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Application of a lumped model to the watershed of Pöllau

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ABSTRACT

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The objective of the present thesis was to simulate the rainfall-runoff processes of Pöllau, a small watershed (58 km²) located in the east part of Styria, in Austria.

The study area of Pöllau near Hartberg was established in 1978 and since then, for thirty-six years it has been the subject of a wide range of research purposes. Therefore, it is well equipped with hydro-meteorological measuring instruments which are nowadays supervised by the Institute of Urban Water Management and Landscape Water Engineering Graz University of Technology.

An attempt was made to summarize the available information, database, international publications and research programs executed in the watershed.

The study gives an overview of the most important terminology and methodology of hydrological modelling, particularly emphasizing the methods also applied in the present work.

The rainfall-runoff process of the catchment was simulated by a lumped hydrological model, HEC-HMS (*Hydrological Engineering's Centre-Hydrological Modelling System*). Firstly, the basin and meteorological models were constructed with Geographical Information System toolbars and other parts of the model were created within the hydrological model. Then, after executing sensitivity analyses with the free parameters, the rainfall-runoff model was successfully calibrated and validated in more continuous simulations describing the seasonal variability of the catchment. The goodness-of-fit was described by numerous objective functions.

The modelling procedure revealed several inadequacies resulting from partly the nature of the applied hydrological model, partly the available hydrological database.

Finally, the results were discussed and future development prospects were outlined.

ABSZTRAKT

Széles Borbála
Pöllau vízgyűjtőjének csapadék-lefolyás modellezése

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Jelen szakdolgozat célja egy osztrák kisvízgyűjtő (58 km²), a kelet-stájerországi Pöllau vízgyűjtőjének csapadék-lefolyás modellezése volt.

A Hartberghez közeli mintavízgyűjtőt 1978 óta fejlesztik. Pöllau számos tanulmány, diplomamunka, kutatás központja és tárgya, köszönhetően több mint harminchat év hidrometeorológiai mérési adatsorainak, topográfiai adottságainak és egyszerű megközelíthetőségének. Jelenleg a Grazi Műszaki Egyetem Vízi Közmű és Környezetmérnöki Tanszéke felelős az adatgyűjtésért és felügyeli a mérőműszereket.

A dolgozat összefoglalja a vízgyűjtőről elérhető legfontosabb információkat, adatokat, nemzetközi publikációkat és kutatómunkákat.

Jelen tanulmány áttekinti a hidrológiai modellezés legalapvetőbb fogalmait és lépéseit, különös részletességgel az alkalmazott eszközöket.

A csapadék-lefolyás kapcsolatát HEC-HMS (*Hydrological Engineering's Centre-Hydrological Modelling System*) összevont paraméterű hidrológiai modellel szimuláltam. Első lépésben térinformatikai eszközökkel létrehoztam a modell vízgyűjtő és meteorológiai modell részét és HEC-HMS alkalmazásával a modell többi részét, majd a szabad paraméterekre elvégzett érzékenységvizsgálatot követően sikeresen kalibráltam és validáltam a modellt. A modellt hosszú idősorokra, több időszakra is felállítottam. Az illeszkedés jóságát több vizualizációs eszközzel és paraméterrel is számszerűsítettem.

A modellezés folyamata feltárt számos pontatlanságot és hibát, melyek részben az alkalmazott modell hiányosságaiból, részben az elérhető bemenő adatok minőségéből fakadtak.

A dolgozat végül összefoglalja és értékeli az elért eredményeket, valamint javaslatokat tesz jövőbeli fejlesztési lehetőségekre.

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Introduction

Under the extreme circumstances of weather conditions, it has become basically relevant to get an appropriate introspection in the magnitude of flood discharges, seasonal variability of runoff and the rainfall responses of small or medium sized watersheds. These research programmes significantly support flood control, hydraulic engineering and urban water management. Furthermore, the results of hydrological models can be applied in hydrodynamic or joint hydrologic-hydraulic models.

There are several existing empirical formulas to determine the magnitude of discharges with a specified return probability, however, these can be only carefully adopted to catchments with different size, soil characteristics, slope or land use. Nowadays, application of hydrological models is becoming widespread. The need for flexible, easy and fast methods is increasing.

However, long time series are other vital parts of model development. Data collection with sufficient measuring instruments and adequate density is an underlying condition of hydrological modelling.

The research area of Pöllau near Hartberg, located in Eastern Styria, Austria was established in 1978 within the framework of the International Hydrological Programme (IHP). It is well equipped with a wide range of modern hydro-meteorological measuring instruments and the data have been registered for almost thirty-six years which gives rare and special opportunities for hydrologists. Measurements, data collection and processing are executed by the Institute of Urban Water Management and Landscape Water Engineering Graz University of Technology.

The primer target of the present study was to construct a lumped hydrological model and analyse the rainfall-runoff processes of the Pöllau catchment near Hartberg located in the east part of Styria, in Austria by applying HEC-HMS (*Hydrological Engineering's Centre-Hydrological Modelling System*).

The thesis is structured in the following way: firstly, I presented the hydrological characteristics of the catchment throughout a field study in March and summarized the available descriptions, publications, reports of different research programs and hydro-meteorological measurements. In addition, I studied the background databases which were provided by the Institute and later applied in the present study. The comprehensive description of the study area is found in the first paragraph, the second paragraph contains information about the data foundation.

The third part of the thesis provides an overall description about hydrological modelling regarding terminology and methodology, while the fourth paragraph describes the steps of construction of the model structure, sensitivity analyses, calibration and validation of the hydrological model.

Finally, the results, drawbacks and development prospects modelling and other revealed inadequacies are discussed in the two last, fifth and sixth paragraphs.

1. Description of the study area

1.1. Topography

Pöllau in Hartberg is located in the east part of Styria, in Austria (Figure 1). The ridgeline of the drainage basin encompasses the area in an arch shape. The geodetic height changes between 399 m aA¹ and 1288 m aA. The average height of the terrain is 710 m aA (TU Graz 2006).

The drainage area of the catchment is 58 km² above the base discharge gauge on Saifenbach (Firle 2008).

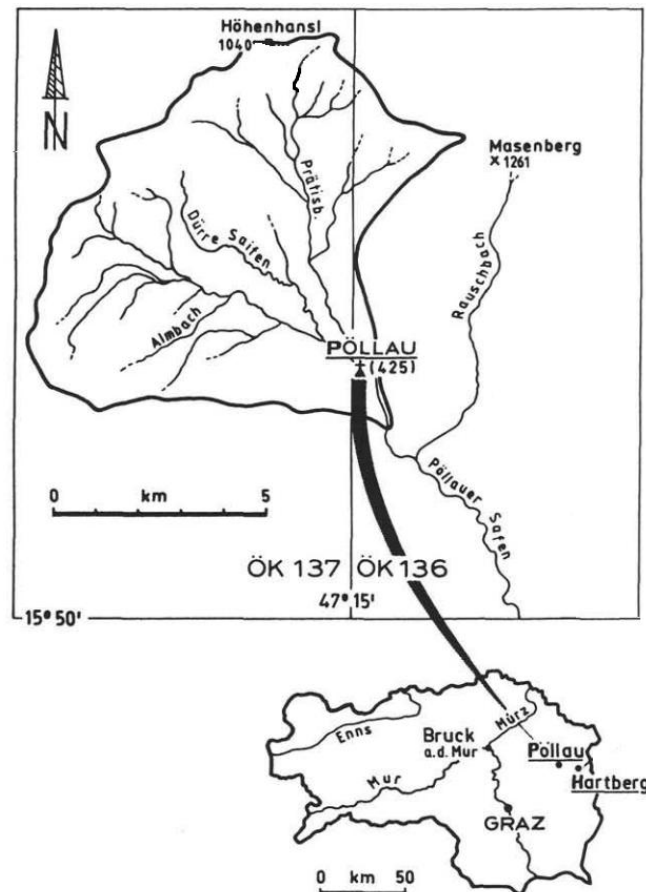


Figure 1 Location of the Pöllau catchment (Source: Rank et al 2003)

1.2. River network

The three main streams of the catchment are Saifenbach (with a drainage area of 31.3 km²), Prätisbach (with a drainage area of 21.1 km²) and Mausbach (with a drainage area of 3.6 km²), the remaining area is 2 km² (TU Graz 2006).

The main flow paths of the watershed have similar runoff time due to the compact form of the subcatchments which results high peak flows with a short time duration at the confluences. 24.2 % of the watercourse is regulated. Prätisbach and Mausbach are regulated by retention reservoirs. The vegetation of the banks is intact (Firle 2008).

¹ The height is given in m aA which refers to the water level of the Adriatic Sea at the Sartorio mole in the Port of Trieste (www.wikipedia.en 08.04.2014).

1.3. Land use

Land use is dominated by silviculture and agriculture (Figure 5). Less than 2% of the area is urban and used by traffic or settlements. The climatically and topographically convenient hill slopes are used to grow special cultivations like grape or fruits. Farmland and green areas dominate in the valleys. Forests cover the steep, south or north facing slopes (Firle 2008).

1.4. Geology and pedology

The geological designation of the Pöllau catchment is tertiary hilly landscape with Eastern Alpine low mountain range character (Firle 2008).

The ridgeline of the drainage basin is a crystal mountain (82.7 % of the area) which encloses the catchment from three sides and defines a clear delimitation from the neighbouring watersheds with its tertiary sediments (12.7 % of the area) and quaternary valley sediments (4.6 % of the area) as it is shown in Figure 2 (Ruch et al 2006). In south-east the valley widely opens in the direction of the Eastern Styrian tertiary basins (Firle 2008).

The predominant physical soil textures in the stream valleys are brown earth and loamy soil with low water retention. In the major part of the region, the physical soil type is loam, loamy sand or sandy loam, while gravelly soil rarely occurs in the area (Firle 2008).

The crystalline basement is mainly impervious. In the valley area, there are thin sediment layers which are covered by a loam layer. Due to the impervious nature of the loam layer and the soil characteristics in the region, the infiltration of water is hindered causing sometimes relatively large surface runoff (Firle 2008).

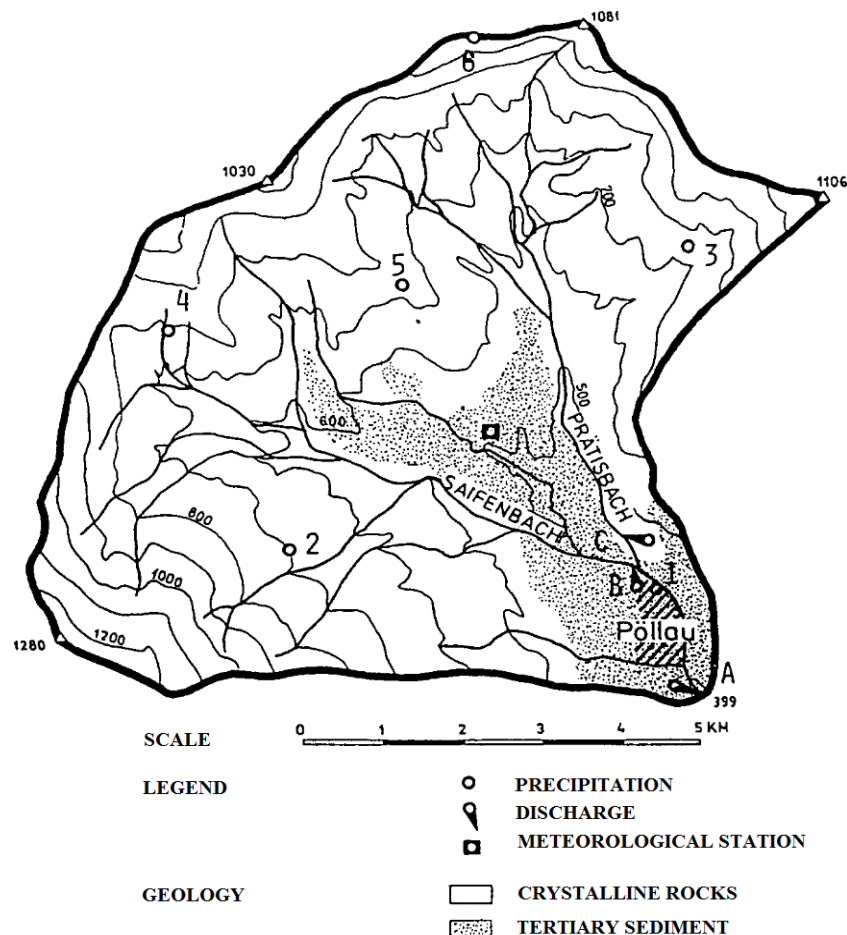


Figure 2 Geology of the Pöllau catchment with the measuring instruments (Bergmann 1993)

Detailed hydrologic investigations found that there are good water storage capacities and the residence time of the groundwater is relative high, for instance, in the metamorphic crystalline of the Pöllauer Saifen (Zojer et al 1996, Bergmann et al 1996).

According to isotope-hydrological investigations in micro-catchments of the Pöllau basin, in the crystalline border mountains, a normal two-component runoff model - with direct runoff and baseflow – is not able to describe precisely the runoff processes of the area. There must be a third type of runoff which is independent from either surface direct flow or baseflow before the flood event. The isotope investigations showed that this type of water (weathered material) also originates from precipitation water such as surface runoff, however, it is stored underground in the unsaturated zone for weeks or even months long. Baseflow is also stored under the surface, in the joint aquifer, but usually for years. During long storm events, the weathered material from the unsaturated zone is pressed out by the infiltrated precipitation ('soil-air cushions'). In this case, direct surface runoff is negligible. According to Figure 3, water from sequential rainfall events infiltrates the soil, meanwhile, soil-air cushions are formed temporarily preventing the mixture of waters and pressing the water out from the saturated zone underneath. This pressure explains the sudden and fast peak flows without any time delay after the beginning of a precipitation event. This result also assumes that infiltration has a great significance in runoff processes. Unfortunately, due to the lack of local precipitation data, the investigations did not have quantitative results (Rank and Papesch 1997).

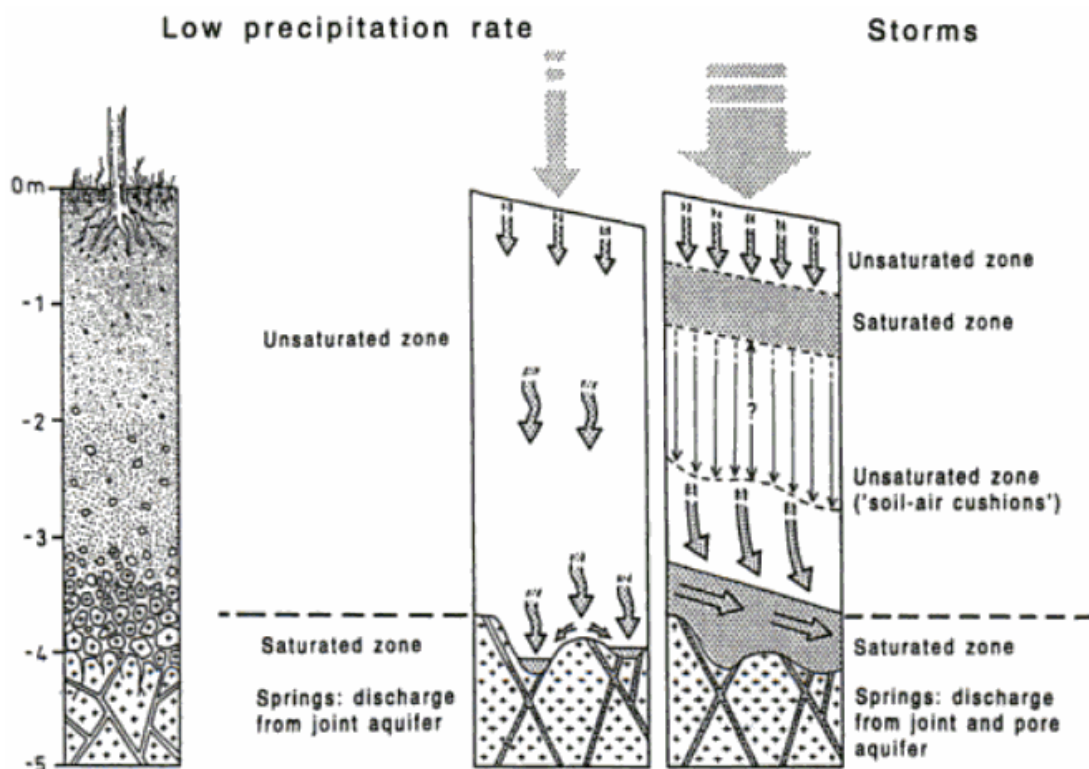


Figure 3 Conceptual hydrogeological runoff model of the crystalline border mountains of Styria (Rank and Papesch 1997)

1.5. Climate

The climate of the area is labelled due to its location on the south-eastern slopes of the Alps (Bergmann et al 2000). The climatic features of the watershed are similar to many Styrian basins' characteristics where Styrian mountains work as climate barriers against the Alps

(Ruch et al 2006). Therefore, the basin is well-protected against northern and north-western influences of the weather, however, it is not sheltered from the southern and south-eastern impacts (Bergmann et al 2000).

Thunderstorms regularly occur in the summer months often causing sudden floods (Firle 2008). Such extreme events in the past were (Amt der Steiermärkischen Landesregierung 1999):

- 4. August 1992: 59.7 mm,
- 24. May 1994: 67.5 mm,
- 31. July 1997: 71.0 mm,
- 5. September 1998: 77.7 mm.

In the contrary, there are long lasting dry periods in the winter months (Firle 2008).

The average annual precipitation changes between 800 and 1000 mm. The monthly maximum precipitation is concentrated in the summer months (Bergmann 2000).

1.6. Summary of the most important characteristics of the watershed

The discharge regime of the main receiver, Pöllauer Saifenbach corresponds with streams in low mountain ranges. It has an all-year-round runoff, with a slight effect of snow melt and high peak flows in the summer months. Table 1 gives an overview of the most important information and data of the watershed.

Table 1 Most important data of the Pöllau catchment (TU Graz 2006)

General	
Area of the total watershed	58.0 km ²
Area of the subcatchments	
Saifenbach	31.3 km ²
Prätisbach	21.1 km ²
Höhenhansl	0.4 km ²
Mausbach	3.6 km ²
Morphology	Low mountain range of the Eastern Alps
Geology and Hydrogeology	Higher parts (headwaters) crystal substratum (82.7 % of the total area), lower parts tertiary hills (12.7 % of the total area), quaternary sedimentation (4.6 % of the total area)
Soil	Mainly brown earth and loamy soil with low permeability
Land use	Woods, mainly coniferous wood 44.6 %
	Meadows, plough-land, pastureland 44.1 %
	Settlements and roads 1.3 %
Morphological data	
Height (min/average/max)	398.47/711.34/1278.75 m aA (Figure 9)
Height of the main spring	880-1040 m aA
Perimeter of the area	33.01 km
Radial length	8.6 km
Medial width of the area	6.8 km
Form (Width/Length)	0.79
Greatest length of the valley	11.78 km
Coordinates of the centroid of the watershed	X=582732, Y=384180
Average slope of the main stream	11.03 %
Average slope	11.57
Density of water network	0.958 km/km ²

Hydrological data	
Runoff volume	Runoff volume of a stream in a low mountain range through the whole year, slight effect of snow melt, peak flows in the summer months
Average annual discharge (1979-2004)	0.49 m ³ /s
Greatest measured peak flow (04.08.1992)	92.14 m ³ /s
Lowest measured flow (05.01.2002)	0.04 m ³ /s
Average annual ground-water level	Not measured
Average ground-water recharge	Approximately 3-4 mm/a
Hydro-meteorological data	
Average annual temperature of the air (1979-2004)	6.9 °C
Average annual precipitation (1979-2004)	868 mm
Greatest daily precipitation height (30.06.1920, Cividino since 1920)	105 mm
Greatest monthly precipitation height (June 1979, Cividino)	341 mm
Average annual evaporation height (1979-2004)	599 mm
Rate of snow	Approximately 7 %
Average snow cover	Approximately 60 days

2. Data foundation

2.1. GIS database: digital terrain model and land use

At the request of the Institute of Urban Water Management and Landscape Water Engineering University of Technology Graz, the Agency of the Government of Styria (Das Land Steiermark) provided numerous GIS databases which were used for hydrological modelling purposes (BlueM [www.wiki.bluemodel.org 18.05.2014] of the watershed, Firle 2008). Within the present study, the undermentioned GIS datasets were used:

- Digital terrain model of the area (raster with a 10 m spatial resolution) (Figure 4),
- CORINE 2000 land use information (two dimensional vector polygons) (Figure 5).

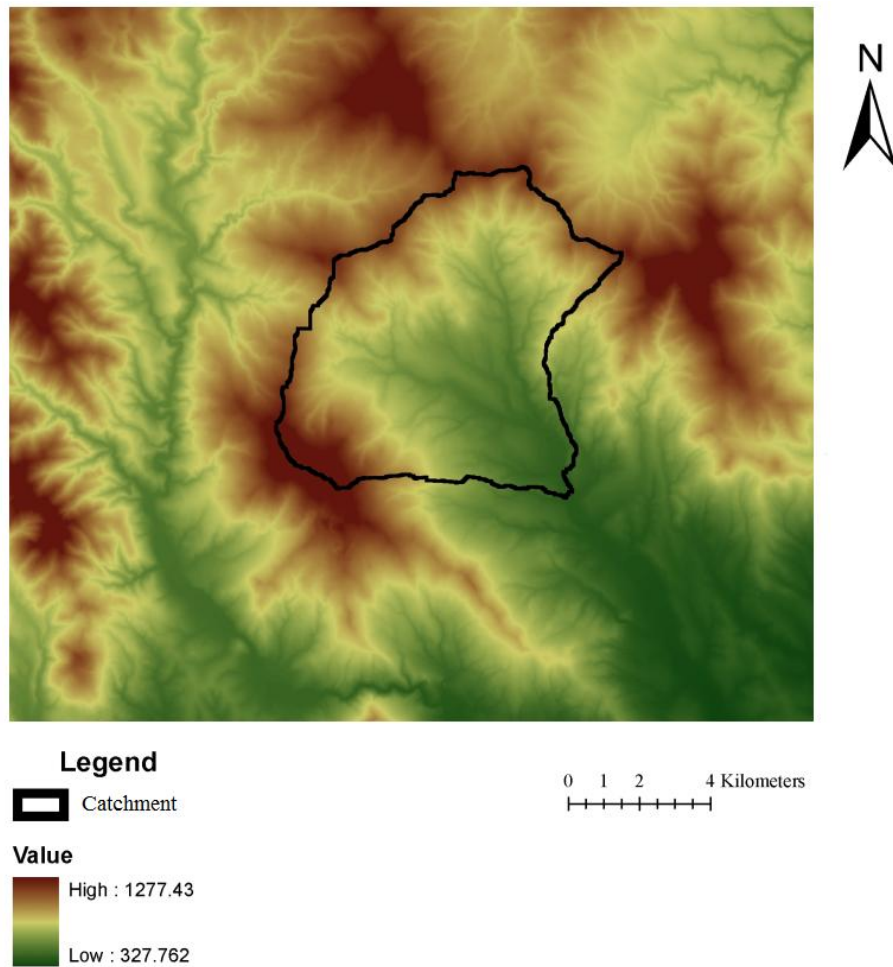


Figure 4 Digital terrain model of the Pöllau catchment (Source: Firle 2008)

The source of the most important land use information of the Pöllau catchment was a CORINE 2000 land use map stored in GIS database. According to CORINE 2000 land use database (Table 2) there are three main different land use types in the watershed, particularly the catchment shows the following structure (Firle 2008):

- 51.5 % of the total watershed's area is agricultural land (42.7 % of the total area complex land structure, 5 % cultivated land with significant natural vegetation and 3.8 % grassland and meadow),
- 44.7 % of the watershed's area is forest (28.3 % coniferous forest and 16.4 % deciduous forest) and
- 3.8 % of the watershed's area is urban area.

Table 2 shows the main land use categories of the watershed. In Table 2, one 'class' means that more than 75 % of the given area is treated in that way. 'Complex parcel of land structure' conceals homogeneous parts of arable land, permanent crops and/or permanent pastures which could be divided into own classes, if more than 75 % of the given area stood under the given agricultural treatment (Firle 2008).

Appendix A contains CORINE land use information about each subbasin (the subbasin delineation is detailed later, in Paragraph 4.1) of the Pöllau catchment.

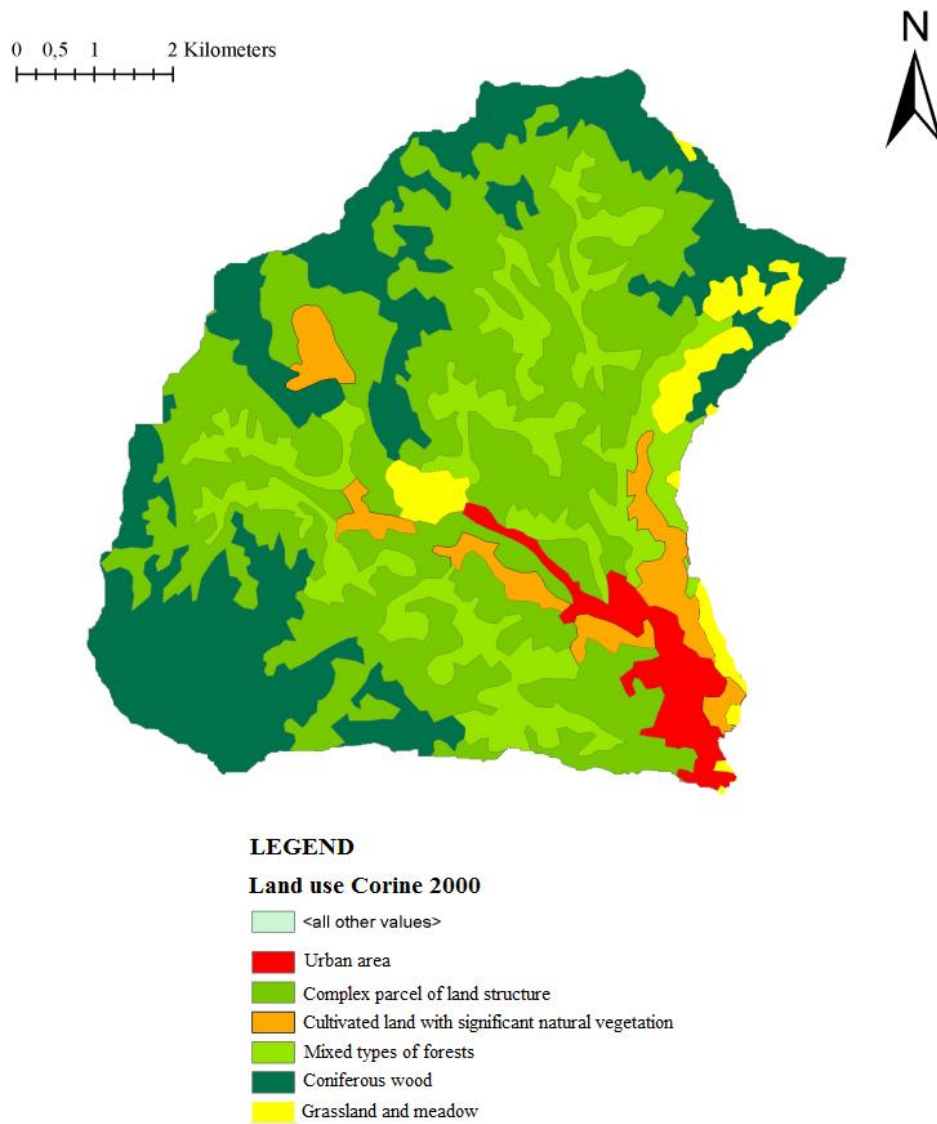


Figure 5 Corine 2000 Land use data of the Pöllau catchment (Source: Firle 2008)

Table 2 CORINE 2000 land use information

Class 1	Class 2	Class 3	Proportion of the total area (%)
Built-up area	Urban area	Urban area	3.8
Agriculture	Heterogeneous agricultural area	Complex parcel of land structure	42.7
Agriculture	Heterogeneous agricultural area	Cultivated land with significant natural vegetation	5.0
Agriculture	Pastures	Grassland and meadow	3.8
Forests and natural area	Forests	Mixed types of forests	16.4
Forests and natural area	Forests	Coniferous wood	28.3

2.2. Soil data

Unfortunately, there is a lack of detailed digital soil maps about the watershed. However, there are three alternative sources which provide proper geological information about the catchment:

- Digitaler Atlas Steiermark (www.gis.steiermark.at 20.03.2014): provides detailed geological and geotechnical maps all over Austria,
- eBOD (www.gis.lebensministerium.at/eBOD 20.03.2014): gives a wide range of information about soil characteristics and physical soil properties (soil type, soil category, permeability, erosion, humus content, water conditions, field capacity) all over Austria,
- BOKU (www.bodenkarte.at 20.03.2014): is a free digital soil map of entire Austria with a 1 km spatial resolution and attribute table, in ESRI shape file format.

Geological and geotechnical formations of the watershed, for each subwatershed can be found in Appendix B.

Appendix C contains detailed soil data of the whole Pöllau catchment, for each subcatchment according to eBOD.

2.3. Hydro-meteorological measurements

2.3.1. Overview

The research area of Pöllau near Hartberg, Eastern Styria was established in 1978 within the framework of the International Hydrological Programme (IHP). The catchment was intended to serve scientific research purposes. Therefore, it is well equipped with hydro-meteorological measuring instruments (Figure 6). The reasons of choosing this catchment were, on the one hand, general scientific objectives, on the other hand, practical purposes such as the geographically favourable location with a good access to the university city of Graz (Bergmann et al 2000).

The measurements were executed by the Institute of Hydraulics and Hydrology Graz University of Technology and the hydrographical service in Styria until the autumn of 2001. Since then the measuring instruments and the data processing of the Pöllau catchment have been supervised by the Institute of Urban Water Management and Landscape Water Engineering Graz University of Technology (Firlre 2008).

Since 2001 the Institute of Water Resources Management, Hydrogeology and Geophysics (previously known as Institute of Hydrogeology and Geothermal Engineering) of Joanneum Research Forschungs mbH was also participating in the measurements with a focus on subsurface runoff processes, especially in the small subcatchment Höhenhansl which together with the whole Pöllau watershed was a part of the AGREALAP (Agri-Environmental Measures and Water Quality in Mountain Catchments) European Union Project from 1995 to 1999. Moreover, the institute also operated a discharge gauge on Zeilerbach from September 1996 to July 2000 and hydro-meteorological data (discharge, water temperature, electrical conductivity, wind, humidity and precipitation) have been also collected in Rabenwald since 2001 (Ruch et al 2006).

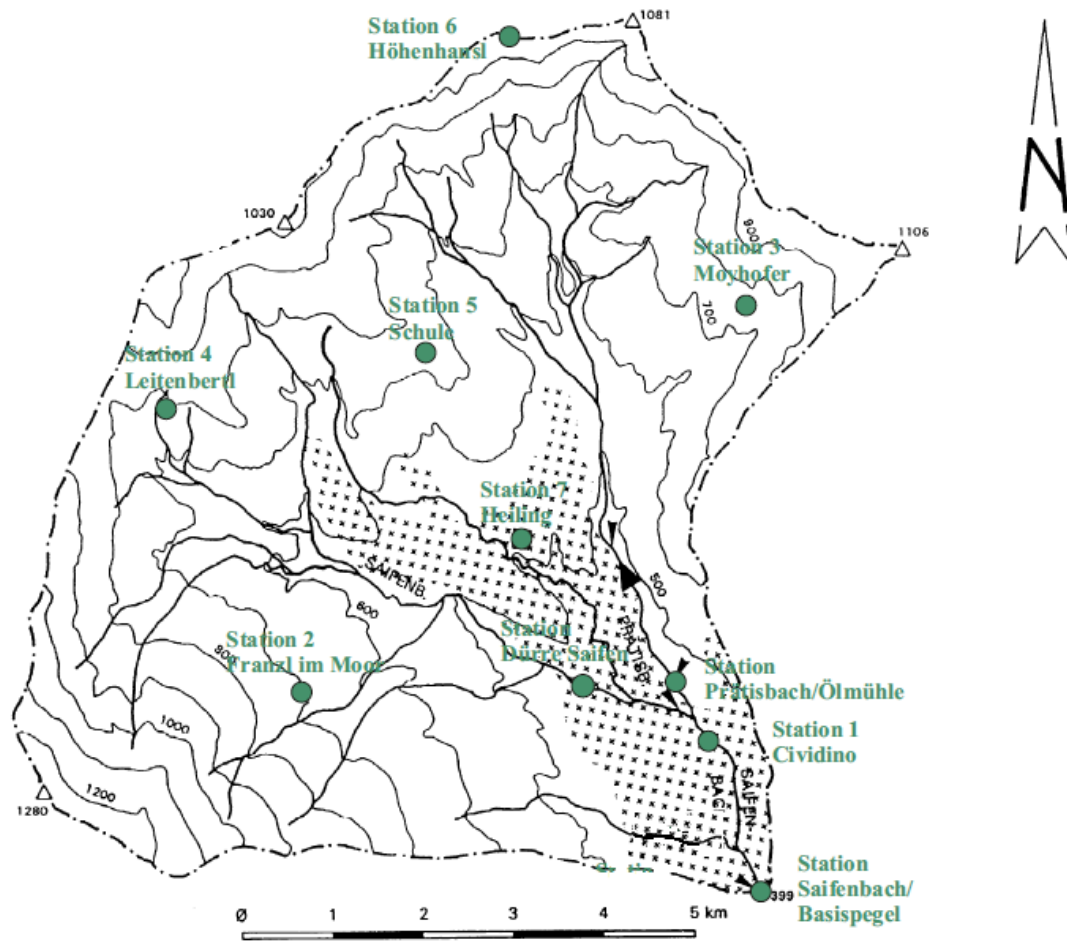


Figure 6 Site plan of the Pöllau catchment (Source: TU Graz 2006)

The formerly used and currently operated measuring instruments and their most important attributes are found in Table 3.

Table 3 Meteorological measurements in the Pöllau catchment (Ruch et al 2006)

Station	Year of establishment	Height (m aA)	Measurement	Available (from-to)	R-analogue DT-digital	Temporal resolution	Remark
Höhenhansl	1979	1040	Precipitation	1980-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth)
Lysimeter station in forest (Hydrometeorology and unsaturated zone)	1995		Precipitation	1995-ongoing	DT	15 minutes (total precipitation)	Tipping bucket RM 826-0.2
			Air temperature, Humidity				Combined sensor (Kombi Sonde Type HP 100 A)
			Surface runoff				1 m ² area
			Water retention, Matrix potential, Ground temperature			Daily	Tensiometer T6 (Fa. UMS)
			Leechate				Pressure plate
Lysimeter station in grassland (Hydrometeorology and unsaturated zone)	1995		Precipitation	1995-ongoing DT	DT	15 minutes (precipitation sum)	Tipping bucket RM 826-0.2
			Air temperature, Humidity				Combined sensor (Kombi Sonde Type HP 100 A)
			Surface runoff			Daily	1 m ² area

Lysimeter station in grassland (Hydrometeorology and unsaturated zone)	1995		Water retention, Matrix potential, Ground temperature Leechate		DT	Daily	Tensiometer T6 (UMS) Pressure plate
Leitenbergl	1979	800	Precipitation	1980-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth)
Moyhofer	1979	740	Precipitation	1980-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth)
Schule-Köppelreith	1979	740	Precipitation	1980-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth)
Franzl am Moor	1979	729	Precipitation	1980-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth)
Heiling	1981	525	Precipitation Meteorological data Wind Air temperature Humidity Air pressure Radiation Ground temperature Evaporation	1982 1991-ongoing April-October	DT DT	variable 10 minutes 10 minutes 10 minutes 10 minutes 1 hour 1 hour	Tipping bucket (0.1 mm and 0.2 mm, Horváth) Weighing-type NIWA Med/K505 (Sommer) Tipping bucket aboveground (0.1 mm, Pair) Vane anemometer INT 1 (Sommer, Kroneis) Wind direction sensor INT 3 (Sommer, Kroneis) Combined sensor moisture-temperature (FG80Hpt 100, Galltec) Barotransmitter Type 317 (Kroneis) Starpyranometer Nr. 8101 (PH. Schenk) Temperature sensor (Own construction) Evaporation tub (Own construction) and water-level sensor (Sommer)
Cividino	1979	420	Precipitation Air temperature, Humidity	1979-ongoing	DT	variable	Tipping bucket (0.1 mm, Horváth) Combined sensor (Kombi Sonde Type HP 100 A)
Rabenwald	2001		Precipitation Air temperature, Humidity	2001-ongoing	DT	15 minutes (precipitation sum)	Tipping bucket RM 826-0.2 Combined sensor (Kombi Sonde Type HP 100 A)
Höhenhansl, Discharge gauge	1992		Water-level Electrical conductivity Temperature	1992-ongoing	DT	5 minutes	Sensor PTCR 1830 Sensor Tetracon
Höhenhansl, Quelle Arzt	1995		Discharge Electrical conductivity Temperature	1995-ongoing	DT	Daily overflow Daily water meter	Sensor PTCR 1830 Sensor Tetracon
Zeilerbach midway	1996		Water-level Electrical conductivity Temperature	1996-2000	DT	5 minutes	Sensor PTCR 1830 Sensor Tetracon
Dürre Saifen	1980 (relocated 1996)		Water-level	1980-ongoing	R		Water level gauge (Rittmayr)
Prätisbach-Wildolzrechen	1988		Water-level	1988-1997, 2000-ongoing	R, DT	5 minutes	Water level gauge, Pressure probe MRS-4 (Sommer)

Pratisbach-Öhlmühle	1980		Water-level	1980-ongoing, 2003-ongoing	R, DT	5 minutes	Water level gauge (Rittmayr)
Mausbach	1996		Water-level	1996-ongoing	DT	5 minutes	Pressure sensor DRS-4 (Sommer)
Saifenbach	1980 (relocated 1983 and 1988)		Water-level	1980-2001, 2001-ongoing	R, DT	5 minutes	Water level gauge, Pressure sensor MRS-4 (Sommer)
Rabenwald	2001		Water-level Electrical conductivity, temperature	2001-ongoing	DT	5 minutes	Sensor PTCR 1830 Sensor Tetracon

The density of measuring instruments in the area is high. The present facilities of the catchment consist of seven precipitation gauges, four discharge gauges and one climate station. The latter also measures the air temperature and evaporation rate (Firle 2008).

The meteorological station in Heiling (Photo 1 and Photo 2) is equipped with precipitation gauges which measure based on different principles (tipping bucket and weighing precipitation gauges) and in different heights (standard height and ground level). Thermometers (air and soil: + 0.1 m, - 0.5 m, -1.0 m), barometer, hygrometer, albedometer, evaporation pan and anemometer are also installed near the station (Ruch et al 2006).



Photo 1 Meteorological station in Heiling I.
(by Günther Gruber 2014)



Photo 2 Meteorological station in Heiling II.
(by Günther Gruber 2014)

The collected precipitation, discharge and evaporation data of the year 2004 were used as the calibration and validation time period of the hydrological model in the present thesis.

2.3.2. Precipitation

The instrumental equipment consists of automatic precipitation gauges with time variable precipitation records: tipping bucket rain gauges and one weighting precipitation gauge. The self-registering precipitation gauges operating on the tipping principle were developed together by the Hydrographical Department and Systems Technology in Research Centre (Figure 7). The instruments were constructed to measure either liquid or solid precipitation and consist of:

- a drain bowl, which is an upper funnel with a surface area of 500 cm^2 collecting precipitation,
- a modified Horner tipping bucket with a volume of 5 cm^3 ,
- electronics with magnetic tape recorder and
- a collecting container.

The instrument also contains some measurement controls such as the possibility of preparing remote data transmission. The elements of equipment are placed altogether in compact houses (TU Graz 1987).

The precipitation heights are time variably recorded on memory cards which are replaced in every two or three year. The tipping buckets are often calibrated by instruments specially designed for field applications and the measured precipitation heights are corrected by the calibrated curves (Ruch et al 2006).

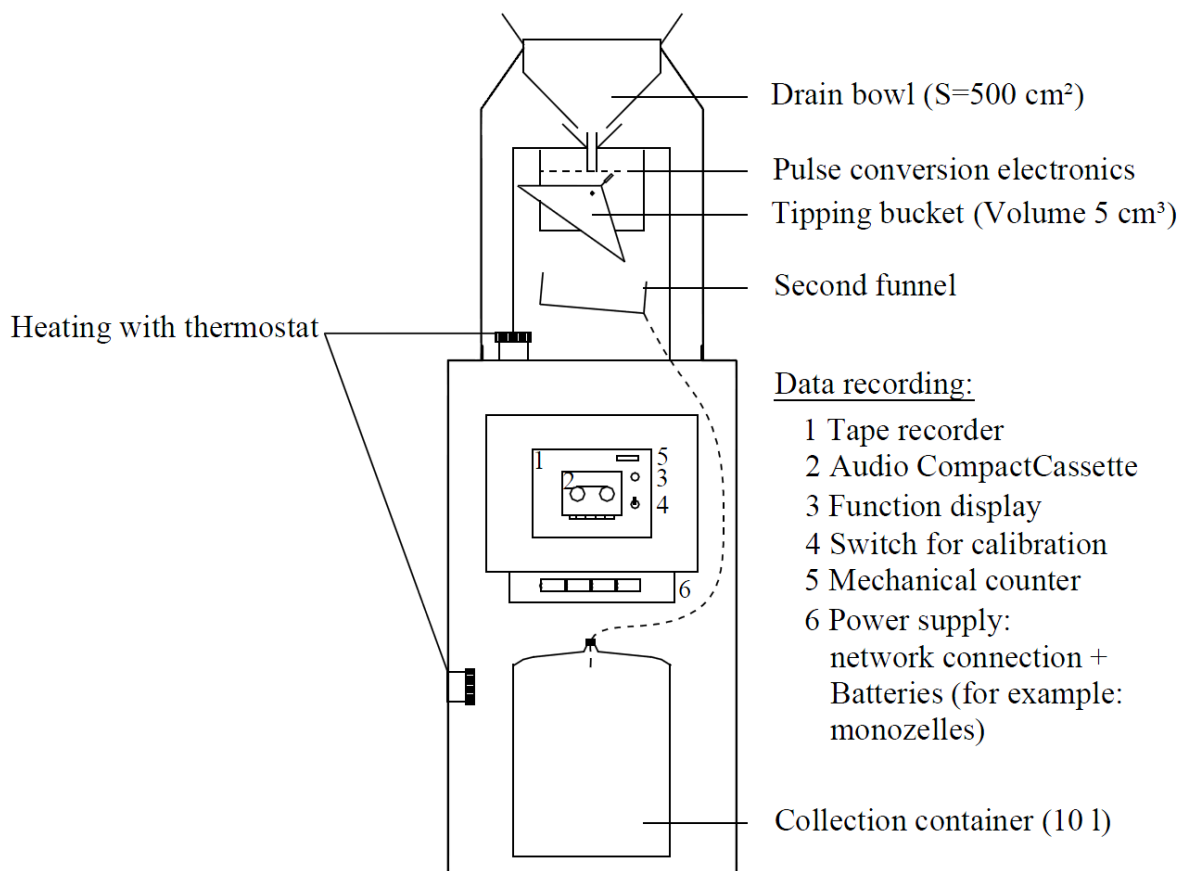


Figure 7 Automatic precipitation gauge (Source: TU Graz 1987)

The precipitation events are recorded in every five minutes by seven precipitation gauges located within the watershed as Figure 8 shows (Firle 2008).

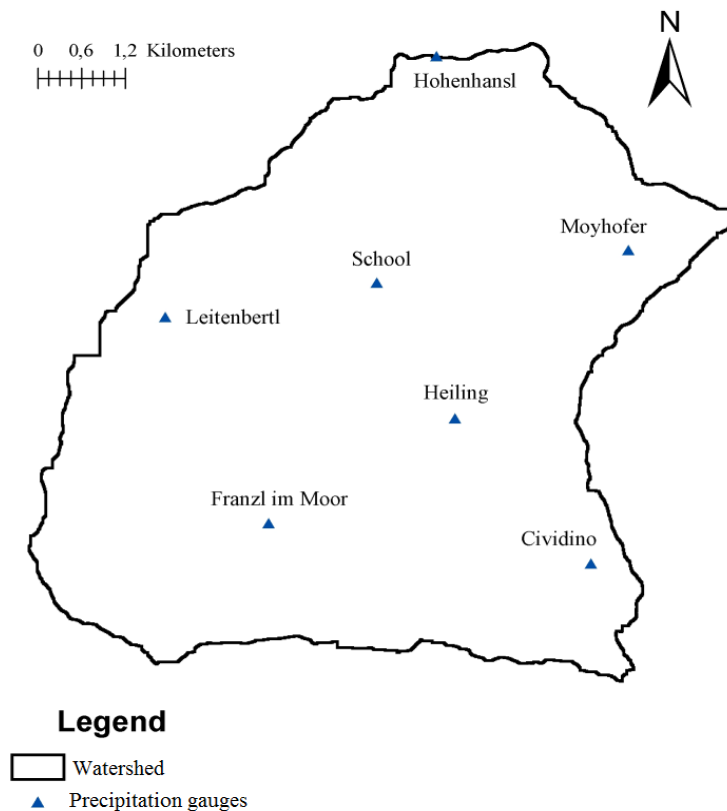


Figure 8 Precipitation gauges in the Pöllau watershed (Source: GIS Database, Firle 2008)

The precipitation gauges are distributed according to height and location in a way that the measurements are representative both for the whole catchment and for the subcatchments (TU Graz 1987). Figure 9 shows the hypsogram, altitude distribution of the precipitation gauges.

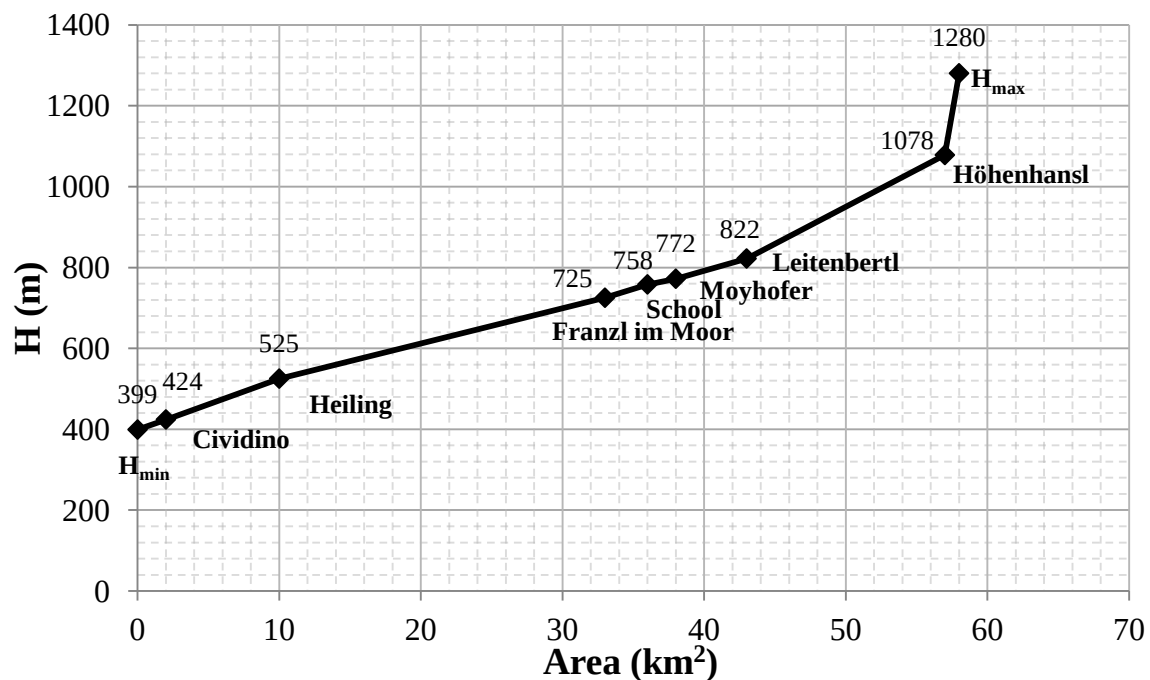


Figure 9 Hypsogram - altitude distribution - of the precipitation gauges and the watershed (TU Graz 2006)

The coordinate system of the available GIS database of the precipitation gauges justified the conversion of the coordinate systems. The locations of the precipitation gauges (Table 4) were known in Gauss-Krüger M34 Coordinate System (Firle 2008). Austria GK M34 is used in Austria - east of 14° 50' E (Müller 2011). However, the other layers were in Bessel 1841 Transverse Mercator projected. The two coordinate systems regarding their spatial references and extents were the same, although, for some reason, their names were different. The calculations and operations do not work between layers, if their projections are not the same, even if there is only a difference in their names. Therefore, after the query of the precipitation gauges' locations, the longitudinal and latitudinal coordinates were collected in a text file according to a certain format (first row is a header representing the feature type; from the second row, each row contains the id and x, y, z coordinates of the precipitation gauges; the last row contains the word 'END') and loaded into ArcGIS (*Samples toolbox/Data Management/Features/Create Features From Text File*).

Table 4 Coordinates of the precipitation gauges

Name of the station	Geographical location		Height (m aA)
	Bessel 1841 Transverse Mercator		
	Geographical longitude	Geographical latitude	
Cividino	712381	241034	424
Franzl im Moor	707932	541620	725
Moyhofer	712894	245602	772
Leitenbertl	706505	244626	822
School Köppelreith	709426	245130	758
Höhenhansl	710247	248430	1078
Heiling	710505	243147	525

2.3.3. Evaporation

The evaporation is measured with an evaporation pan in Heiling. A metal sphere swimming on the water surface is connected to an electronic transmitter (displacement measurement through induction) which measures with 0.1 mm precision. At the beginning of the measurements water is poured into the pan until a marked height. The water level with the sphere starts sinking due to the evaporation.

Evaporation is measured from April to November. The evaporation is registered with one hour time step (Firle 2008).

2.3.4. Discharge

Water level measurements are carried out by pneumatic gauges with writing stripe and pressure gauges with digital registration system (Ruch et al 2006). Besides the normal water surface level, the time of its discrete changes (within a threshold ± 1 cm) is also registered (TU Graz 1987).

Four discharge gauges can be found in the watershed as Figure 10 shows, which register the water level in every five minutes. The official gauges in the catchment are the station in Ölmühle and the base gauge on Saifenbach.

According to the locations of the discharge gauges (Figure 10), the watershed is divided into three subcatchments (Firle 2008):

- Prätisbach Wildholzrechen,
- Prätisbach Ölmühle and
- Dürre Saifen.

Other discharge observations downstream in hierarchical order are the gauge in Waltersdorf on Saifen with a drainage area of 343 km² and Elterndorf on Lafnitz which has a drainage area of 1956 km² (Ruch et al 2006).

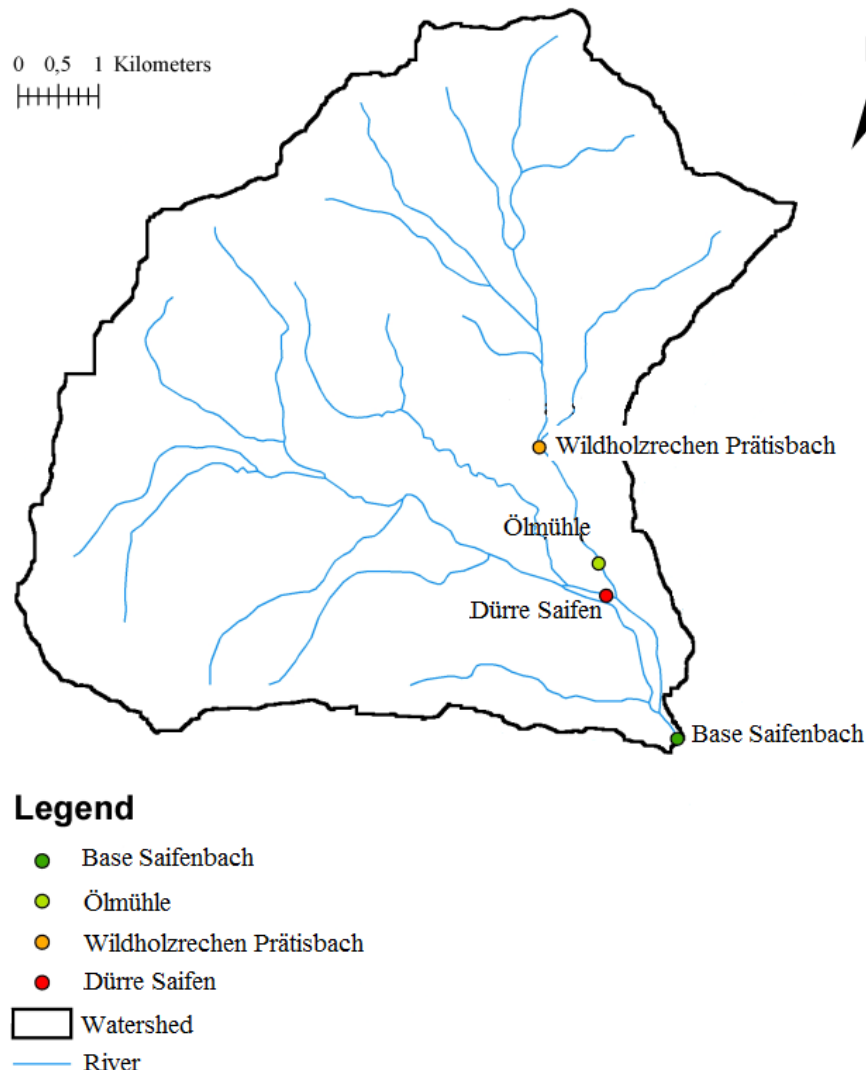


Figure 10 Discharge measurements in the Pöllau catchment (Source: Firle 2008)

The discharge measurements are regularly controlled by hydrometric impellers or with dilution method near the discharge gauges. The other purpose of these measurements is to generate proper rating curves in the cross sections of the gauges (Ruch et al 2006) which are used to generate discharge data from the water surface level measurements.

The locations of the discharge gauges can be found in Table 5.

Table 5 Coordinates of the discharge gauges (Firle 2008)

Station	Geographical location		Height (m aA)
	Bessel 1841 Transverse Mercator		
	Geographical longitude	Geographical latitude	
Saifenbach	712959	239487	400
Ölmühle	712007	241685	430
Wildholzrechen	711366	243141	480
Dürre Saifen	No data		430

In 1993 a method based on velocity measurement using tracers was developed in the subwatershed of Prätisbach. The aim of the method was to find out hydraulic flow parameters of discharge in smaller catchments. In addition, the measured runoff times of the watercourses enabled to detect the points with same runoff times and depict isochrones, the lines of the watershed with same runoff times (Bergmann 1993). The isochrones of the Prätisbach catchment according to measured runoff times can be seen in Figure 11. Figure 12 shows isochrones calculated by the Kirpich formula.

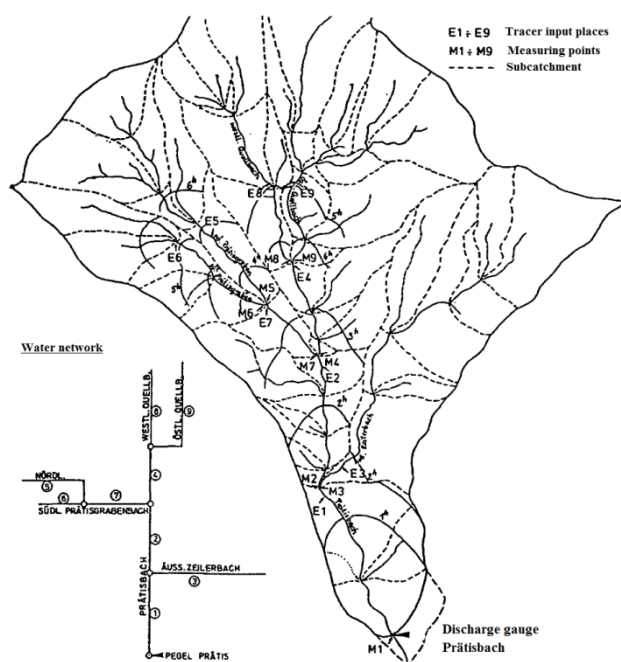


Figure 11 Watershed of Prätisbach with the measured isochrones (original scale: 1:25 000) (Bergmann 1993)



Figure 12 Watershed of Prätisbach with the measured isochrones according to Kirpich (original scale: 1:25 000) (Bergmann1993)

2.3.5. Summary of the hydro-meteorological measurements

Table 6 summarizes the current hydro-meteorological measurements executed in the watershed of Pöllau.

Table 6 Hydro-meteorological measurements in the Pöllau catchment (Firle 2008)

Name	Place of the measurement	Type	Unit	Remark
Base discharge gauge	Saifenbach/Base	Discharge	m ³ /s	Official gauge
Ölmühle	Prätisbach / Ölmühle	Discharge	m ³ /s	Official gauge
Dürre Saifen	Saifenbach/GH Gruber	Discharge	m ³ /s	Use with caution
Wildholzrechen Prätisbach	Prätisbach / Wildholzrechen	Discharge	m ³ /s	Use with caution
Heiling	Central station Heiling	Air temperature	°C	
Heiling	Central station Heiling	Evaporation	mm	
Heiling	Central station Heiling	Precipitation	mm	
Cividino	Pöllau/Cividino	Precipitation	mm	
Franzl im Moor	Rabenwald/Franzl im Moor	Precipitation	mm	
Moyhofer	Zeil/Moyhofer	Precipitation	mm	
Leitenbertl	Sonnleiten/Leitenbertl	Precipitation	mm	
School	Köppelreith/School	Precipitation	mm	
Höhenhansl	Sonnhofen/Höhenhansl	Precipitation	mm	

2.4. Prior control of the time series

Before starting to work with measured times series, a prior check of the data is highly recommended. There are a lot of types of preliminary analyses. Verifying consistency and homogeneity are two important ones. Consistency means that the measurements do not contain errors. The time series are homogeneous, if the hydrological system does not change significantly in the time, if the same type of distribution function with the same parameters can be fitted on different parts of the time series and there is no discontinuity, abrupt rise or sinking in the data set and the diagram is found in a well-defined interval (Kontur et al 1993). Firle (2008) executed these two analyses with precipitation and discharge time series of the year 2004 in her Master thesis, therefore, only her results are summarized in the present thesis.

The consistency was firstly analysed by visual comparison. The rainfall events occur simultaneously, however, the total precipitation and maximal intensities differ from each other. There are some fluctuations in the discharge time series at the base discharge gauge on Saifenbach. Although, regarding the length of the continuous simulations, these errors do not play a significant role in comparing the measured to the simulated discharge time series (Firle 2008). Naturally, the situation is different with event simulations: only a visual check of the results is possible, other goodness-of-fit criterions cannot be applied.

Homogeneity was tested by double sum analysis: the correlated time series are cumulatively summed up and graphically plotted together. If they are consistent and homogeneous, the line will be straight. An arbitrary wavering line reflects no systematics. A transition of the line indicates a nonrecurring but long-lasting effect. A linear trend means a prolonged and increasing impact. According to the double sum analyse of two correlating discharge time series, Dürre Saifen and WHR Prätisbach, the sum line differs from the 45° bisector reference line in the direction of Dürre Saifen because a greater subbasin area belongs to Dürre Saifen.

The linear sum line is discontinuous due to numerous fluctuations which can be the effect of partly the inhomogeneous land use and partly the irregular peak discharges which only occurred at Dürre Saifen in September without any precipitation events (Firle 2008). However, these could be also the results of the fisheries which are usually emptied in autumn as it is later detailed.

According to the results of Firle (2008), the time series are trustworthy. However, there are several facts which have to be considered:

- The discharge time series of the base gauge on Saifenbach show several irregular fluctuations which should be excluded from calibrations,
- The discharge data in September at the discharge gauge of Dürre Saifen should not be used for calibration.

2.5. Flood control reservoirs of the catchment

There are two regulated flood control reservoirs in the Pöllau catchment as parts of a flood protection concept in the area because there were numerous precipitation events in the past with exceptionally great intensity causing floods in the valley basins (Photo 3 and Photo 4) (Firle 2008).



Photo 3 Floods in Pöllau, 1966 (Source: Amt der Steiermärkischen Landesregierung 1999)



Photo 4 Results of the floods, Prätisbach, 28. July 1997 (Source: Amt der Steiermärkischen Landesregierung 1999)

Destructions, especially the floods in 1966 led to an increased focus on flood protection of Pöllau. In 1969 the water board ‘Pöllauer Saifen’ was established by Dienersdorf, Ebersdorf, Hofkirchen bei Hartberg, Kaindorf, Schöneegg bei Pöllau and Sebersdorf as member communities. The main aim of the association was to perform protective construction measures as an important component of flood protection, paying particular attention to the active flood retention. The research works investigated eighteen possible sites, thirteen of them were shortlisted for suitable sites of flood control reservoirs. They found, based on a study in 1991, according to a river basin model and three local regulations of the watercourses in Ebersdorf, Neustift and Hofkirchen, an adequate flood protection of the settlements in the Pöllau valley could be achieved with six flood control reservoirs. Altogether, five flood control reservoirs were built in the Pöllau valley (Figure 13), one of them on Prätisbach (number 1) and the other on Mausbach (number 2) can be found in the catchment which is analysed in the present study. In 1998 a new flood protection dam was built in Ebersdorf. (Amt der Steiermärkischen Landesregierung 1999).

Active flood protection with artificial structures is only applied, if there is no opportunity to exploit or activate natural retention spaces or the stream regulation is not sufficient enough to mitigate rapidly increasing flood waves, for instance, with withholding a certain amount of water. Moreover, the topography must be suitable enough. Major advantages of active flood protection are that the interference in the reaches downstream can be reduced and the effects of such structures are minimal, especially, if there are numerous lateral streams (Amt der Steiermärkischen Landesregierung 1999).



Figure 13 Flood control reservoirs (Source: Amt der Steiermärkischen Landesregierung 1999)

2.5.1. Reservoir on Mausbach

The flood retention basin Mausbach (Photo 5) is found 850 m upstream from the confluence of Mausbach and Saifenbach, 430 m upstream from the base discharge gauge Saifenbach. The storage capacity of the reservoir is 85,000 m³ (Firle 2008).

The main attributes of the flood protection reservoir on Mausbach can be found in Table 7.

The outflow from the reservoir consists of (Firle 2008):

- Normal, bottom outflow and
- Overflow after achieving a specified storage volume.



Photo 5 Flood control reservoir Mausbach (Source: Amt der Steiermärkischen Landesregierung 1999)

Table 7 Flood control reservoir Mausbach (Source: Amt der Steiermärkischen Landesregierung 1999)

Reduction of the peak flow HQ_{100}	m^3/s	From 18.0 to 3.0
Watershed	km^2	3.3
Interlocking device		homogeneous dam
Height of the dam	m	9.0
Usable volume	m^3	47,000
Investment and construction costs	ATS	10.2 million
Funding requirements:		
Federal funds	%	60
State funds	%	30
Wasserverband Pöllauer Saifen	%	10
Constructor and maintainer		Wasserverband Pöllauer Saifen, Water District Pöllau
Construction time		1991-1992

Table 8 contains the general conditions and storage capacities of the reservoir on Mausbach.

Table 8 Storage capacities of the reservoir Mausbach (Source: Firle 2008)

	Height (m aA)	Volume (m^3)	Outflow (m^3/s)
Storage at the beginning of an event	419.00	1,800	Normal outflow: 1.55 Overflow: 0.00
Beginning of the overflow	424.50	45,000	Normal outflow: 2.80 Overflow: 0.00
Filled reservoir	426.50	85,000	Normal outflow: 3.05 Overflow: 72.63

The normal outflow increases until the basin is filled. Figure 14 shows detailed information about the storage-discharge relationship of the retention basin on Mausbach. The overflow begins when the water surface level is 424.5 m aA and also increases continually until the basin is full according to the storage-discharge relationship in Figure 14 (Firle 2008).

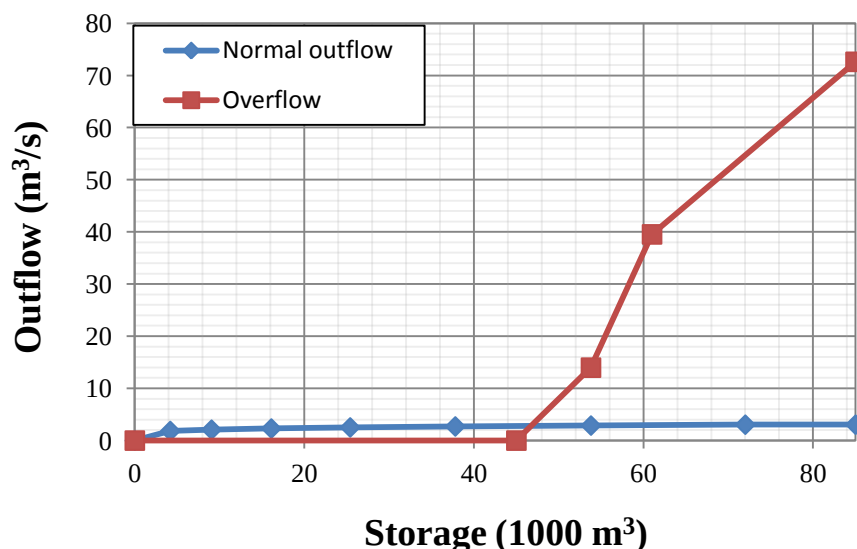


Figure 14 Normal outflow and overflow from the flood control reservoir Mausbach (Source: Firle 2008)

The relationship between storage and water surface level elevation can be seen in Figure 15. Figure 16 shows the connection between the storage and the reservoir's water surface.

The connection between water surface level elevation and the reservoir's water surface simply follows from the above described relationships: a certain water surface is assigned to 419.00 m aA when the storage is on a minimal, base level in the pond and 424.50 m aA. All the other values are linearly interpolated and extrapolated. The base storage in the pond is approximately 4000 m². A water surface of 15,000 m² is assigned to the water surface level of 424.50 m aA (Firle 2008).

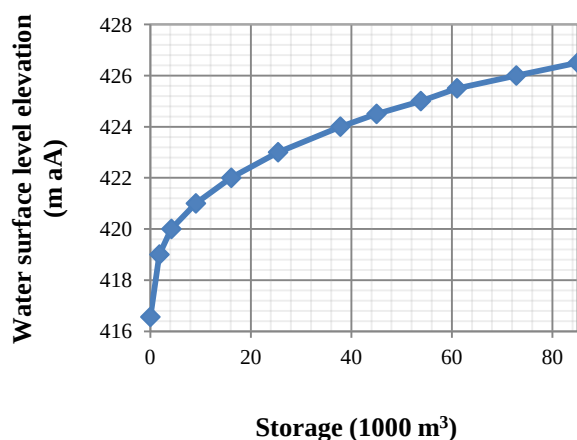


Figure 15 Storage-water surface level elevation relationship of the flood control reservoir Mausbach (Source: Firle 2008)

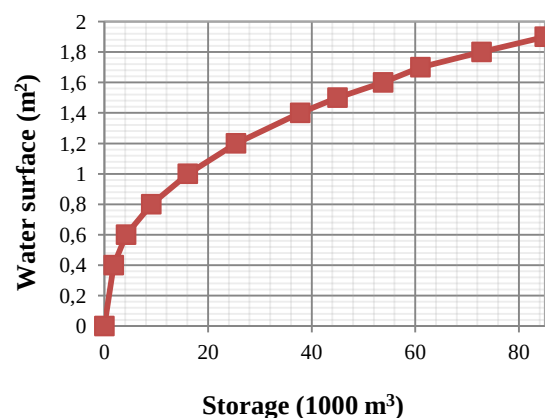


Figure 16 Storage-water surface relationship of the flood control reservoir Mausbach (Source: Firle 2008)

2.5.2. Reservoir on Prätisbach

The flood control reservoir Prätisbach (Photo 6 and Photo 7) is found 1784 m upstream from the confluence of Prätisbach and Saifenbach, 1245 m upstream from the discharge gauge Ölmühle and 2208 m from the base gauge Saifenbach. The storage capacity of the reservoir is 300,000 m³ (Firle 2008).



Photo 6 Flood control reservoir Prätisbach I.
(by Günther Gruber 2014)



Photo 7 Flood control reservoir Prätisbach II.
(by Günther Gruber 2014)

The main attributes of the flood protection reservoir on Prätisbach can be found in Table 9.

Such as on Mausbach, the outflow from the reservoir Prätisbach also consists of (Firle 2008):

- Normal, bottom outflow and
- Overflow after achieving a specified storage volume.

Table 9 Flood control reservoir Prätisbach (Source: Amt der Steiermärkischen Landesregierung 1999)

Reduction of the peak flow HQ ₁₀₀	m ³ /s	From 34.5 to 4.0
Watershed	km ²	20.2
Interlocking device		homogeneous dam
Height of the dam	m	15.8
Usable volume	m ³	134,000
Investment and construction costs	ATS	11.5 million
Funding requirements:		
Federal funds	%	50
State funds	%	40
Wasserverband Pöllauer Saifen	%	10
Constructor and sustainer		Wasserverband Pöllauer Saifen, Water Districts of Pöllau and Pöllauberg
Construction time		1985-1986

Table 10 contains the general conditions and storage capacities of the reservoir on Prätisbach.

Table 10 Storage capacities of the reservoir on Prätisbach (Source: Firle 2008)

	Height (m aA)	Volume (m ³)	Outflow (m ³ /s)
Storage at the beginning of an event	464.00	4,000	Normal outflow: 0.00-4.00 Overflow: 0.00
Beginning of the overflow	470.50	144,791	Normal outflow: 4.00 Overflow: 0.00
Filled reservoir	473.00	300,000	Normal outflow: 4.00 Overflow: 102.66

The outflow from the reservoir is equal to the total inflow and the storage is zero until the inflow does not exceed 4 m³/s (Figure 17). If the inflow further rises, the outflow remains constant 4 m³/s (Figure 17) (Firle 2008).

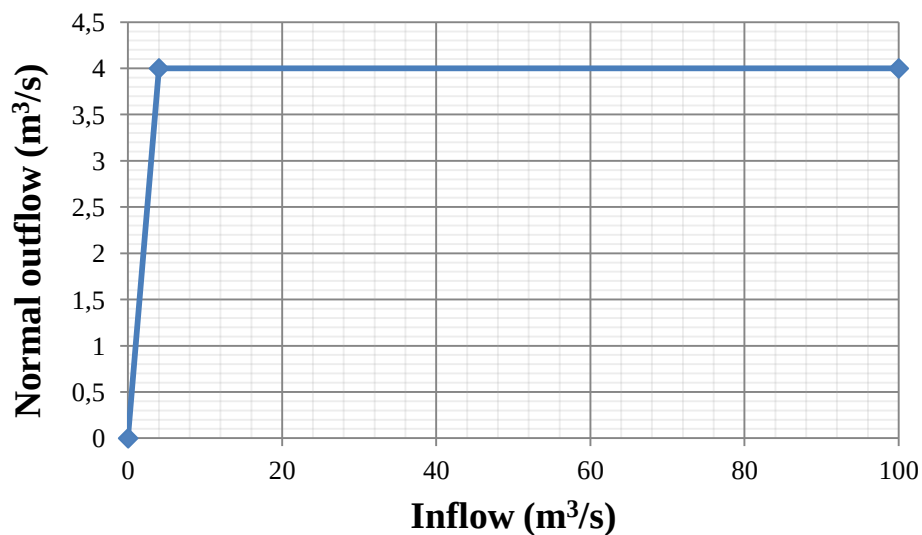


Figure 17 Outflow from the reservoir Prätisbach, if the inflow is less or equal to 100 m³/s (Source: Firle 2008)

The normal outflow remains constant until the basin is filled. Figure 18 shows detailed information about the storage-discharge relationship of the reservoir on Prätisbach. The overflow begins when the water surface level is 470.50 m aA and the stored volume in the reservoir is 144,791 m³. The overflow increases continually until the basin is full according to the storage-discharge relationship in Figure 18 (Firle 2008).

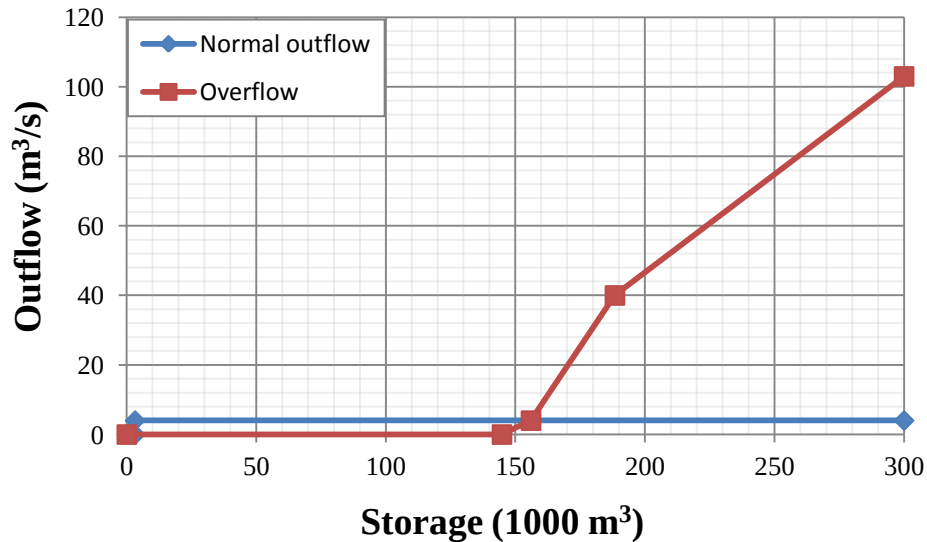


Figure 18 Storage-discharge relationship, Prätisbach (Source: Firle 2008)

If the inflow is less again than $4 \text{ m}^3/\text{s}$, the outflow remains $4 \text{ m}^3/\text{s}$ as long as the reservoir is not emptied (Firle 2008).

The relationship between storage and water surface level elevation can be seen in Figure 19. Figure 20 shows the connection between the storage and the reservoir's water surface.

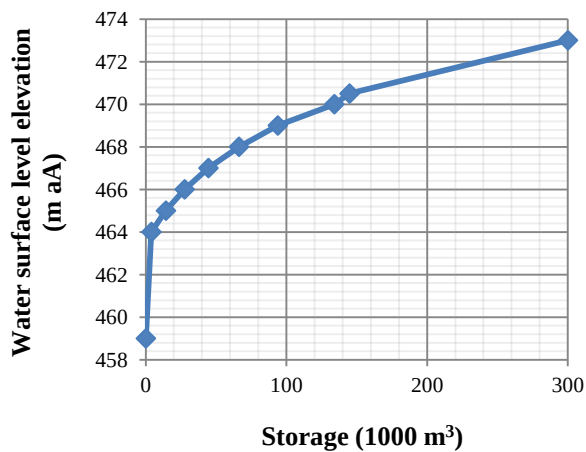


Figure 19 Storage-water surface level elevation relationship of the flood control reservoir Prätisbach (Source: Firle 2008)

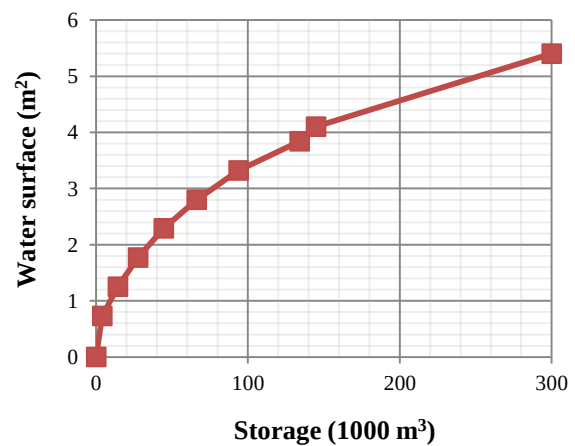


Figure 20 Storage-water surface relationship of the flood control reservoir Prätisbach (Source: Firle 2008)

The connection between water surface level elevation and the reservoir's water surface simply follows from the above described relationships: a certain water surface is assigned to 463.10 m aA ($73,000 \text{ m}^2$) and 470.20 m aA ($140,000 \text{ m}^2$), all the other values are linearly interpolated and extrapolated (Firle 2008).

3. Terminology and methodology of hydrologic modelling

3.1. Classification of hydrological models

There are numerous ways of categorizing hydrological models. The two basic ones are the following (Beven 2001):

- Lumped or distributed and
- Deterministic or stochastic modelling approach.

Lumped models, for example HEC-HMS, NAM (Nielsen and Hansen 1973, Havnø et al 1995), HBV (Bergström 1995), GR4J (Perrin et al 2003), HYCYMODEL (Chaffe et al 2008) treat the whole watershed as a unit with averaged parameters. Distributed models, for instance Mike SHE (DHI 1998), discretize the watershed into parts such as grid squares or triangulated irregular elements and calculate with space-varying parameters specified for each cell, representing local averages of the catchment's physical properties. Although, this type of description is more detailed than the lumped one, the scale of the simulated processes is always greater than reality due to discretization. These models solve the equations for each element accounting for the spatial variability of rainfall or important properties of the basin such as land use, geology, soil texture, runoff characteristics.

Beside the two approaches, another one also exists which combines the main features of the distributed and lumped concepts: semi-distributed or semi-lumped models, for example TOPMODEL (Beven and Kirkby 1979, Beven et al 1984) or SWAT (Arnold et al 1993). However, these models do not perform the calculations on a grid cell basis, but take into account the spatial heterogeneity (topography, land use, soil) of the watershed, mainly throughout extracting information from geospatial information systems. The semi distributed models can be categorised into three groups. They differ from each other in the way, they separate the watershed into homogenous parts with similar hydrological manners (Beven 2001, Széles 2012):

- The first category is a statistical concept which derives the hydrological response of a watershed from probability distribution functions amongst conceptual reservoirs without taking into consideration the physical characteristics of the catchment. Such model is the Probability Distributed Model, PDM (Moore and Clarke 1981).
- HRU (Hydrological Response Units) describes hydrological similarity in a more explicit way overlying different GIS maps (for example soil, vegetation, land use, land cover, geology, slope). In this way, the catchment is divided into parcels called hydrological response units which are organized into grouped response units with similar runoff characteristics. A good example for this type of model is the HBV96 (Lindström et al 1997).
- The third approach assumes that runoff is determined by topography, if the slopes of the catchment are steep enough and the soil layers are shallow with low permeability. This is the basic concept of TOPMODEL (Beven and Kirkby 1979) and GUH (Szilágyi and Parlange 1998).

Most of the models are deterministic with one outcome, if single set of input database and parameters are chosen. Stochastic models contain a certain probability which is the consequence of uncertainty in input data, initial and boundary conditions and wrongly chosen input parameters. Despite the categorization, a sharp difference between deterministic and

stochastic models usually cannot be identified: the output of deterministic models usually has an error part, if a stochastic error model is built into the hydrological model (Beven 2001).

According to the two basic categorizations, the HEC-HMS hydrological model, which was applied in the present study, is basically a deterministic lumped model. In fully lumped models subwatersheds are illustrated by points. They are linked by linear elements called ‘reaches’ represented by lines. Parameters and input data are not spatially distributed within a subwatershed.

3.2. Aspects of model selection

3.2.1. Fundamental difference between event and continuous simulations

Event simulations only model a couple of days or even shorter time periods depending on the length of a single storm event. However, continuous simulations are concerned in more events including dry-weather processes between them (Scharffenberg and Fleming 2010, James 2005).

Long term simulations can be used in water balance, frequency curve, reservoirs, stream stability and environmental or ecological studies. Event models can analyse the characteristics of watersheds, such as runoff times, runoff responses more closely, predicting the peak flow. However, the event simulations usually neglect some of the hydrological processes of a watershed. Another error of event simulations is the huge influence of initial conditions: the simulations are governed and determined by the initial terms specified by the user without further sensitivity analysis, calibration and error analysis. Since the model performance includes only short time interval, the effects of initial or boundary conditions remain in the model throughout the whole simulation (Scharffenberg and Fleming 2010, James 2005). However, the caused errors could be detected by validation with independent time series.

3.2.2. Optimal model complexity

Several components of a model can cause too high complexity, such as unnecessarily high spatial or time resolution, not significant processes which are nonetheless activated. An equilibrium should be found because model accuracy and reliability increases with complexity but only to a certain extent, however, it has also great costs regarding data collection and defining free parameters. If modelling uncertainties are high or a watershed is ungauged or the density of measuring instruments is low, a simpler model is the optimal one (James 2005). Generally, it is advised to choose the simplest model, although, the model has to be able to describe the most important physical properties of a catchment (Széles 2013). A good strategy in deciding optimal model complexity is testing simple models first and then gradually proceeding to more complex ones. If the optimal computed response function is achieved, further refinement of resolution (Széles 2012, Széles et al 2013) or involvement of new processes is not needed (James 2005).

There are several benefits and disadvantages of simple and complex models. Simple models can be unrealistic, although, they can be easily verified or modified, their input data requirement is not so significant and modellers can make less errors with them. Complex models are flexible and have more detailed and complicated results because they can take into account more processes, however, for the same reason, they are more likely to contain errors, their hardware and resources requirements are significant (James 2005).

The aim of the present thesis was to apply the possibly simplest model structure, however, further simplifications were not possible. Continuous simulations basically need to consider more processes, such as evapotranspiration and water recovery between storm events, which involves more free parameters. The structure of the model seems to be also complicated, however, regarding the above detailed process of basin model development in the previous paragraphs, the number of discharge gauges and disaggregated subcatchments, moreover, spatial inhomogeneity of land use and characteristics of the terrain, such complicity was unavoidable.

3.3. Sensitivity analysis

It is basically important to draw a terminological distinction between uncertainty and sensitivity analysis. Uncertainty analysis counts probable sources of errors by characterizing uncertain model inputs with distribution functions and translating them into the uncertainty in outputs. However, the target of sensitivity analysis is assessing the most important drivers of uncertainty by describing the influence of input parameter uncertainties on model responses (Mishra 2009, James 2005).

Sensitivity shows how intensive the change of an objective function is (goodness-of-fit criteria such as peak discharge or Nash-Sutcliffe coefficient which numerically describe the response function, namely the output time series of the model), if some of the model parameters (p_i) are changed:

$$COF_{c,j} = M_c(p_1, p_2, \dots, p_n) \quad (1)$$

where COF is the computed objective function, c is the model complexity, j stands for the chosen objective function, M is an operator. Sensitivity measure can be for example response from arbitrary parameter variation, normalized and average response, variance, extrema. Sensitivity analyses can be categorized in the following way: variation of parameters (results of the combination of chosen parameters are analysed), domain-wide (parameters are varied in the entire range) and local sensitivity analyses (the effect of changing a chosen parameter in relatively narrow ranges is analysed) (James 2005).

A well-known sensitivity analysis is Factor Perturbation Method, where SG_i sensitivity gradients of parameters are partial derivatives of a COF computed objective function with respect to a parameter p_i :

$$SG_i = \frac{\partial COF_0}{\partial p_i} \quad (2)$$

However, factor perturbation makes several simplifications: only one parameter's sensitivity can be analysed at a time, the others are assumed to be constant; the changes are described by single values instead of distributions; the sensitivity gradient is assumed to be linear. Another technique, Monte Carlo Method selects a set of parameters in a random way with errors described by frequency distributions and an objective function is evaluated in each simulation run tending to infinity (James 2005).

To find the optimal parameter set, the free variables need to be examined in only those processes under specified model conditions, when these parameters have an active effect on model output (James 2005).

The objective of this study was to perform simple sensitivity analyses to determine and rank the most sensitive free parameters of the model. This basic step supports the model calibration throughout understanding the behaviour of the model. Regarding the huge number of known sources of errors, for instance field measurements errors, numerical and structural errors of the hydrological modelling tool, simplifications and discretization of the model, user specified boundary and initial conditions, and other unknown errors, uncertainty analyses should extend beyond the scope of the present thesis.

3.4. Parameter optimization

The parameter optimization procedure includes the calibration and validation. Calibration is usually started with the most sensitive parameters proceeding toward less sensitive ones. A sensitivity analysis can support to rank the free parameters according to their sensitivity. If the insensitive parameters can be initially filtered, they can be excluded from calibration, furthermore, similar parameters can be calibrated together.

Figure 21 shows the basic steps and relationships of sensitivity based model calibration. However, the details always depend on the modelling purposes and the subject of the model, the basic steps of calibration are: sensitivity analysis, choosing the optimal values of free parameters throughout a calibration algorithm with assigned limits to achieve the best fit between simulated and measured hydrographs and finally error analysis. Assigning limits of free parameters is basically important because the number of optional parameter sets is infinite (James 2005).

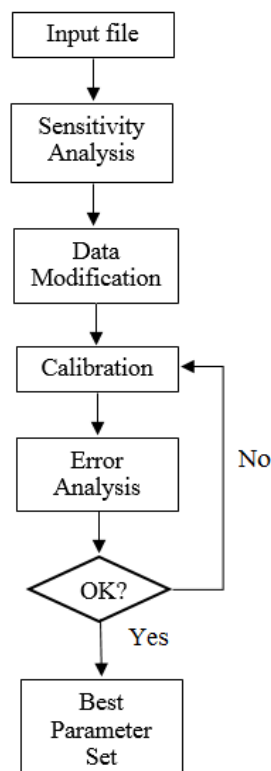


Figure 21 Basic steps of sensitivity based model calibration (Source: James 2005)

Model robustness (persistence of the model under perturbation without adaption of other initial conditions and giving the same global optimal results) and efficiency (number of runs to achieve the global optimum or start to converge to it) should be defined during the calibration procedure.

Different hydrological models contain automatic calibration algorithms, such as Optimization Trial in HEC-HMS. Efficient and robust methods find those global parameter sets which result simulations best corresponding to the measured dataset. Well known automatic calibration procedures are Genetic Algorithm, Multi-Extremum Optimization, Down-Hill Simplex (DHS), Shuffled Complex Evolution (SCE), Simulated Annealing Algorithms (SimA) (James 2005).

Validation justifies the correctness of calibration on independent time series without changing the values of the calibrated parameters. It is also conventional to calibrate the model on a shorter time period and validate it on extended time series also including the calibration time period.

3.5. Performance objective functions

Quantifying goodness of fit between simulated and measured data during the procedure of calibration, validation and sensitivity studies is basically important. Beside visualization, these criteria in an objective way, numerically reflect the capabilities and major weaknesses of hydrological simulations.

With hydrological models, especially if there are too many free parameters which need to be calibrated, it often occurs that more than one combination of the parameters can perform good results (Pedro et al 2008).

The level of agreement between simulated and measured time series can be described in three ways (Chiew and McMahon 1993):

- (1) Graphical plots,
- (2) Statistical parameters,
- (3) Dimensionless parameters.

3.5.1. Visualization

In order to assess model adequacy, visualization is the first and most important step because numerical indices can be sometimes misleading (Chiew and McMahon 1993).

There are several types of graphical plots which can enhance or discredit the results of simulations. Therefore, they have to be chosen carefully and examined critically. Some of them are the following (Chiew and McMahon 1993):

- Hydrographs: the time-series, especially the peaks, can be compared directly,
- Scatter diagrams (X-Y plots): show whether the simulated flows are under- or overestimated,
- Cumulative plots: display the cumulative discharge values of flood events,
- Residual mass curves: show the cumulative difference between discharge values and the mean of measured flow,
- Flow duration curves: show the probability of occurrence of the flows with different magnitudes. Flow duration curves are the graphs of empirical probability functions plotting the percentage of time when flow equalled or exceeded a given value versus the given values of flow.

3.5.2. Statistical parameters

If the model simulations well fit the measured time series, the statistical parameters describing both time series are similar. However, similar statistical parameters do not necessarily indicate a satisfactory flow simulation. There are several statistical parameters which can characterize time series, some of them are:

- Mean:

$$\bar{Q} = \frac{\sum_{i=1}^N (Q(t_i) - Q_a)^2}{N} \quad (3)$$

where $Q(t_i)$ is the measured or simulated discharge at time step t_i , Q_a is the average of the measured or simulated time series, N is the number of time steps.

- Standard deviation:

$$s = \sqrt{\frac{\sum_{i=1}^N (Q(t_i) - Q_a)^2}{(N - 1)}} \quad (4)$$

- Coefficient of skew: shows the asymmetry of the probability distribution of the discharge values:

$$g = \sqrt{N \frac{\sum_{i=1}^N (Q(t_i) - Q_a)^3}{(N - 1)(N - 2)s^3}} \quad (5)$$

- Lag-one autocorrelation coefficient:

$$r_1 = \frac{\sum_{i=1}^{N-1} (Q(t_i) - Q_a)(Q(t_{i+1}) - Q_a)}{\sum_{i=1}^N (Q(t_i) - Q_a)^2} \quad (6)$$

3.5.3. Dimensionless Coefficients

There are numerous functions which have to be chosen carefully, best fitting to the main features of the time series and the properties which should be emphasised. For example simple least squares describe large flows and errors well or simple least squares of m -powered flows emphasize lower flows, if m is smaller than one (James 2005).

Four indices were used which are described in details in Das et al (2008):

- *Nash-Sutcliffe coefficient* (Nash and Sutcliffe 1970): is the most commonly used indicator in describing hydrologic modelling performance:

$$R_m^2 = 1 - \frac{\sum_{i=1}^N (Q_s(t_i) - Q_o(t_i))^2}{\sum_{i=1}^N (Q_o(t_i) - Q_{o,a})^2} \quad (7)$$

where $Q_o(t_i)$ and $Q_s(t_i)$ are the observed and simulated discharge at time step t_i , $Q_{o,a}$ is the mean observed discharge, N is the number of time steps. Nash-Sutcliffe

coefficient changes between $-\infty$ and 1 (perfect fit). The greater the value of Nash-Sutcliffe coefficient is, the better simulated discharge fits the measured one.

- *Relative volume error*: shows the total volume error of the whole simulation.

$$RE = \frac{\sum_{i=1}^N (Q_s(t_i) - Q_o(t_i))}{\sum_{i=1}^N Q_o(t_i)} \quad (8)$$

Throughout the model calibration, the prior aspect was to find those parameter pairs, that the observed and measured volume show a good agreement.

- *Peak error*: is the relative difference between the modelled ($Q_{s,max}$) and measured ($Q_{o,max}$) peak flow indicating the model's ability of estimating peak flow:

$$Peak\ error = \frac{Q_{s,max} - Q_{o,max}}{Q_{o,max}} \quad (9)$$

- *RMSE* (Root mean squared error): is a deviation which is calculated as the root of the average of the squared difference between simulated and observed discharge:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Q_s(t_i) - Q_o(t_i))^2}{N}} \quad (10)$$

4. Rainfall-runoff simulation with HEC-HMS

4.1. Creating the basin and meteorological model of the Pöllau catchment with HEC-GeoHMS

HEC-GeoHMS (*Hydrologic Engineering Centre's Geospatial Hydrologic Modelling Extension*) is an extension of ESRI ArcGIS 10.1 Spatial Analyst toolbar which is publicly accessible. The geospatial tool is able to visualize spatial databases, extract hydrological information from digital elevation models, store the extracted data, perform hydrological analyses, generate input data (such as delineated watersheds and subcatchments and basins, runoff directions according to the deterministic eight algorithm (D8), depressionless or reconditioned digital terrain models) for hydrological models. The basin and meteorological model and further useful inputs for the HEC-HMS project can be directly created by the *Arc Hydro Toolbar* and *HEC-GeoHMS Toolbar*. In a certain respect, HEC-GeoHMS transforms spatial information into hydrological model input data of the HEC-HMS model (Fleming and Doan 2013).

The details of terrain pre-processing and HMS project setup is written below and also illustrated in the following figures. The process had to be done step-by-step, the output of one step was the input of the next one. Following the steps sequentially, the program properly offered the next input layer (Fleming and Doan 2013):

- (1) After creating a new ArcMap project file and customizing the Spatial Analyst Toolbar, the digital elevation model can be loaded into ArcGIS and also projected. It is basically important that the data source of the created raster layer must be valid, the raster file has to contain an access pass otherwise the HEC-HMS model setup is not possible. This was unfortunately a shortcoming of the available data with an already

pre-processed digital elevation model (Firle 2008). Therefore, the raw digital terrain model had to be written into an ASCII file, reloaded into a new project, reprojected and pre-processed from beginning.

- (2) Fill Sinks (Figure 22): if the height of the given cell is smaller than all of its neighbour's, a certain value is added to it, increasing it to the same level of its lowest neighbour. Based on this principle, a depressionless terrain model is created by filling the holes which are the consequences of errors occurring in the elevation model due to interpolation procedures. The significance of this step lies in the fact that water could be trapped in depressions disrupting the continuity of calculations. The 'Fill Threshold' and 'Input Deranged Polygon' options have to be left empty because every pit has to be filled.

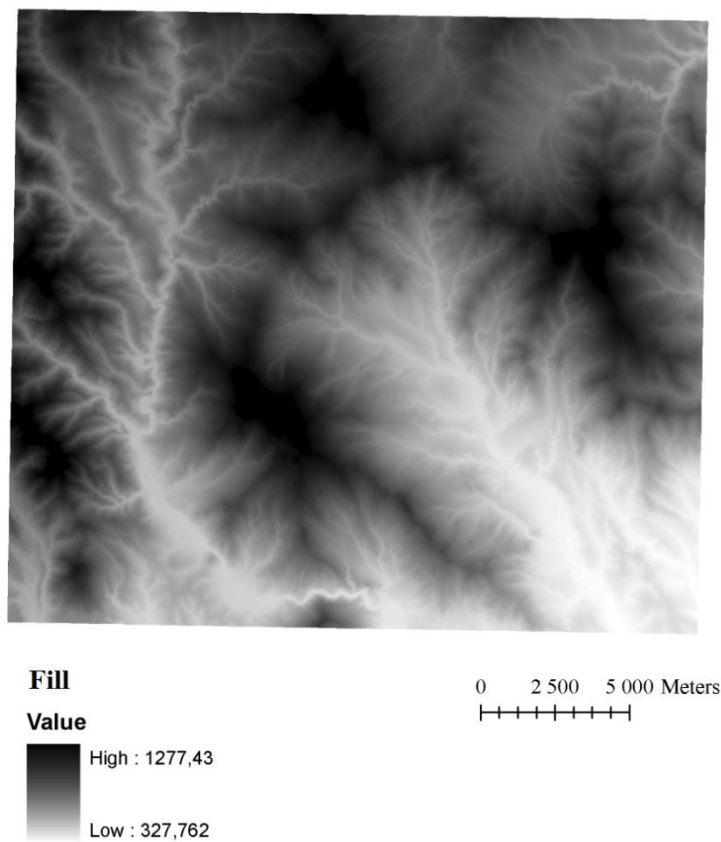


Figure 22 Filled digital terrain model of the Pöllau catchment (Step 2)

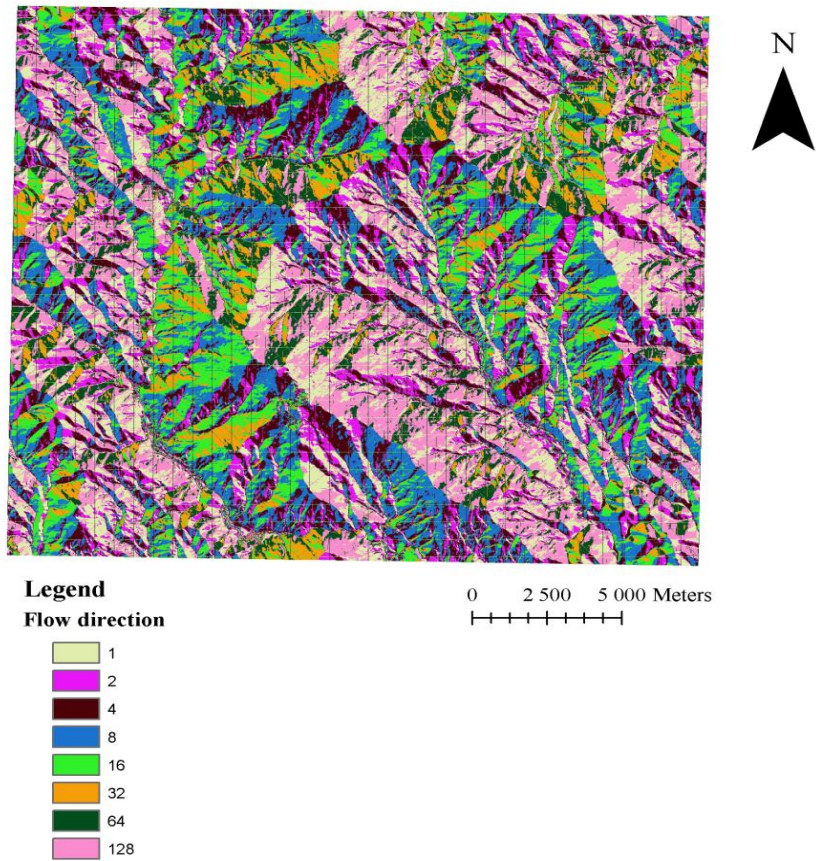


Figure 23 Flow direction raster of the Pöllau catchment (Step 3)

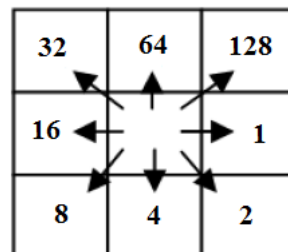


Figure 24 Principle of D8 algorithm (Source: Fleming and Doan 2013)

- (3) Flow Direction (Figure 23): the given cell gets a value representing the direction of its steepest neighbour. This algorithm is the basis principle of the D8 (deterministic eight) runoff calculations (Figure 24).

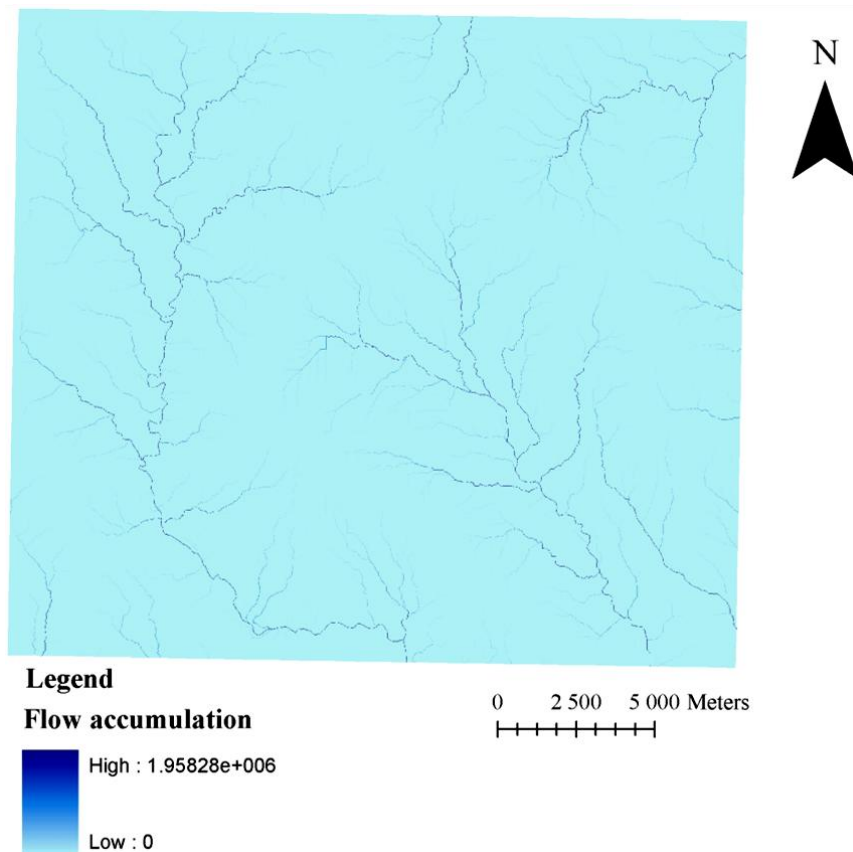


Figure 25 Flow accumulation raster of the Pöllau catchment (Step 4)

- (4) Flow Accumulation (Figure 25): calculates the number of cells located upstream and draining through the given cell.
- (5) Stream Definition (Figure 26): this step visualizes those cells which have a greater Flow Accumulation value than a user-given one (number of cells or area in square kilometre). These cells become parts of the watershed's stream network. It is advised to choose the specified value as 1 % of the greatest subwatershed's area. The smaller the given value is, the more subcatchments are generated in the next steps. This value was chosen to provide the same delineation of a previous Master thesis (Firle 2008) which applied the BlueM hydrological model to simulate the rainfall-runoff processes of the Pöllau watershed.

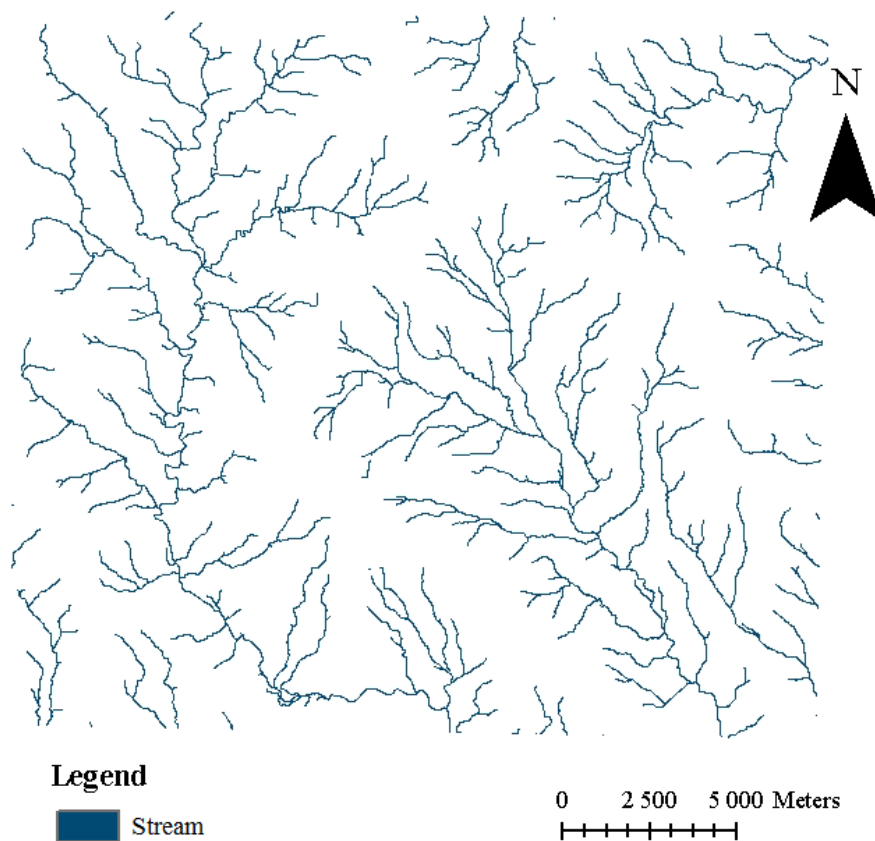


Figure 26 Stream vector layer of the Pöllau catchment (Step 5)

- (6) Stream Segmentation (Figure 27): the stream raster is divided into segments which later represent the reach elements of the HEC-HMS model.
- (7) Catchment Grid Delineation (Figure 28): the watershed is divided into subwatersheds according to the segmented streams.
- (8) Catchment Polygon Processing (Figure 29): the raster of the delineated catchments (Step 7) is modified into a vector layer.
- (9) Drainage Line Processing (Figure 30): a vector layer is created from the stream raster.
- (10) Watershed Aggregation (Figure 31): the upstream subwatersheds are united at every stream confluence point.

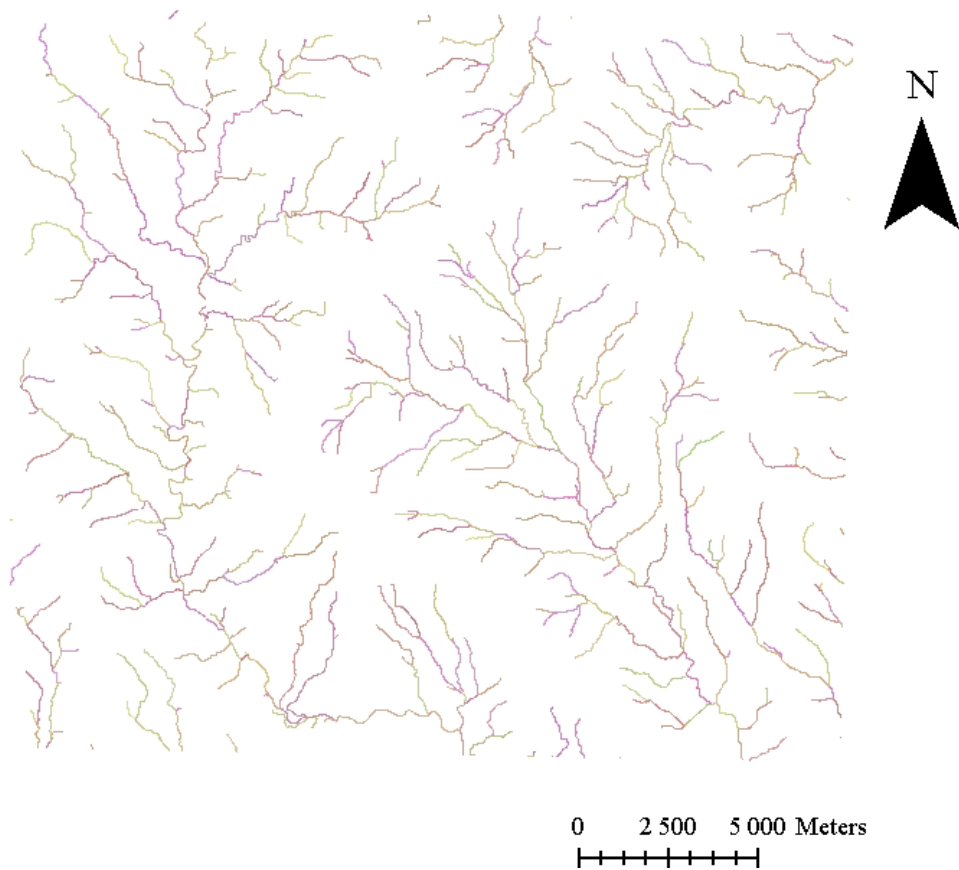


Figure 27 Segmented streams of the Pöllau catchment (Step 6)

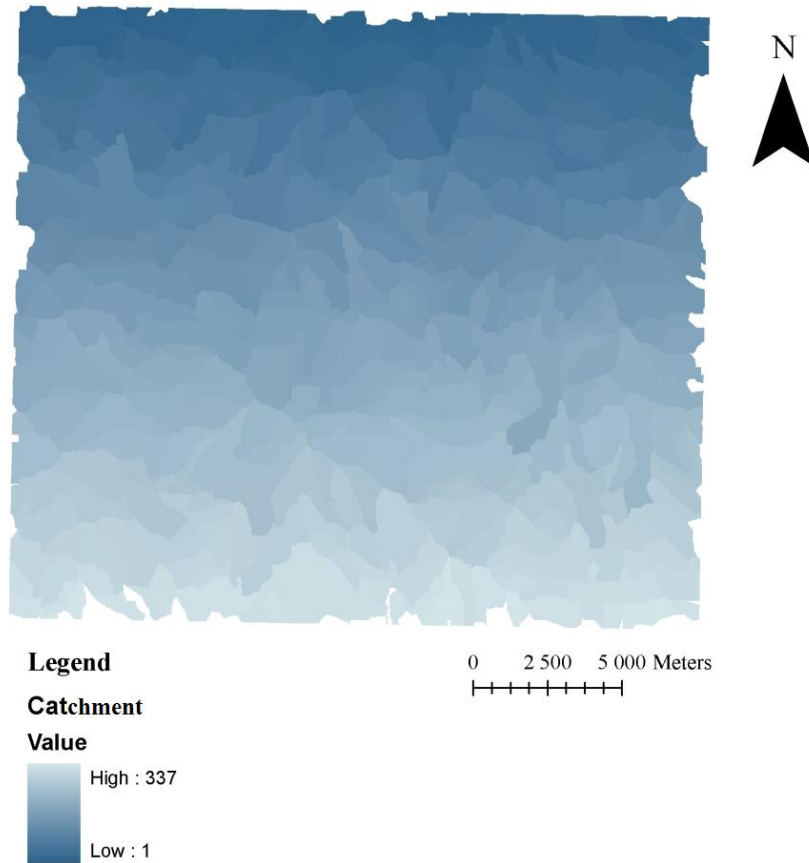


Figure 28 Delineated catchment, Pöllau watershed (Step 7)

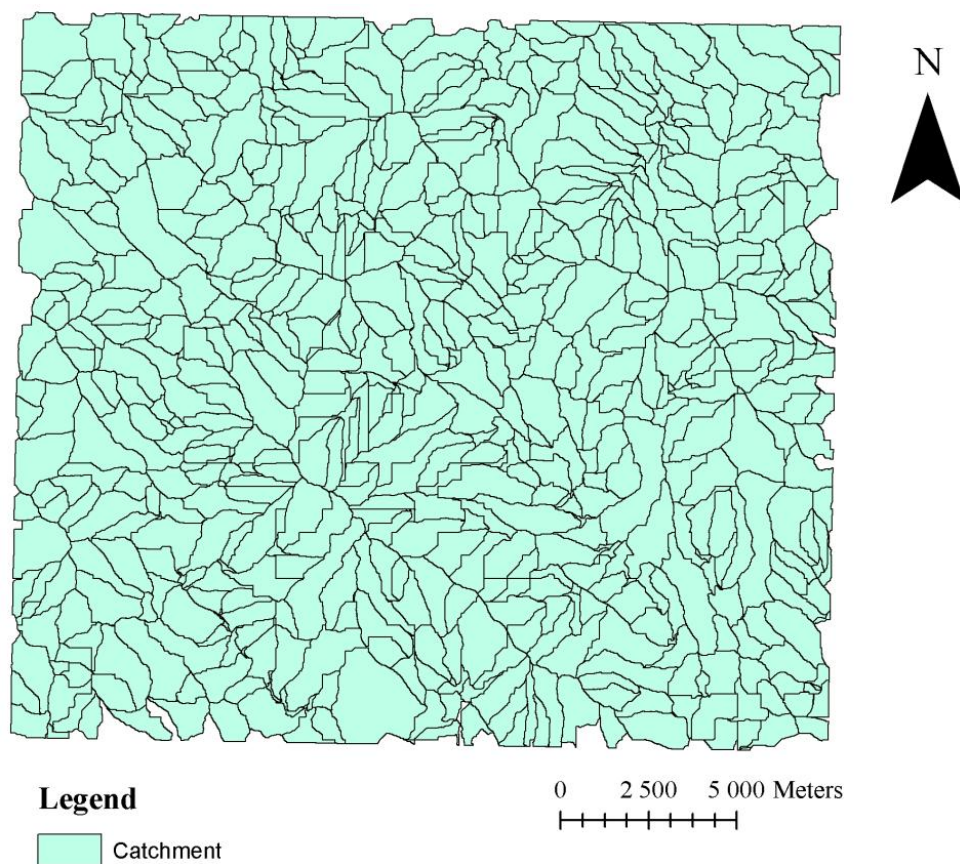


Figure 29 Catchment polygons of the Pöllau catchment (Step 8)

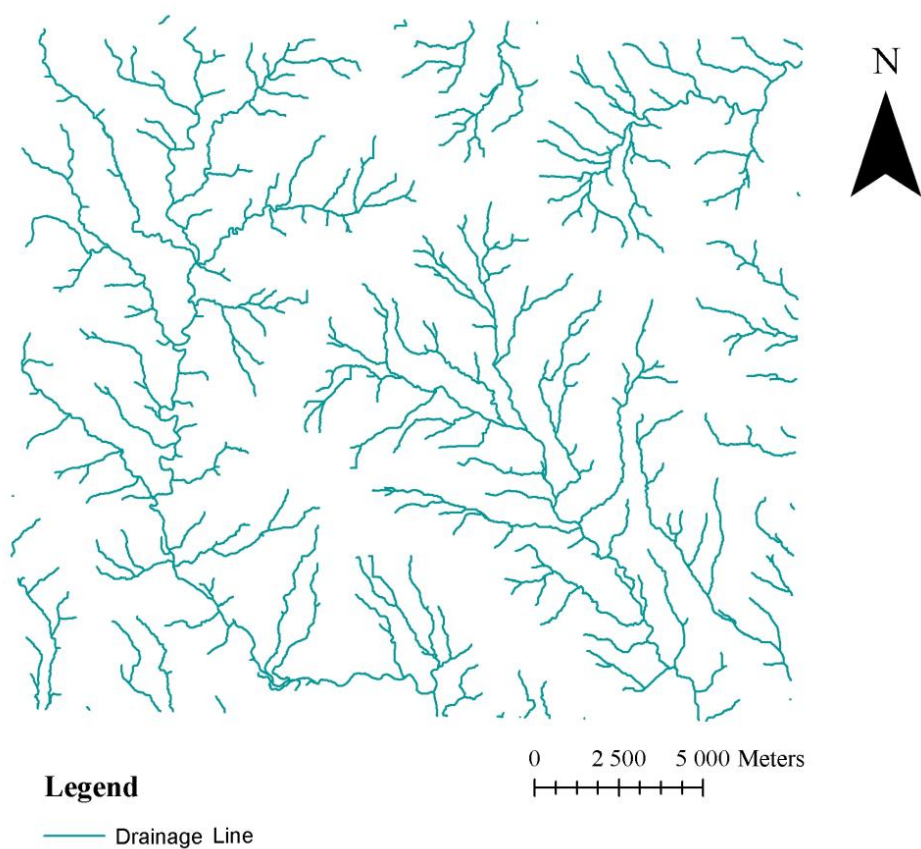


Figure 30 Drainage lines of the Pöllau catchment (Step 9)

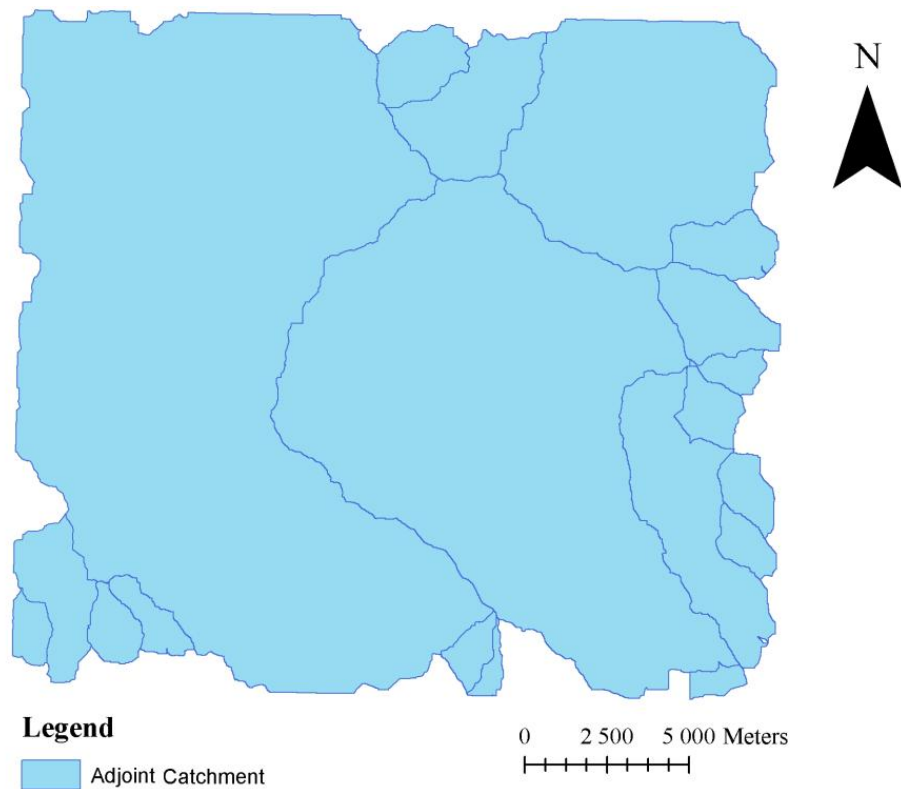


Figure 31 Adjoint catchment of Pöllau (Step 10)

The delineated catchment with its subcatchments, the segmented streams and the belonging attributes as well as geometry data (area, length and connections) were applied to create the HEC-HMS project file. The above mentioned steps were mainly calculated by the *ArcHydro* toolbar, though the HEC-HMS project setup needed the GeoHMS toolkits. The HEC-HMS project was developed by the *Project Setup* menu (Fleming and Doan 2013).

After zooming enough into the outlet point of the watershed, a new project can be started by the *Start New Project* menu. In this first step, a 'Project Area' and a 'Project Point' layer are generated. The project area layer shows the upstream watershed belonging to the outlet point and the project point layer contains the assigned outlet point. Choosing new or the default names, a new project is generated (*Define a New Project* with *Original Stream Definition* extraction method) and also named choosing a target location. After reading the occurred message window of the chosen directory and about further steps, the outlet point or points (in case of multiple outlets) can be manually selected by the *Add Project Points* button. A filled red circle signs, if the selection is correct. After checking the table of *Data Management*, whether the layers which are going to be generated are joined to the right database, the drainage area belonging to the outlet point is hatched (Figure 32). Accepting the shown area and controlling the *Generate Project* editor, a new group layer is created containing all of the pre-processed data (Fleming and Doan 2013).

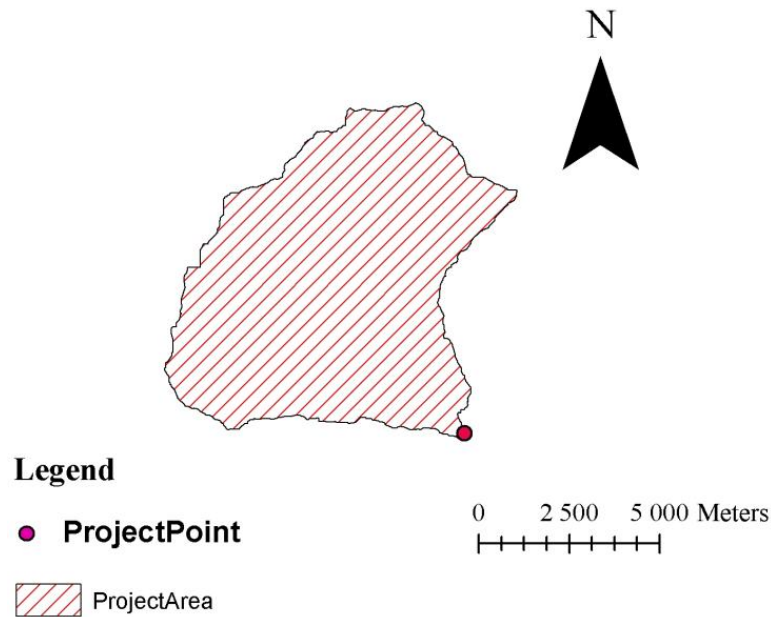


Figure 32 Project area and project point, Pöllau catchment

The subbasin and stream delineation in the newly created HEC-HMS project layer can be modified by the *Basin Processing* menu, if it is necessary (for example: merging or subdividing watersheds, splitting basins at confluences, batching subbasin delineation, merging rivers and creating river profile). In the present study, some of the subcatchments had to be merged to get the same final delineation structure as Firle (2008). This procedure joins subwatersheds in an interactive way. The merge is only possible, if the confluences of subbasins are the same or they are upstream or downstream neighbours. The result is always displayed before it is final, giving an opportunity to choose, whether it is acceptable (Fleming and Doan 2013).

The physical properties of the subcatchments and streams stored in attribute tables, as input data of the HEC-HMS project file, significantly helped the calibration of the HEC-HMS model. The below described queries can be performed by HEC-GeoHMS *Basin Characteristics* menu (Fleming and Doan 2013):

- River Length: the length of each or selected river reach is computed.
- River Slope: the slope between the upstream and downstream ends of each or selected reaches is calculated.
- Basin slope: after creating a slope raster (*Arc Hydro Tools/Terrain Preprocessing/Slope*) the average slope of each or selected basin is calculated.
- Longest Flow Path: the longest flow path layer contains the length, the elevation at different parts and slope between the endpoints of the longest flow path.
- Basin Centroid: the centroid of each or selected subbasin can be computed in four different ways (manually, Centre of Gravity Method, Longest Flow Path Method, 50 % Area Method).
- Centroid Elevation: the elevation of each centroid point is specified.
- Centroidal Flow path: the centroid is projected onto the longest flow path and the centroidal longest flow path is the distance between the projected point and the subbasin outlet.

Hydrologic and hydraulic input data, both discrete average and gridded data, and modelling methods of the HEC-HMS project can be defined by the *Hydrologic Parameters* menu. Applying land use and soil maps, surveyed and precipitation data, hydrological parameters can be even more precisely estimated. *River* and *Basin Auto Name* can be also activated in this menu, naming the reaches and basins from upstream to downstream in a sequential order (Fleming and Doan 2013).

The HEC-HMS model setup (*HMS* menu) consists of the following steps (Fleming and Doan 2013):

- (1) Map to HMS Units: a unit system has to be selected (English or SI) and parameters are converted into the chosen system.
- (2) HMS Data Check: consistency of the dataset is controlled (relationships of the hydrologic elements, uniqueness of the elements' names), errors or inconsistency are filtered out and listed in a message window as a feedback. This step was of utmost importance because the above mentioned merge of subcatchments firstly caused inconsistency.
- (3) HEC-HMS Basin Schematic: a hydrologic network is constructed, the HMS Link contains the connecting elements of the system, while the HMS Node layer shows subbasins and junctions of the HEC-HMS model.
- (4) HMS Legend (Figure 33): the elements of the HMS Link and Node layers are represented by HMS Legend or Regular Legend.

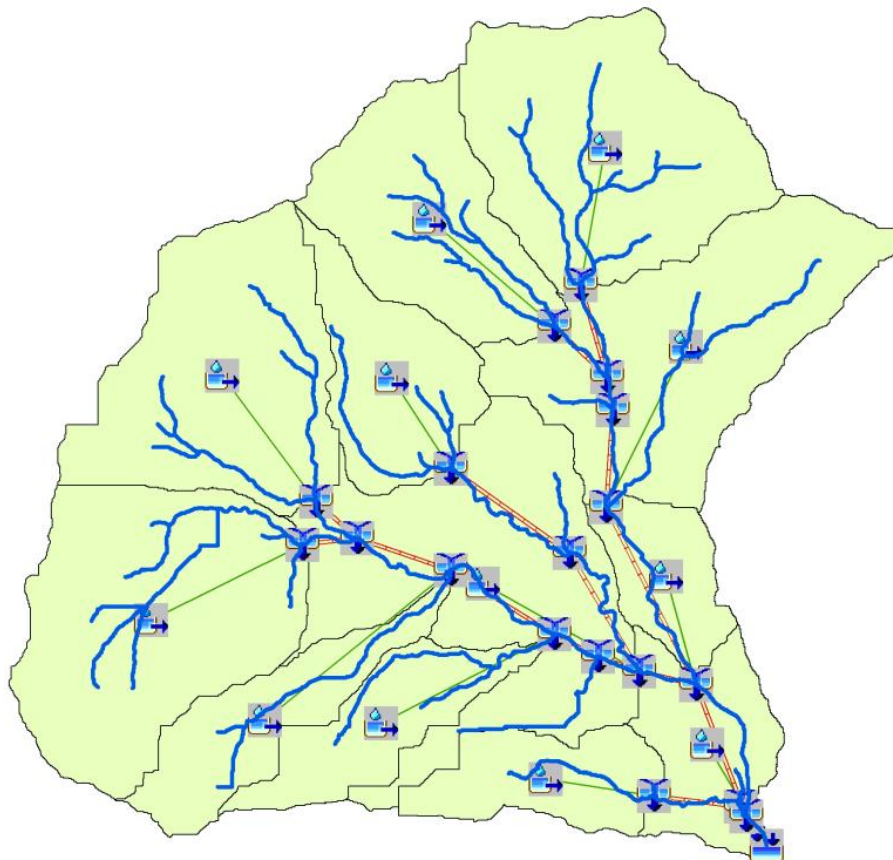


Figure 33 HEC-HMS Basin schematic, Pöllau catchment

- (5) Add Coordinates: geographic coordinates are added to the elements of the HMS Link and Node layers. The main benefit of this step is that the maps can be exported into ASCII files.
- (6) Prepare Data for Model Export: some of the parameters stored in the attribute tables are prepared for export.
- (7) Background Shape File: background maps in shape or text format can be also imported to HEC-HMS which is a great help in the hydrologic model, if the visualization of the subcatchments and reach elements is needed. After copying the created shape or text files into the HEC-HMS project directory, the files can be easily loaded into the hydrological model (*View/Background maps [basin model name]/Add*). It is advised to use the shape file format, which can be later handled in a more flexible way.
- (8) Basin Model File: the basin model can be exported into ASCII file and easily imported into HEC-HMS (*File/Import/Basin model*).
- (9) Meteorological Model: three types of meteorological models can be created in HEC-GeoHMS. However, this step is also possible within the HEC-HMS project:
 - Specified Hyetograph Meteorological Model: a total storm depth has to be specified by the user,
 - Gage Weights Meteorological Model: the meteorological model can be generated after the creation of a Thiessen polygon layer,
 - Inverse Distance Meteorological Model: the model can be generated only with a precipitation gauge layer.

The Gage Weights Meteorological Model was applied in the present study; the meteorological and gauge files, the latter containing the precipitation gauges, were created by HEC-GeoHMS.

In this method, the given area is divided into parts, each of these parts containing a rain gauge in the centre. The points found within a subarea are closer to the precipitation gauge belonging to the given area, than to any other gauges. If the area of i subregion is A_i , its weight is calculated as

$$w_i = \frac{A_i}{\sum_{i=1}^N A_i} \quad (11)$$

where N is the number of precipitation gauges. The $\bar{P}$ spatial average precipitation is

$$\bar{P} = \frac{\sum_{i=1}^N A_i P_i}{\sum_{i=1}^N A_i} \quad (12)$$

Figure 34 illustrates the method in a sample, simplified watershed. According to Figure 34, the precipitation gauges are connected by lines (Step 1), then the created polygon sides are divided by perpendicular bisectors (Step 2). Finally, the intersections of the bisectors form new polygons, the Thiessen polygons (Step 3). Figure 35 shows the Thiessen polygons of the Pöllau catchment. Simple visualization can resolve dubious cases: the distances to the nearest gauges have to be compared, the given point or area belongs to the nearest gauge (Thiessen 1911, Chow et al 1988, Koris et al 1993, www.noaa.gov 01.05.2014).

- (10) Create HEC-HMS Project: a directory is created and all HEC-HMS files generated by HEC-GeoHMS are copied into this directory.

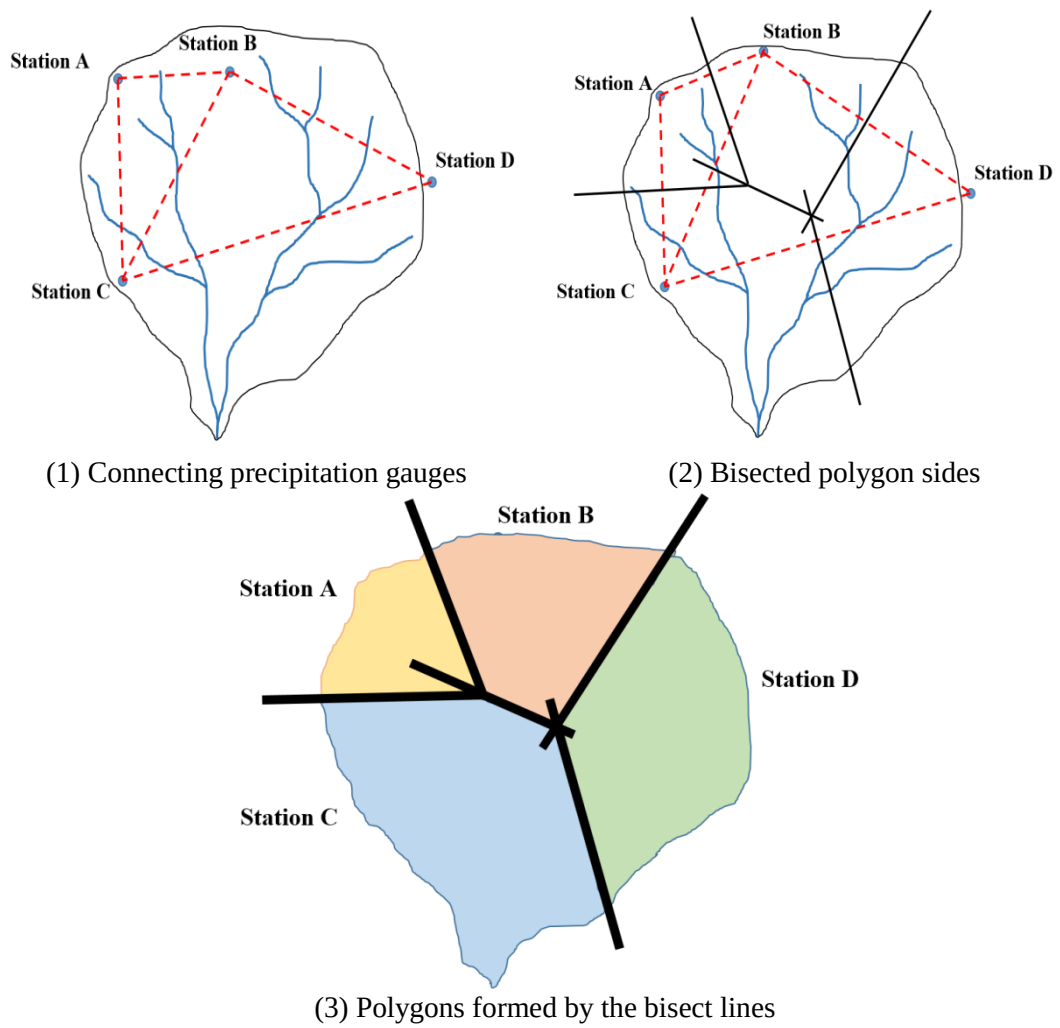


Figure 34 Creation of Thiessen polygons of a sample watershed (Source: www.noaa.gov 01.05.2014)

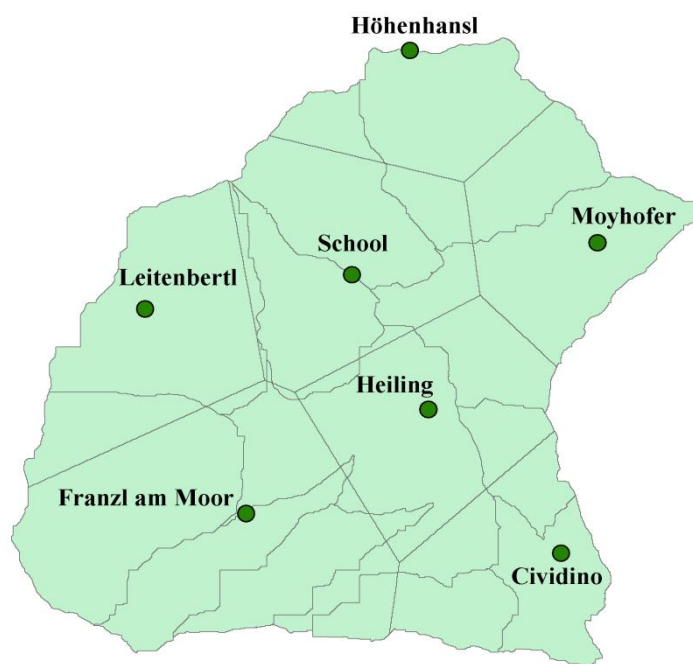


Figure 35 Thiessen polygons, Pöllau catchment

4.2. Description of the applied hydrological model: HEC-HMS overview

HEC-HMS (*Hydrologic Engineering Centre's Hydrologic Modelling System*) is designed to simulate the precipitation-runoff processes of dendritic watershed systems. Being developed by U.S. Army Corps of Engineers with U. S. Federal Government resources for nearly 30 years, the model is therefore public and it can be freely downloaded and used.

The software is expressly user-friendly with its graphical user interface (GUI), graphical and numerical results reporting tools such as graphs, global and element summary tables, own database management system (HEC-DSSVue, *Hydrologic Engineering Centre's Data Storage System*), trial and error function which improves the efficiency of the calibration procedure.

HEC-HMS is basically a lumped hydrological model. However, it contains some facilities of distributed models, such as a linear quasi-distributed runoff transform method (ModClark transform method), gridded precipitation and evaporation, gridded canopy and surface, furthermore, gridded loss methods. If there are more precipitation gauges in a watershed, the program is able to calculate with spatially distributed precipitation data, nonetheless, the subwatersheds and other hydrological elements of the model are fully lumped.

It offers a broad range of hydrologic and hydraulic methods to properly describe watersheds; to simulate flash floods; to analyse the impacts of urbanization and changes in land use on runoff generation; to support flood damage reduction and floodplain regulation; to provide information in flow forecasting; to quantify the effects of hydraulic structures on the river (Scharffenberg and Fleming 2010).

4.3. Main components of the HEC-HMS rainfall-runoff model

The four main components of the program are: basin model, meteorological model, input data and control specifications (Scharffenberg and Fleming 2010).

4.3.1. Basin model

The basin model physically represents the watershed developed by adding and connecting hydrologic elements. There are seven types of hydrologic units which can be sequentially connected in a hierarchic order: subbasin, reach, junction, reservoir, diversion, source and sink. Four of them were used: watershed, reach, junction and reservoir. Figure 36 shows a simplified basin model with the four applied hydrologic units.

Figure 37 shows the complete basin model of the Pöllau catchment, while Figure 38 shows it in a more structured way.

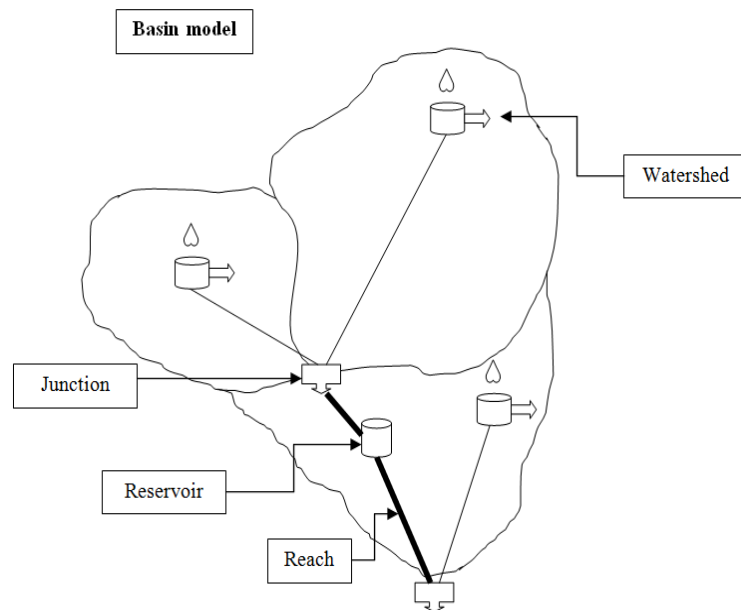


Figure 36 Simplified basin model with the applied hydrologic model components

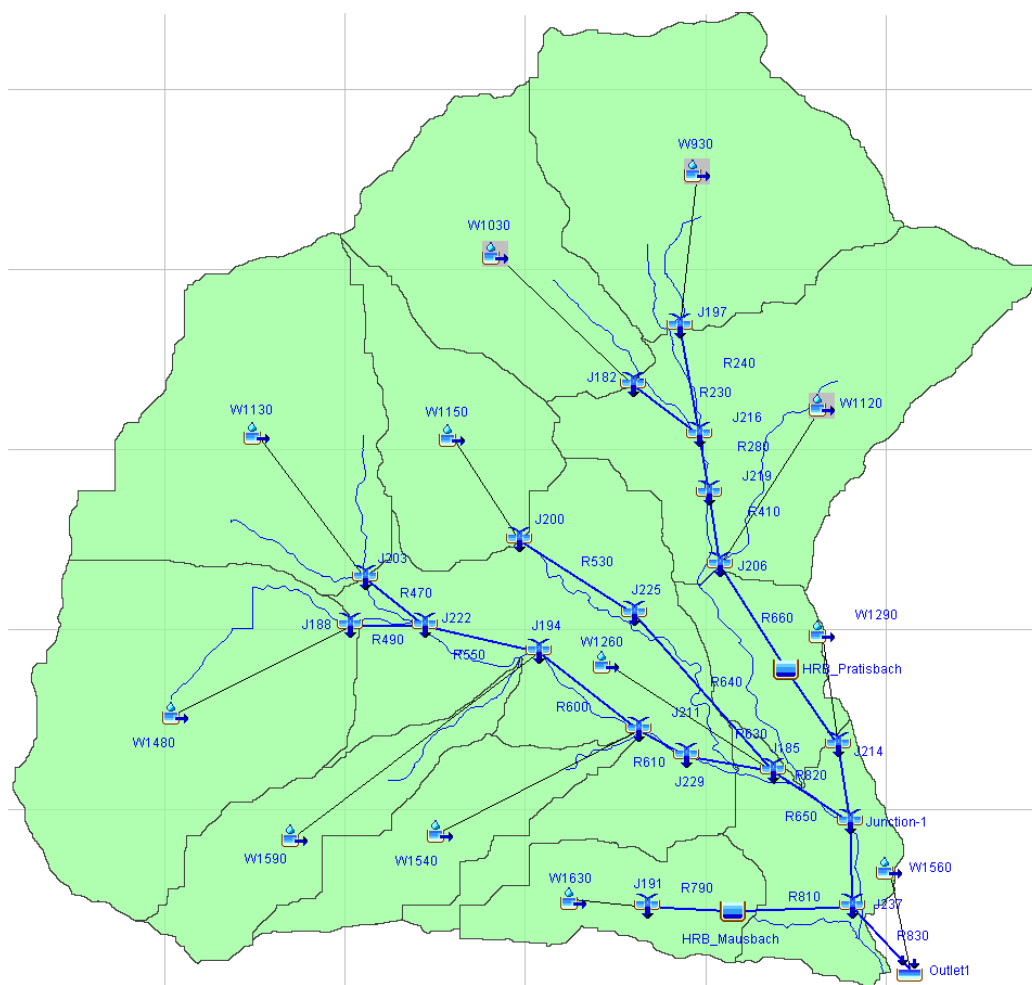


Figure 37 HMS basin model of the Pöllau catchment

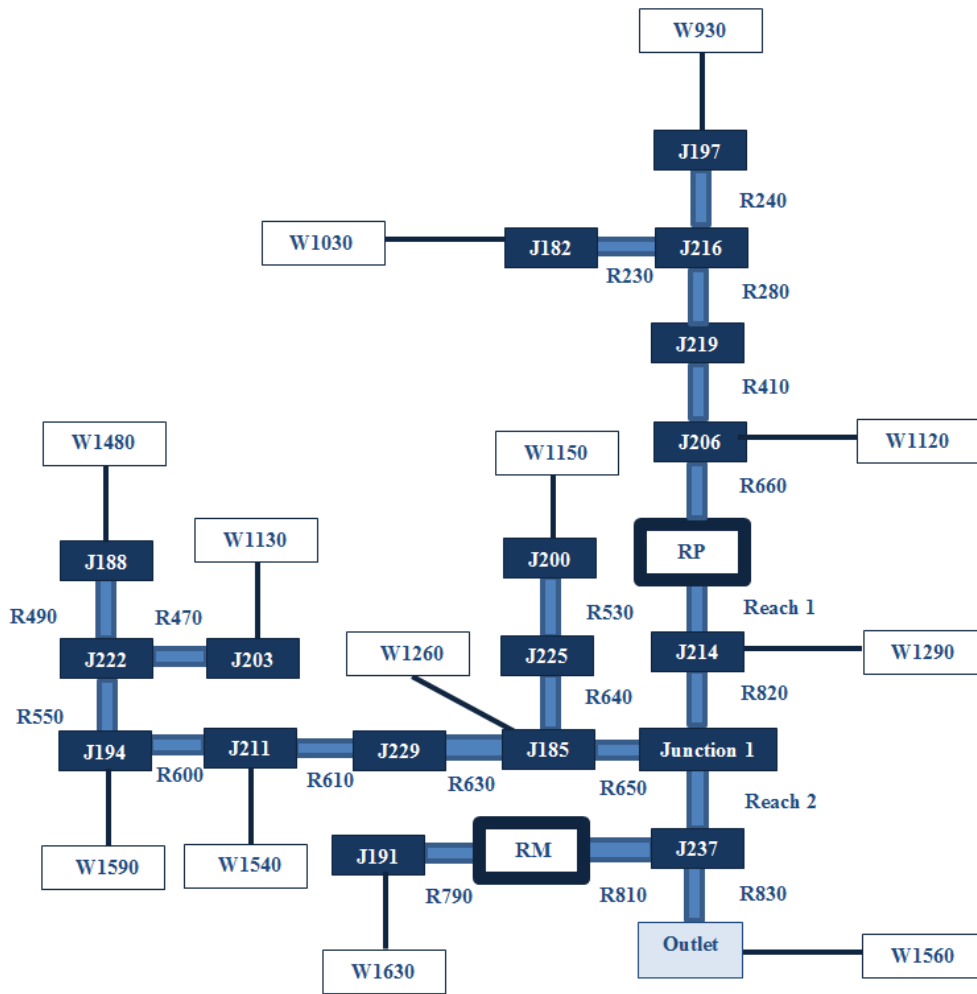


Figure 38 Sematic structure of the basin model, Pöllau catchment (where W represents subbasins, J junctions, R reach elements, RP the reservoir on Prätisbach, RM the reservoir on Mausbach)

Subbasins are those elements of the basin model, which usually have no inflow and one outflow. They are represented by points in lumped models, the size of them has to be given or imported from HEC-GeoHMS as well as in the present study (Scharffenberg and Fleming 2010). The watershed was divided into twelve subbasins in accordance with the Master thesis of Firle (2008). The division was determined by the location of the discharge gauges, land use data and geological information. Table 11 contains the areas and average slopes of the subbasins and the length of the longest flow paths. Appendix A, B and C contain detailed information about land use, pedology and geology of each subwatershed.

The junction element is used to combine stream flow from hydrologic elements located upstream of the junction element.

Table 11 Areas and slopes of the subwatersheds, lengths of the longest flow paths

Number	Subwatershed	Area (km²)	Basin slope (%)	Longest flow path (m)
1	W930	7.26	15	3863
2	W1120	7.52	13	5417
3	W1030	4.69	14	3837
4	W1130	6.78	14	4278
5	W1150	3.23	11	4315
6	W1260	8.39	8	5499
7	W1290	1.85	12	3118
8	W1480	7.72	14	5202
9	W1540	2.54	12	5399
10	W1560	2.79	6	3344
11	W1590	2.84	14	5438
12	W1630	2.34	9	3370

The reach element conveys stream flow downstream in the basin model. They model rivers or streams (Scharffenberg and Fleming 2010). The length of the reach elements (Table 12) must be given by some of the calculation methods, however, it was not necessary in this study. The lengths of the reaches were only used to estimate the runoff times on each element during the calibration of the model.

Table 12 Lengths of the river reaches

Reach	Length (m)
Reach-1	1245
Reach-2	1778
R230	872
R240	1159
R280	365
R410	1063
R470	685
R490	709
R530	1593
R550	1337
R600	1575
R610	537
R630	478
R640	1498
R650	699
R660	616
R790	371
R810	925
R820	539
R830	430

In the HEC-HMS adaptation, reservoirs represented the two flood retention basins. These hydrological elements were only later pasted into the model, within the HEC-HMS project because HEC-GeoHMS does not create reservoirs. Reservoirs are hydrological elements of the model with one or more inflow and one computed outflow. The total volume of the inflow is equal to the total volume of outflow. However, the time distribution of outflow is altered by the reservoir decreasing the critical peak flow, which would cause without reduction damages downstream. The water surface in the reservoir pool is assumed to be level. The outflow from the reservoir is computed with the Modified Puls routing model (level-pool routing model) discretizing time and solving the one dimensional approximation of the continuity equation (13) in a recursive way (Scharffenberg and Fleming 2010, Feldman 2000):

$$I_{avg} - O_{avg} = \frac{\Delta S}{\Delta t} \quad (13)$$

where I_{avg} (m^3/s) is the average inflow during time interval Δt (s), O_{avg} (m^3/s) is the average outflow during Δt and ΔS (m^3) is the storage change.

The complexity of the applied basin model made the calibration definitely difficult, however, such division was necessary regarding the number of discharge gauges, the heterogeneity of land use structure and geology.

4.3.2. Meteorological model

After the creation of one or more basin models, a meteorological model has to be added to the model and matched to the chosen basin model. Meteorological models aim to function as boundary conditions of the model, calculating the frozen or liquid precipitation and evapotranspiration (Scharffenberg and Fleming 2010, Széles et al 2012).

The present study dealt with only liquid precipitation and evapotranspiration.

4.3.3. Control specifications

Time step, start and end time of the simulation have to be given as control specifications of the simulations. A new control specification can be created in *Control Specification Managers* (Scharffenberg and Fleming 2010).

The chosen time step always depends on the length of the simulation. The time windows of the time-series data stored in HEC-DSS files change during the different simulations according to the here specified time interval. Thus, these do not need to be modified independently in each simulation, if the time interval changes.

4.3.4. Input data

There are three types of input data (Scharffenberg and Fleming 2010):

- (1) Time-series data,
- (2) Paired data and
- (3) Gridded data.

Only the first two types of data were applied in the present study. The available precipitation data of the seven precipitation gauges and discharge data of the four discharge gauges stored in ASCII files (Firle 2008) were firstly written into HEC-DSS files and then loaded into the model as time-series data. According to Table 13, the measured data from January 2004 to January 2005, with five-minute time step were used as model input in this work. Firle

modelled exactly the same time series in her Master thesis (2008) which gave an opportunity to compare the results of two different models: BlueM and HEC-HMS.

There are numerous sorts of paired data sets which define a variable as a function of an independent variable. The function usually monotonically increases (Scharffenberg and Fleming 2010). The most important and above described characteristics, the storage-discharge curves of the flood control reservoirs were stored as paired data.

Table 13 Available and applied time-series data (Source: Firlre 2008)

Name	Type	Time period	Time step
Base gauge	Discharge	01.01.2004. 00:00 - 31.12.2004. 23:55	5 min
Ölmühle	Discharge	01.01.2004. 00:00 - 31.12.2004. 23:55	5 min
Dürre Saifen	Discharge	01.01.2004. 00:00 - 31.12.2004. 23:55	5 min
Wildholzrechen	Discharge	01.01.2004. 00:00 - 31.12.2004. 23:55	5 min
Prätisbach			
Heiling	Evaporation	08.04.2004. 07:00 - 31.10.2004. 07:00	1 day
Heiling	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:00	5 min
Cividino	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:01	5 min
Franzl im Moor	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:02	5 min
Moyhofer	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:03	5 min
Leitenbertl	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:04	5 min
School	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:05	5 min
Höhenhansl	Precipitation	01.01.2004. 00:00 - 01.01.2005. 00:06	5 min

4.4. Short description of the available and chosen components of the HEC-HMS rainfall-runoff model

HEC-HMS offers the users numerous calculation methods developed in the United States of America. Therefore, applying these methods in Austrian catchments and accepting the parameters suggested by user's guides requires a proper attention, consideration of different climatic, topographical features and dissimilar runoff characteristics of Austrian catchments. Calculation methods used in the present study are shown below, in Table 17. Sixteen different parameters needed to be calibrated for each subwatershed (twelve) or reach element (twenty) in continuous simulations.

4.4.1. Description of the basin model

4.4.1.1. Subbasin elements

The following, optional components can be chosen to model the hydrological processes of the subbasins (Scharffenberg and Fleming 2010, Feldman 2000):

(1) Canopy method

Canopy represents the vegetation intercepting a certain amount of precipitation which evaporates between storm events. Canopy reduces the total precipitation calculated by the meteorological model and fills the storage during the precipitation until its maximum capacity. Canopy is usually applied in continuous simulations. The available canopy methods

are Gridded Simple Canopy and Simple Canopy. The two methods only differ from each other in one thing: the Gridded type applies the method on a grid cell basis.

Application of a Canopy method had basically one main reason. The simulations were continuous, therefore, an evaporation model was also applied. Canopy ensured that the storage empties and evaporates between storm events. Simple Canopy was used in the present study with two free parameters. Initial Storage (%) is that part of the Canopy storage which is filled initially, therefore, it reduces the interception losses. Max Storage (mm) is the maximum height of water that withholds water on the vegetation.

(2) Surface method

Surface represents the losses in the depressions of the ground surface which evaporates between storm events. After the canopy losses, depression storage can be significant in forests or agricultural lands. Surface runoff is only generated, if the surface storage is filled and the precipitation rate exceeds the infiltration rate. Surface is usually applied in continuous simulations. There are two surface methods in HEC-HMS: Gridded Simple Surface and Simple Surface.

The model was more sensitive to Surface than to Canopy losses. Finally, regarding the already large number of free parameters, Surface method was neglected from the model.

(3) Loss method

Loss represents the subsurface processes of subbasins, such as infiltration. Different Loss methods are applicable to event simulations and continuous simulations. Subbasins do not need to have uniform Loss methods, they can be differently chosen for each subbasin.

There are twelve different loss methods:

- Regular and Gridded SCS Curve Number Loss: the gridded version is the same as the regular type but it is calculated on a grid cell basis. Infiltration is calculated at the end of each time step based on the curve number.
- Initial and Constant Loss: if there is a lack of detailed soil information, this method is the simplest loss method for event simulations.
- Regular and Gridded Deficit and Constant Loss: the gridded version applies the regular type on a grid cell basis. The losses are calculated with one, single soil layer representing continuous changes in soil moisture. Therefore, this method can be applied in quasi continuous simulations.
- Exponential Loss: is an empirical loss method simulating logarithmically decreasing infiltration for only event simulations because of the lack of recovery.
- Regular and Gridded Green and Ampt Loss: the gridded version applies the regular type on a grid cell basis. The method itself simulates infiltration with piston displacement solving the Richard's equation which describes unsteady water flow in soil.
- Smith Parlange Loss: Richard's equation is solved and the wetting front is described by the exponentially scaled saturated conductivity.

- Regular and Gridded Soil Moisture Accounting Loss: the gridded version works on the same principle as the regular type but on a grid cell basis describing different underground processes, such as interflow, tension and gravity storage in long-term, continuous simulations. The losses are calculated with three soil layers besides a Canopy and Surface method.

At first, the regular SCS Curve Number was applied as a loss method which was developed by the Natural Resources Conservation Service. However, the HEC-HMS version of SCS CN method has a great disadvantage. It is only applicable in event simulations. The incremental precipitation excess is calculated by the following equation (14):

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \quad (14)$$

where P_e is the precipitation excess at time t , P is the accumulated rainfall depth at time t , S is the potential maximum retention and I_a is the initial abstraction which can be estimated empirically (15):

$$I_a = 0.2 S \quad (15)$$

The Curve Number (varying 100÷30, from water bodies to permeable soils with great infiltration capacity respectively) expresses the characteristics, such as land use and soil types, of the watershed and creates a link between these characteristics and the maximum retention, S according to equation (16):

$$S = \frac{25,400 - 254 CN}{CN} \quad (16)$$

SCS Curve Number Loss method has three free parameters: Initial Abstraction (mm) and Impervious (%) which can be optionally given, Curve Number (-) which must be given. If Initial Abstraction is left blank, it is calculated according to equations (15) and (16). Impervious represents the percentage of directly connected impervious areas which are not included in the computation of composite curve number.

Curve number is the function of soil type, land use and antecedent moisture. It can be calculated according to tables found in TR55 (USDA 1986). The Curve Numbers of each subbasin are found in Table 14. Appendix A contains the detailed calculations.

According to the available soil information about the catchment (www.gis.lebensministerium.at/eBOD 20.03.2014), the soil types uniformly belong to HSG (Hydrologic Soil Group) A category. The six land use types are matched with six different Curve Numbers in accordance with the HSG category (USDA 1986). Each watershed has more land use categories with different Curve Numbers. For this reason, a composite Curve Number has to be calculated in proportion of the areas with different land use categories according to equation (17):

$$CN_{composite} = \frac{\sum A_i CN_i}{\sum A_i} \quad (17)$$

where $CN_{composite}$ is the composite Curve Number, i is the index of subwatershed with homogeneous land use and soil type, CN_i is the Curve Number of subbasin i , A_i is the drainage area of subbasin i .

Table 14 Calculated Curve Numbers for the subbasins

Subbasin	Curve Number
W930	36
W1120	38
W1030	37
W1130	38
W1150	37
W1260	43
W1290	45
W1480	34
W1540	37
W1560	63
W1590	34
W1630	37

There are several limitations of the SCS CN method (USDA 1986, Mishra and Singh 2003, Galoie 2013): since the method was developed for agricultural sites, its performance is poor on forest or range sites; rainfall intensity is disregarded; the method is inaccurate for small rainfall events; all of the characteristics of the basin are represented by only one parameter, the Curve Number which can result in inaccuracies; the categorization of special and not too general soil types into hydrologic soil groups (HSG) include inaccuracies; the method cannot properly handle inhomogeneous basins regarding land use and soil types; infiltration rate approaches zero during long storm events. However, the method itself is predictable, stable, simple, based on physical properties of the watershed, widely and successfully used in small-to medium-sized, un-gauged catchments.

SCS Curve Number could not be successfully applied throughout the simulations. Initial Abstraction, whether left blank or calculated according to equations (15) and (16), was so high (30÷100 mm) that it consumed the whole precipitation, therefore, it had to be reduced significantly. Another major problem with this method was the unpunctual simulation of the second hydrographs. If the simulation of the first hydrograph was relatively correct, further events were systematically under- or overestimated. This error could not be corrected by the modification of evapotranspiration.

The regular Deficit and Constant Loss method was applied in continuous simulations as the counterpart of Initial and Constant Loss method for event simulations, where initial loss can recover. Therefore, it is advised to use this method with a meteorological model with an evapotranspiration component to dry out the soil between storm events. The method has four free parameters. Initial Deficit (mm) is the height of water which saturates the soil. Maximum Deficit (mm) is the maximum height of water which can be hold in the soil. The Constant Rate (mm/hr) is the intensity of infiltration. If the soil is saturated, Constant Rate can be approximated by the saturated hydraulic conductivity. The fourth parameter, Impervious (%) is the percentage of the directly connected impervious areas where interception is limited in accordance with the given percentage.

(4) Transform method

Transform methods process excessive precipitation to direct runoff. There are seven available Transform methods in HEC-HMS, mainly empirical models and one conceptual model (Kinematic Wave model).

- Clark Unit Hydrograph Transform: the hydrograph is calculated by a time-area curve stored in HEC-HMS, than routed through a linear cascade in accordance with a delay time which results a storage attenuation.
- ModClark Transform: the linear, quasi-distributed transform method applies the modified Clark conceptual unit hydrograph on a grid cell basis.
- SCS Unit Hydrograph Transform: a general hydrograph based on observed data measured in agricultural watersheds is scaled by the time lag.
- Synder Unit Hydrograph Transform: is based on a synthetic unit hydrograph, which is estimated by equations calculating the time base and the width of the hydrograph at 50 % of the peak flow, and a supplementary Clark hydrograph.
- User-Specified S-Graph Transform: is based on a summation unit hydrograph representing the subbasin response to a unit of precipitation.
- User-Specified Unit Hydrograph Transform: a separate unit hydrograph is applied in each subbasin.
- Kinematic Wave Transform: one plane for pervious surfaces and one for impervious surfaces represent urban or undeveloped areas. The composite outflow from the planes are linked to a subcollector channel which enters a collector, than the main channel. All of the elements are specified by different physical parameters.

The SCS Unit Hydrograph was applied in the continuous simulations. The shape of the hydrographs is defined by the more general ‘Standard’ type, while, the type ‘Delmarva’ is only applicable in coastal plains of the United States of America. The only free parameter of the method is Lag Time (min) which is the delay time between the centroid of precipitation mass and the peak flow of the resulted hydrograph. According to studies of the Natural Resources Conservation Service, the Lag Time is approximately 60 % of the time of concentration, which is the sum of travel time in sheet and shallow flow and channel segments. For the first, brief approximation, a chosen Lag time was divided between the subbasins in accordance with their areas. The values were specified throughout event simulations regarding the characteristics of each subbasin, such as soil type, land use and shape of the catchment. The refined values were then applied in the continuous simulations.

(5) Baseflow method

The subsurface processes of each subbasin are calculated by a Baseflow method. This is the amount of water, which is, on the one part, temporarily stored in the watershed, on the other part, joint into the overland flow as delayed subsurface flow. A distinction has to be made between event and continuous simulations. There are four different Baseflow methods in HEC-HMS:

- Constant Monthly Baseflow: a constant baseflow is specified for each month of the year without conserving mass in the subbasin. This method is appropriate for continuous simulations.
- Linear Reservoir Baseflow: a linear reservoir represents the baseflow conserving mass within a subbasin. Infiltration of a Loss method is the inflow to the linear reservoir.
- Nonlinear Boussinesq Baseflow: uses the Boussinesq assumption for event simulations and helps modelling receding channel flow.
- Recession Baseflow: helps to model exponentially receding channel flow for primarily event simulations but it can be consequently applied for continuous simulations.
- Bounded Recession Baseflow: is similar to Recession Baseflow applying the recession method, but completed with monthly baseflow limits. Another difference is the absence of the baseflow's reset after a storm event.

At first, the Constant Monthly Baseflow method was applied for continuous simulations, because the baseflow can be easily determined for each month regarding the available, long discharge time series. However, the runoff was too rapid, the basin was emptied too fast, the method was not sufficient enough.

The Recession Baseflow gave better results for event simulations, however, the method did not work for longer or continuous simulations.

A baseflow method was needed which delayed runoff through subsurface processes and the recession limbs of simulated floods appropriately fitted the measured ones. The Linear Reservoir Baseflow method was successfully implemented in the calibration procedure of continuous simulations. However, this baseflow type is best applied with Soil Moisture Accounting Loss model, it gave very good results in the present study. Subsurface processes are simulated with reservoirs, water is stored and released with a user specified time delay from reservoirs. The method has three or six free parameters for each subbasin whether it is used with one or two groundwater layers which are combined to compute the total baseflow. The Initial Discharge (m^3/s) or Initial Discharge Per Area ($\text{m}^3/\text{s}/\text{km}^2$) describes the initial conditions of the simulation. Firle (2008) applied 0.1 l/s km^2 as baseflow. The Groundwater Coefficient (hr) is the constant response time of the given subbasin. The number of Reservoirs (-) shows how many reservoirs are connected linearly increasing the attenuation of baseflow. More details about the theory of linear dynamic systems are found in Szilágyi and Szöllősi-Nagy (2010) and Széles (2013).

4.4.1.2. Reach elements

Reach elements represent segments of rivers and streams with one or more outflow and one outflow which is computed by a chosen routing method.

The following components simulate the hydrological processes of a reach element (Scharffenberg and Fleming 2010):

(1) Routing method

The six available, typically hydrologic and not hydraulic routing methods are the following:

- Kinematic Wave Routing: gives the best results in urban areas with artificial, fairly steep watercourses because the unsteady flow equation is solved by neglecting the inertial and pressure forces and assuming the river bed slope is equal to the energy slope.
- Lag Routing: simulates only the translation of waves.
- Modified Puls Routing: is based on storage-discharge relationship and continuity equation.
- Muskingum Routing: is based on mass storage and a non-level water surface approximation. Consequently, the method is able to approximate attenuation, an increased storage in the rising limb and a decreased one in the recession limb of the flood can be calculated.
- Muskingum-Cunge Routing: is best suited to reaches with a moderate slope and flood attenuation can be also modelled. It is based on the combination of mass storage and the diffusion representation of the momentum equation.
- Straddle Stagger Routing: models flood attenuation and translation processes based on empirical approximations.

Lag routing was applied in the present study regarding its simplicity and minimal required free parameters. The method does not simulate diffusion or flood attenuation processes: the shape of outflow hydrograph is the same as the inflow one but the ordinates are translated in time. Regarding the relatively short stream segments, the travel times could be specified. The method requires one free parameter, Lag Time (min) which is the time delay between inflow and outflow. Firstly, each Lag Time was proportionately chosen to the length of the given reach element, later these were slightly modified throughout event calibration procedures and the calibrated values were applied in continuous simulations.

(2) Loss/Gain method

There are two Loss/Gain methods: Constant Loss/Gain and Percolation Loss/Gain, but neither of them was applied in the simulations. These elements simulate losses and gains or both from the channel due to interactions between streams and subsurface.

4.4.1.3. Reservoir elements

There are several existing methods in HEC-HMS which describe the properties and operating principles of the reservoirs. The four routing methods which calculate the storage processes are (Scharffenberg and Fleming 2010, Feldman 2000):

- Outflow curve routing: simplest routing which calculates the outflow according to known and user-provided storage-outflow relationship,
- Specified release routing: if the total discharge is known as a specified release, the method tracks the storage on the principle of mass conservation,
- Outlet structures routing: individual and uncontrolled structures of the outlet works are specified by the user such as spillway, low-level outlet pipes, culvert, orifice and numerous other available structures,
- None: if there is no storage in the reservoir and all inflow becomes outflow along the whole simulation.

The first, ‘Outflow curve routing’ method was applied in the model according to the available database. A single storage relationship stored as Paired Data is needed for the calculations, which cannot be looped, but monotonically increasing. There are three choices for specifying the storage method (Scharffenberg and Fleming 2010):

- Storage-Discharge method: a storage-discharge curve has to be specified by the user.
- Elevation-Storage-Discharge method: a storage-discharge and an elevation-storage curve have to be given and a primer one has to be selected. A common table will be created containing the primer relationship and the third type is interpolated into the table’s third column according to the non-primer relationship.
- Elevation-Area-Discharge method: an elevation-area and an elevation-discharge curve have to be given and a primer one has to be selected. A common table will be created containing the primer relationship and the third type of data is interpolated into the table’s third column according to the non-primer relationship.

Irrespectively of the type of the given storage method, the routing is always calculated with the storage-discharge curve. The relationships are stored as Paired Data in HEC-HMS and can be created by the Paired Data Manager in two ways (Scharffenberg and Fleming 2010):

- Manually entered or
- Loaded from Data Storage System (HEC-DSS) files.

In the basin model of Pöllau, the ‘Storage-Discharge’ method was applied. According to the descriptions and storing-releasing principles of the flood control reservoirs Mausbach and Prätisbach, the curves in Figure 14 and Figure 18 were treated as one in the cases of each reservoir: the normal outflow and overflow were added together (Figure 39 and Figure 40).

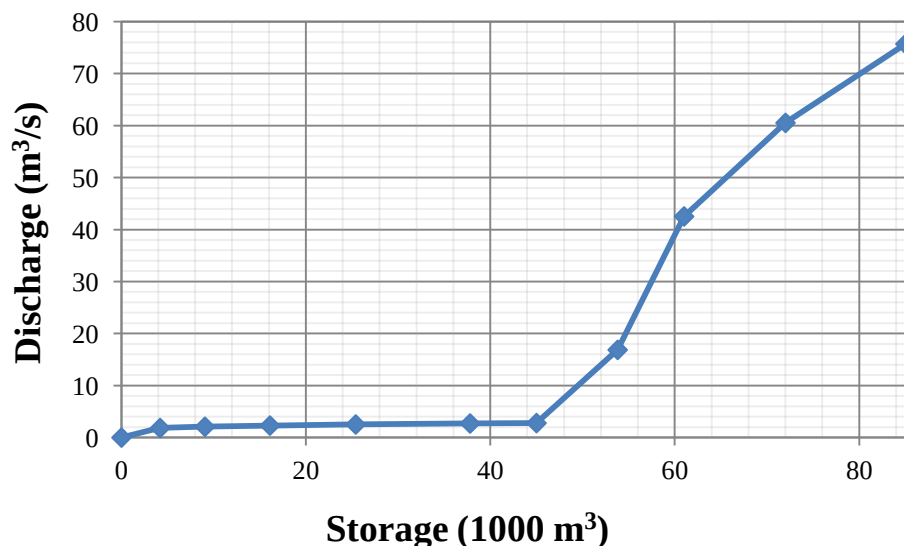


Figure 39 Storage-discharge relationship of the retention reservoir on Mausbach

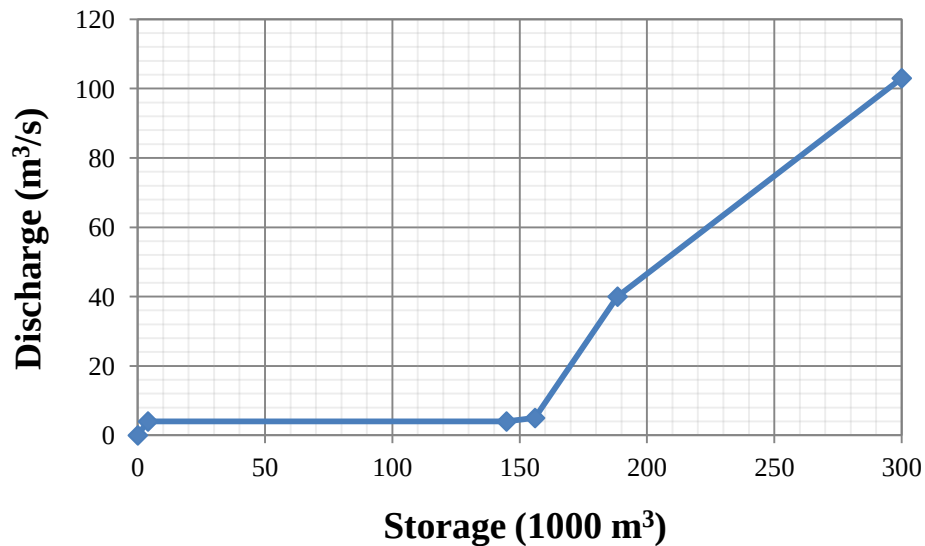


Figure 40 Storage-discharge relationship of the retention reservoir on Prätisbach

The Initial Condition, the initial storage of the reservoir also has to be set. There are three available options (Scharffenberg and Fleming 2010):

- Inflow = Outflow: the initial inflow to the reservoir is transformed to storage according to the storage-discharge relationship and producing an outflow from the reservoir,
- Discharge: with some storage methods it is also possible to specify a discharge value, the storage is interpolated from the storage-discharge curve.
- Storage: a volume of water in the reservoir can be set with some storage method,
- Elevation: with some storage methods an elevation can be also specified and a storage value is interpolated from the elevation-storage curve.

Table 15 shows the possible initial conditions with the different storage methods. ‘Inflow = Outflow’ method was applied as initial condition in both cases.

Table 15 Available initial conditions for the three storage methods of the Outflow curve routing method (Scharffenberg and Fleming 2010)

Storage method	Available initial conditions
Storage-Discharge	Discharge, Storage, Inflow = Outflow
Elevation-Storage-Discharge	Discharge, Storage, Elevation, Inflow = Outflow
Elevation-Area-Discharge	Discharge, Elevation, Inflow = Outflow

4.4.2. Description of the meteorological model

4.4.2.1. Precipitation

There are eight different precipitation types (Scharffenberg and Fleming 2010):

- (1) No precipitation method: if there are no subbasins in the basin model,
- (2) Frequency storm: calculates with a synthetic storm from statistical precipitation data with different probability of exceedance,

- (3) Gage weights: is based on the Thiessen polygons method with recording (which measure the real precipitation as it occurs) and non-recording gauges (which estimate the total precipitation depth),
- (4) Gridded precipitation: is able to handle spatially distributed precipitation, such as radar-based precipitation, the ModClark gridded transform method requires the use of this meteorological model,
- (5) Inverse Distance: an index is matched with every gauge, according to its longitude and latitude location, expressing the distance from some nodes of the subwatersheds,
- (6) SCS Storm: a designed storm is applied which was developed by the Natural Resources Conservation Service,
- (7) Specified Hyetograph: is usually used when external precipitation time series are available or there is only one gauge on the whole watershed,
- (8) Standard Project Storm: the instructions of the Engineering Manual are followed.

Due to the large number of available precipitation gauges, it was necessary to spatially distribute precipitation, which was calculated by the Gage Weights Meteorological Model (Thiessen polygons method) with HEC-GeoHMS. This meteorological model uses different parameters for each gauge and subbasin.

The structure of this meteorological model in the *Watershed Explorer* is complicated. There are several icons one level under the meteorological model (Scharffenberg and Fleming 2010):

- Gage Weights precipitation icon is only showed, if *Use Indexing* under *Options* in the *Component Editor* of the meteorological model is activated taking into consideration regional differences in monthly or annual precipitation throughout an index depth for each subbasin.
- Precipitation Gages icon is always showed. If any of the *Use Indexing* or *Total Override* options are disabled, only information for total storm gauges are shown (where either time-series gauges or total storm gauges can be chosen defining a total depth and an index for the chosen gauge). If any of these options is active, further information about time-series gages appears where also indices can be given to the gauges.
- Names of each watershed with separate precipitation icon where the gauges for each subbasin can be specified and the gauge weights (depth and time weights) can be given for the selected gauges.

In this study, only *Replace Missing* was activated under the *Options* menu, therefore, only Precipitation Gages icon and each watershed appeared in the *Watershed Explorer*. No total depth was determined for any of the gauges. Regarding the available time series data and the gauge weights calculated by HEC-GeoHMS, the gauge weights were defined according to the calculated weights, all of the time weights were set equally 1 which means, all of the gauges were working without pause.

It is strongly advised to control the created meteorological model in HEC-HMS because errors in the gauge weights can occur, as they also occurred in the present work. The gauge weights of Moyhofer were false. Therefore, the subbasin and Thiessen polygon layers were intersected in ArcGIS (*Analysis Tools/Overlay/Intersect*). Different regions of the subbasins belonging to different polygons were collected into a table. The depth weights were defined as follows: the area of a given region was compared to the total area of the subbasin which contained it.

4.4.2.2. Evapotranspiration

In the nature, much of the precipitation returns to the atmosphere due to evaporation from the surface of the vegetation, land, water bodies and transpiration of vegetation. Evapotranspiration is minimal, if there is a storm. Therefore, this model component can be omitted during an event simulation (Feldman 2000). This is an important fact because the reduction of free parameters can help the calibration, especially, if these parameters cannot be determined explicitly but need to be calibrated.

Long-term, continuous simulations required an evapotranspiration model. Evapotranspiration consists of evaporation from the ground surface and transpiration of the vegetation. Evapotranspiration is only compatible with four loss methods (regular or gridded deficit constant and regular or gridded soil moisture accounting loss methods), however, these methods do not require an evapotranspiration model. If it is not included, evapotranspiration is assumed to be zero. There are three available evapotranspiration methods in HEC-HMS (Scharffenberg and Fleming 2010):

- (1) Priestley Taylor: evapotranspiration is computed by the Priestley-Taylor equation,
- (2) Gridded Priestley Taylor: the same as regular Priestley Taylor method, but the equation is solved on each grid cell, the method was developed to be used with gridded ModClark transform method,
- (3) Monthly Average: is based on measured or in another way collected (for example eddy covariance technique) evaporation data.

The Monthly Average method was applied in the present study. It requires two data for each subbasin: the monthly total amount of evaporation and a factor, called pan coefficient which modifies and corrects the evaporation data. Daily evaporation is measured in Heiling from April to October. The measured evaporation data from April to October in the year 2004 were used in the continuous simulations (Figure 41).

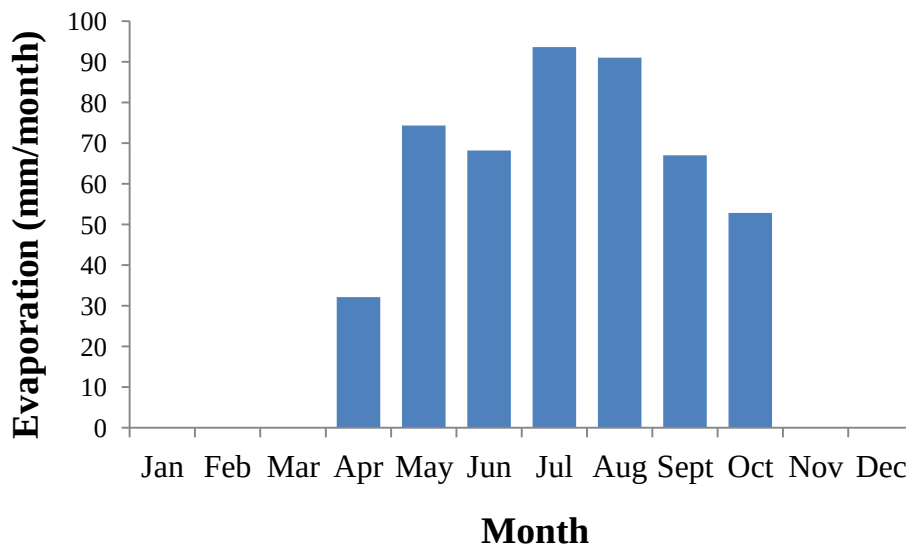


Figure 41 Monthly evaporation data (Source: Firlie 2008)

4.5. Continuous simulations with HEC-HMS

The first release of HEC-HMS, Version 1.0 was only capable of modelling event simulations. The improvements of later versions included methods, such as soil moisture accounting method, which were able to handle continuous simulations as well (Scharffenberg and Fleming 2010).

The selected hydrological model elements have to be in accordance with the modelling time interval. The applied loss and baseflow methods have to be chosen carefully. Evapotranspiration method plays a major part in continuous simulation. However, its effect is usually minor with short simulations. Only four loss methods take into consideration evapotranspiration and can be applied in continuous simulations, which are regular or gridded deficit constant and regular or gridded soil moisture accounting loss methods (Scharffenberg and Fleming 2010).

The study performs the results of continuous simulations characterizing the seasonal variability of the Pöllau catchment. Event simulations were only modelled in the first steps of getting acquainted with model parameters, the rainfall response and main hydrologic characteristics of the watershed. They also helped to determine runoff times and specify the free parameters of Transform and Routing methods.

4.6. Choosing the analysed time intervals of the model

The primer aim of model simulations was to calibrate the model for an as long time period as it was possible. The best would have been a calibration throughout the whole year, although, it was not possible due to the available hydrological elements of the HEC-HMS model which could not take into consideration the seasonal variability of Losses and Baseflow. For this reason, the model was calibrated for months or seasons.

An important aspect of choosing a proper time interval is a long antecedent dry period before the events. This generally means, the simulations are relatively independent of the initial and boundary conditions' influences. Therefore, the free parameters describe the hydrological characteristics of the watershed correctly and may be applicable for other time series which means that the model is robust enough.

The time series of January and February could not be applied in the calibration procedure because the precipitation-discharge measurements were not coherent. Usually the winter months are omitted from rainfall-runoff model simulations, if the precipitation gauges are not able to measure snow which was also the case in these instruments in 2004.

August was also not modelled in the summer simulations because there was a flood event which significantly differed from the others according to the under detailed correlation analyses (Appendix E) between peak flows and total precipitation or maximal precipitation intensity. The peak discharge entailed uncertainty, namely, it was exceptionally high, although the runoff was too swift comparing to other flood events in summer months.

According to preliminary control of the time series (Paragraph 2.4), the discharge time series on Dürre Saifen were not correctly measured in September which meant that part of the upper catchments could not be calibrated. On this reason, September was only used as validation time interval of the model. There were no significant flood events in November. It follows that this month was also not adequate for calibration, however, it could be involved in the

validation of autumn months. The model was finally calibrated in October and validated in an extended time interval, from September to November including the calibration time series as well.

4.7. Sensitivity analyses

The aim of sensitivity analyses was to collect the most sensitive parameters of the model which have the greatest influence on the model output and filter out those which have no or minimal effects on it. The less sensitive ones could be neglected at the first steps of calibration. The two applied objective functions were volume error and peak flow. Regarding the huge number of free parameters, sensitivity analysis played a very important role and made the calibration procedure significantly easier.

Sensitivity analysis was performed for one month, in June. Sensitivity of free parameters naturally changes, if the length of simulated time interval is modified. It is evident that baseflow and evapotranspiration play a more significant role in long term simulations, therefore, the sensitivity of parameters characterizing these two hydrologic elements also changes.

During the sensitivity analyses, the free parameters of the HEC-HMS model, one at a time, were perturbed with -20, -10, +10, +20 %, except for Groundwater reservoirs when fractions cannot be given only integers. Figure 42 and Figure 43 show the results of sensitivity analyses.

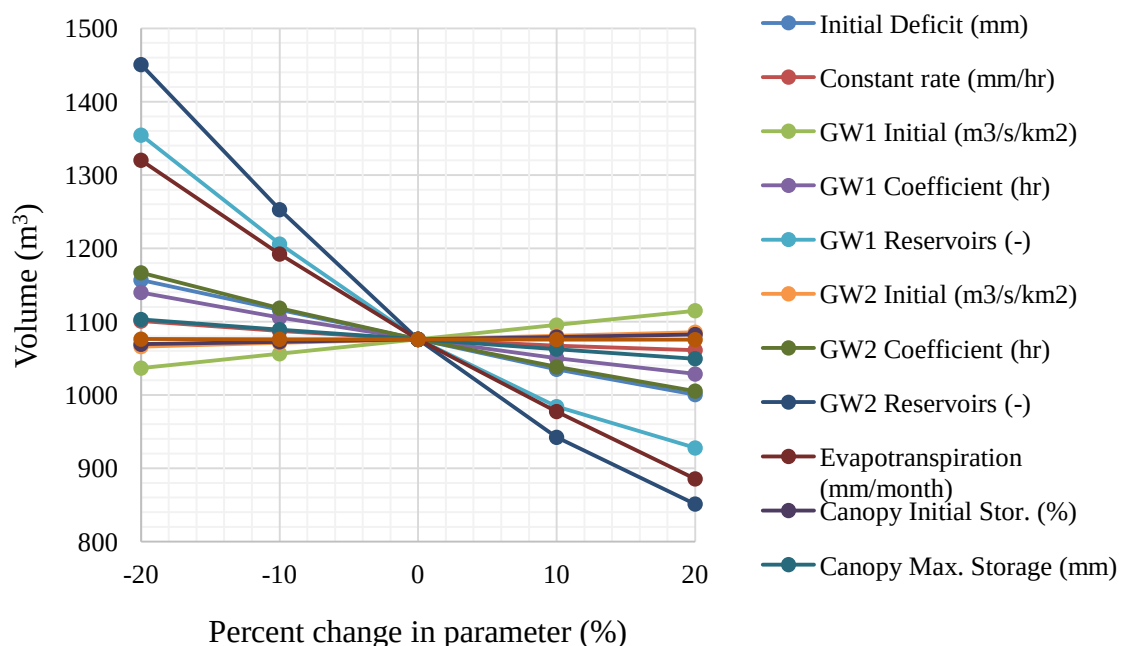


Figure 42 Sensitivity analysis of the free parameters, changes in the discharge volumes

Impervious area of Deficit and Constant Loss method was not applied in the model, therefore, it does not occur in the figures. Similarly, Maximal Storage of Deficit and Constant Loss had only an indirect effect on the model output: Initial Storage of the Loss method significantly influenced the magnitude of peak flow and Initial Storage has to be smaller or equal to the Maximal Storage.

Those free parameters which had only a minimal effect on discharge volumes, usually had a greater influence on peak flow (for example Constant rate of Deficit and Constant Loss, GW2

Initial Discharge Per Area of Linear Reservoirs Baseflow, Lag of Lag Routing method). SCS Unit Hydrograph Transform method only changes the peaks but has no influence on discharge volumes. Usually, the elements of Linear Reservoir Baseflow method primarily change the runoff volumes. Their effect on peak flows is not as noticeable. Evapotranspiration has a huge influence both on discharge volumes and peak flows.

The discrete values of sensitivity analyses were connected with lines which revealed the nonlinear nature of some free parameters (Evapotranspiration, Initial Deficit of Deficit and Constant Loss, GW2 Reservoirs of Linear Reservoir Baseflow). It is generally true with most of the parameters, that a positive or negative perturbation with the same magnitude does not have the same effect.

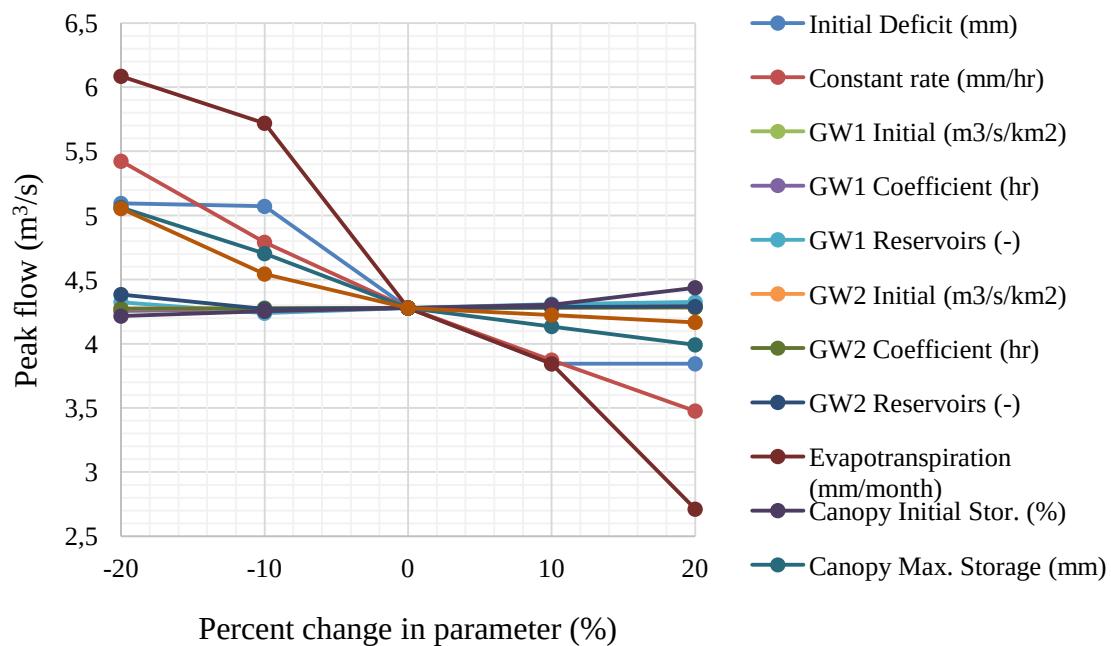


Figure 43 Sensitivity analysis of the free parameters, changes in the peak flow

The normalised change in objective function was divided by the normalised parameter variation, then the obtained sensitivity gradients were ranked (Figure 44 and Figure 45). These results supported the process of model calibrations: the shapes of measured and simulated hydrographs were fitted first with those parameters that got a higher rank. Besides volume and peak flow, other objective functions could be also analysed, for example Nash Sutcliffe Coefficient could show the goodness of fit between the hydrographs: usually Transform and Routing methods define the starting and ending times of flood waves, moreover, the gradient of the hydrographs' limbs.

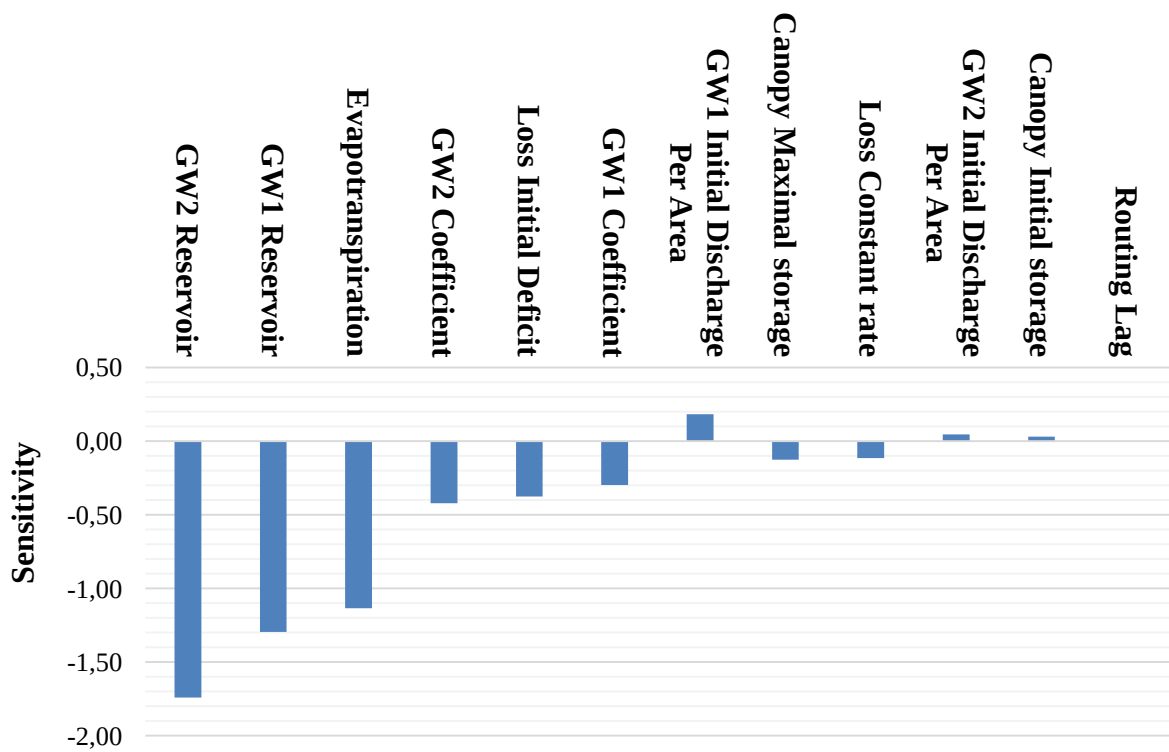


Figure 44 Ranked sensitivity gradients (in the case of -20 % perturbation) for volume

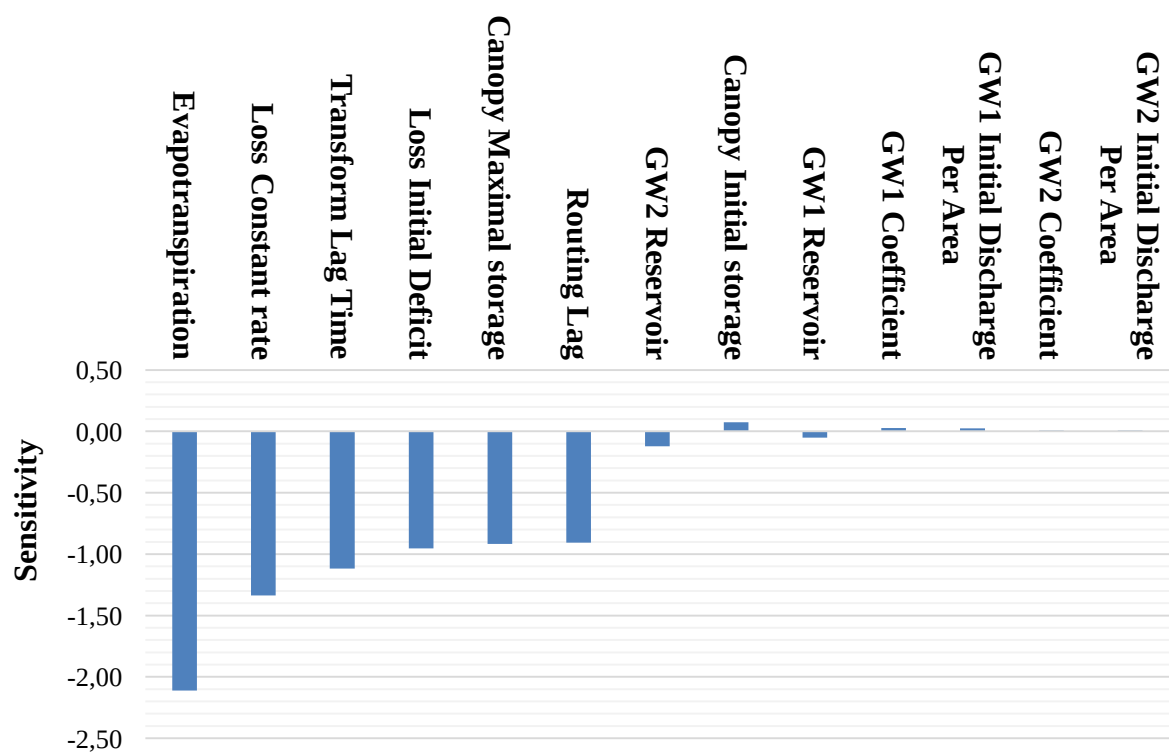


Figure 45 Ranked sensitivity gradients (in the case of -20 % perturbation) for peak flow

4.8. Calibration and validation of the HEC-HMS rainfall-runoff model

4.8.1. Basic principles of the calibration

According to Baffaut (1988) the objective functions of model calibration were classified in the following way: minimalizing relative volume error and peak error are the highest of priority, than the times-to-peak follows and finally root mean square error should be minimal. The main goal of the thesis was to accomplish the first three criterions, meanwhile, the fourth one was also analysed.

The time series of the discharge measurements were used in a hierarchic order from upstream to downstream to properly calibrate the hydrological model comparing the measured runoff with the simulated one.

Table 16 Location of the discharge gauges and the adherent subbasins and reaches

Discharge gauge	Location	Subbasins	Reaches
Wildholzrechen Prätisbach	J206	W930, W1030, W1120	R230, R240, R280, R410
Ölmühle Prätisbach	J214	WHR Prätisbach + W1290, RP	WHR Prätisbach + R660, Reach1
Dürre Saifen	J185	W1130, W1480, W1590, W1540, W1260, W1150	R470, R490, R550, R600, R610, R630, R530, R640
Base Saifenbach	Outlet	Ölmühle + Dürre Saifen + W1630, W1560, RM	Ölmühle + Dürre Saifen + Reach2, R650, R790, R810, R820, R830

Comparing the surface runoff volumes to the precipitation volumes (Kontur et al 1993), only a small proportion of the precipitation (approximately 1 % in June and July) becomes direct surface runoff. This means that losses and groundwater discharge play a significant role.

However, HEC-HMS offers automated calibration methods, regarding the huge number of free parameters, trial and error technique did not give realistic and good results. It follows, the model was calibrated manually according to visual check and minimalizing relative volume and peak errors. Visual check was considered a priority in calibration because objective functions can be misleading, since, they usually apply only one aspect in describing goodness-of-fit.

4.8.2. Parameterisation of the model

Table 17 shows the applied hydrological elements and their parameters for continuous simulations. All together the number of free parameters was sixteen, however, this number was reduced by sensitivity analysis and during the calibration procedure: the model was only indirectly sensitive to Maximum Storage of the applied Loss method, Initial Storage of Simple Canopy and Impervious of Deficit and Constant Loss were 0 % for each subbasin, such as the number of GW 2 reservoirs remained one in each simulation run. Furthermore, the Rate of Evapotranspiration could be given in an explicit way according to hydro-meteorological measurements, evaporation measurements in Heiling. In this way, only eleven free parameters were calibrated.

Table 17 Applied methods and their parameters in continuous simulations

	Methods	Parameters	Unit
Canopy	Simple Canopy	Initial Storage Max Storage	% mm
Loss	Deficit and Constant Loss	Initial Deficit Maximum Storage Constant Rate Impervious	mm mm mm/hr %
Transform	SCS Unit Hydrograph	Lag Time	min
Baseflow	Linear Reservoir Baseflow	GW 1 Initial GW 1 Coefficient GW 1 Reservoir GW 2 Initial GW 2 Coefficient GW 2 Reservoir	m ³ /s hr - m ³ /s hr -
Routing	Lag Routing	Lag Time	min
Evapotranspiration	Constant Average	Rate Coefficient	mm/month -

4.8.3. Calibration of the model

The model was calibrated in more months, approximately for three seasons: for spring from March to May, for summer from June to July and finally an autumn calibration was performed in October. The separation of calibrations was required due to seasonal variability. The model could handle only evapotranspiration differently for each month, other basic hydrological elements, such as baseflow or canopy, could not take into consideration the differences between months. The initial and boundary conditions also significantly differed from each other for a couple of months.

All of the above described methods helping to visualize and numerically describe the simulation results are presented in the calibration of the summer months. Generally speaking, hydrographs and dimensionless coefficients are usually enough in order to consider model results. For this reason, only these two methods are applied in the evaluation other calibrations and validations.

Figure 46 up to Figure 50 show the results of the calibration from the beginning of June to the end of July 2004. These graphical plots help to visualize the results, however, since they enhance different aspects, they should be chosen carefully. The most commonly used figures are hyetographs (Figure 46) which provide a direct comparison between simulated and measured flows and scatter plots (Figure 47) which indicate whether the measurements are overestimated or underestimated (Chiew and McMahon 1993).

According to the hydrographs in Figure 46, simulations well fitted the measured discharge time series, the shapes also showed a good agreement. However, there were some inadequacies in peaks. The main reason of this was presumably that the discharge gauges were not calibrated as it is detailed under, in the discussions of the thesis. The recession limbs of the simulated hydrographs and the second, consecutive waves are sometimes not correct. A

systematic error cannot be established: the inaccuracies in peaks occur irregularly. If the first peaks or smaller hydrographs disappear, it usually means that the initial conditions and losses are overestimated and this consumes runoff. It is a common problem of continuous simulations that the calibrated model cannot simulate smaller events well, if bigger floods also occur between the events and consequently, losses are greater in the latter case. Differences in the second hydrographs implied unpunctuality of the estimated evapotranspiration method: if second peaks were smaller, the evapotranspiration was too big and it had to be reduced.

Figure 47 shows the scatter diagram (X-Y plot) of the results. The point pairs show the measured and simulated discharge pairs, the dividing line with a slope of 1:1 is red and the black line is the line of best fit according to linear regression, relating simulated flow to recorded flow. According to Figure 47, flows are usually but only slightly underestimated, the greatest difference can be observed at the base discharge gauge. The latter problem is more notable in Figure 48 and Figure 49. Figure 48 shows the cumulative discharge volumes and the cumulative difference from the mean of recorded flows is found in Figure 49. The discharge gauges upstream from the base gauge were calibrated satisfactorily, therefore, it is not likely that the inadequacies of the upstream calibrations superposed. It is also unlikely that the additional subbasins (W1560 and W1630) were not calibrated correctly. As it is mentioned above and later detailed in the discussions, the measurement errors at the base gauge, especially the missing peak flows could cause great differences in cumulative discharge volumes (Figure 48) and residual mass curves (Figure 49) of the base discharge gauge on Saifenbach.

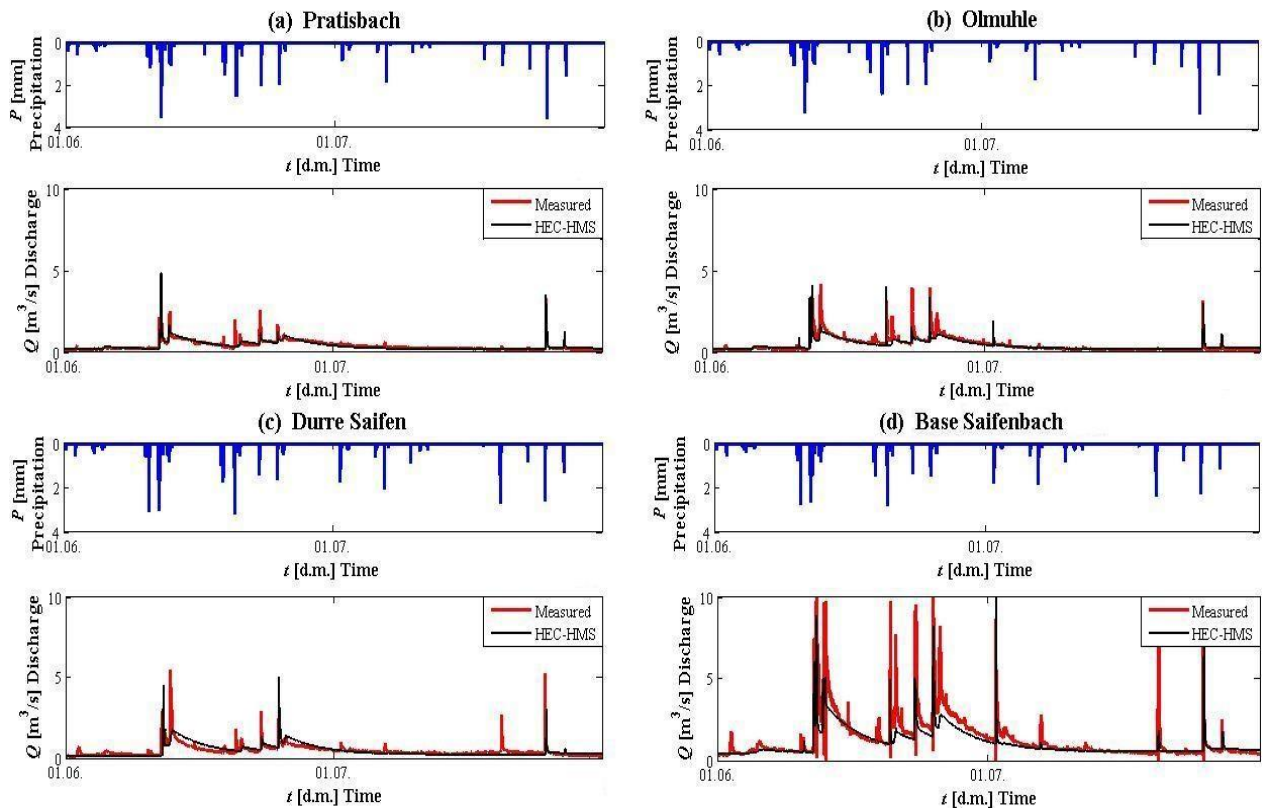


Figure 46 Hydrographs of the simulated (black) and measured (red) flows of the HEC-HMS calibration from the beginning of June to the end of July 2004 with the simultaneously measured precipitation (top blue bar) data

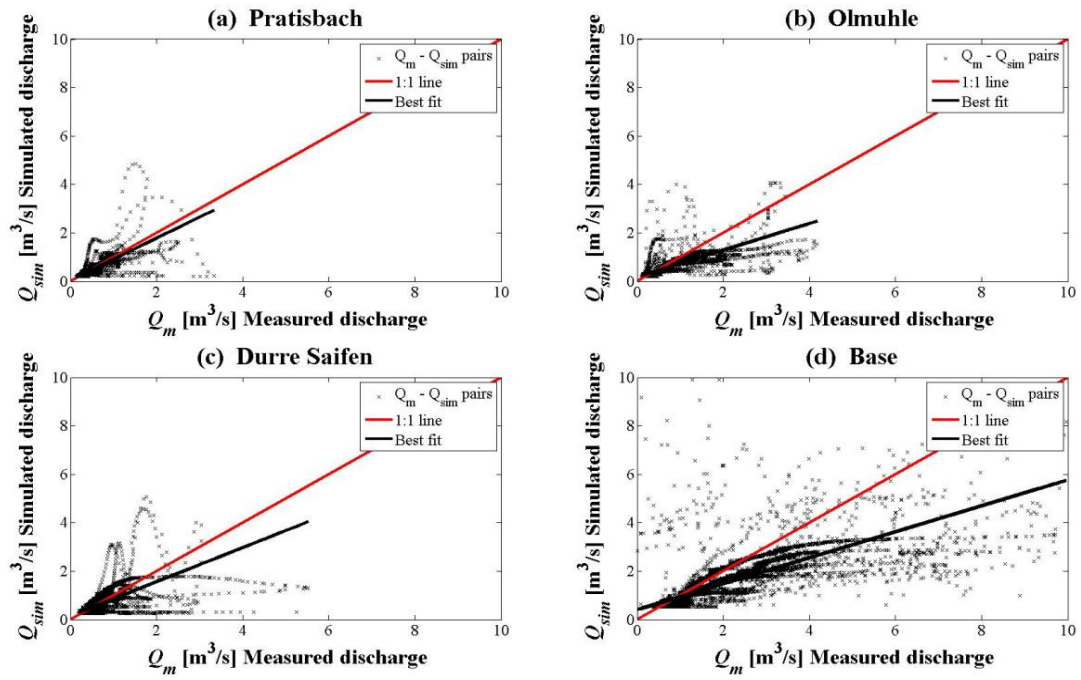


Figure 47 Scatter diagram comparing simulated and measured discharge, HEC-HMS, June-July 2004

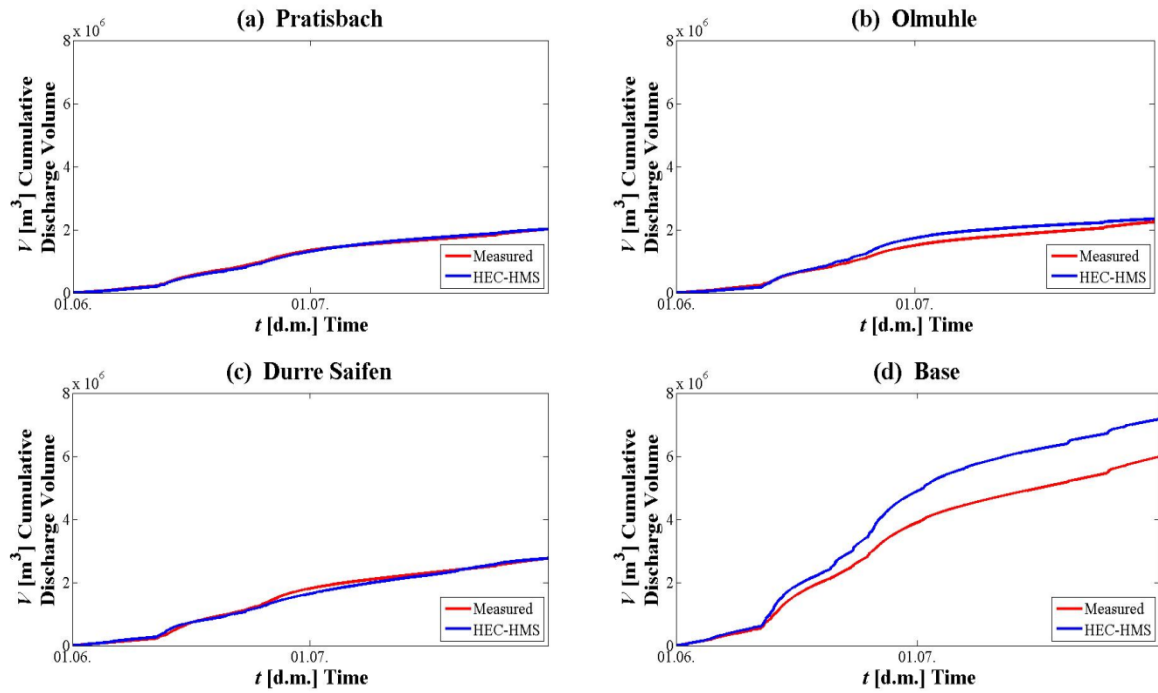


Figure 48 Cumulative discharge volumes of simulated and measured flows, HEC-HMS, June-July 2004

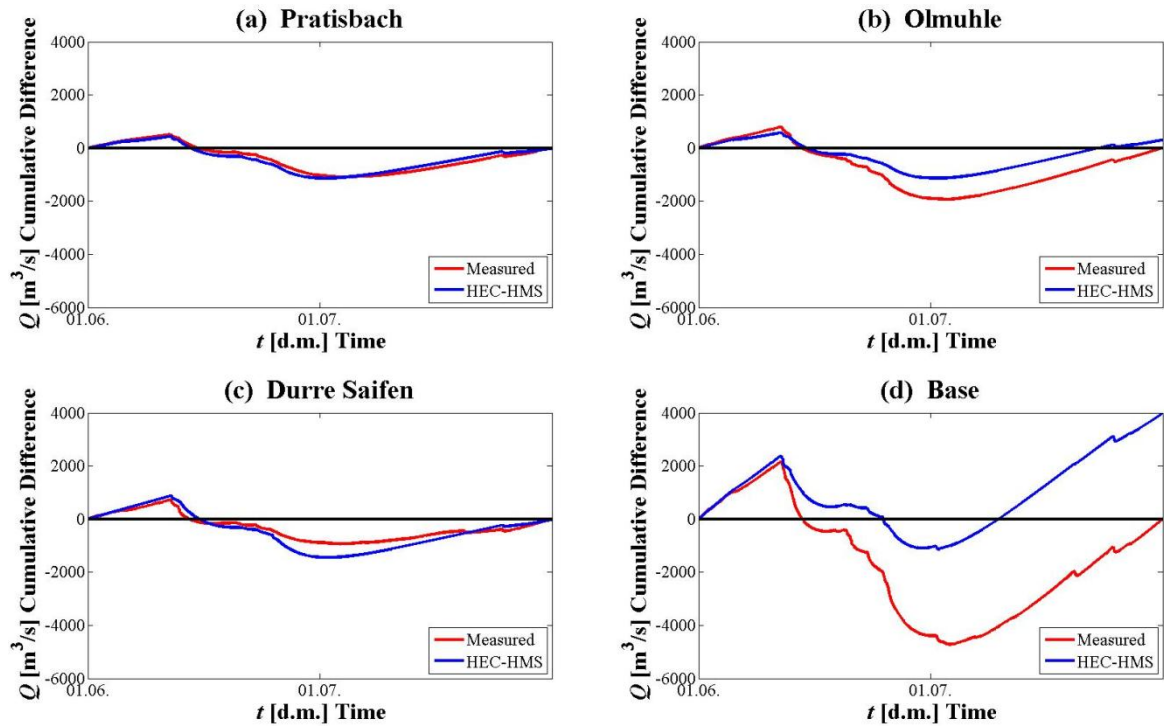


Figure 49 Residual mass curves of simulated and measured flows, HEC-HMS, June-July 2004

The last visual plot, the flow duration curves are found in Figure 50. These curves show the percentage of time when a given flow is equalled or exceeded. These diagrams show that flows were simulated satisfactorily at each gauge.

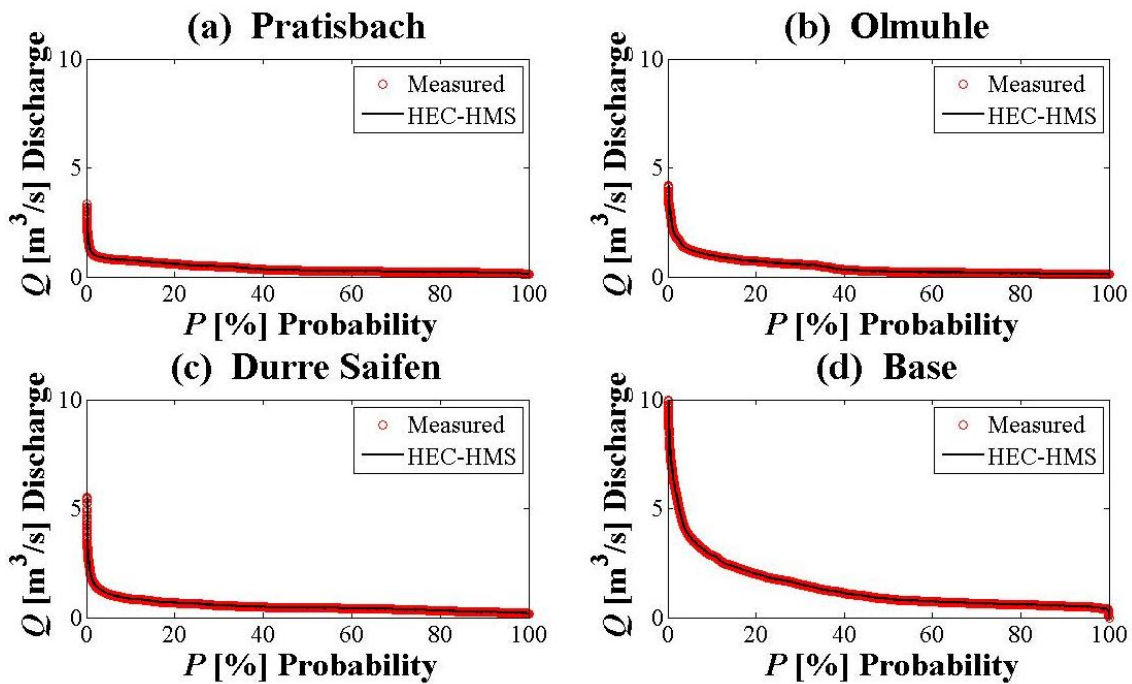


Figure 50 Flow duration curves of simulated and measured discharge, calibration with HEC-HMS from June to July 2004

Statistical parameters are found in Table 18. These are simple indices which generally describe time series, such as mean, standard deviation, skewness and lag-1 autocorrelation coefficient. Table 18 gives further opportunities to compare simulated with recorded flows: means, standard deviations and autocorrelation show a good agreement, however, there are huge differences between the measurements and model simulations according to skewness.

Table 18 Statistical parameters describing the calibration results of HEC-HMS, June-July 2004

Discharge gauges	Mean (m ³ /s)		Standard deviation		Skewness		Lag-1 Autocorrelation coefficient	
	Measured	HEC-HMS	Measured	HEC-HMS	Measured	HEC-HMS	Measured	HEC-HMS
WHR Prätisbach	0.3896	0.3899	0.2562	0.2673	12.3199	14.1380	0.9972	0.9976
Ölmühle Prätisbach	0.4518	0.4336	0.4544	0.3059	5.5239	10.5278	0.9980	0.9958
Dürre Saifen	0.5328	0.5337	0.3590	0.3804	10.1189	7.3767	0.9941	0.9980
Base, Saifenbach	1.3838	1.1534	1.2419	0.8276	1.1773	2.2656	0.9700	0.9969

Table 19 contains dimensionless coefficients of model calibrations from June to the end of July, such as Nash Sutcliffe Coefficient, Relative volume error, Peak error and Routed mean squared error. The model was primarily calibrated according to minimalizing relative volume error adjusting the measured and simulated runoff volumes and peak error reducing the difference between measured and modelled peak flows. However, the latter had difficulties due to some incorrectness in discharge measurements and irregular discharge fluctuations at the base gauge on Saifenbach which are in Paragraph 2.4 and also later detailed in the thesis. The results of the calibration in June and July according to Table 19 are good, especially the volume error is minimal. The Nash Sutcliffe Coefficients are universally about 60 %, except at Dürre Saifen.

Table 19 Dimensionless coefficients describing the results of the calibration from the beginning of June to the end of July 2004, HEC-HMS and BlueM

Discharge gauges	R_m^2		Relative volume error		Peak error		RMSE	
	HEC-HMS	BlueM	HEC-HMS	BlueM	HEC-HMS	BlueM	HEC-HMS	BlueM
WHR Prätisbach	0.6436	0.2378	0.0008	0.1471	0.4577	-0.7500	0.1530	0.2341
Ölmühle Prätisbach	0.6489	0.2112	-0.0404	0.0598	-0.0242	-0.7976	0.2692	0.4133
Dürre Saifen	0.2866	-0.0523	0.0016	0.3642	-0.0804	-0.7351	0.3032	0.3781
Base, Saifenbach	0.5947	0.1071	-0.1665	-0.0344	-0.0046	-0.7214	0.7906	1.2279

The model was also calibrated in the spring months (Figure 51 and Table 21). Generally, the initial conditions (especially Baseflow and Loss) and the parameters of evapotranspiration as well as canopy differed from the summer months.

Although, the calibration results were not good. It is important to note that the measured precipitation and discharge time series were not entirely coherent, especially not in March when floods were measured, although, there was no rainfall event.

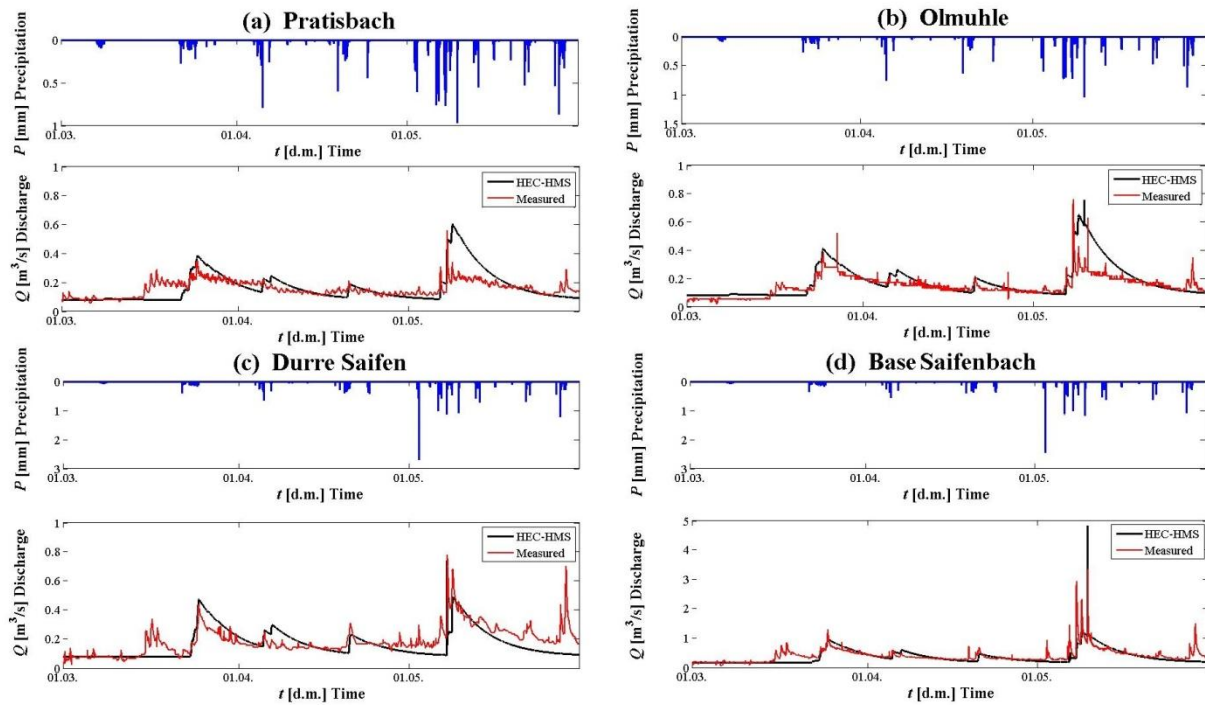


Figure 51 Hydrographs of the simulated (black) and measured (red) flows of the HEC-HMS calibration from the beginning of March to the end of May 2004 with the simultaneously measured precipitation (top blue bar) data

The Nash Sutcliffe Coefficients are even negative at WHR Prätisbach and Ölmühle, furthermore, peak and relative volume errors are also great.

Table 20 Dimensionless coefficients describing the results of the continuous calibration, HEC-HMS, March-May 2004

Discharge gauges	R_m^2	Relative volume error	Peak error	RMSE
WHR Prätisbach	-1.1718	0.0466	0.0750	0.0765
Ölmühle Prätisbach	-0.2374	0.1876	-0.0105	0.0756
Dürre Saifen	0.2176	-0.1228	-0.0564	0.0839
Base, Saifenbach	0.4315	-0.1114	0.4367	0.1808

The model was also set up in the autumn months. It was calibrated in October regarding the above mentioned (paragraph 4.5) inadequacies of the time series. Naturally, the initial conditions, evapotranspiration and canopy were different again. In addition, the elements of Baseflow were profoundly different. The shape of the hydrographs is different regarding the recession limbs and runoff is faster than in spring or summer. As a consequence, Groundwater Coefficients (GW1 and GW2) and the number of reservoirs had to be modified, however, the exact shape could not be achieved and the simulated hydrographs were too wide, the modelled surface runoff was not as rapid as the measured one.

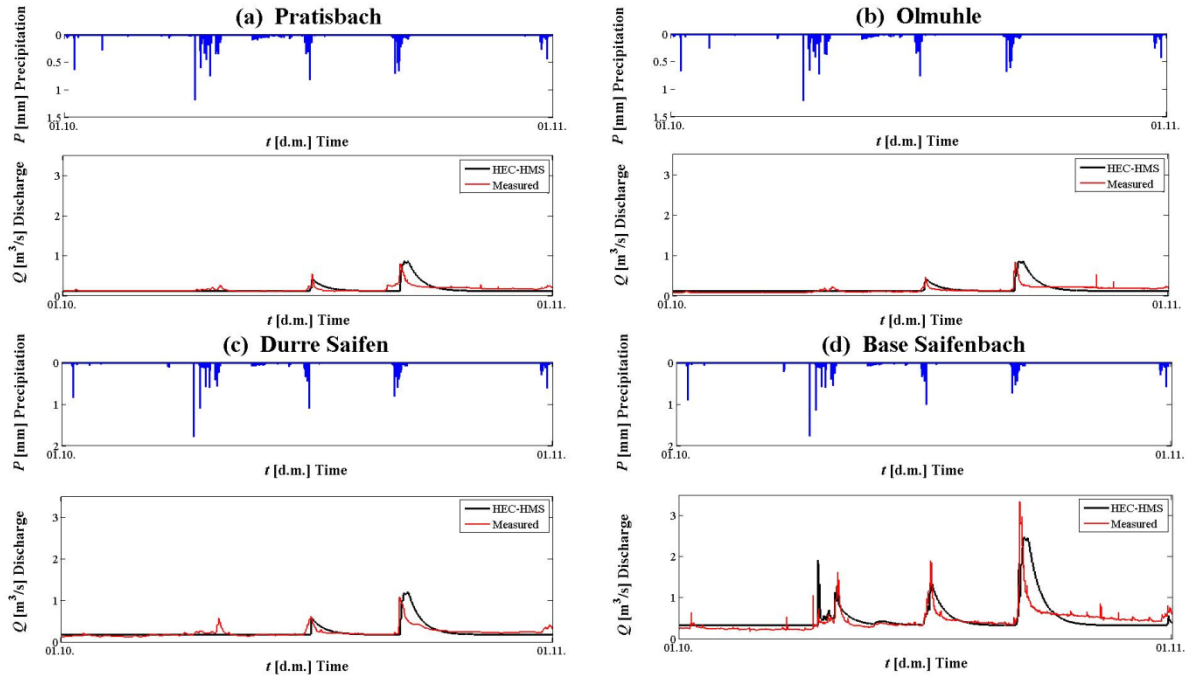


Figure 52 Hydrographs of the simulated (black) and measured (red) flows of the HEC-HMS calibration in October 2004 with the simultaneously measured precipitation (top blue bar) data

According to the calculated dimensionless coefficients, the results are generally better than the results of spring calibrations, however, worse than the summer ones. The relative volume error is minimal, which was the prime target of the calibrations. However, Nash Sutcliffe Coefficients are negative, except at the base discharge gauge which refers to an exceptionally bad model fit.

Table 21 Dimensionless coefficients describing the results of the calibration in October 2004, comparison of HEC-HMS and BlueM

Discharge gauges	R_m^2		Relative volume error		Peak error		RMSE	
	HEC-HMS	BlueM	HEC-HMS	BlueM	HEC-HMS	BlueM	HEC-HMS	BlueM
WHR Prätisbach	-0.7112	-8.2431	-0.0303	0.0137	0.0722	-0.5152	0.0924	0.1164
Ölmühle Prätisbach	-0.7328	-3.0134	0.0778	0.9044	0.0390	-0.5440	0.0981	0.1550
Dürre Saifen	-0.2416	-0.7478	0.0213	0.5015	0.1174	-0.5970	0.1165	0.1388
Base, Saifenbach	0.1372	-0.1201	0.0736	0.5752	-0.2600	-0.6564	0.2648	0.3254

4.8.4. Validation of the model

Regarding the available data, instead of validation, the results of HEC-HMS calibration were in the most cases only compared with the calibration results of Firle (2008). However, there were basic differences between the two models:

- The BlueM simulations included a long time interval instead of dividing it in shorter terms as HEC-HMS: six months, from the beginning of May to the end of October were modelled by Firle (2008),

- BlueM simulations applied a three-hour-time step instead of 5 minutes as HEC-HMS which could be one of the reasons of the worth simulation results, since peaks appear rapidly and surface runoff is also very fast in the Pöllau catchment,
- The precipitation of the BlueM simulations was not entirely spatially distributed, but the precipitation gauge with the greatest weight was applied for each subbasin.

Figure 53 shows the comparison of BlueM (blue colour) and HEC-HMS (black colour) simulations from June to the end of July. Appendix D (Figure 1 up to 4) contains the same graphs but in an enlarged form. Figure 53 shows that BlueM generally underestimates the peak flows and the shapes of the hydrographs do not fit the measured ones (with red colour in Figure 53), the watershed should be emptied faster and runoff should be more rapid. According to Table 19, the dimensionless coefficients describing the BlueM results are generally worth than the HEC-HMS results.

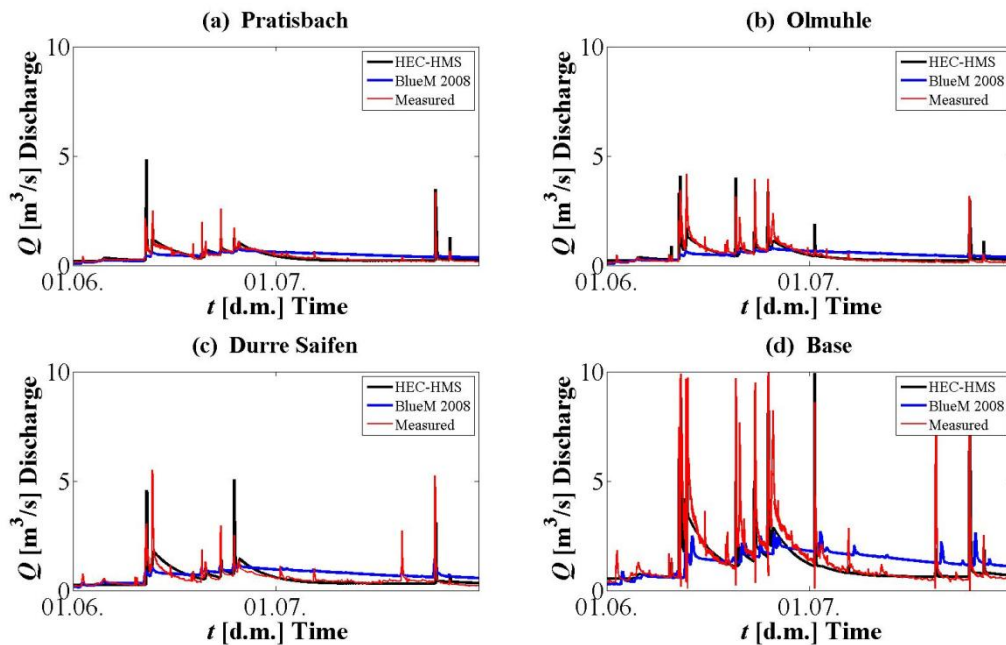


Figure 53 Comparison of computed (BlueM with blue [Firle 2008] and HEC-HMS with black) and observed (red) hydrographs from the beginning of June to the end of July 2004

The autumn calibration in October was controlled in two ways: comparing the results with the BlueM simulations and validating the model in an expanded time interval, from the beginning of September to the end of November. According to Figure 54, the hydrographs modelled by BlueM did not fit well the measured time series which were verified by objective functions found in Table 21. Nash Sutcliffe Coefficients of the BlueM simulations were generally negative and relative volume errors were high, even it was close to 100 % at Ölmühle on Prätisbach.

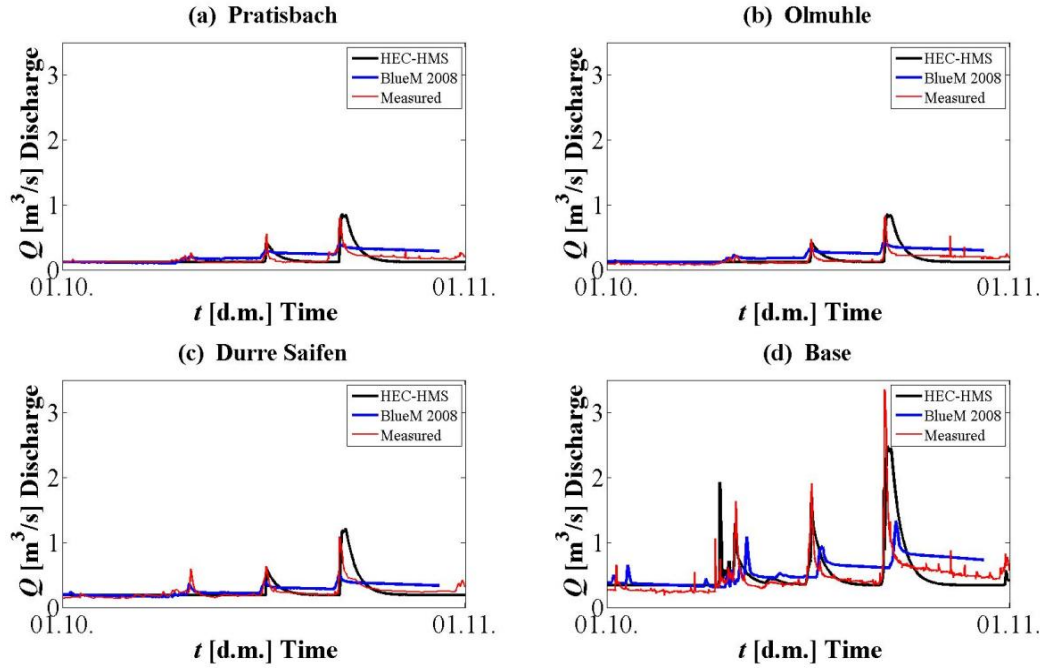


Figure 54 Comparison of computed (BlueM with blue [Firle 2008] and HEC-HMS with black) and observed (red) hydrographs, October 2004

The HEC-HMS model was also validated in an expanded time interval from the beginning of September to the end of October (Figure 55). The results of Dürre Saifen especially in September cannot be regarded relevant due to the several inadequacies of the measurements which are detailed in paragraph 4.5 and at the end of the thesis but the discharge measurements of other gauges are correct.

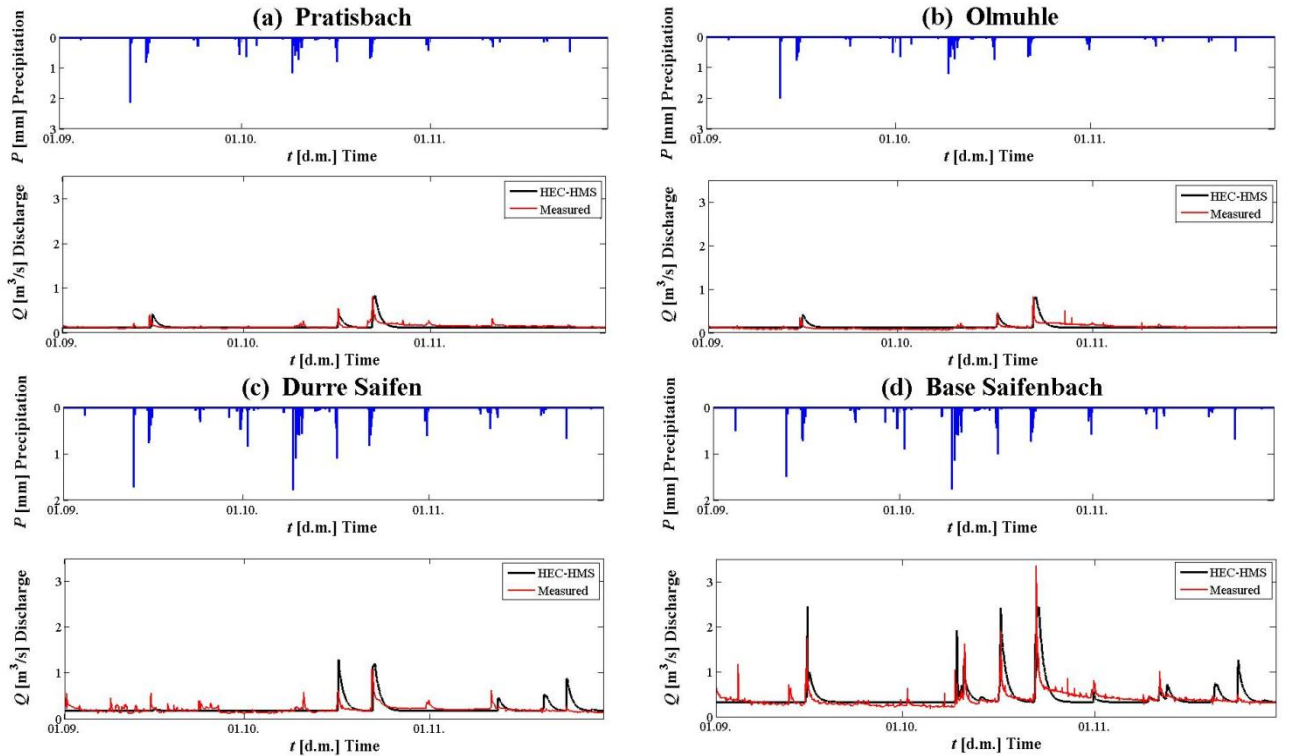


Figure 55 Validation of HEC-HMS: hydrographs of simulated and measured flows from September to the end of November 2004

According to Table 22, in general, the validation results are not worth than the calibration which is a great achievement. Relative volume errors and peak errors are minimal at each discharge gauge which was the prime target of calibrations.

Table 22 Dimensionless coefficients describing the results of the validation of HEC-HMS, September-November 2004

Discharge gauge	R_m^2	Relative volume error	Peak error	RMSE
WHR Prätisbach	-0.6492	-0.0756	0.0418	0.0613
Ölmühle Prätisbach	-0.5884	0.0534	0.0037	0.0639
Dürre Saifen	-1.4663	0.0409	0.1963	0.1184
Base, Saifenbach	-0.0693	0.0789	-0.2663	0.1937

The spring calibration from the beginning of March to the end of May could not be compared to the BlueM simulations because Firle (2008) did not model this time period and the available database also did not make it possible.

5. Conclusions

5.1. Discussion of the results and possible reasons of inaccuracy

In the present study and also in a previous Master thesis (Firle 2008), one of the greatest problems of the calibrations was the incorrect estimation of peak flows. This incorrectness could have several reasons.

The discharge gauges have not been calibrated recently on the watershed. The watercourse, river bed, the upstream and downstream cross sections could have also changed during the years producing different rating curves in the cross sections of the discharge gauges.

If the stream swells over due to the relatively huge discharge volumes and water surface level exceeds the limits of the gauge's rating curve, an extrapolation is needed to specify discharge. In these cases, the error of the specified discharge can definitely increase. A similar problem occurred in Bükkös Creek, Hungary (Széles 2012, Széles et al 2013) where the same problem was finally solved by a proper rating curve generated by the one dimensional hydrodynamic model of the creek.

The discharge measurements of the year 2004 entail such degree of uncertainty, that the volume of peaks can be significantly different. There are several irregular fluctuations in the measured time series during scarce rainfalls, when the runoff rapidly and drastically changes in a short time. Regarding these facts, the outputs of simulations cannot be numerically described by goodness of fit criterions. Moreover, the parameters which have a great influence on the magnitude of the peak discharges, such as Loss or Evapotranspiration, cannot be calibrated properly enough.

However, it is not sure that the lack of calibration caused the measurement errors at the Base discharge gauge. On a closer inspection, the measured discharge could never exceed $10 \text{ m}^3/\text{s}$ in the year 2004. Approaching $10 \text{ m}^3/\text{s}$, the discharge always decreased with more than 90 % in a few minutes. This could have been an instrumental error at the Base discharge gauge.

The representativeness of evaporation measurements is also questionable because evaporation is measured in a meadow in Heiling. Evaporation of forests, which are also dominant in Pöllau, significantly differs from the evaporation of grassland and meadow.

The time series of 2004 contain several events when floods without any measured rainfall were recorded by the discharge gauges. A possible explanation for these events could be the drainage of the artificial fishponds located in the watershed, for example near Pöllauer Saifen. Fishponds are usually drained in autumn when the activity of vegetation and fertilization is minimal, however, the documentation about their operation is not public or not available.

Selecting the remarkable flood events of the year 2004 and plotting the peak flows measured by the base discharge gauge on Saifenbach versus the total precipitation describing the whole catchment (according to the Thiessen-polygon gauge weights, each subarea of the subcatchments belonging to the given precipitation gauges were calculated back and added together; while the base discharge gauge is the outlet point of the whole watershed, this method was performed for all of the subbasins; than the areas were normalized producing new precipitation gauge weights which were applied in calculating the precipitation masses describing the whole watershed). The correlation between the peak runoff and total precipitation, which are two dependent random variable connected by a stochastic relationship, is $r=0.49$ (Figure 56) which is stable regarding a sample with 27 elements (Kontur et al 1993). Figure 56 shows a weak connection between precipitation and discharge. The details of the calculations can be found in Appendix E.

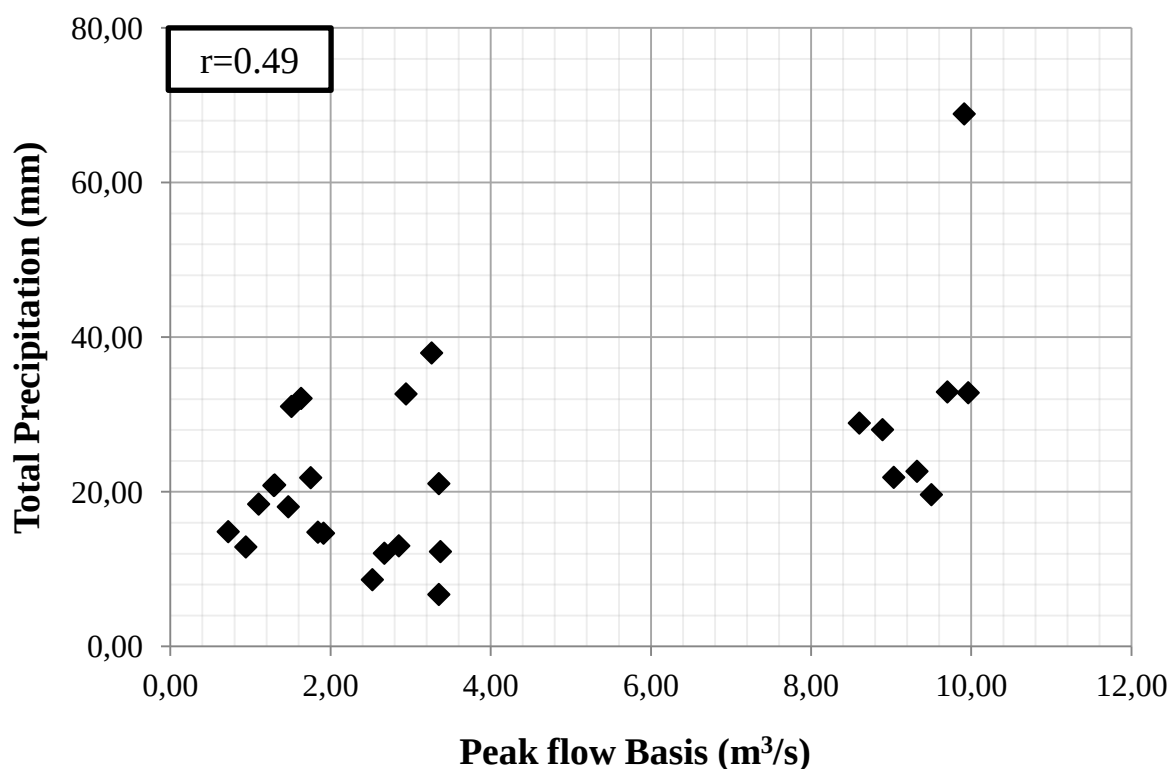


Figure 56 Correlation connection between the remarkable events' peak flows of the base discharge gauge and the adherent total precipitation masses

Table 23 contains further correlation coefficients describing the connection between the peak discharges of other water surface level measuring instruments and the adherent maximal intensity or total precipitation.

Table 23 Correlation between peak discharges of the four water surface level gauges and the adherent maximal intensity and total precipitation

Discharge gauge	Correlation coefficient (-)	
	Peak discharge-Maximal intensity of precipitation	Peak discharge-Total precipitation
WHR Prätisbach	0.75	0.48
Ölmühle	0.36	0.55
Dürre Saifen	0.61	0.58
Base, Saifenbach	0.59	0.49

5.2. Future development perspectives

The most urgent developments would be the calibration of the discharge gauges, the control of the Base gauge on Saifenbach and actualization of the rating curves. Possibly, the peak flows and the measurement of huger volumes would be in this way correct. Furthermore, the irregular fluctuations in the discharge measurements would also vanish.

It would be also necessary to measure evaporation in forests. Evaporation and also transpiration of areas with different land use categories should be clarified. However, the measured evaporation could be modified by a factor which was also calibrated, this was only a rough estimation of real evapotranspiration.

Another drawback of the model is that it could not take into consideration the daily changes of evapotranspiration, it only calculated with average values. Other elements of the hydrological circle had a five-minute or hourly temporal resolution.

According to the results of the present study and the results of Firle (2008), hydrological models of the Pöllau catchment need further developments. My opinion is that future progresses should lay more emphasis on subsurface processes. Naturally, this would entail other hydrological measurements in the catchment, namely groundwater level and soil moisture measurements.

According to the HEC-HMS model results, the seasonal variability is significant. This means that longer time series should be modelled by a more flexible hydrological model which can take into consideration the changed runoff conditions of the catchment regarding subsurface processes and vegetation in a minimal monthly bases. Another solution which was also applied in the present thesis is the separation of longer time series into shorter intervals.

The seasonal variability of parameters should be validated in other years. According to the results of this study, initial conditions and the parameters of baseflow, vegetation coverage and evapotranspiration monthly or seasonably vary. An annual variability of these parameters should be controlled by independent time series.

I find it necessary and also interesting to try out other hydrological models in the Pöllau watershed. Regarding the steep slopes of the catchment, a topography determined semi-distributed hydrological model, such as TOPMODEL could be adopted on the watershed. Unfortunately, the GRASS GIS version of TOPMODEL cannot take into account the spatial heterogeneity of rainfall, although, regarding the open source nature of the model, this missing element can be easily substituted by code modification.

Another recently developed approach (Széles 2013) which applied the discrete linear cascade model (Szilágyi and Szöllösi-Nagy 2010) in analysing surface runoff processes on digital terrain models could be also tested in the watershed of Pöllau.

Regarding the available database, especially its length and variety, a wide range of hydrological analyses could be performed in the watershed. Not only rainfall-runoff models, but other models and methods should be tried out. The measured time series could be controlled and characterized by numerous statistical methods. The spatial distribution of precipitation and its effects on rainfall-runoff models could be studied because the relation between the number of precipitation gauges and the size of the catchment allows utilizing various types of methods to spatially distributed precipitation. The available digital terrain model of the catchment provides further research objectives, such as analysing the effect of spatial distribution on the outputs of hydrological models, testing different flow routing algorithms or generating the time-area curve of the catchment.

6. Summary

The present thesis focuses on the rainfall-runoff processes of a small watershed (58 km²), Pöllau located in the east part of Styria, in Austria. A lumped hydrological model, HEC-HMS (*Hydrological Engineering's Centre-Hydrological Modelling System*) was applied on the catchment to analyse the basic hydrological processes.

Hydro-meteorological measurements have been executed in the watershed of Pöllau since 1978. The density of different measuring instruments in the catchment is great: seven precipitation gauges, four discharge gauges and one meteorological station with evapotranspiration, air and ground temperature, wind velocity and direction, radiation, air pressure and humidity measuring equipment have been operated in the area by the Institute of Urban Water Management and Landscape Water Engineering Graz University of Technology for almost thirty-six years. Numerous research programmes, international publications and theses have intended to describe general, hydrological or geological behaviour of the catchment in the recent years. The present thesis reviewed the available information and database about Pöllau.

An overview of the basic terminology and methodology of hydrological modelling was followed by the description of the process and steps of model development.

After the details of the operation of the implemented hydrological model and its available and applied hydrological elements, the results of sensitivity analysis and simulations with different methods and goodness-of-fit criterions were visually and numerically delineated. The data foundations of the study were the precipitation, discharge and evaporation measurements of the year 2004 which were also applied in the Master thesis of Firle (2008). This gave an opportunity to compare the results of the present thesis with the BlueM simulations. The rainfall-runoff model was successfully calibrated and validated in more event and continuous simulations. The model had difficulties in peak flow simulations which resulted from partly the nature and limitations of the applied hydrological model, partly the available hydrological database.

The results were discussed from more perspectives and suggestions about future developments were given.

On the whole, the calibration was successful according to the statistical objective functions. The calibrated model could be applied in climate change studies and investigations: the present has been already modelled, the near future in 25 or 50 years should be modelled and the differences of the two model outputs can be compared. Runoff processes and water balance calculations can be performed by the present model.

One of the greatest benefits of well calibrated and validated hydrological models is the ability to estimate the runoff response of a catchment or even other ungauged watersheds with similar land use, geology and soil characteristics without frequent measurements. This is not only a cost-efficient solution but sometimes field trips are not feasible or there is a need for rapid interventions in emergency situations, such as floods, when the outputs and results of such models are useful.

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Appendices

Appendix A: CORINE 2000 Land use information and SCS Curve Number for each subbasin

Table 1 CORINE 2000 Land use information and SCS Curve Numbers of watersheds W930, W1120, W1030

Subbasin	CN	W930			W1120			W1030		
Land use class		A _i (km ²)	A _i (%)	CN _i *A _i	%	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i
Not totally urban area	77	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Complex parcel of land structure	43	3.397	46.794	146.058	2.581	34.321	110.970	2.546	54.330	109.462
Cultivated land with significant natural vegetation	49	0.000	0.000	0.000	0.149	1.987	7.322	0.000	0.000	0.000
Grassland and meadow	49	0.039	0.537	1.908	1.269	16.880	62.193	0.000	0.000	0.000
Coniferous wood	30	2.724	37.532	81.731	1.819	24.197	54.584	1.639	34.982	49.173
Mixed types of forests	30	1.099	15.137	32.963	1.700	22.614	51.013	0.501	10.688	15.023
Summa		7.259		262.661	7.519		286.083	4.686		173.658
Curve Number				36			38			37

Table 2 CORINE 2000 Land use information and SCS Curve Numbers of watersheds W1130, W1150, W1260

Subbasin	CN	W1130			W1150			W1260		
Land use class		A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i
Not totally urban area	77	0.000	0.000	0.000	0.000	0.000	0.000	0.471	5.620	36.304
Complex parcel of land structure	43	3.410	50.308	146.614	1.637	50.598	70.370	4.587	54.671	197.220
Cultivated land with significant natural vegetation	49	0.569	8.396	27.884	0.000	0.000	0.000	0.974	11.606	47.708
Grassland and meadow	49	0.000	0.000	0.000	0.109	3.368	5.337	0.480	5.719	23.509
Coniferous wood	30	1.900	28.031	56.993	1.007	31.133	30.208	0.190	2.268	5.707
Mixed types of forests	30	0.899	13.265	26.972	0.482	14.901	14.458	1.688	20.117	50.629
Summa		6.778		258.462	3.234		120.373	8.389		361.078
Curve Number				38			37			43

Table 3 CORINE 2000 Land use information and SCS Curve Numbers of watersheds W1290, W1480, W1540

Subbasin	CN	W1290			W1480			W1540		
Land use class		A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i
Not totally urban area	77	0.222	11.985	17.108	0.000	0.000	0.000	0.000	0.000	0.000
Complex parcel of land structure	43	0.268	14.456	11.523	2.262	29.282	97.251	1.401	55.053	60.226
Cultivated land with significant natural vegetation	49	0.726	39.155	35.567	0.012	0.157	0.595	0.008	0.297	0.370
Grassland and meadow	49	0.024	1.278	1.161	0.000	0.000	0.000	0.000	0.000	0.000
Coniferous wood	30	0.000	0.000	0.000	4.659	60.317	139.763	0.593	23.319	17.797
Mixed types of forests	30	0.614	33.126	18.423	0.791	10.244	23.738	0.543	21.332	16.281
Summa		1.854		83.782	7.724		261.346	2.544		94.674
Curve Number				45			34			37

Table 4 CORINE 2000 Land use information and SCS Curve Numbers of watersheds W930, W1120, W1030

Subbasin	CN	W1560			W1590			W1630		
Land use class		A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i	A _i (km ²)	A _i (%)	CN _i *A _i
Not totally urban area	77	1.484	53.215	114.284	0.000	0.000	0.000	0.004	0.160	0.288
Complex parcel of land structure	43	0.581	20.848	25.004	0.859	30.260	36.929	1.238	52.830	53.214
Cultivated land with significant natural vegetation	49	0.428	15.341	20.966	0.025	0.871	1.211	0.000	0.000	0.000
Grassland and meadow	49	0.295	10.575	14.453	0.000	0.000	0.000	0.000	0.000	0.000
Coniferous wood	30	0.000	0.000	0.000	1.682	59.264	50.459	0.166	7.085	4.979
Mixed types of forests	30	0.001	0.020	0.017	0.273	9.605	8.178	0.935	39.925	28.058
Summa		2.789		174.724	2.838		96.777	2.343		86.539
Curve Number				63			34			37

Appendix B: Geological, geotechnical information about each subwatershed

Table 5 Geological, geotechnical information about subbasins W930, W1120, W1030, W1130, W1150, W1260

Subcatchemnt	W930	W1120	W1030	W1130	W1150	W1260
Type	%	%	%	%	%	%
Augen gneiss., Grobgnieiss, pale granite, Whiteschist	80	0	60	70	75	3
Tommer slate	0	0	0	25	8	10
Alluvium, Colluvium, Scree	0	3	0	0	0	7
Boulder gravel, Block Conglomerate	5	0	5	0	3	0
Strallegger Gneiss	15	80	35	0	10	4
Paragneiss	0	0	0	0	0	0
Granitgneiss, Metagranite, Orthogneiss	0	10	0	2	0	3
Birkfelder Quartzphyllit, Schist with phyllites, Mürztaler Quartzphyllit	0	0	0	3	2	
Amphibolite	0	0	0	0	2	3
Boulder gravel, Block Conglomerate	0	2	0	0	0	70
Two-mica (biotite-muscovite) Granite	0	5	0	0	0	0

Table 6 Geological, geotechnical information about subbasins W1290, W1480, W1540, W1560, W1590, W1630

Subcatchemnt	W1290	W1480	W1540	W1560	W1590	W1630
Type	%	%	%	%	%	%
Augen gneiss., Grobgnieiss, pale granite, Whiteschist	0	5	10	3	3	20
Tommer slate	0	65	77	2	10	80
Alluvium, Colluvium, Scree	10	0	2	30	2	0
Boulder gravel, Block Conglomerate	25	0	1	60	0	0
Strallegger Gneiss	65	0	0	5	0	0
Paragneiss	0	25	10	0	70	0
Granitgneiss, Metagranite, Orthogneiss	0	5	0	0	15	0
Birkfelder Quartzphyllit, Schist with phyllites, Mürztaler Quartzphyllit	0	0	0	0	0	0
Amphibolite	0	0	0	0	0	0
Boulder gravel, Block Conglomerate	0	0	0	0	0	0
Two-mica (biotite-muscovite) Granite	0	0	0	0	0	0

Appendix C: Soil types, water conditions, permeability and field capacity for each subwatershed

Description of soil types according to BOKU (2007):

Leptic Cambisol (English Brown earth, German Braunerde) developed under progressive weathering processes. It has generally profound soil layers (100 cm or more). If bedrock is close, the layers are shallow. Its water storage capacity is high.

Dystric Planosol (English Stagnosol, German Pseudogley) has an impermeable soil horizon, therefore, percolation water is usually ponded in it. It consists of a pond zone with rust stains and concretions and a pond horizon which shows marbling. This structure causes reductive conditions in the pond zone in wet periods and oxidation conditions in dry periods. Its water storage capacity is very high.

Calcaric Fulvisol (English Auboden, German Grauer Auboden) is a sedimentation formation which was created by rapidly flowing and oscillating streams, brooks and rivers. It consists of layered stratification of different grain sizes. It was formed by rock material with a low loam or clay content. Dystric Fluvisol (German Brauner Auboden) was formed by bedrock material as well but with a relative high loam and clay content. These soil types have a low or medium-high water storage capacity respectively.

Dystric Leptosol (English Rendzina and Ranker, German Ranker) is a humus-rich soil formation on firm or loose bedrock. It has shallow depths and acidic A-horizons. Its water storage capacity is low-medium.

Gleysol (English and German Gley) was formed under the influence of upcoming groundwater. It is found in valleys and basins in headwater regions, on slopes with deep water-impermeable layers. Under the A-horizon, there is a well-aerated and marbling Go-horizon (oxidative conditions) and below there is a reductive, always wet and coherent Gr horizon. The water storage capacity of this soil is very high.

Table 7 Explanation to the notations I: soil type and field capacity

Soil type		Field capacity	
S	Sand	5	Very high (higher than 300 mm)
zS	Silty sand	4	High (220-300 mm)
IS	Loamy sand	3	Medium (140-220 mm)
tS	Clayey sand	2	Low (60-140 mm)
sL	Sandy loam	1	Very low (lower than 60 mm)
IZ	Loamy silt	0	Bog and half-bog or no data

Table 8 Explanation to the notations II: eater conditions and permeability

Water conditions		Permeability	
0	Non-uniform	0	Not described
1	Very dry	1	Very low
2	From very dry to dry	2	From very low to low
3	Dry	3	Low
4	From dry to moderately dry	4	From low to moderate
5	Moderately dry	5	Moderate
6	From moderately dry to well supplied	6	From moderate to high
7	Well supplied	7	High
8	From well supplied to moderately moist	8	From high to very high
9	Moderately moist	9	Very high
10	Moderately moist to moist		
11	Moist		
12	From moist to saturated		
13	Saturated		
14	Periodically saturated		
15	Periodically saturated with dominance of dry phase		
16	Periodically saturated with dominance of saturated phase		

Table 9 Soil types, water conditions, permeability and field capacity of the watershed W930

FAO	Type	W930				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS (50), zS (50)	5	5 (50), 7 (50)	2
Dystric Planosol	Stagnosol	3	IS	3 (50), 14 (50)	3	2 (50), 3 (50)
	Relic soil	2	IS	7	5	3
	Complex soil	35	IS (50), S (50)	3 (50), 5 (50)	5 (50), 7 (50)	1 (50), 2 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	30				

Table 10 Soil types, water conditions, permeability and field capacity of the watershed W1120 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1120				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS	5 (50), 7 (50)	7	2 (50), 3 (50)
Dystric Planosol	Stagnosol	5	IS	3 (50), 14 (50)	3	2 (50), 3 (50)
	Relic soil	0				
	Complex soil	30	IS	3	5 (80), 7 (20)	2 (50), 3 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	5	IS	10	7	3
	Built-up areas	0				
	Forest	30				

Table 11 Soil types, water conditions, permeability and field capacity of the watershed W1030 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1030				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS (50), zS (50)	5	5 (50), 7 (50)	2
Dystric Planosol	Stagnosol	0				
	Relic soil	0				
	Complex soil	40	IS (50), S (50)	3 (50), 5 (50)	7 (70), 5 (30)	1 (50), 2 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	30				

Table 12 Soil types, water conditions, permeability and field capacity of the watershed W1130 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1130				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS	5 (70), 7 (30)	5 (50), 7 (50)	2 (50), 3 (50)
Dystric Planosol	Stagnosol	5	IS	14	3	3
	Relic soil	0				
	Complex soil	30	IS (80), S (20)	3 (50), 5 (50)	5	2 (50), 3 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	35				

Table 13 Soil types, water conditions, permeability and field capacity of the watershed W1150 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1150				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS (90), S (10)	5 (70), 7 (30)	5 (30), 7 (70)	2 (70), 3 (30)
Dystric Planosol	Stagnosol	10	IS	14	1	2
	Relic soil	0				
	Complex soil	30	IS (50), S (50)	3 (50), 5 (50)	7	1 (50), 2 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	30				

Table 14 Soil types, water conditions, permeability and field capacity of the watershed W1260 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1260				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	25	IS	14 (50), 5 (25), 7 (25)	3 (50), 5 (50)	2 (50), 3 (50)
Dystric Planosol	Stagnosol	20	IS	14	1 (50), 2 (50)	2
	Relic soil	0				
	Complex soil	25	IS (60), sL (40)	5 (60), 3 (40)	5	3
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	10	IS	3	5	2
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	20				

Table 15 Soil types, water conditions, permeability and field capacity of the watershed W1290 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1290				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	25	IS (90), zS (10)	5 (90), 3 (10)	7	3
Dystric Planosol	Stagnosol	20	IS	14 (10), 15 (70), 7 (20)	3 (80), 1 (20)	2 (80), 3 (20)
	Relic soil	0				
	Complex soil	15	IS	3 (50), 15 (50)	3 (50), 5 (50)	3
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	5	IS	10	7	3
	Built-up areas	0				
	Forest	35				

Table 16 Soil types, water conditions, permeability and field capacity of the watershed W1480 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1480				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS (50), zS (50)	5	7 (50), 6 (50)	2
Dystric Planosol	Stagnosol	5	IS	14	1	2
	Relic soil	5	IS	7	5	3
	Complex soil	30	IS (50), sL (50)	3 (70), 9 (30)	5	3
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	30				

Table 17 Soil types, water conditions, permeability and field capacity of the watershed W1540

FAO	Type	W1540				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	30	IS	5	7	2
Dystric Planosol	Stagnosol	5	IS	15	3	2
	Relic soil	0				
	Complex soil	30	S	3	7	1
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	35				

Table 18 Soil types, water conditions, permeability and field capacity of the watershed W1560 (the values in brackets refer to the percentage of given soil type)

FAO	Type	W1560				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	10	zS	5	7	3
Dystric Planosol	Stagnosol	20	IS	15	3	2
	Relic soil	3	IS	7	5	3
	Complex soil	15	IS	3 (45), 5 (45), 10 (10)	3 (50), 5 (50)	3
Calcaric/Dystric Fulvisol	Alluvial soil	13	IS	5	7	2
Dystric Leptosol	Rendzina+Ranker	2				
Gleysol	Gley	2	IS	10	7	2
	Built-up areas	35				
	Forest	0				

Table 19 Soil types, water conditions, permeability and field capacity of the watershed W1590

FAO	Type	W1590				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	35	IS	5	7	2
Dystric Planosol	Stagnosol	5	IS	15	3	2
	Relic soil	0				
	Complex soil	25	sL (50), IS (50)	3 (50), 10 (50)	5 (50), 7 (50)	1 (50), 3 (50)
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	35				

Table 20 Soil types, water conditions, permeability and field capacity of the watershed W1630

FAO	Type	W1630				
		%	Soil type	Water conditions	Permeability	Field capacity
Leptic Cambisol	Brown earth	20	IS	5	7	2
Dystric Planosol	Stagnosol	5	IZ	14	3	3
	Relic soil	5	IS	7	5	3
	Complex soil	10	IS (50), tS (50)	5	5	3
Calcaric/Dystric Fulvisol	Alluvial soil	0				
Dystric Leptosol	Rendzina+Ranker	0				
Gleysol	Gley	0				
	Built-up areas	0				
	Forest	60				

Appendix D: Comparison of the BlueM (Firle 2008) and HEC-HMS simulation results from the beginning of June to the end of July 2004

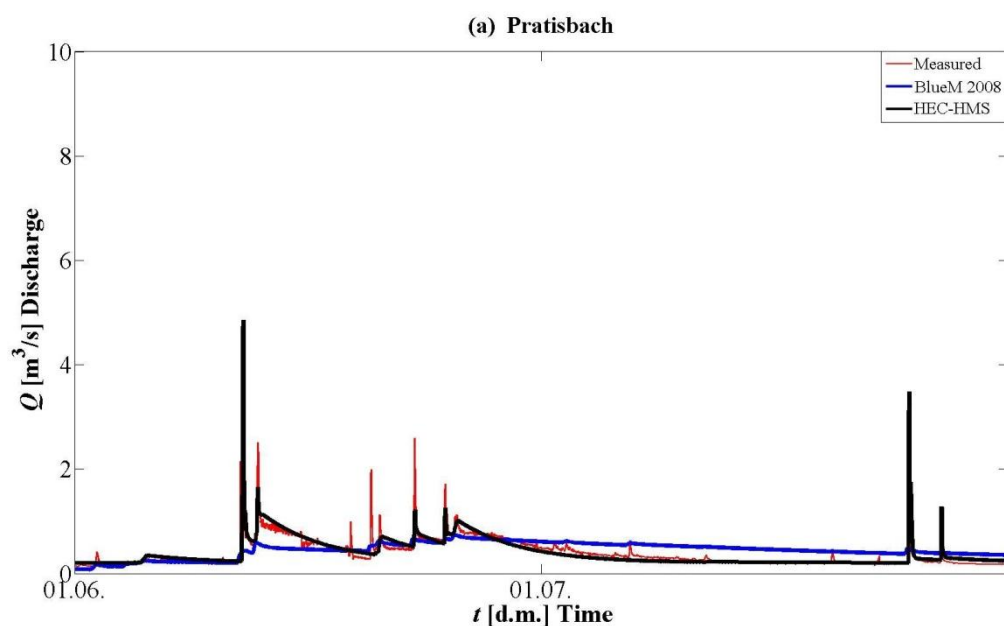


Figure 1 Wildholzrechen Prätisbach, results of BlueM simulations (blue colour), HEC-HMS (black colour) and measured (red colour) discharge in June-July 2004

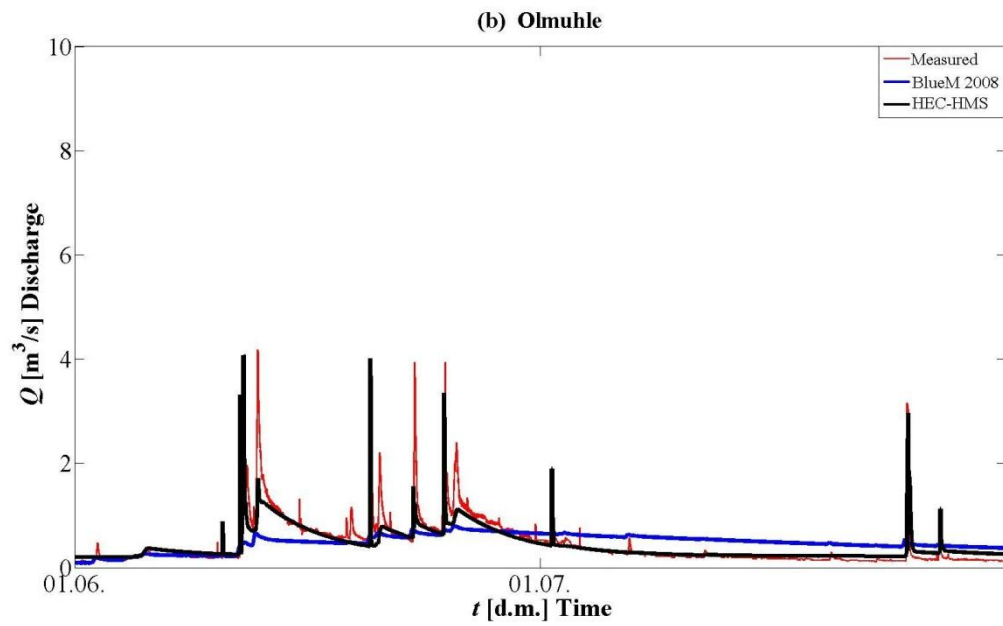


Figure 2 Ölmühle, results of BlueM simulations (blue colour), HEC-HMS (black colour) and measured (red colour) discharge in June-July 2004

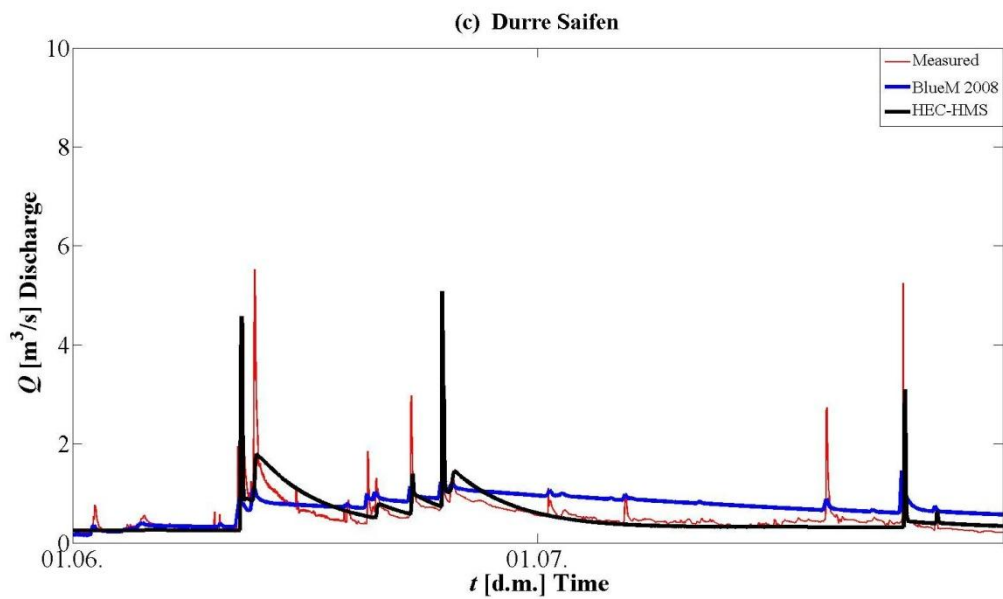


Figure 3 Dürre Saifen, results of BlueM simulations (blue colour), HEC-HMS (black colour) and measured (red colour) discharge in June-July 2004

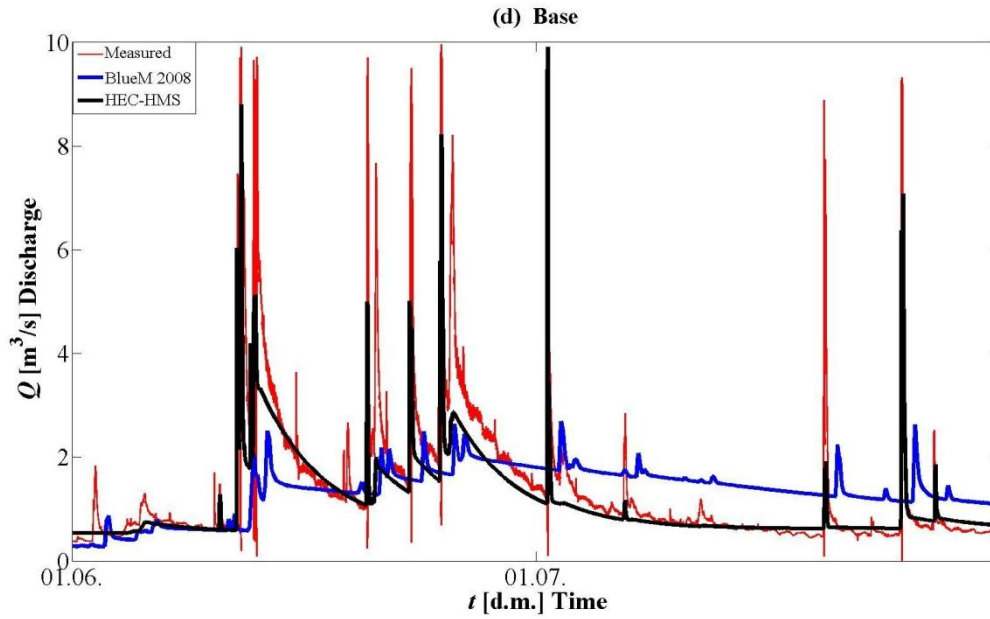


Figure 4 Base Saifenbach, results of BlueM simulations (blue colour), HEC-HMS (black colour) and measured (red colour) discharge in June-July 2004

Appendix E: Correlation calculations between peak discharge and total precipitation, Base discharge gauge Saifenbach

Notes to the correlation calculations found in Table 21:

- y (m^3/s) peak discharges and x (mm) total precipitation values with i indices (first column) are found in the second and third columns.
- Δy and Δx are the differences between the given value and the average.
- $\Delta^2 y$ and $\Delta^2 x$ are the squared values of Δy and Δx respectively in the fifth and seventh columns.
- $\Delta y \cdot \Delta x$ is the product of Δy and Δx found in the eighth column.
- The sums and averages ($\bar{y}$ and $\bar{x}$) of y and x are found at the bottoms of the second and third columns.
- σ_y and σ_x are the standard deviations of Δy and Δx respectively.
- r (-) is the correlation coefficient calculated as follows (A.E.1)

$$r = \frac{\sum \Delta x \Delta y}{(N - 1) \sigma_y \sigma_x} \quad (\text{A.E.1})$$

The stability of the correlation coefficient is determined according to Figure 2-31. in Kontur et al (1993) as the function of the number of records.

Table 21 Correlation calculations

i	y (m ³ /s)	x (mm)	Δy (m ³ /s)	$\Delta^2 y$ (m ⁶ /s ²)	Δx (mm)	$\Delta^2 x$ (mm ²)	$\Delta y * \Delta x$
1	1.30	20.90	-3	9	-2	4	6
2	0.94	12.88	-3	11	-10	102	33
3	1.47	18.08	-3	8	-5	24	14
4	2.94	32.67	-1	2	10	94	-13
5	3.35	6.73	-1	1	-16	264	15
6	1.51	31.05	-3	7	8	65	-22
7	1.84	14.79	-2	6	-8	67	20
8	1.29	20.82	-3	9	-2	5	6
9	9.91	68.88	6	32	46	2107	260
10	2.67	12.06	-2	2	-11	119	17
11	9.70	32.93	5	30	10	99	54
12	9.50	19.64	5	28	-3	11	-18
13	9.96	32.82	6	33	10	97	56
14	8.60	28.90	4	19	6	35	26
15	2.85	13.02	-1	2	-10	99	14
16	8.89	28.05	5	22	5	26	24
17	9.32	22.66	5	26	0	0	-2
18	2.52	8.65	-2	3	-14	206	25
19	9.03	21.88	5	23	-1	1	-5
20	3.26	37.97	-1	1	15	225	-15
21	3.37	12.28	-1	1	-11	115	9
22	1.10	18.42	-3	10	-5	21	14
23	0.72	14.86	-4	12	-8	66	29
24	1.75	21.84	-2	6	-1	1	3
25	1.63	32.09	-3	7	9	83	-24
26	1.91	14.66	-2	5	-8	69	19
27	3.35	21.07	-1	1	-2	4	2
Σ :	114.68	620.60	0	314	0	4009	548
Average:	4.25	22.99					
σ_y (m ³ /s)	3.47						
σ_x (mm)	12.42						
r	0.49						
Stability (10 %) $N=27$	$r=0.36$						