AN ANALYSIS OF THE RESILIENCE OF THE VOLTHERBEEK TO FLOODING DURING EXTREME RAIN EVENTS

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February, 2018

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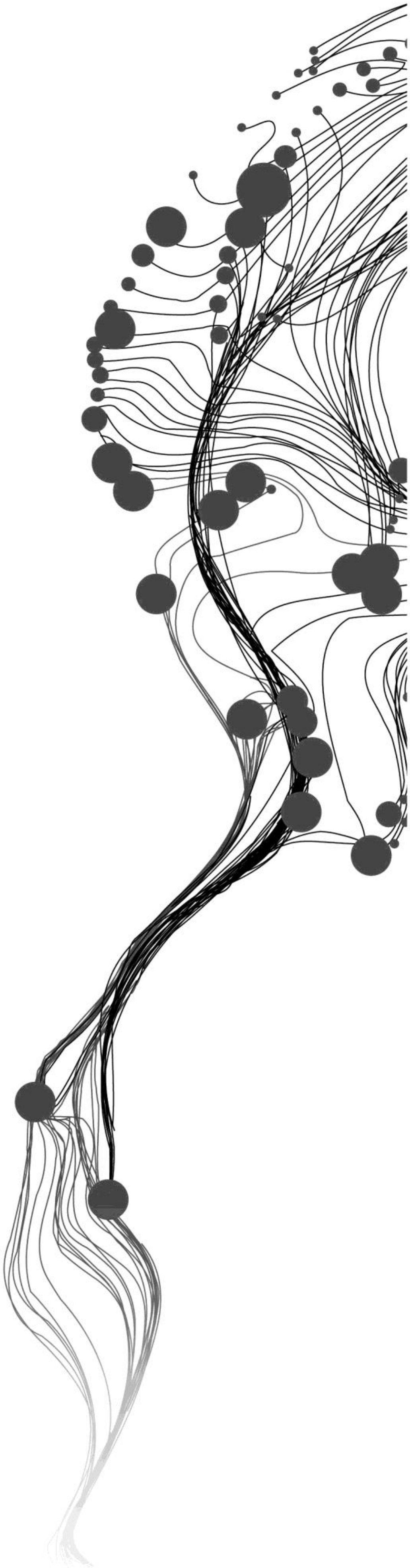

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SIMON NDEWENI WANYONYI
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ABSTRACT

Flooding is a global phenomenon that causes casualties and property loss on every inhabited continent. The ongoing development of low-lying flood-prone areas within the Netherlands increases exposure of lands to flood risks. The main objective of this research is to assess the resilience of the Voltherbeek, a tributary of the Dinkel, to flooding during extreme rain events by assessing the catchment's response to rainfall and determining the flood extents and depths. The Voltherbeek flow dynamics are quite erratic. Peak spills occur rapidly after rainfall due to the less permeable clay soils in the area while very low flows are experienced in dry periods. The Limburg Soil Erosion Model (LISEM) is used in this research to simulate the catchment's infiltration and stream discharge for extreme rain events. The extreme rain events are designed by determining the total rainfall duration and based on pre-defined rainfall depths for extreme rain events a multiplication factor is determined and multiplied by the calibrated storm rainfall intensities.

In this research LISEM is calibrated on in-situ discharge measurements and validated on an independent storm. LISEM calibration generates a Nash-Sutcliffe efficiency coefficient (NS) of 0.91 and Relative Volume Error (RV_E) of +5.4% which indicates a well performing model. LISEM validation generates an NS of 0.62 and an RV_E of +19% which are acceptable hence the model performs well. A sensitivity analysis is carried out on the calibrated parameter set by varying the hydraulic conductivity (Ks), soil moisture (θ), Manning's n channel and Manning's n slopes one parameter at the time. The Manning's n channel and Manning's n slopes are varied at the same time during the sensitive analysis of the Manning's n. The generated NS ranges from -5.7 to 0.91 with the systematic 20% variation of the Ks. This shows that the Ks is a sensitive parameter. The generated NS ranges from -103.2 to 0.91 with the systematic 20% variation of the θ. The initial soil moisture conditions greatly influence the soil storage capacity by regulating the infiltration rate and hence the discharge simulated greatly influencing the model performance. The results of the sensitivity analysis indicate that θ is a sensitive parameter. A systematic 20% variation of the Manning's n channel and Manning's n slopes generates NS value ranges from 0.72 to 0.91. The Manning's n channel and Manning's n slopes are therefore not sensitive parameters. The model sensitivity analysis and performance results are comparable to results by other research carried out using LISEM for flood modelling. Most studies report a lag in the time-to-peak in the simulated discharge measurements with the peak discharges slightly varying from the in-situ discharge measurements.

The calibrated parameter set is used for simulation of the extreme rain events. The storm event corresponding to the calibration period is multiplied by a multiplication factor of 2, 3, 4 and 5 to simulate rainfall with return periods of twice in one year, once in 2 years, 10 years, and 50 years respectively. Simulations are run for dry soil conditions, the antecedent soil moisture for the calibrated storm event and saturated soil moisture conditions to assess the resilience of the Voltherbeek to flooding during extreme rains events. The research findings show that rainfall with return periods of twice in one year, once in 2 years, 10 years, and 50 years have rainfall depths of 33 mm, 50 mm, 66 mm and 83 mm respectively based on a calibrated storm event of 16 mm recorded in the ITC rainfall gauging station. An evaluation of the flood extents and depths for the extreme rain events shows that for dry soil conditions, rainfall with a return period of twice in one year does not generate floods in the catchment. In dry soil conditions, rains with return periods of 2 years, 10 years, and 50 years generate a maximum flood depth of 0.75 m on farms on the northeast region of the catchment. In wet and saturated soil conditions rains with return periods of twice in one year, once in 2 years, 10 years, and 50 years generate maximum flood depths of 0.75 m on farms on the northeast region of the catchment. In saturated soil condition, the flooded area increases to the south-west and north-west regions of the catchment during the rainfall with a return period of 50 years.

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1. INTRODUCTION

1.1. Background information

Flooding is a global phenomenon that causes casualties and property loss on every inhabited continent (Teng et al., 2017). Low-lying and densely populated regions around the world are more prone to flood risks necessitating a continuous assessment of changes in flood risk exposure to safeguard human populations, for ecological conservation and providing guidance to policymakers regarding risk reduction (Maaskant et al., 2009). The Netherlands is potentially a very vulnerable country in Europe in terms of risk exposure to extreme flooding events (Wiering & Winnubst, 2017). The Netherlands undertakes continuous preventive and risk reduction measures against flooding from storm surges and rising river water levels, for example, the Delta Works flood protection system of coastal dunes, dikes and storm surge barriers (van Herk et al., 2015).

The ongoing development of low-lying flood-prone areas within the Netherlands increases exposure of lands to flood risks (Maaskant et al., 2009). In the Netherlands' Delta, small fluctuations in surface water levels substantially alter exposed land and surface-groundwater interface areas (O'Connor & Moffett, 2015). Consequently, the Netherlands flood management policy aims at continuous improvement by considering new visions and challenges to protect human beings, the ecology, to ensure socio-economic security and to make the country flood resilient (Delta Programme Commissioner, 2017). According to Vink et al., (2013), the flood solution of giving more "room" to the river lays emphasis on maintaining a more natural river course for ecological preservation and retaining water upstream to dampen flood peaks downstream. The retention of water for longer durations upstream is attained using dams and weirs resulting in elevated water levels. Brocca et al., (2011) identifies water levels as one of the important state variables in catchment hydrological flood modeling. River water levels and soil moisture are important components of the water balance that influence boundary fluxes governing the flow of water across hydrological model boundaries (Rientjes et al., 2013). In this research, the Voltherbeek's resilience to flooding during extreme rainfall is assessed by evaluating the catchment's response to rainfall-runoff production and the flood extents and depths produced for dry, wet and saturated soil conditions.

The Limburg Soil Erosion Model (LISEM) is used in this research to simulate the catchment's infiltration and stream discharge for extreme rain events (Sheikh et al., 2010). LISEM is a physically based numerical model that simulates for a single event the water balance, overland flow, river flow and flooding (Jetten & van den Bout, 2017). LISEM is designed to simulate the stream flow, flood extents and depths of the Voltherbeek catchment using prescribed soil depth conditions, soil texture, terrain, and land cover. The model is calibrated on in-situ discharge measurements and validated on an independent storm. The extreme rain events are designed by determining the total rainfall duration and based on pre-defined rainfall depths for extreme rain events by Wijngaard & Kok, (2004), a multiplication factor is determined and multiplied by the calibrated storm rainfall intensities.

1.2. Problem statement

The Voltherbeek is part of the Network Ecologically Valuable Waterways (NEWW) (Aaldenberg et al., 2015) obligating the regional water authority to undertake measures to restore the stream to a more natural watercourse (Aaldenberg et al., 2015). Moreover, the Voltherbeek flow dynamics are quite erratic. Peak spills occur rapidly after rainfall due to the less permeable clay soils in the area while very low flows are experienced in dry periods (Aaldenberg et al., 2015). The catchment generates less runoff during summer due to a lower groundwater level and high evaporation rate while rainwater is discharged faster in winter due to wet soil conditions (Den Haag, 2011). Moreover, the frequency and intensity of rainfall events are expected to increase resulting in more frequent inundation and flood damage due to climate change (Sušnik et al., 2014).

Understanding the streams response to rainfall-runoff production during extreme rain events is important in flood management planning initiatives and minimizes the uncertainty of flood risks enhancing socio-economic development (Lu & Stead, 2013). This study will enable an understanding of the Voltherbeek flow and flood dynamics by mapping flood-prone areas and flood depths for extreme rain events.

1.3. Objectives

The main objective of this research is to assess the resilience of the Voltherbeek to flooding during extreme rain events by assessing the catchment's response to rainfall-runoff production and mapping the flood extents and depths.

The specific objectives of the research are: -

a) To design an application of LISEM for the Voltherbeek that includes parameterization of the stream cross-section, land use, topography, and soils;
b) To calibrate and validate the LISEM for the Voltherbeek using independent storm events;
c) To design storm events applicable to the catchment and determine their rainfall depths;
d) To generate and evaluate flood maps for extreme rain events for dry, wet and saturated soil conditions showing flood-prone areas, and depths.

1.4. Research questions

With reference to the research objectives, the following research questions are posed: -

a) Does the calibration of the LISEM for the Voltherbeek catchment on the generated peak flows of storm events enable reliable modeling of discharge?
b) Under which conditions of soil moisture content and extreme rain event will the Voltherbeek runoff cause flooding and what is the return period of such an event?
c) Which sections of the Voltherbeek are prone to flooding during the simulated extreme rainfall and what are the flood extents and depths?

2. LITERATURE REVIEW

Floods have different characteristics and can be classified as flash floods, coastal floods or river floods based on geography, climate and the human population living within the affected area (Messner et al., 2007). Agriculture and urbanization are increasingly threatening resilience to river flooding globally necessitating human interventions (Biron et al., 2014). Providing space for rivers to divert and allow flooding in some sections of the river reach is a common practice being adopted in floodplains to facilitate water availability and to mitigate against flood risks (Biron et al., 2014). Current river management initiatives to safeguard property and human beings from extreme floods largely alter river morphologies threatening catchments water balance (Death et al., 2015). The atmosphere, catchments, and rivers are important components of the water cycle in quantifying the frequency and magnitude of floods (Blöschl et al., 2015). To assess resilience to flooding, the runoff generation processes, precipitation, and catchment characteristics have to be evaluated and the findings incorporated in river management initiatives (Emmanuel et al., 2015).

During floods, a spatial redistribution of water from the river, atmosphere, and groundwater takes place that needs to be quantified (Chormanski et al., 2011). Numerical models enable the simulation of floods through quantification of the water balance components for river management initiatives (Costabile & Macchione, 2015). The estimation of water balance storage components is complex due to their spatial and temporal variability (Muthuwatta et al., 2010). Flood simulation models facilitate the understanding, comparing and testing of alternative options for flood damage minimization and understanding the river flow regimes (Alemseged & Rientjes, 2007). However, the performance of models in the rainfall-runoff simulation is uncertain necessitating the quantification of model uncertainties and calibration (Sanchez-Moreno et al., 2014). Sanchez-Moreno et al., (2014) identifies the absence of sufficient data and adequate spatial resolutions of soil characteristics as a hindrance in obtaining appropriate model performance. According to Alemseged & Rientjes, (2007), the assessment of model uncertainties during rainfall-runoff model simulation design provides an in-depth insight into the effectiveness of model parameterization. Effective parameterization enhances the reliability of the model simulations resulting in effective river flow regime understanding and flood control (Alemseged & Rientjes, 2007). Khu et al., (2008) identify in-situ river discharge measurements as observations within the modeling domain that can be used as a performance objective for model calibration.

Several studies have been carried out using LISEM for flood modeling identifying the saturated hydraulic conductivity (Ks) as the most important parameter of the model structure (Sheikh et al., 2010). LISEM is an important physically-based hydrological model for planning and conservation purposes that can be adopted on small catchments up to 1000 Km^2 (De Roo, 2000). LISEM offers the flexibility of choosing time steps from as low as 1 second to 15 minutes (De Roo, 2000). Jetten & Chavarro, (2016) recommend a resolution of 5 or 10 m for accurate simulation of runoff in a catchment using LISEM. Digital elevation models are the most common source of topographical information for flood models due to their reliability and ease of data retrievable (Teng et al., 2017).

Sanchez-Moreno et al., (2014) in their study concluded that calibrating of the LISEM on measured discharge at an outlet by varying the initial moisture content, suction at the wetting front and Manning's roughness produces valid scenarios of flood modeling. LISEM is highly sensitive to initial soil moisture and has to be accurately initialized for flood simulations especially for low rainfall and runoff fractions (Sheikh et al., 2010).

3. STUDY AREA AND DATASETS

3.1. The Voltherbeek catchment

Figure 1 shows the digital elevation model of the study area (upper panel) and zoomed in world topographic map to the study area (lower panel). The study area is located between Denekamp and Rossum in the municipality of Dinkelland in the Twente region. The study focussed on the upstream reach of the Voltherbeek, which is, in turn, a tributary of the Dinkel in Overijssel located within latitude 52°23' N and longitude 6°57'E. The Voltherbeek main drainage originates from the Paasberg and Tankenberg near Oldenzaal and flows downstream to the Agelerbroek into the Tilligterbeek (Aaldenberg et al., 2015). The modeling domain concentrated on the section upstream of the Linderdijk weir, having a catchment area of 11.4 Km^2. The elevation within the study area varies between 22 m and 53 m above mean sea level.

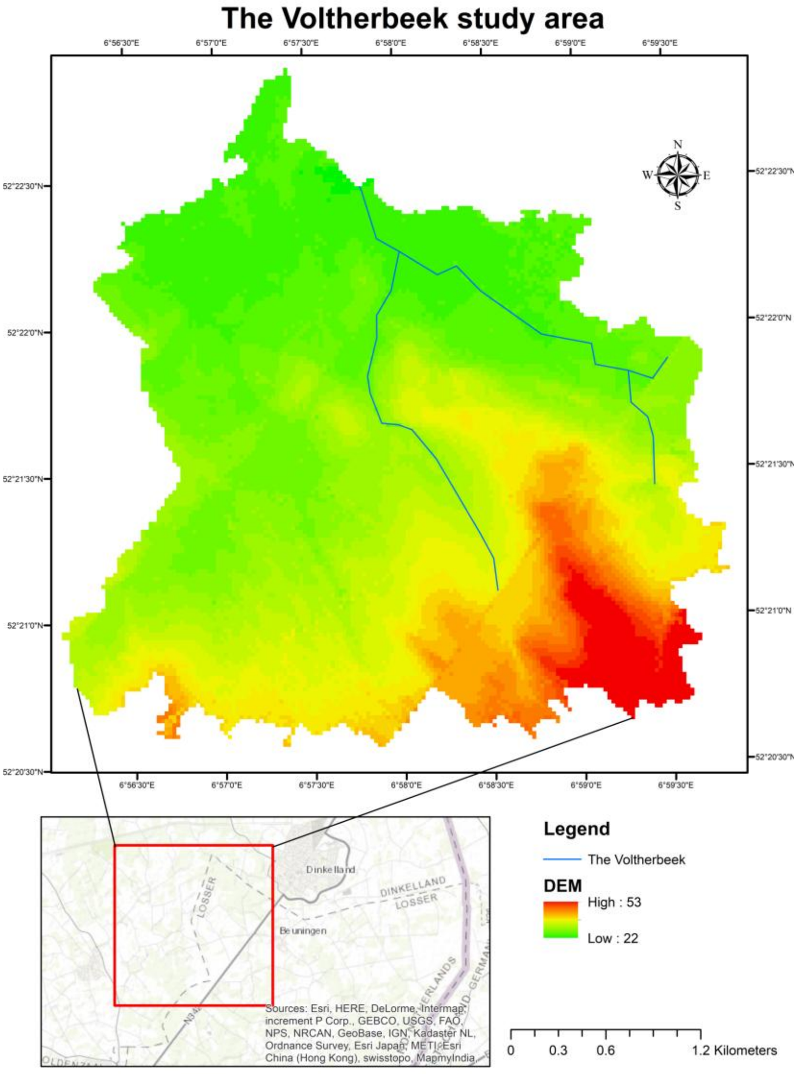

Figure 1: Study area showing the Voltherbeek upstream and modeling domain (Nationaal georegister, 2017) and (ESRI)

Figure 2 shows the annual precipitation retrieved from the Twenthe station for the period 1975 to 2015. The Twente region is classified as temperate with precipitation evenly distributed over the year. The area receives an annual rainfall of approximately 740 mm per year (Royal Netherlands Meteorological Institute, 2017). The monthly average temperature ranges from 3°C in January to approximately 17°C in July (Dente et al., 2011).

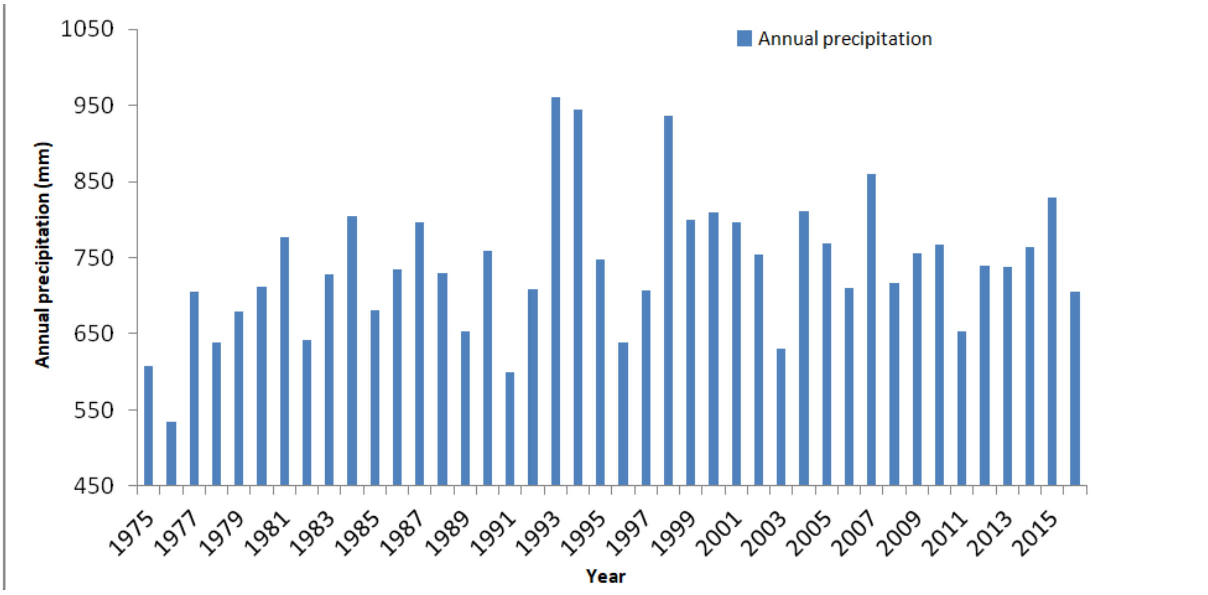

Figure 2: The Twenthe station annual precipitation (mm) (Royal Netherlands Meteorological Institute, 2017)

3.2. Spatial datasets

3.2.1. Digital elevation model (DEM)

DEMs are used in flood models for the creation of elevation properties, river flow characterization, delineation of catchments and stream order characterization (Rahman & Di, 2017). The DEM for this research is retrieved from Algemeen Hoogtebestand Nederland 2 (AHN2) (Nationaal georegister, 2017) with a resolution of 50 cm. The AHN2 has the advantages of high accuracy and more point density (van der Sande et al., 2010). The vertical offset of the AHN2 is up to 4 cm between the overlapping strips (van der Sande et al., 2010). The DEM covering the Voltherbeek catchment is filled and resampled to 10 m resolution. The 10 m resolution is adopted also for other maps used in the study. The resampled DEM is used for catchment delineation in ArcGIS. The Voltherbeek catchment is delineated by creating flow direction and flow accumulation layers. The raster calculator tool is then used to determine the actual river flow lines from the flow accumulation raster. A digitized Voltherbeek flow line is overlaid on the river flow lines generated from the raster calculation operation and an outlet is created at the section corresponding to the flow line river mouth. The Watershed Tool is used to generate the Voltherbeek water shade.

3.2.2. Soils

The study area is predominantly characterized by two soil texture classes, sand, and loam. Figure 3 shows the spatial distribution of the soil texture classes in the study area. The eastern part of the modeling domain is predominantly sandy while the western part comprises mainly loam soil. Other soil texture classes are patches of black meadow (sand) clay brook lands and debris (sand) as listed in Table 1. Benninga et al., (2018) translation of the soil texture names from Dutch to English is adopted in this research.

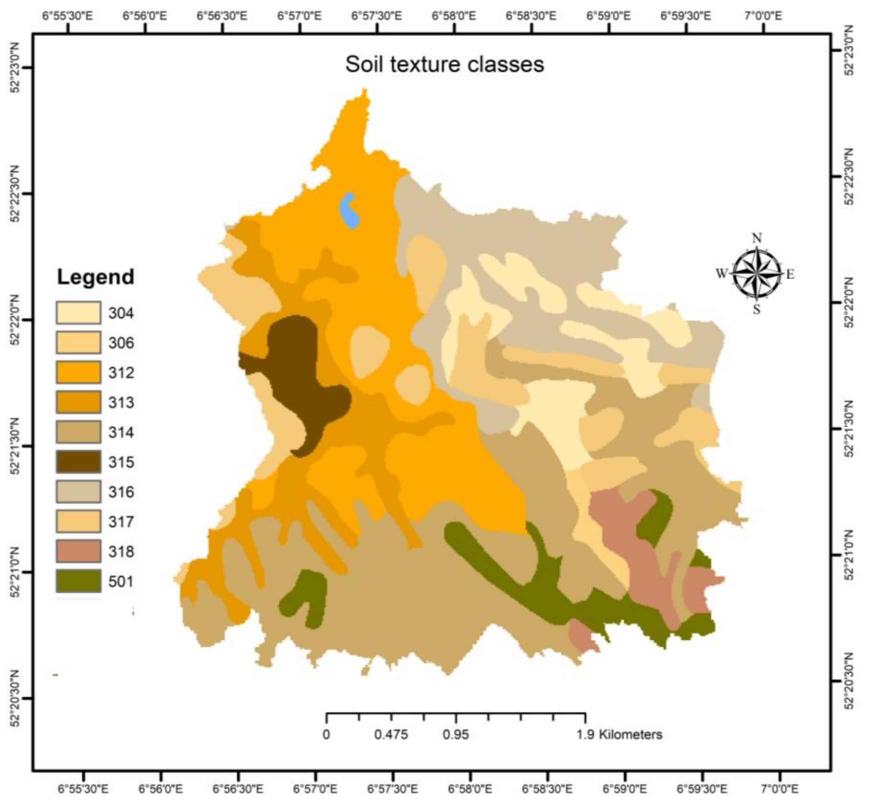

Figure 3: Spatial distribution of soil texture classes (Wösten et al., 2013)

Table 1: Soil texture classes names (Wösten et al., 2013)

Texture class	Soil type
304	Weakly loamy podzol soil
306	Weak loamy sandy soil on loamy subsoil
312	Loamy podzol soil
313	Loamy soil
314	Loamy sandy soil on loamy subsoil
315	Loamy sandy soil with boulder clay
316	Loamy sandy soil with clay cover
317	Loamy sandy soil with thick man-made earth soil cover
318	Loamy sandy soil with thick man-made earth soil cover on loamy subsoil
501	Loam and former clay loamy soil

Soil properties are important parameters in flood modeling since they influence the water storage capacity influencing the probability of flood occurrence in floodplains (Jetten & Chavarro, 2016). Soil properties for this research are retrieved from soil physical units map in vector format containing the Netherlands soil texture classes. The map is clipped to the Voltherbeek catchment extent and converted to raster format. The raster map containing the various texture classes is then resampled to 10 m resolution. Soil properties influence the soil moisture content, which is a major state regulating the exchange fluxes between land and the atmosphere during water balance calculations (Jawson & Niemann, 2007). Soil texture properties influence the soil moisture, porosity and hydraulic conductivity which are essential in enhancing the performance of hydrological models in simulating catchment runoff (Lefrancq et al., 2017). In this research, the effects of agricultural land use on the structural change of the soil are not considered. The porosity, saturated hydraulic conductivity and residual soil moisture contents of the various soil texture classes within the Voltherbeek are retrieved from Wösten et al., (2001) and Wösten et al., (2013). Wösten et al., (2001) list the soil moisture parameters based on particle size analyses in a laboratory that are adopted in this research for LISEM parameterization.

3.2.3. Land use

The spatial distribution of the land cover types is illustrated in Figure 4. Most of the study area is covered with pasture as the predominant land cover. The catchment is characterized by clusters of forests and cultivated farms. Changes in catchment land use such as increased impermeable paved surfaces and intensive farming in the Netherlands has led to an increase in flooding due to more runoff production (De Roo, 2000). Land use changes increase the catchment runoff production process and amplify peak discharges (De Roo, 2000). Land use data used in the research is obtained from LGN6 with a spatial resolution of 25 m (Hazeu et al., 2012). The Voltherbeek catchment land use classes are extracted by processing the LGN6 on ArcGIS using the extract by mask tool. The extracted land use map are then reclassified into 6 land use classes and resampled to 10 m resolution. The Manning's coefficients are retrieved from Phillips & Tadayon, (2006). The Manning's coefficients are used for parameterization of the catchments surface and channel roughness. The surface and channels roughness parameters are used for generation of the Manning's n and fraction of land cover maps used as land use input maps for LISEM.

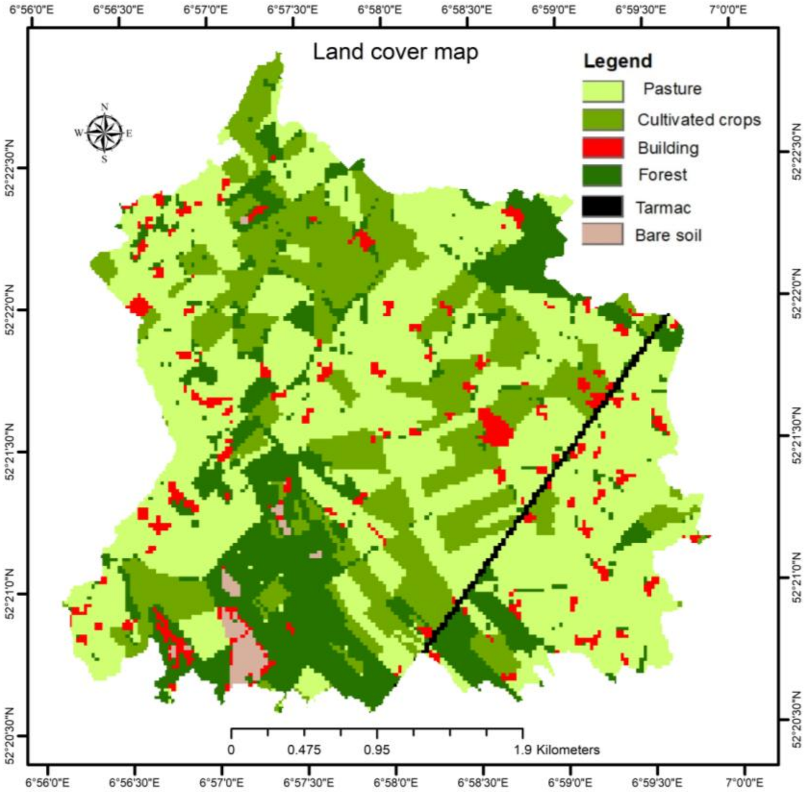

Figure 4: Spatial distribution of land cover types (Wagenigen University & Research, 2017)

3.3. Insitu measurements

3.3.1. Water level measurements

ITC operates one water level gauging station within the study area. One DL.0CS/N/RS485 datalogger is shown in Figure 7(A) (manufactured by STS) is installed at the stream. The sensor is set to store water level measurements every 5 minutes in ASCII format. Figure 5 shows the water levels recorded by the datalogger in response to rainfall received in the catchment. To ensure a unified scale in the modeling and avoid errors related to time-space model discretization (Alemseged & Rientjes, 2007), the 5 minute time step is adopted in preceding simulations. The water level measurements are used to calculate the discharge produced as a result of the rainfall. Water level measurements used in the research are available for the period 8th July 2016 to 28th November 2017. The water levels are analyzed in 5 time periods to identify peak events corresponding to independent storm events that are used for calibration and validation of LISEM. Calibration and validation storm events used in the research are selected from period 2 (17th November 2016 to 19th November 2016) and period 3 (8th March 2017 to 9th March 2017) respectively.

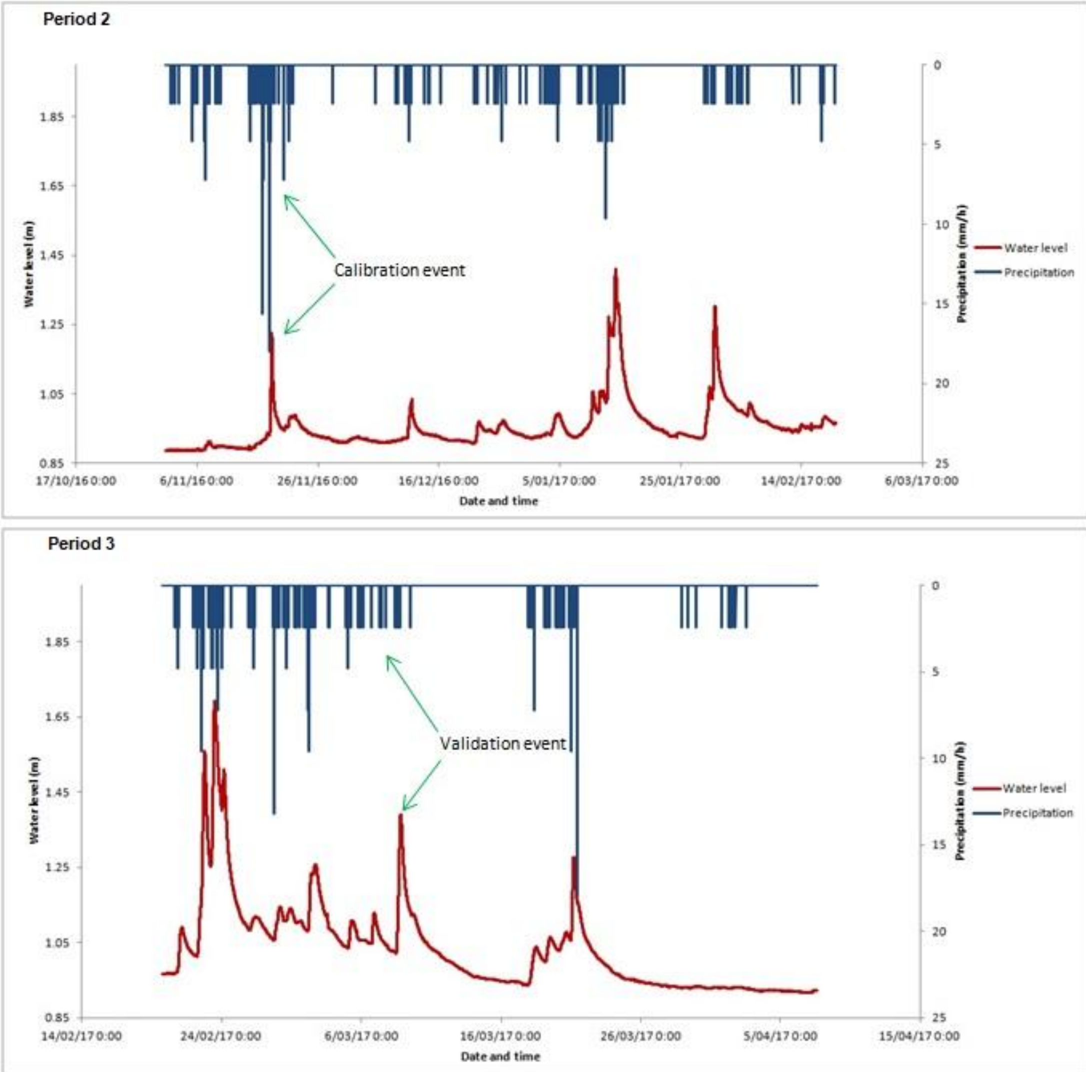

Figure 5: In-situ pre-processed rainfall and water level measurements for periods 2 and 3

The discharge produced by the rainfall received is calculated by first retrieving the channel slope from the grad map created during the pre-processing of the channel map. The streamflow depth is then calculated for the runoff fraction of the stream flow by subtracting the lowest water level height recorded during the storm event. Next, the wetted perimeter is calculated by multiplying the channel depth by two and multiplying the result by the stream width. The hydraulic radius is calculated by dividing the cross-sectional area of the channel corresponding to the runoff fraction of the stream flow by the wetted perimeter. The discharge produced is calculated using the Manning equation (Leon et al., 2006).

3.3.2. Rainfall

The ITC monitors rainfall within the study area using a tipping bucket. A Davis bucket is shown in Figure 7(C) has been installed on a farm next to the Voltherbeek. In-situ rainfall measurements used in the research is available for the period 8th July 2016 to 16th November 2017. In Figure 5, the processed rainfall data is plotted to check the water level rise in response to the received rainfall. The bucket tips when precipitation of 0.2 mm is collected. Each tip is recorded by a datalogger. The in-situ precipitation is converted into rainfall intensities that are used as rainfall forcing for LISEM during model calibration and validation.

3.3.3. Soil moisture

ITC manages 20 soil moisture and temperature monitoring stations within the Twente region. Soil moisture measurements used in the research are retrieved from Twente soil moisture monitoring network site station ITCSM_07. The station has one Em50 ECH20 datalogger shown in Figure 7(B) (manufactured by Decagon). The probes are calibrated for the soil type of the area (Dente et al., 2011). The data logger stores the 5 cm, 10 cm, 20 cm, and 40 cm depth soil moisture every 15 minutes. Figure 6 shows in-situ soil moisture measurements for the 5 cm, 10 cm, 20 cm, and 40 cm depth collected for the period 1st January 2016 to 31st December 2017. The in-situ soil moisture measurements are used for initializing the soil moisture content for model calibration and validation.

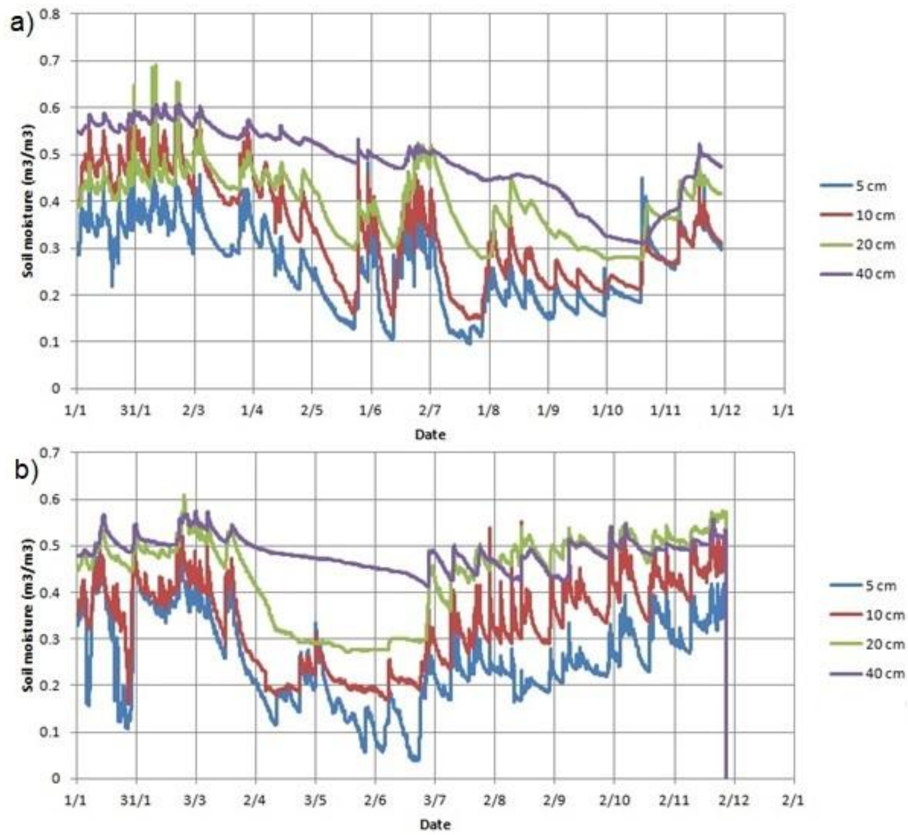

Figure 6: Soil moisture contents for 5, 10, 20 and 40 cm depths for the years 2016 (a) and 2017 (b)

A B C

Figure 7: ITC stations within the Voltherbeek (A) water level station (B) soil moisture station (C) rainfall gauging station

3.3.4. Calibration and validation events

The in-situ water level measurements are grouped into five periods for easy analysis. The peak water levels in each of the five periods are assessed in relation to the in-situ rainfall measurements to identify independent peak water levels corresponding to independent rainfall events. Peak independent water level events in winter are given preference since faster runoff generation occurs during the winter season and are more likely to generate floods. The peak water levels for the period 17th November 2016 to 19th November 2016 and 8th March 2017 to 9th March 2017 are selected for the LISEM calibration and validation respectively. These two events are selected due to the gradual water level rise to a single peak water level and gradual fall to a minimum water level in response to independent storm events. The in-situ water level measurements are used for calculating the discharges used for model calibration and validation.

4. FLOOD MODELLING

4.1. Model structure

LISEM model structure comprises routine functions for calculating the catchments total interception, infiltration, surface storage, overland flow, channel flow and generated discharge as illustrated in Figure 8 (Jetten & van den Bout, 2017). LISEM is a physically based numerical model that simulates for a single event the water balance, overland flow, river flow, flood depth and extent (Jetten & van den Bout, 2017). The model handles sub-grid cell surface properties containing the catchment characteristics (Jetten & van den Bout, 2017). LISEM uses sub-grid information from spatial data of the DEM, soils and land use to simulate the catchments response to rainfall forcing (Jetten & Chavarro, 2016). During a rain event, vegetation and roofs intercept part of the rain before it reaches the ground surface. The rain reaching the ground surface either infiltrates or is stored as surface storage in depressions depending on the soil properties. Once the storage capacity is exceeded, runoff is generated for the respective grid cell using the Green and Ampt Infiltration method (Sheikh et al., 2010) and routed as overland flow influenced by the Manning roughness coefficient into the channel or generating a flood directly (Jetten & van den Bout, 2017).

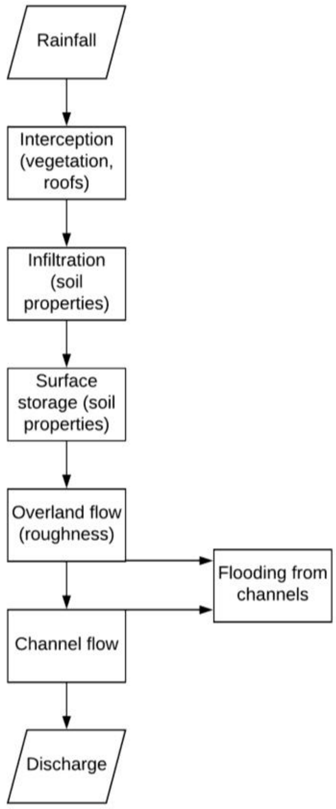

Figure 8: LISEM model structure for rainfall-runoff and flood routing (Jetten & Chavarro, 2016)

According to Jetten & van den Bout, (2017), LISEM routes runoff using three types of flow in an ordered process; overland flow, channel flow, and flooding as illustrated in Figure 9. The stream is the coupling link (Jetten & van den Bout, 2017) whereby the overland flow flows into the stream, generating stream flow. Eventually, the stream overflows when it's storage capacity is exceeded generating a flood which may recede back into the channel after some time. LISEM has the option to solve infiltration using the Green and Ampt infiltration model (Jetten & van den Bout, 2017) according to Equation 1;

$$f = f_{pot} = -K_S\left(\psi\frac{\theta_s - \theta_i}{F} + 1\right)$$ Equation 1

Where:

f = infiltration rate (m s^{-1})

f_{pot} = potential infiltration rate (m s^{-1})

K_s = saturated conductivity (m s^{-1})

ψ = matric pressure at the wetting front (m)

θ_s = porosity (m^3 m^{-3})

θ_i = initial soil moisture content (m^3 m^{-3})

F = cumulative infiltrated water (m)

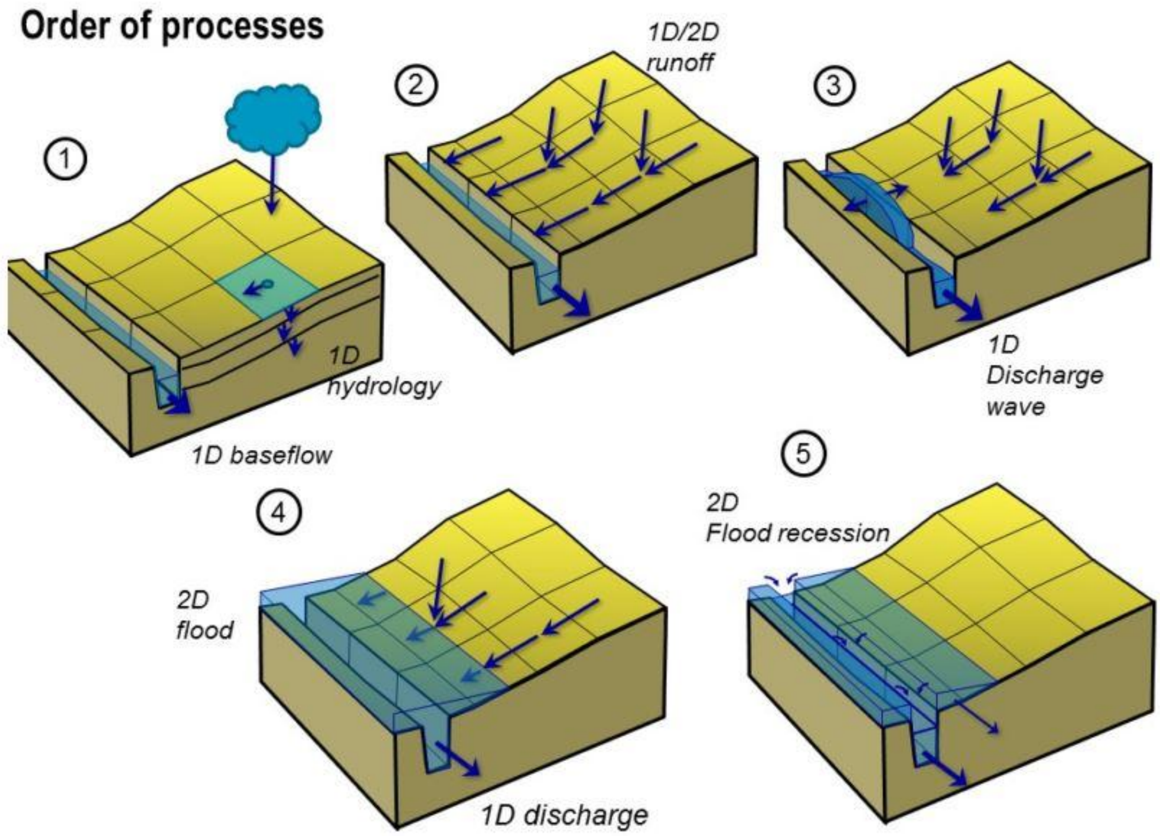

Figure 9: Order of flow processes as is routed by the DEM with the stream acting as the coupling link for water balance calculation in LISEM flood modeling (Jetten & van den Bout, 2017)

The Manning's n coefficient influences the runoff velocity which in turn regulates the infiltrated depth and is used in the solution of the kinematic wave equations for flow routing in a catchment (Hernandez et al., 2000). The water is routed over local drainage networks according to Equation 2 and Equation 3Equation 3 for the 1D overland flow and diffusive wave 2D respectively (Jetten & van den Bout, 2017);

a) 1D Overland flow – Kinematic wave;

$$\frac{dA}{dt} + \frac{dQ}{dx} = q - infil$$ Equation 2

Where:

Q = discharge ($m^3\ s^{-1}$)

A = cross-sectional area (m^2)

$infil$ = infiltration ($m^3\ s^{-1}$)

q = the other sources of water (rainfall and snowmelt) ($m^3\ s^{-1}$)

t = time step (s)

x = width of the grid cell (m)

b) Diffusive wave 2D:

$$\frac{dA_{i,j}}{dt} + Q_{in,i,j} - Q_{out,i,j} = q_{i,j} - I_{i,j}$$ Equation 3

Where:

Q_{in} = discharge inflow ($m^3\ s^{-1}$)

Q_{out} = discharge outflow ($m^3\ s^{-1}$)

i = row

j = column

4.2. Parameterization

LISEM input maps are generated using a PCRaster script generating the DEM, soils, land use and channel maps (Jetten & Chavarro, 2016). The initial soil moisture and the saturated hydraulic conductivity are the key parameters that influence the infiltration rate and hence the catchment runoff in LISEM (Hessel et al., 2003). The Manning's n influences the runoff production in a catchment since LISEM calculates flow velocity using the Manning's equation (Hessel et al., 2003) according to Equation 4. The slope angle is also an important parameter that needs to be well generated since the channels discharge is a function of the slope angle (Hessel et al., 2003) in LISEM channel flow routing.

$$Q = \frac{1}{n} AR^{2/3} S^{1/2}$$ Equation 4

Where:

n = Manning's roughness coefficient (-)

R =hydraulic radius (m)

S = friction slope (-)

4.3. Application to the Voltherbeek

In order to generate the DEM, soils, land use and channel maps for LISEM, in-situ data and spatial data are pre-processed and converted to .map format using a PCRaster script that calculates the water balance for the Voltherbeek on a daily time step. The initial soil moisture map is generated by checking the antecedent soil moisture from the in-situ measured soil moisture content and multiplying the porosity map by a multiplication factor that generates an initial soil moisture map that matches the in-situ measured soil moisture content.

Table 2 lists the soil parameters adopted in this research to characterise the residual soil moisture, saturated soil moisture and saturated hydraulic conductivity for the various soil texture classes. The soil characteristic and land use parameters used in this research for the PCRaster scripting are adopted from literature. Soil parameters are adopted from two key BOFEK2012 kinds of literature. Each soil texture class is analyzed by checking the texture class building block value listed by Wösten et al., (2013) and the corresponding parameters defining the soil characteristics of the soil block is retrieved from Wösten et al., (2001). The parameters are then listed in a text file and run on the PCRaster script generating the Ks, θ, porosity and soil layer depth maps that serve as inputs for LISEM.

Table 2: Parameters defining the Voltherbeek soil texture classes (Wösten et al., 2013)

Class	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	Ks (mm/h)
304	0.02	0.42	5.2
306	0.02	0.42	5.2
312	0.02	0.46	6.4
313	0.02	0.46	6.4
314	0.02	0.46	6.4
315	0.02	0.46	6.4
316	0.01	0.46	0.9
317	0.02	0.46	6.4
318	0.02	0.46	6.4
501	0	0.43	0.6

The land use map is used to generate the Manning's n, cover fraction, leaf area index, crop height and canopy storage maps. The Manning's equation is adopted in this research for calculation of the in-situ discharge due to its simplicity and ease of use. Table 3 lists the Manning's n values (Phillips & Tadayon, 2006) adopted in this research for the pasture, cultivated, building, forest, tarmac and bare soil land covers for the Voltherbeek catchment. The resultant land use maps (Manning's n, cover fraction, leaf area index, crop height and canopy storage maps) are used as input maps for LISEM.

Table 3: Manning's n values for the land cover types (Phillips & Tadayon, 2006)

Land cover	Manning's n value (-)
Pasture	0.03
Cultivated	0.035
Building	0.013
Forest	0.1
Tarmac	0.016
Bare soil	0.02

4.4. Calibration and error metrics

In this research, the initial soil moisture values are used for the model calibration and validation. The Green and Ampt model is very sensitive to the saturated hydraulic conductivity (Ks) and the initial soil moisture content necessitating the use of in-situ measured soil moisture measurements for model calibration (Jetten, 2002). The initial soil moisture is set as close as possible to the in-situ soil moisture content by using a multiplication factor. The model is then calibrated by decreasing the Ks to fit the simulated peak as close as possible to the in-situ generated peak. Next, the initial soil moisture is increased systematically to reduce the infiltration rate and increase the simulated discharge to improve the match with the in-situ discharge. In order to match the time-to-peak of the simulated discharge to the in-situ discharge, the Manning's n channel and Manning's n slopes are increased systematically.

The model performance is assessed by both visually inspecting the match of the simulated discharge with the observed discharge and quantitatively by calculating the Nash-Sutcliffe efficiency coefficient (NS) (Nash & Sutcliffe, 1970) and the Relative Volume Error (RV_E) (Deckers et al., 2010) given by;

$$NS = 1 - \frac{\sum_{t=1}^{t=N}[Q_{sim}(t) - Q_{obs}(t)]^2}{\sum_{=1}^{i=N}[Q_{obs}(t) - \overline{Q_{obs}}]^2}$$

Equation 5

$$RV_E = \left(\frac{\sum_{t=1}^{t=N}[Q_{sim}(i) - Q_{obs}(t)]^2}{\sum_{t=1}^{t=N} Q_{obs}}\right) \times 100\%$$

Equation 6

Where:

N = total number of time steps (-)

Q_{sim} = simulated discharge ($m^3 s^{-1}$)

Q_{obs} = observed discharge ($m^3 s^{-1}$)

$\overline{Q_{obs}}$ = mean of observed discharge over the calibration or validation period ($m^3 s^{-1}$)

5. RESEARCH METHODOLOGY

5.1. In-situ data collection

Figure 10 illustrates the data types, series of pre-processing steps, model parameters and, methods that are adopted in this research with reference to the research objectives;

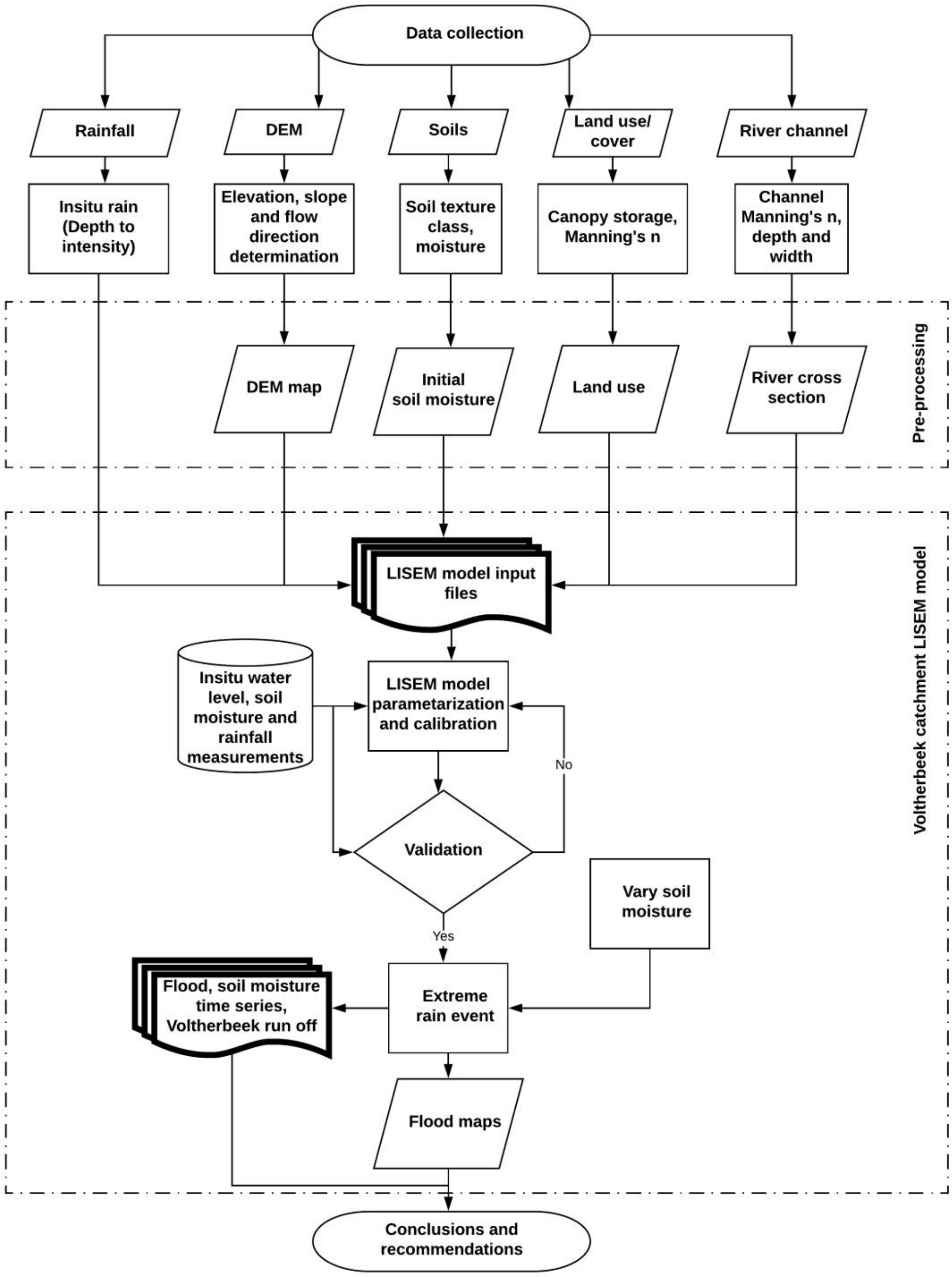

Figure 10: Flowchart of adopted research approach

During the fieldwork, a walk along the Voltherbeek was conducted to visually check the land use, soil texture classes, and download in-situ water-level, rainfall and soil moisture measurements as shown in Figure 11. The in-situ rainfall measurements were downloaded from a tipping bucket located adjacent to the Voltherbeek. Water levels were downloaded from the water level logger located at the outlet point of the study modeling domain.

Figure 11: Soil moisture sampling and automatically logged data downloading during fieldwork

5.2. Pre-processing

Table 4 lists LISEM input maps (DEM, soil, land use, and channel maps) created by the PCRaster script during the pre-processing of the in-situ and spatial datasets. The maps are first converted into TIF format and later to .map format. Each map is resampled to a 10 m resolution before conversion from TIF to .map format for further PCRaster pre-processing.

5.3. Calculating stream discharges

The Voltherbeek flow is very low during summer due to a lower groundwater level and high evaporation (Aaldenberg et al., 2015) and LISEM does not consider the baseflow apart from an assumed stationary baseflow (Jetten & van den Bout, 2017). The initial water level at the start of the simulation events is therefore subtracted from subsequent in-situ water levels in order to subtract the catchments baseflow from the in-situ discharges. This ensures that the in-situ discharge calculated is as a result of direct runoff. The channels wetted perimeter and cross-sectional area are calculated and used for calculating the hydraulic radius. The Manning's formula (Equation 4) is used for calculating the discharge. The slope adopted in the study is 0.005 m m^{-1} based on the slope extracted from the slope map generated in the pre-processing steps

Table 4: LISEM input maps for flood modeling

Variable	**Map (.map)**	**Description**	**Units**
Catchment	dem	Digital elevation model	m
	grad	Sine of slope gradient in direction of flow	
	ldd	Local surface drainage direction network	
	outlet	Main catchment outlet corresponding to LDD map and reporting for hydrograph	
Land use	per	Fraction of cover by vegetation and residue	-
	lai	Leaf area index of the plant cover in a grid cell	m^2/m^2
	ch	Plant height	m
Surface	rr	Random roughness standard deviation of heights	cm
	n	Manning's n	-
Infiltration	ksat1	Saturated hydraulic conductivity	mm/h
	psi1	Average suction at the wetting front	cm
	thetas1	Porosity	-
	thetai1	Initial moisture content	-
	depth1	Depth to bottom of layer 1	mm
Channels	lddchan	LDD of man channel	
	chanwidt	Channel width	m
	chanside	Channel side angle	
	changrad	Slope gradient channel bed	-
	chanman	Mannings n of channel bed	mm/h
Channel flood	chandepth	Channel depth	m
	chanaxq	Maximum limiting channel discharge	m^3/s
	hmxinit	Initial flood level	m

5.4. LISEM calibration and sensitivity analysis

Table 5 shows the multiplication factors for the Ks, θ, Manning's n slopes and Manning's n channel adopted in the research during each model run of LISEM calibration. The one parameter at a time calibration strategy is adopted for the research (Lefrancq et al., 2017). The model calibration and validation is done for independent storms based on the in-situ soil moisture and discharge measurements. The initial soil moisture is set as close to the in-situ soil moisture content as possible during the calibration and validation exercises. The calibration data is the storm event of the period 17th November 2016 to 19th November 2016. The calibration strategy is to optimize each parameter by varying one parameter at a time. The overall model performance is evaluated using the NS and RV_E.

A well-performing model should have an NS close to 1 and the RV_E value should be close to zero (Akhtar et al., 2009). The NS varies between $-\infty$ and 1 and performs best when a value 1 is generated, NS values between 0.9 and 1 indicate extremely well model performance while NS values between 0.8 and 0.9 indicate the model performs very well while NS values between 0.6 and 0.8 indicate the model performs reasonably well (Rientjes, 2015). The RV_E varies between $-\infty$ and ∞. The model performs best when the model generates a value 0. An RV_E value between +5% and -5% indicates that the model performs well while an RV_E between +5% and +10% and between -5% and -10% indicate a model with reasonable performance (Rientjes, 2015).

The NS ensures an acceptable match of the discharge peaks and the RV_E the goodness of fit of the overall water balance (Deckers et al., 2010). The objective functions enable the optimization of the model parameters for simulation of the peak flows which are of interest in this research (Deckers et al., 2010).

Table 5: Optimization of each parameter set (the numbers represent LISEM multiplication factors)

	Ks	theta	Manning's n slopes	Manning's n channel
Run 1	1	1	1	1
Run 2	0.5	1	1	1
Run 3	0.2	1	1	1
Run 4	0.1	1	1	1
Run 5	0.2	1.02	1	1
Run 6	0.2	1.04	1	1
Run 7	0.2	1.05	1	1
Run 8	0.2	1.02	2	2
Run 9	0.2	1.02	3	3
Run 10	0.2	1.02	4	4
Run 11	0.2	1.02	5	5

5.5. Design storm

To determine the design storms, the rainfall depth and return period of rainfall are required. To calculate the rainfall depth, the rainfall intensity of the calibrated storm event is converted to rainfall depth. The duration of the rain is then calculated. The duration of the calibrated storm is two days. The return periods to consider in the research are determined based on Overeem, (2009) and Sušnik et al., (2014) analysis of the Dutch extreme rain events for storm design against flooding from surface water. Flooding from surface water is permitted averagely once in 10 years, while sewer systems can discharge a design storm of 2 years and extreme events of 10 years to 25 years result in inundation of streets and underpasses (Overeem, 2009). Extreme rain events with return periods of twice in one year, once in 2 years, 10 years, and 50 years are considered in this research to assess the resilience of the Voltherbeek to flooding. Table 6 lists the flood depths for rain events with return periods of twice in one year, once in 2 years, 10 years, and 50 years for rains of a 2-day duration according to Wijngaard & Kok, (2004). A multiplication factor that yields a rainfall depth closely matching the 2-day rainfall depth as documented by Wijngaard & Kok, (2004) is then determined and multiplied by the calibrated storm event intensities to obtain the extreme storm event intensities.

Table 6: Rainfall depths for the design storms (Wijngaard & Kok, 2004)

Return period	Multiplication factor	Rainfall depth (mm)
2 times per year	2	35
2	3	48
10	4	65
50	5	84

6. RESULTS AND DISCUSSION

6.1. Calibration

The model calibration is based on the in-situ discharge for the period 17th November 2016 to 19th November 2016. This enables a better understanding of the stream's flow regime since the flow routing, stream storage, time-to-peak and the duration of flow are well captured. The model calibration strategy is carried out systematically to ensure objectivity in the parameterization. The calibration strategy enables the optimization of each parameter for a better model performance. Through a systematic variation of each parameter, while holding the other parameters constant, model performance issues due to uncertainty in model parameters are reduced (Zhang et al., 2016).

6.1.1. Ks optimization

The Ks is first optimized in the study to simulate the peak discharge as accurate as possible. Table 7 outlines the Ks multiplication factor variation for each model run during the Ks optimization to match the in-situ peak discharge and the generated NS and RV_E values. Figure 12 illustrates the resulting plots of simulated streamflow hydrographs, the in-situ streamflow hydrograph and the in-situ rainfall forcing for the model runs during the Ks optimization. During the calibration period, a total of 16.6 mm of rain is recorded by the tipping bucket with a maximum rainfall intensity of 18 mm h^{-1}. The in-situ peak discharge is 2.6 m^3 s^{-1}. A visual inspection of the match between the simulated streamflow hydrograph and the in-situ streamflow hydrograph for run 1 indicates a mismatch. The model produces a very low discharge as compared to the in-situ discharge. The model infiltrates more water as compared to the actual catchment infiltration's capacity. Run 1 generates an RV_E greater than 100% and a negative NS indicating a poor performing model.

Table 7: Optimization of the Ks to match the in-situ discharge peaks

	Ks	**θ**	**n slopes**	**n channel**	**NS(-)**	**RV_E (%)**	**Peak Q (m^3 s^{-1})**
Run 1	1	1	1	1	-0.92	117.4	0.36
Run 2	0.5	1	1	1	-0.696	103.7	0.56
Run 3	0.2	1	1	1	-0.123	68.6	2.22
Run 4	0.1	1	1	1	-2.285	200.8	5.28

The Ks value is systematically reduced to reduce the infiltration and increase the generated discharge. The simulated peak for run 3 gives the closest match to the in-situ peak discharge. The NS for run 3 is less negative and the RV_E lower as compared to the other runs. The overall match between the simulated streamflow hydrograph and the in-situ streamflow hydrograph is best for run 3 hence it is selected. A multiplication factor of 0.2 (run 3) is adopted for the Ks for subsequent runs since it yields the best performing model in simulating the peak discharge.

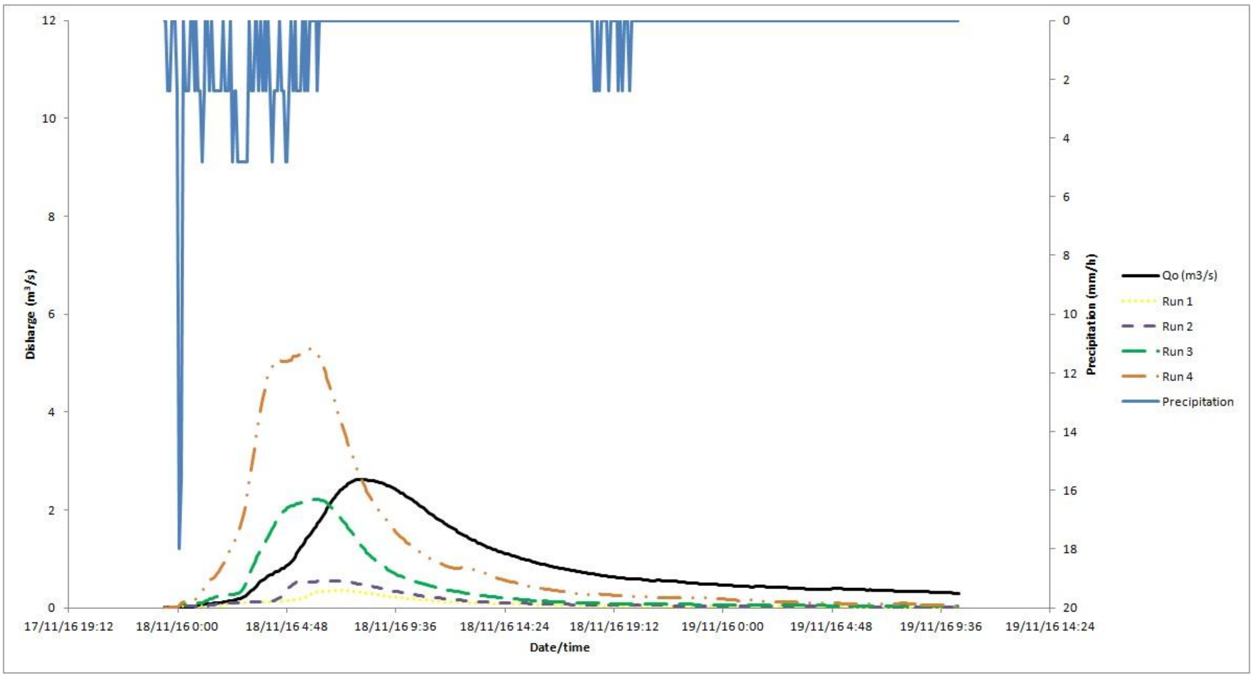

Figure 12: Visual inspection of the simulated discharges in comparison to the in-situ discharges for varied Ks values

6.1.2. Soil moisture Optimization

Since the peak is well simulated, the next step is to ensure the soil moisture is well calculated by increasing the soil moisture systematically using the θ multiplication factors as shown in Table 8 while holding the Ks, the Manning's n channel and Manning's n slope constant. Increasing the initial soil moisture makes the soil wetter hence reducing the infiltration rate which leads to more stream discharge in the subsequent simulations as illustrated in Figure 13. The range of multiplication factor could not exceed 1.05 since this would increase the soil moisture beyond the porosity which would not be realistic.

Table 8: Optimization of the θ to balance the mass water balance

	Ks	θ	n slopes	n channel	NS (-)	RV_E (%)	Peak Q (m^3 s^{-1})
Run 5	0.2	1.02	1	1	-0.259	77	3
Run 6	0.2	1.04	1	1	-0.518	92.8	3.72
Run 7	0.2	1.05	1	1	-10.649	712.1	8.97

A multiplication factor of 1.02 (run 5) is adopted for the θ for subsequent simulations. The initial soil moisture has a great influence on the discharge volume simulations since it dictates how much water can infiltrate before runoff is generated influencing the stream discharge and hence the model performance.

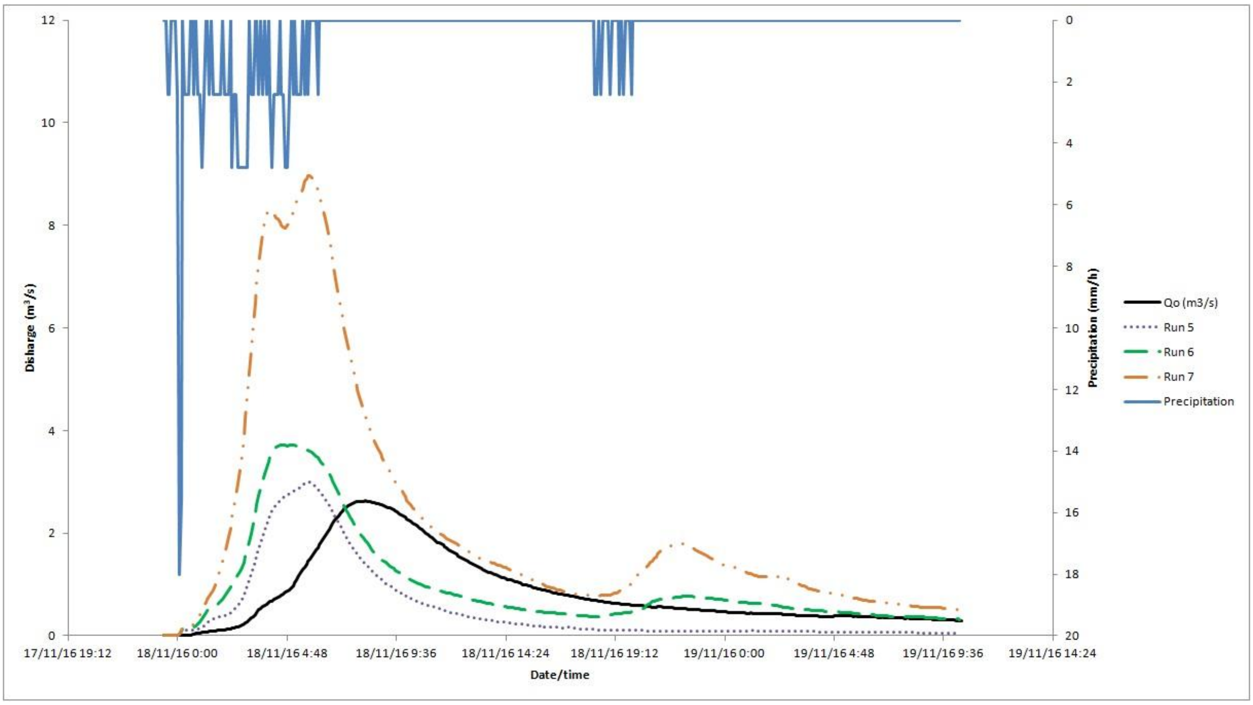

Figure 13: Visual inspection of the simulated discharges in comparison to the in-situ discharges for varied θ values

6.1.3. Manning’s n channel and Manning’s n slopes optimization

Run 5 parameter set simulates a stream-flow with an early time to peak as compared to the in-situ stream-flow hydrograph. The Manning’s n slopes and channels are systematically increased as illustrated in Table 9 to improve the model performance, but ensuring the multiplication factors does not make the Manning’s n values exceed the maximum allowable Manning’s n value for each land use as outlined by Phillips & Tadayon, (2006). Figure 14 illustrates the plots of the simulated discharges and in-situ discharge for run 8 to run 11 to optimize the Manning’s n channel and Mannings’s n slopes. Increasing the Manning’s n value reduces the runoff flow rate delaying the time the runoff takes to reach the stream channel and hence contributing to the discharge recorded on the outlet point. The reduced flow rate also increases the time for more water to infiltrate decreasing the volume of discharge generated.

Table 9: Optimization of the Manning's n to match the time to peak of the in-situ and simulated discharges

	Ks	θ	n slopes	n channel	NS (-)	RV_E (%)	Peak Q (m^3 s^{-1})
Run 8	0.2	1.02	2	2	0.089	55.7	4
Run 9	0.2	1.02	3	3	0.392	37.2	4.23
Run 10	0.2	1.02	4	4	0.378	38.0	4.21
Run 11	0.2	1.02	5	5	0.129	53.2	4.03

Run 9 multiplication factor of 3 for the Manning’s n channel and Mannings’s n slopes are adopted for the model generating an NS of 0.392 and RV_E of 37.2 which are still unacceptable.

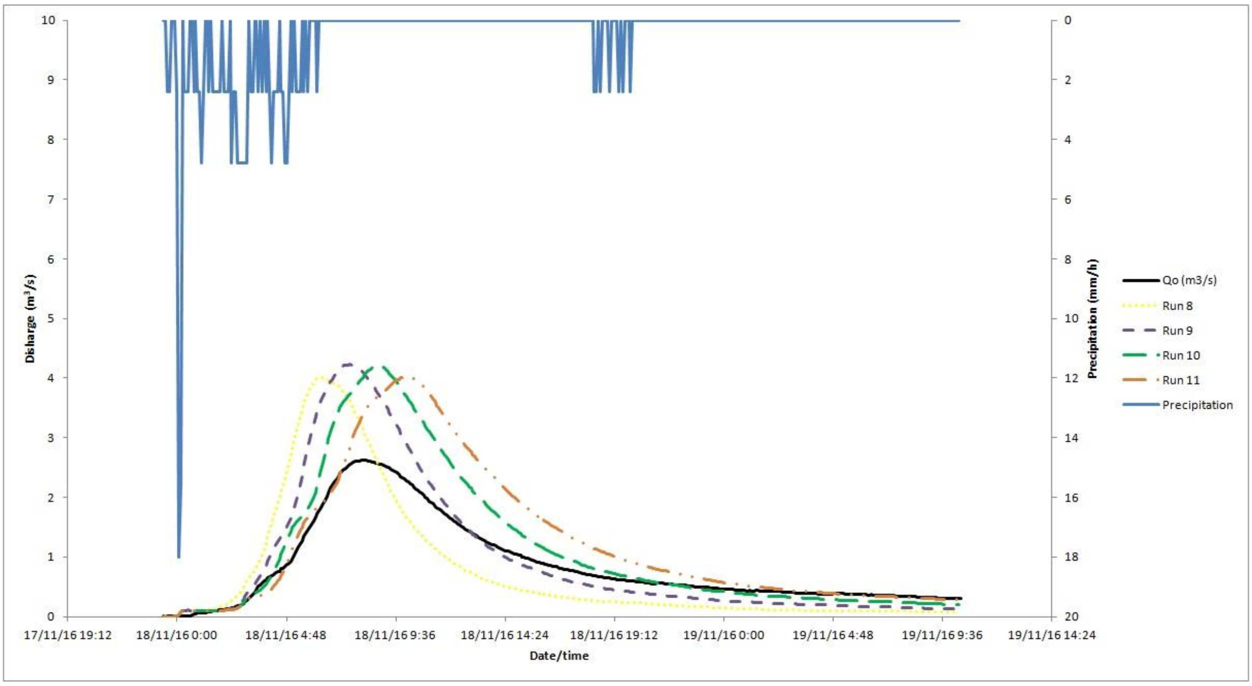

Figure 14: Visual inspection of the simulated discharges in comparison to the in-situ discharges for varied Manning's n values

6.1.4. Optimal model parameters

To optimize the parameters a visual inspection of the match between the simulated discharge and in-situ discharge is assessed on the run 9 results then the NS and RV_E are used as performance indicators. To improve model performance, the Ks is increased systematically to lower the simulated peak and reduce the runoff volume generated and the Manning's n channel and Mannings's n slopes reduced to match the time-to-peak as shown in Table 10 and Figure 15. This ensures the mass water balance error and match between the simulated streamflow hydrograph and the in-situ streamflow hydrograph is improved. Run 14 generates an NS of 0.91 and RVE of +5.4% which indicates a well-performing model. The parameter set for Run 14 is adopted as the calibrated parameter set.

In summary, the ranges of the multiplication factors for the model parameters adopted during the calibration are highlighted in Table 11.

Table 10: Fine tuning of the parameters to attain the optimal parameter set (the numbers represent LISEM multiplication factors)

	Ks	θ	n slopes	n channel	NS (-)	RV_E (%)	Peak Q (m^3 s^{-1})
Run 12	0.22	1.02	5	5	0.661	20.7	2.96
Run 13	0.23	1.02	5	5	0.697	18.5	2.56
Run 14	0.23	1.02	3	3	0.912	5.4	2.82

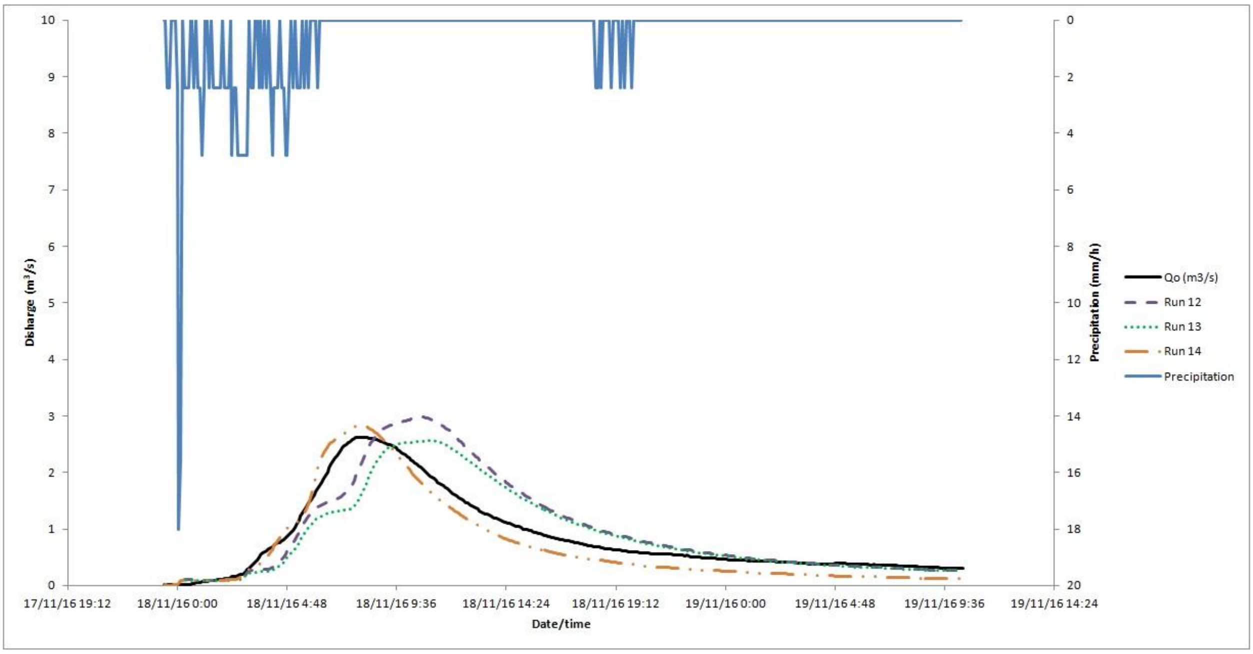

Figure 15: Visual inspection of the simulated discharges in comparison to the in-situ discharges for the optimization of the parameters

Table 11: LISEM parameters optimized for calibration and their value ranges

Parameter	Multiplication factor value range	Units
Ks	0.2 – 1.0	mm/h
Manning's n slopes	1.0 – 5.0	(-)
θ	1.0 – 1.05	(-)
Manning's n channel	1.0 – 5.0	(-)

6.2. Validation

Validation of the model is based on an independent event in the year 2017 with a different flow regime and rainfall pattern. The validation period is from 8th March 2017 to 9th March 2017. The highest in-situ water level recorded during the validation period is 1.4 m. The peak in-situ discharge is 3.4 $m^3 s^{-1}$. The calibrated parameter set (run 14) is used to simulate the discharge after setting the initial soil moisture close to the in-situ measured soil moisture (0.485 $m^3 m^{-3}$) by multiplying the porosity map by a factor close to 1 to make the initial soil moisture saturated. A total of 6 mm rain is received during the validation period with a maximum rainfall intensity of 2.4 mm h^{-1}.

The model validation generates an NS of 0.62 and an RV_E of +19% which are acceptable hence the model performs reasonably well. The peak discharge simulated is 4.0 $m^3 s^{-1}$ compared to a peak in-situ discharge of 3.4 $m^3 s^{-1}$. A visual inspection shows the model has a lag in the time to peak and slightly overestimates the peak discharge as shown in Figure 16. The rising limb of the simulated discharge is slightly steeper than the in-situ discharge while the falling limb of the simulated discharge is systematically higher than the in-situ discharge. Land use, especially agricultural and pasture land cover changes with time (season) hence the calibrated Manning's n slopes values may not be a true representation of the actual field conditions during the validation period. Seasonal variation also influences the canopy cover of the forested areas altering the actual land surface and channel roughness hence the model gives a delayed response in the time to peak. The validation result shows a sensitive response to the initial soil moisture content. The initial soil moisture content greatly influences the peak discharge.

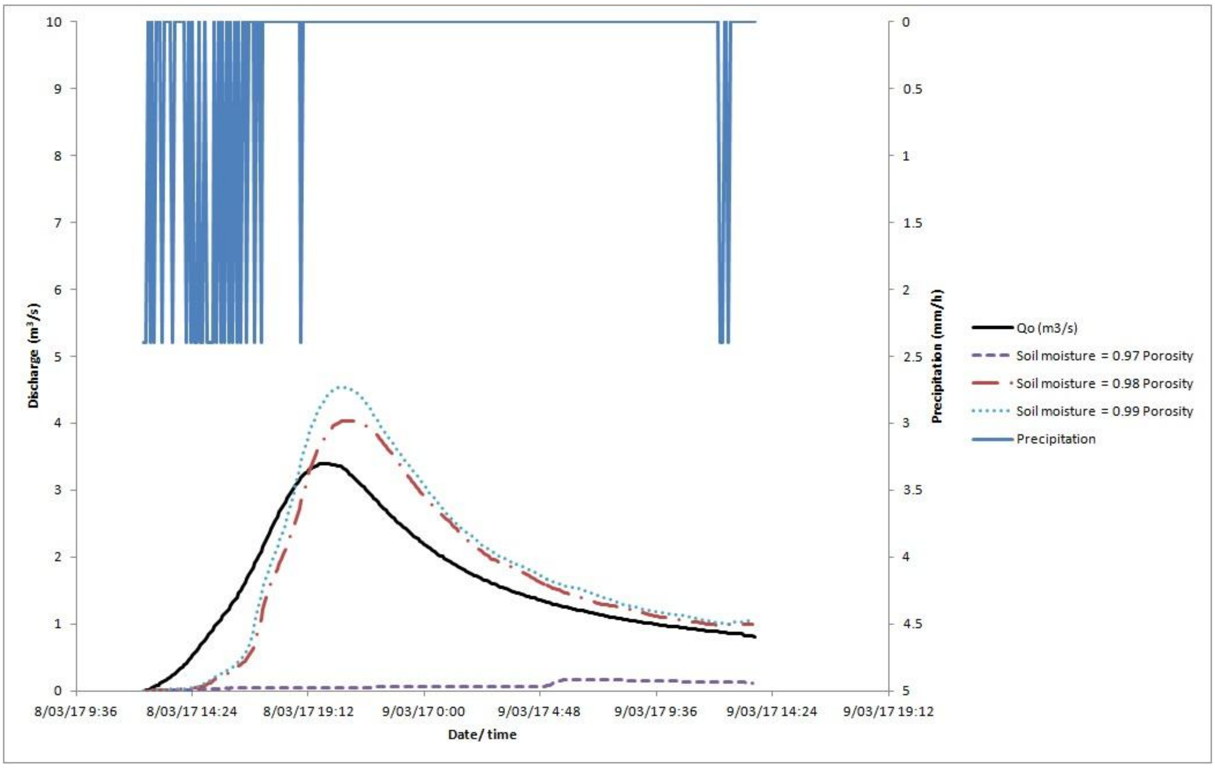

Figure 16: Figure 16: Visual inspection of the simulated discharges in comparison to the in-situ discharges for the validation of the calibrated parameters

6.3. Sensitivity analysis

Figure 17 illustrates the variation in model performance in response to a systematic 20% variation in the Ks, θ, Manning's n channel and Manning's n slopes during the sensitivity analysis of the model. The sensitivity analysis is carried out on the calibrated parameter set by varying the Ks, θ, Manning's n channel and Manning's n slopes one parameter at the time. The Manning's n channel and Manning's n slopes are varied at the same time during the sensitive analysis of the Manning's n. The generated NS ranges from -5.7 to 0.91 with the systematic 20% variation of the Ks. A small decrease of the Ks greatly increases the simulated peak discharge and hence the model performance while a 20% increase in the Ks significantly lowers the simulated peak greatly influencing the model performance. This shows that the Ks is a sensitive parameter. The generated NS ranges from -103.2 to 0.91 with the systematic 20% variation of the θ. The initial soil moisture conditions greatly influence the soil storage capacity by regulating the infiltration rate and hence the discharge simulated greatly influencing the model performance. The results of the sensitivity analysis indicate that soil moisture is a sensitive parameter.

A systematic 20% variation of the Manning's n channel and Manning's n slopes generates NS value ranges from 0.72 to 0.91. The simulated peak discharge and total volume is not altered considerably with the 20% variation of the Manning's n channel and Manning's n slopes but only shifts the time to peak. The Manning's n channel and Manning's n slopes are therefore not sensitive parameters.

The model sensitivity analysis and performance results are comparable to results by other research carried out using LISEM for flood modeling. Most studies report a lag in the time-to-peak in the simulated discharge measurements with the peak discharges slightly varying from the in-situ discharge measurements.

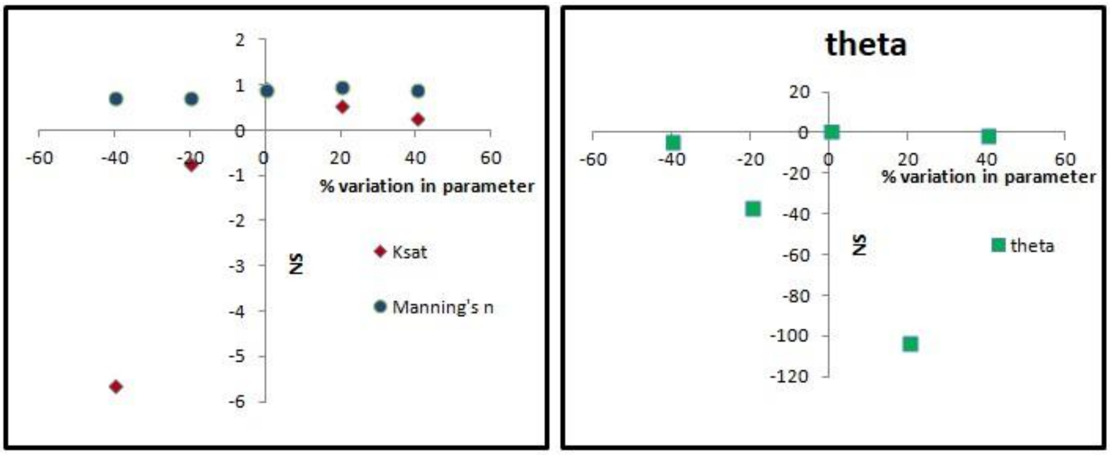

Figure 17: Model performance sensitivity to 20% variation of the parameters

6.4. Resilience to extreme rain events

The calibrated parameter set is used for simulation of the extreme rain events. The storm event corresponding to the calibration period is multiplied by a multiplication factor of 2, 3, 4 and 5 to simulate rainfall with return periods of twice in one year, once in 2 years, 10 years, and 50 years respectively. Simulations are run for dry soil conditions, the antecedent soil moisture for the calibrated storm event and saturated soil moisture conditions to assess the resilience of the Voltherbeek to flooding during extreme rains events. An assessment is then made of the flood extents and depths to identify flood-prone areas.

6.4.1. Flood scenarios for dry soil conditions

Table 12 summarises the catchments response during extreme rain events for dry soil conditions highlighting the interception, infiltration, surface storage, and runoff depths in mm of the total rainfall received. Figure 18 illustrates the flood extents and depths for rainfall with return periods of twice in one year, once in 2 years, 10 years, and 50 years for dry soil conditions. Rainfall with a return period of twice in one year produces no flood in the catchment. Rainfall with a return period of 2 years inundates small sections of the farms on the northeast region of the catchment with water level heights of 0.25 m to 0.5 m. Rainfall with a return period of 10 years inundates small sections of farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m. Rainfall with a return period of 50 years inundates a larger section of farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m. The regions on the flood extent maps with 1 m to 1.25 m depth are not inundated areas but stream sections.

Table 12: Summary of the catchments response to extreme rain events for dry soil conditions

Return period (Years)	Total rain (mm)	Max. intensity (mm/h)	Total Discharge (mm)	Total interception (mm)	Total infiltration (mm)	Surface storage (mm)	Overland flow (mm)	Channel storage (mm)	Total outflow (mm)
Twice in 1yr	33.2	36	1.1	0.1	31.4	0	0	0	1.1
2	49.8	54	5.4	0.1	38.9	0	1.5	0	0
10	66.4	72	10	0.1	42.9	0	1	0	10
50	83.0	90	15.5	0.1	45.4	0	2.4	0.1	15.5

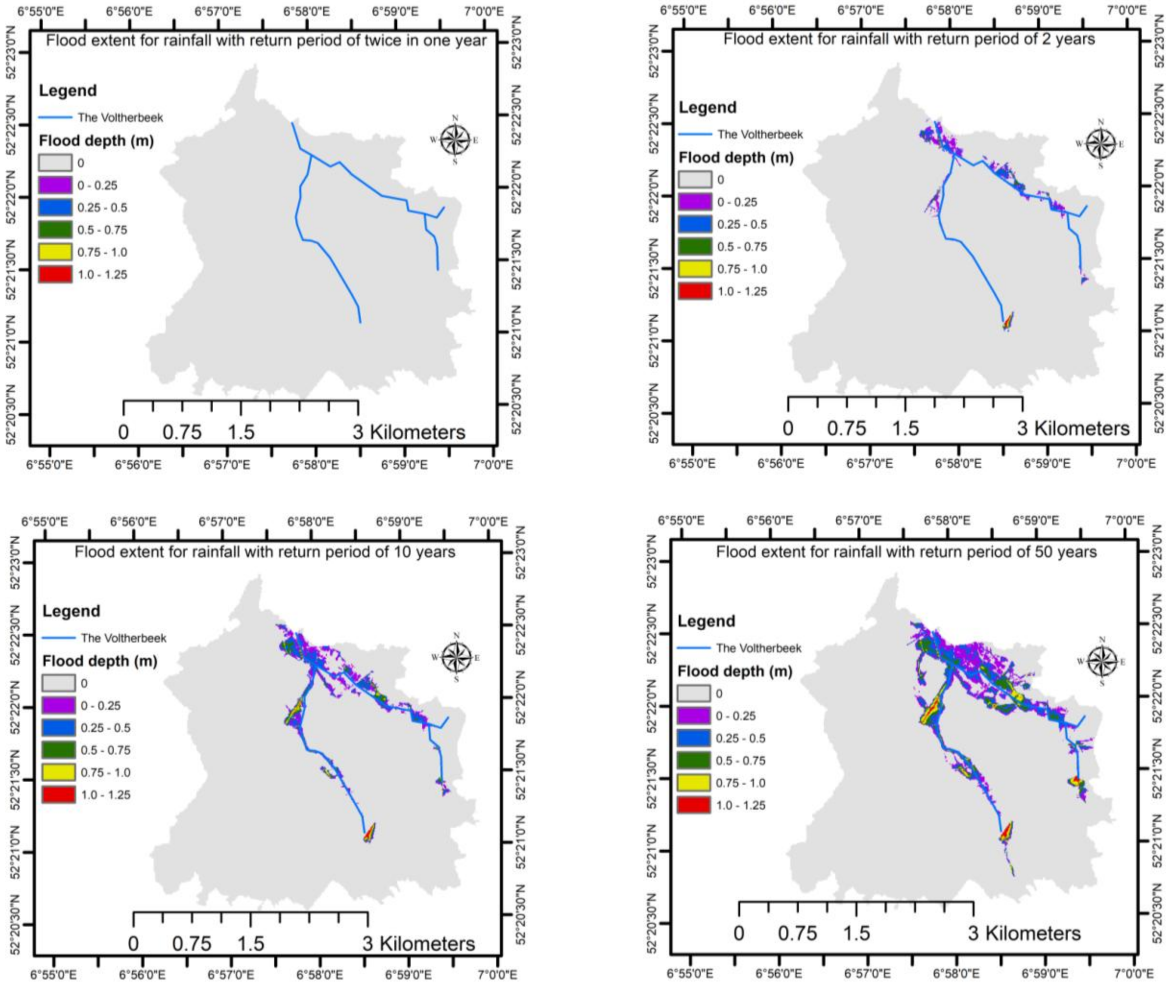

Figure 18: Flood extents and depths during extreme rainfall for dry soil conditions

6.4.2. Flood scenarios for wet soil conditions

Table 13 summarises the catchments response during extreme rain events for wet soil conditions highlighting the interception, infiltration, surface storage, and runoff depths in mm of the total rain received. Figure 19 illustrates the flood extents and depths for rainfall with return periods of twice in one year, once in 2, 10, and 50 years for wet soil conditions. Rainfall with a return period of twice in one year, once in 2 years, and 10 years produce a similar trend of inundations of small sections of the farms on the northeast region of the catchment with water level heights of 0.25 m to 0.5 m. Rainfall with a return period of 10 years inundates small sections of farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m. Rainfall with a return period of 50 years inundates a larger section of farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m. The regions on the flood extent maps with 1 m to 1.25 m depth are not inundated areas but stream sections.

Table 13: Summary of the catchments response to extreme rain events for wet soil conditions

Return period (Years)	Total rain (mm)	Max. intensity (mm/h)	Total Discharge (mm)	Total interception (mm)	Total infiltration (mm)	Surface storage (mm)	Overland flow (mm)	Channel storage (mm)	Total outflow (mm)
Twice in 1yr	33.2	36	5.1	0.1	19.2	0.1	1.4	0	5.1
2	49.8	54	10	0.1	20.8	0.1	0.8	0.1	10
10	66.4	72	15.6	0.1	21.7	0.2	2.5	0.1	15.6
50	83	90	20.9	0.1	22.1	0.2	3.5	0.1	20.9

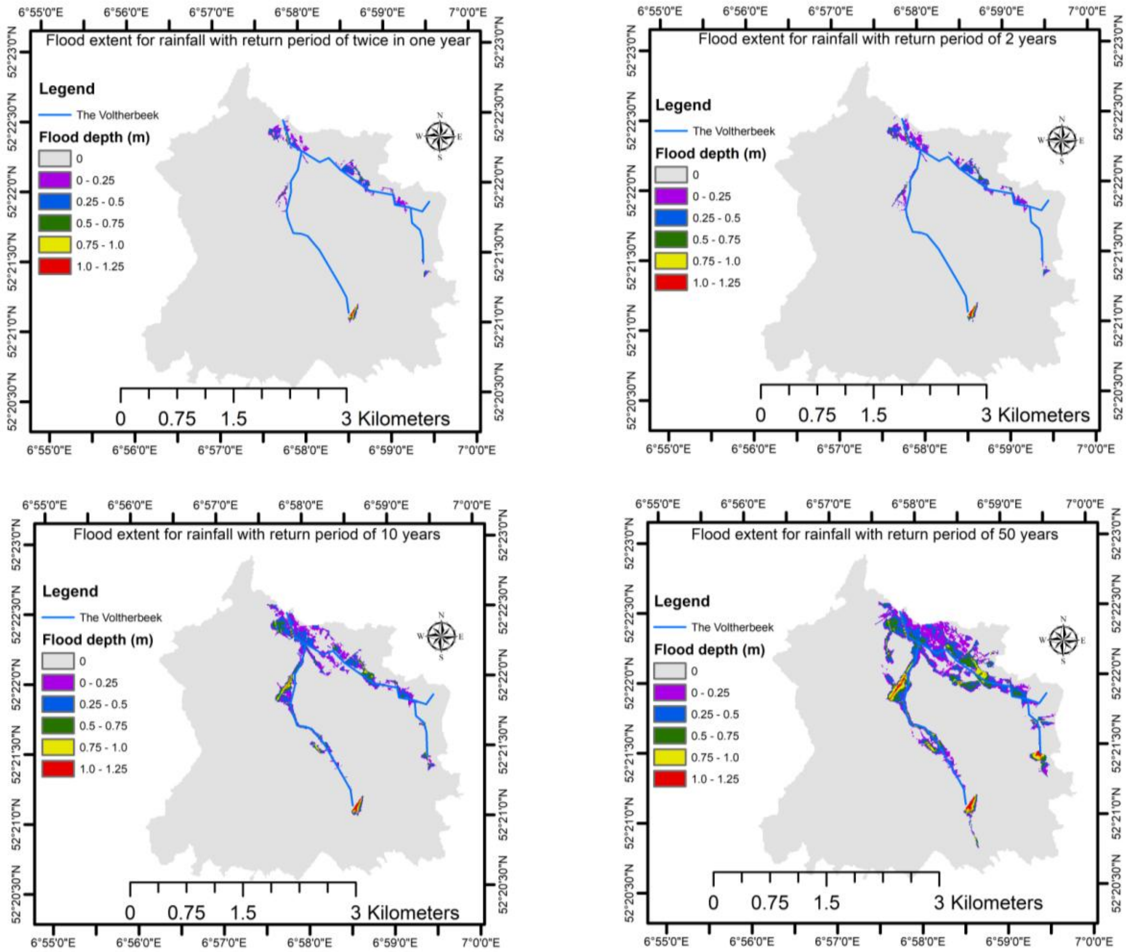

Figure 19: Flood extents and depths during extreme rainfall for wet soil conditions

6.4.3. Flood scenarios for saturated soil conditions

Table 14 summarises the catchments response during extreme rain events for saturated soil conditions highlighting the interception, infiltration, surface storage, and runoff depths in mm of the total rain received. Figure 20 illustrates the flood extents and depths for rainfall with return periods of twice in one year, once in 2 years, 10 years, and 50 years for saturated soil conditions. Rainfall with a return period of twice in one year inundates small sections of the farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m. Rainfall with a return period of 2 years inundates slightly larger area of the farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m as compared to the area of inundated areas produced by the rain with a return period of once in two years. Similarly, rainfall with a return period of 10 years inundates a larger area of the farms on the northeast region of the catchment with water level heights of 0.25 m to 0.75 m as compared to the area of inundated areas produced by the rain with a return period 2years. Rainfall with a return period of 50 years inundates a much larger area of the catchment. The farms on the northeast region of the catchment are inundated with water level heights of 0.25 m to 0.75 m with sections of the areas south-west and north-west of the catchment inundated with water level heights of 0.25 m to 0.75 m. The regions on the flood extent maps with 1 m to 1.25 m depth of inundation are stream sections. The regions on the south-west of the flood extent map with a return period of 50 years with 1 m to 1.25 m depth of inundation are permanent water bodies.

Table 14: Summary of the catchments response to extreme rain events for saturated soil conditions

Return period (Years)	**Total rain (mm)**	**Max. intensity (mm/h)**	**Total Discharge (mm)**	**Total interception (mm)**	**Total infiltration (mm)**	**Surface storage (mm)**	**Overland flow (mm)**	**Channel storage (mm)**	**Total outflow (mm)**
Twice in 1yr	33.2	36	10.5	0.1	0	0.8	1.1	0.1	10.5
2	49.8	54	16.7	0.1	0	0.8	2.6	0.1	16.7
10	66.4	72	22.1	0.1	0	0.7	3.7	0.2	22.1
50	83	90	25.9	0.1	0	0.8	35.8	0.3	25.9

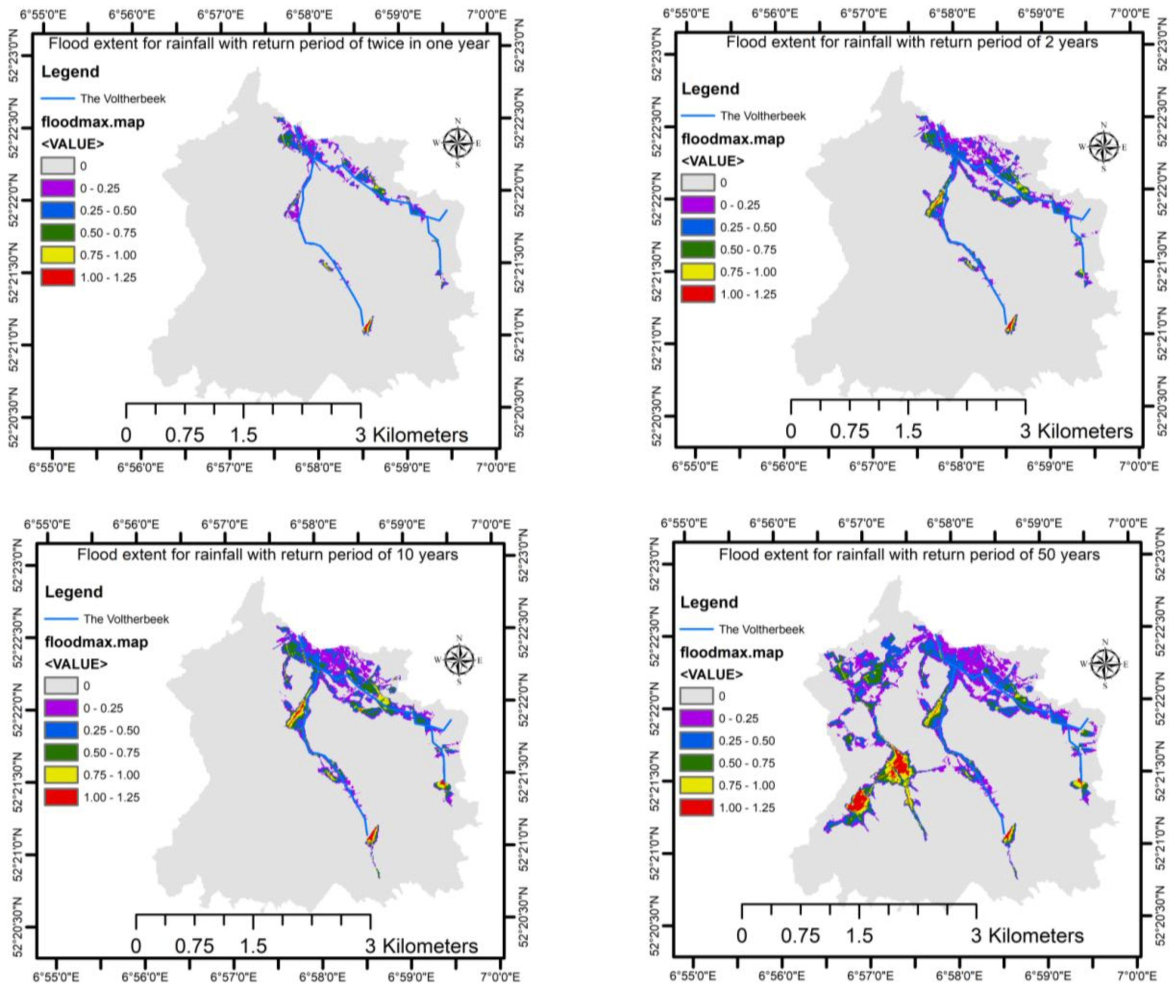

Figure 20: Flood extents and depths during extreme rainfall for saturated soil conditions

7. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this research is to assess the resilience of the Voltherbeek to flooding during extreme rain events by assessing the catchment's response to rainfall-runoff production and mapping the flood extents and depths. This chapter summarises the research findings and recommendations according to the specific objectives and research questions posed.

The calibration of LISEM on generated peak discharge from in-situ water levels and antecedent soil moisture measurements generates an NS of 0.9 and RV_E of +5%. An NS of between 0.9 and 1 indicates an extremely well performing model while an RV_E of between +5% and -5% indicates a well performing model. LISEM validation on an independent storm event generates an NS of 0.62 and an RV_E of +19%. An NS of between 0.6 and 0.8 indicates the model performs well. Based on the calibration and validation results, it can be concluded that the calibration of LISEM on the generated peak flows from in-situ water levels and antecedent soil moisture measurements yields a well performing model. The research findings show that the model simulations can be reliably applied in the Voltherbeek catchment for identification of flood-prone areas on condition that the model parameterization is objectively undertaken and the sensitive parameters are optimized. Based on the calibration and validation results it can also be concluded that each storm event generates run-off differently depending on the rainfall intensities and duration. The initial soil moisture and catchment land cover characteristics also influence the run-off production process. It is therefore important to assess the land cover characteristics during a storm event for effective parameterization and reliable model performance.

An analysis of the sensitive parameters by varying the saturated hydraulic conductivity, soil moisture, Manning's n channel and Manning's n slopes shows that small variations in the Ks influences the peak discharge and total discharge volume greatly influencing the model performance. The soil moisture greatly influences the infiltration rate in turn regulating the runoff volumes generated and consequently the discharge volumes. Small variations in the soil moisture therefore greatly influence the overall model performance. On the other hand, a variation of the Manning's n slopes and Manning's n channel does not influence the total discharge volume by a great magnitude but shifts the time-to-peak. The study findings show that the Ks and θ are sensitive parameters and have to be optimized during model parameterization to attain reliable model performance and reliable flood extent and depth simulations. LISEM is not sensitive to the Manning's n channel and Manning's n slopes. However, the Manning's n channel and Manning's n slopes are important for matching the time-to-peak.

The analysis of the extreme rain events is based on the calibrated storm event with a total rainfall depth of 16 mm and maximum rainfall intensity of 18 mm h^{-1} recorded in the ITC rainfall gauging station. Based on the calibrated storm event, rainfall with a return period of twice in one year, once in 2 years, 10 years and 50 years have rainfall depths of 33 mm, 50 mm, 66 mm and 83 mm respectively. Based on the calibrated storm event, the maximum rainfall intensities for rainfall with return periods of twice in one year, once in 2 years, 10 years and 50 years are 36 mm h^{-1}, 54 mm h^{-1}, 72 mm h^{-1} and 90 mm h^{-1} respectively.

In dry soil conditions, between 0 and 2.4 mm of the total rainfall depth received produces runoff in the catchment during the extreme rain events. In wet soils between 1.4 mm and 3.5 mm of the total rainfall depth received produces runoff in the catchment during the extreme rain events. In saturated soils between 1.1 mm and 35.8 mm of the total rainfall received produces runoff in the catchment during the extreme rain events. During a rainfall event with a return period of 50 years 35.8 mm of the total rainfall received produces runoff. The results show that the runoff produced during extreme rain events for dry and wet soils are almost comparable. The results also show that rainfall with a return period of 50 years for saturated soil conditions produces the highest runoff. It can be concluded that the soil moisture content influences rainfall production in the catchment.

An evaluation of the flood extents and depths for the extreme rain events shows that under dry soil conditions, rainfall with a return period of twice in one year does not generate floods in the catchment. In dry soil conditions, rains with return periods of 2 years, 5 years and 10 years generate a maximum flood depth of 0.75 m on farms in the northeast region of the catchment. In wet and saturated soil conditions rains with return periods of twice in one year, once in 2 years, 10 years and 50 years generate maximum flood depths of 0.75 m on farms on the northeast region of the catchment. In saturated soil condition, the flooded area extent increases to the south-west and north-west regions of the catchment during a rainfall with a return period of 50 years. The study shows that the farms on the northeast region of the catchment are prone to flooding during each of the extreme rain events both for dry, wet and saturated soil conditions. It is therefore recommended that flood mitigation measures are undertaken in the Voltherbeek to safeguard the farms against flooding from extreme rain events.

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Script for generating LISEM input maps

```
#! --matrixtable --radians --lddin

binding
### input maps ###
DEM = dem.map; # digital elevation model
soilunit = soils.map; # main texture class units
riverwid = river.map; # stream channel width (m)
landunit = landuse.map; # land use types
rainfall_tss = rain.tss; # rainfall data in mm/day
ETP_tss = ETpdaily.tss; # Potential evapotranspiration in mm/day
soildata_tbl = soils.tbl; # 1 = ksat, 2=pore, 3=field capacity,
landusedata_tbl = landdata.tbl; # landcover properties

ksat_cal = scalar(1); # OVERALL factor multipled with Ksat affecting all fluxes

### output maps ###
# basic topography related maps
Ldd = ldd.map; # local Drain Direction surface runoff
grad = grad.map; # slope, sine!
id = id.map; # pluviograph influence zones (1-n)
outlet = outlet.map; # location main outlet
landuse = landunit.map; # land units (1-n)

# vegetation maps
Cover= per.map; # cover fraction (-)
lai= lai.map; # leaf area index (m2/m2) for interception storage
cropheight= ch.map; # plant height in m, for erosion, not used

# Green and Ampt infiltration maps
ksat = ksat1.map; # sat hydraulic conductivity (mm/h)
pore = thetas1.map; # porosity
thetai = thetai1.map; # initial moisture content (-)
psi = psi1.map; # suction unsat zone (cm)
soildep = soildep1.map; # soil depth (mm), assumed constant here
theta_fc = fieldcap.map; # field capacity (-)
theta_wp = wilting.map; # wilting point (-)
SoilMoisture = moist; # daily soil moisture maps (mm)
interception = intc; # daily interception (mm)
surfstor = ss;

# Surface maps
rr = rr.map; # surface roughness (cm)
mann = n.map; # mannings n ()

# channel maps
```

```
lddchan = lddchan.map; # channel 1D network
chanwidth = chanwidt.map; # channel width (m)
changrad = changrad.map; # channel gradient, sine
chanman = chanman.map; # channel manning (-)
chanksat = chanksat.map; # Ksat of the channel if it is not lined with concrete (mm/h)
chanside = chanside.map; # angle channel side walls, 0 = rectangular, 1 = 45o

# channel flooding maps
chandepth = chandepth.map; # channel depth (m), if 0 the channel will not flood (infinitely deep)
chanmaxq = chanmaxq.map; # maximum discharge (m3/s) in culverts located in channel
floodzone = floodzone.map; # potential flood zone
hmxInit = hmxinit.map; # initial flood level (m)
barriersc = barriers.map; # weir regulating flow

#output graphs
p_tss = pavg.tss; # average daily rainfall (mm)
ETpavg_tss = ETpavg.tss; # average daily ETp (mm)
intc_tss = Intcavg.tss; # average daily interception in canopy (mm)
inf_tss = INFavg.tss; # average daily infiltration (mm)
eta_tss = ETaavg.tss; # average daily ETa (evap and transp ftrom soil) (mm)
perc_tss = percavg.tss; # average daily percolation (mm)
RO_tss = roavg.tss; # average daily runoff (mm)
moisture_tss = moisture.tss; # average daily soil moisture (mm)
theta_tss = theta.tss; # average daily theta (-)
ETfact_tss = ETfactor.tss; # average daily ratio ETa/ETp
ETpcum_tss = ETpcum.tss; # average cumulative ETp (mm)
Pcum_tss = pcum.tss; # average cumulative rainfall (mm)
intccum_tss = intcum.tss; # average cumulative interception (mm)
ETacum_tss = ETacum.tss; # average cumulative ETa (mm)
PERCcum_tss = perccum.tss; # average daily cumulative percolation (mm)
INFcum_tss = infilcum.tss; # average cumulative interception (mm)
ROcum_tss = runoffcum.tss; # average cumulative runoff (mm)
wbal_tss = wbal.tss; # water balance error in mm average per cell

areamap
DEM;

timer
1 1 1;

initial

mask = mask.map; #DEM/DEM;
nrCells = maptotal(mask); # nr cells in catchment
dx = celllength();

### CHANNEL MAPS ###
report DEM = DEM;
```

```
report Ldd = lddcreate(DEM,1e20,1e20,1e20,1e20); # create a channel network
report grad = max(sin(atan(slope((DEM)*mask))), 0.005)*mask; # sine gradient (-),
make sure slope > 0.005
report ws.map=catchment(Ldd, pit(Ldd));
asp = scalar( aspect(DEM));
shade = cos(15)*sin(grad)*cos(asp+45) + sin(15)*cos(grad);
report shade.map = (shade-mapminimum(shade))/(mapmaximum(shade)-
mapminimum(shade));
#### not used in lisem
report ups.map = accuflux(Ldd,1)*mask; # for display, a color map with the flow
network
report chanwidth = scalar(if (riverwid ne 0, 2)); # channel width (m)
rivfrac = riverwid/celllength(); # fraction of riverwidth in a stream gridcell, 0 elsewhere
report chanmask = if(riverwid ne 0, 1)*mask; # create missing value outside channel
report lddchan = lddcreate(if(chanmask eq 1,DEM),1e20,1e20,1e20,1e20); # create a
channel network
report outlet = cover(scalar(pit(lddchan) ne 0),0)*mask;
report outpoint = cover(scalar(pit(lddchan)),0)*mask;
mainout = outlet;
changrad = max(0,sin(atan(slope(chanmask*DEM))));
report changrad = windowaverage(changrad, 5*celllength())*chanmask; # channel
slope, copy surface but smooth to avoid abrupt changes
report chanman = chanmask*0.05; # fairly rough channel with vegetation
report chanside = chanmask*scalar(0); # rectangular channel
report chandepth = min(1.5,max(1.5,chanwidth/8)); # channel depth approx 1.5m

### SOIL MAPS ###
report ksat = lookupscalar(soildata_tbl, 1, soilunit);
Ksat = ksat_cal * ksat * 24 * mask; #convert to mm/day, 24 h timestep
pore = lookupscalar(soildata_tbl, 2, soilunit); # read porosity in column 2 (-)
theta_fc = lookupscalar(soildata_tbl, 3, soilunit); # field capacity in column 3 (-)
report pore = pore * mask; # porosity (-)
theta_wp = lookupscalar(soildata_tbl, 6, soilunit); # wilting point in column 4 (-)
psdi_param = lookupscalar(soildata_tbl, 4, soilunit);#brooks corey parameter, used for
percolation, data from wet_spa model page 49 manual
# pore size distribution index
theta_fc = theta_fc * mask; #field capacity (-)
report soildep = 2000.0 * mask; # soil depth 2 m everywhere
theta = theta_fc; # initialize soil moisture
report thetai = theta; #save initial moisture for mass balance
SoilMoisture = theta*soildep; # initial soil moisture in mm
SMinit = SoilMoisture; # save initial moisture for water balance

# defaults
# some default values
report D50 = 20 * mask; # fine material
report cohsoil = 8 * mask; # strong clay aggregates
report aggrstab = 12 * mask; # aggregate stability
report chancoh = 20 * mask; # strong channels?
```

```
report litter = scalar(0.5);
report compfrc = 0 * mask; # crust fraction assumed zero
report crustfrc = 0 * mask; # crust fraction assumed zero
report hardsurf = 0 * mask; # hard fraction assumed zero
report drumstore = 0 * mask; # storage of rainwater assumed zero
report roadwidt = 0 * mask; # factored in land cover hence assumed as zero here
report grasswid = 0 * mask; # factored in land cover hence assumed as zero here
report id = mask; # factored in land cover hence assumed as zero here
report hmxInit = 0 * mask; # no finittial flood
report bufferid = 0 * mask; # no buffer
report buffervol = 0 * mask; # no buffer
report housecover = 0 * mask; # factored in land cover hence assumed as zero here
report flowbarrierindex = 0 * mask; # assumed non
report flowboundary = 1 * mask; # assumed free outflow
report chanmaxq = 0 * mask;
report chanksat = 0 * mask;
report floodzone = 1 * mask; # assumed equal flooding

### initialize totals ###
ETa = 0 * mask;
Perc = 0 * mask;
Infil = 0 * mask;
ETacum = 0;
ETpcum = 0;
Pcum = 0;
Pzcum = 0;
percum = 0;
intccum = 0;
infilcum = 0;
Tacum = 0;
Eacum = 0;
infcum = 0;
rocum = 0;
canstore = 0;
surfstor = 0;
interception = 0;

dynamic
P_stat = timeinputscalar(rainfall_tss, nominal(mask)); # get the rainfall values at the stations
idp = 2;
Pinterpol = inversedistance(mask gt 0, P_stat, idp, 0, 0); # inverse distance interpolation with
power 2
# has no effect when there is only one station
report P = Pinterpol*mask; # restrict to area mask
report p_tss = maptotal(P)/nrCells; # write a graph of the average daily rainfall
Pcum = Pcum + P; #calculate cumulative P for outut
report Pcum_tss = maptotal(Pcum)/nrCells; # write a graph of the average cumulative rainfall
ETp = timeinputscalar(ETP_tss, nominal(mask)); # read potential evapotranspiration from a
file and give the whole area that value
```

# ETp is the potential evapotranspiration (in mm) report ETpavg_tss = maptotal(ETp)/nrCells;
ETpcum = ETpcum + ETp;
report ETpcum_tss = maptotal(ETpcum)/nrCells;

LAND COVER MAPS
report Cover = lookupscalar(landusedata_tbl, 4, landunit)*mask; # canopy cover
lai = ln(1-min(Cover, 0.99))/-0.4; #LAI of plants inside grid cell (m2/m2)
report lai = if(Cover gt 0, lai/ Cover, 0);
Smax = max(0, 0.2856*lai); # interception storage in mm
report Smax = Smax*(1-rivfrac); # no canopy storage in river
report cohplant = Cover * 4 * mask; # additional plant root strength
interception = interception + P; # wetting of the canopy and effective rainfall Pe
interception = min(Smax, interception); # cannot be more than the canopy storage capacity smax in mm
intccum = intccum + interception; # report cumulative interception
report intccum_tss = maptotal(intccum)/nrCells; # graph with spatial average cumulative interception (mm)
report cropheight = lookupscalar(landusedata_tbl, 3, landunit)*mask; # landcoverheights
Pe = max(P - interception, 0); # effective rainfall not be less than 0
ETptemp = max(0, ETp - interception); #drying of the canopy with ETp and the remaining ETp
#temporary ETp by subtracting the interception, cannot be less than 0
interception = max(0, interception - ETp); #decrease the interception because of evaporation, cannot be less than 0
ETp = ETptemp; # potential evaporation is now the ETp minus what was used for interception evaporation
dthour = 4; # dthour is the duration of rainfall in a day
# it is used in infil/runoff fraction,

SOIL SURFACE MAPS###
report rr = max(lookupscalar(landusedata_tbl, 1, landunit) * mask, 0.01); # micro relief, random roughness (=std dev in cm)
report mann = lookupscalar(landusedata_tbl, 2, landunit)*mask; # Manning's n (-)
report infildepth = min(400, soildep);
store = max(0, infildepth*(pore-theta)); # effective soil storage above GW in mm
Infilcap = min(store, ksat*dthour); #infiltration capacity in mm per day (24 hours)
Infilcap = (1-rivfrac)*Infilcap; # infil is smaller in cells with river channel, no infil in rivers
fract = if (Pe gt 0, exp(-Infilcap/Pe), 0); # fraction based on MMF (Shrestha and Jetten, 2017)
fract = if (riverwid gt 0, 1.0, fract) * mask; # runoff fraction is 1 in river cells, so no storage
surfstor = surfstor + Pe; # max runoff and rainfall is
runoff = accufractionflux(Ldd, surfstor, fract); # effective rainfall + surface storage downstream
surfstor = accufractionstate(Ldd, surfstor, fract)*mask; # surfstorage in mm
Infil = if (surfstor gt Infilcap, Infilcap, surfstor); # infiltration is the smallest of infilcap(store) and surface store

```
surfstor = max(0, surfstor-Infil); # decrease surface storage with infiltrated water (in mm)
report inf_tss = maptotal(Infil)/nrCells; # daily infiltration avg per cell mm

infcum = infcum + Infil;
report INFcum_tss = maptotal(infcum)/nrCells; # cumulative infiltration in mm

runoffout = maptotal(if(outlet eq 1, runoff, 0))/nrCells;
rocum = rocum + runoffout;
report RO_tss = runoffout;
report ROcum_tss = rocum; # total runoff lost from the catchment in mm, avg per cell

### actual evapotranspiration###
ETpoint = theta_wp + (theta_fc - theta_wp)*0.667; # actual evapotranspiration ETa linear
with soil moisture content (mm)
ETfactor = 1/(1+(theta/ETpoint)**6); # variation on curve based on matrix potential
report ETfact_tss = maptotal(ETfactor)/nrCells; # average ETa/ETp factor
# FAO crop factor to account for specific crops or vegetation, 1.0 for grass
Ta = ETp * ETfactor * Cover; # actual transpiration (mm)
Ea = ETp * ETfactor * (1-Cover) * (theta/pore); #actual soil evaporation (mm)
Ta = (1-rivfrac)*Ta;
Ea = (1-rivfrac)*Ea + rivfrac * ETp;
ETa = Ea + Ta; # ETa sum of the Evap and Transp
ETa = min(ETa, SoilMoisture); # cannot be more than soil moisture present
report eta_tss = maptotal(ETa)/nrCells; # graphs with average and cumulative average ETa of
all cells
ETacum = ETacum + ETa;
report ETacum_tss = maptotal(ETacum)/nrCells;

### INFILTRATION MAPS for 1 layer GREEN & AMPT###
report psi = lookupscalar(soildata_tbl, 4, soilunit)*mask; # read column 3 of soil table
psi_par = lookupscalar(soildata_tbl, 7, soilunit)*mask; # read column 3 of soil table
theta_e = if (theta gt 0.5*theta_fc, theta/pore, 0);
bcp = (2+3*psi_par)/psi_par; #brooks corey parameter, used for percolation
Perc = Ksat * theta_e**bcp; # assume dH/dz = 1: percolation depends on unsaturated hydr
conductivity
# based on Brooks Corey equation
Perc = min(Perc, SoilMoisture); # percolation less than available water
report Perc = (1-rivfrac)*Perc; # no percolation in channel part of river cells
report perc_tss = maptotal(Perc)/nrCells; # graph with average spatial percolation
percum = percum + Perc;
report PERCcum_tss = maptotal(percum)/nrCells; # cumulative percolation

SoilMoisture = SoilMoisture + (Infil - ETa - Perc);
SoilMoisture = max(0, SoilMoisture); # cannot be less than zero
theta = if (soildep gt 0, SoilMoisture/soildep, pore); # average soil moisture content
(cm3/cm3) = (-), cannot be more that porosity
theta = if (theta lt 0, 0, theta); # cannot be less than 0
```

```
report theta = if (theta gt pore, pore, theta); # cannot be less than theta_r and more than porosity
report SoilMoisture = theta * soildep; # calc new soil moisture based on adjusted theta (mm)
report theta_tss = maptotal(theta)/nrCells;
report moisture_tss = maptotal(SoilMoisture)/nrCells; # graph with average theta of all cells

dMoisture = soildep*(theta - thetai); # change in moisture between start and end
allout = intccum + ETacum + percum + rocum;
WB = (Pcum - allout - dMoisture)/Pcum; # mass balance error
report wbal_tss = maptotal(WB)/nrCells;

### Ground water###
dx = celllength();
# basic directions for groundwater movement
ldd2 = ldd(2*mask); #south, row + 1
ldd4 = ldd(4*mask); #west, col - 1
ldd6 = ldd(6*mask); #east, col + 1
ldd8 = ldd(8*mask); #north, row - 1
z = (DEM-mapminimum(DEM)+1) - soildep/1000; # gravity potential equals dem of bedrock, soildepth is in mmm, convert to m
# assume more averaged (smooth) subsurface DEM over which GW flows
GWDepth = 600.0 * mask;
GWDepth = GWDepth + if(theta lt pore, Perc/(pore-theta), 0);
GWDepth = min (GWDepth, soildep);
h = GWDepth/1000; # add percolation amount to GW depth (convert to height in mm)
H = h + z; # total hydraulic potential in m
dHdL2 = sin(atan((upstream(ldd2, H)-H)/dx));
dHdL4 = sin(atan((upstream(ldd4, H)-H)/dx));
dHdL6 = sin(atan((upstream(ldd6, H)-H)/dx));
dHdL8 = sin(atan((upstream(ldd8, H)-H)/dx));
# sine of potential differences between central cell
# dH/dx = tan so atan(dH/dx) is angle
# and cells in 4 directions EW ans NS (in m)
h2 = (h+upstream(ldd2, h))/2.0;
h4 = (h+upstream(ldd4, h))/2.0;
h6 = (h+upstream(ldd6, h))/2.0;
h8 = (h+upstream(ldd8, h))/2.0;
dQ = Ksat/1000 * dx * (h2*dHdL2 + h8*dHdL8 + h4*dHdL4 + h6*dHdL6); # sum of all fluxes in m3/day, ksat in m/day, divide by 1000
SumGWbefore = maptotal(h); # sum GW before movement
h = h + 5*dQ/(dx*dx); # add in/out flow to the cell in m
h = max(0, min(h, soildep/1000)); # h must between 0 and soildepth: 0 < h < soildepth

### mass balance correction ###
SumGWafter = maptotal(h); # sum GW after the movement
errorh = (SumGWbefore - SumGWafter)*mask; #total mass balance error in GW depth (before - after)
```

```
wetcells = maptotal(scalar(h gt 0))*mask; # calc which cells have GW
h = h + if(h gt 0, errorh/wetcells, 0); # smooth out the error over all wet cells
h = max(0, min(h, soildep/1000)); # correct again: h must between 0 and soildepth: 0 < h < soildepth
SumGWafter = maptotal(h);
report error.tss = if (SumGWbefore gt 0.001,(SumGWbefore - SumGWafter)/SumGWbefore,0); # report any remaining error in the mass balance

### mass balance correction ###
GWDepth = h*1000; # saturated zone converted from m back to mm for comparison with the other fluxesin the model
margin = 200;
GWDepth = max(0, min(GWDepth, soildep - margin)); # confine groundwater between 0 and a dpeth of margin form the surface
GWloss = if(GWDepth gt 300, 0.035*GWDepth, 0); # subtract a loss when GWDepth is above a threshold
GWloss = min(GWloss, GWDepth); # can not be more than there is
report GWDepth = GWDepth - GWloss;#/theta_s; # lower the GW with GWloss each timestep
```