. Both of them show the biggest drop in r^2 and NSE during summer season of 2003. However, Allenbach still maintains the lowest NSE for both the simulated runoffs.

So overall, it may be inferred that both the Meteo and RdisaggH simulated runoffs do not capture the summer season of 2003 low flow spells for all catchments. Since both the simulated runoffs are behaving in the same way, meaning that they showed decrease r^2 and NSE values, it maybe well be an issue with PREVAH rather than the datasets. This is because the two catchments with worst drop in r^2 and NSE values are actually the low elevation catchments while the rest are high elevation catchments. Since PREVAH has been proven to do a better job in high alpine catchment which the consistent high r^2 and NSE values in Weisse Lutschine also proves, the significant drop in r^2 and NSE for Mentue and Goldach may have to do more with PREVAH rather than the datasets.

However based on just NSE evaluation, both the precipitation datasets do not yield a good simulated runoff in the dry spell summer period of 2003 in all five catchments.

6.3.2 Case study: 2005

On 21^{st} and 22^{nd} August 2005, a heavy precipitation event on the northern side of the Swiss Alps which was soon followed by an extended warm spell leading to strong moisture convergence in the Alpine region triggered the "floods of the century", one of the most catastrophic in the last 100 years mostly in the central part of Switzerland [Beniston, 2006]. Based on Bensiton (2006), Allenbach, Weisse Lutschine and Emme were severely affected than Mentue and Goldach.

The r^2 and NSE evaluation of all five catchments for 2005 shows that Weisse Lutschine again has the highest value of $r^2 = 0.88; NSE = 0.88$ and $r^2 = 0.9; NSE = 0.85$ for Meteo and RdisaggH simulated runoffs respectively (See figure 5.15). This is followed by Emme (See figure 5.19) with $r^2 = 0.78; NSE = 0.78$ and $r^2 = 0.82; NSE = 0.82$, and then surprisingly Allenbach with $r^2 = 0.73; NSE = 0.67$ and $r^2 = 0.75; NSE = 0.75$(See figure 5.11) respectively. Mentue has the lowest $r^2 = 0.65$ and $NSE = 0.64$ and $r^2 = 0.65; NSE = 0.64$ for Meteo and RdisaggH simulated runoffs respectively.

For all catchments, the r^2 and NSE values for both Meteo and RdisaggH simulated runoffs significantly increased as compared to that to time period: 2003-2010. Of these, Allenbach showed a remarkably distinct increase in both r^2 and NSE values for both simulated runoffs (See figure 5.11) followed by Goldach (See figure 5.17), both of which are catchments with the smallest area in this investigation (See Chapter 2).

The r^2 and NSE for Meteo and RdisaggH simulated runoffs show that the RdisaggH simulated runoff give slightly higher r^2 and NSE values for Weisse Lutschine, Emme, Allenbach and Mentue. In Goldach, the Meteo simulated runoff shows better values with $r^2 = 0.73$ and $NSE = 0.68$.

The r^2 and NSE for both the Meteo and RdisaggH simulated runoffs slightly decreases in the summer season (JJA) of 2005 for Weisse Lutschine and Allenbach. However, they increase significantly for Emme and to a small degree for Goldach. Mentue shows the most notable fall from $r^2 = 0.65$ and $NSE = 0.64$ to $r^2 = 0.07$ and $NSE = -0.67$ for Meteo simulated runoff and from $r^2 = 0.65$ and $NSE = 0.64$ to $r^2 = 0.07$ and $NSE = -0.17$ for RdisaggH simulated runoff.

6.3.3 Case study: 2007

2007 was another year of severe flooding events in Switzerland. All r^2 and NSE values in the five catchments for the year 2007 matches somewhat closely with r^2 and NSE values of time period: 2003-2010. Among the catchments, Weisse Lutschine has the highest value with $r^2 = 0.75; NSE = 0.68$ and $r^2 = 0.84; NSE = 0.84$ for Meteo and RdisaggH simulated runoffs respectively. This is consecutively followed by Emme, Mentue, Allenbach and Goldach. Goldach has the worst value with $r^2 = 0.01; NSE = -0.1$ and $r^2 = 0.29; NSE = 0.23$ for the Meteo and RdisaggH simulated runoffs. In all five catchments, the RdisaggH simulated runoff gives higher r^2 and NSE values in 2007.

However, in the summer season, the r^2 and NSE values deteriorates for all catchments except for RdisaggH simulated runoff for Goldach and Allenbach. For summer season, in Goldach, $r^2 = 0.66; NSE = 0.66$ while for Allenbach, $r^2 = 0.55; NSE = 0.55$. Also during the summer season, the r^2 and NSE of Meteo simulated runoff shows the biggest drop to $r^2 = 0.35; NSE = -0.38$ in Weisse Lutschine while Goldach shows the worst value of $r^2 = 0.02; NSE = -0.01$ for Meteo simulated runoff. Interestingly, Goldach also shows the best value for RdisaggH simulated runoff for summer season of 2007 in all catchments with $r^2 = 0.66; NSE = 0.66$. Thus, for the summer season, the RdisaggH simulated runoff give higher and better r^2 and NSE values for all the catchments, with Goldach performing the best.

6.3.4 High precipitation events

The time period: 2003 - 2010 is a very interesting time frame for hydrologist purely from research point of view and not from humanitarianism side. This is because during this short time period, wide range of precipitation events occurred including five flood events with higher than 5 year return period [**?**]. This makes the RdisaggH precipitation dataset very interesting as well as this time period for high event analysis.

In this section, two specific precipitation events are chosen for evaluation. The first is the historic flood event of 21^{st} and 22^{nd} August 2005, and second is the severe flooding of 8^{th} and 9^{th} August 2007. Figure 6.7 and figure 6.8 show time slice of RdisaggH precipitation data for entire Switzerland during the course of event. Here, figure 6.7 shows the intensity of precipitation particularly in Emme on 21^{st} August 2005 at 23:00 hours midnight while figure 6.8 shows the precipitation in Weisse Lutschine and partly in Emme on 22^{nd} August 2005 at 13:00 hours mid-day.

Similarly, figure 6.9 shows heavy shower in the central part of Switzerland on 8^{th} August 2007 at 16:00 hours in the evening while figure 6.10 shows high precipitation in Allenbach and Goldach catchments on 9^{th} August 2007 at 02:00 hours in the morning.

The Meteo precipitation dataset consistently varies with the RdisaggH precipitation dataset, particularly during the high events of August 2005 and 2007, especially for Allenbach (See figure 6.1 and figure 6.2) and Weisse Lutschine (See figure 6.3 and figure 6.4) while capturing the same events very well for Mentue (6.5, 6.6. There is a significant variation between the two precipitation datasets in Goldach and Emme catchments (See table 5.1).

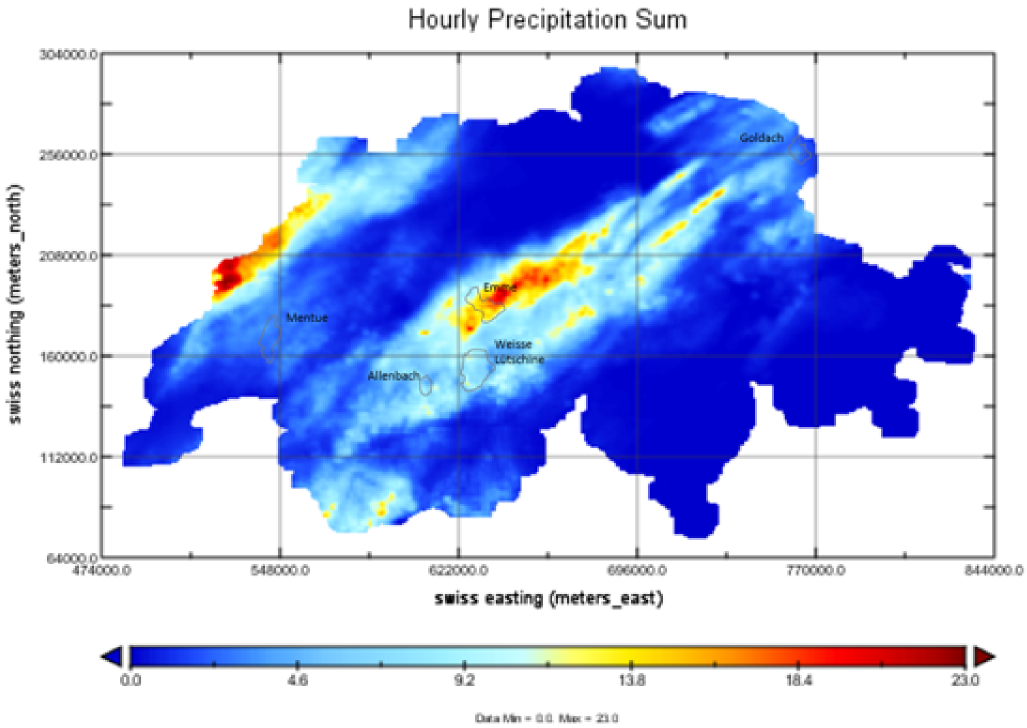


FIGURE 6.7: Precipitation distribution from RdisaggH dataset across Switzerland at 23:00, 21 August 2005

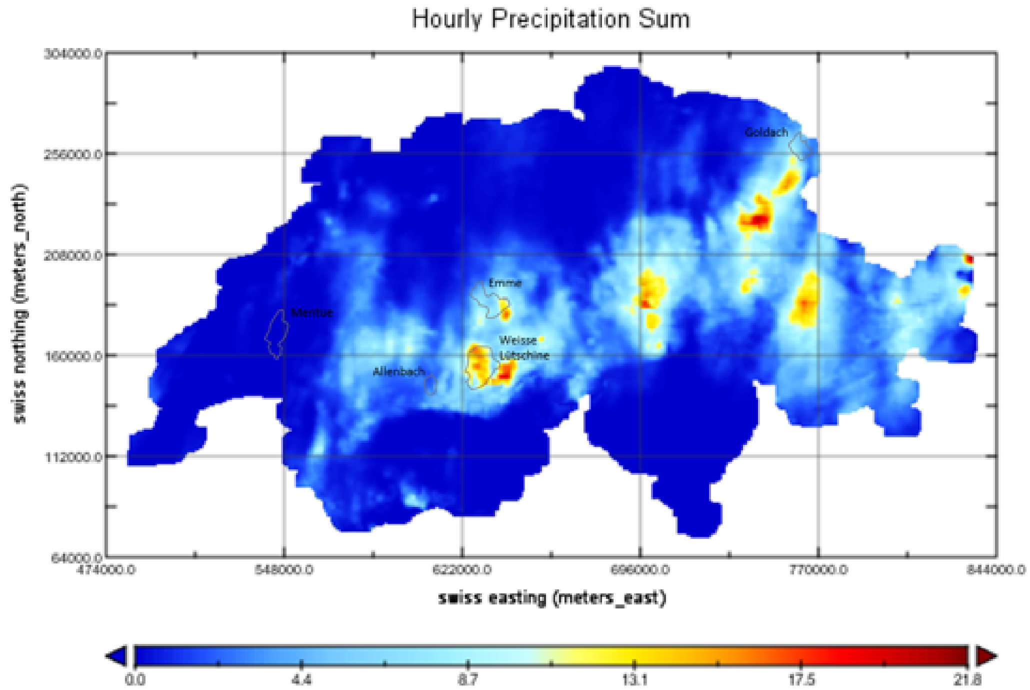


FIGURE 6.8: Precipitation distribution from RdisaggH dataset across Switzerland at 13:00, 22 August 2005

To see how these two precipitation datasets simulate their runoff in an event of such high precipitation such as of 21^{st} and 22^{nd} August 2005, and 8^{th} and 9^{th} August 2007, the respective hydrographs have been plotted.

For Allenbach, as shown in figures under table 6.1, the Meteo simulated runoff seem to reproduce the peak event of 21^{st} and 22^{nd} August 2005 better but overestimating the recession period. RdisaggH simulated runoff seem to genuinely underestimate the high peak event. This is the one of the issues with RdisaggH data i.e. overall small positive bias with systematic underestimation of high precipitation intensities and over estimation of low intensities (MeteoSwiss2013). However during the 8^{th} and 9^{th} August 2007, it is the opposite with Meteo simulated runoff grossly underestimating the peak while RdisaggH simulated runoff captures half of the peak but still underestimates the high peak value and then overestimating the recession period.

For Mentue, both simulated runoffs show no peak 21^{st} and 22^{nd} August 2005, In fact they are both flat as shown in the figure under table 6.2. During the 8^{th} and 9^{th} August 2007, Meteo simulated runoff underestimates the peak while capturing the recession period very well. On the other hand RdisaggH simulated runoff again captures half of the peak event and again overestimates the recession period.

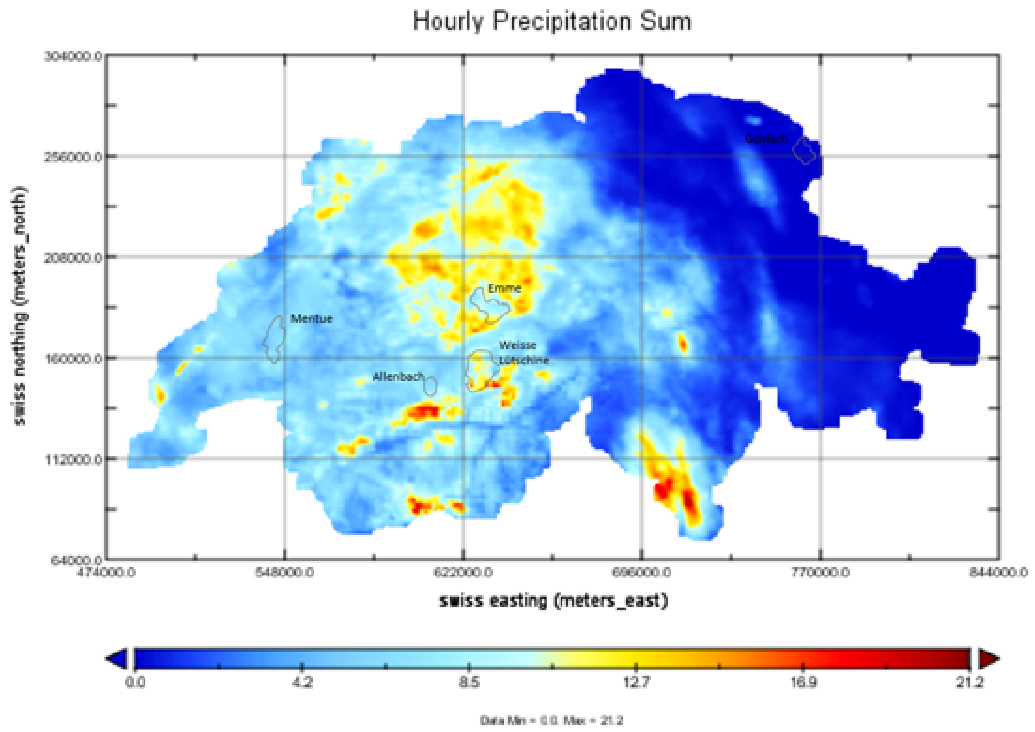


FIGURE 6.9: Precipitation distribution from RdisaggH dataset across Switzerland at 16:00, 8 August 2007

For Weisse Lutschine, as shown in figures under table 6.3, the Meteo simulated runoff seem to reproduce the peak event of 21^{st} and 22^{nd} August 2005 better by capturing the precise magnitude of the peak and recession period while RdisaggH simulated runoff overestimates the peak and the recession period. However, it precisely reproduces the start of the peak event along with the diurnal cycles. During the 8^{th} and 9^{th} August 2007, both simulated runoff captures the start of the peak event very well but then overestimates the peak runoff value and the recession period. Here again, the RdisaggH simulated runoff exceeds the Meteo simulated runoff in its overestimation.

For Goldach, as shown in figures under table 6.4, both Meteo and RdisaggH simulated runoffs seem to reproduce the peak event of 21^{st} and 22^{nd} August 2005 very well with overestimation during the recession period. To a certain extent, the Meteo simulated runoff may have performed slightly better in capturing the peaks. However during the 8^{th} and 9^{th} August 2007, Meteo simulated runoff completely misses to capture the high flood event while RdisaggH does well in capturing the peak as well as starting period of the event as well as the recession period with slight overestimation.

For Emme, as shown in figures under table 6.5, both Meteo and RdisaggH simulated runoffs seem to reproduce the peak event of 21^{st} and 22^{nd} August 2005 very well. Here there are two additional peaks withing the peak event. While Meteo simulated runoff

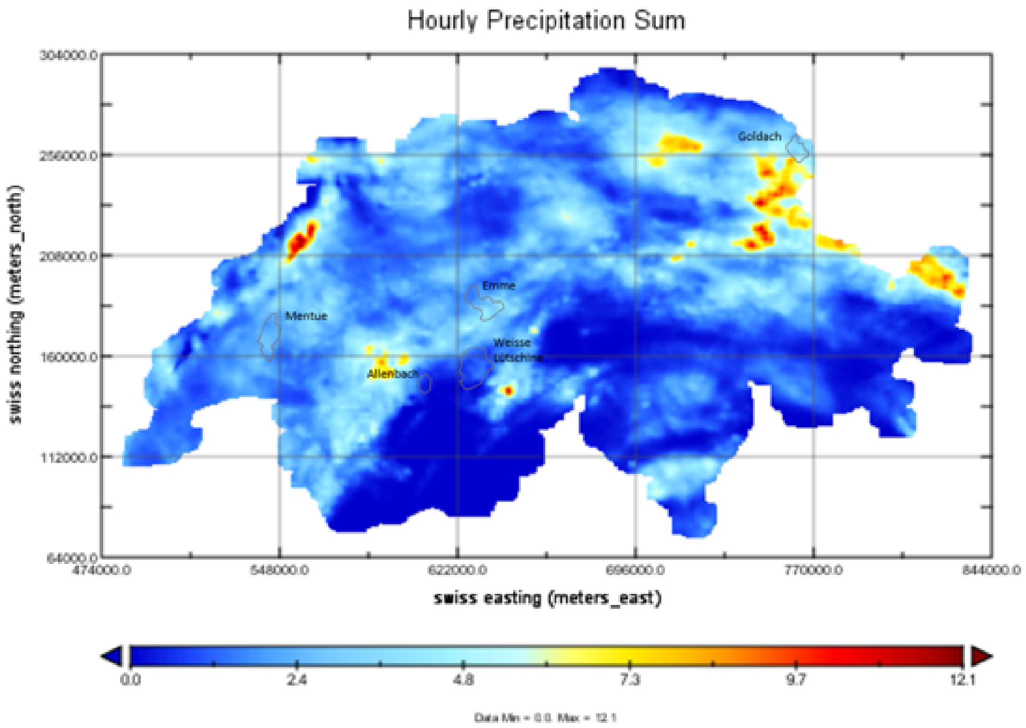
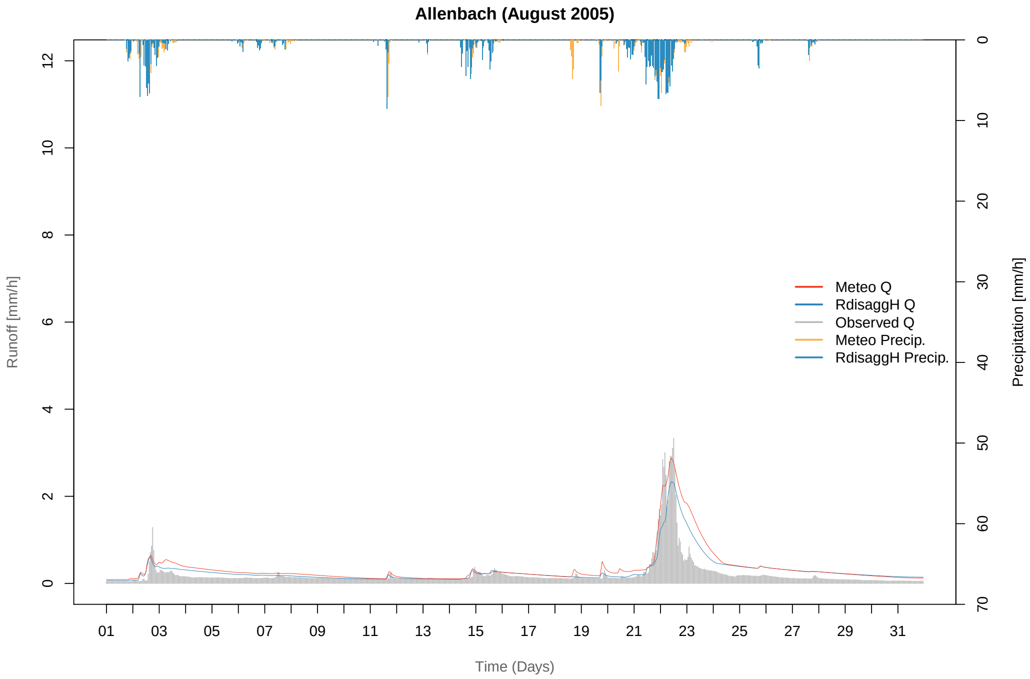


FIGURE 6.10: Precipitation distribution from RdisaggH dataset across Switzerland at 02:00, 9 August 2007

slightly reproduces the first peak, the second one is reproduced by RdiaggH simulated runoff albeit to a certain extent only. Both simulated runoffs then overestimate the recession period. During the 8^{th} and 9^{th} August 2007, both simulated runoff picks up the peak flood event very well with slight overestimation during the recession period. In fact they both appear almost the same in the hydrograph.



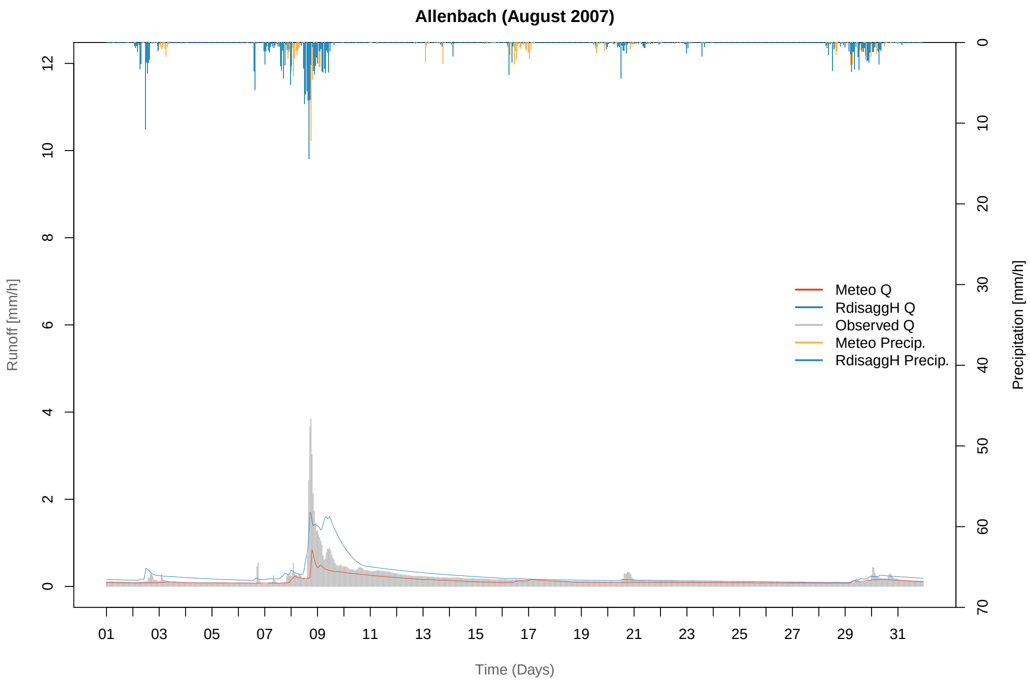
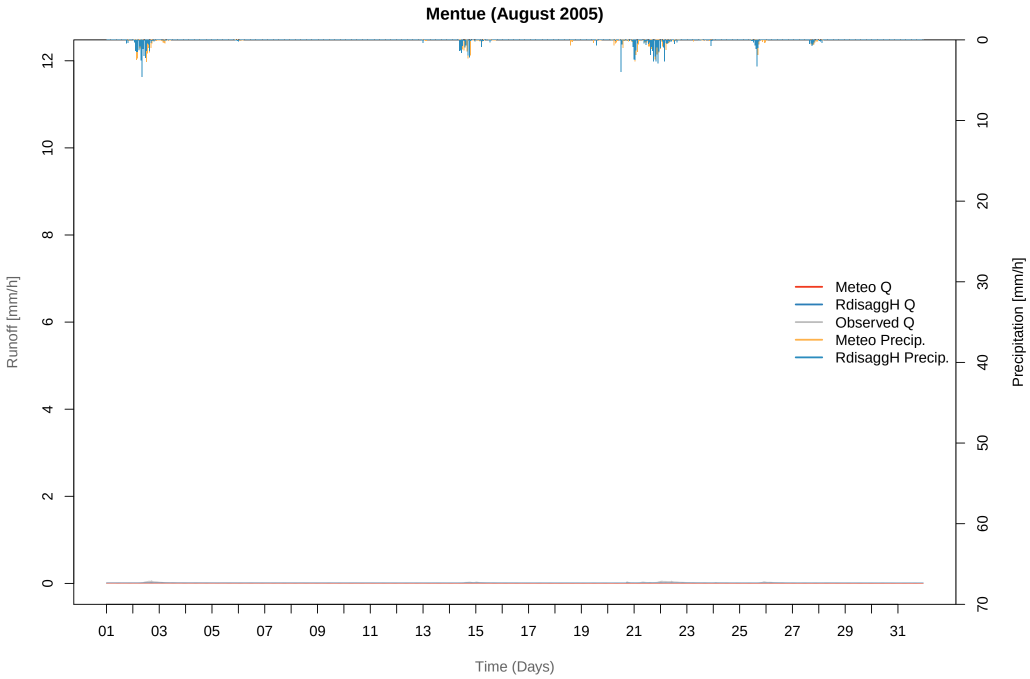


TABLE 6.1: Hydrographs showing flood events of 2005 ($21^{st} - 22^{nd} Aug.$) and 2007 ($8^{th} - 9^{th} Aug.$) for Allenbach



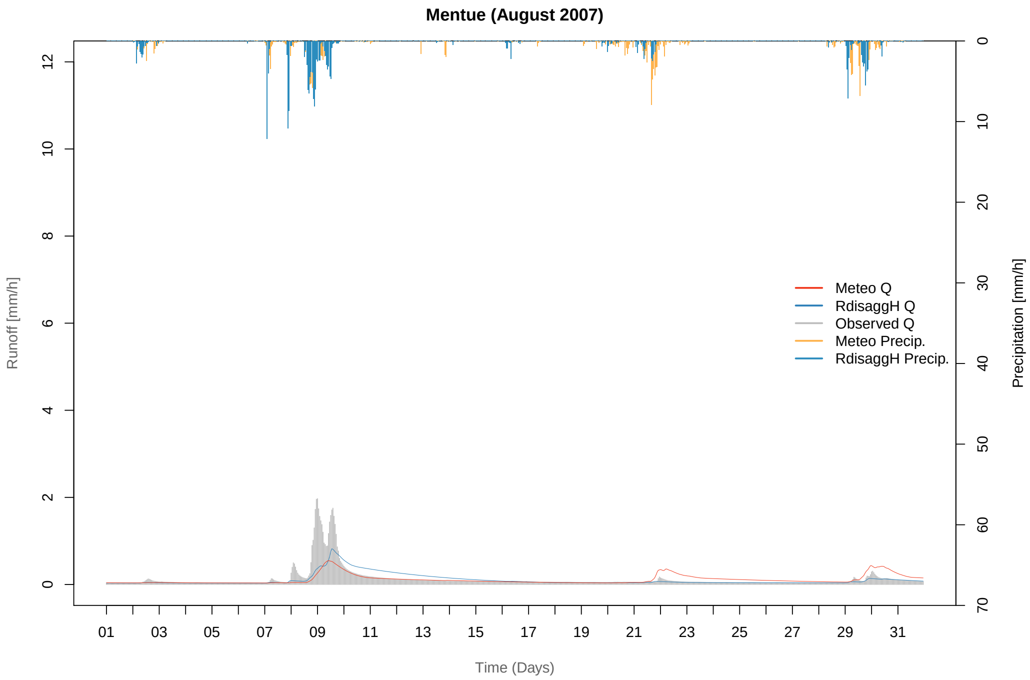
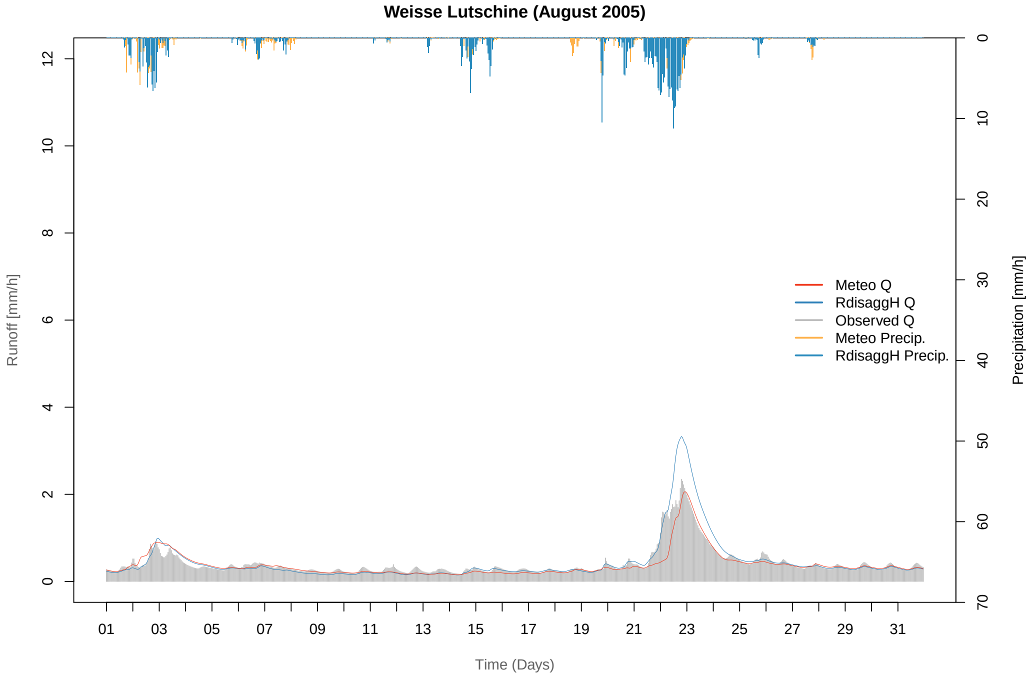


TABLE 6.2: Hydrographs showing flood events of 2005 ($21^{st} - 22^{nd} Aug.$) and 2007 ($8^{th} - 9^{th} Aug.$) for Mentue



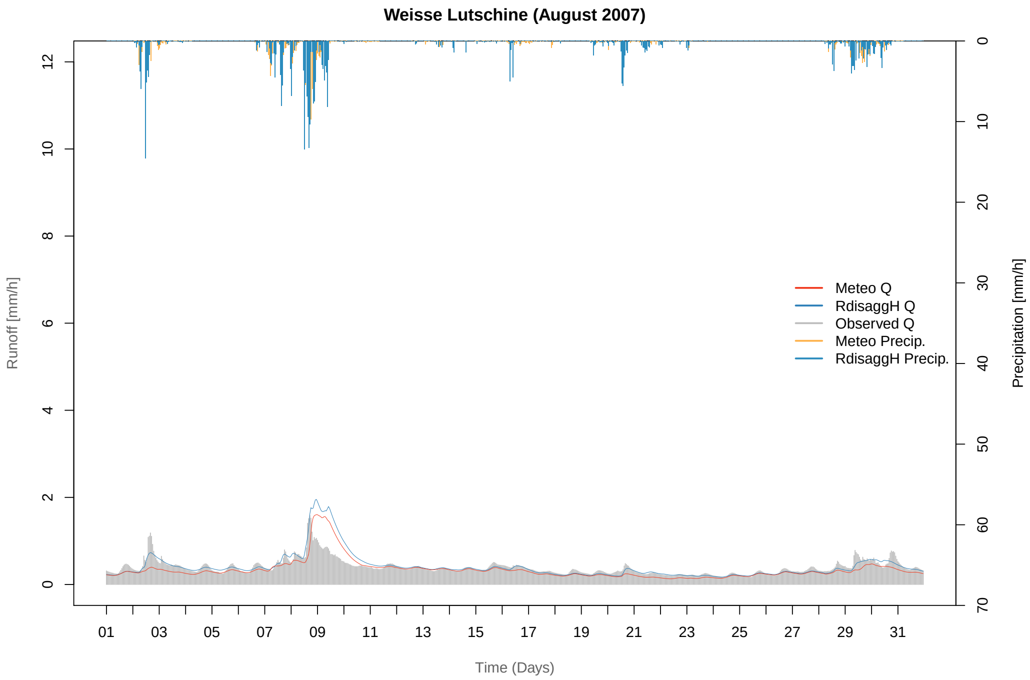
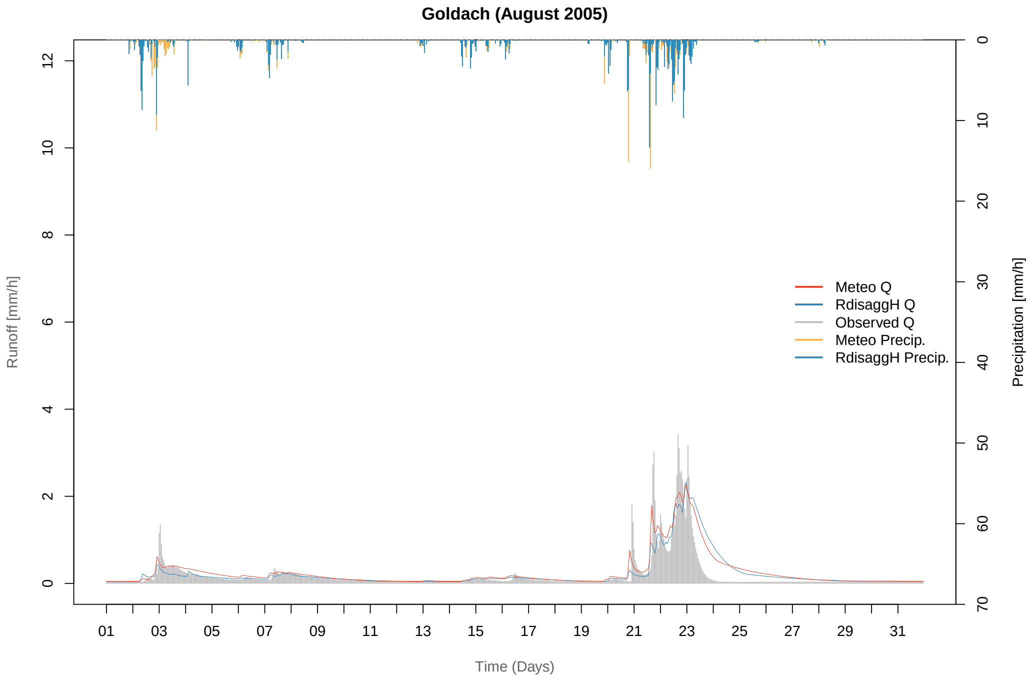


TABLE 6.3: Hydrographs showing flood events of 2005 ($21^{st} - 22^{nd} Aug.$) and 2007 ($8^{th} - 9^{th} Aug.$) for Weisse Lutschine



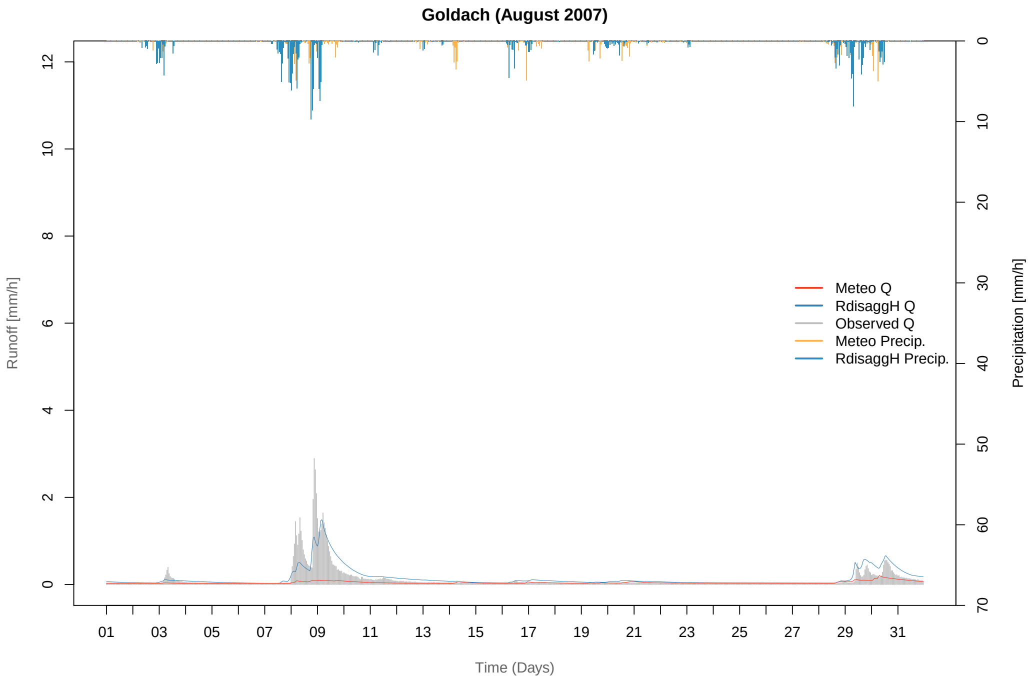
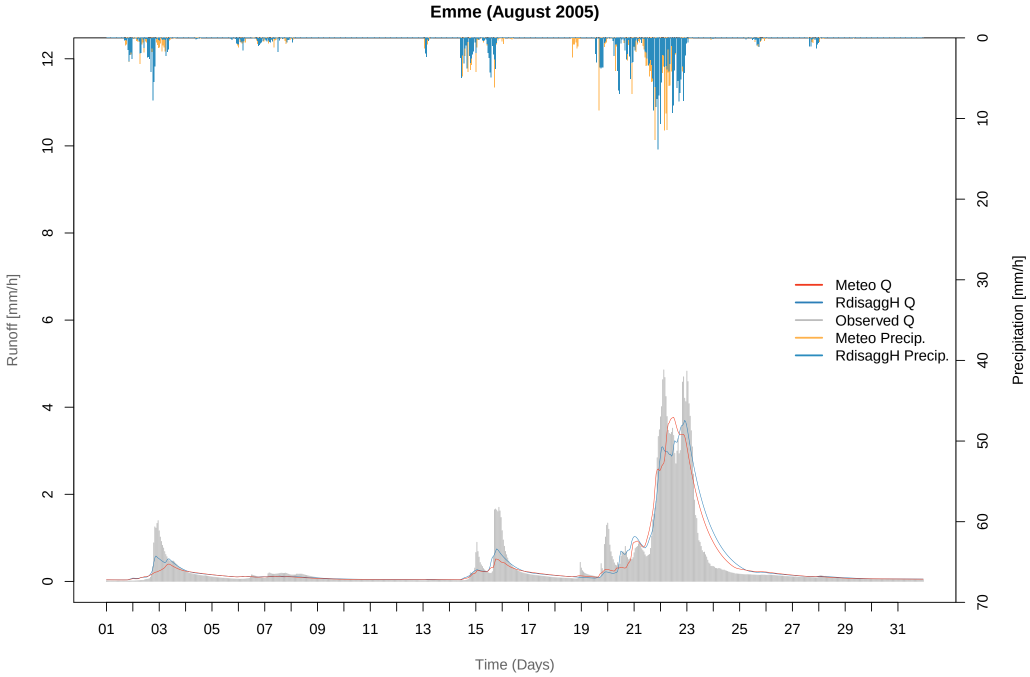


TABLE 6.4: Hydrographs showing flood events of 2005 ($21^{st} - 22^{nd} Aug.$) and 2007 ($8^{th} - 9^{th} Aug.$) for Goldach



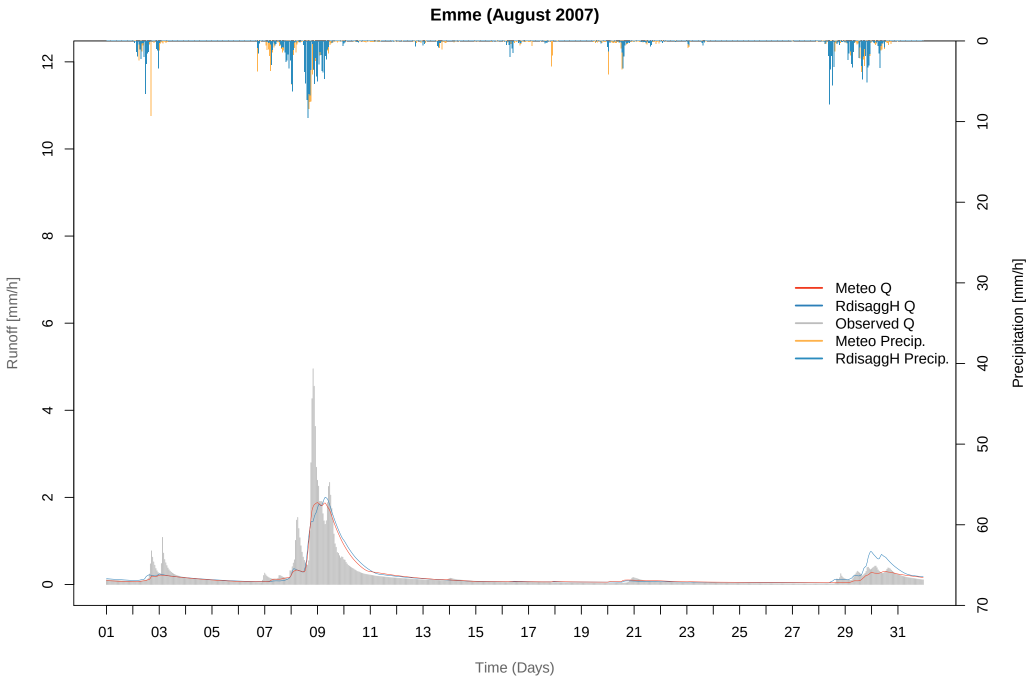


TABLE 6.5: Hydrographs showing flood events of 2005 ($21^{st} - 22^{nd} Aug.$) and 2007 ($8^{th} - 9^{th} Aug.$) for Emme

Chapter 7

Conclusions

This thesis evaluated two different types of precipitation datasets: an hourly precipitation RdisaggH (a gridded precipitation dataset based on radar and rain gauges) which is a product from MeteoSwiss and the gridded data from raingauge stations using PREVAH model.

As a first step, only relevant datasets were extracted from the NetCDF files of RdisaggH product by clipping the respective catchment boundaries using their elevation band ASCII files. After the extraction process, bilinear interpolation were performed to downscale the catchment datasets from $2km \times 2km$ to $500m \times 500m$ spatial resolution. Finally, the resulting values were averaged according to their respective elevation band cells. The final results were then tuned to the format of PREVAH input files.

The second step was to calibrate and validate both these datasets separately for each catchment and run full simulation in PREVAH for each dataset. The results were the simulated runoff for respective dataset along with their NSE.

The third step was the analysis, first the intercomparison of the precipitation datasets, second the calibration and validation of the datasets in PREVAH, and finally the comparison of the simulated runoffs with the observed runoff by applying different statistical methods such as coefficient of determination (r^2), root mean square difference (RMSD) and Nash Sutcliffe Efficiency (NSE).

Based on the results mentioned in Chapter 5 and the discussions in Chapter 6, there were significant differences in the two precipitation datasets with RdisaggH dataset having persistent high values and therefore higher precipitation aggregates for all catchments except Mentue.

Allenbach followed by Weisse Lutschine and Goldach had the highest RMSD values for time period: 2003 - 2010. Large discrepancies between the two dataset could be seen during spring and summer seasons. Weisse Lutschine also had high r^2 value because both precipitation datasets captured the seasonal cycle very well despite their large discrepancies. For Allenbach, these discrepancies seemed to reduce significantly in 2005 while getting worse again in 2007. These discrepancies were consistently high in Weisse Lutschine throughout 2003, 2005 and 2007.

The highest discrepancies between two datasets for Allenbach and Weisse Lutschine suggest that there is high variation between the two particularly in alpine catchments [Sikorska and Seibert, 2016]. In both catchments, the Meteo dataset showed lower precipitation sums than the RdisaggH dataset in all case studies. This may be a result of an error in spatial precipitation estimation from rain gauge station because the rain gauge stations are located in accessible places usually at lower elevations but alpine catchments could have high spatial and temporal precipitation variability which could then not be captured by these stations. However, such events are then captured by the radar beams and included in RdisaggH dataset despite the fact that RdisaggH dataset inherently suffer from issues related to topographic shielding of radar beams in high alpine regions, a systematic underestimation of high precipitation intensities and an overestimation of low intensities [MeteoSwiss and Frei, 2013]. It is possible that both Allenbach and Weisse Lutschine are just well under the threshold and escapes the shielding of radar beams.

Studies have also shown that in smaller catchments like Allenbach and Goldach, the uncertainties related with precipitation interpolation immensely grows with the increase in the resolution of the interpolation due to higher precipitation variability while averaging over smaller areas[Wood et al., 2000] [Goodrich et al., 1995]. Another issue here could be that the Meteo data is not always interpolated from the same set of stations every year. It is perhaps the reason why RMSD values plummeted so drastically for Allenbach and Goldach from 2005 to 2007. As a matter of fact, all catchments have shown high discrepancies between the two precipitation datasets in 2007 as compared to 2003 and 2005.

On the basis of this precipitation analysis, it could be said that the two precipitation datasets varies a lot depending upon the topographic characteristics and size as well as the placement and number of the rain gauge stations in that catchment that had been used for interpolation of the gridded precipitation dataset.

While Weisse Lutschine showed the highest discrepancies between the two precipitation datasets in all time period: 2003 - 2010, 2003, 2005 and 2007, this catchment surprisingly showed the best NSE and r^2 values for both Meteo and RdisaggH simulated runoffs for all time periods followed by Emme. The credit for this could be attributed more to the model PREVAH than the RdiaggH dataset because PREVAH is believed to well represent the hydrological processes such as snow accumulation and snow as well as glacier melt in the alpine region [Viviroli et al., 2009].

The RdisaggH simulated runoff also showed good NSE in Mentue while Allenbach and Goldach fell in the bottom categories when the comparison was made just for time period: 2003 - 2010. Goldach showed some remarkable improvement in NSE for 2003 and 2005, particularly for Meteo simulated runoff while Allenbach showed improvement in NSE for 2005. It is interesting to note that the year 2005 showed the best NSE for RdisaggH simulated runoff for all catchments while the years 2003 and 2007 varied depending upon the catchment. For instance, smaller catchments like Allenbach and Goldach gave the worst NSE for Meteo simulated runoffs in 2007 but moderate or good NSE for 2003 and 2005, while Mentue gave the worst NSE for Meteo simulated runoff in 2003 but moderate or good NSE in 2005 and 2007. The poor performance of simulated runoff for Allenbach and Goldach could also be due to the limitation of the PREVAH for smaller catchments rather than the datasets [Viviroli et al., 2009]. NSE for Weisse Lutschine and Emme were significantly good for both simulated runoffs. Thus, all in all, it could be said that RdisaggH simulated runoff genuinely gave better NSE than the Meteo simulated runoff.

It could also be inferred that a-glacio-nival catchment - Weisse Lutschine, and nivo-pluvial pralpin catchment - Emme, all of which have an area larger than $100km^2$ performed exceptionally well followed by pluvial jurassien catchment - Mentue which also has an area greater than $100km^2$. However nival alpin catchment - Allenbach and pluvial suprieur catchment - Goldach, both of which have an area less than $50km^2$ did not yield good NSE values. Altitude also seemed to have an important role to play in the performance of the model output as the interpolation of gridded data is absolutely dependent upon elevation of rain gauge stations along with their density and how well they can capture the heavy precipitation events. Based on discussions from Chapter 6,and particularly the plots provided in Appendix A on the long term monthly means for time period: 2005 and 2007, it could be said that RdisaggH dataset genuinely captures the seasonal cycles better than the Meteo simulated runoff. Exceptions were for Allenbach in 2007 where the spring cycle was missed and in Goldach in 2007 where the winter cycle was missed and spring cycle was grossly overestimated. However, the Meteo simulated runoffs also could not capture the seasons very well in these time period. The long term monthly means for time period: 2004 - 2010 also showed the seasonal cycles of the hydrological regime were well captured in Weisse Lutschine, Emme and Mentue catchments by RdisaggH simulated runoff while it missed out the peaks in spring for Allenbach while overestimating the peaks also in spring for Goldach. It could thus be that PREVAH does not capture the snowmelt period in spring for smaller alpine catchments like Allenbach while the overestimation of during spring could simply be due to the inherent issue with the RdisaggH dataset overestimating the low precipitation intensities [MeteoSwiss and Frei, 2013].

Thus, RdisaggH simulated runoff seemed to produce good results for catchments larger than $100km^2$ as opposed to those below $50km^2$. In fact, PREVAH seemed to have complimented the RdisaggH dataset for catchments larger than $100km^2$ despite the discrepancies in the dataset such as in the case of Weisse Lutschine. The larger catchments at higher elevation produced more realistic simulated runoffs than the ones at lower elevation. RdisaggH dataset also managed to capture the seasonal variability of these larger catchment better than the Meteo dataset. In all catchments, RdisaggH simulated runoff overestimated the recession period to a varying degree for extreme precipitation events such as that of 21^{st} and 22^{nd} August 2005, and 8^{th} and $9th$ August 2007. RdisaggH simulated runoff also captured these flood events better than the Meteo simulated runoff in larger catchment with an exception of Weisse Lutschine where it overestimated the peak.

One of the key issue with this hourly precipitation RdisaggH product from MeteoSwiss is its short time series from May 2003 to December 2010. Furthermore, this was an abnormal time period from a hydrological point of view, with drought in 2003 to historic flooding in 2005 and later again in 2007, some having 5 to 100 years return periods [Girons Lopez et al., 2015] [Beniston, 2006]. So this might not have been a normal time series dataset and therefore may not have been able to represent the hydrological regime of the catchment very well. The discrepancies in two precipitation datasets may also have fallen victim to this issue whereby their existing weakness like in the extraction process or interpolation process from the rain gauge stations may have been further amplified which can only ignite further scientific curiosity. Therefore, it only holds better prospects for further assessment of this experimental dataset in future for more Swiss catchments.

Appendix A

Hydrographs

A.1 Allenbach

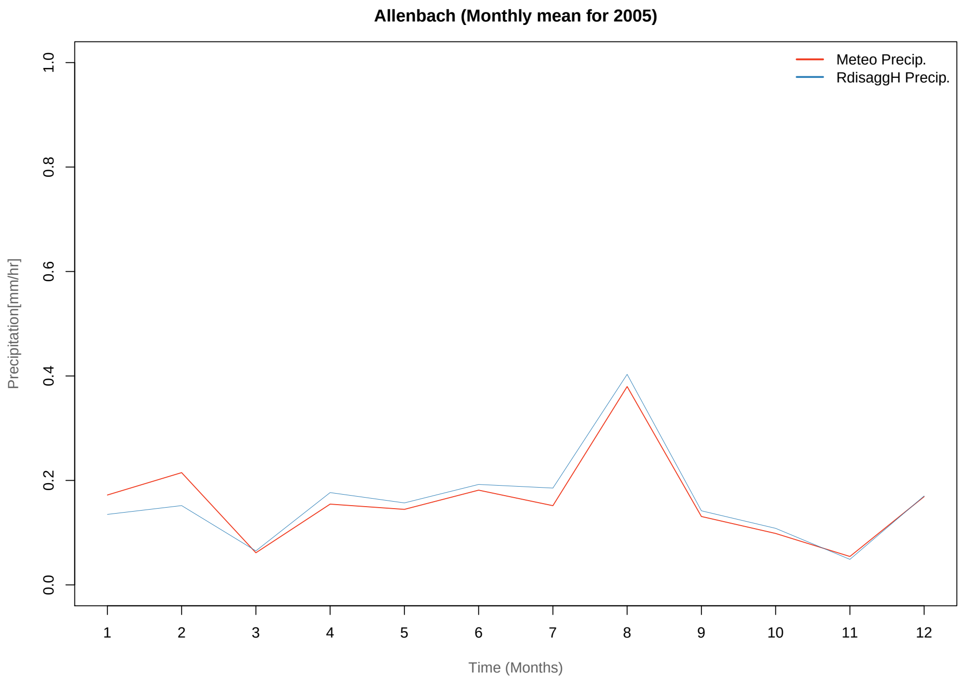


Figure A.1: 2005 precipitation monthly mean, Allenbach

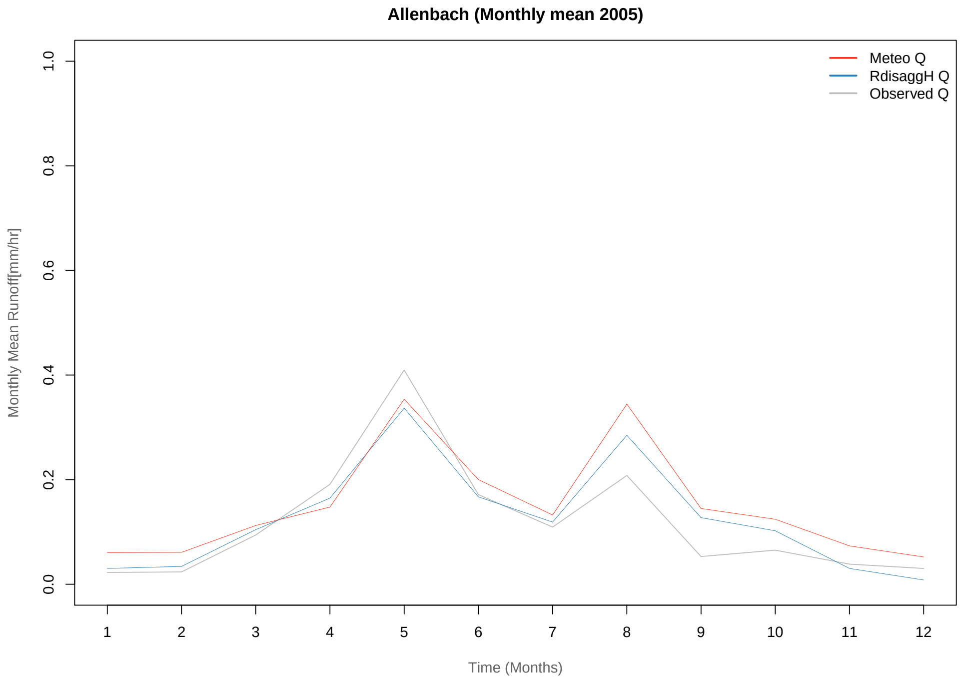


FIGURE A.2: 2005 runoff monthly mean, Allenbach

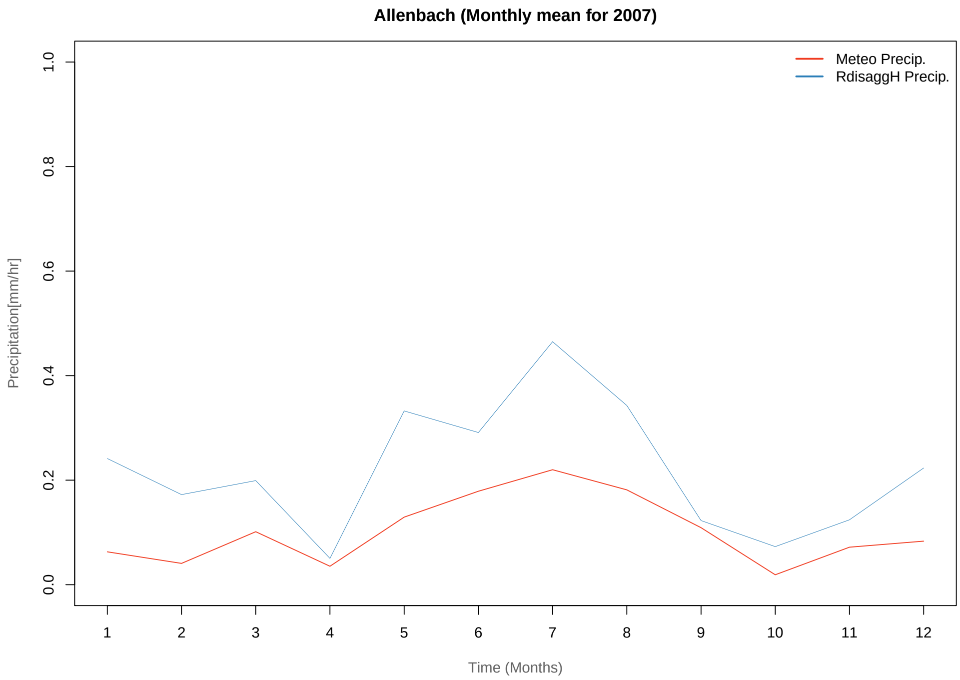


FIGURE A.3: 2007 precipitation monthly mean, Allenbach

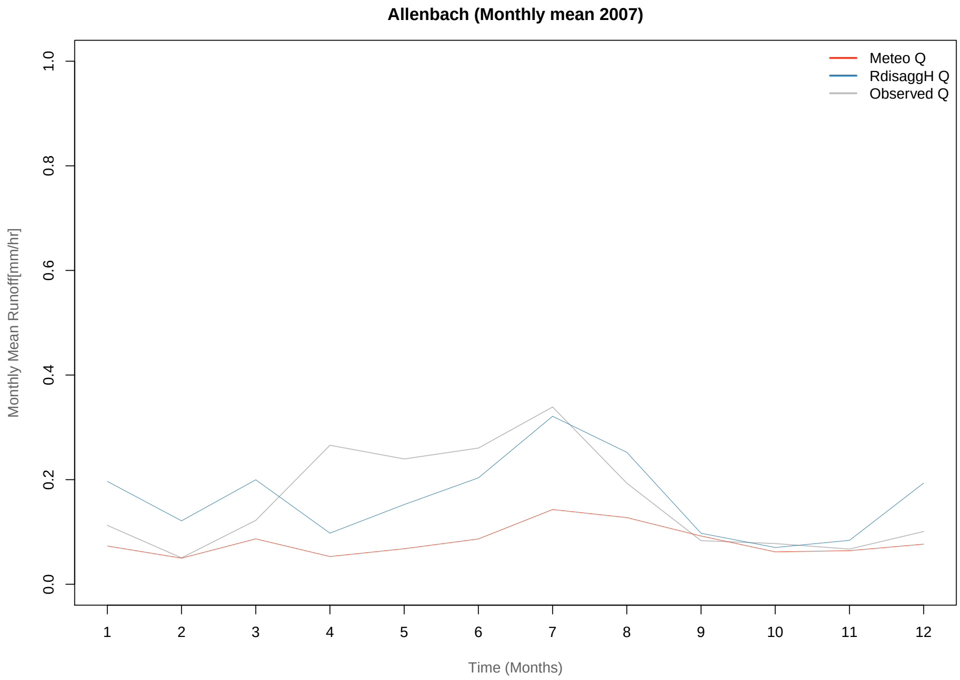


FIGURE A.4: 2007 runoff monthly mean, Allenbach

A.2 Mentue

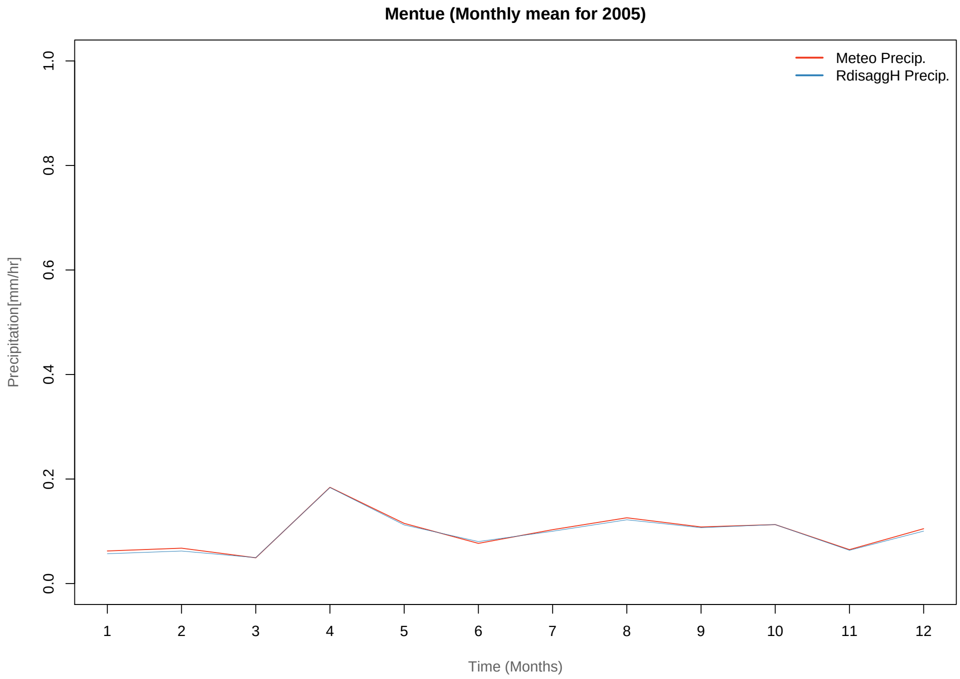


FIGURE A.5: 2005 precipitation monthly mean, Mentue

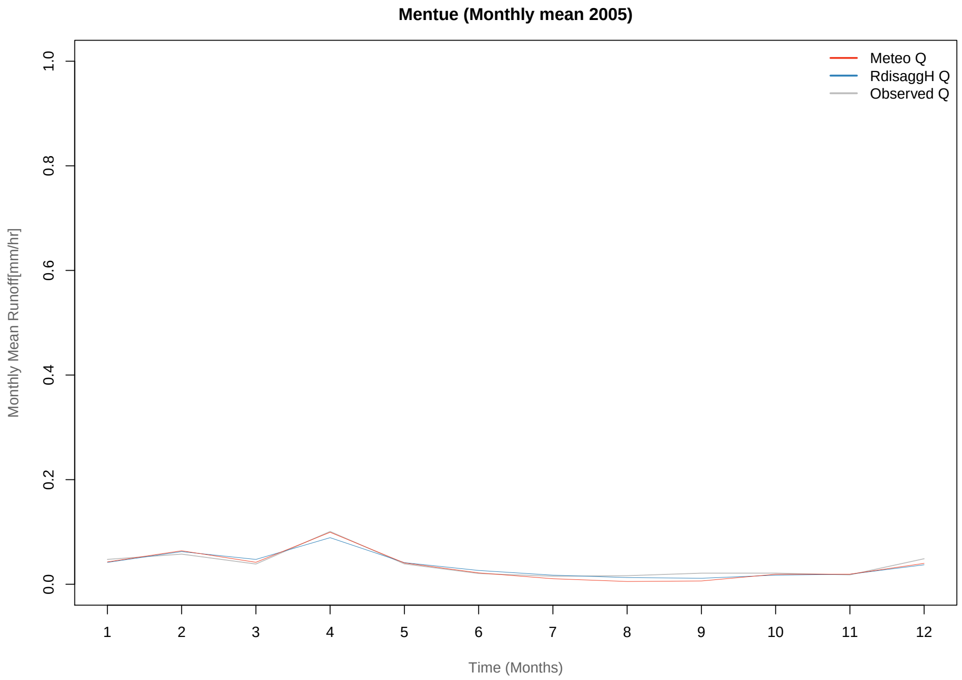


FIGURE A.6: 2005 runoff monthly mean, Mentue

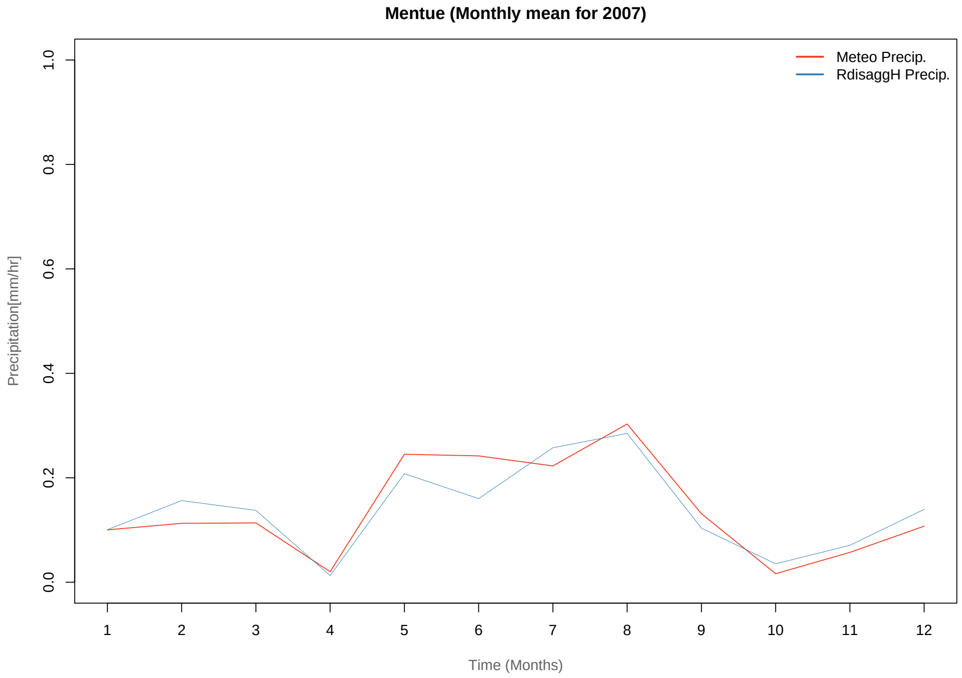


FIGURE A.7: 2007 precipitation monthly mean, Mentue

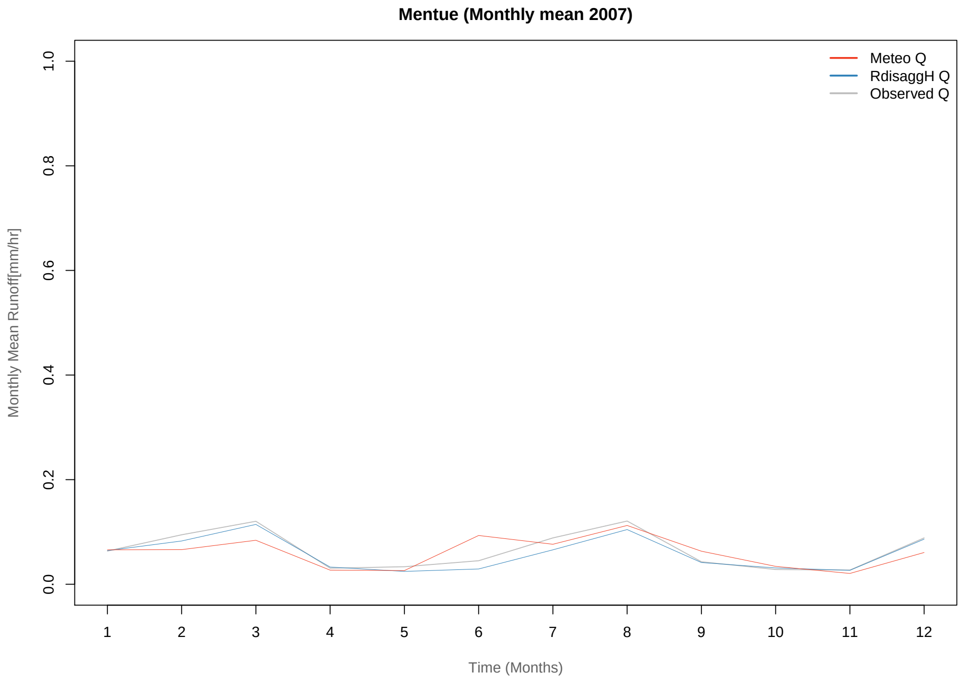


Figure A.8: 2007 runoff monthly mean, Mentue

A.3 Weisse Lutschine

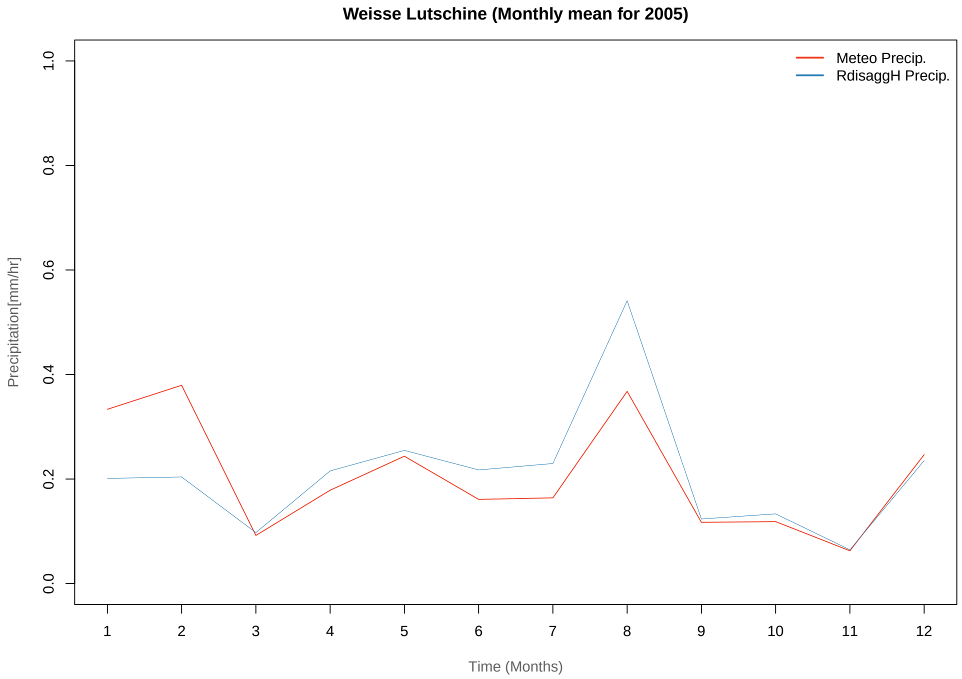


Figure A.9: 2005 precipitation monthly mean, Weisse Lutschine

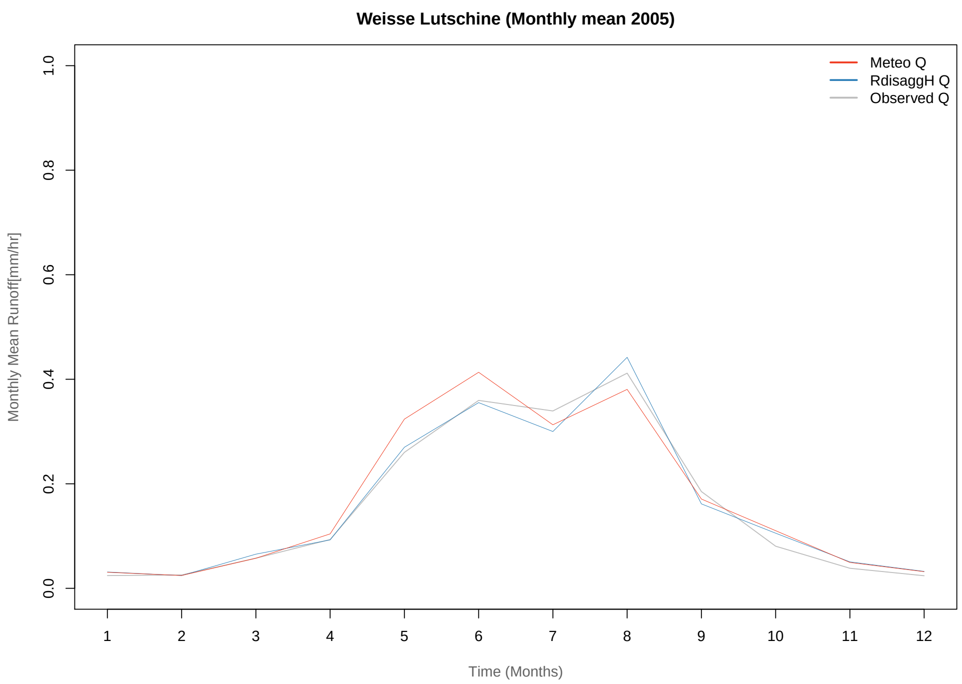


FIGURE A.10: 2005 runoff monthly mean, Weisse Lutschine

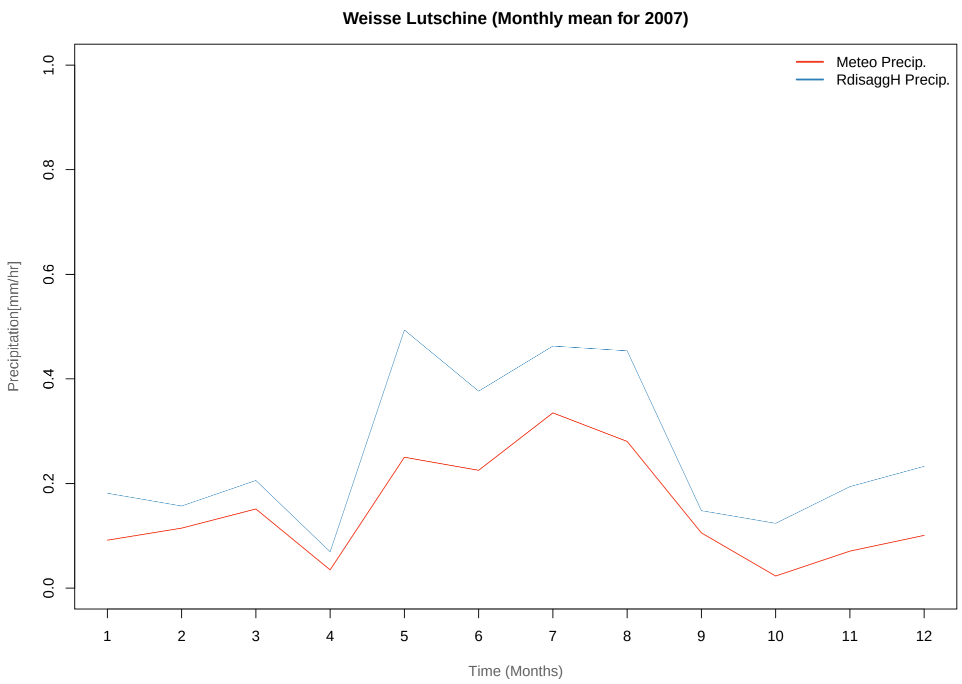


FIGURE A.11: 2007 precipitation monthly mean, Weisse Lutschine

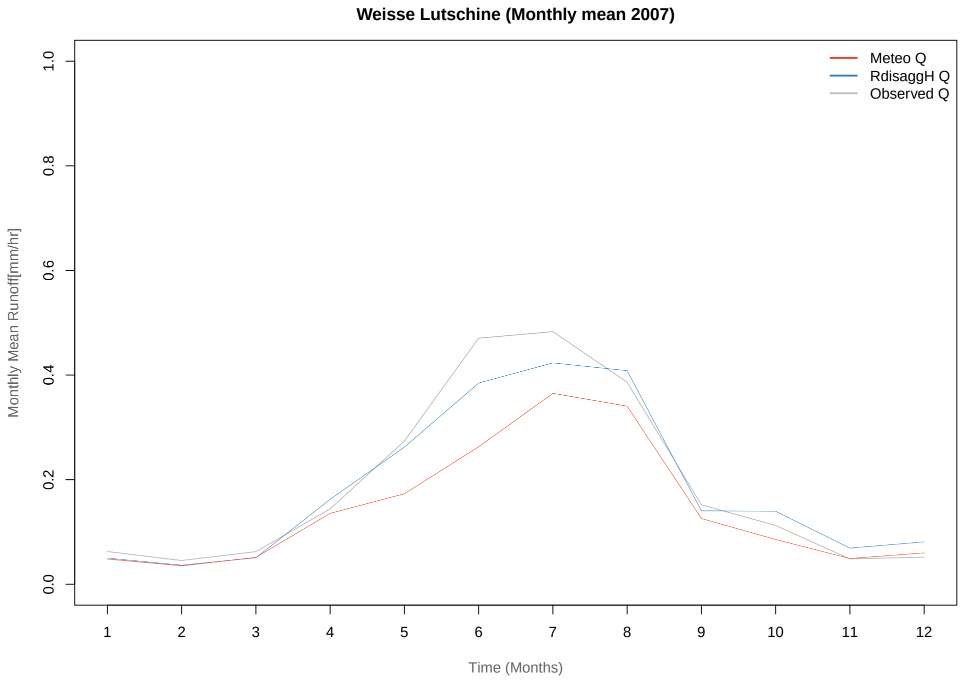


Figure A.12: 2007 runoff monthly mean, Weisse Lutschine

A.4 Goldach

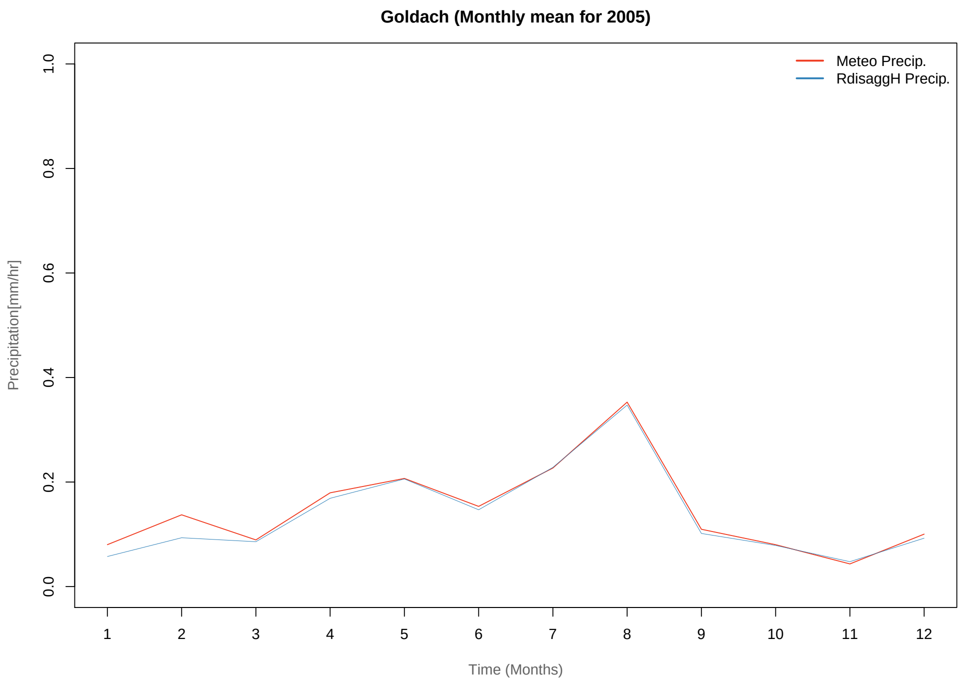


Figure A.13: 2005 precipitation monthly mean, Goldach

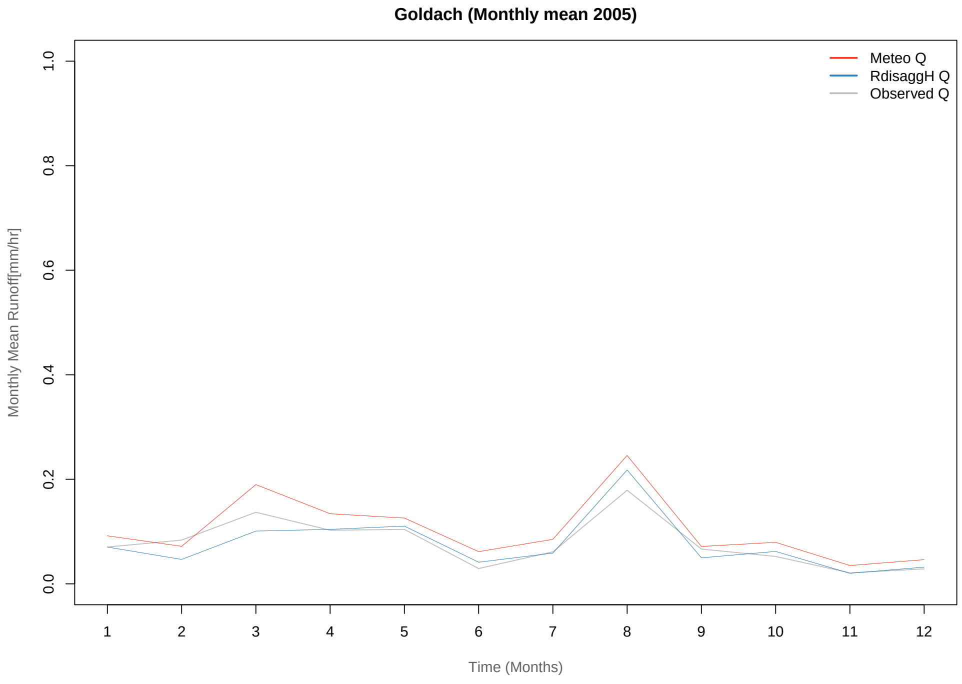


FIGURE A.14: 2005 runoff monthly mean, Goldach

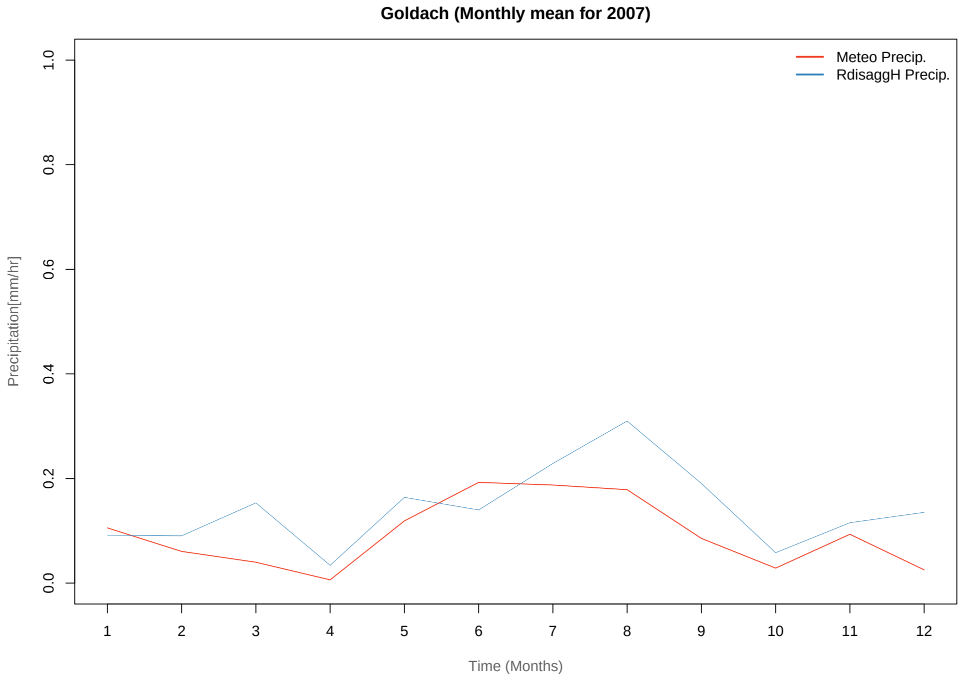


FIGURE A.15: 2007 precipitation monthly mean, Goldach

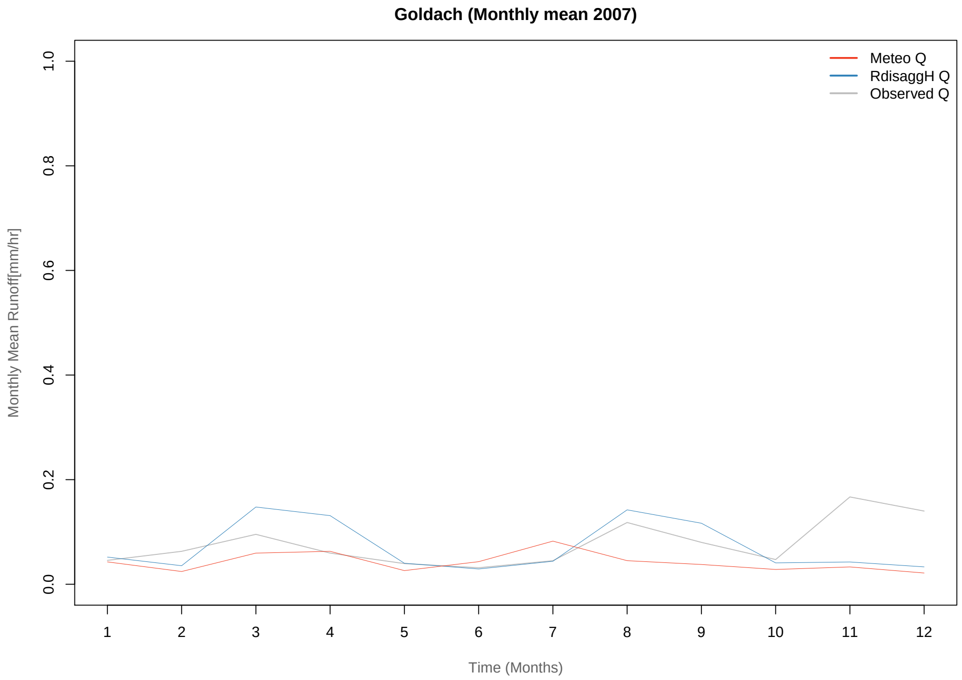


FIGURE A.16: 2007 runoff monthly mean, Goldach

A.5 Emme

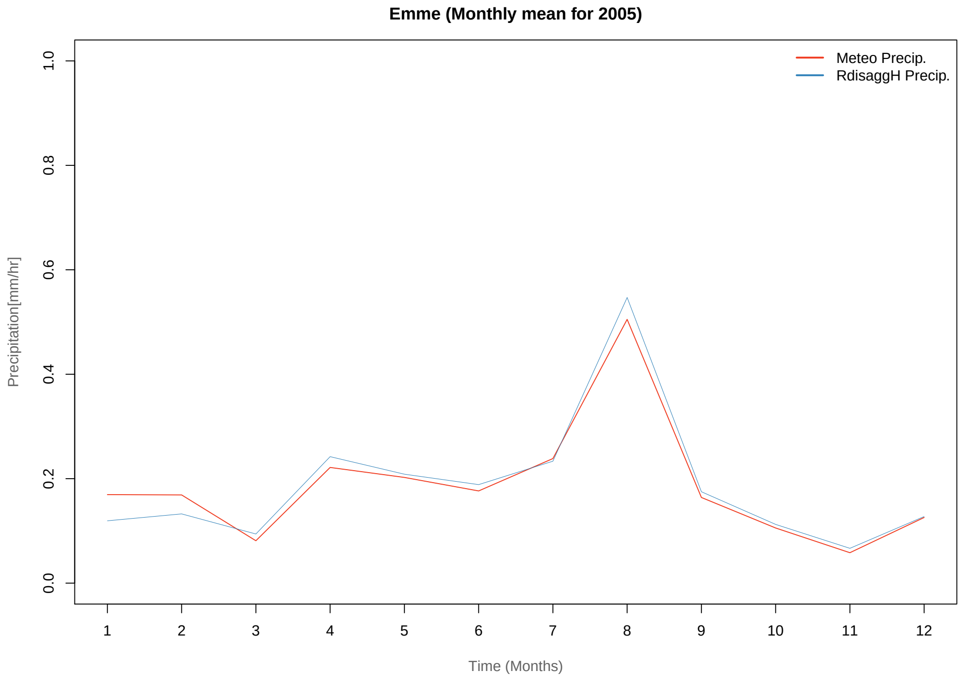


FIGURE A.17: 2005 precipitation monthly mean, Emme

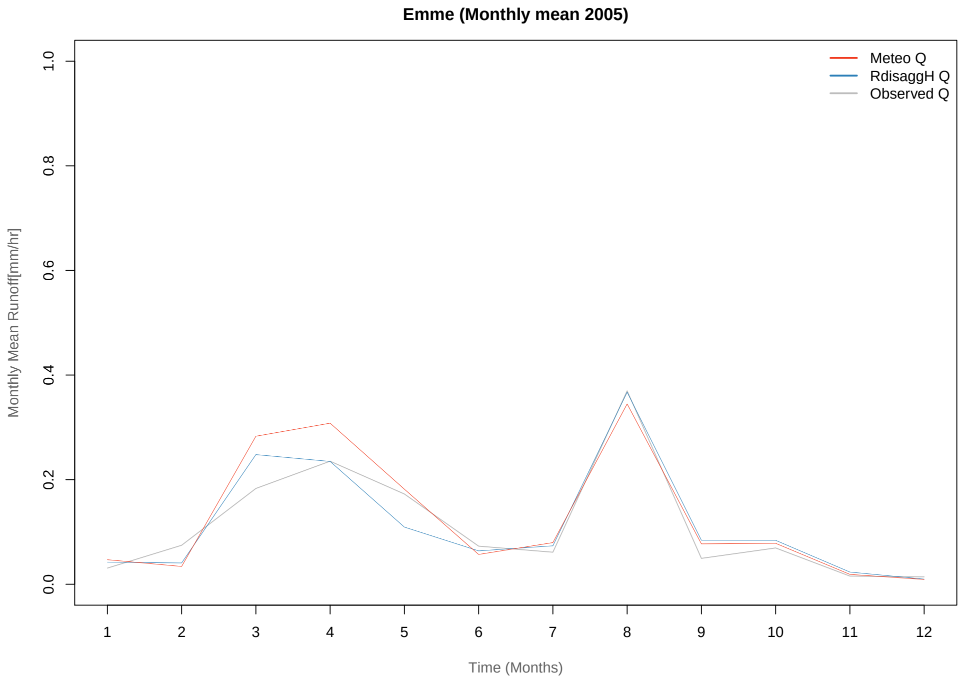


FIGURE A.18: 2005 runoff monthly mean, Emme

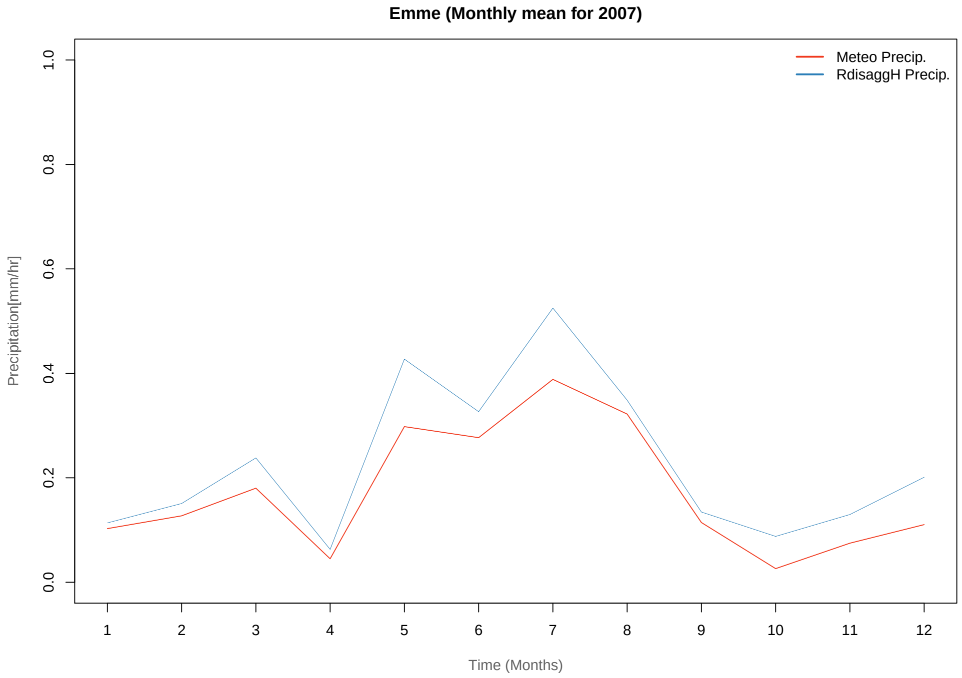


FIGURE A.19: 2007 precipitation monthly mean, Emme

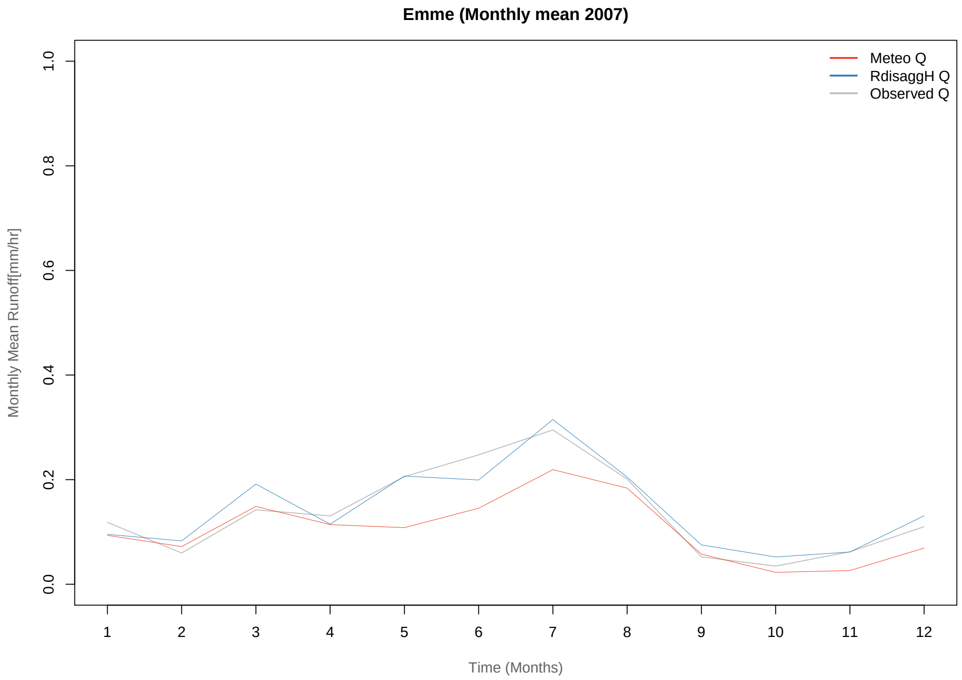


FIGURE A.20: 2007 runoff monthly mean, Emme

Appendix B

Tables and figures

Time Period		Allenbach	Mentue	Weisse Lutschine	Goldach	Emme
2003	*Jan-Dec*	0.94	0.77	0.89	0.72	0.91
	JJA	0.88	0.96	0.8	0.83	0.94
	August	0.88	0.99	0.72	0.9	0.9
2005	*Jan-Dec*	0.77	0.78	0.07	0.59	0.76
	JJA	0.72	0.98	0.02	0.89	0.84
	August	0.69	0.99	0	0.89	0.82
2007	*Jan-Dec*	0.51	0.68	0.52	0.5	0.71
	JJA	0.55	0.74	0.61	0.38	0.78
	August	0.33	0.75	0.8	0.48	0.92

TABLE B.1: The correlation coefficient (r^2) values between RdisaggH error and Meteo error. Here, $Meteoerror(Error1) = Obs.runoff - Meteosimulatedrunoff$ and $RdisaggHerror(Error2) = Obs.runoff - RdisaggHsimulatedrunoff$

	Precipitation Sums [mm]			Runoff Sums [mm]		
	Precip. Total	Spring	Summer	Q Total	Spring	Summer
Allenbach						
2003 - 2010						
Meteo	8892	1908	3731	7682	1846	2856
RdisaggH	11847	2895	4642	8509	2544	2987
Observed				9767	4108	3301
2003						
Meteo	807.02	124.87	386.23	607	66	258
RdisaggH	969.01	136.94	499.08	538	24	232
Observed				666	225	200
2005						
Meteo	1352.43	264.63	525.94	1342	453	499
RdisaggH	1378.56	292.44	576.33	1130	447	421
Observed				1035	512	359
2007						
Meteo	892.9	197.01	427.44	711	153	263
RdisaggH	1868.92	431.81	810.69	1386	332	573
Observed				1363	460	583
Mentue						
2003 - 2010						
Meteo	8680	2173	2734	3764	1079	556
RdisaggH	7609	1853	2428	3024	1013	429
Observed				3109	1048	484
2003						
Meteo	566.26	75.83	216.09	127	18	23
RdisaggH	553.54	70.96	211.72	97	12	21
Observed				100	20	28
2005						
Meteo	854.25	254.96	225.74	312	113	27
RdisaggH	837.95	252.65	223.15	318	130	41
Observed				323	130	38
2007						
Meteo	1227.42	281.49	565.41	555	101	207
RdisaggH	1191.42	266.35	519.01	504	127	147
Observed				556	136	188
Weisse Lutschine						
2003 - 2010						
Meteo	9910	2331	3461	10096	1919	5735
RdisaggH	14361	3675	5409	11844	2477	6523
Observed				11628	2324	6906
2003						
Meteo	883.73	157.44	335.42	985	90	687
RdisaggH	1073.18	173.56	490.92	1032	89	720
Observed				1450	230	984

Table B.2: Intercomparison between precipitation and runoff totals for time period 2003-2010, 2003, 2005 and 2007 along with spring and summer seasons (Part 1).

	Precipitation Sums [mm]			Runoff Sums [mm]		
	Precip. Total	Spring	Summer	Q Total	Spring	Summer
			Weisse Lutschine (contd.)			
2005						
Meteo	1715.23	378.44	511.66	1482	359	814
RdisaggH	1768.45	417.35	730.14	1426	316	808
Observed				1400	303	818
2007						
Meteo	1306.62	323.85	620.08	1261	264	714
RdisaggH	2200.52	570.31	952.99	1598	350	895
Observed				1679	354	985
			Goldach			
2003 - 2010						
Meteo	7591	1706	2951	4289	1502	1128
RdisaggH	9933	2413	3911	5737	2303	1616
Observed				6282	1969	1745
2003						
Meteo	781.46	119.69	290.97	337	48	78
RdisaggH	751.23	115.48	284.34	243	37	48
Observed				255	39	50
2005						
Meteo	1279.28	349.52	541.83	914	331	290
RdisaggH	1205.18	338.63	533.81	681	232	235
Observed				692	253	200
2007						
Meteo	855.14	122.7	411.12	381	109	126
RdisaggH	1227.29	260.61	501.43	638	234	159
Observed				616	143	144
			Emme			
2003 - 2010						
Meteo	9714	2458	3855	5759	2464	1590
RdisaggH	12532	3197	5068	7623	2928	2427
Observed				7758	3030	2664
2003						
Meteo	906.21	148.4	405.5	397	65	111
RdisaggH	924.99	138.21	430.21	386	60	124
Observed				393	99	130
2005						
Meteo	1596.67	370.55	680.33	1125	567	357
RdisaggH	1618.22	399.64	716.47	1023	435	374
Observed				988	434	373
2007						
Meteo	1509.1	388.19	728.01	917	273	404
RdisaggH	1970.63	540.43	885.26	1235	379	530
Observed				1173	353	547

Table B.3: Intercomparison between precipitation and runoff totals for time period 2003-2010, 2003, 2005 and 2007 along with spring and summer seasons (Part 2).

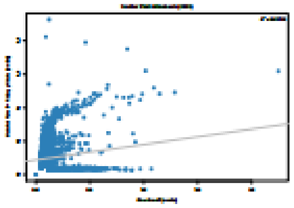
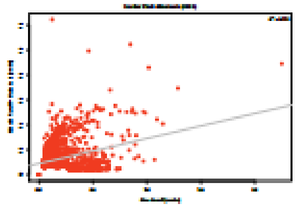
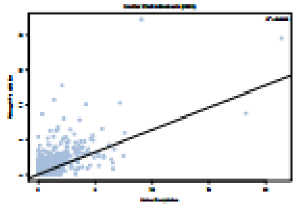
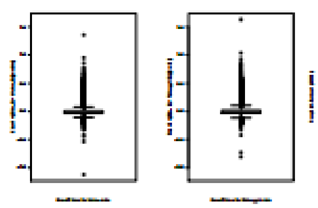
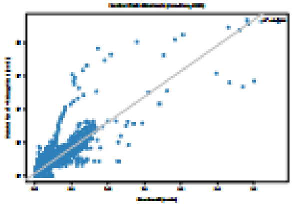
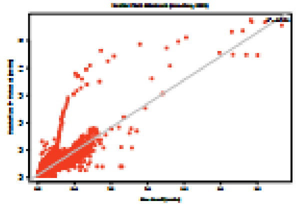
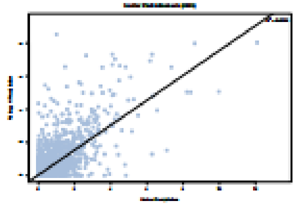
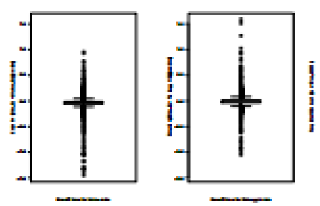
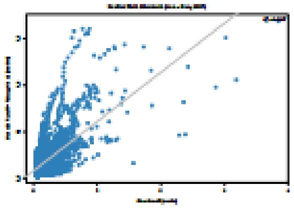
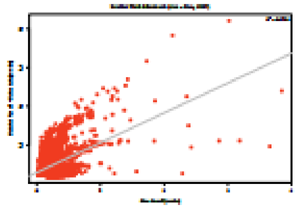
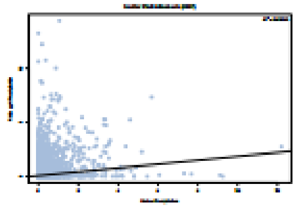
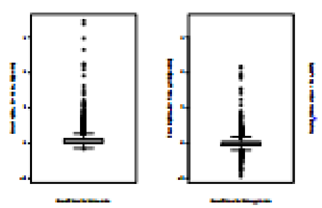
Year of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.1: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are of yearly period for Allenbach

JJA of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

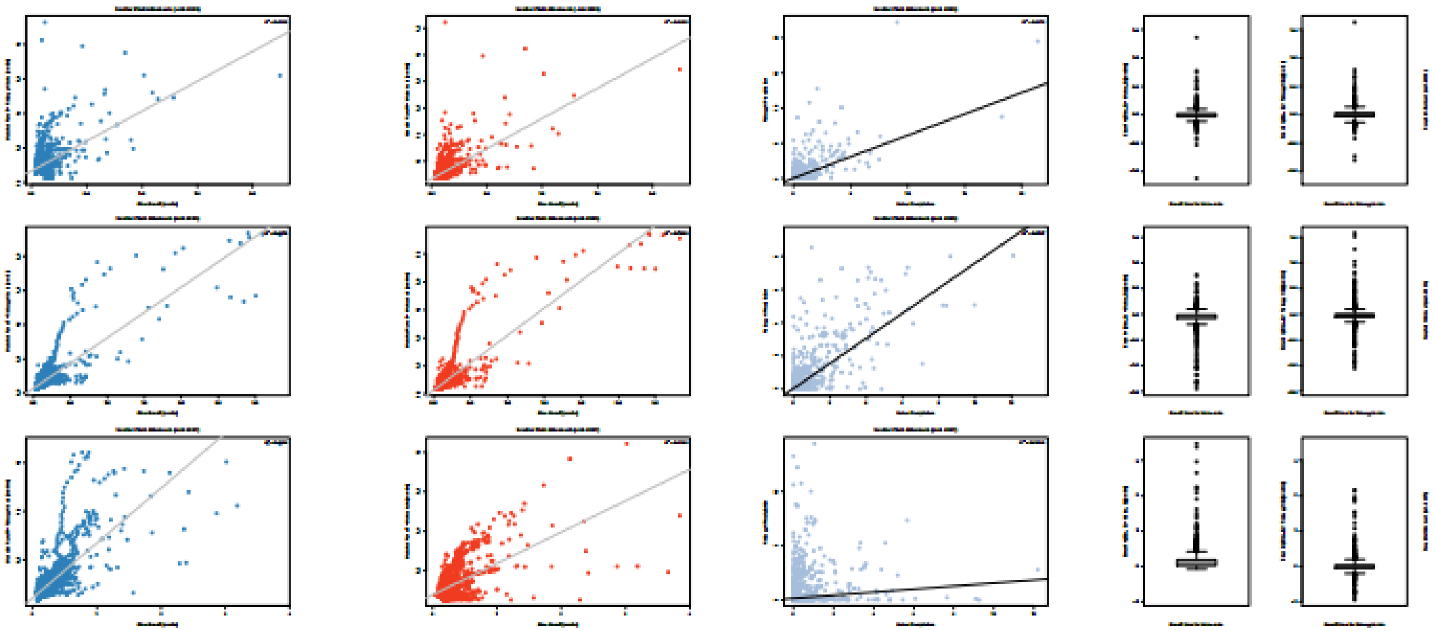


FIGURE B.2: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are for summer season (JJA) for Allenbach

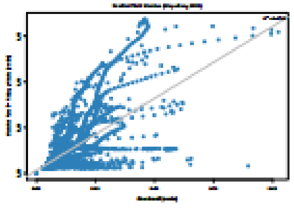
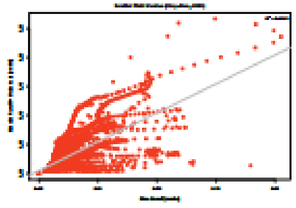
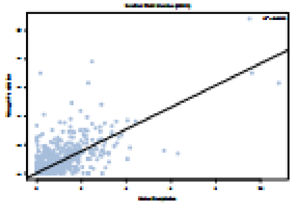
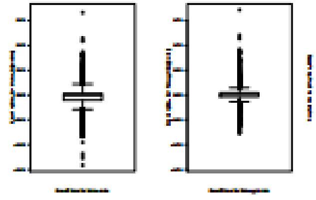
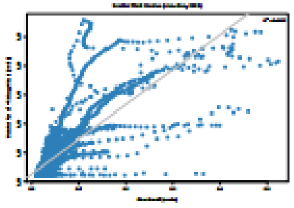
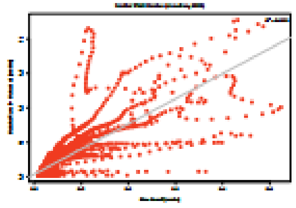
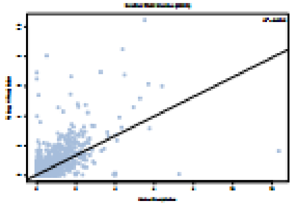
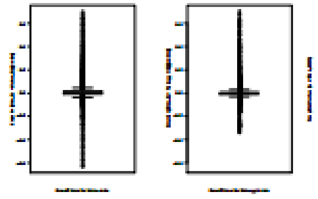
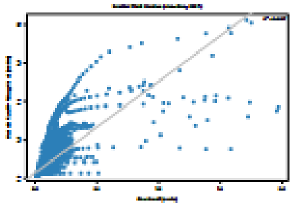
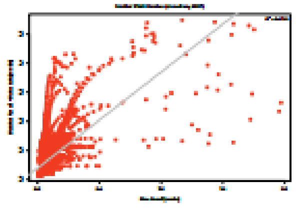
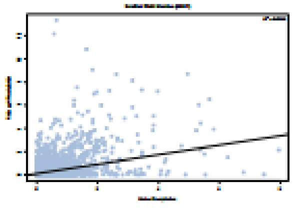
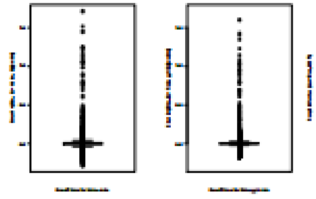
Year of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.3: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are of yearly period for Mentue

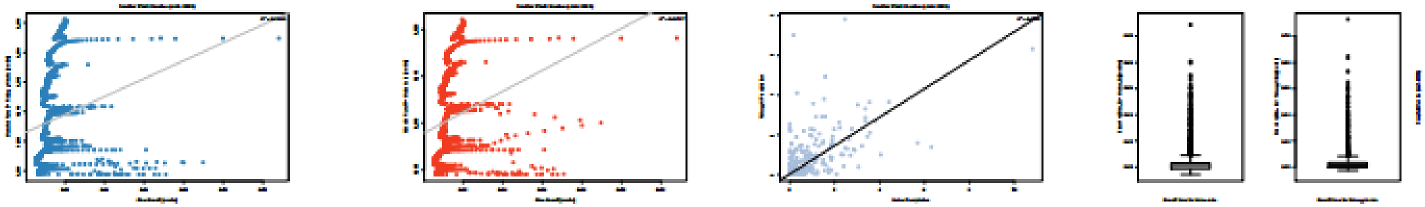
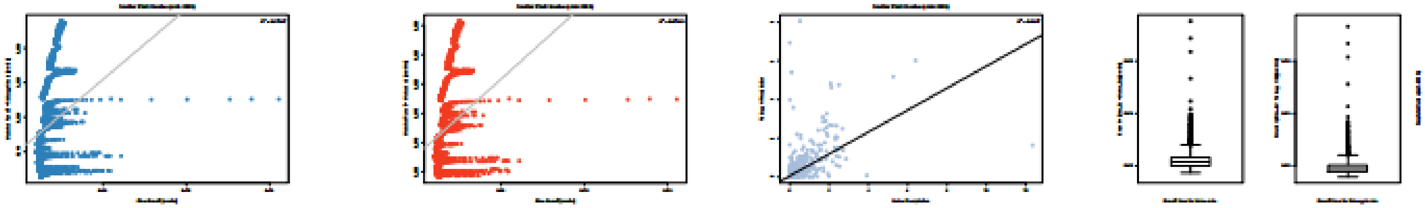
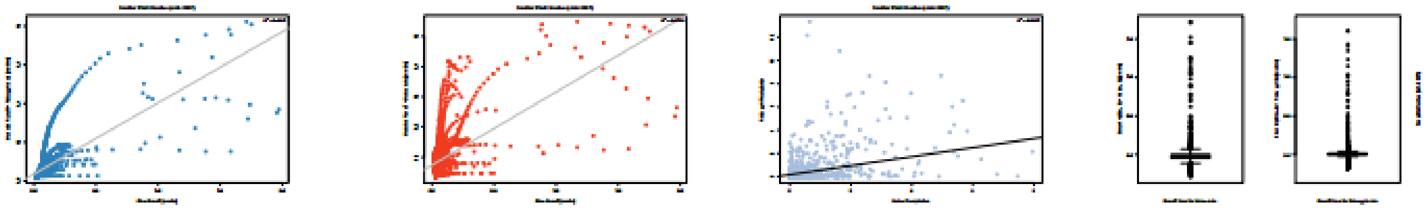
JJA of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.4: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are for summer season (JJA) for Mentue

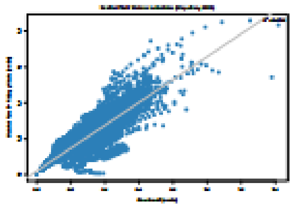
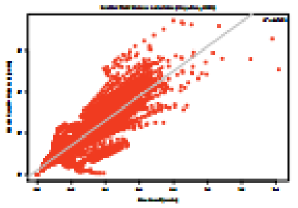
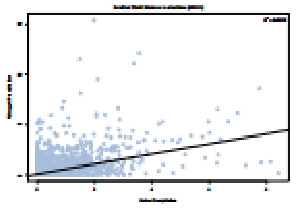
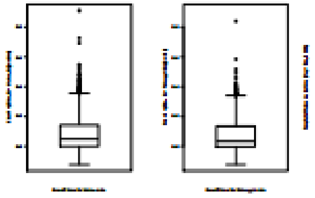
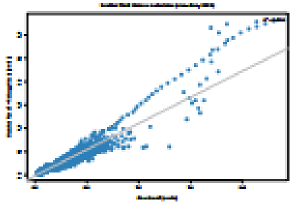
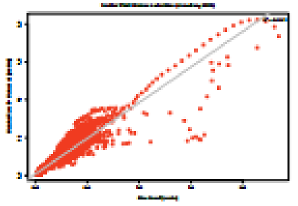
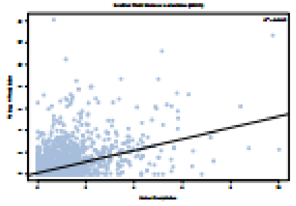
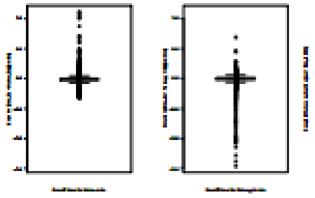
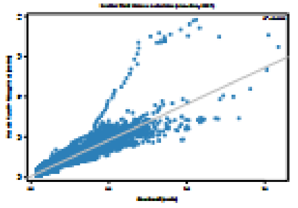
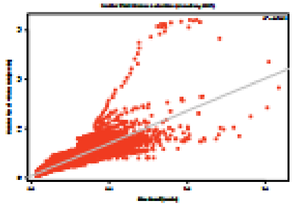
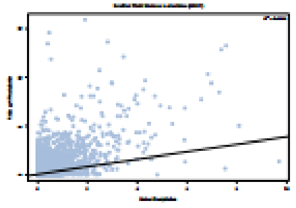
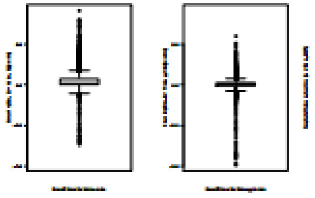
Year of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.5: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are of yearly period for Weisse Lutschine

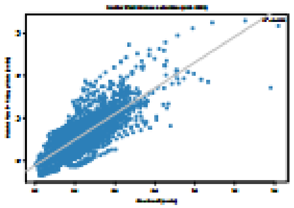
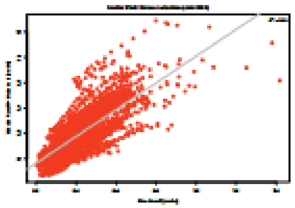
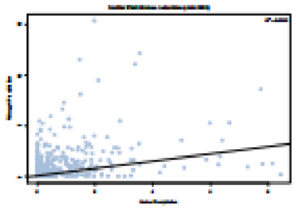
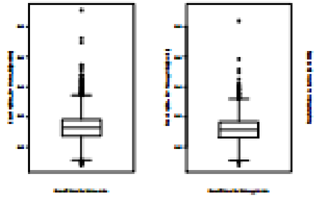
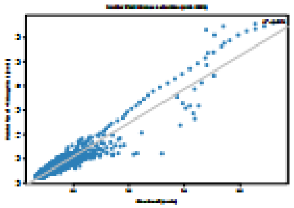
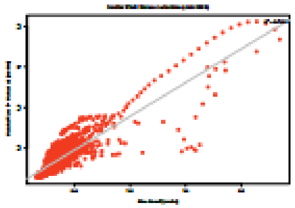
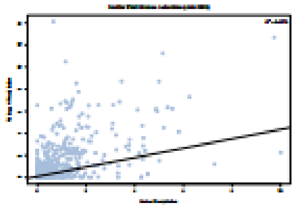
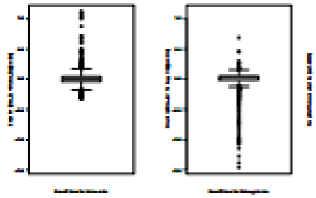
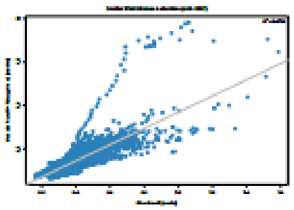
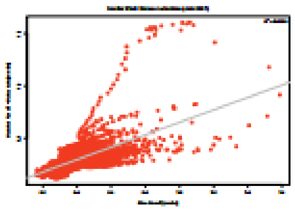
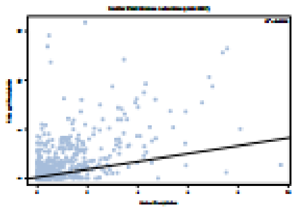
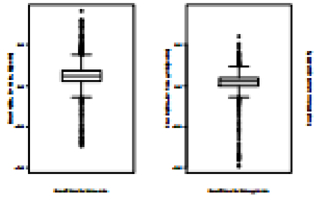
JJA of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.6: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are for summer season (JJA) for Weisse Lutschine

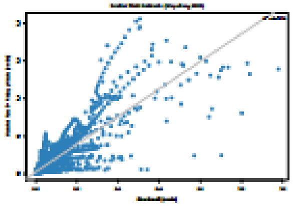
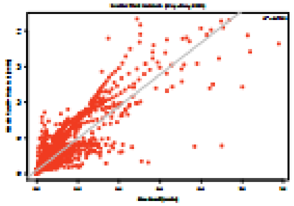
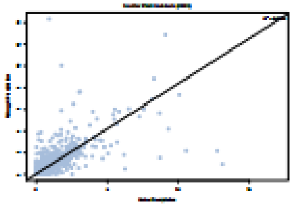
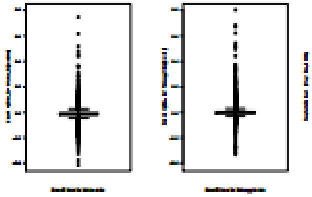
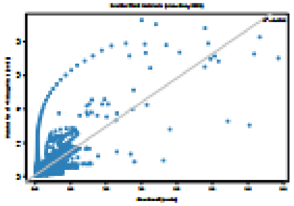
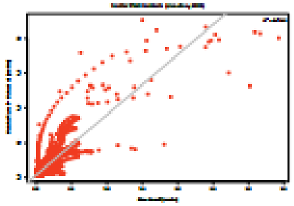
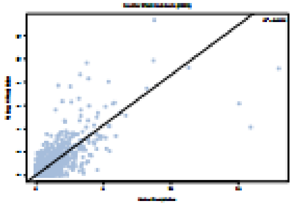
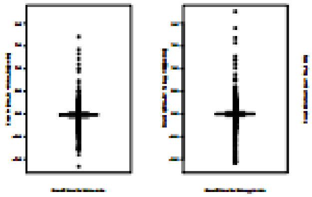
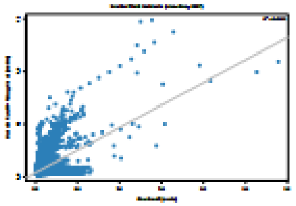
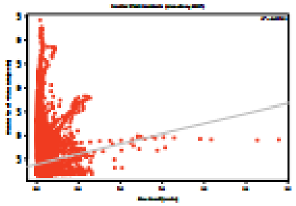
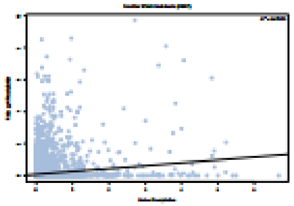
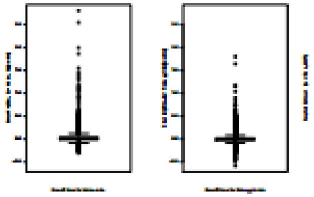
Year of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.7: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are of yearly period for Goldach

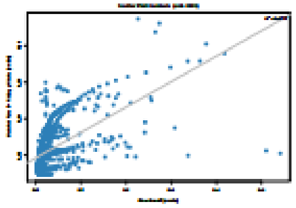
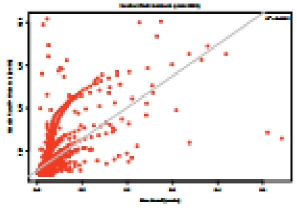
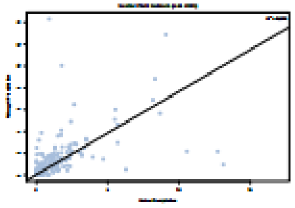
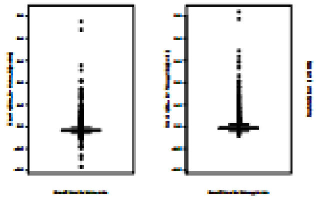
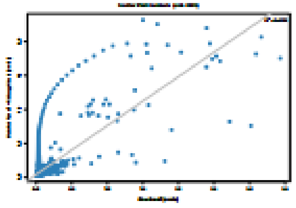
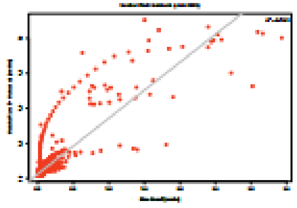
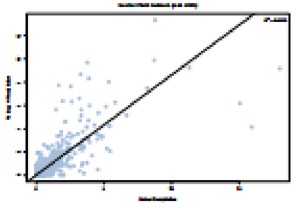
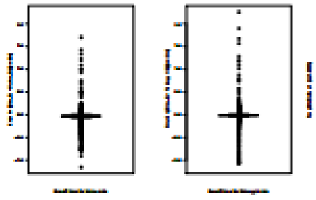
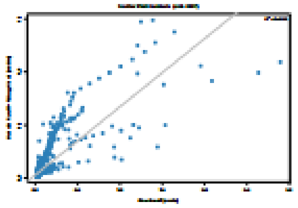
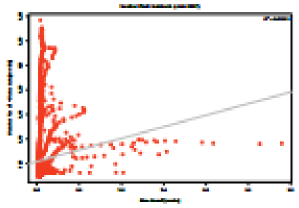
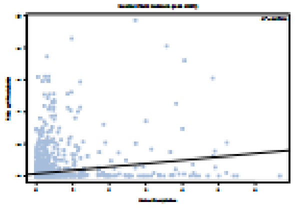
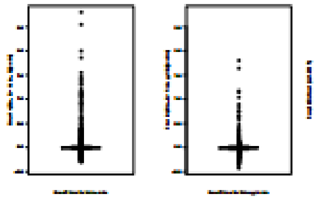
JJA of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.8: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are for summer season (JJA) for Goldach

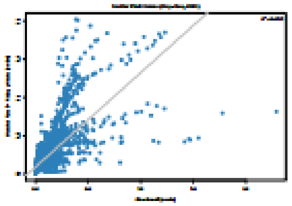
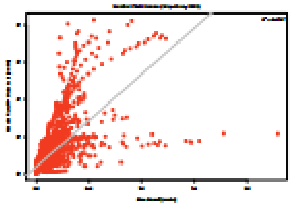
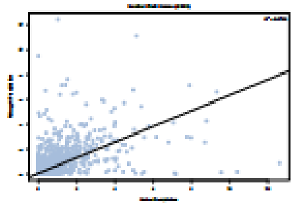
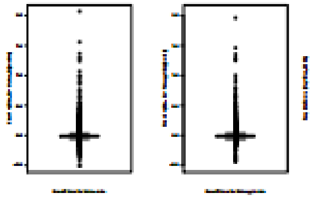
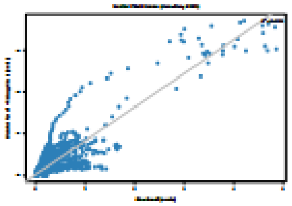
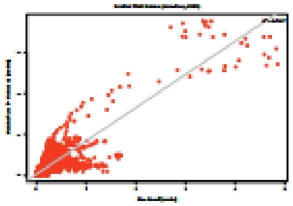
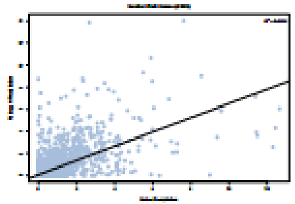
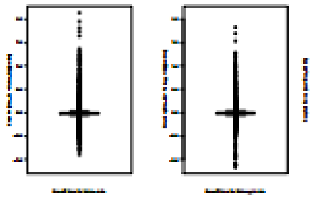
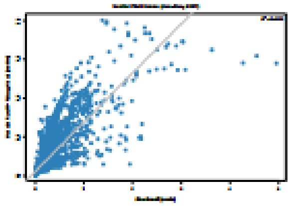
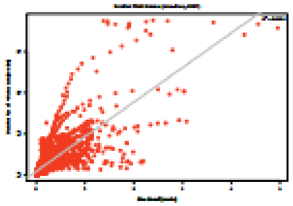
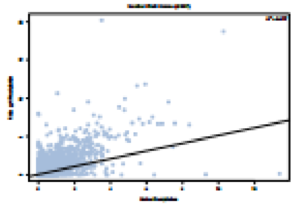
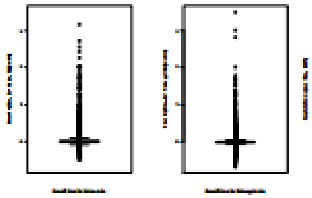
Year of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.9: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are of yearly period for Emme

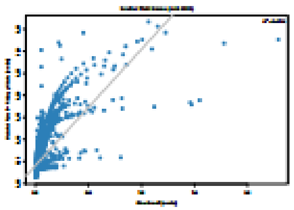
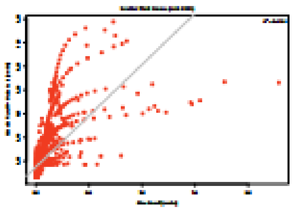
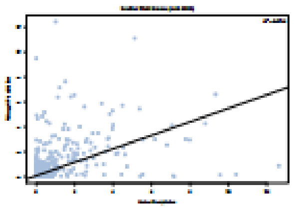
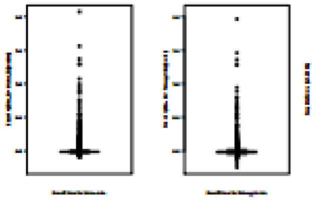
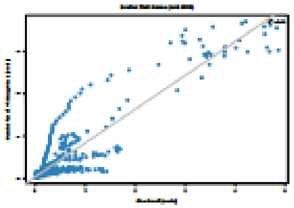
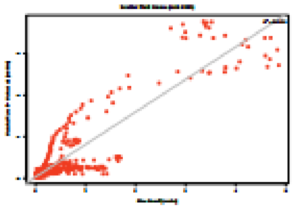
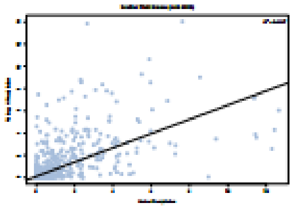
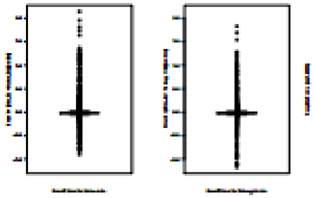
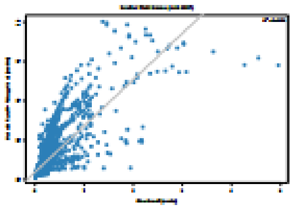
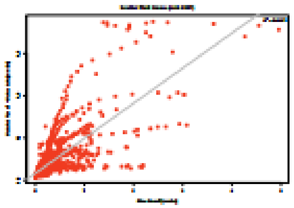
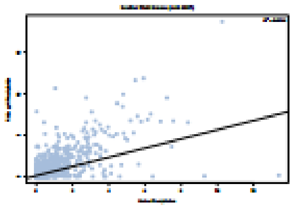
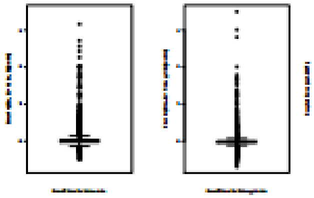
JJA of:	Scatter Plot RdisaggH Q vs. Obs. Q	Scatter Plot Meteo Q. vs. Obs. Q	Scatter Plot RdisaggH Precip. vs. Meteo. Precip.	Box plot Err. 1 and Err. 2
2003				
2005				
2007				

FIGURE B.10: Scatter plots showing correlation between RdisaggH and Meteo. precipitation datasets and their simulated runoffs with the obs. runoff. The box plot illustrates the correlation of RdisaggH and Meteo. errors. Here, error 1 = obs. runoff - Meteo. runoff, and error 2 = obs. runoff - RdisaggH runoff. All these plots are for summer season (JJA) for Emme

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