Master's Thesis
TVVR 20/5021

Application of HEC-HMS modelling on River Storån

Model evaluation and analysis of the processes by using soil moisture accounting loss method

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Box 118
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Water Resources Engineering
TVVR 20/5021
ISSN 1101-9824

Lund 2020
www.tvrl.lth.se

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English title	Application of HEC-HMS modelling on River Storån
Author	Pooja Makki Vijayaprakash
Supervisor	Magnus Persson
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Examiner	Magnus Larson
Language	English
Year	2020
Keywords	River Storån, HEC-HMS, SMA, streamflow, baseflow, evapotranspiration

Acknowledgements

Firstly, I am grateful to Lund University for giving me an opportunity to study and extend my horizons both academically and personally. It has been a great experience learning from the amazing teaching faculty from the department of Water Resource Engineering. I will cherish it all throughout my life.

I would like to express my sincere gratitude to my supervisor Magnus Persson and my co-supervisor Clemens Klante for being patient and guiding me through the completion of my thesis. I truly appreciate your encouragement and support. I would like to also thank Swedish Water Research for allowing to use their office for work.

Lastly, I would like to thank my family and friends for being my pillar of support at times of doubt.

Abstract

River Storån, a major tributary of Lake Bolmen which is a source of fresh water to Skåne county of Sweden is found to alter the colour of water in the lake due to the presence of natural organic matter. Hence it is of utmost importance to study the river to understand the dynamics of generation and flow of water from the river to the lake. This is done by application of a hydrological modelling system called HEC-HMS (version 4.3) developed by Hydrologic Engineering Centre**,** US Army Corps. River Storån is modelled using soil moisture accounting loss method, a method chosen for simulations run for a long period of time. During the application, data collected are assembled and input into the model components of HEC-HMS. Later the model is calibrated from 2005 to 2010 followed by optimization and validation from 2011 to August 2019.

The results obtained showed that the model underestimated the observed flow over the years and the reasons for underestimation was attributed to three factors, namely the climatic conditions, geological conditions and topological conditions. The temperature being an important climatic condition influenced processes like snowmelt and evapotranspiration and due to its inaccuracy, the model failed to recognise the type of precipitation falling specially during winter and spring. This led to the model generating low flow whenever the temperature went below 0°C. Further the generalization with respect to soil characteristics and depth led to quick response of the model to the precipitation which resulted in the simulated flow being more dependent on baseflow than on surface flow. Lastly, the exclusion of wetlands and small water bodies across the basin disregarded its impact on the process of evapotranspiration over the years.

Through the model evaluation it was found that the RSR, NSE and Pbias value of both calibration and validation was found be same i.e., 0.9, 0.2 and -1% respectively. The PEPF was found to be 18% and 16% for calibration and validation and PEV was found to be 1% and -3% respectively. Although the model evaluation does not meet the expected value it is found to be satisfactory as the model successfully generates total volume, peak discharge and date of peak discharge very close to the expected value. This was followed by a discussion on the limitations of the model and recommendations to overcome it.

The hydrological model HEC-HMS application to River Storån did not give the expected result but was found to work well for the areas which is prone to snowfall and heavy precipitation all through the year. The model is user friendly and is found compatible with Arc GIS which makes the parameterization easy. Further research and study is highly recommended to upgrade the model for better efficiency of the model.

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Abbreviation

ATI	Antecedent Temperature Index
CLMS	Copernicus Land Monitoring Service
DEM	Digital Elevation Model
ET	Evapotranspiration
GW	Groundwater
HEC-HMS	Hydrological Modelling System-Hydrological Modelling System
MAP	Mean Areal Precipitation
NSE	Nash-Sutcliffe Efficiency
Pbias	Percentage Bias
PEPF	Percent Error in Peak Flow
PEV	Percent Error in Volume
RSR	RMSE-Observations Standard deviation Ratio
SGU	Sveriges geologiska undersökning
SMA	Soil Moisture Accounting
SMHI	Swedish Meteorological Hydrological Institute
SWE	Snow Water Equivalent
USGS	U.S. Geological Survey

1.Introduction

1.1 Background

According to USGS water is an important element of hydrological cycle and precipitation is the main source of water. The hydrological cycle (water cycle) is a complex process where the precipitation falling is evaporated and transpired from land, water bodies and vegetation and when the precipitation exceeds the water storage capacity of vegetation it runs down the plant bodies and joins the precipitation that directly fell onto the land. Depending on the surface inundations and soil properties the water either infiltrates or flows into the stream channel as overland flow (surface runoff). The water that infiltrates the ground remains in partially saturated soil layers for some time post which it is drawn by plants though capillary action or moves as inter flow. This inter-flow eventually joins the stream channel and results in the direct run-off. A part of this infiltrated water also percolates and joins the aquifers as groundwater. Though the water moves slowly in the aquifer (baseflow), over time it joins the stream channel. Thus, stream flow is a combination of all the above along with direct precipitation falling onto the water-body.

This knowledge about run-off and stream flow is used for several purposes like to understand the hydrological and hydraulic characteristics of water bodies or flood forecasting and responses or future water availability etc. However, most of the time neither the precipitation nor the stream flow data found are accurate or sufficient enough. In order to overcome this barrier physical models or hydrological/hydraulic models are used. A hydrological model is a conceptual model which uses mathematical equation to simulate run-off or total flow which helps one to understand the natural water cycle better (Feldman, 2000).

According to (Persson, 2011) Lake Bolmen acts as a major source of drinking water for central part of Scania, Sweden. It has three main tributaries namely Storån River, Lillån River and Lake Unnen. Over recent years the colour of the lake Bolmen has changed due to natural organic material (NOM). It was found that the colour of Lake Bolmen is correlated with the inflow from its major tributary, River Storån. Hence, in the current study an attempt is made to understand the hydrology of Storån river basin. In order to understand the mechanism involved, historic data pertaining to precipitation and discharge is used in a hydrologic model called Hydrologic Modelling System (HEC-HMS) to simulate the stream flow. This model is computed for a time period of 14 years spanning from 2005 to August 2019. The results are obtained and the model is evaluated to measure the performance.

1.2 Aims and Objectives:

The main aim of this study is to apply the hydrological model, HEC-HMS to River Storån and evaluate the model.

Objectives

- Application of HEC-HMS to River Storån using Soil Moisture Accounting loss method.
- Analyse the results and the possible processes and parameters influencing the result.
- Evaluate the model performance and recommend solutions to overcome the limitations found during the application of the model to the basin.

1.3 Methodology

Firstly, a study was done on the basin, its location, climatic condition and geology which was continued by a detailed literature study on the processes involved in HEC-HMS and soil moisture accounting loss method was chosen for the current basin. Later the data pertaining to meteorology, hydrology and geology of the basin was collected. The collected data was used to assemble the parameter which was used later in the program to calculate losses, transformation and define boundaries within the basin. Further, digital elevation model of the basin was downloaded and processed in Arc GIS 10.5.1. Once processed, the basin and stream characteristics were defined using HEC-GeoHMS to create HMS model files. This was imported into HEC-HMS software wherein all the parameters with respect to basin, meteorological and control specification components were entered and calibrated from the year 2005 to 2010. Upon calibration it was optimized and further validated from the year 2011 to August of 2019. Lastly the model was evaluated using statistical indices like RSR, NSE, Pbias, PEPF and PEV.

The results obtained after calibration and validation were analysed. A brief study was done on the processes influencing the model and the results. Later the limitations of the model were discussed and possible suggestions were recommended for future study.

2.Study Area

2.1 Geography

Storån river basin is located in the southern Sweden. It is the largest tributary contributing 40% of inflow to lake Bolmen located in Jonkoping county of Sweden. The basin along with Lake Bolmen is a part of much bigger basin called River Lagan which is considered to be one among the main 22 catchments in Sweden by SMHI. The river basin is found to be 630 km^2 in area and is in line with the Lagan's main channel to the east and Nissan to the west. The river begins with Österån and Västerån branching to join Långasjön lying few miles southwest of Skillingyard. Further flowing through Flaten and across the urban area of Hillestorp and Forsheda it reaches Hammargårdsviken, north of lake Bolmen (Figure 1). The largest tributary of River Storån is however river Havridaån which flows through Kulltorp and joins Storån at Bredaryd (Länsstyrelsen, 2006).

2.2 Meteorology

Sweden has four seasons namely, spring spanning from March to May, summer from June to August, fall/autumn from September to November and winter from mid-November/ December to February. The basin being a part of Jönköping county of Sweden has cold and temperate climate with an average annual temperature of 6.1°C. With an average temperature of 15.8°C and -3.0°C, July and January is considered to be the hottest and coldest month of the year respectively. The county receives around 615 mm of rainfall per year. The county receives lowest rainfall in the month of February which is about 31 mm and highest during July ranging up to 71 mm (Weather and Climate).

2.3 Geology

The basin belongs to Fennoscandia shield comprising of old crystalline rocks and metamorphic rocks. The Precambrian rocks found here is approximately 1750 -1900 years old and belongs to SW Swedish Gneiss province/Sveconorwegian Province. The geological evolution of the above-mentioned rocks started approximately 1.75 Ga ago (Gothian orogeny) and was metamorphosed at the time of Sveconorwegian orogeny about 1.1- 0.9 Ga ago (Sveriges geologiska undersökning).

The river basin is majorly occupied by forest (64%) followed by lakes (4%) and rest occupied by marshes and agricultural land (Tumdedo, 2010). Although the formation of soil in Sweden started 2.5 million years ago during quaternary geological age the soil type currently found in Sweden was formed during and after last ice age which ended 10000 years ago. The soil formed during ice age can be referred as glacial soil and the one formed later as post glacial soil. The ice sheets formed during ice age transported bedrock materials and old soil resulting in the formation of moraine which occupies 75% of the country. The moraine found in the study area are mainly composed of sand and silt. The eroded materials formed by melting of these ice sheets eventually led to the formation of glacial or post glacial sediments consisting of fine-grained soil. Post ice age the land submerged under the weight of several meters thick ice started to uplift, this resulted in the formation of several flat clay plains made of either silt or clay. Further the frost action led to the production of peatland consisting of organic matter. In areas where there is heavy rainfall the peat turns into curved domes called bog which uses rainfall as its only source of nutrition (Sveriges geologiska undersökning, 2020).

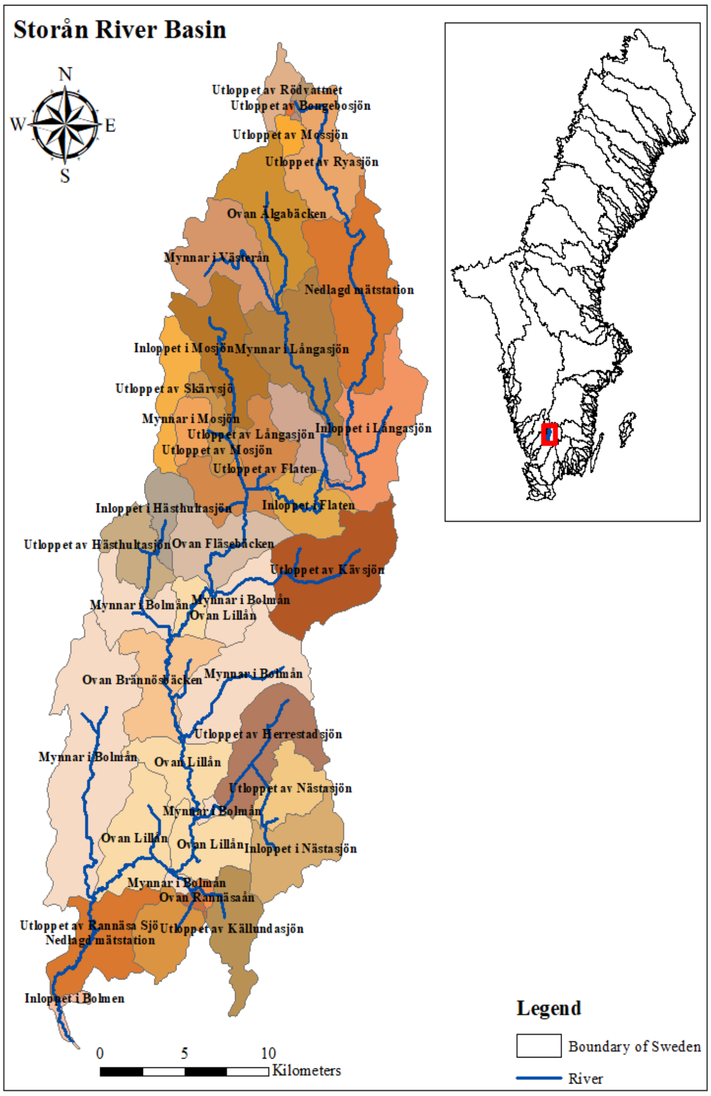

Figure 1: Overview of the study area (Storån River Basin)

3.Data Collection and Parameter Assembly

3.1 Data Collection

The terrain pre-processing starts with the reconditioning of Digital Elevation Model (DEM). DEM tiles of resolution 1-Arc (approximately 30 m) for the basin was downloaded from the United States Geological Survey (USGS) which were later mosaiced to form one tile. This DEM was clipped along the border of the basin using the polygon shapefile of the county downloaded from ESRI (Figure 2).

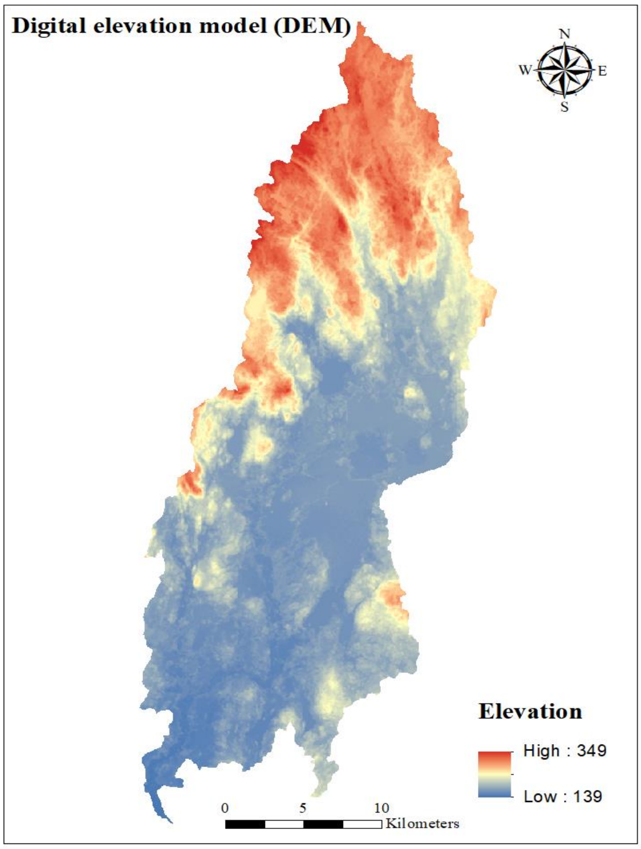

Figure 2: Projected DEM of the basin

Geological data of the basin like vegetation cover and type, soil characteristics, imperviousness were derived from the land cover files downloaded from Copernicus Land Monitoring Service (CLMS). Meteorological data pertaining to daily precipitation, daily temperature and monthly evapotranspiration of each station with their respective geographical locations were downloaded from Swedish Meteorological and Hydrological Institute (SMHI). Flow data from the outlet of basin, percentage of soil and type of soil for further reference for each sub-basin were downloaded from Vattenwebb of SMHI.

3.2 Parameter Assembly

3.2.1 Basin model

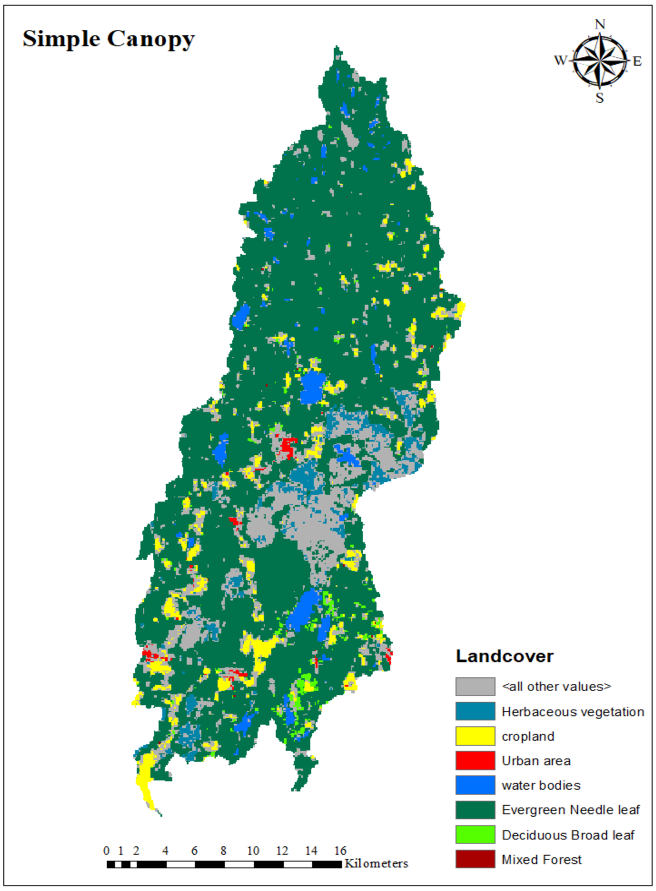

Figure 3: Map of vegetation across the basin for Simple canopy method

- Simple canopy method requires maximum storage value assigned to each of the sub-basins so the landcover grid files downloaded from CLMS was transformed to shapefile as shown in the figure 3. Each type of vegetation was further classified based on Buchhorn et al (2019) as shown in table 1 and a maximum storage value was assigned respectively (Liu & De Smedt, 2004). The initial storage value was considered to be zero.

Table 1: Land cover and Interception storage values

Vegetation type	Max Storage (mm)
Herbaceous vegetation	2.0
Cropland	2.0
Urban are	0.5
Water bodies	0.0
Evergreen needle leaf	2.0
Deciduous broad leaf forest	2.0
Mixed forest	3.0

- Similarly, the simple surface method requires the user to define maximum storage value. The maximum storage value in here depends on the slope of the terrain extracted from the DEM in ArcGIS (Figure 4). The slope thus extracted has values assigned to it as shown in the table 2. These values are later allotted to the subbasins in the catchment as surface storage value.
- The SMA loss method requires several parameters to calculate the loss from three layers. Firstly, the initial storage condition needs to be defined for each layer. Hence based on the rule the soil layer was assigned 50%, groundwater layer 1 as 20 % and groundwater layer 2 as 20%.

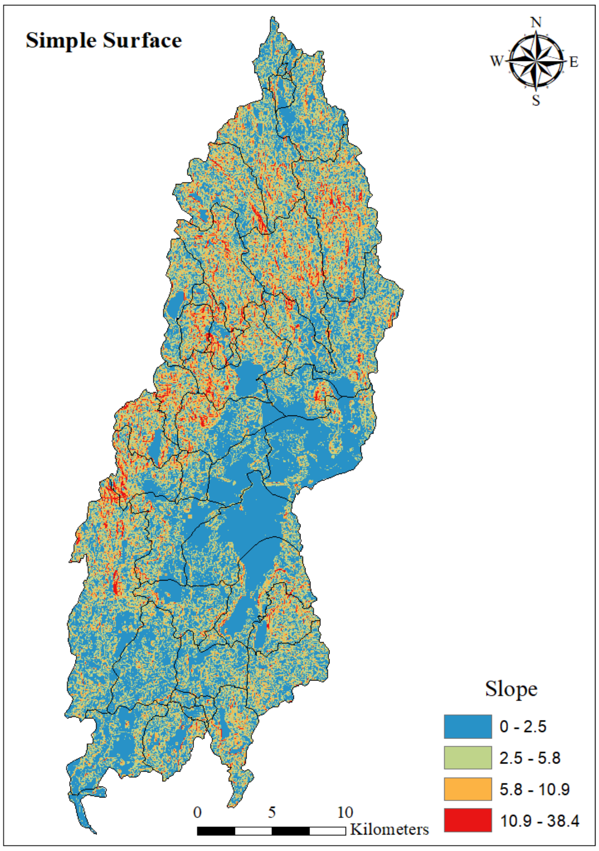

Figure 4: Slope across the basin for surface storage

Table 2: Slope and Surface storage values

Type of surface	Slope (%)	Surface Storage (mm)
Paved Impervious Areas	NA	3.18-6.35
Flat, Furrowed Land	0-5	50.8
Moderate to Gentle Slopes	5-30	6.35-12.70
Steep, Smooth Slopes	>30	1.02

- Followed by infiltration which pertains only to the top soil, four major soil type (peat silt, moraine, sandy silt, thin soil) were considered for the calculation of maximum infiltration all across the basin. For instance, table 3 below represents the soil type and its characteristics for the subbasin *Inloppet I Bolmen (W1060)*. Similarly, the calculation is done for all the subbasins depending upon the soil composition and their percentage coverage.

Table 3: Infiltration values of different soil type of sub-basin Inloppet i Bolmen (W1060)

W1060	Infiltration rate (mm/h)	Soil percentage	Max-Infiltration (mm/h)
Peat silt	80	0.3	57
Moraine	29	0.3	
Sandy silt	120	0.2	
Thin soil	3	0.2	

Maximum Infiltration = $\sum_{i=1}^{n}(Infiltration\ rate * soil\ percentage)$

$$= (80 * 0.3) + (29 * 0.3) + (120 * 0.2) + (3 * 0.2)$$

$$= 57\ \mathrm{mm/h}$$

- Along with the calculation of infiltration, an assumed imperviousness of 20 % is assigned for all the subbasins.
- This is continued by defining soil storage condition. This includes the calculation of soil storage, tension storage and soil percolation. Below is an example of calculation for the subbasin *Inloppet I Bolmen (W1060).* The soil characteristics defined in table 4 is used to calculate max soil storage and max tension storage.

Table 4: Soil type and characteristics of sub-basin W1060 Inloppet i Bolmen (W1060)

W1060	Soil Percentage (%)	Depth (mm)	Porosity (%)	Field Capacity (%)
Moraine	0.3	2200	0.3	0.2
Thin soil and cold mountains	0.2	500	0.4	0.1
Peat	0.3	1250	0.7	0.7
Glaciofluvial	0.1	400	0.3	0.1
Sand	0.1	1250	0.4	0.2
Clay	0	400	0.5	0.4

Max-soil storage $=\sum_{i=1}^{n}(Soil\ percentage * depth * porosity)$

$$= (0.3 * 2200 * 0.3) + (0.2 * 500 * 0.4) + (0.3 * 1250 * 0.7) + (0.1 * 400 * 0.3) + (0.1 * 1250 * 0.4) + (0.0 * 400 * 0.5)$$

$$= 563 \text{ mm}$$

Max-tension storage $=\sum_{i=1}^{n}(Soil\ percentage * depth * field\ capacity)$

$$= (0.3 * 2200 * 0.2) + (0.2 * 500 * 0.1) + (0.3 * 1250 * 0.7) + (0.1 * 400 * 0.1) + (0.1 * 1250 * 0.2) + (0.0 * 400 * 0.4)$$

$$= 436 \text{ mm}$$

- Further, as a rule the soil percolation was given as 40% of infiltration rate. The GW1 and GW2 percolation rates were assigned as 10% of infiltration rate. The GW1 and GW2 coefficients were entered as 120 and 386 hr respectively. The GW1 and GW2 storage were given as 100 and 250 mm respectively. Over the period of calibration these values were altered to obtain better fit.
- For Unit Clark transform method time of concentration (t_C) and storage coefficients (R) are essential parameters. For the calculation of both t_C and R, the longest flow length (L), the slope (S), area of the subbasin (A) were all estimated from the basin DEM using ArcGIS. These initial values however were changed during the calibration for better fit.
- The values of K and X for routing were calibrated with the value of X ranging between 0.1 to 0.5.
- Similarly, the values assigned for baseflow calculations were based on assumptions which were later calibrated accordingly.

3.2.2 Meteorological model

- The distribution of precipitation over the basin was done using Thiessen polygon method. This method requires precipitation data pertaining to stations which are located within or outside the study area. A total of 10 stations were selected for the method, among which station Kävsjö D was the only station present within the basin, remaining 9 stations were located outside the basin boundary. The Thiessen Polygon method evaluates weights of gages in relative to their area because of which only five stations namely Hestra D, Skillingaryd Kävsjö D, Bakarebo D and

Åby was found to have an influence on the study area (Figure 5). The values obtained were later assigned to their respective subbasin in meteorological model for computation.

- For monthly average evapotranspiration method apart from the monthly ET values, a crop coefficient value of 0.7 was assigned.

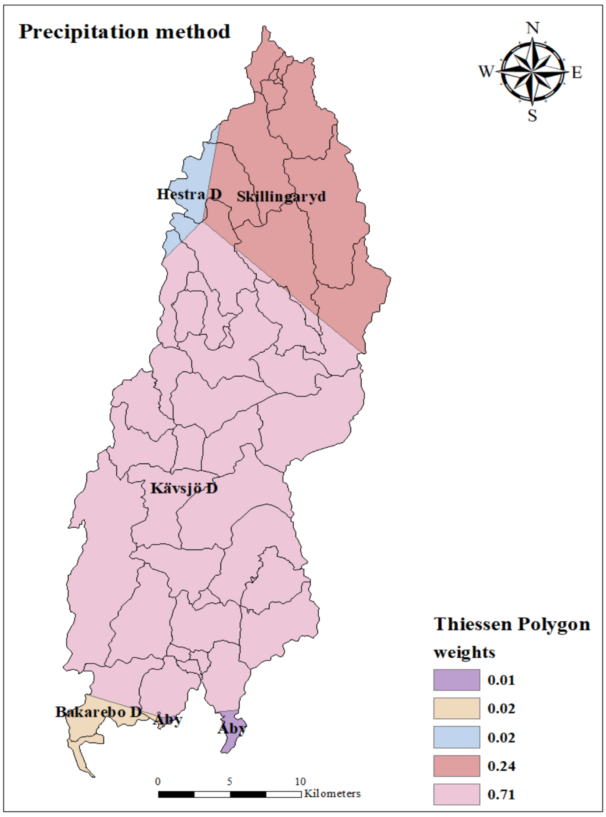

Figure 5: Thiessen Polygon method of precipitation distribution across basin

- The snowmelt calculation was done by temperature index method. The values used were calibrated to meet the best fit. Table 5 below shows the initial values assigned based on the default values suggested by HEC-HMS manual. Further an individual elevation band was assigned to each subbasin wherein their respective elevation extracted from the DEM through ArcGIS was allotted along with the details regarding initial SWE (10 mm), initial cold content (0 mm), initial liquid water (1 mm), initial cold content ATI (0°C) and initial melt ATI (0°C-day).

Table 5: Initial values of Temperature Index Snowmelt method

PX Temperature (°C)	0.9
Base Temperature (°C)	0
ATI coefficient	0.98 (as suggested in HEC-HMS)
Wet melt rate (mm/ °C-day)	5
Rain Rate Limit (mm/day)	1.5
Cold Limit (mm/day)	20
Cold Coefficient	0.4
Water Capacity (%)	10
Ground melt (mm/day)	0
ATI-Melt rate Function	Assigned through paired data manager
ATI-Cold rate Function	Assigned through paired data manager

4.HEC-HMS System

Hydrological Modelling System (HEC-HMS) 4.3 program is a product developed by the US Army Corps of research and development program. It was produced by Hydrologic engineering centre (HEC) (Feldman, 2000).

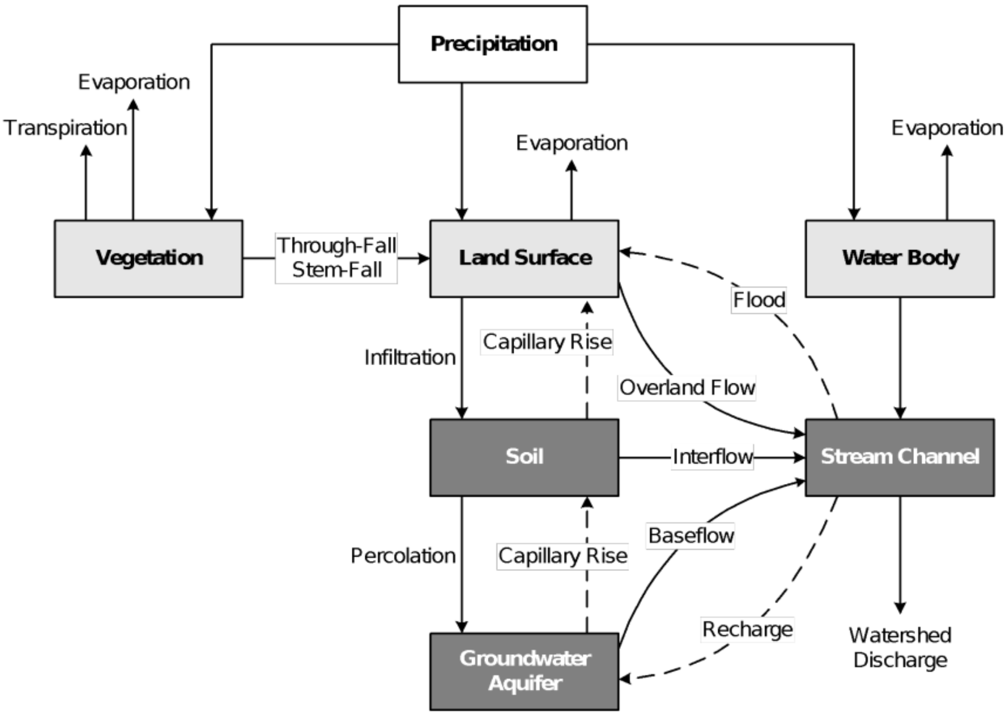

Figure 6: System diagram of the runoff process at local scale (Source: Ward,1975)

The program HEC-HMS works on the principle of watershed runoff process which begins with the precipitation as shown in figure 6 falling onto the vegetation, land surface and water bodies only to be returned to atmosphere through evaporation and transpiration. Some precipitation on vegetation falls onto the land surface joining the precipitation that had directly fallen onto the surface. A part of it infiltrates and the rest joins the stream. The precipitation that has infiltrated is stored in upper/partially saturated soil layer. This water further gets carried to surface by capillary action or flows horizontally as interflow or further percolates vertically to join the aquifers as groundwater. All of the water mentioned above eventually flow towards the stream to join in. The model mimics this process and simulate the flow considering all the losses, transformation and attenuation.

The model HEC-HMS comprises of three basic model components namely, basin model, meteorological model, control specifications.

4.1 Basin model Component

The physical properties of the basin and the topography of the stream network are described using the basin model. The main principle of the basin model is to convert atmospheric conditions into stream flow and this is done by hydrologic elements. These hydrologic elements break down the basin into manageable pieces. All these pieces are further connected in a dendric network to form a stream system.

Subbasin is a hydrologic element in the basin model which has no inflow and has only one outflow. The outflow is derived after subtracting all the losses from the precipitation, then transforming the excess precipitation and adding the baseflow (Scharffenberg et al., 2010).

According to the program, the land and water in the basin can be categorized either as direct-connected impervious surface or pervious surface. The area of the basin where all the precipitation falling onto it runs off without being subjected to any kind of loss are said to be direct-connected impervious surface and the area where the precipitation goes through losses are called pervious surface. Here land and basin are considered to be pervious surface which undergoes losses before reaching the stream. The first loss the basin undergoes is the loss from vegetation (canopy).

4.1.1 Canopy - Interception Storage

This storage represents the water held by the vegetation on land and is expressed as effective depth of water. The only inflow into this storage is through precipitation. When the canopy storage fills up, the precipitation becomes available for other storages. The water in the canopy storage is lost only through evapotranspiration (Feldman, 2000).

For the current project simple canopy method was chosen. This method represents the plant canopy wherein the potential evapotranspiration is multiplied by the crop coefficient to determine the amount of evapotranspiration from the canopy storage. The canopy is set to evaporate only during dry periods when there is no precipitation. Here the initial condition of the canopy is specified in terms of percentage which represents the amount of canopy storage that is full of water at the beginning of the simulation. The crop coefficient applied to the potential evapotranspiration is used for computing the water extracted by the canopy from the soil. Similarly, to account for extraction of water from the soil simple method is chosen which extracts water at evapotranspiration rate.

Once the canopy storage is emptied the unused potential evaporation is used up by next storage (surface storage).

4.1.2 Surface- Interception Storage

This storage represents the volume of water held in shallow surface depressions on soil surface and is expressed as the effective depth of water. The precipitation which is not captured by canopy will fall onto the surface and further infiltrate into the soil. When the precipitation rate exceeds the infiltration rate the water in the surface storage turns into surface runoff and the storage remains filled. Once the precipitation stops the water in the surface storage either infiltrates or gets evaporated.

In the current project simple surface method is chosen. This method represents the soil surface. Similar to that of simple canopy method an initial condition is specified. This indicates the amount of storage that is full of water at the beginning of the simulation. Once the surface storage is emptied the unused potential evaporation and infiltration is used by next storage (Scharffenberg et al., 2010).

4.1.3 Soil Moisture Accounting Loss Method (SMA)

Unlike other event-based models present in HEC-HMS, *soil moisture accounting loss model (SMA)* is a continuous model which simulates both wet and dry weather condition where in it mimics the natural processes below the surface. Selecting a canopy and surface loss method although optional for other loss methods, for SMA it is mandatory to include a canopy and surface method.

Soil moisture accounting loss method comprises of two storage layers to simulate flow in the basin through soil. It is used in conjunction with canopy method and surface method. Layers included in soil moisture accounting are *soil profile storage* and *groundwater storage.*

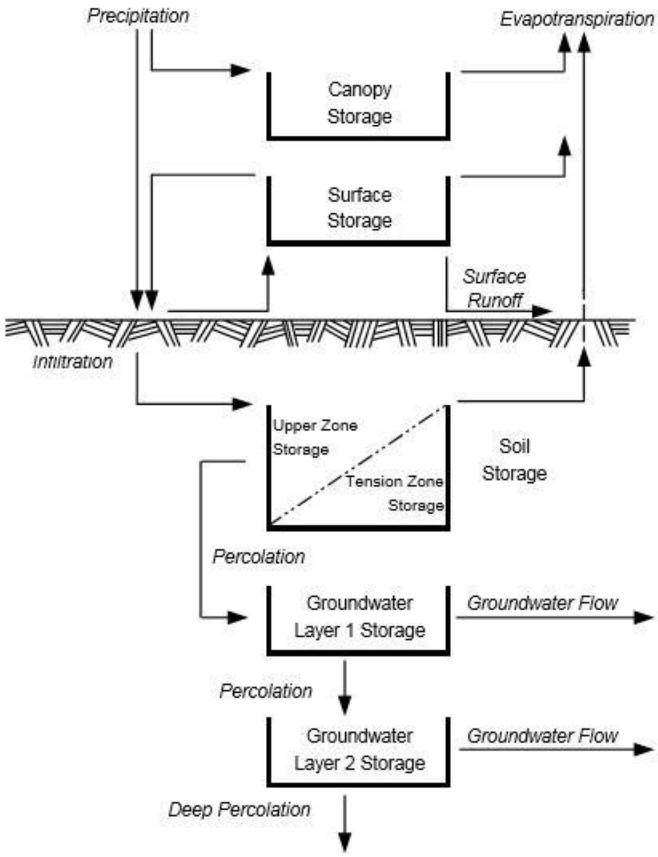

Figure 7: Conceptual schematic of the continuous soil moisture accounting algorithm (Feldman,2000)

The soil profile storage represents the water stored in the top layer of the soil. It is divided into upper zone or gravity storage and tension storage. The groundwater storage represents the horizontal interflow processes. It is divided into two layers, groundwater layer 1 (GW 1) and groundwater layer 2 (GW 2) as shown in figure 7.

***Soil profile storage**:*

The upper zone of soil profile storage gets the inflow through infiltration of water from the surface storage. The water in this layer is stored in the pores of the soil and is lost either to evapotranspiration or percolation. However, in the tension zone the water is lost only through evapotranspiration. The ET gets reduced below the potential rate in tension zone, this is due to the resistance offered to the loss of water by the soil particles as the water in this layer is stored by attaching itself to the soil particle (Feldman, 2000).

Further, the initial conditions representing the amount of soil that is full of water at the beginning of the simulation is specified in terms of percentage. When a surface method is chosen the actual infiltration at a particular time interval act as a linear function of surface and soil storage and hence a maximum infiltration rate is set which acts as an upper boundary condition for infiltration from surface to soil storage. Percentage of imperviousness is also specified wherein all the precipitation falling onto this portion of basin is converted to excess and subjected to direct runoff.

***Groundwater storage**:*

When the soil storage which accounts for the total storage available in the soil layer exceeds the tension storage the water percolates from the soil layer into the upper groundwater layer. The water initially entering into the upper layer is lost either to percolation into second layer or to the interflow. This water entering into the second groundwater layer further percolates into deep percolation or turns into interflow.

The soil percolation rate defines the upper boundary condition for the percolation from the soil layer into the upper groundwater layer. The actual percolation is a linear function of the current storage in the soil layer and the current storage in the upper groundwater layer. Similarly, the percolation rate of the upper groundwater layer defines the upper boundary condition for the percolation of water from the upper to the lower layer, where the actual percolation is a linear function of the current storage in upper and lower groundwater layers. This holds true even in the case of lower groundwater layer and deep percolation. However, deep percolation is not computed in this program. The groundwater coefficients set for upper- and lower-layer acts as a time lag on linear reservoir for transforming water in the storage to become lateral outflow or baseflow.

The reason to choose SMA loss method is mainly due to the fact that, this layered loss is not taken into account by other loss methods in HEC-HMS which makes it much more accurate and reliable while simulating a flow for a long period of time.

4.1.4 Clark Unit Hydrograph (Clark UH)

So far surface and sub-surface processes have been conceptually defined by subbasin, however the surface runoff still needs to be calculated i.e., the precipitation excess derived has to be transformed into direct runoff. The method used for this process of transformation is called Clark Unit Hydrograph transform method

Clark Unit hydrograph is an empirical model which is based on the assumption that there is a linear relationship between precipitation and the runoff response. This model derives the UH by establishing a linkage between the runoff and excess precipitation using processes like translation and attenuation. Where translation can be defined as the movement of excess rainfall under gravity from the point of origin flowing across the drainage area towards the catchment outlet unaffected by storage and attenuation can be defined as the reduction in the magnitude of the runoff as the excess gets stored in soil, channel and land surfaces across the basin (Feldman, 2000).

Unit hydrograph theory

Clark Unit Hydrograph method uses linear channel model (Dooge,1959) to represent the time taken by the water to reach the basin outlet without attenuation. This time or delay by water is represented by time-area histogram where it defines the watershed area that produces discharge at the basin outlet as a function of time. Within HEC-HMS program a time-area relationship is built in so as to obtain a temporal distribution adequate enough to obtain UH for the basin which is given as

$$\frac{A_t}{A} = \left\{ \begin{matrix} 1.414\left(\frac{t}{t_c}\right)^{1.5} for\ t\ \leq \frac{t_c}{2} \\ 1 - 1.414\ \left(1 - \frac{t}{t_c}\right)^{1.5}\ for\ t\ \geq \frac{t_c}{2} \end{matrix} \right\} \tag{1}$$

Where A_t= cumulative watershed area contributing at time t; A=total watershed area and t_c= time of concentration of watershed. The only parameter required to calculate the translation of the basin is t_c which is calculated using Kirpich's method (Perdikaris et al., 2018) given as

$$t_C = 0.066\left(\frac{L^{0.77}}{S^{-0.385}}\right) \tag{2}$$

Where t_C = time of concentration expressed in hours, L =length of stream from upstream to the point of outlet (m); *S*= average slope.

Further attenuation or short-term storage of water is critical in transformation of excess precipitation into runoff. This is represented by the linear reservoir model which is based on the continuity equation as shown below.

$$\frac{dS}{dt} = I_t - O_t \tag{3}$$

Where $\frac{dS}{dt}$ = time rate change of water in storage at time *t*; I_t = average flow to storage time *t*; O_t= outflow from storage at time *t*.

With the linear reservoir model, storage at time *t* is related to outflow as

$$S_t = RO_t \tag{4}$$

Where R = a constant linear reservoir parameter. Upon substituting the value of S in equation 4 by equation 3 and solving it we get

$$O_t = C_A I_t + C_B O_{t-1} \tag{5}$$

Where C_A , C_B = routing coefficients. They are calculated from

$$C_A = \frac{\Delta t}{R + 0.5\Delta t} \tag{6}$$

$$C_B = 1 - C_A \tag{7}$$

The average outflow during period *t* is given as

$$\overline{O_t} = \frac{O_{t-1} + O_t}{2} \tag{8}$$

If the inflow ordinates used in the above equation 5 is the runoff produced by unit depth of excess rainfall, then the average outflow obtained from equation 8 represent Clark's unit hydrograph ordinates U_t.

In HEC-HMS program the basin storage coefficient R represents the storage effect in the basin as the excess flows to the outlet of the basin. It is calculated using the equation given by Sabol (1988).

$$K = \frac{t_C}{1.46 - 0.0867\left(\frac{L^2}{A}\right)} \quad (9)$$

4.1.5 Muskingum model:

Stream flow routing is a process of deriving the shape of downstream hydrograph by using upstream hydrograph as a boundary condition. One of the common methods of determining stream flow routing is the Muskingum routing model which is based on finite difference approximation of the continuity equation.

$$\left(\frac{I_{t-1} + I_t}{2}\right) - \left(\frac{O_{t-1} + O_t}{2}\right) = \left(\frac{S_t - S_{t-1}}{\Delta t}\right) \quad (10)$$

The reduced magnitude and the lengthened time travel of a flood wave in the stream channel (attenuation) can be attributed to the storage in the reach between two sections called as the prism storage and wedge storage (Figure 8). When the flow across the stream is uniform, the volume stored in the reach *i.e.*, the water below the line parallel to the stream bed is said to be prism storage. However, when the outflow varies with respect to the inflow into the reach, the volume stored between the parallel line and the actual water surface is called the wedge storage. Although the storage in the reach is expressed as the sum of prism storage and wedge storage, the prism storage is expressed as the outflow rate O multiplied by the travel time K and the wedge storage is expressed as the weighted difference between inflow and outflow $(I - O)$ multiplied by the time travel K. Thus, the equation is given as

$$S_t = KO_t + KX(I_t - O_t) = K[XI_t + (1 - X)O_t] \quad (11)$$

Where K and X are called Muskingum coefficients, K is storage constant with the dimension of time and X is dimensionless weight given as $0 \leq X \leq 0.5$.

Further the wedge storage is considered positive during the rising stage of the flood and negative during falling stages of the flood. The value of X is 0.0 if the downstream condition is such that the storage and outflow are highly correlated and it is 0.5 if equal weights is given to outflow and inflow which will lead to uniform progressive wave with no attenuation across the reach.

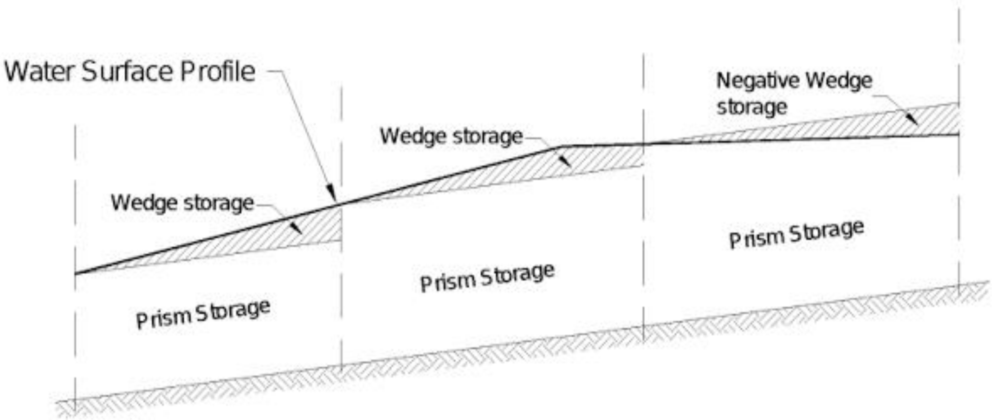

Figure 8: Wedge Storage (Source: Linsley et al., 1982)

If the equation 10 is substituted into 11 the resulting equation is

$$O_t = \left(\frac{\Delta t - 2KX}{2K(1-X)+\Delta t}\right) I_t + \left(\frac{\Delta t + 2KX}{2K(1-X)+\Delta t}\right) I_{t-1} + \left(\frac{2K(1-X)-\Delta t}{2K(1-X)+\Delta t}\right) O_{t-1} \tag{12}$$

When the inflow hydrograph ordinates(I_t for all t), an initial condition ($O_{t=0}$) and the parameters K and X are provided the program computes the equation 12 recursively to obtain the ordinates of outflow hydrograph.

In the case of ungauged watershed, the parameters K is estimated using characteristics of the stream given as

$$K = \frac{L}{V_W} \tag{13}$$

Where V_W = flood wave velocity, using Seddon's law it is estimated as

$$V_W = \frac{1}{B}\frac{dQ}{dy} \tag{14}$$

Where B = top width of the water surface and $\frac{dQ}{dy}$ = slope of the discharge rating curve at a representative channel cross section.

And the value of X is estimated using Cunge (1969) as follows

$$X = \frac{1}{2}\left(1 - \frac{Q_O}{BS_o c\Delta x}\right) \tag{15}$$

Where Q_O= a reference flow from the inflow hydrograph; B = top width of flow area; S_O=bed slope; c = flood wave speed and Δx = the length of the reach. However, as mentioned earlier X is considered to approach 0.0 when the channel has a mild slope and over-bank flow and will be 0.5 when channel is steeper and the flow does not go out of the bank. The natural channels are said to have X values ranging between 0.0 to 0.5. In the current project both the values of K and X are initially calculated but later calibrated to get the best possible fit (Feldman,2000).

4.1.6 Linear reservoir:

This baseflow model is used in conjunction with soil moisture accounting loss method. It assumes that the reservoirs are linear *i.e.*, at every time step of the simulation the outflow is a linear function of the average storage during the time step. The model simulates the subsurface flow similar to the storage and movement of water through reservoir. Mathematically this model works same as Clark's UH model (Feldman, 2000).

Although normally the infiltration is equally distributed between two groundwater layers defined by the model, working in conjunction with SMA the infiltration is connected to the lateral outflow of the groundwater layers.

The initial baseflow used in the beginning of the simulation can be specified by two methods namely initial discharge and initial discharge per area. The initial discharge represents initial baseflow as discharge expressed as units of volume per time, whereas initial discharge per area represents the initial baseflow as volume per area per time. For both the layers groundwater layer 1 and 2 the initial condition specified must be the same.

The groundwater storage coefficient used in the model act as a time constant measured in hours for the linear reservoir for each layer. The number of reservoirs is used for computing baseflow routing. Higher the number of the reservoirs, greater will be the attenuation. (Scharffenberg et al., 2010).

4.2 Meteorological model

4.2.1 User-specified gage weights

This method allows the user to assign fraction of precipitation occurring in each gage using weighing method (Thiessen polygon method) to compute mean areal precipitation (MAP) across the basin (HEC-HMS technical reference manual).

The precipitation depth of the basin is derived from the depths of the gages using the equation

$$P_{MAP} = \frac{\sum_I (w_i \sum_t p_i(t))}{\sum_i w_i} \tag{16}$$

Where P_{MAP}= total storm MAP over the subbasin; $p_i(t)$ = precipitation depth measured at time t at gage i and w_i = weighting factor assigned to gage i. If the gage i is not a recording device then $\sum p_i(t)$ is considered to be equal to total storm depth.

The gage weight of the subabsins is computed through interpolation. As meteorological trends lead to the variation in the mean annual precipitation, in order to estimate depth factors an index precipitation is introduced to both the gages and the subbasin. This adjusts the gage data before calculating the MAP for subbasin therein reducing the variation in the mean annual precipitation. The precipitation gage data is then written as

$$P_{MAP} = \frac{\sum_i \left(\frac{I_{sub}}{I_i} w_i \sum_t p_i(t)\right)}{\sum_i w_i} \tag{17}$$

Where P_{MAP}= total storm MAP over the subbasin; $p_i(t)$ = precipitation depth measured at time t at gage i; I_{sub} is the index precipitation for the subbasin; I_i is the index precipitation for the gage. If the gage i is not a recording device then $\sum p_i(t)$ is considered to be equal to total storm depth. The index precipitation for a gage is the mean annual precipitation calculated from the historical records at the gage and for that of the subbasin the mean annual precipitation is obtained by studying regional information on precipitation pattern.

The mean areal precipitation computed is further distributed in time across the subbasin to derive the hyetograph. A temporal pattern is established by using the weighting process again with only recording gages. The hyetograph is computed using the equation

$$p(t) = \frac{P_{MAP}}{\sum_i (w_i \sum_t p_i(t))} \sum_i w_i p_i(t) \tag{18}$$

Where P_{MAP}= total storm MAP over the subbasin; $p_i(t)$ = precipitation depth measured at time t at gage i; w_i is the temporal weight for gage i.

This method however requires MAP weighting factor for all the gages used in obtaining hyetograph for the subbasin and it also requires a temporal weighting factor. This is estimated by using Thiessen Polygon Method.

This method is based on the assumption that the precipitation depth at any given point in the basin can be calculated from the precipitation depth from the nearest gage to that point. Using the Thiessen polygon network, the weights of gages are evaluated in relative to their area. The method involves a process wherein the subbasins are divided into polygons by the perpendicular bisectors that join the gages nearest to the point. Lastly, the area of each polygon weighs the amount of rainfall of the station towards the centre of the respective polygon. Thereby assigning the weighting factor to all the polygons in the basin (Schumann,1998).

4.2.2 Snowmelt:

Snowmelt runoff plays an important role in hydrological cycle. It acts a source of water in many parts of the world. During winter the water is stored in the form of snow and the rate of release due to melting of this snow during summer are needed not only to study streamflow but also for flood forecasting (Singh & Singh, 2001). The amount of snowmelt and the time of melt is highly influenced by the combining effect of several energy sources. The melt occurs under two conditions, one in the presence of rain (wet melt) and the other in the absence of rain (dry melt). Data for evaluating the melt is obtained from meteorological stations where factors influencing melt like temperature, precipitation, humidity, wind, short-wave radiation and long-wave radiation etc is downloaded (Van Mullen & Garen, 2004). The water content of snowpack is generally measured in terms of snow water equivalent (SWE). SWE is the depth of water obtained by melting a unit column of snowpack.

There are two ways to compute snowmelt from the snowpack. Energy balance approach and temperature index or degree-day approach. Currently in HEC-HMS only degree day approach is available. The temperature index or degree-day computes the total daily melt to a coefficient times the temperature difference between the mean daily temperature and base temperature, which is given as

$$M = C_M(T_a - T_b) \tag{19}$$

Where M= snowmelt in mm/d; C_M= the degree-day coefficient in mm/degree-day in °C; T_a= mean daily air temperature in °C; T_b= base temperature in °C. The value of C_M varies with season and location ranging from 1.6 to 6 mm/degree-day C (Van Mullen & Garen, 2004).

The temperature index method included in HEC-HMS calculates the liquid water available (M) at the soil surface which further infiltrates or flows to the stream as direct runoff. This method works on the conceptual representation of cold energy stored in the pack with limited pre-defined conditions.

Values are assigned individually to both the subbasins and the entire basin. The subbasins are provided with elevation bands (min 1 to max 10) and air temperature gages. Further initial conditions are defined for each of these elevation bands (Table 6).

Table 6: Initial conditions of snowmelt process

PX temperature (°C)	Used for distinguishing between snow and rain. When air temperature is less than the specified temperature, the precipitation is assumed to be snow, else it is considered to be rain. The maximum value allowed is 1°C
Base temperature (°C)	Typically assigned value is 0°C. The difference between the base temperature and the air

	temperature gives temperature index which is used for computing snowmelt.
Wet Melt rate (mm/°C-day)	It is defined as the rate at which the snowpack melts under rain-on-snow condition. This happens when the rate of the rain falling onto the ground exceeds rain rate limit given. It is applicable only when the precipitation falling is in the form of rain.
Rain rate limit (mm/day)	This limit differentiates between dry melt and wet melt. Rain rate exceeding this value results in computing wet melt and when the rain rate is less than the limit given then only dry melt is computed. Default value is 0 mm/day.
ATI Coefficient	When the precipitation rate is less than the rain rate, the meltrate computation for the time intervals starts with antecedent meltrate index which requires a coefficient to update from one-time interval to the other. The default value of this coefficient is 0.98.
ATI-Meltrate function	It is a function used to calculate the meltrate from the current meltrate index. The function needs certain meltrates assigned over a range of meltrate index values in *Paired data manager* before being used in the meteorological model. Typically, meltrate for dry conditions ranges from 1-4 mm/°C-day
Meltrate pattern	Defines the percentage adjustment as a function of the time of year
Cold limit (mm/day)	Accounts for the rapid change in the temperature of snowpack during high precipitation rate. That is when the precipitation rate is greater than cold limit, the antecedent cold index is set to the temperature of the precipitation. If temperature is

	above the base temperature then cold content index is set similar to base temperature else it is set to the actual temperature. If precipitation rate is less than the cold limit the cold index is calculated as antecedent index. Default value given is 0 mm/day.
Coldrate coefficient	Used for updating antecedent cold content index from one interval to next. Default value 0.5.
ATI-Coldrate function	Used for computing cold content from the current cold content index. Before being used for snowmelt method, the function needs to be specified in *Paired Data Manager*. Typically, the cold rate ranges from 1.22-1.32 mm/°C-day.
Water capacity (%)	Defines the amount of melted water that can accumulate in snowpack before it turns into surface runoff or infiltrates into soil surface. Typically ranging from 3-5 %.
Groundmelt method	Defines the method by which the snow accumulated above the unfrozen ground melts by the heat transferred from ground. Two methods namely, constant value or annual pattern.
Groundmelt (mm/day)	Value assigned based on the method chosen above.

In order to calculate the air temperature for each elevation in the subbasins, it is assigned with several parameter data *i.e.*, each subbasin has a specified lapse rate. By multiplying this lapse rate with the difference between the band elevation and the gage elevation we get a value, that when added to the specified temperature gage, the air temperature for each elevation is obtained. The specified temperature gage and gage elevation used above are recorded in *time-series gage.* Since the air temperature is cooler in higher elevation the lapse rate assigned should be negative. Use of precipitation index is optional and is used for adjusting orographic trends of precipitation. The number of elevation band used for subbasins depends on the kind of terrain. If there is little variation in terrain then only one elevation band is used and if the variation is significant then multiple elevation band is created. Parameter data is assigned (Table 7) to each of these elevation band to define their size, elevation and initial condition of snowpack in the band (Scharffenberg et al., 2018).

Table 7: Initial condition for each elevation band in snowmelt process

Percent (%)	Represents the percentage of subbasin that each elevation band compose.
Elevation (m)	Average elevation of band.
Index (m)	Used in combination with the index assigned for each subbasin so as to adjust the precipitation of each band (optional).
Initial SWE (mm)	Snow water equivalent at the beginning obtained either by interpolating from actual measurements or just set 0 mm.
Initial cold content (mm)	Defined as the heat required to raise the temperature of snowpack to 0°C. If there is no snow the value is set to zero else it is written as the product obtained by multiplying depth of snow, snow density, heat capacity of snow and number of degrees below freezing point.
Initial liquid water (mm)	The liquid water held by snow at the beginning which can be considered only if the snowpack temperature was at 0°C. It could be set to zero when there is no snow or when the air temperature has been below freezing point for several days.
Initial cold content ATI (°C)	It is the temperature index assigned to snow that is present at the surface of the snowpack. If the initial temperature is not known, it could be set to zero.
Initial melt ATI (°C-Day)	Defined as the accumulated melting degree days since the last period of continuous air temperature below freezing. If there was no snow found it could be set to zero.

4.2.3 Evapotranspiration (ET)

As a part of hydrological cycle, the free water gets evaporated from vegetation and land surfaces. Simultaneously the water is extracted from the soil by the vegetation through the plant root system and transpired into the atmosphere. This combining act of evaporation and transpiration is said to be evapotranspiration. Among evaporation and transpiration, the transpiration is found to have major contribution in water movement and in total the evapotranspiration is responsible for returning 50 to 60 % of precipitation back to the atmosphere. The amount of evapotranspiration generated when there is infinite supply of water is called potential evapotranspiration. Evaporation is normally taken into consideration for simulations that is run over a long time period and accordingly the loss methods found in HEC-HMS are deficit constant, gridded deficit constant, soil moisture accounting and gridded soil moisture accounting. The meteorological model computes the potential ET and the subbasin computes actual ET based on soil water limitations (Scharffenberg et al., 2018).

In the current project monthly average evapotranspiration method was chosen wherein the potential ET is calculated by multiplying the monthly pan evaporation depths and monthly varying pan correction coefficients, scaled to the time-interval. The potential ET volume is extracted from different zone, firstly from canopy interception followed by surface interception and finally soil profile. In soil profile if the potential ET extracted from upper zone proves to be insufficient then it moves to tension zone followed by next available storage.

Up until the extraction of ET from the upper soil storage the potential ET is equal to actual ET. But when the potential ET is drawn from the tension zone, the actual ET becomes a percentage of potential ET which is given as

$$ActEvapSoil = PotEvapSoil * f(CurSoilStore, MaxTenStore)$$

Where $ActEvapSoil$ = calculated ET from soil storage; $PotEvapSoil$ = calculated maximum potential ET; $MaxTenStore$ = user specified maximum storage in the tension zone of soil storage and $f(\bullet)$ can be defined as follows.

- When current storage in the soil profile exceeds tension zone storage ($CurSoilStore, MaxTenStore$ >1) the water is removed from the upper zone just like in canopy and surface interception and when the storage in soil profile exceeds and reaches tension storage the $f(\bullet)$ is determined similar to percolation (Feldman,2000).

4.3 Control specifications

The principle is to control the simulation run. The time to start and stop the simulation along with the time interval is specified under this model component. The start date/time and the end date/time is specified in the *time window*. This runs both for event and continuous simulation. Based on the time specified and the method chosen in the basin model the simulation is differentiated into event or continuous simulation. Along with the start and end time, time interval for performing computation during simulation is specified. When the computation is run for the shorter time interval, the results are interpolated to the interval specified in the control specification.

4.4 Input data components

For any hydrologic simulation measured atmospheric data to define initial condition or boundary condition or parameters is essential. Time-series data, paired data and gridded data is used to specify these measured data.

In the current project data regarding precipitation, temperature and observed flow are specified under time-series data. Here the precipitation data specified is used for estimating basin-average rainfall whereas observed flow is used for calibrating and optimizing model and the temperature data is used for estimating evapotranspiration. All these data are specified as gages which can be shared by multiple subbasins or meteorologic models.

Paired data component describes inputs that are functional where data input is dependent on independent variable. In the current project the functional data specified in paired data are the ATI-meltrate and ATI-coldrate which is dependent on the temperature data specified in time-series data component and is used in the estimation of snowmelt.

4.5 Model Evaluation

4.5.1 Nash-Sutcliffe efficiency (NSE): NSE determines the relative magnitude of the residual variance compared to the measured data variance (Nash & Sutcliffe, 1970). It indicates how well the plot of observed versus simulated data fits the 1:1 line. The equation is given as

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right] \tag{20}$$

Where O_i= the ith observed flow (m^3/s); S_i= the ith simulated flow (m^3/s) and $\bar{O}$= the mean observed flow (m^3/s) and n is the total number of observed data.

NSE ranges from -∞ to 1.0, where NSE = 1.0 is the optimal value. Values ranging between 0.0 to 1.0 is considered as acceptable levels of performance and values ≤ 0.0 is considered to be unacceptable as it represents the mean observed flow being a better predictor than the simulated flow (Moriasi. et al., 2013).

4.5.2 Percentage bias (Pbais): Measures the average tendency of the simulated flows to be larger or smaller than their observed counterparts. The optimal value is 0.0 where in the positive value represent model bias towards underestimation and negative value represent overestimation (Gupta et al.,1999). The equation is as follows,

$$Pbias = \left[\frac{\sum_{i=1}^{n}(O_i - S_i) * (100)}{\sum_{i=1}^{n}(O_i)}\right] \tag{21}$$

Where Pbias represents the deviation of the data being evaluated, expressed as a percentage.

4.5.3 RMSE-observations standard deviation ratio (RSR): RSR is computed as the ratio of the RMSE and standard deviation of the measured data. It incorporates both error index and normalization factor so that the resulting statistics and report values can be applied to various constituents. The optimal value is 0.0 which represents zero RMSE and perfect model simulation.

Therefore, lower the value of RSR, lower the value of RMSE and better the model simulation performance (Moriasi et al., 2013).

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}(O_i - S_i)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right]} \tag{22}$$

The *Percent error in peak flow (PEPF)* measures the magnitude of the computed peak flow without taking the total volume or timing of the peak into consideration. Whereas *Percent error in volume (PEV)* considers the computed volume and disregards the magnitude of the peak flow (Liu & De Smedt, 2004). For both PEPF and PEV the optimal value is found to be 0.0 expressed in percentage.

$$PEPF = 100 \left|\frac{O_{peak} - S_{peak}}{O_{peak}}\right| \tag{23}$$

$$PEV = 100 \left|\frac{V_{Obs} - V_{Sim}}{V_{Obs}}\right| \tag{24}$$

Where O_{peak}= observed peak flow; S_{peak}= simulated peak flow; V_{Obs}= volume of observed hydrograph; V_{Sim}= volume of simulated hydrograph (Cunderllk & Simonovic, 2004).

5.Simulations

5.1 Model Set-up

The two DEM frames downloaded is merged by mosaicking technique in ArcGIS 10.5.1. The delineation of basin and watershed is the first step in hydrologic modelling followed by the extraction of basic basin properties.

1. **Terrain pre-processing**: The process of refining the DEM to delineate the basin is called terrain pre-processing. The DEM is processed using Arc Hydro toolbox in Arc GIS 10.5.1. The process starts with *DEM Reconditioning* wherein the DEM is modified by imposing linear features (burning/fencing) onto it. Further *Fill sinks* feature is used to modified the elevation value. By modifying the elevation value, the issue with water being unable to flow as it gets trapped in the cells with higher elevation is solved. Through this step the sinks in the grid are filled and a surface drainage pattern is obtained.
2. **Terrain processing**: Once the terrain pre-processing is done it is further computed to create data pertaining to delineation of stream. This is done using following functions in sequence

   Flow direction: Computes the flow direction for the grids. The grid thus created has values assigned to each cell representing the direction of the steepest descent from that cell.

   Flow accumulation: Uses the totally filled DEM to compute flow accumulation grid where for each input grid the number of cells accumulated in the upstream of cell is determined.

   Stream definition: Using the flow accumulation grid and user specified threshold a stream grid is created. Input cells having value greater than the threshold are assigned value 1 and rest as no data.

   Stream segmentation: Creates a grid of stream segments having unique identification.

   Catchment grid delineation: Creates a grid where the values assigned to each cell, indicating to which catchment they belong to.

   Catchment polygon processing: Converts the above catchment grid to catchment polygon feature class.

   Drainage line processing: Converts the input stream link grid to drainage line feature class.

Adjoint catchment processing: Generates the aggregated upstream catchments from the catchment feature class.

Drainage point processing: Generates the drainage point associated to the catchment.

Slope: Generates a slope grid for the DEM in terms of percentage or degree (ESRI, 2011).

The hydrologic skeleton so developed in terrain processing step is used for delineating basin and sub-basin. This is done using HEC-GeoHMS as explained below.

3. **Project Setup**
   This menu extracts data that is used for developing HEC-HMS project. Here a control point is specified at the downstream outlet which represent downstream boundary for the HEC-HMS project. From here HEC-GeoHMS will extract data for the drainage area in the upstream of the basin.
4. **Basin processing**:

   Basin Merge: Used for merging multiple sub-basins together into one sub-basin.

   River profile: It is created by extracting elevation from the terrain model along stream line and hence provides information on slopes and grade breaks for selecting delineation points.

5. **Stream and sub-basin characteristics**: In this step the topographic characteristics of stream and sub-basin are extracted and stored in attribute tables. These tables can be used further by exporting to other programs or spreadsheet for computation.

   River length: This computes the river length of routing reaches in the river layer.

   River slope: This function extracts the upstream and downstream elevation of a river reach to estimate the slope.

   Basin slope: Computes average basin slope in the basin.

   Longest Flow path: Computes longest flow length, upstream and downstream elevation, slope between end points.

   Basin centroid: Identifies the centroid of the subbasin. It can be defined both by the tool as well as the user. The centroid defined by the program is a function of shape of the sub-basin and needs to be evaluated once created.

Centroid elevation: Computes elevation for each centroid point using DEM.

Centroid flow path: Computes the centroidal longest flow path, it is measured as the distance between the projected point on the longest flow path to the subbasin outlet.

6. Hydrologic parameter estimation

Select HMS Processes: HEC-HMS modelling methods are chosen and stored in attribute tables which is later on included in HEC-HMS project files.

River Auto name: This process names the reaches in sequence from upstream to downstream with the inclusion of letter 'R' in the beginning followed by specific numbers.

Basin Auto name: This process names the sub-basins in sequence from upstream to downstream with the inclusion of letter 'W' in the beginning followed by specific numbers.

7. Hydrologic modelling system

Map to HMS unit: Converts the physical characteristics of the reaches and the subbasins to a user-selected unit system.

HMS data check: Checks if the data provided are in correlation with the hydrologic structure of the model. This step makes sure that the relationship between the stream segments, subbasin and outlet points are intact.

HEC-HMS schematic: This tool builds a hydrologic network containing all the HEC-HMS model elements and shows their connectivity. It is the GIS representation of HEC-HMS model. It creates two layers, HMS Link layer (showing connectivity) and HMS Node Layer (node locations of subbasin and junction).

HMS legend: Uses HEC-HMS element icons to represent point and line features in the HMS NODE/Link layers.

Add coordinates: Attaches the geographic coordinates to the HMS node and link layers.

Prepare data for model export: This tool gathers all the information from the attribute table to the subbasin and river layer in preparation for the export of the model file from HEC-GeoHMS to HEC-HMS.

Background shape file: These files capture geographic information regarding subbasin boundaries and stream reaches.

Basin model file: The model file has information on geographic information, hydrologic elements and their connectivity in terms of ASCII text file which is then loaded into HEC-HMS software for modelling (Figure 9). Once loaded and model components are generated the parameters are input. Lastly, the model is run for calibration followed by validation (Fleming & Doan, 2013).

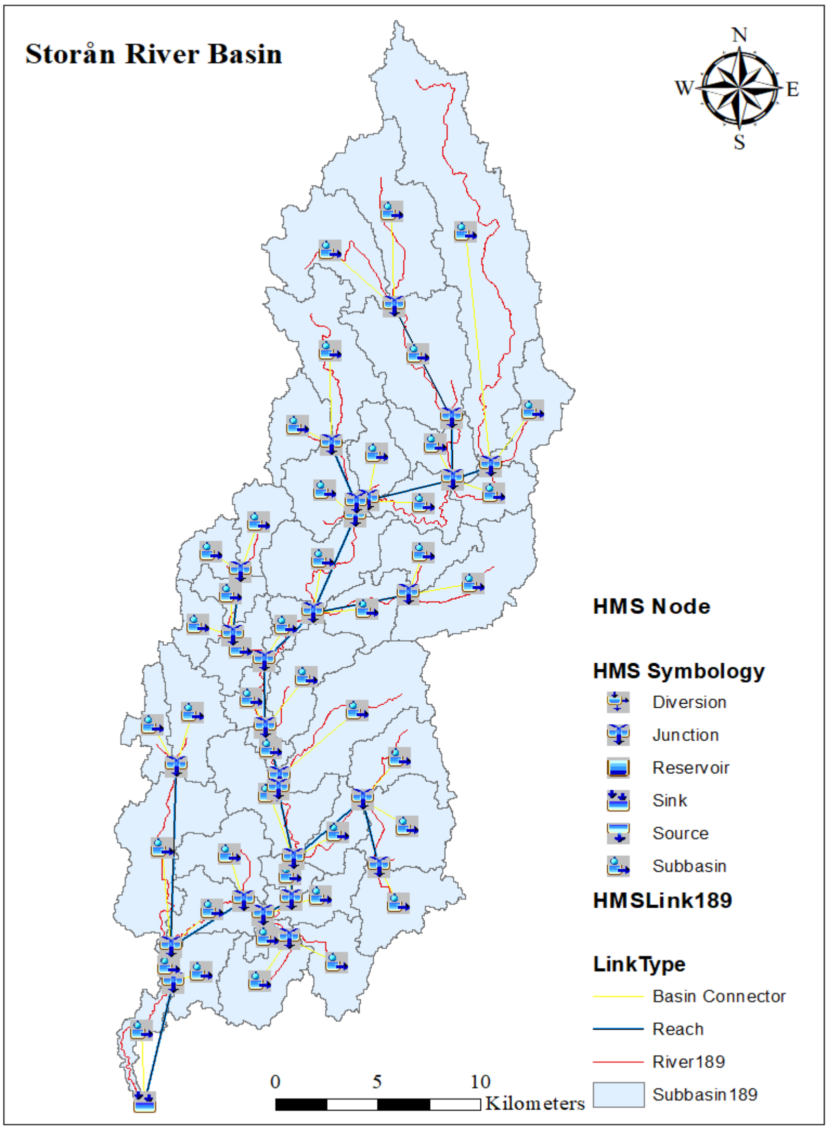

Figure 9: HEC-HMS model of Storan river basin

5.2 Calibration and Validation

5.2.1 Calibration

For the current study, the calibrated timeline was from the 1st of January 2005 to 31st December 2010. Although most of the parameters were calculated, due to the unevenness of the data used, an attempt was made to change each parameter and see its impact on the model. Table 8 below shows initial and calibrated values for all the parameters involved in the modelling except for snowmelt.

The parameters of temperature index method for snowmelt were assigned with mostly default values suggested by HEC-HMS. However, during the process of calibration the ground melt value was changed from 0 to 0.99 mm/day and the water capacity was changed from 3 % to 10 %. The rest of the values were kept intact.

The ET was calculated only for dry periods and no changes were done with respect to canopy values that were initially assigned. Although an attempt was made to see its impact over the outflow, no major change was found. Similarly, for surface method no changes were made for max storage values that were initially assigned but the initial storage and imperviousness was raised by 10 % (table 8).

Table 8: Initial and Calibrated values of sub-basin Inloppet I Bolmen (W1060)

W1060	Initial values	Calibrated values
Simple Canopy		
Max Storage(mm)	2	2
Initial storage (%)	0	0
Simple Surface		
Max Storage(mm)	50.8	50.8
Initial storage (%)	0	10
Soil Moisture Accounting		
Max-Infiltration(mm/h)	57.65	59.3
Impervious (%)	10	20
Soil storage(mm)	605.7	494.9
Tension storage(mm)	502.1	477.7

Soil percolation(mm/h)	23	23.72
GW 1 storage(mm)	100	85
GW 1percolation (mm/h)	2.4	2.4
GW 1 coefficient (h)	120	90
GW 2 storage(mm)	250	350
GW2 percolation (mm/h)	2.4	2.4
GW 2 coefficient (h)	386	340
Clark Unit Hydrograph		
Time of Concentration (h)	4.6	8.56
Storage coefficient(h)	0.02	8.56
Muskingum Routing(R530)		
K(h)	0.85	20.32
X	0.25	0.15
Linear Reservoir		
GW 1 Initial (m^3/s)	0.09	0.3
GW 1 coefficient (h)	120	90
GW 1 Reservoirs	5	2
GW 2 Initial (m^3/s)	0.05	0.15
GW 2 coefficient (h)	386	340
GW 2 Reservoirs	5	6

According to Singh and Jain (2015) soil storage, soil percolation, maximum infiltration, impervious area, and tension storage were said to be highly sensitive parameters in SMA and this was found to be true in the current study as well. However, an initial percentage of water in the soil, GW1, GW2 seems to have an effect at the beginning of the simulation. The imperviousness percentage assigned in the model does not justify the actual basin as the area of the basin consists of few wetlands which were not taken into account. Groundwater storage and coefficients for both layers were calibrated and they seem to be fairly sensitive in the current loss method.

Although the parameters of Clark unit transform method were initially calculated it was further calibrated as the initial values were found to be too low for the basin. The linear reservoir parameters were highly sensitive. This can be seen in the result as the outflow being dependent on baseflow, any minor change in the values led to a major difference in the outflow.

Similarly, Muskingum K and X value had to be calibrated from the initial value assigned. The X value which represents attenuation, the initial value being 0.2 was later changed ranging from 0 to 0.5. Changing just X value did not show a major impact, but when the K value was altered along with it, it had a visible change in the smoothness of the simulated flow.

5.2.2 Optimization Trail Manager

The calibrated model was later optimized by the default optimization trail manager available in HEC-HMS. This further enhanced the fit of the simulated and observed graph to some extent. Since the number of sub-basins and reaches being high, the number of parameters associated with them were high as well due to which the optimization did not respond after few iterations. So, it was continued with manually changing parameters and running the model. When a satisfying result was obtained, it was further validated.

5.2.3 Validation

The validation was performed from the 1st of January 2011 to the 31st of August 2019. Apart from the time-series data like precipitation values and discharge values all the other parameters remained the same. The temperature data used was of the year 2010 and the same values were repeated for the rest of the years both for calibration and validation. This was done because the data obtained from SMHI were inaccurate with a significant amount of missing data, which made linear interpolation impossible. However, for the year 2010 the data was found to be intact and usable.

6.Results

6.1 Calibration

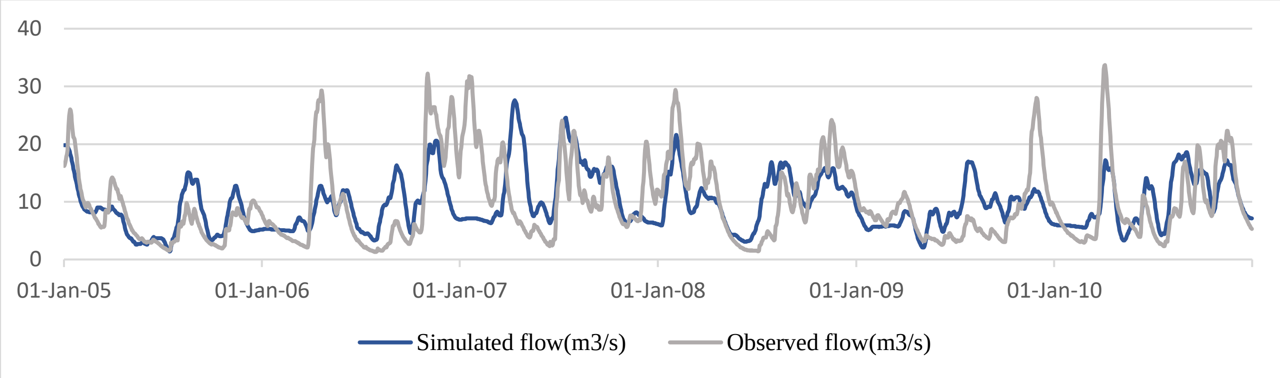

Figure 10: Result of calibration (2005-2010)

From the visual observation of figure 10 it is noted that the simulated flow from the model resulted in lower outflow than the observed outflow. The model underestimated the flow especially during winter where the flow is found be bare minimum. This is followed by the underestimation of flow during spring except for the year 2007. Further the model overestimates the outflow during summer and fall.

Most of the peak discharge is found to occur in winter and spring. However, the model fails to recognise peak discharge. In the year 2007 the number of peak discharges is high and once again model highly underestimate the occurrence of peak discharge. This is shown in the table 9 where although the volume of peak discharge is close to that of observed value, the date of peak discharge is found to be one week apart. Even though this is the case the model has successfully estimated the total volume over the span of five years of calibration.

Table 9: Simulated result of calibration (2005-2010)

	Volume (mm)	Peak discharge (m3/s)	Date of Peak Discharge
Observed	2947	34	04-Apr-07
Calibration (2005-2010)	2915	28	12-Apr-07

6.2 Validation

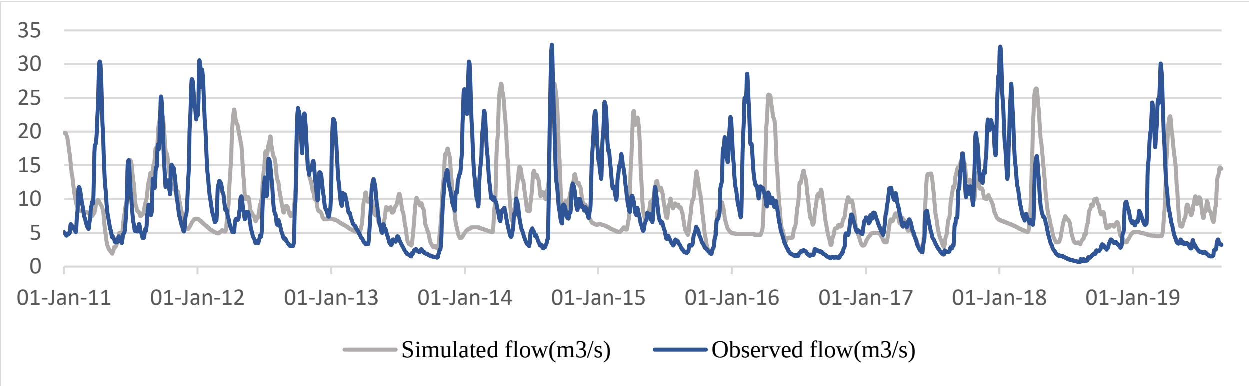

Figure 11: Results of validation (2011-Aug 2019)

In contrast to calibration, validation overestimates the total flow. Seasonally the model tends to underestimate only winter and overestimate the flow during summer, fall and spring. Except for the year 2011 and 2017 the model has over estimated spring flow all along the time of validation (Figure 11).

From the observed flow the peak discharge is found to occur mostly during winter, spring and fewer times during fall. The model successfully recognises the volume and dates of peak discharge very close to the observed value (Table 10). This however do not ensure that all the peak discharge across the span of 9 years is accurately estimated by the model. In the graph above (Figure 11) it is clearly evident that the model is not accurate in estimating all the peak discharge but in turn underestimates the flow during several important events.

Table 10: Simulated result of validation (2011- Aug 2019)

	Volume (mm)	**Peak discharge (m3/s)**	**Date of Peak Discharge**
Observed	3776	33	26-Aug-14
Validation (2011-2019)	3900	28	28-Aug-14

6.3 Model Evaluation

Table 11: Evaluation of the model simulations

Model Evaluation	Optimal value	Calibration	Validation
RMSE Std Dev (RSR)	0	0.9	0.9
NSE	1	0.2	0.2
Percent Bias (Pbias)	0	-1%	-1%
PEPF	0	18%	16%
PEV	0	1%	-3%

The model evaluation of calibration shows that the RSR value is high and the NSE value is too low. The Pbias being negative represents overestimation. PEPF value seems to be bit high, whereas PEV values are very close to an optimal value of 0, this proves that the peak discharge is well estimated (Table 11). A comparison of statistical performance between the calibrated and observed values shows that the model tends to underestimate the volume and peak discharge. However, looking at the date of peak discharge, the model seems to have given a satisfactory result.

Further, the RSR, NSE and Pbias values of validation remains same as calibrated values. However, PEPF value seem to be high as calibrated value and PEV value to be negative as the total volume is slightly overestimated (Table 11). The time of peak discharge of observed and validation is found to be very close and acceptable. In spite of not meeting the expected values, both the calibrated and validated results seem to be acceptable. The performance of the model can be said to be satisfactory.

7.Discussions

The precipitation data of station Kavsjo showed that the highest precipitation occurred during summer season followed by fall, winter and spring respectively and the observed flow/discharge was found to be highest during winter followed by spring fall and summer. This means that the precipitation fallen during summer and fall led to the maximum outflow during winter and spring leading to fall and summer to have minimum/low outflow.

The model however seems to have a quick response to the precipitation falling onto the study area. This is evident as the outflow is found to be highest during summer followed by fall, spring and winter both during calibration and validation. Further the total outflow obtained from the model is lower than the observed flow. This untimely underestimation of the final discharge can be attributed to three aspects. As explained by Riggs (1985) the stream flow is influenced by climatic conditions, geological factors and topographical factors.

7.1 Climatic Conditions

The climatic conditions and geological factors of the basin are interconnected, influencing the processes all along while producing streamflow. Climatic conditions comprise of precipitation, temperature, wind, humidity and sunlight. When a study is conducted for a long time period the climatic factor that has highest influence are precipitation and temperature.

The type of precipitation falling on to the basin is dependent on temperature and it in turn influences processes like evapotranspiration and snowmelt in the basin. The loss of precipitation in the form of storage is affected by the geological factors which comprise of soil characteristic and initial condition of the same in the basin.

The monthly evapotranspiration method chosen uses monthly values without taking into account the variation in short-wave radiation from the sun over the period of time chosen. The monthly ET values once assigned are not changed yearly and the daily temperature data used was of the year 2010 from Hagsmult station over the entire period of study. Both of these facts hinder any possibility of ET and temperature variability over the years of study. This effects the precipitation loss by evaporation from both surfaces and water bodies in the basin.

The other process which contributes to streamflow is the yearly snowmelt. The information regarding the functionality of the snowmelt process in HEC-HMS being sparse, parameters were assigned with standard values. The base temperature was given as 0°C as a result as soon as the temperature hits 0°C there is no runoff generated in the model. This is however not true in reality as the snowmelt runoff is not just governed by the temperature but also by the latent heat emitted by the soil, the short-wave radiation of sun and the rain falling onto the runoff resulting in runoff below the snow. These three factors are not taken into consideration because of which as shown in the graph below (Figure 12) no runoff occurs during the winter season.

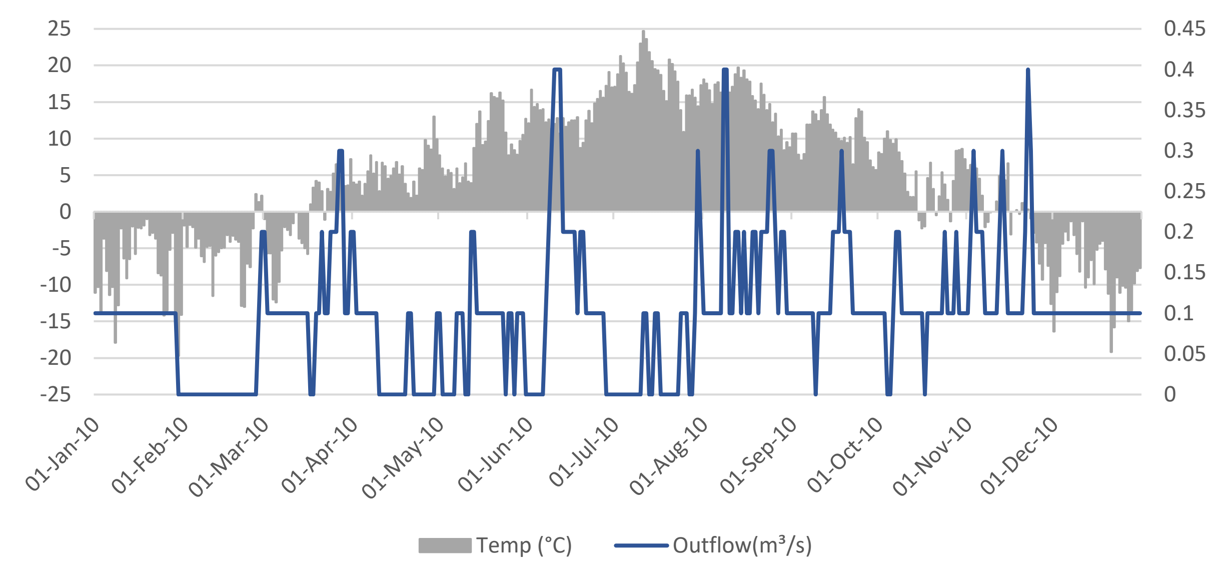

Figure 12: Simulated outflow variation with respect to temperature

7.2 Geological factors

Further, soil and rock composition of the basin and their characteristics has high influence on processes like infiltration, percolation and also evaporation through plant roots. In the model with the depth of soil to bedrock unknown, an assumption of 6 m depth was made and each layer was assigned certain depth and soil composition (Table 4). The soil in the study area is mainly comprised of moraine, peat and sand which has high infiltration rate and this resulted in quick response by the model to the precipitation. Wherein the water was transmitted to the groundwater layer quickly and the baseflow contributed to the stream flow in a short period of time than that of the observed flow. This led to low direct runoff as can be seen in the graph below (Figure 13) where the streamflow is found to be more dependent on baseflow than direct runoff. The quick response however simulated a volume of runoff very close to that of the observed total runoff but as one can note from the observed flow that in reality the basin's response to precipitation was not as quick as that of the model.

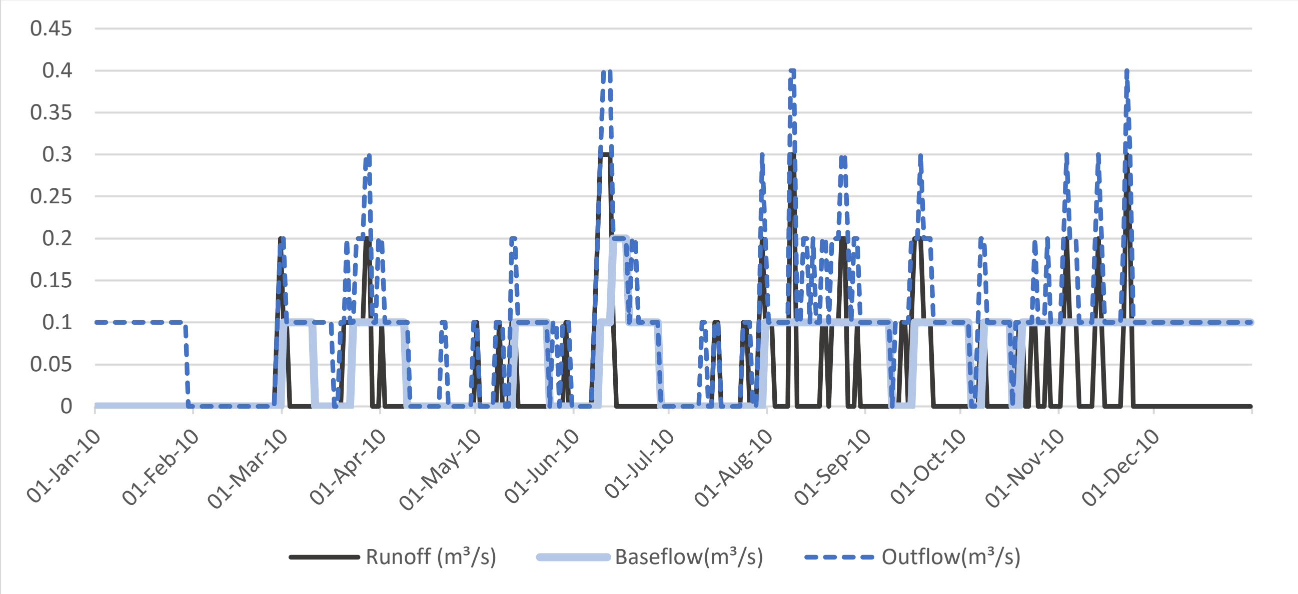

Figure 13: Simulated outflow dependency on baseflow and runoff

7.3 Topographical factors

This comprises of physical factors such as slope, altitude, wetlands and river bodies and top soil layer of the basin. The slope value assigned was generalised and only a single band of elevation was given during snowmelt as not much of a difference was seen between upstream and downstream area. The imperviousness of the basin was assigned to be 20% for each of the subbasin as the basin was found to be dominated by vegetation. The imperviousness although very small impacts the surface runoff and the number of elevation band determine the altitude difference thereby influencing the temperature and the processes associated with it.

According to Hayashi et al (1998) wetland is largely governed by evapotranspiration, infiltration, and precipitation *i.e.*, the snowmelt runoff largely gets accumulated in the wetland which eventually infiltrates and flows laterally to be taken by plants on later stage because of which the contribution from wetland to deep aquifers is low. During summer unless there is a huge event, no runoff occurs within a wetland. This shows that the wetland plays an important role in the hydrology of the river. It contributes in the energy balance of the river by being a part of the evapotranspiration process, infiltration, and snowmelt. In the current study Store Mosse national park is a huge wetland found in the south east of the basin. This wetland was ignored and the area was considered similar to the rest of the basin. Similarly, several small wetlands across the basin were ignored. Since the modelling was for a period that lasted more than a decade, ignoring the presence of wetland in the basin could have contributed to the unsatisfactory performance of the model.

8.Limitations and Recommendation

The inaccuracy in the simulated flow with respect to observed flow can be attributed to many reasons as mentioned in the discussion but there are few limitations with respect to the model, basin and the data available as well. These limitations quite often lead to inaccuracies which can be either corrected or improved in the future. Below are the few drawbacks found during the application of model and further recommendations are suggested for the improvement.

- A total of 630 km^2 of the basin is considered in the current study. This seemingly large basin has 44 sub basins and 23 reaches (Figure 9). Simplifications is much needed when a basin of this size is used. One solution to this problem would be choosing a gridded method wherein the data used need not be entered manually but could be input through HEC-GeoHMS and later imported into HEC-HMS software. Also, one could reduce the number of sub-basins during the terrain pre-processing step by merging the adjacent sub basins into an acceptable number of sub-basins so that parameterization becomes easy.
- Type of loss method: In the current project soil moisture accounting loss method has been chosen. This method in itself consists of 17 parameters. Along with these parameters, other parameters with respect to transforming, routing, and baseflow are to be taken into consideration. Collection and assembly of these data is a time-consuming process as most of the measured data found are either inaccurate or insufficient. Hence when one attempts to understand the working of the modelling the chosen loss method is of utmost importance. So, for a large basin a much simpler loss method could be chosen so that a new user can understand the model better and work with ease.
- Generalization: When a huge basin is considered, the generalisation of parameters must be avoided as much as possible. Generalisation with respect to the type of soil, vegetation cover, slope etc was done in this project to ease the process. However, the result being not so satisfactory generalisation is not recommended. Instead, one could choose simple methods which require less parameter but still gives a satisfactory result or could perform field measurements which will give better data for use.
- Temperature data: Firstly, the daily temperature data obtained had several days of data missing, due to which temperature data of the year 2010 were used for all the years simulated. Secondly, in the entire basin the only available station for temperature data was Kävsjö. This was not interpolated and the data was directly used. The temperature being the most important data type, an attempt must be made to obtain the most accurate data possible

and this is possible only when enough number of measuring stations are available. In order to study the basin, measuring stations must be allotted in and around the basin so that the data obtained are more reliable and accurate.

- Soil to bedrock depth varies in reality but due to lack of information a depth of 6 m was assumed. Apart from the total depth, depth with respect to each soil type was assumed as well. The depth of soil is crucial as it defines the storage capacity of each layer involved in the modelling. Soil storage being one among the sensitive parameter it has to be as accurate as possible for better results.
- The temperature index method chosen had a number of parameters. Snowmelt plays a prominent role in the run-off volume all through the year. However, not many studies or research are available about the use of this method in HEC-HMS. Hence most of the parameter values used were the ones mentioned as default by the program. Further analysis and research are recommended so that the values used meets the climatic and geological condition of the study area.
- Reach: Reach being a hydrological element that connects junction or sub basin in the upstream to junction or sub basins in downstream is considered to have no loss. This is the reason the outflow perfectly follows the inflow of the reach. Different method of loss is available in HEC-HMS for reach, such as constant loss and percolation loss. The user is recommended to use one of these as it might impact the end result.
- Data pertaining to relative humidity, long-wave radiation, short-wave radiation, air pressure, etc were not taken into consideration. These data normally have a major impact when a simulation is run for a long period of time. It is highly recommended that these meteorological aspects to be taken into consideration when simulating the model in the future.
- Observed data: The flow data downloaded from SMHI is a simulated flow obtained by HYPE software. In cases like ungauged catchments the specific discharge is assumed to be similar to the nearby catchments which have similar landscape. However, the spatial-temporal variability between the sub-basins result in a difference between specific discharges of sub-basins (Karlsen et al., 2016)and the error is found to be higher in daily discharges followed by monthly and annual discharge. Hence the observed values against which the simulated values are compared, cannot be considered to be accurate and precise. An attempt must be made to obtain raw observed data so that the model can be optimized to get the most accurate result.

9.Conclusion

In the results it is evident that the model has underestimated the flow during calibration but has overestimated during validation. This is attributed to three main criteria *i.e.,* climatic factors, geological factors and topographical factors. Climatic factors like temperature and precipitation play an important role when a long period of time is considered. The inaccurate temperature data impacted not only evapotranspiration process but also snowmelt process. Lack of information regarding snowmelt parameter further increased inaccuracy in identifying the type of precipitation falling onto the surface. This led to underestimation of flow during winter and spring. Further due to generalisation of soil characteristics and soil depth across the basin resulted in quick response to precipitation by the model. This resulted in low surface run-off because of which the streamflow is dependent on baseflow then on surface flow. Lastly excluding wetlands and water bodies impacted the evapotranspiration over the years.

The model evaluation shows that the it has underperformed. Both the RSR and NSE values are found to be 0.9 and 0.2 which is less than the optimal value, 0 and 1 respectively. Although Pbias, PEPF and PEV values seems very close to optimal value it is the RSR and NSE value that is of importance as it gives qualitative assessment of the model over quantitative assessment by those mentioned above.

However, both calibration and validation were performed with the intention to meet the desirable volume which the model has done successfully. Although there was inaccuracies and generalisation in the data used, the model seems to successfully recognise the peak discharge very close to the observed data. Except for the fact that the model demands more data because of SMA loss method, the model in itself was found to be easy to learn and easy to work with.

Further, for future use the model is recommend with few changes. Fewer number of subbasins and a different method of loss is to be chosen if the area is large and ungauged. When a simulation is run for a long period of time data pertaining to temperature, precipitation and discharges should be accurate and reliable as these factors influences most of the processes involved in the production of streamflow. Generalisation must be avoided as much as possible especially topological and geological factors like imperviousness, wetlands/water bodies, soil characteristics and soil depth. This could be done by installing more gages or use of grided data.

To conclude the software HEC-HMS is a user-friendly program. It is found to have several features and methods to mimic the natural water cycle. It is compatible with Arc GIS application which makes the parameterization easy. It is suitable to be used on the basins which has snowfall and heavy rainfall all through the year. The results although just satisfactory it is mostly due to inaccurate and inconsistent data which can be improved. Altogether the model needs to be researched and studied further as there are few aspects of it which can be upgraded to make the model more efficient.

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11.Appendix

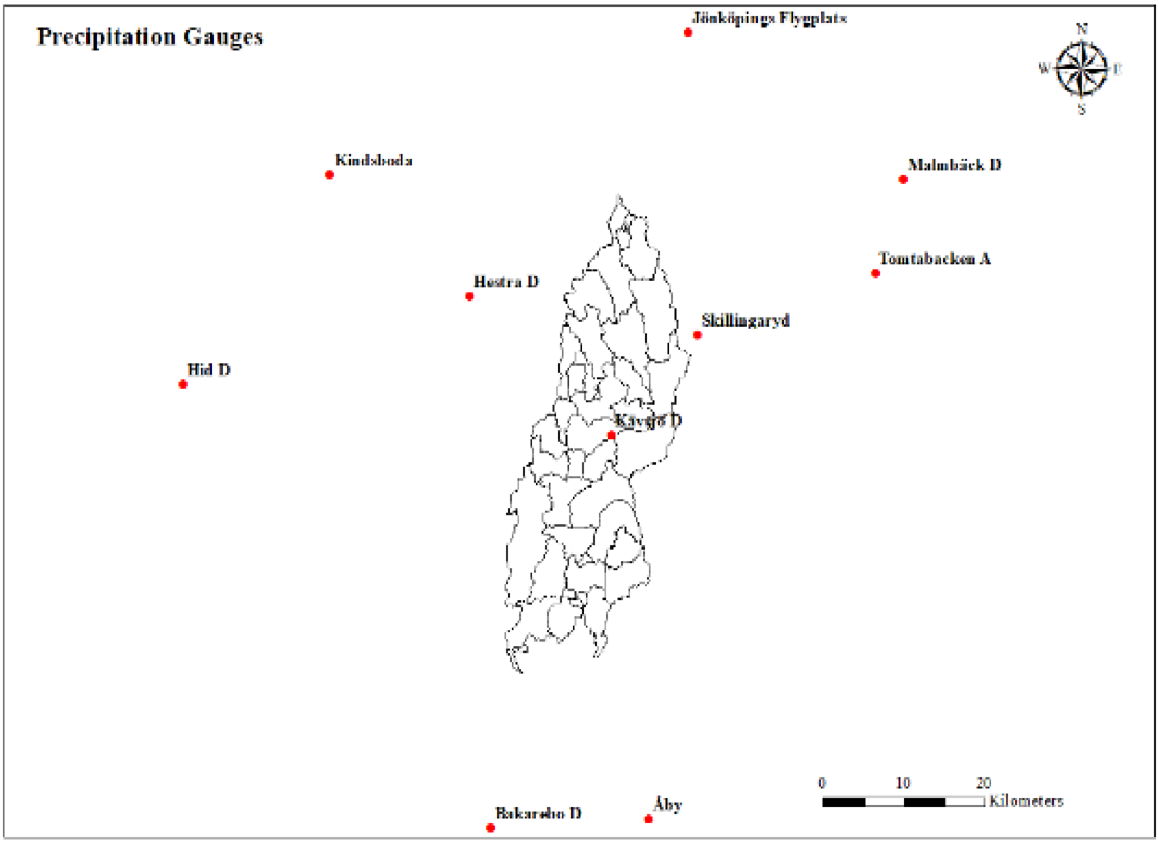

Figure 1: Precipitation gauges used for Thiessen Polygon method

Table 1: Sub-basins and SMA loss parameters

Sub-Basin	Name	Max_Infiltration (mm/h)	Soil storage(mm)	Tension storage(mm)	Percolation(mm/h)	
					Soil	GW1/2
W1060	Inloppet i Bolmen	59.3	494.9	477.7	23.72	2.4
W1050	Nedlagd mätstation	40.3	495.7	478	16.12	2.4
W1040	Mynnar i Lillån	38.8	495.7	478	15.52	2.4
W1030	Ovan Lillån	30.2	619.9	592.4	12.08	2.9

W1020	Mynnar i Bolmån	25.6	603.1	486	10.24	3.3
W100	Ovan Lillån	41.4	619.9	592.4	16.56	2.9
W990	Ovan Lillån	27.9	493.3	473.8	11.16	2.4
W970	Inloppet i Nästasjön	29.1	571.7	474.1	11.64	3.1
W960	Ovan Brännösbäcken	43.4	597.3	501.8	17.36	3.1
W940	Mynnar i Bolmån	40.4	570.3	503.2	16.16	2.8
W930	Mynnar i Bolmån	34.3	484.2	468.2	13.72	2.3
W910	Ovan Lillån	24.9	597.3	501.8	9.96	3.1
W900	Mynnar i Bolmån	47.6	570.3	503.2	19.04	2.8
W880	Ovan Fläsebäcken	36.3	468.6	447.1	14.52	2.3
W870	Mynnar i Bolmån	49.1	572.3	519.3	19.64	2.6
W860	Inloppet i Flaten	36.7	468.6	447.1	14.68	2.3
W850	Utloppet av Hästhultasjön	43.7	572.3	519.3	17.48	2.6
W840	Mynnar i Flaten	39.1	572.3	519.3	15.64	2.6
W830	Utloppet av Flaten	47.9	570.3	503.2	19.16	2.8
W820	Utloppet av Långasjön	78.9	710	709.9	31.56	2.2
W810	Mynnar i Mosjön	42.3	466.2	413.3	16.92	2.5
W800	Inloppet i Långasjön	43.9	468.6	447.1	17.56	2.3
W790	Utloppet av Skärvsjö	37	468.6	447.1	14.8	2.3
W780	Inloppet i Mosjön	36.7	466.2	413.3	14.68	2.5

W770	Mynnar i Långasjön	39.1	438.6	400.9	15.64	2.3
W760	Mynnar i Västerån	43.2	750	730.2	17.28	2
W750	Nedlagd mätstation	36.7	458.6	384.3	14.68	2.2
W740	Ovan Älgabäcken	29.4	750	741.9	11.76	2
W730	Utloppet av Mossjön	37.2	458.6	384.3	14.88	2.2
W720	Utloppet av Rödvattnet	40.8	438.6	400.9	16.32	2.3
W710	Utloppet av Rannäsa Sjö	40.6	468.6	407.2	16.24	2.3
W700	Ovan Rannäsaån	56.9	438.6	400.9	22.76	2.3
W690	Mynnar i Bolmån	43.3	442.7	402.5	17.32	2.3
W660	Utloppet av Källundasjön	36.1	456.6	419.9	14.44	2.3
W650	Inloppet i Herrestadsjön	44.2	482.6	444.6	17.68	2.4
W640	Utloppet av Nästasjön	38.5	442.7	402.5	15.4	2.3
W620	Utloppet av Herrestadsjön	34.7	390	377.4	13.88	1.9
W610	Utloppet av Kävsjön	39.1	428.9	404.4	15.64	2.4
W600	Inloppet i Hästhultasjön	45.9	464.9	443.3	18.36	1.9
W580	Mynnar i Bongebosjön	28.8	417.9	373.2	11.52	2.5
W570	Inloppet i Bongebosjön	24.6	423.1	395	9.84	1.9
W560	Utloppet av Ryasjön	28.4	421	397	11.36	1.8
W550	Utloppet av Bongebosjön	26.8	503.3	476.4	10.72	2.2
W540	Utloppet av Mosjön	85.1	503.3	476.4	34.04	2.2

Table 2: Reaches and Routing Parameter

Reach	Muskingum K(h)
R30	31.76
R90	31.12
R110	30.4
R120	29.76
R130	29.12
R140	41
R160	40
R210	27.04
R220	26.4
R230	25.8
R250	25.12
R260	39
R270	39
R310	23.6
R330	23.12
R360	22.64
R370	22.08
R380	21.6
R410	40
R440	40
R450	20.08
R460	22
R470	22
R480	22.2
R510	40
R530	20.32