Master Thesis
TVVR 16/5012

Rainfall Runoff Modeling in Kävlinge River Basin with HEC-HMS

Hydrologic Response to the Climate of the Future

Kaitlin Wicher

Division of Water Resources Engineering
Department of Building and Environmental Technology
Lund University

Rainfall Runoff Modeling in Kävlinge River Basin with HEC-HMS

Hydrologic Response to the Climate of the Future

By:
Kaitlin Wicher

Master Thesis

Division of Water Resources Engineering
Department of Building & Environmental Technology
Lund University
Box 118
221 00 Lund, Sweden

Water Resources Engineering
TVVR-16/5012
ISSN 1101-9824

Lund 2016
www.tvrl.lth.se

Master Thesis
Division of Water Resources Engineering
Department of Building & Environmental Technology
Lund University

Swedish title:	Regnvattenavrinningsmodellering i Kävlingeån med HEC-HMS: hydrologisk respons till framtidens klimat
English title:	Rainfall Runoff Modeling in Kävlinge River Basin with HEC-HMS: Hydrologic Response to the Climate of the Future
Author:	Kaitlin Wicher
Supervisor:	Linus Zhang - Department of Water Resources Engineering
Supervisor:	Linda Parkefelt - Sweden Water Research/Sydvatten AB
Examiner:	Kenneth M Persson - Department of Water Resources Engineering/Sydvatten AB
Language	English
Year:	Spring 2016
Keywords:	HEC-HMS, Rainfall Runoff, Kävlinge, Modeling, GIS
Cover Photo:	Bertil Hagberg/Sesamphoto “Vombsjön”

Acknowledgements

I would first like to thank Lund University for the opportunity to study at Lunds Tekniska Högskola, the Faculty of Engineering at Lund University. As a recipient of the Lund University Global Scholarship I was able to complete the two year Master's of Science in Water Resources Engineering with a complete tuition waiver. Without this contribution to my education I would not have been able to have the amazing experience of studying in Sweden.

Thanks should go to Sydvatten AB for providing for me the opportunity to work with Sweden Water Research at their Ideon office and at their headquarters in Malmö. Linda Parkefelt and Kenneth M Persson helped significantly in the initial development of the project. I would also like to thank Linus Zhang for his knowledge of river basin modeling, his encouragement and advice. I would like to thank all my teachers, classmates and colleagues on campus and at the offices for our time spent together and our break time fikas, you have made my time as a student so enjoyable.

Additionally, thanks to the American Army Corps of Engineers Hydrologic Engineering Center for their HEC-HMS software manuals, technical theory documents and support center which have been crucial to the project. Also, the online community of GIS and HEC-HMS users as well as the Army Corps of Engineers who have posted solutions and explanations of the model, your insight has been greatly appreciated.

Abstract

This Master's thesis work was carried out at Lund University’s Faculty of Engineering in conjunction with Sydvatten AB, Southern Sweden's drinking water provider and their research division Sweden Water Research. The purpose of the study was to gain an understanding of the runoff response in the Kävlinge River Basin and study the increased runoff that is expected to occur due to climate change using the modeling program HEC-HMS, the hydrological engineering center of the Army Corps of Engineers Hydrologic Modeling System. Additionally statistical and seasonal patterns were evaluated to provide Sydvatten with a basis for further climate change studies and documentation that assesses the level of risk that is associated for Vomb Lake. The study showed that Sydvatten’s water supply at Vomb Lake is expected to be significantly impacted by climate change and has resulted in percentage estimates of precipitation and flow increases in the basin.

Sammanfattning

Examensarbetet genomfördes vid Lunds Tekniskas Högskola i samarbete med Skånes största dricksvattenproducent Sydvatten AB och det kommunala forskningsbolaget Sweden Water Research AB. Syftet med studien var att få en bättre förståelse av hur avrinningen förväntas ändras på grund av klimatförändringarna. Till hjälp för arbetet har modelleringsprogrammet HEC-HMS, US Army Corps of Engineer's hydrologiska modell Hydrologic Modeling System använts för att modellera olika avrinningsförhållanden i området. Dessutom har statistiska nederbördsmönster utvärderades för att ge Sydvatten AB en grund för vidare studier som behandlar klimatförändringar och dokumentera den tillhörande effekten för Vombsjön. Studien visade att Vombsjön förväntas påverkas avsevärt av klimatförändringar, vilket får stora konsekvenser för Sydvattens möjlighet att ta ut råvatten ur sjön. I rapporten redovisas procentuella uppskattningar av nederbörd och ökade flöden i avrinningsområdet.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Climate change is expected to affect Sweden to a larger degree than the rest of the world according to Lund University's report for a Climate Secure Sweden. Predicted rises in temperature are more prevalent in the north-eastern and eastern parts of Europe during the winter months. Populated regions along the coast of Sweden which has traditionally been a seafaring country will experience a rise in sea level and an increase in annual rainfall. If international climate political ambition is achieved a two-degree overall increase in temperature is expected by 2100. This would be attained if overall greenhouse gas release is reduced 40 to 70 percent by the year 2050 with the hopes of zero or negative release at the turn of the century (Hall et al., 2015).

Extreme weather occurrences such as heavy rainstorms and flooding in waterways are expected to occur more frequently and more intensely even though the number of storms in a year is to go unchanged. Climate modeling suggests that low pressure which comes over the Atlantic Ocean from the west will extend further and shift more north than previously recorded. Thus return periods of storm events will change over time. An increase in temperature is expected to result in rainier summers as well as earlier snow melting. The Climate Secure Sweden report indicates that the same rain storm event estimated from 1961 to 1990 to occur once every 20 years (a 20 year return period) will occur as a 4 to 8 year return period storm at the end of the century (Hall et al., 2015).

Sydvatten AB and its partner company Sweden Water Research are concerned about the impact of climate change on Vomb Lake, one of their sources of water for drinking water production. This study aims to address Sydvatten AB's expectation that climate change will effect water availability. Previous research focused on the minor catchment of Vomb Lake and the effect of agricultural management practices on the quality of water but have neglected to study the entire runoff area into Vomb Lake, Kävlinge River Basin and its hydrologic runoff processes.

Sydvatten AB is a municipally owned business that produces and delivers drinking water to 900,000 inhabitants of Skåne. Lake Vomb is one of their two water sources, the other being a larger lake located farther north in the region of Småland. The Kävlinge River Basin is the source of half of Sydvatten AB's water supply. To study the environmental and organizational reasons for changes in water quality and quantity Sweden Water Research was created by Sydvatten with NSVA and VA Syd, other municipal water actors in Skåne. Sweden Water Research is a recently founded division of Sydvatten that focuses on issues not directly related to their everyday operations.

This study details the characteristics of the Kävlinge River Basin and the expected result of climate change on the river basin in the year 2100 in contrast to recent years. Precipitation is the major form of water input into the hydrologic system and quantity of rainfall is analyzed. Existing research pertaining to the area was gathered for review and a hydrologic model using the US Army Corps of Engineers Hydrologic Modeling System or HEC-HMS was made to quantify these future changes to the water supply. The current tools, theories and equations that govern each aspect of the model will be researched and an appropriate method will be chosen. Measured data from the Swedish Meteorological and Hydrological Institute (SMHI) used as input to the model is evaluated.

HEC-HMS is a public domain dendritic river basin modelling tool developed by the Hydrologic Engineering Center with the American Army Corps of Engineers is considered a standard in for hydrologic simulation in the United States (Hydrologic Engineering Center, 2016). The program which began as HEC-1, first developed in 1992, has been developed into fully integrated graphical user interface. The second major release of the program brought about changes that made it possible to model continuously, during wet and dry periods, with the addition of the soil moisture accounting method as opposed to single storm event simulations (Scharffenberg, 2015). It is a numerical model that includes a large set of methods to emulate watershed, channel, and water-control structure behaviour, thus predicting flow, stage and timing. The HEC-HMS simulation methods represent watershed evaporation and transpiration, runoff volume, direct runoff including overland flow and interflow, base flow and channel flow. Hydrological standards, modern and widely used methods of calculating watershed and runoff behaviors are included in the model. The United States Federal Emergency Management Agency or FEMA widely uses HEC-HMS to mitigate disasters due to flooding (Hydrologic Engineering Center, 2015).

1.2 Problem Description

Climate change is an issue effecting every corner of the globe. Sydvatten AB wants to be prepared for changes in the quantity of water available for drinking water production in Skåne that may occur due to changes in temperature and precipitation in the Kävlinge River Basin. Sydvatten is interested in expanding its research division to address issues that will affect the watersheds where they acquire water to ensure that the company achieves its mission to provide their community partners and citizens with a high quality and even quality of water without unplanned disruptions.

Understanding the hydrological processes of a river basin is fundamental to the creation of an accurate model. While models are always necessarily simplifications of the reality they are meant to mimic, with a focused study and adjustments to model parameters, a true perception of how the most significant processes in the catchment can be formed.

HEC-HMS is used to model the potential changes in conditions in the Kävlinge River Basin including a rise in temperature and an increase in occurrence of heavy rainfall. The objectives of this study is to clarify and quantify the change in runoff in Kävlinge River Basin due to climate change and describe in detail relevant hydrologic characteristics of the basin for future research. Gathered climate change and estimated climate change statistics are presented. A study was carried out for the most recent years 2013 to 2014 to serve as a basis of reference and calibrate. A prediction model was made for the year 2100.

1.3 Study Area

Kävlinge River Basin is located in the southern most Swedish province of Skåne stretching almost entirely from the east Baltic coast to the Öresund Sea in the west. It forms a distorted teardrop shape covering 1,204 square kilometers just north of Lund. The river basin constitutes about half of Skåne and empties into the Öresund (the Penny) Sound. The Kävlinge River Basin landscape is used mainly for agricultural purposes, estimated at 78 percent. A few small towns dot the landscape.

Vomb Lake is located centrally in the Kävlinge River Basin and is 12 km^2 in size. Vomb Lake provides on average 1.2 m^3 of water per second to the water treatment facility Vombverket located nearby. Burlöv, Malmö, Staffanstorp, Svedala, Vellinge as well as parts of Lund and Eslöv are served by water produced from this facility (Sydvatten AB, 2016). The outline and location of Kävlinge River Basin can be seen in Figure 1. Major cities are shown in orange and municipality borders in grey.

Figure 1- Kävlinge River Basin

The confluence of the rivers in the basin occurs after Vomb Lake and the main outflowing river branch is named Kävlingeån River. Ån meaning stream in Swedish. There are two main stretches of river that effect the outgoing flow of Vomb lake, the Klingavälsån which meets the Kävlingeån directly after Vomb lake and the Björkaån branch that is the main source of flow into Vomb. The Bråån River flows directly east meeting the Kävlingeån close to the mouth of the river. The river basin and its reaches in nearly all of its complexity is shown in Figure 2.

Figure 2 - Vomb Lake and Kävlinge River Branches (SMHI)

The upstream portion of the basin Björkåån and Klingavälsån are only considered in this study since the aim of the project is to estimate changes in the Kävlinge River Basin that would directly affect the availability of water in Vomb Lake. These river branches have precipitation that flows into Vomb Lake. The components of the hydrologic model are explained in the technical theory that is contained in later sections.

2 Predicted Climate Scenario

The Swedish Meteorological and Hydrological Institute's RCP8.5 climate change model data is used to elucidate the effects of climate change on the Kävlinge River Basin. Research at SMHI is often focused on the RCP8.5 climate change scenario which assumes little change in current greenhouse gas emissions and is chosen to be the focus for this study. The RCP8.5 climate change model predicts solar radiation to increase to 8.5 W/m^2. This case is neither overly optimistic nor pessimistic about the ambitions of scientists and governmental agencies to curb climate change.

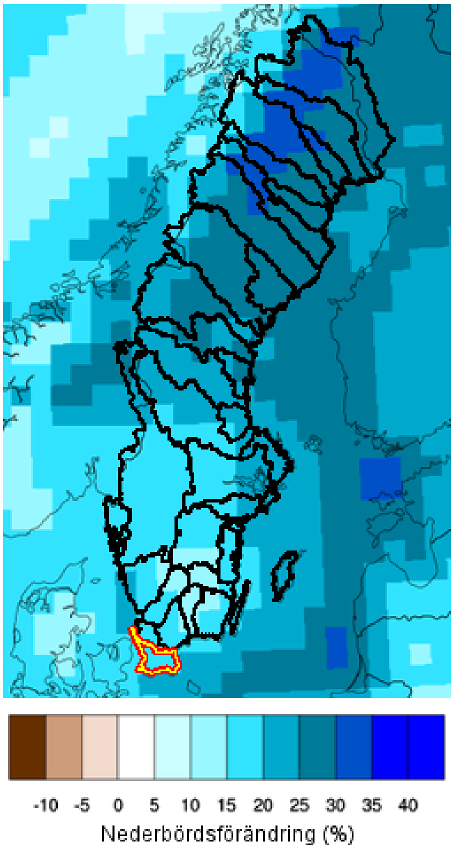


Figure 3 - RCP8.5 Model Average Percent Increase in Precipitation: 1971-2000 compared to 2000-2100 (SMHI)

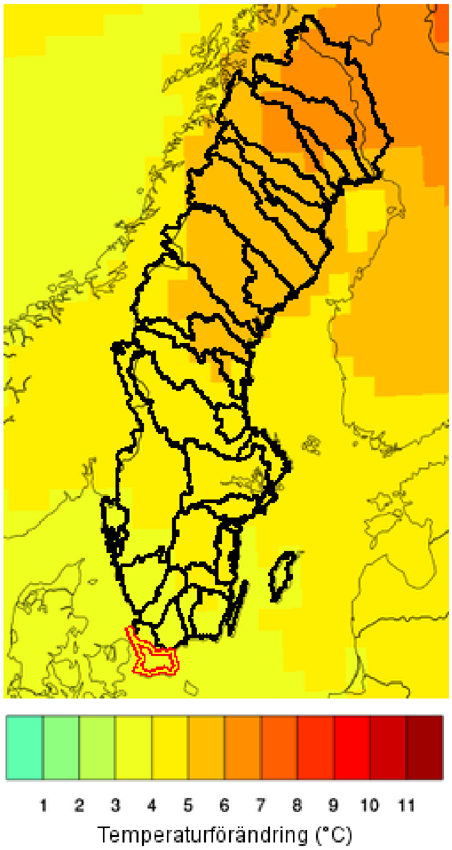


Figure 4 - RCP8.5 Average Increase in Temperature: 1971-2000 compared to 2000-2100 (SMHI)

Figure 3 shows the change in precipitation (nederbördsförändring) in percent throughout Sweden as estimated by the SMHI RCP8.5 climate model. The model compares the averages computed for historical data during the period of 1971 to 2000 to the predicted values for the period 2000 to 2100. In Skåne, the area outlined in yellow in Figure 3 the change in precipitation is predicted to be between 15 and 20 percent.

Figure 4 shows the estimated increase in temperature in Sweden according to the average of the nine global climate models studied by SMHI. In Skåne the temperature is expected to be 4.31 degrees Celsius warmer in the year 2100 compared to the period of reference 1971-2000, with a maximum expected increase of 6 degrees and a minimum of 3 degrees. The temperature increase of 4.31 degrees Celsius served as the basis for the predictive climate scenario. The figure shows that the most northern regions of Sweden will warm at a faster rate than the southern regions. Norrland can expect a temperature increase of six to seven degrees.

In Figure 5 the percent change in yearly precipitation values is seen for the time period used as reference 1961 to 1990 and the predicted continuation of these patterns in Skåne. The data is based off of nine climate change models including RCP8.5 models from Canada, France, the European Union, Japan, the United Kingdom, Germany, Norway and the United States. More information about the models used by each country and their parameters can be found on the website for the Swedish Meteorological and Hydrological Institute.

The black line in the center in Figure 5 indicates the percent change in the average precipitation in Skåne according to the average of nine global climate change models. The grey field shows the variation between the climate models, the highest and lowest values. The yellow bars rising above average indicates rainfall higher than normal measured from historical data and the bars below average indicate the rainfall less than average based on historical data. This graph shows visually the steady increase in precipitation to a twenty percent increase in average yearly precipitation values by the year 2100.

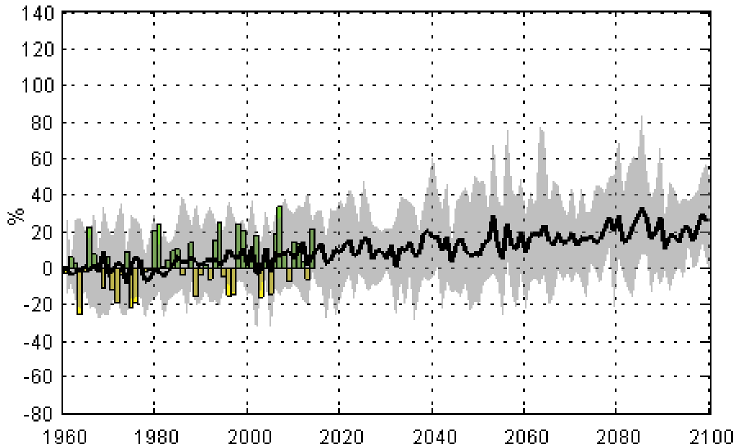


Figure 5 - Percent Change in Yearly Precipitation in Skåne: average values of years 1961-2100 compared to 1961-1990 (SMHI)

Table 1 summarizes the data from SMHI's average of the nine RCP8.5 global climate scenarios mentioned above for the region of Skåne. In percentage you can see the yearly variation among the early 2000 years, year 2008 to 2014. These years were chosen because they are the most recent years that also had a complete available set of measured weather data for the Kävlinge River Basin. The percentage 25.1% for the year 2100 was used to modify available precipitation gauge data to a dataset for a future model scenario. Variation from year to year is evident in this graph. The reference period has a yearly precipitation average of 642.1 mm. The year 2100 with a 25.1 percent increase is expected to have a yearly precipitation average of 803.3.

Table 1 - Increase in Yearly Precipitation in Skåne: Average climate model predicted percent increase from average values from the period 1961-1990

YEAR	2008	2009	2010	2011	2012	2013	2014
%	7.7	9.4	5.2	8.7	14.2	1.6	6.4

YEAR	2094	2095	2096	2097	2098	2099	2100
%	21.6	22.4	14.4	22.4	29.9	25.0	25.1

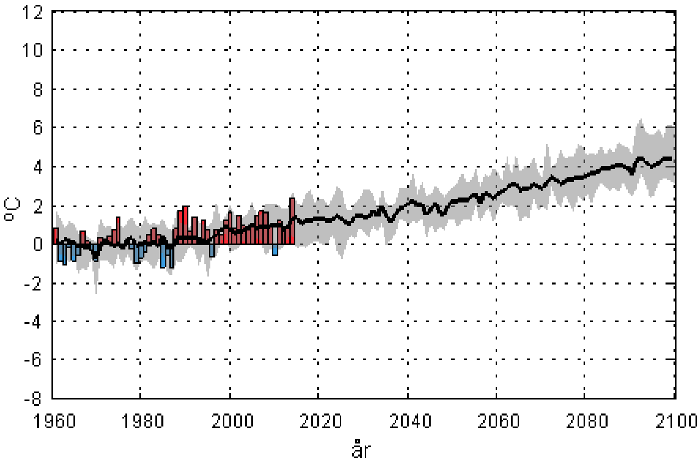


Figure 6 - Percent Change in Yearly Temperature in Skåne: average values of years 1961-2100 compared to 1961-1990 (SMHI)

For comparison and for the sake of comprehensiveness the values of percent increase in average yearly rainfall for the entirety of Sweden are included here, in Table 2. The time frame and method at arriving at these values are the same as those for Table 1. It is clear that climate predictions for Sweden indicate a greater increase in precipitation than that of Skåne. The average increase in precipitation for the years 2008 to 2014 is 6.3 percent while the average increase in precipitation estimated for the years 2094 to 2100 is 28.0. The average increase in precipitation for the year 2100 is slightly higher for the Sweden as a whole when compared to the Skåne region, 27.1 to 25.1 percent.

Table 2 - Increase in Yearly Precipitation in Sweden: Average climate model predicted percent increase from average values from the period 1961-1990

YEAR	2008	2009	2010	2011	2012	2013	2014
%	7.9	7.5	5.0	9.2	4.7	3.8	6.3

YEAR	2094	2095	2096	2097	2098	2099	2100
%	27.5	28.3	20.0	32.3	28.9	32.2	27.1

Predicted values for runoff from an HBV model using the RCP8.5 scenario model provides an image of how the Kävlinge river basin will respond to changed meteorological conditions. The one year mean, ten year mean, one hundred year mean, and two hundred year mean change in return period compared to the reference period is provided in Table 3 and Table 4. The one year mean return period increase is 6.24 for the period 2008 to 2014 as compared to the period of reference, years 1963 to 1992. The percent increase is 5.2 for the ten year return period and 6.9 for the one hundred year return period.

Table 3 - Percent Increase in Runoff in the HBV RCP8.5 Scenario Model in Kävlinge River Basin (compared to average values of reference period 1963-1992)

	2008	2009	2010	2011	2012	2013	2014
1-YEAR MEAN	6.0	11.3	5.6	3.2	18.5	-0.2	-0.7
10-YEAR MEAN	4.3	5.0	4.9	4.3	4.8	6.2	6.8
100-YEAR MEAN	6.5	7.1	6.7	5.9	6.2	7.8	8.5
200-YEAR MEAN	6.9	7.5	7.1	6.3	6.5	8.1	8.8

Table 4 shows the percent increase in runoff projected by SMHI's predictive model. The one year mean is expected to rise to around a 12 percent (average from 2096 to 2098) runoff increase, the ten year 30 and the hundred year 33.

Table 4 - Percent Increase in Runoff in the HBV RCP8.5 Scenario Model in Kävlinge River Basin (compared to average values of reference period 1963-1992

	2096	2097	2098
1-YEAR MEAN	5.3	9.2	22.5
10-YEAR MEAN	30.2	30.6	29.3
100-YEAR MEAN	33.5	33.7	31.4
200-YEAR MEAN	34.1	34.3	31.8

3 HEC-HMS Model

3.1 Model Components

The model is divided into three components a physical basin model, a meteorological model and control specifications. HEC-GeoHMS, the GIS-based physical basin model preparation tool for HEC-HMS, was used to delineate the river basin using GIS capabilities in ESRI's ArcMap. Mathematical methods to describe the transfer and exchange of water between the meteorologic model and the physical model are explained in the section Technical Theory of Methods.

The spatial distribution information was derived from GIS maps using HEC-GeoHMS, a HEC-HMS extension tool developed specifically to prepare a physical basin model for the program. A digital elevation map or DEM is used to assess the direction of water flow, subbasin centroids and lag time to calculate runoff. The river basin model is assigned properties taken from land coverage maps such as imperviousness, land use and subbasin area. Geospatial maps were thereafter formed as input to HEC-HMS modelling program.

All files of the meteorological model were first stored and managed using the HEC-DSS, the Hydrologic Engineering Center Data Storage System. Time series data was downloaded from SMHI to include the meteorological components such as precipitation, temperature and sunshine hours and relative humidity for evapotranspiration. Additional time series data, flow records, were added to the data management system but were only used as an objective function for calibration. Tables for snow melt, cold melt rate and wet melt rate were also input. The basin model and meteorological files were uploaded to the HEC-HMS interface where control specifications were entered and modified between model runs.

Control specifications are defined in the HEC-HMS program interface to define the run time of each model. Control specifications include starting date and time, ending date and time and the computational time step.

3.2 Summary of Hydrological Processes

HEC-HMS's Technical Reference Manual provides the schematic Figure 4 an outline of the processes modeled in HEC-HMS. Snowmelt computation is the only process that is not shown in the diagram. Precipitation falls on the earth's surface directly on the ground, on the vegetation cover or on a body of water. Evaporation can occur from the vegetation cover, the water bodies or the land surface but transpiration only occurs from the vegetation. Transpiration is the process by which groundwater is taken in by plant roots and is then released into the atmosphere as vapor from leaf surfaces.

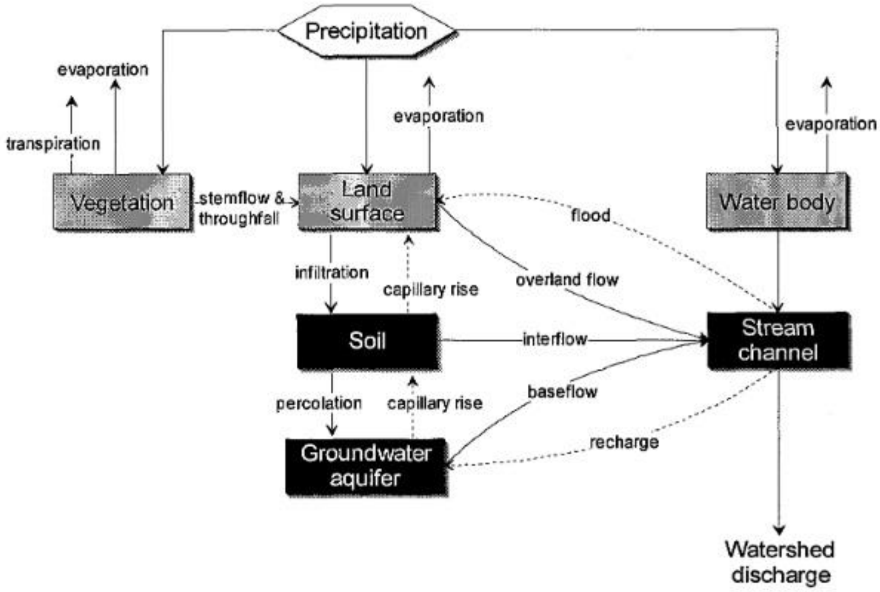


Figure 4 - Runoff Processes at a Local Scale (Scharffenberg, 2015)

Water infiltrates into the soil which may be transported away as interflow or sink deeper into the soil, percolating into the groundwater aquifer. Water runs directly off of the surface as overland flow during periods of soil saturation typical of heavy rainstorms. The groundwater aquifer can receive water from the stream channel as recharge or release water to the stream channel as baseflow. Capillary rise occurs from the groundwater aquifer to the soil layer and from the soil layer to the surface layer. The water flows the length of the stream channel until it reaches the river basin outlet. Watershed discharge is calculated at this river basin outlet.

3.3 Physical Basin Model

Geospatial maps served as the basis for the creation of the physical basin model. Elevation maps and subbasin boundaries were used to estimate subbasin lag time, reach length, reach slope and subbasin area. Figure 5 shows the final physical basin map used in the HEC-HMS model.

Figure 5 - Physical Basin Model in HEC-HMS

3.3.1 Digital Elevation Model

A 50 meter by 50 meter digital elevation map was downloaded from the Swedish National Land Survey's (Lantmäteriet) Geoportalen, an open GIS database. Reconditioning of the digital elevation model was necessary to modify the map so that it is useful for hydrologic modelling. Reconditioning 'burns' in streams since most elevation maps do not properly show the elevation of stream beds. This process modifies that elevation map to artificially drop the elevation at the locations of the input stream map. A data preparation tool called Fill Sinks is also used to prevent storage of water in upstream concave surface areas that would normally allow water to infiltrate and flow downstream.

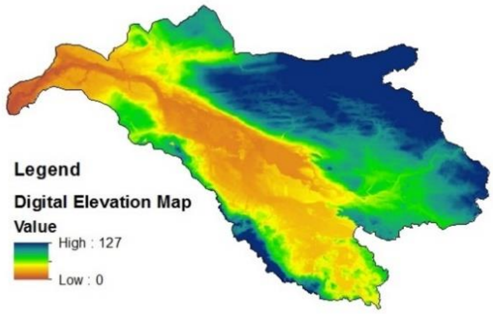


Figure 6 - Digital Elevation Model

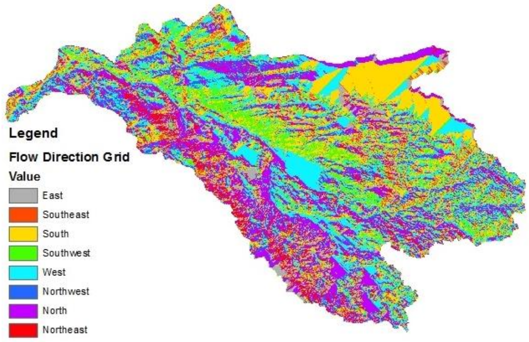


Figure 7 - Flow Direction Grid Map

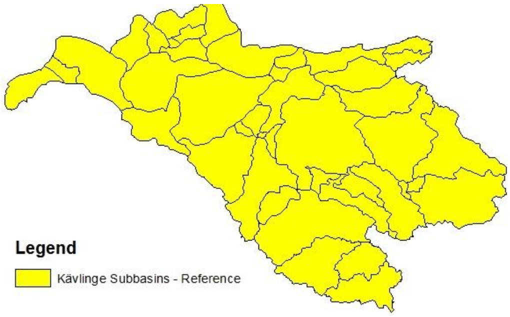


Figure 8 - SMHI Defined Subbasins

Figure 9 - Modified Modeled Subbasins

Figure 10 - Agree DEM with Original Streams

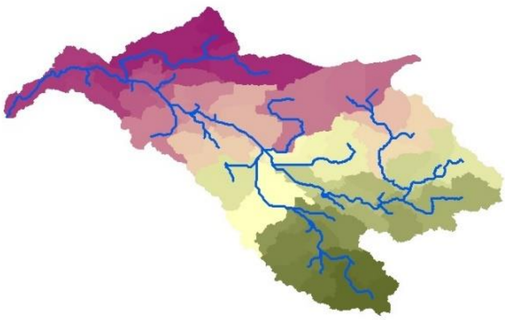


Figure 11 - Modeled Stream Links

3.3.2 Soil Types and Land Cover

GIS soil type maps were sourced from the Geological Survey of Sweden (Sveriges Geologiska Undersökning) and land use maps from the Swedish Department of Agriculture (Jordbruksverket). Soil is classified based on its physical properties as well as its method or time of formation. For the purpose of this study the rate of infiltration was of highest importance so the soil layer was modified accordingly to group similar soil types suitable for use in the HEC-GeoHMS model.

Layers defining soil types in the river basin were reviewed and simplified into four main categories clay, silt/sandy silt/clayey sands/till, silty sands/fine sands and well sorted sands/glacial outwash. These classifications are shown in Figure 12. Clays were combined into one category shown as green. Postglacial fine clay, postglacial clay, postglacial coarse clay, glacial fine clay, glacial coarse clay, saprolite and all varieties of till were included. Light blue is assigned to the soil types fitting into the category described by silt/sandy silt/clayey sand/till which is often labeled moraine meaning it is poorly sorted glacial wash out. Orange includes silty sands and fine sands. Yellow is assigned to glaciofluvial sediments known as 'isälvsediment' sand and postglacial sand for the category well sorted sands/glacial outwash.

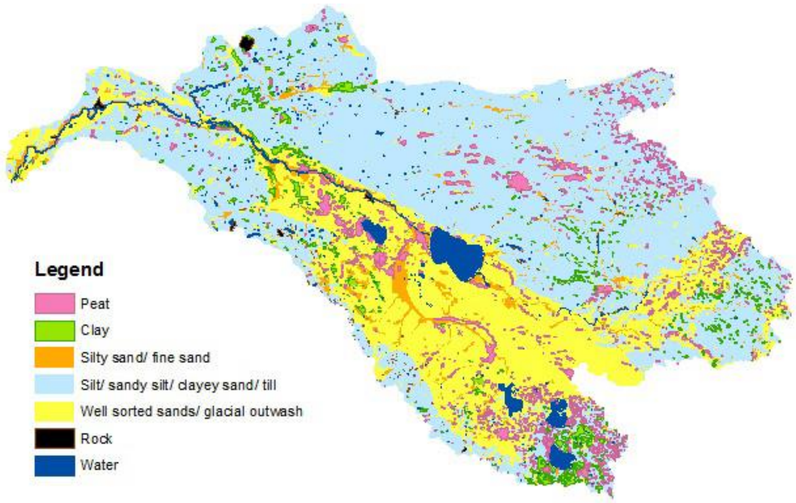


Figure 12 - Soil Type Classifications

Other land classes that did not fit into a specified category were peat (in purple) and rock (in black). Several types of peat were grouped together: bog peat, fen peat, peat and gyjtja. A category of rock outcroppings was created from the categories for crystalline rock 'urberg', Phanerozoic dolerite 'Fanerozoisk diabas', and sedimentary rock. Major lakes labeled water is colored dark blue and included for visual orientation.

Till which is Sweden's most common land type, covering around 75 percent of the landmass, is the most significant in Kävlinge River Basin (Sveriges Geologiska Undersökning). The riverbed is hugged by varying types of sand and glaciofluvial sediments. There are scattered patches of peat, larger patches near the main lakes and smaller patches throughout the basin. Less than a dozen major rock outcroppings occur in the river basin. Clay is present in large amounts near the southern lakes and the north-eastern area but in much less significant portions than silt and sands.

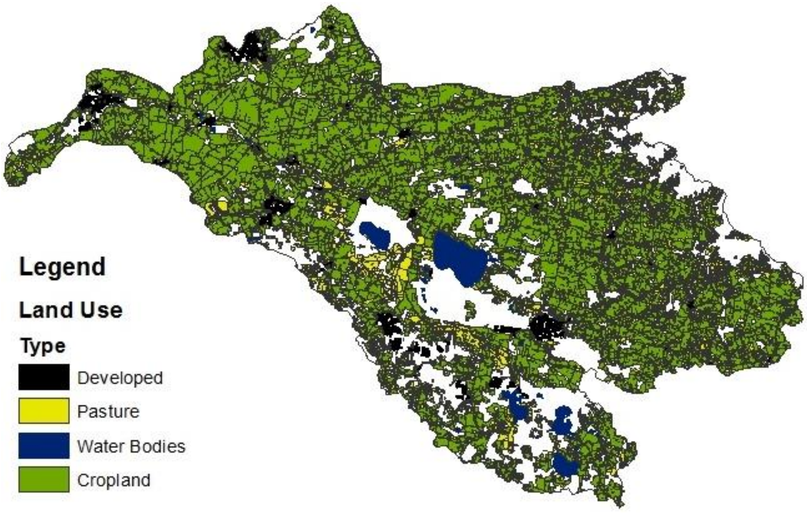


Figure 13 - Land Use Classifications

Figure 13 maps out the land use throughout the river basin. GIS maps from Lantmäteriet provided highly detailed visuals of the amount of developed and farmed land in the Kävlinge River Basin which were then recategorized to be presented in a logical manner for this study. Imperviousness that may have been created by developed land can be seen. Black areas in Figure 13 show the location of buildings and paved land. The blue shows locations of bodies of water. Much of the white space can be attributed to marshland. Cropland is in green with the boundaries of each plot in grey, some areas of pastureland are also present. Estimates of imperviousness were entered into each subbasins physical model characteristics.

3.4 Meteorological Specifications

Daily time series data were used for all of the input data besides solar radiation, relative humidity, and sunshine which were all included as hourly time-series data. Nine gauges were used to describe the temporal variation in temperature and precipitation. In this study each of the nine gauges monitored both temperature and precipitation.

Certain hydrologic parameters such as air pressure and air temperature show strong correlation to elevation. As elevation increases both air pressure and air temperature decrease (Scharffenberg, 2015). Relative humidity data was available for the basin in this case which has a positive correlation to elevation, the opposite of air pressure. Because these atmospheric characteristics are highly dependent on elevation, in order to estimate values for regions other than the location where the measurements were taken, a reference elevation height for each basin was added into the model.

ArcGIS was used to calculate the area where the influence of one precipitation gauge would end and another precipitation gauge would be assumed to have influence. This was done be creating perpendicular bisectors. Theissen polygons were created to define which subbasins were affected by which gauges. Theissen polygons are area-based weighting scheme that assumes the precipitation read at the gauge to be constant in the area associated with that gauge.

3.4.1 Shortwave Radiation - FAO56

Shortwave radiation is defined as the sunrays that reach the earth. It is visible light and ultraviolet light. Cloud cover can reduce the amount of rays that make it to the soil surface (Scharffenberg, 2015). Inclusion of shortwave radiation data is important when modelling continuously in connection with the Soil Moisture Accounting Method (State Climate Office of North Carolina, 2013).

3.4.2 Longwave Radiation - FAO56

Longwave radiation is defined as indirect radiation. It is the energy emitted or radiated from the clouds, the atmosphere and the surface of the earth (Scharffenberg, 2015). Longwave radiation also called infrared light has less energy than shortwave radiation (State Climate Office of North Carolina, 2013).

3.4.3 Precipitation - Gauge Weights

Precipitation includes rain and more solid forms such as snow. The distribution of precipitation over the river basin was specified using the Gauge Weights Method. Using ArcGIS Thiessen polygons were constructed that used perpendicular bisectors to define which rain gauges affect which subbasin. Figure 13 shows how the weather data was divided between the subbasins. Note that the temperature data was collected at the same weather stations and temperature data was distributed in the same manner (Scharffenberg, 2015).

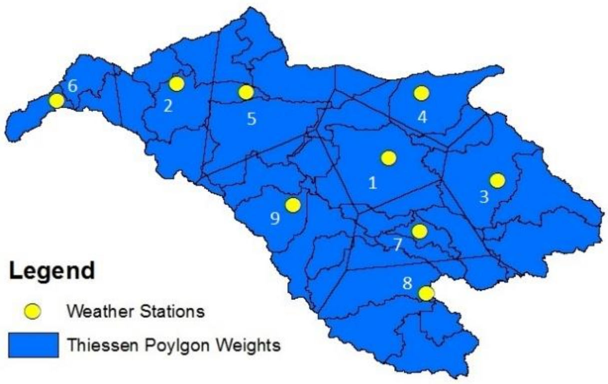


Figure 14 - Precipitation Gauges with Polygons

3.4.4 Evapotranspiration - Monthly Average

The Monthly Average Method was chosen for the Evapotranspiration modelling. Evapotranspiration is a term combining water evaporating from the land surface and water evaporating from vegetation as well as water transpiring from plant roots to the atmosphere. Transpiration is responsible for most of the water transfer and is the source from which an estimate sixty percent of all water returns to the atmosphere. Potential evapotranspiration is the limit to how much water can be taken up or returned to the atmosphere. This depends on water holding capacity of the air which is defined by the atmospheric conditions. In HEC-HMS modeling the actual evapotranspiration is based on the soil water limitations (Scharffenberg, 2015).

The Monthly Average Method is the most elementary method for modeling evapotranspiration. Using monthly ranges for the amount of precipitation in the Skåne region from the Centre for Ecology and Hydrology and an estimated yearly evapotranspiration average from SHMI the millimeters of transpiration (EU Water and Climate Change Project, 2016).

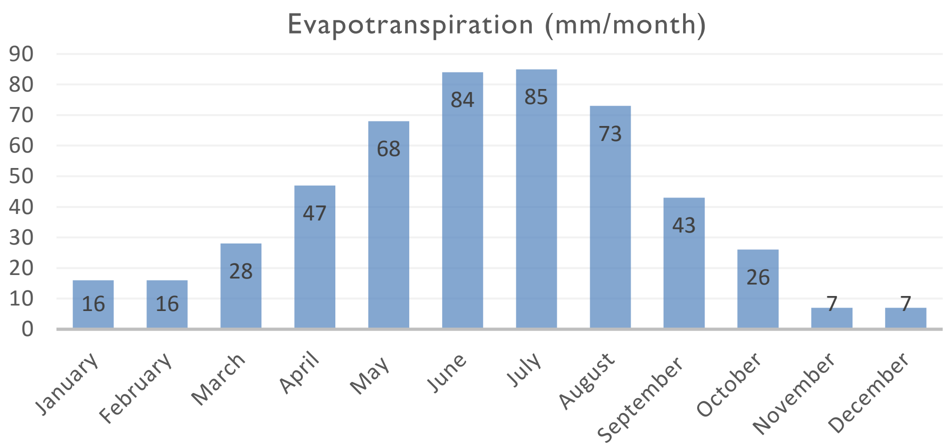


Figure 15 - Input Evapotranspiration Limits

3.4.5 Snowmelt - Temperature Index

Snow is not a common form of precipitation in Skåne but a snowmelt calculation method, the Temperature Index Method, was included to ensure a comprehensive model. Snowpack retains fallen snow and absorbed rain preventing it from contributing to normal runoff. When temperatures rise above zero degrees Celsius snow begins to melt. Snow often undergoes a cycle of melting and refreezing within the snowpack forming crystals. SWE or snow water equivalent is a means of measuring the amount of water found in a snowpack (Scharffenberg, 2015).

The Temperature Index Method is an extension of the degree-day approach to snowpack modeling. Here a melt coefficient changes depending on the atmospheric and internal snowpack conditions. This melt-rate relationship is defined as linearly increasing with temperature in this study. The Temperature Index Method only moderately incorporates previous conditions and models separately each subbasin. A Px Temperature is given which defines at what temperature the rain falling will be modeled as snow fall (Scharffenberg, 2015). The temperature index is the difference between the gauge temperature and the defined base temperature. When the difference between the two is zero no snowmelt occurs. The base temperature is recommended to be set at zero degrees and consequently set at 0 degrees Celsius.

Included variables are Meltrate (mm/deg C-Day), the ATI-Meltrate Coefficient, Rain Rate Limit (mm/day), cold limit (mm/day), an ATI-Coldrate Coefficient, percent water snowpack capacity, groundmelt and functions for ATI meltrate and coldrate. Base temperature and Px temperature are included as mentioned.

3.5 Control specifications

The control specifications define the time interval and time step for the period to be modelled. An exact time and data is given for the beginning of the simulation in addition to the end time and date. The period of study was limited by the amount of available data in the area. Precipitation and temperature data was available from several gauges within the basin. Radiation and sunshine data from gauges located in Kävlinge river basin were not available but a gauge close to the basin in Lund was used.

Because these inputs are required for continuous studies the study period the availability of these radiation and sunshine data was the limiting factor. This gauge only collected data from the beginning of 2013. The time period for the study was chosen to be January 1st 2013 to Dec 31st 2014. The future climate situation is modeled using modified data for the entire year 2014. When the time interval of the data does not concur with that of the simulation run time interval the missing data is automatically linearly interpolated (Scharffenberg, 2015).

4 Technical Theory of Methods

River basin hydrology is driven by precipitation and evapotranspiration as well as the soil characteristics and basin slope. The mathematical methods used to describe the natural processes of translating precipitation into stream flow and stream flow to the outlet are described by the following methods. HEC-HMS provides several methods for each process, one is chosen.

For water lost to the ground the Soil Moisture Accounting Method was chosen. To describe how water runs off surfaces in a subbasin area moving towards the outlet the Soil Conservation Survey Unit Hydrograph (SCS UH) Method was chosen for water translation. Channel flow is described using the Muskingum-Cunge Routing method.

A basic threshold method was chosen for creation of a vegetation canopy and surface using the Simple Canopy and Simple Surface Methods. Baseflow was simulated using the Linear Reservoir Baseflow Method which is normally used in conjunction with the Soil Moisture Accounting Method for groundwater loss. These processes are further described in the following sections and are summarized from the Hydrologic Engineering Center's HEC-HMS User's Manual Version 4.1 (Scharffenberg 2015).

4.1 Loss Method – Soil Moisture Accounting

The Soil Moisture Accounting Method calculates water loss to groundwater for periods of both wet periods (rainfall is occurring) as well as dry periods, accordingly the Soil Moisture Accounting Method is suitable for continuous modelling and was used in this study. This loss method water movement on vegetation, through the soil surface and profile, and in groundwater. Flow in and out of the layers are computed for every time step.

These three layers of the soil moisture accounting loss method compute canopy and surface interception, soil storage (tensions storage and gravity storage) and upper groundwater and lower groundwater percolation. The groundwater layers do not try to simulate interaction with the underlying aquifer but models rather shallow interflow processes.

The canopy stores water up to a set maximum after which excess flows to the surface. Any surface depressions are filled, also until a set maximum, then infiltrates in to the soil at a defined rate. If the flow to the soil layer exceeds the infiltration rate the excess flow occurs as runoff.

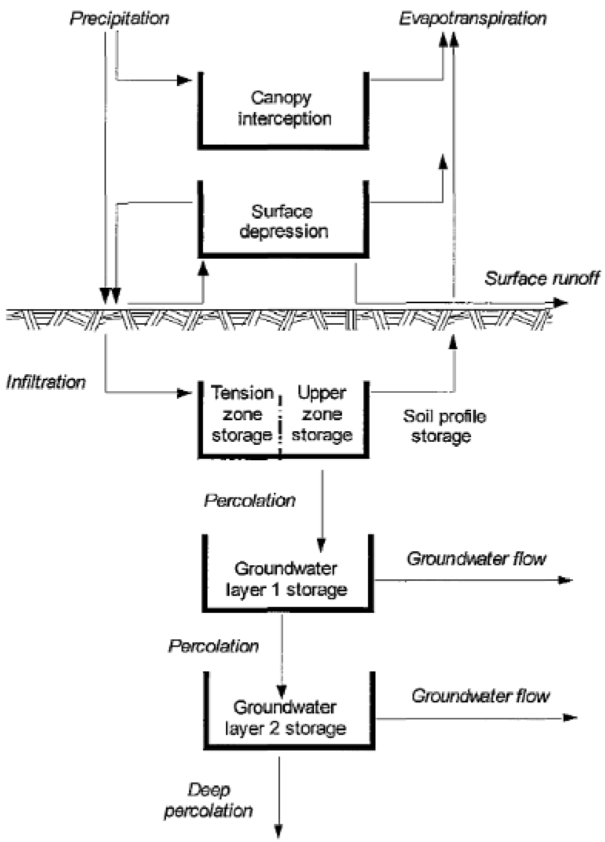


Figure 16 - Soil Moisture Accounting HEC HMS (Feldman, 2000)

Outflow from the surface and soil profile can occur in the form of evapotranspiration. The soil profile has an upper storage zone and a tension storage zone. The upper storage zone holds water in its pores and can lose water to percolation or evapotranspiration. The tension zone storage loses water to evapotranspiration and represents water attached to soil particles (Scharffenberg, 2015).

4.2 Transform Method – SCS UH

Transformation refers to the translation of precipitation over the area of a subbasin to a volume of water output at the subbasin outlet. Hydrographs are empirical methods of depicting runoff of excess precipitation in a linear manner so if two times as much excess precipitation occurs then twice the hydrograph ordinates is produced!!!!!! The method chosen here is the SCS Unit Hydrograph. This method by the Soil Conservation Survey provides a generalized unit hydrograph using parameters to define the shape of the runoff response hydrograph. The unit hydrograph peak and estimated time to peak are defined by the following relationship.

$$U_p = 2.08\,\frac{A}{T_p}$$

$$T_p = \frac{\Delta t}{2} + t_{lag}$$

Where Δt is the excess precipitation duration which is also the computational interval to the run and tlag is the basin lag, the time between the peak of precipitation of a rainfall event and the peak of the runoff volume. The computational interval must be less than .29 times the basin lag to result in adequate parameter definition. This method assumes that the precipitation is distributed evenly over the area and is constant during each interval, Δt (Feldman, 2000).

4.3 Routing Method – Muskingum-Cunge

The Muskingum-Cunge routing method describes how water is translated or flows down the river channel. This method is a simple standard in channel routing that stem from the continuity and momentum equation but includes parameters that are not physically based. The basis of the method from the lateral flow

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_t$$

and the diffusion form of the momentum equation

$$S_f = S_o - \frac{\partial x}{\partial y}$$

are combined using a linear approximation yields the convective diffusion equation. C is wave celerity (dQ/dA) and μ is hydraulic diffusivity ($Q/2BS_o$). B is the top width of the channel.

$$\frac{\partial Q}{\partial t} + c\frac{\partial Q}{\partial x} = \mu\frac{\partial^2 Q}{\partial x^2} + cQ_L$$

The partial derivatives are approximated using the finite difference method.

$$O = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} + C_4(q_L \Delta x)$$

where

$$C_1 = \frac{\frac{\Delta t}{K} + 2X}{\frac{\Delta t}{K} + 2(1-X)}$$

$$C_2 = \frac{\frac{\Delta t}{K} - 2X}{\frac{\Delta t}{K} + 2(1-X)}$$

$$C_3 = \frac{2(1-X) - \frac{\Delta t}{K}}{\frac{\Delta t}{K} + 2(1-X)}$$

$$C_4 = \frac{2\frac{\Delta t}{K}}{\frac{\Delta t}{K} + 2(1-X)}$$

with $K = \Delta x/c$ and $X = 0.5(1 - Q/BS_o c\Delta x)$

The variables C, Q and B change over time, being recalculated every time step (Δt) and every distance step (Δx). A suitable choice of the time and distance steps is crucial to produce accurate results and provide for calculation stability. Several guidelines for selecting an appropriate time step can be found in the HEC-HMS Technical Reference Manual. The distance step is then calculated as Δx = c Δt. The distance step is constrained by the equation

$$\Delta x = \frac{1}{2}\left(c\Delta t + \frac{Q_0}{BS_0c}\right)$$

where Q_0 is the reference flow, calculated from the equation below. Q_b is baseflow and Q_{peak} is the hydrograph's inflow peak.

For this study channel width was estimated from detailed GIS maps of the rivers in the basin and Manning's n or roughness coefficient is estimated for each stream length, both required input for the Muskingum-Cunge method. The Manning's number is set as .04 for each reach and the shape of the reaches are designated as 3 to 1. Channel width at different locations along the river's length is measured and used to enter individual reach width. The Manning's number is estimated as a clean winding natural streamflow with some pools and shoals with type normal (FishXing, 2004).

4.4 Canopy Method – Simple Canopy

Plants on the landscape that intercept water before reaching the ground is called groundcover or vegetation canopy. Adding a canopy layer is required for continuous simulation in conjunction with the Soil Moisture Accounting Method. Water that has been intercepted by the canopy layer evaporates when it is not raining. Water is taken up by the roots of the plants in the process called transpiration. With the simple canopy method all rain is taken up by the canopy until the storage capacity is filled, after the limit is reached all water falls to the soil surface. Potential evapotranspiration occurs first in the HEC-HMS model from the canopy, then the soil layer if the potential evapotranspiration has not yet been reached.

4.5 Surface Method – Simple Surface

The surface method layer allows for water to infiltrate into the ground and allows the surface to hold water even during periods when no precipitation is falling. Agricultural land if tilled can have a highly varying surface in which case it is important to include a surface model. For continuous simulations a surface layer is required. The simple surface method was chosen.

4.6 Baseflow Method – Linear Reservoir

The Linear Reservoir Method is the baseflow method used in conjunction with the Soil Moisture Accounting Method. This methods simulates baseflow and water storage as water retention and movement through reservoirs. This process is linear, the outflow is a linear function of the average storage in the reservoir at each time step. The outflow from both groundwater layer reservoirs are computed and combined to find the total baseflow. The Linear Reservoir Method corresponds mathematically to the Clark Unit Hydrograph Method model of runoff response (Scharffenberg, 2015).

5 Study of Input Data

Input data to the hydrologic model included time-series data in the form of values per day or per hour, tables and parameters that are specific to each of the hydrologic processes. Summarized data on precipitation, temperature and flow are discussed in this section.

5.1 Precipitation and Temperature Data

SMHI's Luftwebb provided the precipitation data for nine precipitation gauges in the river basin for the rainfall runoff study in HEC-HMS. Nine evenly distributed points throughout the basin were chosen and the temperature and precipitation data there were taken from the SMHI database. This PT HBV model data is in effect interpolated from nearby weather stations and were not actual weather gauges in Kävlinge River Basin. No weather stations are located in the basin to use measured data. Several tables and figures were created to illustrate the distribution of precipitation and the change in precipitation and temperature with time.

Table 5 summarizes the average rainfall at each gauge station from the years 2008 to 2014. Standard deviation was calculated between gauges and years.

Table 5 - Standard Deviation in Average Annual Rainfall (between gauges and years)

	2008	2009	2010	2011	2012	2013	2014	SD
Gauge 1	2.15	1.85	2.09	2.19	2.04	1.84	2.43	0.20
Gauge 2	2.12	1.84	2.10	2.24	1.93	1.78	2.40	0.22
Gauge 3	2.17	1.87	2.19	2.19	2.17	1.91	2.44	0.19
Gauge 4	2.29	1.99	2.25	2.33	2.20	1.99	2.60	0.21
Gauge 5	2.23	1.93	2.16	2.31	2.03	1.86	2.51	0.23
Gauge 6	1.98	1.72	1.99	2.13	1.79	1.64	2.20	0.21
Gauge 7	2.02	1.74	2.04	2.08	1.97	1.76	2.30	0.19
Gauge 8	2.02	1.72	2.14	2.08	2.03	1.80	2.29	0.20
Gauge 9	2.04	1.75	2.08	2.14	1.92	1.77	2.35	0.21
SD	.11	.10	.08	.10	.13	.11	.13	

To see the distribution of rainfall over the basin the precipitation data was graphed. Figure 17 shows that there are slight changes in precipitation over the area and that changes in distribution of precipitation in the basin will not be a major cause of change in flow. Therefore spatial variation is not likely important to a prediction of precipitation of the future.

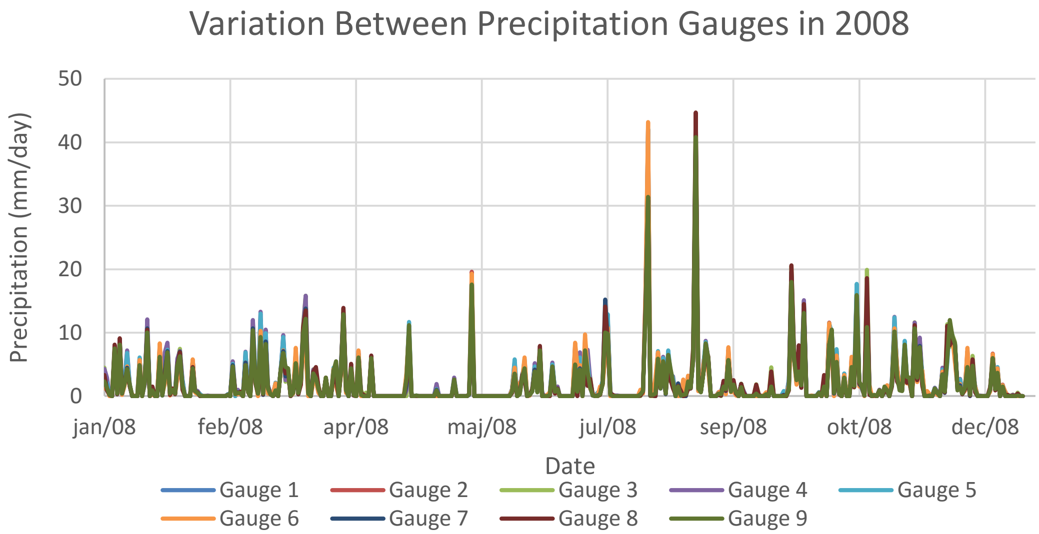


Figure 17 - Luftwebb 2008 Precipitation Data

Kävlinge River Basin does not encompass a large enough area for large changes in temperature to occur to be significant. Figure 18 shows the change in temperature from gauge to gauge. Differences are not significant enough to encourage further study of weather patterns and storm distribution in the basin.

Table 5 - Precipitation Gauge Statistics Summary for year 2100 (mm/day)

GAUGE	1	2	3	4	5	6	7	8	9
Minimum	0	0	0	0	0	0	0	0	0
Quartile 1	0	0	0	0	0	0	0	0	0
Median	0.36	0.35	0.32	0.48	0.37	0.27	0.27	0.31	0.31
Quartile 3	2.99	2.85	3.06	3.45	3.00	2.58	2.87	2.98	2.79
Maximum	33.67	31.31	33.28	34.48	32.45	28.35	32.63	30.71	33.88

5.2 Flow Measurements

Flow data recorded by SMHI for recent years were used as a means of studying the runoff patterns in Kävlinge River Basin up until the runoff reaches Vomb Lake. The precipitation gauge station numbered nine in Figure 14 shows the location of the precipitation gauge which in Figure 18 this is the approximate location of the south flow recording station numbered 2116. Gauge 2116 is the stream flow calibration point for the model using Klingavälsån station data in the southern upstream region of the basin only a few tens of meters from the actual recording point. The Björkaån station in the northern region upstream of Vomb Lake is at the junction located nearest the precipitation gauge station numbered three in Figure 14, junction J233 in Figure 18. Vomb Lake outflow is shown at Junction 327 (J327).

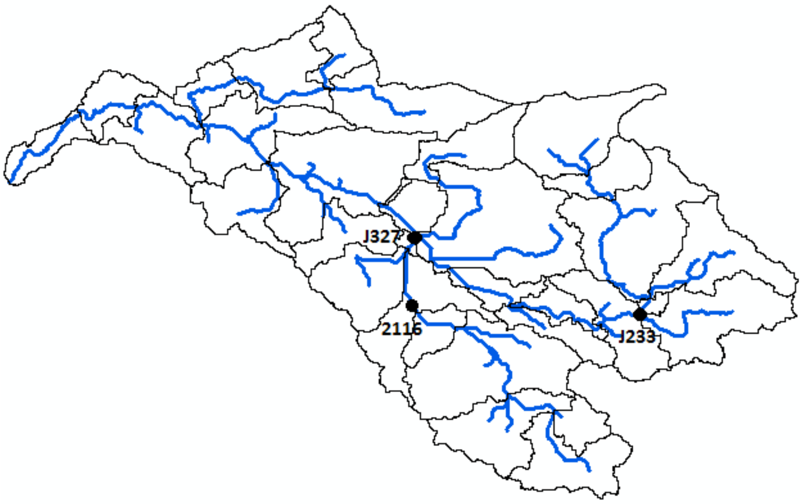


Figure 18 - Location of Calibration Points

Statistics were gathered for the flow measurement data of the three gauge stations Björkaån, Klingavälsån and Vomb Lake for a descriptive analysis of basin characteristics. Eggelstad and Klingavälsån are the two upstream discharge areas. Data collected from SMHI Eggelstad together with Klingavälsån constitute a slightly larger area than the area designated as the catchment area of Vomb Lake but this slight discrepancy is ignored.

Annual maximum flow is the most reliable frequency function for continuous studies therefore statistics on an annual basis are included here (Hydrologic Engineering Center, 2015). Table 6 shows the flow averages for recent years 2008-2014 used for the HEC-HMS model setup and calibration in addition to the recording period average for each flow station, usually from 1971 to 2015. The slightly lower values for the time period 2008 to 2014 do not indicate a decrease in runoff but is more likely attributed to the fact that a smaller data set was averaged. Discharge per unit area was calculated using the recording period average flow indicating the contribution each discharge area has on the basin.

Table 6 - Flow Station Statistics from 2008 to 2014 (SMHI)

	Eggelstad	Klingavälsån	Vombsjön
Discharge Area	262 km^2	192 km^2	447 km^2
Average Flow for 2008- 2014	2.57 m^3/s	1.54 m^3/s	3.13 m^3/s
Average Flow of Recorded Period	3.04 m^3/s (1973-2015)	1.82 m^3/s (1971-2015)	3.32 m^3/s (1969-2015)
Discharge per Unit Area	.01160	.00948	.00743

Daily flow statistics for the three stations including the minimum flow for the period, the median and the maximum are presented in Table 7. Also included are the values for quartile 3 the middle number between the median and maximum and the quartile 1 the middle number between the minimum and the median. The data in Table 7 shows that the median for the upstream daily flow statistics average 1.22 m^3/s and downstream at Lake Vomb 1.5 m^3/s.

Table 7 - Statistics of Flow Station Data from 2008 to 2014 (m^3/s)

	Eggelstad	Klingavälsån	Vombsjön
Minimum	0.07	0.17	0.30
Quartile 1	0.38	0.53	0.50
Median	1.21	1.22	1.50
Quartile 3	3.09	2.21	3.50
Maximum	40.90	10.80	33.00

Data from the previous century in Table 8 shows the average flow values from year to year and the average of the highest flow each year. As compared to Table 6 the average yearly flows have not varied greatly, when counting the previous reference period of 1971 to 2015 or that from 1900 to 2000.

Table 8 - Average Flow and Average of Highest Yearly Flow from 1900 to 2000 (SMHI)

	Eggelstad	Klingavälsån	Vombsjön
Average Flow	3.05 m^3/s	1.73 m^3/s	3.5 m^3/s
Average High Flow	30 m^3/s	8.3 m^3/s	19 m^3/s

The Figures 18, 19 and 20 on the following page graph the flow measurements of the gauge stations Eggelstad, Klingavälsån and Vomb Lake. The horizontal line in each graph indicates the average flow value for the period. Vomb Lake's flow in Figure 20 is regulated and shows marked changes in outflow. Vomb Lake cannot therefore be used for calibration. Vomb Lake's hydrograph is manipulated by the extraction of water by Sydvatten's pumps and the regulation device at the lake exit.

Seasonal patterns are best observed using Figure 18 and Figure 19. Outflow peaks during the winter months then settles down to summer minimum. Summer months therefore show lower values than yearly averages but higher than the daily averages. Extreme flows showing exaggerated peaks average between 10 and 40 (Figure 18) and 5 and 12 (Figure 19). The highest flows at the Eggelstad station reached 40 m^3/s twice in the last seven years. The Klingavälsån station in Figure 19 reached 10 m^3/s and 9 m^3/s twice in the last seven years.

These statistics will be discussed in relation to the findings of the predictive HEC-HMS model for the year 2100.

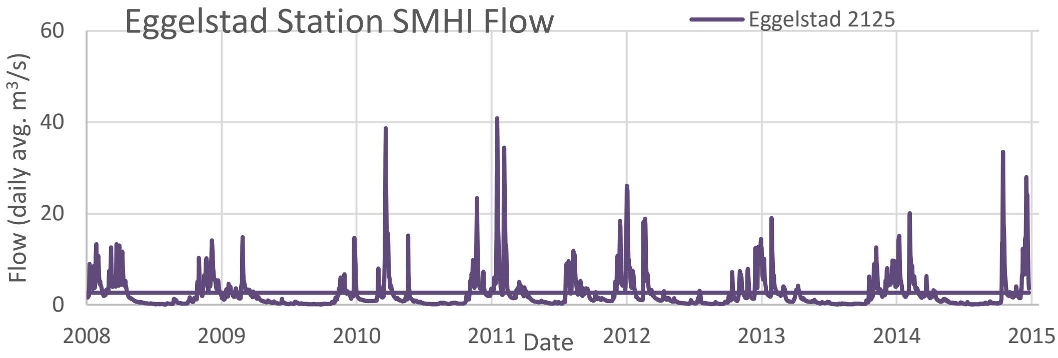


Figure 18 - Recorded Flow at Eggelstad 2008 to 2015

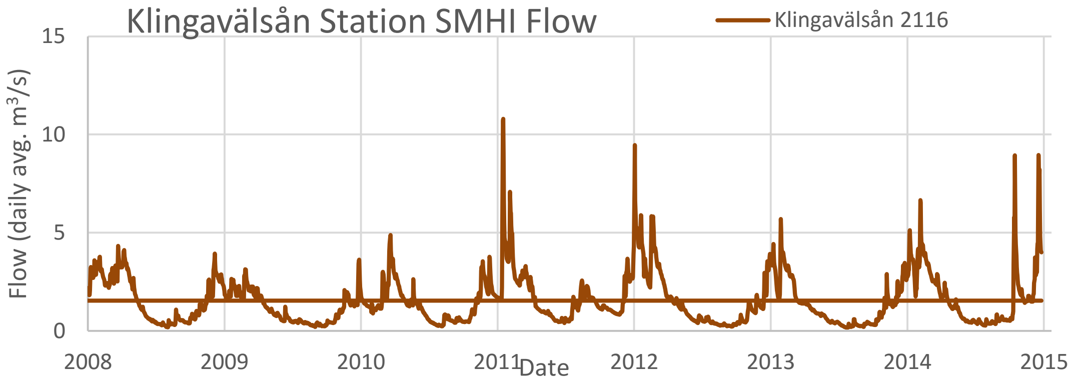


Figure 19 - Recorded Flow at Klingavälsån 2008 to 2015

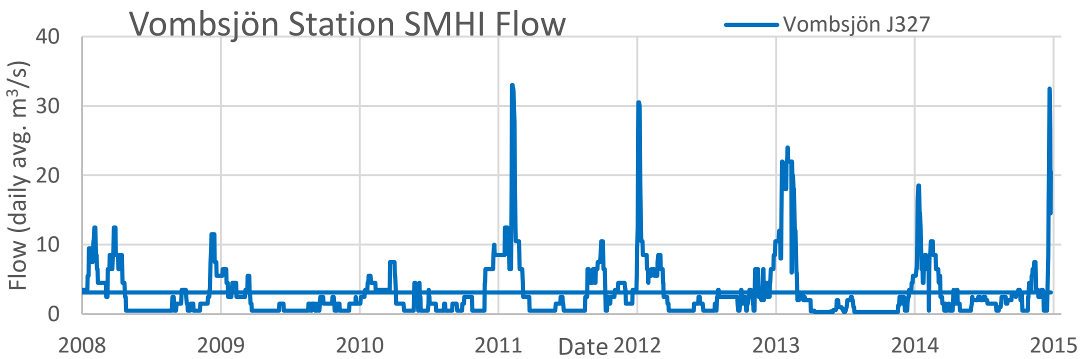


Figure 20 - Recorded Flow at Vomb Lake 2008 to 2015

6 Calibration

The HEC-HMS model was calibrated by making manual adjustments to the parameters for the simulation of year 2014 until a suitable result was achieved. The outflow observed at the upstream locations, station 2116 and junction 233, was fitted as closely as possible to the flow modeled through an iterative procedure. Initial parameters entered were estimated from the HEC-HMS Technical Manual. Recommended reference values were chosen when physical data did not provide enough information. Model accuracy was verified using year 2013.

6.1 Calibration Procedure

Baseflow provide the continuous model with an underlying flow. These highly sensitive parameters provides the underlying flow for the model. These parameters were arguably the most important to the calibration procedure. The groundwater coefficient was calibrated to a value of 120. At a groundwater coefficient of one individual rainstorms were evident while a baseflow of any kind was lacking. Groundwater coefficients of 200 or higher produced a high initial simulation peak that overestimated flow. Initial groundwater flow was 0.1 m^3/s per square kilometer. Flows of 0.8 to 0.12 appeared acceptable.

Computational values used for Groundwater 1 (%) and Groundwater 2 (%) may cause an observably large peak in the beginning of the simulation if these values are near one hundred percent. Soil storage and tension is an area based parameters that varied from basin to basin. On a whole these two values were kept even on a square meter basis. Maximum infiltration in millimeter per hour was calibrated to 5. Groundwater 1 and 2 Storage, Percolation, and Coefficient values were significant players in the initial calibration of baseflow.

The presence of surface and canopy layers is one of the main differences between continuous and single-event studies. Surface and canopy layer input parameters provide initial conditions for the physical basin environment in addition to describing the type of surface and canopy cover. Maximum storage was roughly input to be the same per square kilometers from basin to basin. The moisture content of both layers and the set threshold for maximum water containment at the beginning of a simulation determine when saturation will occur. Higher initial moisture content is more likely to have an initial modulation of value that does not correspond to the observed outflow values. Initial storage for both surface and cover were calibrated to be between 20 and 30 percent. The tension reduction uptake method is chosen as opposed to the simple uptake method with a crop coefficient of 1. The Loss Method contained the largest number of adjustable parameters. The loss method provided necessary large scale adjustments parameter along with parameters used to fine tune the model.

Tables 9 and 10 shows snapshots of the input parameter slots. Red asterisks denote mandatory fields. The former shows the Loss Method Parameters for one of the subbasins and the later shows the baseflow tab and its parameters.

Subbasin | Canopy | Surface | Loss | Transform | **Baseflow** | Options

Basin Name:	**Basin 1**
Element Name:	**W1650**
Initial Type:	Discharge Per Area
*GW 1 Initial (M3/S /KM2)	0,1
*GW 1 Coefficient:	120
GW 1 Reservoirs:	1
GW 2 Initial (M3/S /KM2)	
GW 2 Coefficient:	
GW 2 Reservoirs:	1

Table 9 - Baseflow Parameters

Transform | Baseflow | Options | Subbasin | Canopy | Surface | **Loss**

Basin Name:	**Basin 1**
Element Name:	**W1650**
*Soil (%)	30
*Groundwater 1 (%)	30
*Groundwater 2 (%)	30
*Max Infiltration (MM/HR)	5
*Impervious (%)	12
*Soil Storage (MM)	61
*Tension Storage (MM)	3
*Soil Percolation (MM/HR)	10
*GW 1 Storage (MM)	65
*GW 1 Percolation (MM/HR)	1,2
*GW 1 Coefficient (HR)	100
*GW 2 Storage (MM)	65
*GW 2 Percolation (MM/HR)	1,2
*GW 2 Coefficient (HR)	100

Table 10 – Loss Method Parameters

6.2 Calibration Results

Figures 24, 25 and 26 graph outflow at the three locations comparing observed flow to modeled flow. The solid blue lines denote the total outflow at that junction that was the result of the model simulation. The dashed blue lines denote reaches that are upstream of the junction. The black dotted line denotes the observed outflow at the junction that was measured by a gauge station. The initial high peak and decline relates to the model warm up period and is ignored.

Peaks from October to January in J233 and 2116 graphs show moderate correspondance to the observed events of heavy runoff. The fall of 2014 results in two distinct peaks which the model has been able to accurately predict, with J233 lacking a few days of the highest outflow and 2116 for that same time period showing an outflow slightly above that which was observed. Automated calibration of runoff volume showed a volume error of 10 to 14 percent (see Appendix).

Summer storms result in an increased runoff that is not observed in the measured data. Increases in runoff observed at the two locations between the summer months of June to the beginning of the fall are not modeled by HEC-HMS which shows those time periods as flowing at minimum values of 1 m^3/s or even less. The outflow peaks observed in the upstream legs during the months of February and March each year is likely due to the modulated surge in outflow observed in the Junction 327 past Vomb Lake.

It is evident that the resulting graphs are slight variations of each other. The observed data shows that the runoff of the upstream legs of the river have disparate responses. Calibration showed that the outflow produced by the HEC-HMS model at the two upstream locations resulted in hydrographs that were evidently similar. HEC-HMS models the runoff response at all three locations (J233, 2116 and J327) as though they interrelated to the degree that their outflow diagram only slight vary. It appears as an averaged response throughout the subbasins with no distinct flow variations between reaches.

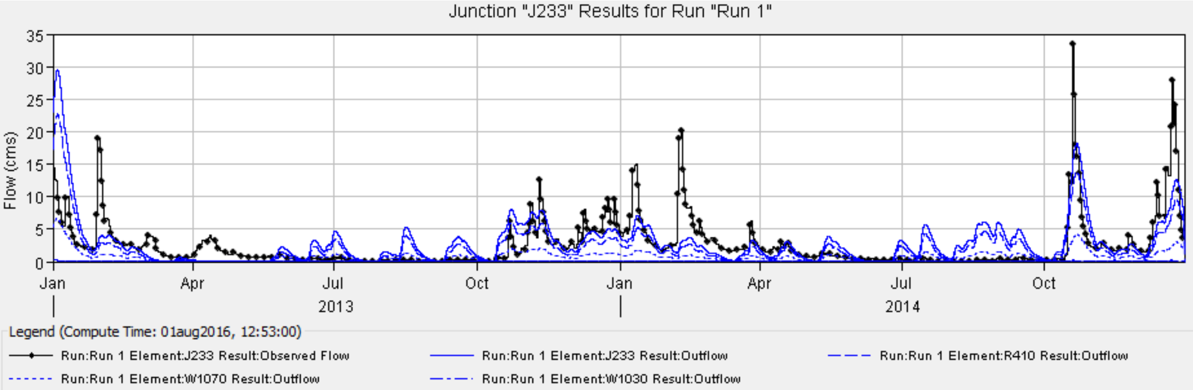


Figure 24 - Continuous Outflow at Junction 233 for Calibration Years

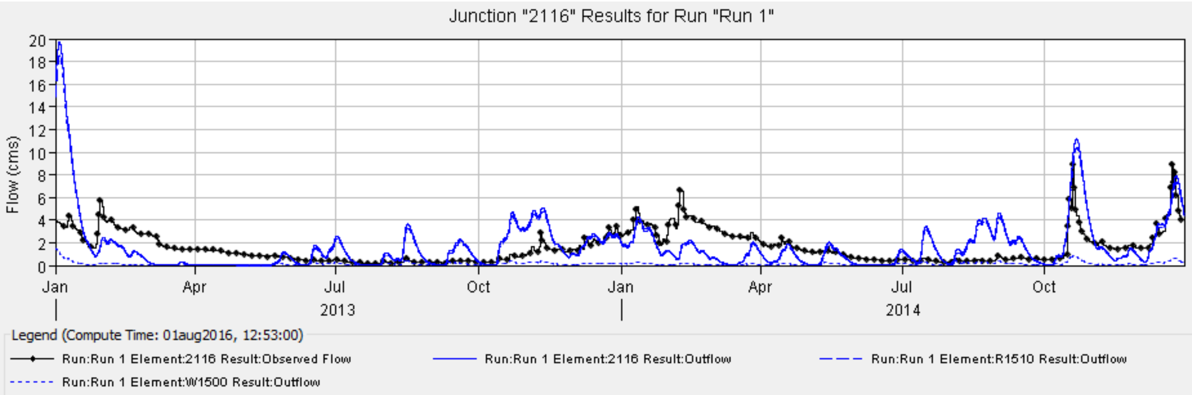


Figure 25 - Continuous Outflow at 2116 for Calibration Years

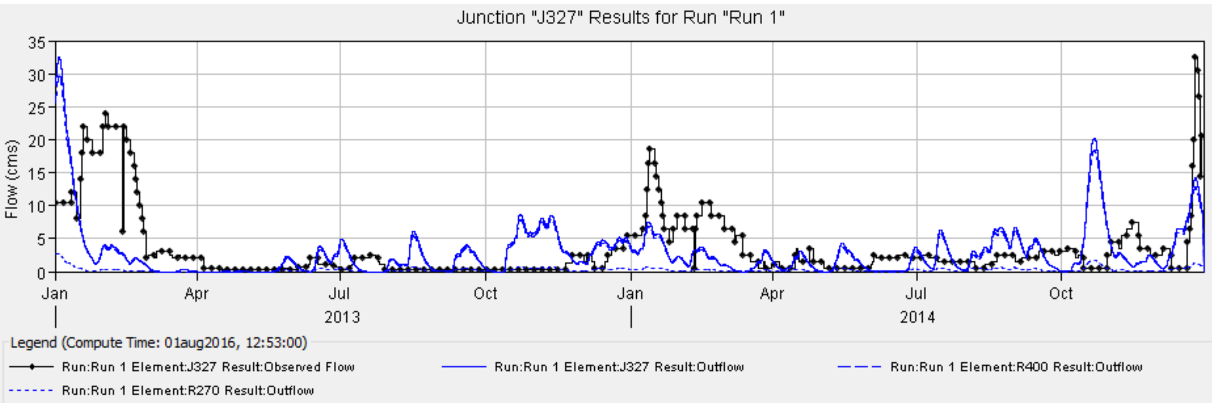


Figure 26 - Continuous Outflow at Junction 327 for Calibration Years

Overall calibration results show that the model while not wholely unsatisfactory are highly relevant at Junction 233. The more responsive outflow of J233 has been satifactory in manifesting the extreme peaks of outflow that occur. This is critically important because while the 2116 station is influencial actor in the upstream portion of the Kävlinge River Basin, the river leg does not flow directly into Vomb Lake. It is Junction 233 that is the main source of inflow to Vomb Lake. Junction J233 is therefore a suitable representative of the outflow occuring in the basin that can be used for the climate change prediction model of year 2100.

The time step of the simulation was on a 15 minute interval which was significantly smaller than individual subbasins time series data on precipitation and temperature to allow for the runoff calculation and for the results to be compared to the daily flow values recorded.

Modulated flow at the junction after lake Vomb, J327, is not an indictor of model accuracy. This location has flow that has a controlled release that is adjusted to increase outflow or prevent flooding downstream. Vomb Lake also acts a natural attenuation body. Sydvatten AB as stated before draws water from the lake 1.2 m^3/s. Junction 327 was therefore not considered while calibrating.

Additionally the Optimization Trial function of HEC-HMS was used to calculate the percent volume error between the observed values of 2014 at J23 as the objective function and the modeled values. The results table is in the appendix and shows moderate to very good correlation with a 13.55 percent difference in volume.

7 Results

Predicted increases in temperature and rainfall representing the changed climate of the future investigated with the HEC-HMS model resulted in an increased runoff and increased peak runoff height as seen in Figure 28 to 30. The results of the simulation for year 2014 and the adapted climate scenario for the simulation of 2100 are compared at the three junctions 233, 2116 and 327. Figure 28 represents the main branch of inflow into Lake Vomb and as such, as well as other reasons discussed in the calibration section, most conclusions are drawn from this graph.

Junction 233 is considered the most pertinent and accurate in predicting flow into Lake Vomb. Statistical comparison of the outflow for these two simulations show a 25 percent increase in outflow when comparing 2014 to 2100. This results when values of flow calculated to several orders of 10 less than 1 where thrown out from the calculation being regarded as at a level of accuracy not practically possible. The model is affirming and conclusive in the argument that climate change will play a major role in the quantity of water flowing in the Kävlinge River Basin.

For comparison Table 4 shows the projected increases in runoff by return period. In summary, the Kävlinge River Basin's one year mean is expected to rise to around a 12 percent runoff increase, the ten year 30 and the hundred year 33. The year to year comparison in this study shows a value between the 10 year and 1 year mean percent increase in flow. This is well within the expected SMHI range and has important implications for Sydvatten's daily operations. The juxtaposition of 2014 and 2100, an 85 year gap, resulting in an outflow percent increase less than that of the 100 year mean and 10 year mean indicate a suitable figure for preparation for a climate change response analysis. Applicability of the data is increased due to the fact that the reference period was adjusted for current meteorological and hydrological conditions as well as the fact that all input data was of local origin.

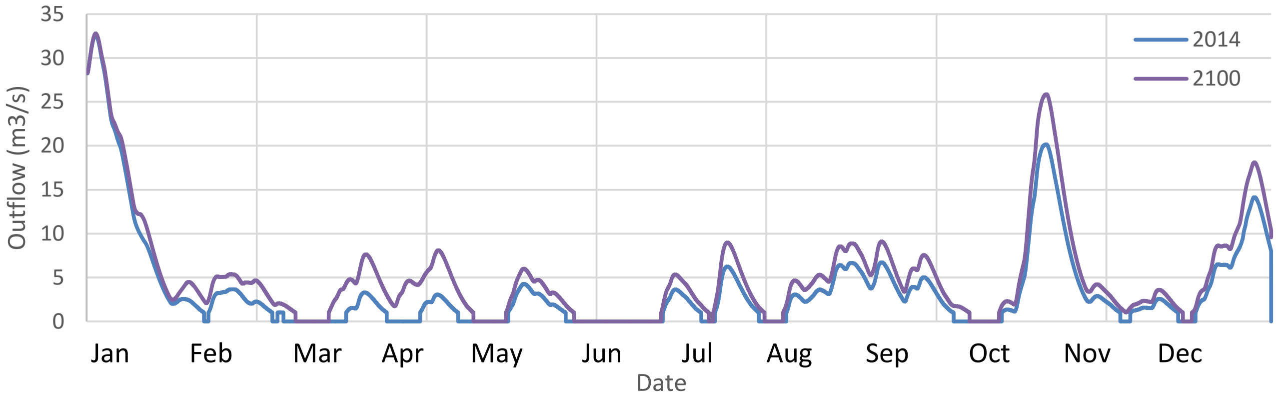


Figure 23 - Modeled Outflow at Weather Station J327

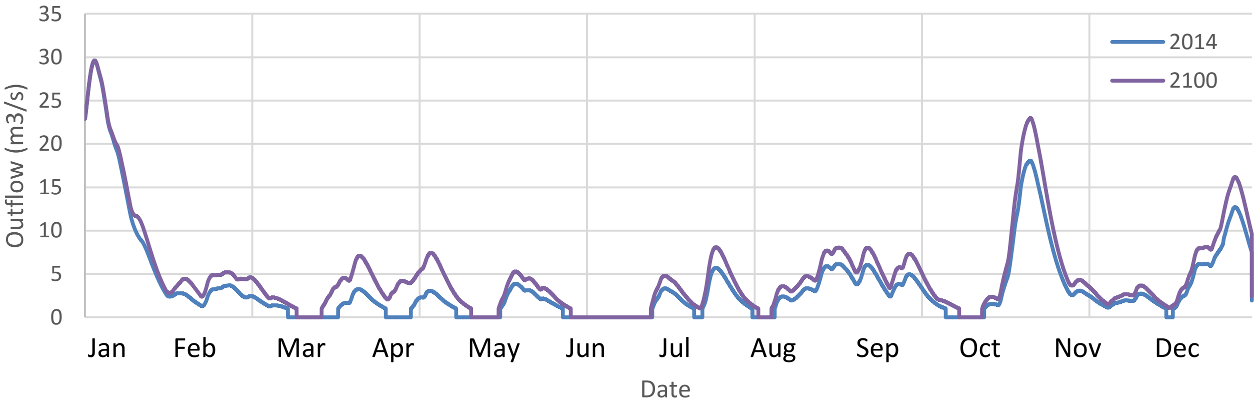


Figure 22 - Modeled Outflow at Weather Station J233

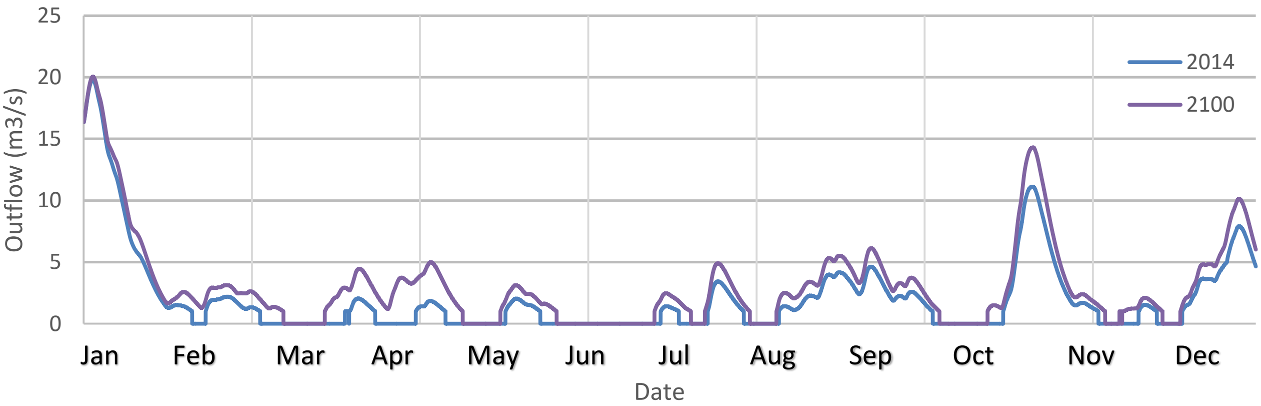


Figure 21 - Modeled Outflow at Station 2116

While the model is not satisfactory for flood prediction because of it insufficient correlation to observed stream flow it sheds some light on the availability of water in the basin due to heavy rainstorms. Heavy rainstorms are predicted to occur 8 to 10 days more often in the future. The 2100 climate scenario included the addition of 9 heavy rainstorms in February, March and April. Added heavy rainstorms for the early Spring months of the meteorological model of 2100 did not appear to result in significant changes in runoff instead that extra volume of water contributed to increased height in runoff peaks during these months. Table 11 shows the major peaks that occurred in the simulation and their percent increase in flow. The expected extreme flow events are concluded to occur with flows 28 percent higher than currently.

Table 11 - Percent Increase in High Flow from 2014 to 2100

	January Peak	Increase (%)	October Peak	Increase (%)	December Peak	Increase (%)
J233	*29.6 m^3/s*	*0.3*	*22.9 m^3/s*	*27.1*	*16.2 m^3/s*	*27.4*
2116	*20.0 m^3/s*	*1.5*	*14.3 m^3/s*	*28.9*	*10.1 m^3/s*	*28.2*
J327	*32.7 m^3/s*	*0.8*	*25.9 m^3/s*	*28.4*	*18.1 m^3/s*	*28.0*

8 Discussion

Most physical basin characteristics in this study were estimated from maps. Uncertainties pertaining to the physical model include inaccuracy of the assessment of river widths, lag time and variation of the determined subbasins from those outlined by HEC-HMS. It is likely that the floodplain contains numerous ponds and streamside depressions that play a role in the retaining of water that where not modeled.

Parameters of the hydrologic model were often estimated using HEC-HMS recommended values or a best estimate. While most the parameters are suitable for the level of accuracy required by the model it is ideal to have field measurements to ensure model accuracy. The physical basin model's complexity was sufficiently represented using simple mathematical methods to mimicked natural processes.

Any backwater effect resulting from the damming of the lake could be included in the model if the Modified-Puls Routing Method was used instead of the Muskingum-Cunge. Development of a storage-discharge relationship required for this method for each reach could not be determined without intensive investigation of the river bed and storage capabilities. Historical data including significant amounts of long records of river discharge and riverbed geometry would be necessary to compute the storage-discharge relationship in HEC-RAS or HEC-2 (Schaffenberg, 20). Field investigation of flood marks or stage levels to correlate to observed discharge could provide data for preparation of the storage-discharge table.

Although the flow routing model is insufficient to show variations between the two upstream river legs, the model is useful for climate change research to facilitate an understanding of the flow of the future. A description of the discharge properties for all the various river reaches would be the only effective manner to ensure a more accurate runoff response pertaining to each river leg. The Modified-Puls method would adequately provide for the development of hydrographs unique to Björkeån and Klingavälsån the northern and southern upstream portions of the basin. Such a discharge relationship could be used to more accurately account for the way flow is attenuated as it flows through Vomb Lake. The distribution of precipitation during rainstorm events should be evaluated for its effect on runoff.

The semi-disturbed nature of the HEC-HMS model may hinder accurate modeling of the Kävlinge River Basin. Collectivizing the subbasin characteristics that can be described using one defined parameter is not always realistic but during the calibration procedure it became evident that the most physical basin parameters related to ground cover and canopy would not have a significant impact on the outflow. Imperviousness appeared to be the sole exception to this guideline. Changing land use management including cropland partitioning could be planned and modeled with this software to decrease or slow direct runoff into the main river.

The quantity of water that is withdrawn from the subbasin could decrease in the coming years due to an increase in use of water from the Bolmen tunnel whose capacity has not been reached. If this occurs research of the basin would be recommended to shift away from quantitative studies of the water to quality related issues. Sydvatten AB's biological and chemical research division already works closely with local farmers to reduce the biochemical load on the river basin.

9 Conclusions

Climate change will continue to be an added pressure on societies around the world. This must be accounted for presently in order to be properly managed in the future. Even with aggressive mitigation of these effects by political actors and regulation the rate at which the earth warms is expected to at least double from the hundred years past to the coming hundred (EPA, 2016). Competing interests such as resilience to flooding and providing a constant water supply need to be negotiated through integrated water resources management.

Kävlinge River Basin is an important and valuable source of drinking water for the region that must be safeguarded. It is expected that water demand will increase steadily as Skåne's population increases including the possibility of growth of demand due to an increase in the number of municipalities served. Sweden, already known for its rainy summers, has already been experiencing the visible effects of changing return periods and increased rainfall.

The primary objective of the study was to investigate the effects of climate change on the Kävlinge River Basin through research and a developed runoff model. The findings presented show that the basin will be significantly impacted by increasing temperatures and precipitation which will in turn lead to higher amounts of runoff. If Sydvatten AB opts to invest in increasing water withdrawal from Vomb Lake these changes should be taken into account and be considered when making decisions.

The compiled study will be handed over to Sweden Water Research and can be the tool with which other studies on changes in precipitation will effect water runoff. It provides the company with access to a fully developed and relevant model with an English language interface that can be made available to their employees. This fits into Sydvatten AB's plan to become more open to a global market and English speaking research partners.

The developed Kävlinge River Basin model may also be used for further studies regarding changes in land use, the addition of water structures or single event heavy rain storms. The HEC-HMS model, the preparatory GIS maps showing land use, elevation and soil type were made available to Sydvatten AB and Sweden Water Research. These entities are public companies that work under tight budgets with little flexibility to spend money on expensive software licenses.

This paper provide Sweden Water Research with support for their climate change report as well as enabling further investigation. Beyond estimations of increased flow, the precipitation and temperature values, statistics and trends compiled here provides the research company evidence to proceed with monitoring of the river basin. The knowledge and understanding enabled by this research should be instrumental in further management of the Kävlinge River Basin. Sydvatten's goal to continue to be a high quality leading edge water provider can be achieved with appropriate integrated water resources management.

10 References

Environmental Protection Agency. (2016). Future Climate Change. [online] Available at: https://www3.epa.gov/climatechange/science/future.html. [Accessed 28 Jul. 2016]

EU Water and Climate Change Project. (2016). Centre for Ecology and Hydrology. Evaporation in Average Year. [online] Available at: http://www.waterandclimatechange.eu/evaporation/average-monthly-1985-1999. [Accessed 15 Apr. 2016]

FishXing. (2004). Manning's n values for Channels, Closed Conduits Flowing Partially Full, and Corrugated Metal Pipes. [online] Available at: http://www.fsl.orst.edu/geowater/FX3/help/8_Hydraulic_Reference/Mannings_n_Tables.htm [Accessed 28 Jan. 2016]

Feldman, A. (2000). Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS Technical Reference Manual, Version 4.1. U.S. Army Corps of Engineers Institute for Water Resources.

Fleming M. and Doan, J. (2013). HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual, Version 10.1. Hydrologic Engineering Center. U.S. Army Corps of Engineers Institute for Water Resources.

Fleming M. and Doan, J. (2009). HEC-GeoHMS Geospatial Hydrologic Modeling Extension User's Manual, Version 4.2. Hydrologic Engineering Center. U.S. Army Corps of Engineers Institute for Water Resources. [online] Available at: http://www.hec.usace.army.mil/software/hec-geohms/documentation/HEC-GeoHMS_Users_Manual_4.2.pdf. [Accessed 8 Feb. 2016]

Graham, Anne. (2014). IAP 2014 Hydrology Tools Exercise. [online] Available at: https://libraries.mit.edu/files/gis/HydrologyToolsExerciseHEC-GeoHMS_IAP2014.pdf [Accessed 28 Jan. 2016]

Hall, M, Lund, E & Rummukainen, M (red) 2015. Klimatsäkrat Skåne. CEC Rapport Nr 02. Centrum för miljö-och klimatforskning, Lunds universitet. ISBN 978-91-981577-4-1.

Hydrologic Engineering Center. (2015). Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS Application Guide, Version 2015. U.S. Army Corps of Engineers Institute for Water Resources.

Hydrologic Engineering Center. (2016). US Army Corps of Engineers. HEC-HMS Hydrologic Modeling System, Release number 4.1. [online] Available at: http://www.hec.usace.army.mil. [Accessed 8 Feb. 2016]

Jordbruksverket. (2016). [online]. Available at: http://www.jordbruksverket.se. [Accessed 22 Jan. 2016]

Lantmäteriet (2016). [online] Available at: http://www.lantmäteriet.se. [Accessed 22 Jan. 2016]

Merwade, Venkatesh. (2012). Terrain Processing and HMS: Model Development using GeoHMS. School of Civil Engineering, Purdue University. [online] Available at: http://web.ics.purdue.edu/~vmerwade/education/geohms.pdf.[Accessed 30 Feb. 2016]

Merwade, Venkatesh. (2012). Watershed and Stream Network Delineation using ArcHydro Tools. School of Civil Engineering, Purdue University. [online] Available at: http://web.ics.purdue.edu/~vmerwade/education/terrain_processing.pdf. [Accessed 28 Feb. 2016]

National Oceanic and Atmospheric Administration. (2005). National Operational Hydrologic Remote Sensing Center and National Weather Service Office of Hydrology Hydrologic Research Laboratory. U.S. Department of Commerce. Unit Hydrograph Technical Manual. Available at: http://www.nohrsc.noaa.gov/technology/gis/uhg_manual.html. [Accessed 20 Jun. 2016]

Scharffenberg, W. (2015). Hydrologic Engineering Center's Hydrologic Modeling System HEC-HMS User's Manual, Version 4.1. U.S. Army Corps of Engineers Institute for Water Resources.

State Climate Office of North Carolina. (2013). Longwave and Shortwave Radiation. NC State University. [online]. Available at: https://climate.ncsu.edu/edu/k12/.LWSW [Accessed 29 Apr. 2016]

Sveriges Meteorologiska och Hydrologiska Institut, SMHI. (2016). Avdustningkartor normalvärder. Klimat data. [online] Available at: http://www.smhi.se/klimatdata/hydrologi/avdunstning. [Accessed 10 Apr. 2016]

Sveriges Meteorologiska och Hydrologiska Institut, SMHI. (2016). Luftwebb. Temperatur och nederbördsdata. [online] Available at: http://luftwebb.smhi.se/ [Accessed 28 Jan. 2016]

Sveriges Meteorologiska och Hydrologiska Institut, SMHI. (2016). Meteorologiska observationer, Open Data. [online] Available at: http://opendata-download-metobs.smhi.se/explore/. [Accessed 20 Jan. 2016]

Sveriges Meteorologiska och Hydrologiska Institut, SMHI. (2016). Vattenwebb. Modelldata Per Område. Image. Kävlinge River Basin. [online] Available at: http://vattenwebb.smhi.se/modelarea/ [Accessed 20 May. 2016]

Sveriges Geologiska Undersökning. (2016). Geoportalens GIS Kartor.

Sveriges Geologiska Undersökning. (2016). [online] Available at: http://www.sgu.se. [Accessed 19 Jan. 2016]

Sydvatten AB. (2016). Sydvatten Home. [online] Available at: http://www.sydvatten.se. [Accessed 15 Jan. 2016]

Vombsjön Vattenförekomst. (2011). Vatteninformationssytem Sverige. Lansstyrelsen. [online] Available at: http://www.viss.lansstyrelsen.se. [Accessed 20 Jan. 2016]

11 Appendix

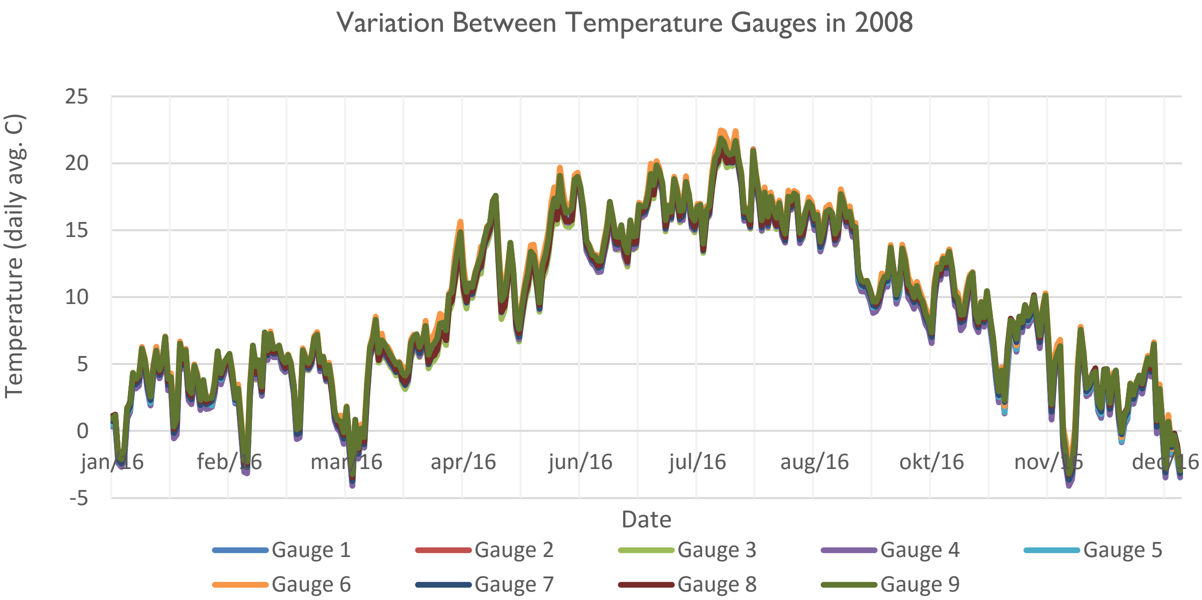


Figure A - Luftwebb 2008 Temperature Data

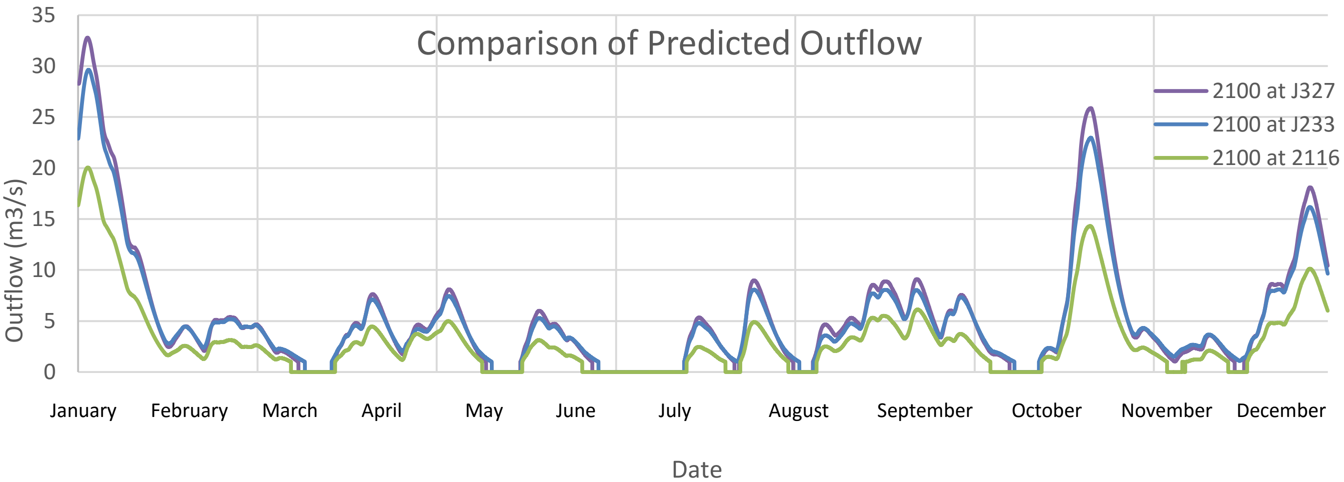


Figure B – Comparison of Outflow of Year 2100

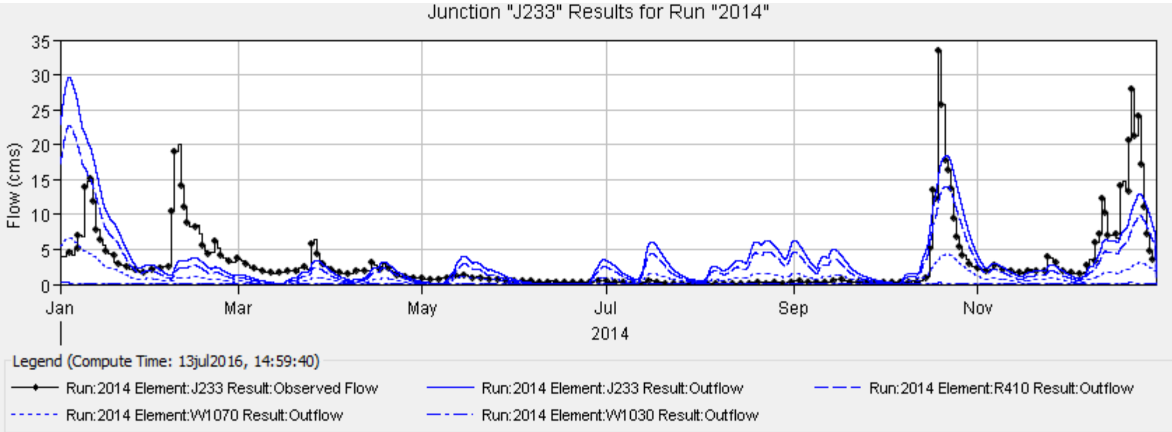


Figure C - Outflow Results at Eggelstad (Junction 233) year 2100

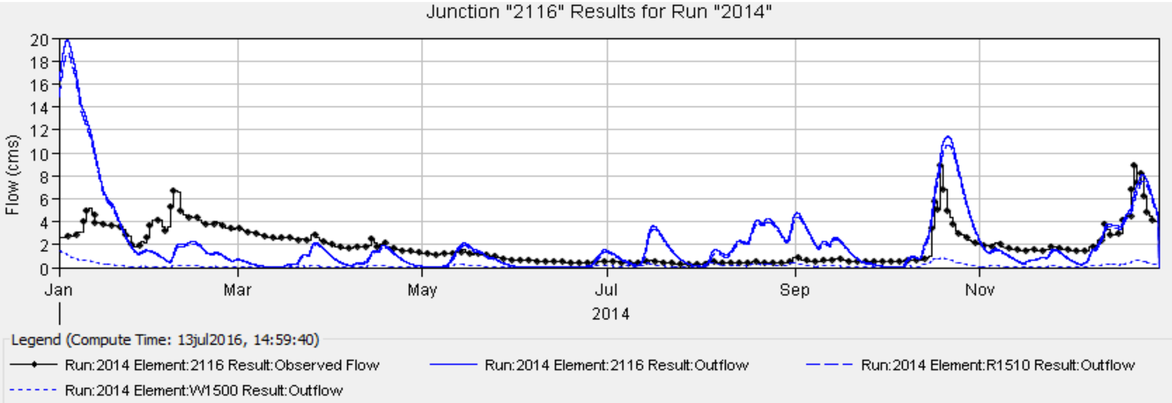


Figure D - Outflow Results at Klingavälsån year 2100

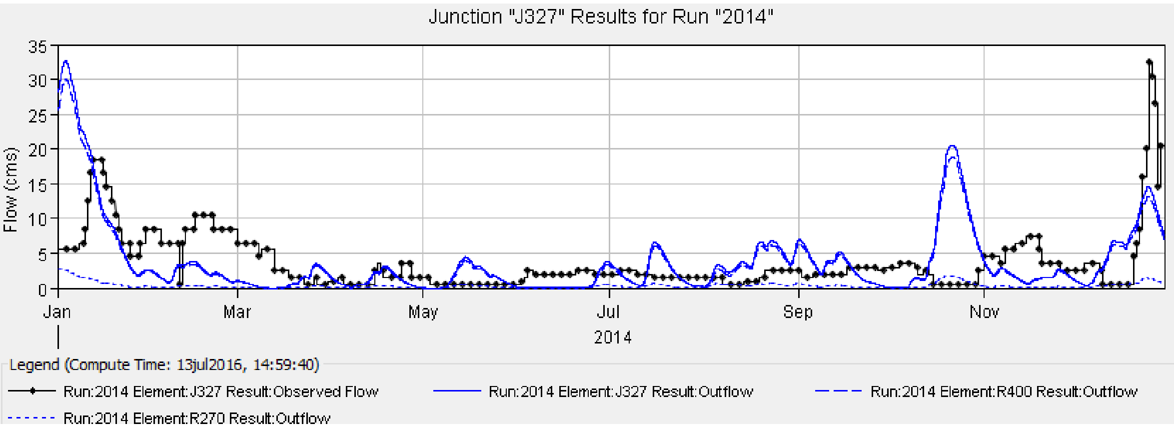
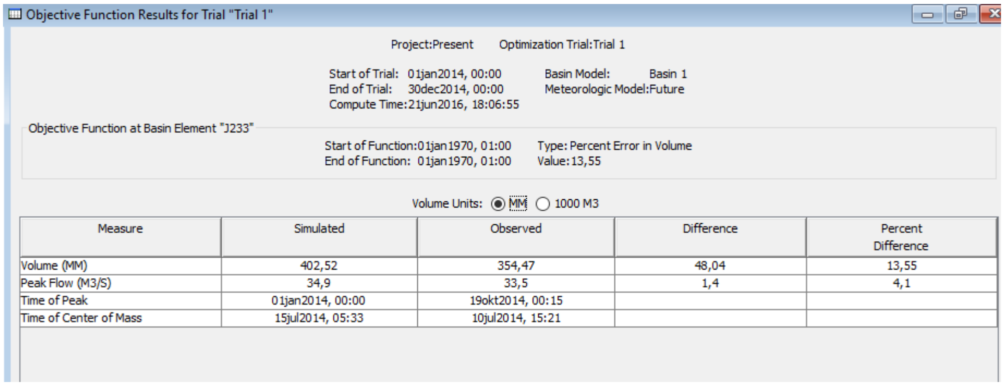


Figure E - Outflow Results at Vomb Lake (Junction 327) year 2100


Objective Function Results for Trial "Trial 1"

Project:Present Optimization Trial:Trial 1

Start of Trial: 01jan2014, 00:00 Basin Model: Basin 1
End of Trial: 30dec2014, 00:00 Meteorologic Model:Future
Compute Time:21jun2016, 18:06:55

Objective Function at Basin Element "J233"

Start of Function:01jan1970, 01:00 Type: Percent Error in Volume
End of Function: 01jan1970, 01:00 Value:13,55

Volume Units: MM 1000 M3

Measure	Simulated	Observed	Difference	Percent Difference
Volume (MM)	402,52	354,47	48,04	13,55
Peak Flow (M3/S)	34,9	33,5	1,4	4,1
Time of Peak	01jan2014, 00:00	19okt2014, 00:15		
Time of Center of Mass	15jul2014, 05:33	10jul2014, 15:21		

Figure F – Optimization Trial Results

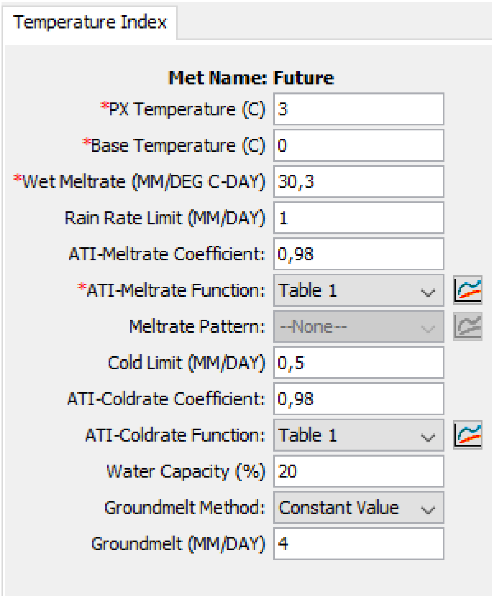


Figure G – Temperature Index Parameter Table