Master Thesis
TVVR 18/5009

Rainfall-Runoff Simulation and Modelling Using HEC-HMS and HEC-RAS Models: Case Studies from Nepal and Sweden

Hydrologic and Hydraulic Model Development for Flood Inundation Mapping of Kävlinge and Kankai River Basin

Jeevika Khadka
Jagritee Bhaukajee

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

Water Resources Engineering
TVVR-18/5009
ISSN 1101-9824

Lund 2018
www.tvrl.lth.se

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English title:	Rainfall-Runoff Simulation and Modelling Using HEC-HMS and HEC-RAS Models: Case Studies from Nepal and Sweden
Author(s):	Jeevika Khadka Jagritee Bhaukajee
Supervisor:	Linus Zhang - Department of Water Resources Engineering Mattias Frisk and Magnus Ihrsjo- 4IT AB
Examiner:	Kenneth M Persson - Department of Water Resources Engineering
Language	English
Year:	2018
Keywords:	HEC-HMS, HEC-RAS, Kankai, Kävlinge, Rainfall Runoff, Flood Inundation, Modelling.
Cover Photo:	Flooding in Mahakali River, Nepal (Picture Credit: Madhab Uprety)

Acknowledgements

We would like to express our sincere gratitude to our supervisor at Lund University, Linus Zhang for his involvement, cooperation and encouragement during the project. We truly appreciate his guidance, comments and advices from the initial development of the project till its completion. His knowledge on hydrology and hydraulics was essential for the successful completion of the thesis.

We are very thankful to 4IT AB for providing us the opportunity to work at their Ideon office in Lund. We are very grateful to Mattias Frisk, our supervisor from 4IT AB for showing great interest in our work and progress, helping us in acquiring data and guiding us in the writing process.

Our sincere gratitude goes to Bjorn Almstrom from the Divison of Water Resources Engineering at Lund University for his help and support during the model development. We are also thankful to Gerhard Berman from the Department of Biomedical Engineering in Lund University for providing us the geological maps of Sweden and guiding us to read and analyze those maps.

Additionally, we extend our deep gratitude to Mr. Madhab Uprety who coordinated with Department of Hydrology and Meteorology (DHM), Nepal and provided us Hydro and Meteorological data. Also, we are thankful to him for his overall guidance during this thesis.

We are also very grateful to Lund University and Swedish Institute Study Scholarship (SISS) for giving us the opportunity to study at Lunds Tekniska Hogskola, the Faculty of Engineering at Lund University and providing us scholarship that covered our tuition fees and living expenses. Without this we would not have this wonderful experience of studying in Sweden.

Lastly, we are thankful to our family and friends for their constant support and encouragement throughout our stay in Sweden.

Abstract

Floods are probably the most frequent, widespread and disastrous hazards of the world. Almost every year, Sweden and Nepal are affected by floods though their nature and impact differs due to complete different geographical and hydrological setting. This study aims to develop Hydrologic Engineering Centre's Hydrologic Modelling System (HEC-HMS) and Hydrologic Engineering Centre's River Analysis System (HEC-RAS) models for Kankai River basin of Nepal and Kävlinge river basin of Sweden to analyse the effects of rainfall on surface runoff and peak discharges of these rivers and ultimately produce flood inundation levels to assess the flood risks in both areas. Being a rainfed catchment, the flood discharges of Kankai River are highly affected by the extreme rainfall events whereas Kävlinge River has a significant influence of ground water. Apart from some extreme events, HEC-HMS modelling using Soil Moisture Accounting (SMA) loss method, manage to simulate flood discharges of Kankai River more accurately than Kävlinge River. The flooding impact of Kävlinge River is significantly less as the catchment is small with defined flow route while the Kankai River being a large catchment with braided river form, inundates vast downstream flood plain region during high flood level. With numerous people living along the river and downstream plains, flood risk is predominately high in the Kankai River catchment.

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List of Abbreviations

DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DTM	Digital Terrain Model
GoN	Government of Nepal
GW	Ground Water
HEC-HMS	Hydrologic Engineering Centre’s Hydrologic Modelling System
HEC-RAS	Hydrologic Engineering Centre’s River Analysis System
ICIMOD	International Centre for Integrated Mountain Development
SMA	Soil Moisture Accounting
SMHI	Swedish Meteorological and Hydrological Institute
TIN	Triangular Irregular Networks

CHAPTER 1. INTRODUCTION

1.1 General Background

With the alteration of natural environment due to human interventions together with the effects of global climate change, recent years have seen floods to occur more frequently and unpredictably across the globe. Urbanization and changing of demographic features within the river flood plain has led to increased exposure of communities to flood hazard. Developing countries in particular are facing the wrath of these kind of disaster as the vulnerability level is very high across these regions due to poor socio-economic conditions and haphazard settlements. On the other hand, developed countries with significantly more built up areas and infrastructures in place are subjected to huge economic losses if flood is not managed properly. Therefore, sufficient and reliable flood predictions and proper design of control and mitigation measures remains a major challenge everywhere. However, this requires a proper understanding of underlying hydrological and hydro-dynamic processes of river and the associated catchment characteristics. A rainfall runoff modelling (hydrological) anticipate evaluating the runoff from precipitation in a catchment and hydraulic modelling aims to evaluate magnitude of floods and the area inundated by them. Combination of both will result in runoff simulation and flood inundation levels.

In Sweden, Swedish Civil Contingencies Agency (MSB) prepares flood inundation maps for built areas which are at risk and close to watercourses. These maps facilitate in carrying out various risk and vulnerability analyses and further support in emergency preparedness and land use planning by local authorities. Considering the changing nature of geomorphological characteristics of river and flow regime, these maps require periodic updates and the water basin models also require further calibration and validation with new set of data.

In Nepal, the context is completely different with very little done with respect to flood modelling and inundation mapping of medium and small rivers in particular. Even the flood models developed for major river basins are hardly put into operational mode for flood warning and decision support systems. So far, the hydro-met stations network coverage is fairly sparse across Nepal and the country seriously lacks long time series of flow and rainfall data.

1.2 Rainfall-Runoff Modelling

Reliable estimates of stream flow from a catchment are required to help policy makers to inform decisions on water planning and management. There are range of methods available to estimate streamflow from catchments, using observed data wherever possible, or using empirical and statistical techniques to estimate river discharge, more commonly known as rainfall-runoff models (Vaze, 2012).

All Rainfall-Runoff (R-R) models are the simplified characterizations of the real-world system (Moradkhani, 2009). Runoff models helps to visualize the response of water systems due to changes in the land-use and meteorological events. Physical processes that converts rainfall to runoff is conceptualized with set of equations by employing various parameters that describes the catchment. Modelling surface runoff is challenging as the calculation involves complexities with many interconnected variables. However general model components include inputs, governing equations, boundary conditions or parameters, model processes, and outputs.

There are wide ranges of R-R models currently used by researchers and practitioners, however their applications are highly dependent on the purposes for which the modelling is undertaken. As many of the R-R models are used merely for research purposes for the purpose of understanding the hydrological processes that govern a real-world system, some are developed and employed as tools for simulation and prediction that in turn allows decision makers for proper planning and operation in context of flood risk management (Moradkhani, 2009). For instance, the real-time flood forecasting and warning, currently operational in many countries, employs the results of rainfall-runoff modelling. So far, these hydrological models also estimate flood frequencies, provide inputs for flood routing and inundation prediction. Often the end-results are utilized in the impact assessment of climate and land use change together with integrated watershed management.

1.3 Flood Inundation Modelling

Flood inundation models are required to understand, assess and predict flood events and their impact in the areas. Recent years have shown systematic improvement in the capability of flood inundation modelling and mapping (Teng, 2017). The results from hydraulic models can be used in flood risk mapping, flood damage assessment, real time flood forecasting, flood related engineering, water resource planning, investigating flood plain erosion and sediment transport, floodplain ecology, river system hydrology (Teng, 2017). However accurate flood modelling at high spatio-temporal resolutions still remains a significant challenge in any hydrologic and hydraulic studies. This is mainly due to the complex and chaotic nature of flooding and uncertainty associated with the conceptualization of processes and the modelling parameters itself. Good inundation maps could help in designing the flood risk management strategies and their implementations. Preparedness activities and timely response can be undertaken if the forecast information comes with the level of impact of flood. Even for recovery and damage assessment, flood risk mapping plays a crucial role. So far flood inundation maps can be utilized in environmental and ecological assessments of the watersheds.

1.4 Objectives and Research Direction

This study seeks to develop hydrological and hydraulic models for two rivers of varied catchment characteristics located on complete different climatic zones and physiographic region. First objective is to develop a physical based hydrological model with HEC-HMS software and simulate the effects of rainfall on surface runoff and flood discharges. Further the study also aims to evaluate the performance of the models by doing a thorough sensitivity analysis. Second objective is to develop a hydraulic model with HEC-RAS software to produce flood inundation maps for different flood scenarios for both rivers and critically assess the flood risk in both regions.

The above-mentioned objectives overall underline the following three research questions which this study intends to address.

1. What could be the effects of rainfall on surface runoff and peak discharges in different river basins when modelled with similar modelling process?
2. How will the model parameters of rainfall-runoff modelling process behave for the rivers of different climatic region and with distinct catchment characteristics?
3. What could be impacts of floods in terms of its extent and scale across the watershed?

To explore the potential answers on the above research questions, this study will develop HEC-HMS and HEC-RAS models for Kankai and Kävlinge river basins of Nepal and Sweden respectively. Significance of different model parameters will be analysed and discussed by undertaking thorough sensitivity check. Using HEC-RAS 1D model, inundation maps for 100-year flood will be generated and their potential impacts across the adjoin area will be discussed with possible recommendation on flood management strategies.

CHAPTER 2. STUDY AREA

Kävlinge river basin of Sweden and Kankai river basin of Nepal are the two different study areas in this thesis project. The geographic location of these two countries are highlighted in red in the world map below. Detailed description of two study areas has been provided in the following sections.

Figure 2.1: Location of Sweden and Nepal in the world map. (Dlouhy, 2006)

2.1 Geographic location, Topography and Geology

Kävlinge river basin is situated in the southern part of Sweden in Skåne county extending between 12.99° - 14.028° East and 55.73° - 55.64° North.

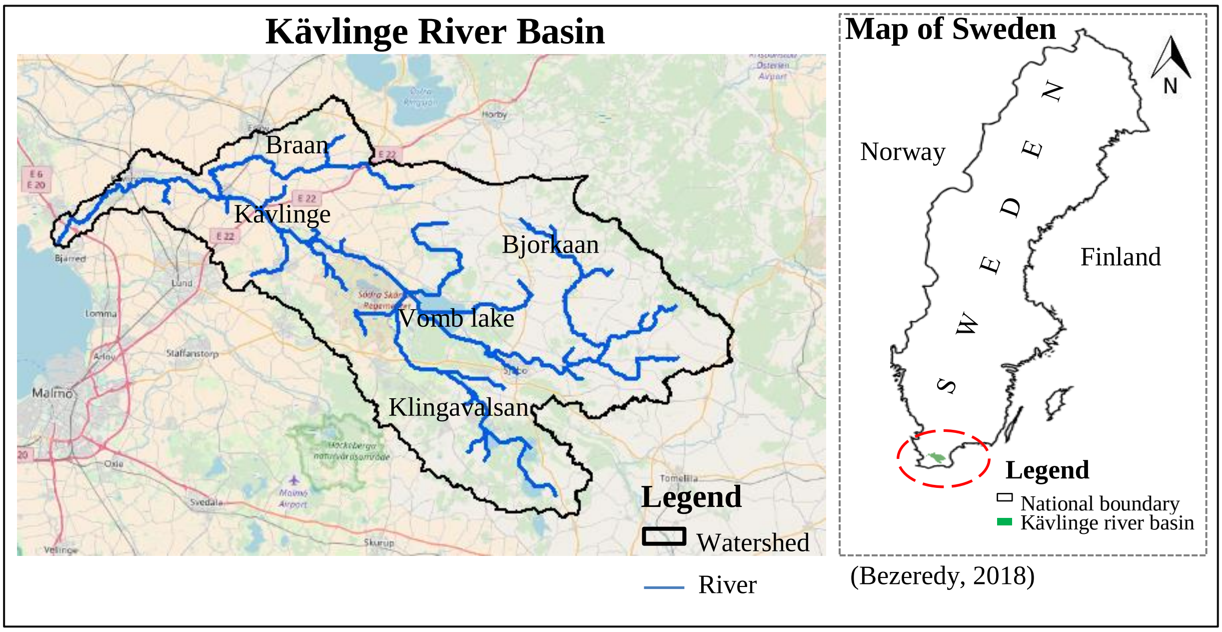


Figure 2.2: Location map of Kävlinge River Basin

Kävlinge river basin has a distorted waterdrop shape with an area of 1204 square kilometre. The topography of Kävlinge basin is almost flat with some major rock outcroppings. Small communities are present near this basin. The land is mainly used for agricultural purposes. Till is the dominant soil type in this area which is also the most common land form in entire Sweden. In Sweden, till covers approximately 75 percentage of the land mass (Sveriges Geologiska Undersökning, 2018). Sand and glaciofluvial sediments are present in the river bed and the surrounding area of lakes are dominated by peat.

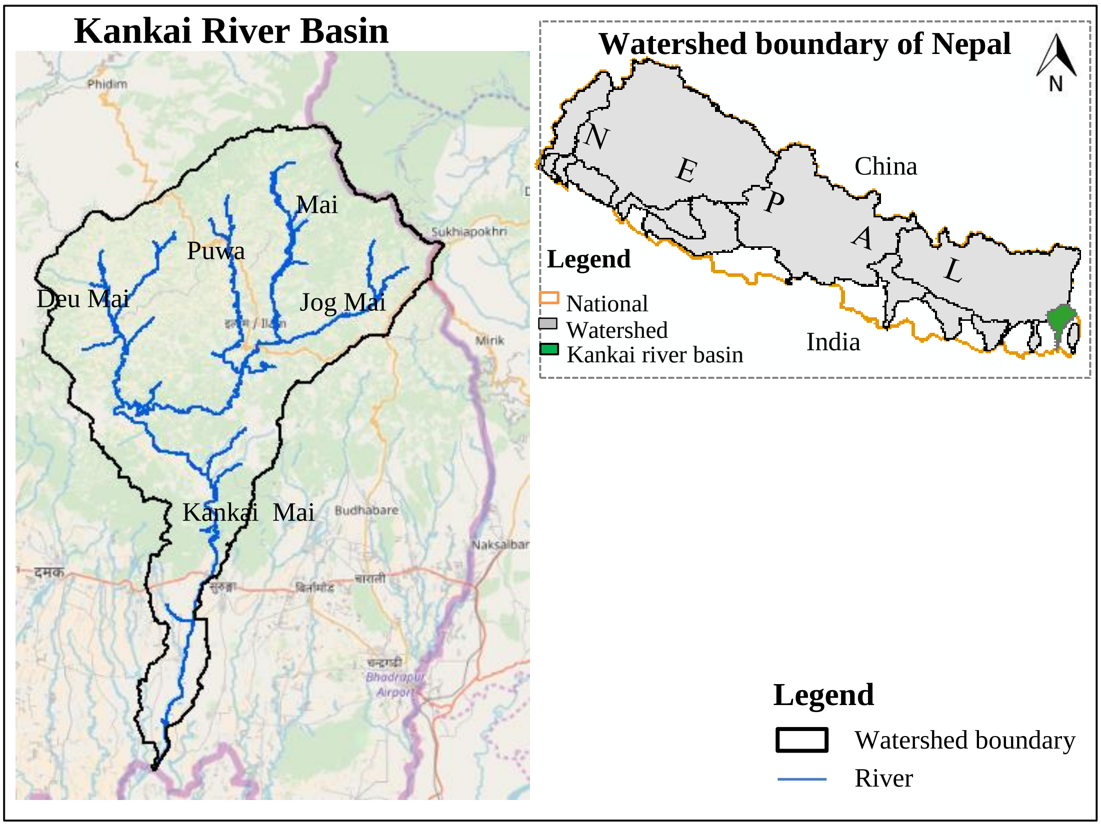


Figure 2.3: Location map of Kankai River Basin

Kankai River basin is situated in the eastern part of Nepal bordering with India on two sides. It is situated between 26.46° - 27.10° north and 87.819° - 88.00° east. One of the largest river basin, Koshi is located in the western side of this basin. The catchment area of Kankai River basin is 1284 km^2. This watershed covers Ilam and Jhapa Districts. The topography of Kankai basin is highly varied. The upper part of the basin lies in hilly region with steep terrain while the lowermost narrowed part of basin lies in flat plains with mild slope. The entire basin area is dominated with forest and cropland. High percentage of clay is present in the soil of this basin area. The upper Kankai basin is dominated by sandy loam whereas the lower basin has variety in the land form with sand, clay and clay loam as major soil type.

2.2 Climatic Condition

Kävlinge basin lies in the southernmost part of Sweden which has temperate climate with four distinct seasons. Spring runs from March/April to May, summer from June to August, fall from September to October/November and winter from November/December to

February/March. Precipitation occurs throughout the year with maximum average precipitation during October/November. On an average, Kävlinge river basin receives precipitation of 664 mm to 874 mm per year. Snowfall mainly occurs from December through March. Snow is a common form of precipitation in Sweden, but it is not a common form of precipitation in Skåne. There is a large variation in temperature from -8 ˚C in winter up to 24˚C during summer in an average in a year. (SMHI, 2018) The yearly average evapotranspiration in Sweden is around 500 mm/year (EU Water and Climate Change Project, 2018). On average, the warmest month is August, the coolest months is February, end of October and beginning of November is the wettest month and March is the driest month. (SMHI, 2018)

Nepal in overall has monsoon climate. However, in a close study, two different climatic condition exists within Kankai River basin. The upper Kankai basin lies in hilly region and lower part of the basin in flat plains. Hence, a huge geographic variation exists in the basin. Relatively, upper Kankai basin has temperate climate and lower part has tropical climate. There are four major seasons in Nepal. Spring lasts from March to June, Monsoon/Summer lasts from July to late August, Autumn from September to early November and winter from mid-November to February. Precipitation is concentrated in summer months. There is no precipitation in the form of snow in this basin. The average temperature in this basin ranges from 12˚C in winter up to 27˚C during summer in upper hilly region. In the lower region, winter temperature ranges from 7˚C to 23 ˚C and summer temperature from 24˚C to 35˚C, sometimes exceeding 37 ˚C. (DHM, 2018) The yearly average evapotranspiration in Nepal is around 1200 mm/year (EU Water and Climate Change Project, 2018). On average, the warmest month is July, the coolest month is February, July/August is the wettest month and March/April is the driest month. (DHM, 2018)

2.3 Hydrology and drainage

The watershed of Kävlinge basin has dendritic drainage system with rivers flowing from east to west of Sweden which debouches into Oresund. Vomb lake with a size of 12 square kilometers lies almost in the centre of this river basin. Bjorkaan river stretch is one of the main source of flow to Vomb and Klingavalsan is a main tributary that affects the outflow of Kävlinge river. Klingavalsan meets the Kävlinge river at the downstream of Vomb lake and Braan joins the river almost at the outlet of the basin. The total stretch of Kävlinge river is 48.6 km. and the longest flow path in this basin i.e. from the most upstream of the basin to the downstream end is 88.4 km. (Sydvatten AB, 2018)

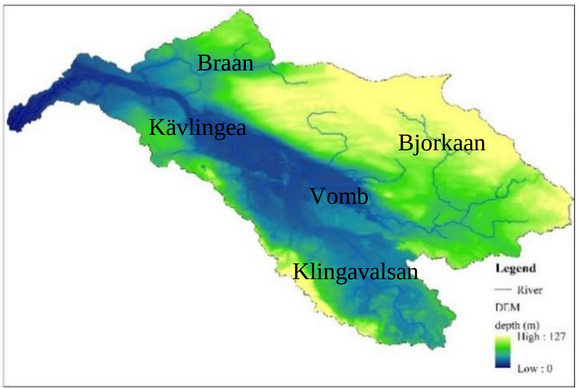


Figure 2.4 Kävlinge River Branches and Vomb Lake and (SMHI, 2018)

Kankai River is a transboundary rain fed perennial river that drains into Mahananda river of India. It originates from Mai Pokhari in Mahabharat range in Ilam district. It is called as Deumai Khola (river) at its origin and altitude at its origin is about 1820 m amsl. The extent of Kankai Mai river starts from Mainachuli weather station (denoted with a red dot in the Figure 2.5 to Indo-Nepal Boundary (downstream) and is about 28 km long. The southern reach of the river hits the Indian side at about 28 km chainage and again returns to Nepal side at the southern part. Major tributary of this river is Puwa khola. (ICIMOD, 2018)

The river channel is narrow and steep at upstream area of the basin and widens up when it reaches the lower flat terrain of Nepal. Kankai Mai lies entirely in the flat plain of the basin. The longest flow path in this basin i.e. Jog Mai and Kankai Mai stretches for 109 m.

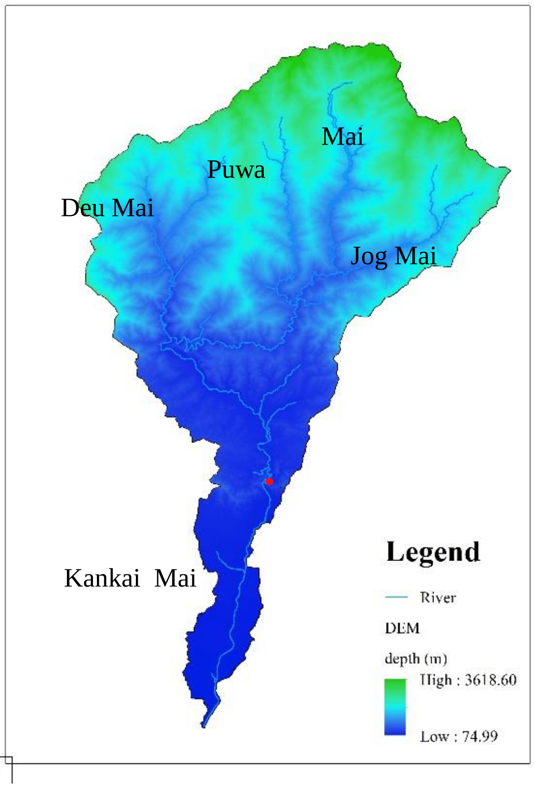


Figure 2.5: Kankai River Branches

CHAPTER 3. LITERATURE REVIEW

3.1 Model and software description

This chapter provides an insight on the theoretical and mathematical background involved behind the software describing the data processing and modelling procedures. Mainly three open source softwares are used for the project: ArcGIS, HEC-HMS and HEC-RAS. HEC-HMS is used for hydrologic and HEC-RAS is used for hydraulic modelling. While ArcGIS is used as a platform for generating physical basin models for HEC-HMS and geometric model of river for HEC-RAS using interfacing hydrological extensions HEC-GeoHMS and HEC-GeoRAS respectively.

3.1.1 ArcGIS: HEC-GeoHMS and HEC-GeoRAS

HEC-GeoHMS and HEC-GeoRAS are interfacing tools between GIS and HEC-HMS and HEC-RAS respectively. HEC-GeoHMS is a geospatial hydrology toolkit in ArcGIS to create hydrologic inputs that can be directly used with HEC-HMS. It allows to visualize spatial information, extract watershed physical characteristics from DEM (Digital Elevation Model) and GIS data, perform spatial analysis, delineate sub basins and streams to develop hydrologic parameters as well as construct inputs to hydrologic models. (Fleming et. al., 2013)

HEC-GeoRAS is an extension in ArcGIS that provides set of procedures, geospatial data processing toolkit and utilities for preparing geometric data that can be exported to HRC-RAS. It uses DTM (Digital Terrain Model) in the form of TIN (Triangulated Irregular Network) or grid for generating geometric data of river (channel, banks, flood banks and their cross sections). HEC-GeoRAS also extracts roughness coefficient (Manning's n) value for the cross sections along the river length from land use data. Further it can also be used to import the simulation results from HEC-RAS to ArcGIS for good visualization of results obtained from HEC-RAS. An animated floodplain results can be generated with this extension in ArcGIS. (Ackerman, 2011)

HEC-GeoHMS 10.2 and HEC-GeoRAS 10.2 version was used during this project.

3.1.2 Rainfall Runoff Model: HEC-HMS

Hydrologic Modelling System (HEC-HMS) is an open source computer software developed by U.S. Army Corps of Engineering´s Hydrologic Engineering Center that helps in simulating the hydrologic cycle (precipitation, evapotranspiration, infiltration, surface runoff and baseflow) of a catchment by describing it's physical and meteorological properties. A simple schematic representation of runoff process replicated in HEC-HMS is shown in *figure 3.1*. Wide options of mathematical models for all the hydrological components that conceptually represent watershed behaviour are incorporated in this program. The program uses separate model to represent each component of the runoff process like model to compute runoff volume, model of direct runoff/baseflow/ channel flow as well as alternative models to account for the cumulative losses for e.g.: SCS CN loss model. Then, it computes runoff volume by subtracting losses (infiltration, storage, interception, evaporation etc.) from precipitation. HEC-HMS 4.2.1 was used during this project. (Fleming and Brauer, 2016)

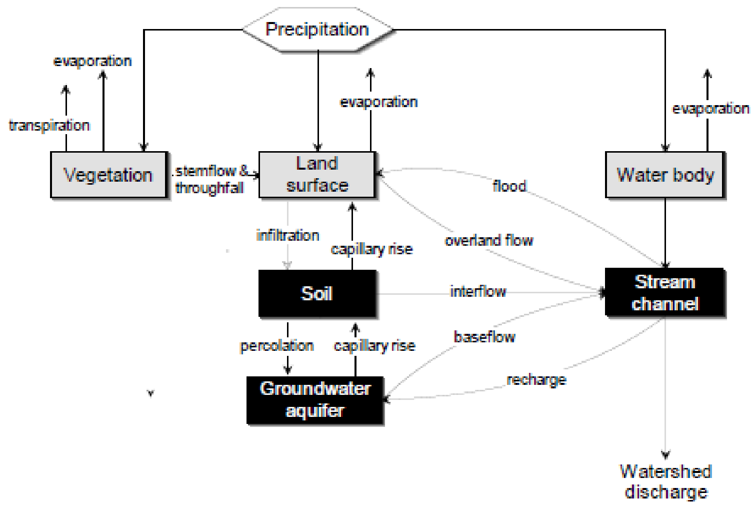


Figure 3.1: System diagram of runoff process (Feldman, 2000)

Different components included in the HEC-HMS are listed below.

- Basin Models: The physical basin area with hydrologic elements (subbasins, junctions, reach, reservoirs) and drainage network of the catchment are included in basin models.
- Meteorological Models: Information regarding meteorological components such as temperature, precipitation evapotranspiration, sunshine, humidity, snowmelt is defined in meteorological model. HEC-HMS provides variety of options to define each meteorological element.
- Control Specification: Starting date and time, ending date and time and computational time step for the simulation are defines in control specification.
- Timeseries Data: Real time series data for all the meteorological elements defined in meteorological model are fed in this part. Apart from above mentioned meteorological element, discharge data can also be supplied for calibration and simulation of the developed model. It can be supplied to the software manually or in the form of HEC-DSS, the Hydrologic Engineering Center Data Storage System.
- Paired Data: Meteorological data in tabular/graphical form are supplied as paired data. (Scharffenberg, 2016)

In HEC-HMS, the hydrological procedure of changing rainfall into runoff has been represented by four processes: loss, transform, baseflow and transform. These processes are described in following section:

Loss method

This model computes the runoff volume of the catchment by calculating losses through interception, surface storage, infiltration, evaporation, transpiration and then subtracting it to the precipitation at each time step. HEC-HMS provides five options for calculating the losses. In this project, Soil Moisture Accounting (SMA) has been used in case of Kävlinge and Kankai river basin.

Soil moisture accounting is an empirical model in HMS that allows for long term simulation of hydrologic processes that occurs over time in a catchment. It accounts for both wet and dry behaviour. It simulates water movement and storage through both surface and subsurface layers. Storage components include canopy interception and depression storage on surface layer while subsurface layer include soil profile and groundwater layer. The flow components included in this method are precipitation, evapotranspiration and surface runoff on the surface and infiltration and percolation in the subsurface layer. SMA depicts the real hydrological process which is described in the *figure 3.2* below:

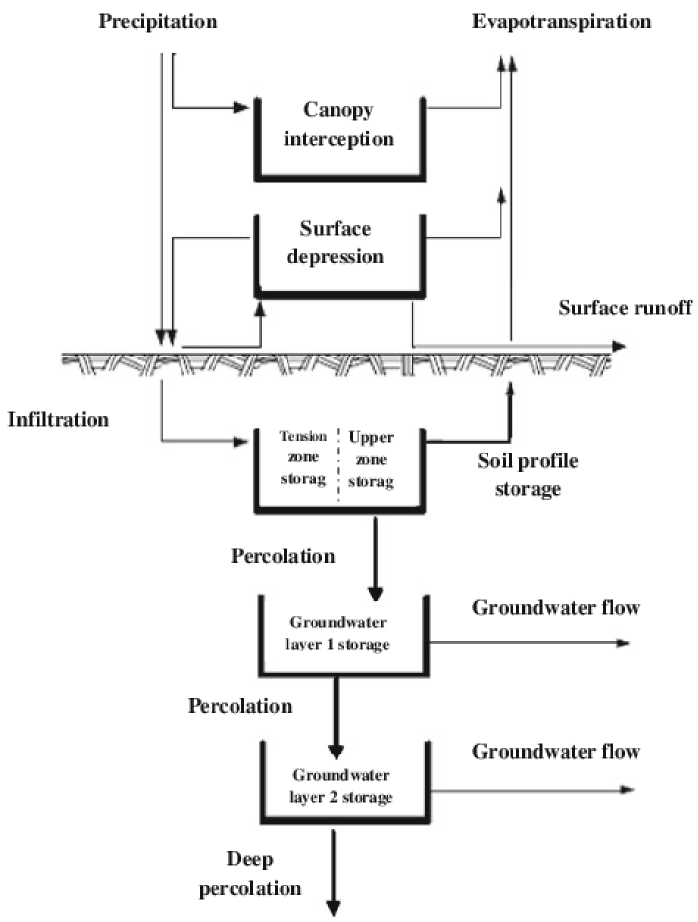


Figure 3.2: Conceptual schematics of soil moisture accounting (Bennett, 1998)

Transform method

Transform methods is an approach for computing direct runoff at the outlet of watershed area from the excess precipitation falling over it and this is done based on principles of unit hydrograph. Unit hydrograph can be defined as the runoff hydrograph produced from excess rainfall of unit depth occurring over the watershed. The theories of unit hydrograph are i) excess precipitation and runoff produced are directly proportional to each other, ii) excess precipitation is distributed uniformly with respect to time and space over the watershed area and iii) runoff produced from given excess rainfall is independent of time of occurrence and precedent moisture content (Subramanya, 2008).

The transformation method used for this study was SCS Unit Hydrograph. The resulting runoff hydrograph from this model is described by properties of unit hydrograph using one or more equations of the parameters involved. The peak of unit hydrograph and its time of peak is given by following equations.

$$Up = 2.08 * \frac{A}{Tp} \text{ and} \quad (3.1)$$

$$Tp = \frac{\Delta t}{2} + tlag \quad (3.2)$$

where, U_p = Peak of unit hydrograph, A = Area of watershed, Tp = Time of peak, Δt = Excess precipitation duration and t_{lag} = Basin lag (Feldman, 2000)

Basin lag can be defined as the time difference between the peak of unit hydrograph and centroid of the associated excess rainfall hyetograph which is depicted in the *figure 3.3* below.

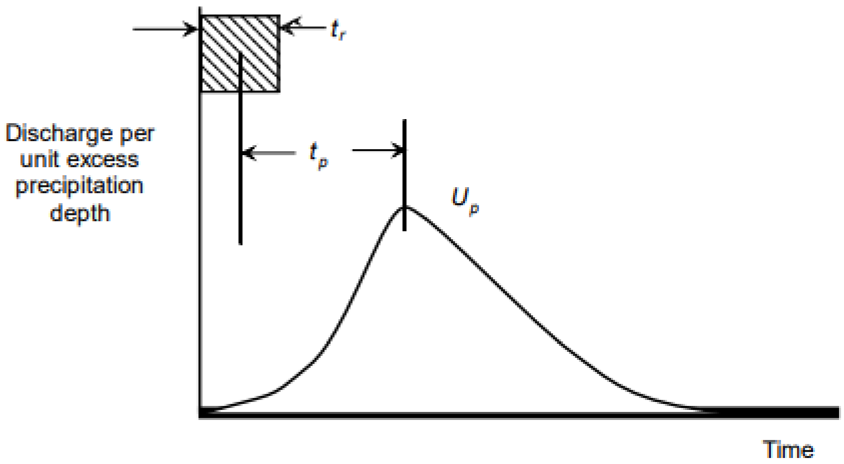


Figure 3.3: Unit Hydrograph (Feldman, 2000)

In this figure, t_p = time of peak, U_p = Peak of unit hydrograph and t_r = rainfall duration. (Feldman, 2000)

Base-flow Method

Subsurface flow in the catchment is illustrated by baseflow in HMS. Baseflow comprises of interflow and flow in groundwater aquifer. There is insignificant contribution of baseflow in case of short rainfall event, so it can be ignored. While in case of long rainfall event, the base-flow contributes to the recession limb of hydrograph and has a significant contribution in flood volume. (Cunderlik and Simonovik, 2004)

In this project, linear reservoir model has been used for baseflow computation.

Linear reservoir base-flow method is used when soil moisture accounting (SMA) method is used for loss method in HMS. Simulation of baseflow in HMS considers it as passage and storage zone of water through subsurface layer between different groundwater reservoirs. In this method, the outflow at each time step between different groundwater reservoirs is assumed to be directly proportional to average storage during the time step. Mathematically, it is explained by following equations which are based on simple continuity equation.

$$S_t = RO_t \tag{3.3}$$

$$O_t = C_A I_t + C_B O_{t-1} \tag{3.4}$$

where, S_t = Storage at time t, R= Constant linear reservoir parameter, O_t = Outflow from storage at time t and C_A and C_B = Routing coefficients. (Feldman, 2000)

Route Method

Flood routing is a technique of determining the flow hydrograph at the downstream point of catchment with sound information regarding hydrograph at its upstream. It is an approach to estimate how the magnitude and celerity of a flood wave varies than that at the inflow point as it moves along the catchment. Flood routing along the catchment is a function of basin characteristics such as slope and length of channel, channel roughness, channel shape, downstream control and initial flow condition (Rahman et al., 2017). The hydrologic modelling is based on continuity equation while hydraulic modelling is based on combination of continuity and momentum equation which is known as Saint-Venant equations (Larsson, 2017). In this project, Muskingum Cunge method has been used for river routing because of its high accuracy over other methods.

Muskingum Cunge routing method is based on simplification of convective diffusion equation which is combination of continuity equation and momentum equation. The equations are as follows:

- Continuity equation

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q_L \tag{3.5}$$

- Diffusion form of momentum equation

$$S_f = S_o - \frac{\partial y}{\partial x} \quad (3.6)$$

- Convective diffusion equation

$$\frac{\partial Q}{\partial t} + c\,\frac{\partial Q}{\partial x} = \mu\,\frac{\partial^2 Q}{\partial x^2} + cq_L \quad (3.7)$$

where, q_L = lateral flow, c = Celerity of wave and μ = Hydraulic diffusivity

The outflow is given by following equation:

$$O_t = C_1 I_{t-1} + C_2 I_t + C_3 O_{t-1} + C_4(q_L \Delta x) \quad (3.8)$$

The coefficients are:

$$C_1 = \frac{\frac{\Delta t}{K}+2X}{\frac{\Delta t}{K}+2(1-X)},\ C_2 = \frac{\frac{\Delta t}{K}-2X}{\frac{\Delta t}{K}+2(1-X)},\ C_3 = \frac{2(1-X)-\frac{\Delta t}{K}}{\frac{\Delta t}{K}+2(1-X)} \text{ and } C_4 = \frac{2\frac{\Delta t}{K}}{\frac{\Delta t}{K}+2(1-X)} \quad (3.9)$$

The parameters K and X are calculated as:

$$K = \frac{\Delta x}{c} \text{ and } X = \frac{1}{2}\left(1 - \frac{Q}{BS_o \Delta x}\right) \quad (3.10)$$

where, Δt and Δx are time and distance steps for computation.

X will approach 0 for channels with mild slopes and overbank flow while for steeper streams with well-defined channels *X* approach 0.5. (Feldman, 2000)

Q = reference flow from inflow hydrograph = x A^m (3.21)

The exponent m has major effect on the calculation of travel time of the hydrograph through a reach which can be calculated using Manning's Equation. Further, the equation for X and K shows that they dependency on channel parameters and Manning's coefficient which makes this method more reliable for flood routing. (Merkel, 2002)

3.1.3 Hydraulic Model: HEC-RAS

HEC-RAS is a tool developed for analysing hydraulics of river system developed by U.S. Army Corps of Engineering´s Hydrologic Engineering Center. It consists of graphical user interface, data storage and management capabilities as well as reporting facilities. The main input of HEC-RAS for performing hydraulic analysis are geometric data and flow data. Basic geometric data consists of physical feature of river i.e. channel length, banks, flood banks and cross-sections of the river while additional geometric data defining bridge and culverts, levee alignment, blocked structures, inline structures and storage area can also be incorporated in the software. HEC-RAS has capability of performing one-dimensional and two-dimensional hydraulic calculations. Based on the purpose of the study, HEC-RAS provides different options for performing river analysis which are one-dimensional steady flow for water surface profile computation, one and two-dimensional unsteady flow simulation, quasi unsteady flow for sediment transport computation and water quality analysis (Brunner, 2016).

In this project, one dimensional (1-D) steady flow analysis has been performed for Kävlinge and Kankai river basin and the result has been used to generate flood inundation area. 1-D steady flow analysis is useful for calculating water surface profile. In this analysis, the flow is assumed to be gradually varying along its length. It can calculate the water surface profile for subcritical, supercritical and mixed flow condition. Governing equation for calculation of water surface profile is Energy equation which is written as follows:

$$Z_2 + Y_2 + \frac{\alpha_2 {V_2}^2}{2g} = Z_1 + Y_1 + \frac{\alpha_1 {V_1}^2}{2g} + h_e \quad (3.12)$$

Where, Z_1 and Z_2 = elevation of bottom of the channel at cross-section 1 and 2

Y_1 and Y_2 = depth of water at cross-section 1 and 2

V_1 and V_2 = velocity of water at cross-section 1 and 2

α_1 and α_2 = velocity weighing factors

g = acceleration due to gravity

h_e = energy headloss

Water surface profile between any two cross sections is calculated by solving the energy equation (3.12) in an iterative way. This process is called as standard step method. The calculation proceeds upstream if the flow is subcritical and downstream if the flow is supercritical (French, 1987). For the computation of water surface, each cross-section of river is divided into left overbank, main channel and right over bank and the energy is calculated for each section. The final energy of the channel is the mean of the energy calculated for all three sections (Brunner, 2016). The head loss in the equation 3.12 comprises of loss due to friction and contraction/expansion. The friction loss is given by Manning's equation which is given below:

$$h_f = LS_f \quad (3.13)$$

Where,

S_f = representative friction slope (slope of energy grade line)

$= \frac{Q}{K}$

Q = Flow in the channel length

K = conveyance factor = $\frac{1.486}{n} A R^{2/3}$

n= Manning's roughness coefficient

A = Area of the channel

R = hydraulic radius which is calculated as area per wetted perimeter

L = distance weighted reach length

$= \frac{L_{lob}Q_{lob} + L_{ch}Q_{ch} + L_{rob}Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}}$

L_{lob} , L_{ch} , L_{rob} = cross-section reach length in left overbank, main channel and right overbank respectively.

Q_{lob} , Q_{ch} , Q_{rob} = average mean flow between sections for left overbank, main channel and right over bank respectively.

The contraction/expansion loss is calculated as:

$$h_{ce} = C \left| \frac{\alpha_2 {V_2}^2}{2g} - \frac{\alpha_1 {V_1}^2}{2g} \right| \quad (3.14)$$

Where, C = Coefficient of contraction/expansion.

Combining friction loss and loss due to contraction/expansion, the total energy loss equation is given below:

$$h_e = LS_f + C\left|\frac{\alpha_2 V_2^2}{2g} - \frac{\alpha_1 V_1^2}{2g}\right| \quad (3.15)$$

Velocity weighing factor, α is calculated as

$$\alpha = \frac{Q_1 V_1^2 + Q_2 V_2^2}{(Q_1 + Q_2)V^2}$$

Where, V =mean velocity of the reach length. (Brunner, 2016)

3.2 Theory

3.2.1 Flood Frequency Analysis

Flood frequency analysis is an estimation of how often a certain amount of flow is reoccurring. Such estimation is pre-requisite for carrying out hydraulic computation of river and developing flood inundation map. The analysis is done by fitting a probability model to the sample of annual extreme flood values recorded over a long period of time, for a catchment. The model parameters established can then be used to predict the extreme events of large recurrence interval (Pegram and Parak, 2004). For this project, Gumbel Distribution method has been selected for flood frequency analysis.

Gumbel's distribution is a statistical method commonly used for predicting extreme hydrological events such as floods (Haan, 1977). According to Gumbel, the probability (P) of occurrence of any extreme event is given by the following equation:

$$P(X \geq x_o) = 1 - e^{-e^{y}} \quad (3.16)$$

where y is a dimensionless variable given by

$$y = \frac{1.285(x - \bar{x})}{\sigma_x} + 0.577$$

Where, $\bar{x}$ = mean and σ_x = standard deviation of the variate X.

Rearranging the above equation, the equation for fitting the Gumbel distribution to observed series of flood flows at different return periods T is given as

$$x_T = \bar{x} + K\sigma_x \quad (3.17)$$

where, $K = \frac{y_T - 0.577}{1.2825}$ and $y_T = -\left[\ln\ln\frac{T}{T-1}\right]$

Recurrence interval T is calculated as

$$T = \frac{1}{P}$$. (Subramanya, 2008)

CHAPTER 4. MATERIALS AND METHODS

This chapter gives a detailed overview on data required for the model development and stepwise procedures for the simulation and modelling.

4.1 Data Acquistion and Analysis

A good understanding of the topographical, hydrological and climatic condition of the study area and proper set of data defining them are very important for analysing and replicating the actual hydrologic and hydraulic situation. Further, the quality of data used for modelling directly affects the output, so the collected data should be screened and processed before using them.

4.1.1 Data for Hydrologic Modelling: HEC-HMS

Data required for hydrologic modelling (HEC-HMS) are:

i. Digital Elevation Model (DEM):
ii. Land use and Soil cover
iii. Climate data (precipitation, temperature, evapotranspiration, humidity, sunshine)
iv. Flow data

i. Digital Elevation Model (DEM)

DEM (Digital Elevation Model) represented the topographic feature of the study area. For Kävlinge, a 2m spatial resolution DEM was downloaded from an open source, Swedish National Land Survey's (Lantmäteriet) Geoportalen. For Kankai, two DEMs were acquired; one of 20m spatial resolution DEM from Department of Survey, Government of Nepal (GoN) and another of 30 m resolution downloaded from an open source, USGS. The DEMs acquired for both study areas were refined using tools in HEC-GeoHMS that has been explained in section 4.2.1 below.

ii. Land use and Soil cover

Land use

GIS layer for land use of Kävlinge was downloaded from Swedish Board of Agriculture (Jordbruksverket). As shown in the *Figure 4.1*, land use in Kävlinge river basin has been classified into four categories as cropland, water bodies, developed area and pasture. Cropland is a dominant land type whereas developed areas is least present in the river basin. Land use map for Kankai was downloaded from ICIMOD(a), which is shown in *Figure 4.2* below. As shown in the *Figure 4.2*, the land use in the Kankai River basin has been classified into five categories as cropland, water bodies, developed area, pasture and barren land. The basin is dominated by forest and cropland. Developed area in the river basin is very less.

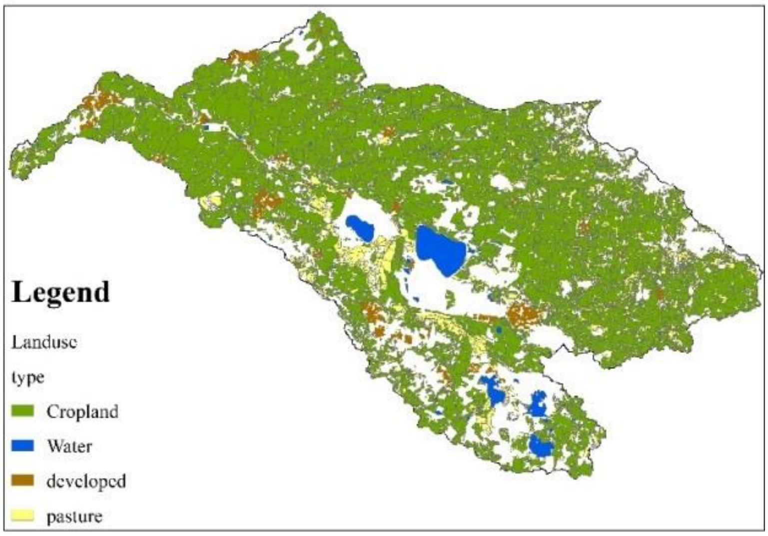


Figure 4.1: Land use classification of Kävlinge River Basin

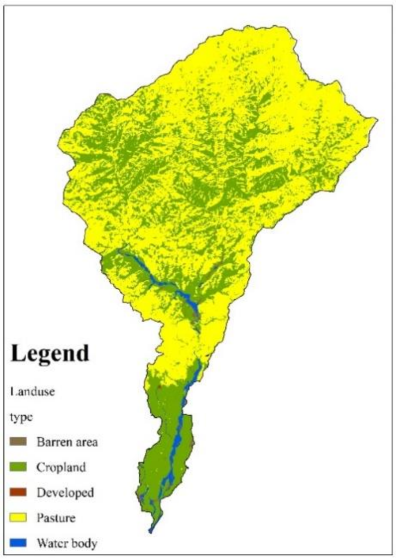


Figure 4.2: Land use classification of Kankai River Basin

Soil cover

Soil cover map of Sweden was obtained from Geological Survey of Sweden (Sveriges Geologiska Undersökning). It represents the top layer of soil in the basin area. The original soil layer map included many classifications of soil type which were narrowed down to four basic categories as clay, clayey till, sand and sandy silty till. Geological description of the study area is mentioned in Chapter 2 of this report. The soil layer classification for Kävlinge river basin used in the project is shown in *Figure 4.3* below.

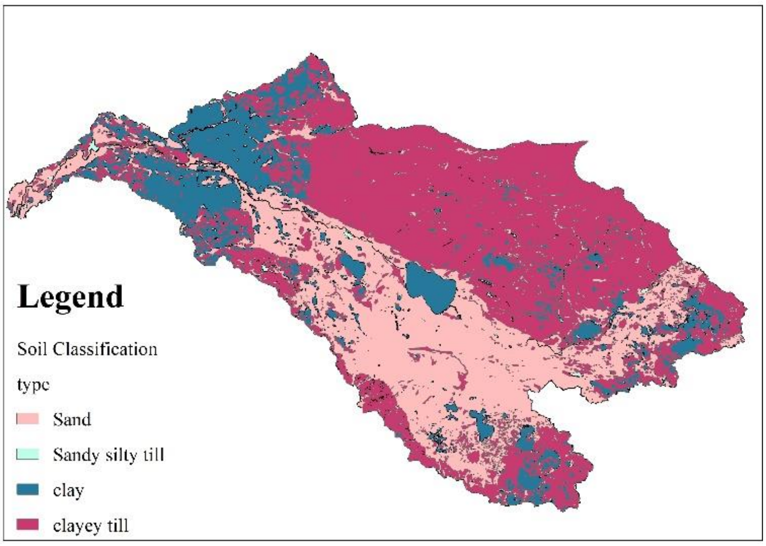


Figure 4.3: Soil classification of Kävlinge River Basin

Figure 4.4: Soil classification of Kankai River Basin

Soil cover map of Kankai River basin was downloaded from Soil and Terrain (SOTER) database programme, ISRCI. Soil layers for Kankai were also narrowed down and categorized into four major classes: clay, clay loam, sand and sandy loam. Soil classification map of Kankai basin is shown in *Figure 4.4*.

iii. Climate data

Climate data includes precipitation, sunshine, humidity and temperature data. Climate data for Kävlinge were downloaded from database of Swedish Meteorological and Hydrological Institute (SMHI, 2018). There are 9 evenly distributed temperature and precipitation gauges in Kävlinge basin. However, the data available at those 9 stations were not real time data but were interpolated from nearby weather stations. Data for humidity and sunshine were available at only one station for the study area. The climate data used for the study was for the period of 2008 to 2014. *Figure 4.5* below shows the location of precipitation and temperature gauging stations in Kävlinge river basin.

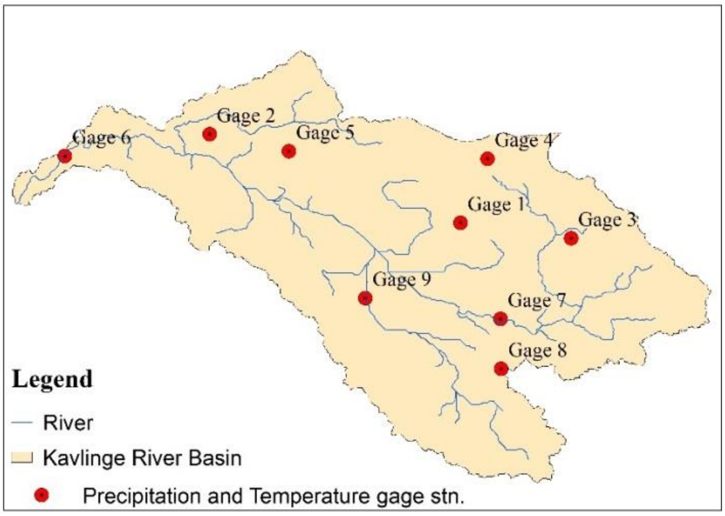


Figure 4.5: Precipitation and Temperature gauging station of Kävlinge basin

The precipitation and temperature pattern in Kävlinge is shown in *Figure 4.6* and *Figure 4.7* below.

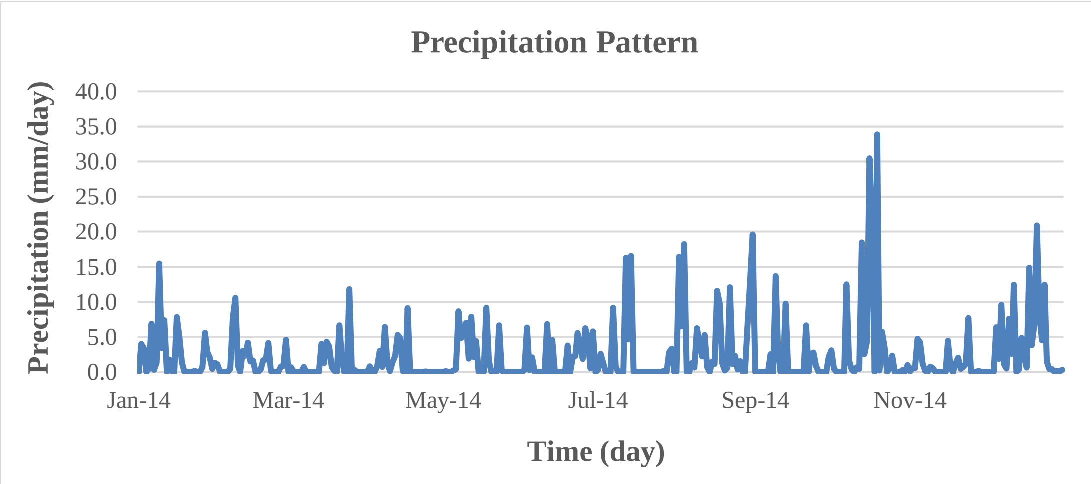


Figure 4.6: Precipitation pattern in Kävlinge river basin

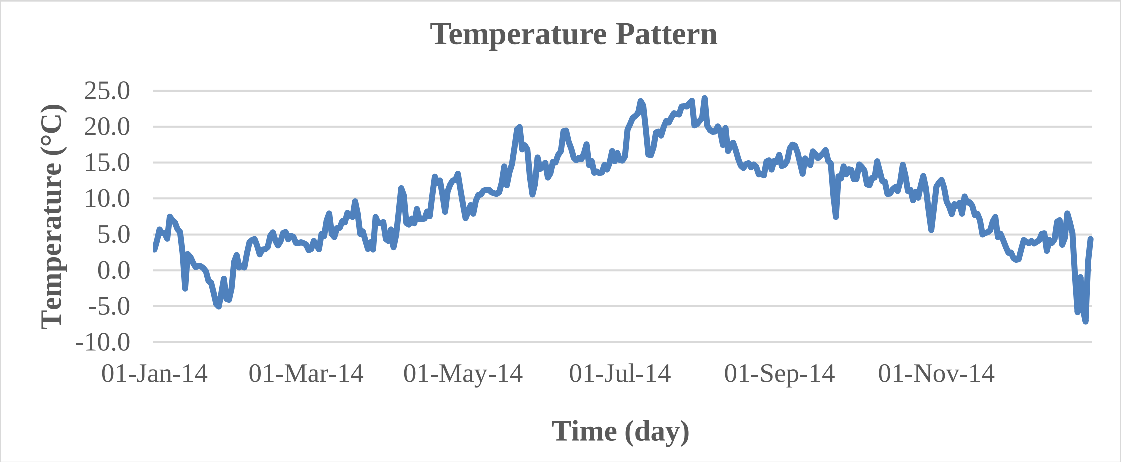


Figure 4.7: Temperature pattern in Kävlinge river basin

For Kankai river basin, climate data were obtained from Department of Hydrology and Meteorology (DHM), Government of Nepal. Data for precipitation was used from six sparsely distributed precipitation gauging stations. Out of six only two stations are situated within the basin and remaining four lies around its periphery. Humidity and temperature data were obtained from four climatology stations. Out of four only one station lies within the basin and three around the basin periphery. The climate data used in Kankai river basin was for the period of 2000 to 2006. *Figure 4.8* and *Figure 4.9* below shows the location of precipitation and humidity and temperature gauging stations respectively.

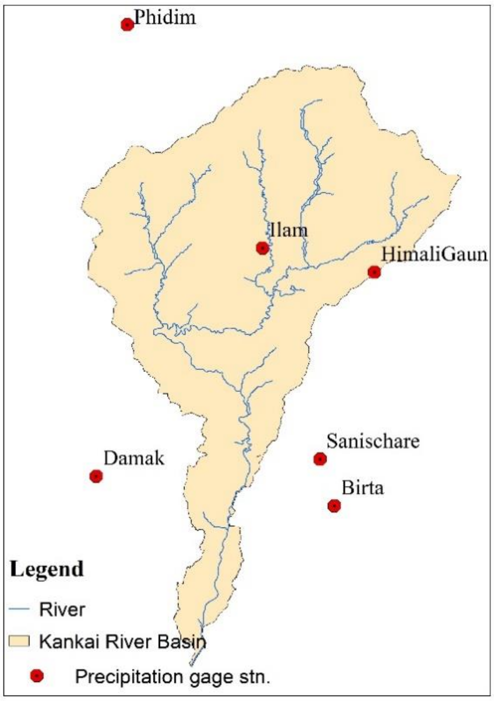


Figure 4.8: Precipitation gauge station of Kankai basin.

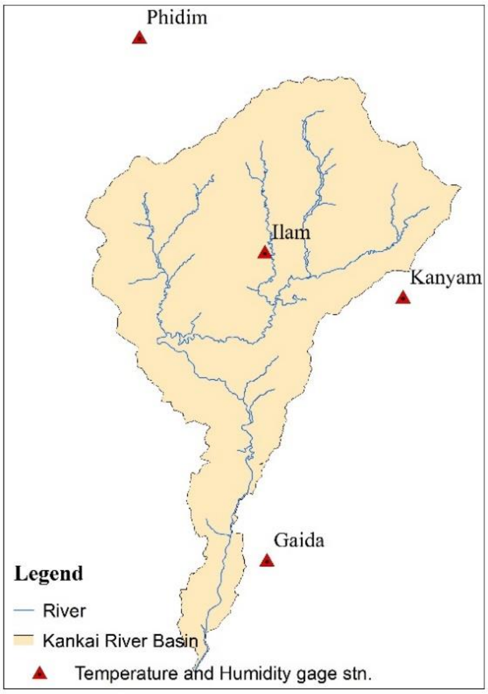


Figure 4.9: Temperature gage station of Kankai basin

Precipitation and temperature data for the year 2006 for gaging station Ilam of Kankai basin has been shown in *Figure 4.10* and *Figure 4.11* respectively. These graphs below represent the pattern of rainfall and temperature of the study area.

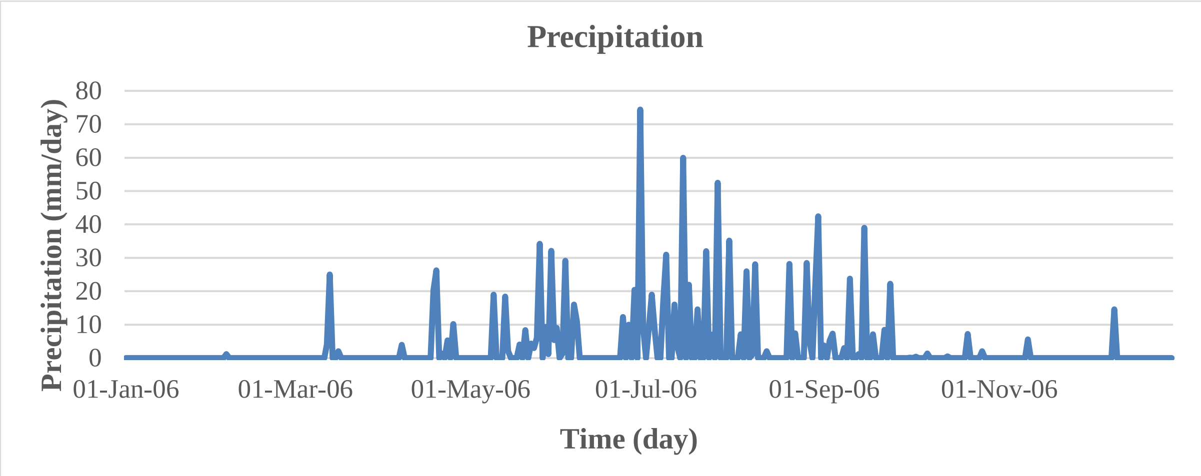


Figure 4.10: Precipitation pattern in Kankai river basin

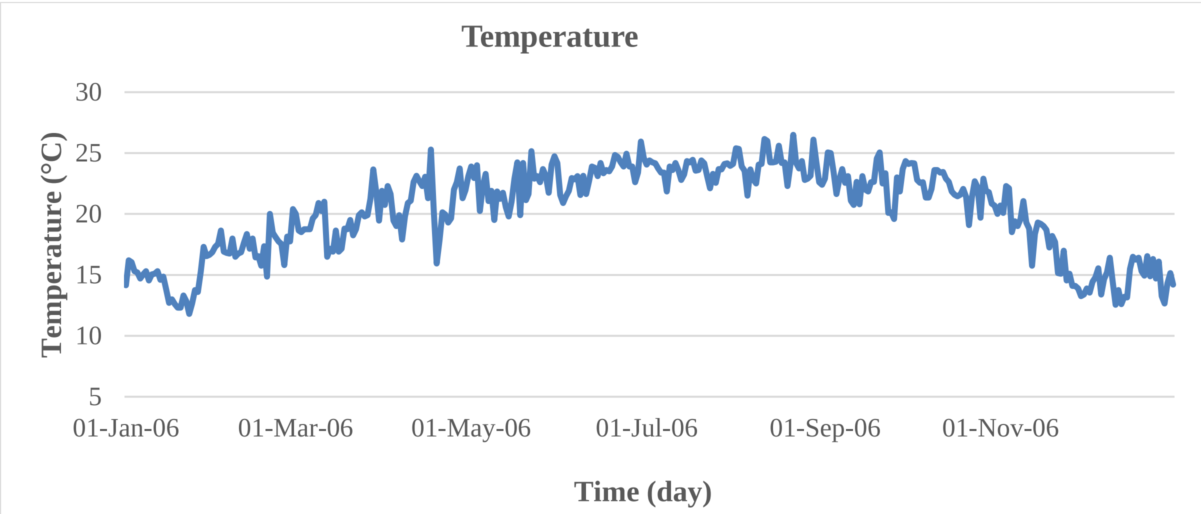


Figure 4.11: Temperature pattern in Kankai river basin

For both basins, yearly average evapotranspiration value from the year 1985 to 1999 was taken from EU Water and Climate Change Project, Centre for Ecology and Hydrology.

iv. <u>Flow data</u>

Daily discharge data are used for the calibration of hydrological model. In case of Kävlinge, there are five discharge gauging stations along the river stretch namely Klingavalsan (2116), Ellinge (2126), Hogsmoll (2171), Vomb (2018) and Egglestad (2125). Daily flow data at these stations were downloaded from database of Swedish Meteorological and Hydrological Institute (SMHI, 2018). Location of discharge stations of Kävlinge river basin is shown in *Figure 4.12* below. Out of the above five mentioned discharge stations, first four stations were used for calibration and validation of hydrological model.

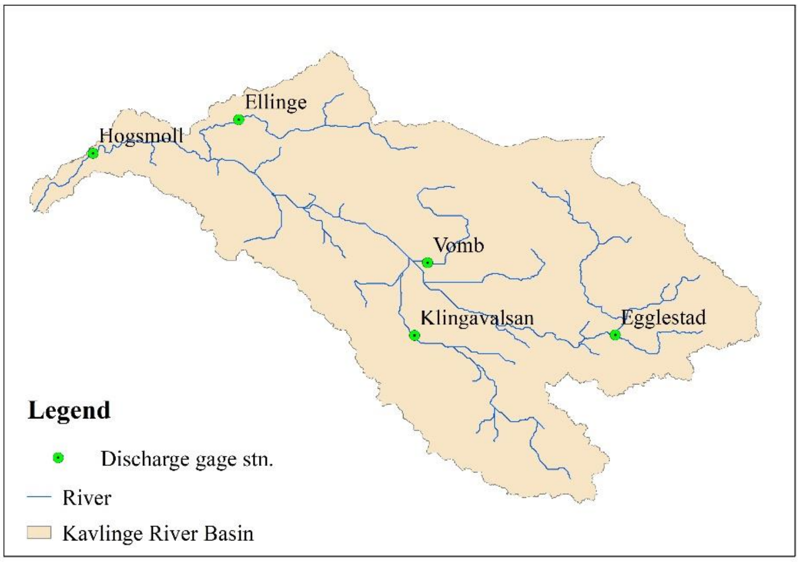


Figure 4.12 :Discharge gauge station of Kävlinge River Basin

There are three discharge stations in Kankai River basin namely Puwa, Rajdwali and Mainachuli. Daily discharge data of these stations were obtained from Department of Hydrology and Meteorology (DHM), Government of Nepal. Location of discharge stations of Kankai river basin is shown in *Figure 4.13* below. However, discharge gage station Puwa has not been used for hydrological analysis because of large missing data.

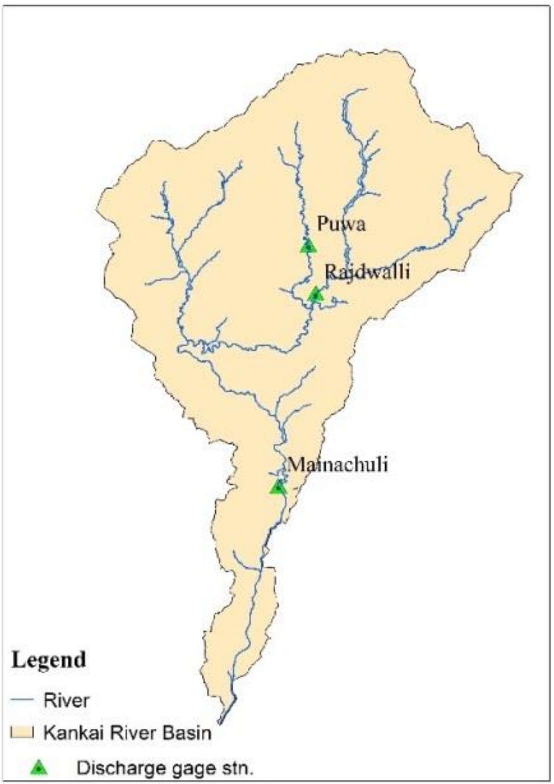


Figure 4.13: Discharge gauge station of Kankai River Basin

4.1.2 Data for Hydraulic Modelling: HEC-RAS

Data required for Hydraulic modelling (HEC-RAS) are:

i. Triangulated Irregular Network (TIN)
ii. Land use
iii. Flow data

i. Triangulated Irregular Network (TIN)

Digital Terrain Model in the form of Triangulated Irregular Network (TIN) is required for the hydraulic analysis of river system. TIN must be of high-resolution with continuous surface and should represent bottom of the river and adjacent flood plains as all the cross-sectional data will be extracted from it. TIN for both study areas were derived from their respective DEM.

ii. Land use

The Manning's value for different land use types used in both basins are listed in *Table 4.1* below.

Table 4.1: Manning's n values (Chow et al., 1988)

Land use	**Manning's n**
Cropland	0.05
Pasture	0.05
Barren land	0.04
Water bodies	0.035
Forest	0.1
Developed areas	0.12

iii. Flow data

Discharge gages of Kävlinge and Kankai basin are shown in *Figure 4.12* and *Figure 4.13* respectively. In case of Kävlinge, discharge stations Egglestad (2125), Klingavalsan (2116) and Ellinge (2126) has been used for hydraulic analysis while in case Kankai, Mainachuli discharge station has been used for hydraulic analysis.

4.2 Methodology

4.2.1 Hydrological Model Development

Rainfall runoff modelling was carried out with the help of HEC-HMS and HEC-GeoHMS a hydrological extension in ArcGIS. Detailed description regarding these software has been done in *Section 3.1.1*.

An overview of working mechanism of rainfall runoff model is shown with the help of schematic diagram below in *figure 4.14*.

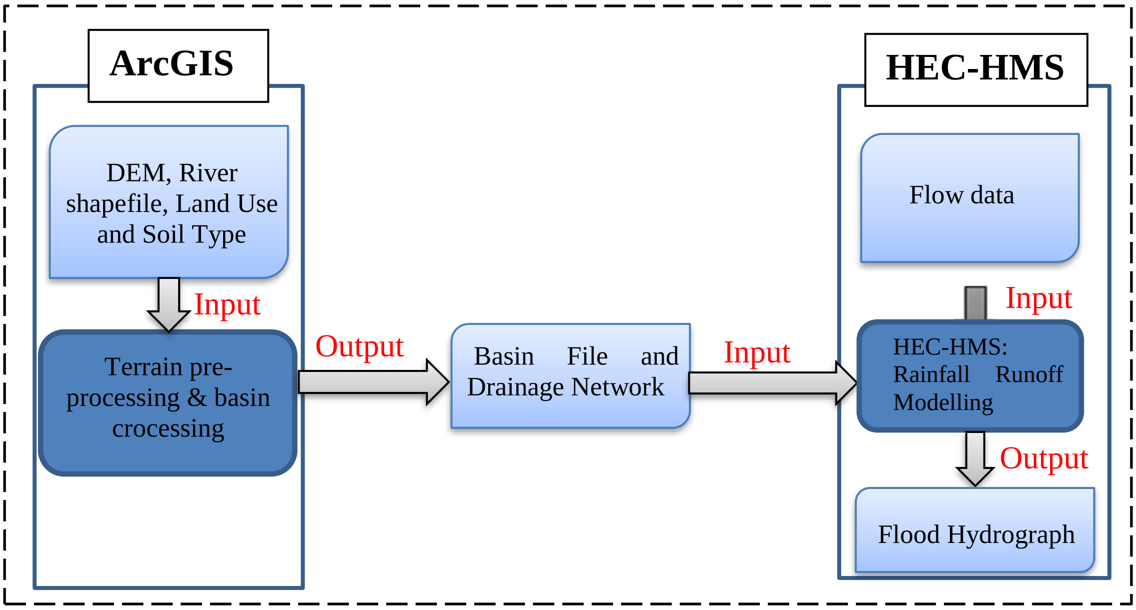


Figure 4.14: Modelling approach Rainfall Runoff Modelling

The methodology used for carrying out Rainfall Runoff Modelling can be described by categorizing them into two sections, which are as follows:

i. Creating Basin Model
ii. Developing Hydrological Parameters
iii. Hydrological Modelling

i. Creating Basin Model

Basin model was created with the help of HEC-GeoHMS, a hydrological toolkit in ArcGIS.

Terrain Pre-processing

Before carrying out terrain pre-processing, the input terrain data DEM was refined using DEM reconditioning. After this process, the DEM was pre-processed in HEC-GeoHMS to derive sub-basins and drainage network of the catchment. The steps included were fill sinks, flow direction, flow accumulation, stream definition, stream segmentation, catchment grid delineation, catchment polygon processing, drainage line processing and adjoint catchment processing.

After terrain pre-processing, HEC-HMS project was created. At first, a project point was defined at the downstream end of the watershed based on which the software delineated the project area. The resulting project area for Kävlinge river basin was 1105.64 km^2 and that for Kankai River basin was 1279.69 km^2.

Basin Processing

The delineated sub-basins and rivers were merged based on river junctions. Then, batch points were imported and delineated which represented discharge stations. There were four batch points in Kävlinge river basin and two in Kankai River basin.

For each of the sub-basins and river, physical characteristics were computed based on the refined DEM. The computed characteristics for river included river length and river slope and for basin included basin slope, longest flowpath to the basin, basin centroid, centroid elevation and centroidal longest flowpath. To calculate basin slope, watershed slope was required which was calculated using ArcHydro tool.

Some major characteristics of the basin model for Kävlinge and Kankai are tabulated in *Table 4.2* below:

Table 4.2: Basin Model characteristics

Characteristics	Kävlinge River Basin	Kankai River Basin
Basin area (km^2)	1105.64	1279.69
Number of sub-basin after terrain pre-processing	31	42
Number of sub-basin after basin merge	18	23
Number of batch points	4	2

ii. Developing hydrological parameters

This step parameterizes the values of different hydrological processes involved in modelling. The hydrological parameters were estimated by using the land and soil use data for each sub-basin. Different steps involved for developing hydrological parameters are as follows:

Select HMS processes: HMS processes for modelling loss, transform, base-flow and routing were selected. In this project, same HMS processes were selected for both study areas which are listed below in *Table 4.3.*

Table 4.3: Selected methods for HMS

HMS Processes	Method
Loss	Soil Moisture Accounting (SMA)
Transform	SCS Unit Hydrograph
Base-flow	Linear Reservoir
Routing	Muskingum-Cunge

CN Lag: This function calculated lag time for transform method based on CN grid. CN grid was generated in ArcGIS using land use and soil cover layers. CN values adopted for different land use type for Kävlinge and Kankai basin are given in *Table 4.4* and *Table 4.5* below.

Table 4.4: CN values adopted for Kävlinge River Basin (Feldman, 2000)

Description	A	B	C	D
Water bodies	100	100	100	100
Developed areas	61	75	83	87
Pasture	68	79	86	89
Cropland	71	80	87	90

Table 4.5: CN values adopted for Kankai River Basin (Feldman, 2000)

Description	A	B	C	D
Water bodies	100	100	100	100
Developed areas	61	75	83	87
Forest	68	79	86	89
Cropland	71	80	87	90
Barren land	76	85	90	93

Developing HEC-HMS model files : In this step, model files such as background- map file, basin model file and meteorological model file required for HEC-HMS were generated. At first, all the physical characteristic values of reaches and sub-basins were converted to user defined unitary system. In this case, SI system was used for both cases. After this HMS basin schematics and legends were added to the basin map. HMS basin schematics included HMS links that represented river and HMS nodes that represented sub-basins and junctions. By adding HMS legend, HMS nodes representing sub-basins and junctions were replaced with HMS legend. Further, coordinates were added to the features in HMS nodes and HMS links.

Finally, background-map file and basin file were created for exporting them to HMS. Gauge weight method was chosen for creating meteorological model file for both basins. For using this method, Thiessen polygon for the available precipitation stations within or in the periphery of the basin area was created in ArcGIS. Thiessen polygon of Kävlinge and Kankai are shown in Appendix B.

iii. Hydrological Modelling

After completion of building model framework in HEC-GeoHMS, modelling was performed in HEC-HMS by importing files from ArcGIS which were:

- Background- map and river
- Basin file with extension '. basin'
- Meteorological files with extensions '. met' and '. gage'.

Basin models for Kävlinge and Kankai in HEC-HMS are given in *Figure 4.15* and *Figure 4.16* respectively. The initial values of loss parameters like canopy storage and percentage impervious were calculated using landuse data. And initial values of loss parameters like surface storage, infiltration rate, soil percolation rate, soil storage, tension zone storage and GW1 percolation rate was calculated using soil type data. Streamflow recession analysis was carried out to get the initial values of parameters like GW1 storage depth, GW1 coefficient, GW2 storage depth and GW2 coefficient. These calculations were done based on method described in a paper named 'Tutorial on using HEC-GeoHMS to develop Soil Moisture Accounting Method Inputs for HEC-HMS'. Likewise, all the meteorological components included for modelling of the basin were defined. Different meteorological components included for modelling Kävlinge and Kankai River basin are listed in *Table 4.6*.

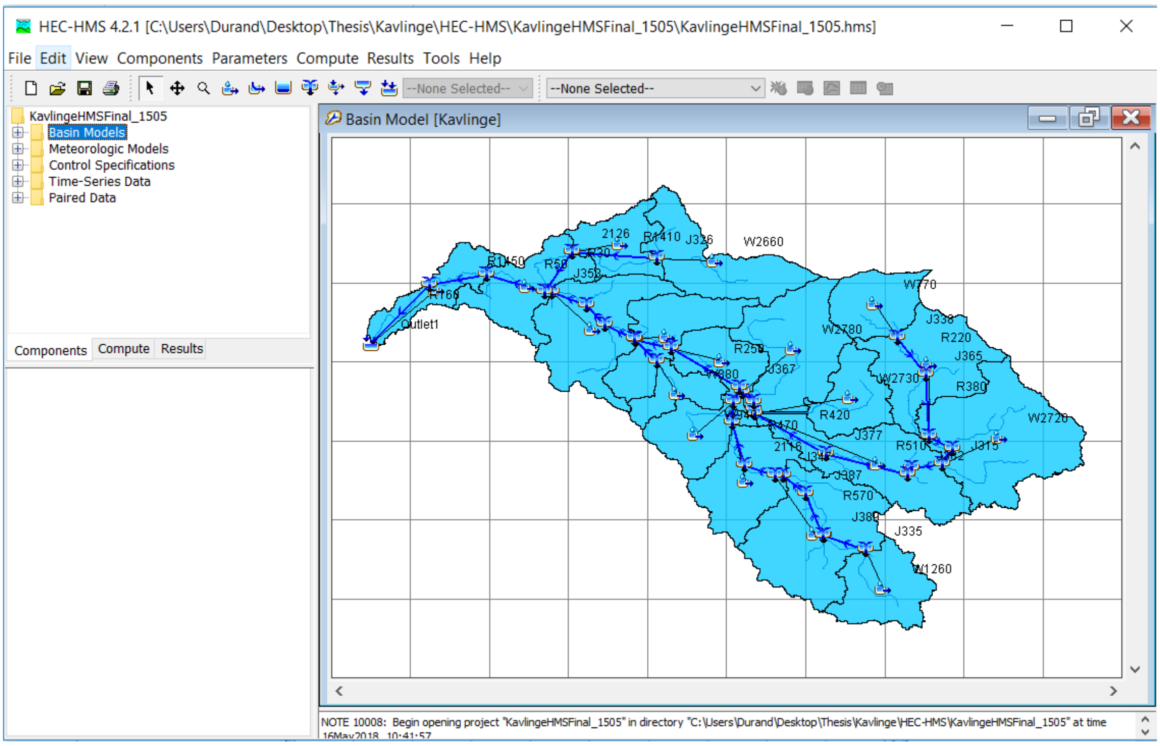


Figure 4.15: HEC-HMS Basin Model Map of Kävlinge river basin

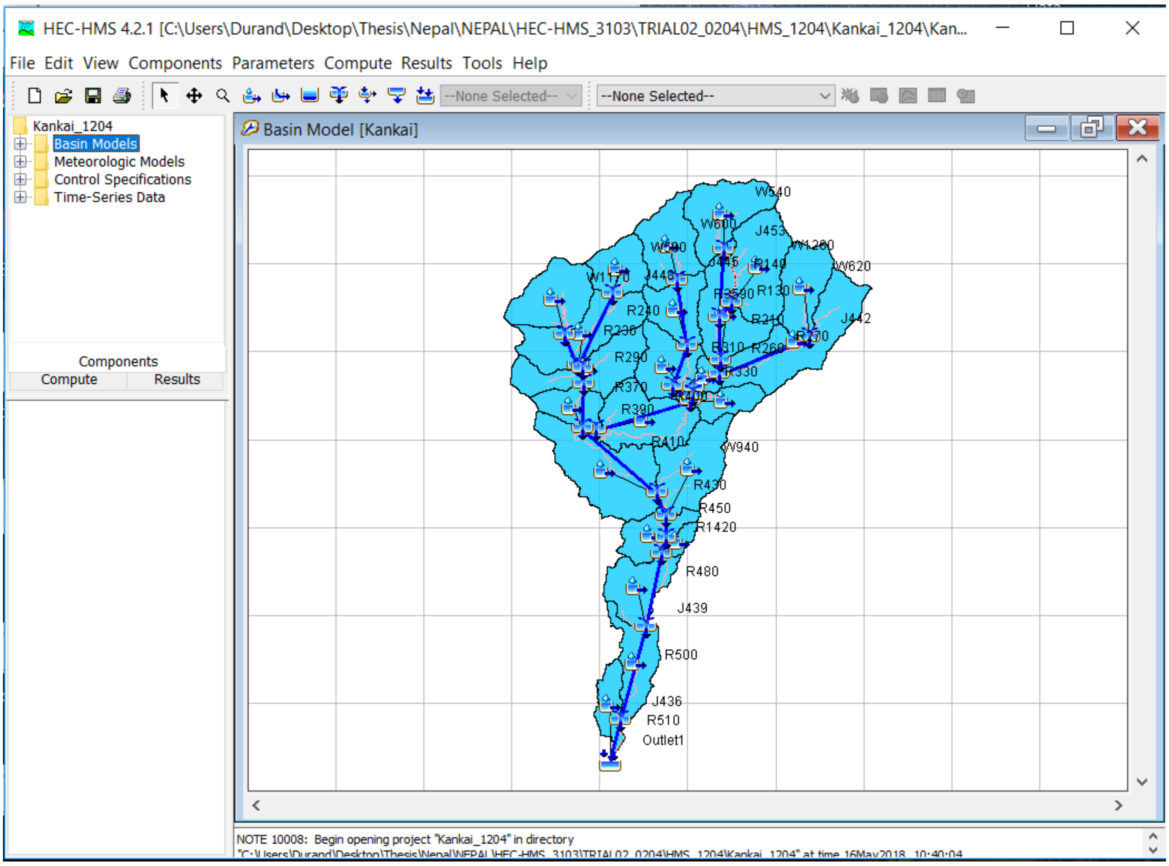


Figure 4.16: HEC-HMS Basin Model Map of Kankai river basin.

Table 4.6: Meteorological Specifications of Kävlinge and Kankai river basin

Meteorological components	Kävlinge River Basin	Kankai River Basin
Shortwave radiation	FAO56	-------
Longwave radiation	FAO56	FAO56
Precipitation	Gauge Weight	Gauge Weight
Evapotranspiration	Monthly Average	Monthly Average
Snowmelt	Temperature Index	---------

Snowmelt was not included for modelling Kankai River basin because there is no precipitation in the form of snow in the basin area. Also, shortwave radiation was not included for Kankai basin due to unavailability of sunshine data. After the meteorological components were defined, real time series data defining them were entered. Description of all the time-series data entered for both models are given in Section 3.1.2. All time-series data were entered manually for both models. Finally, simulation run time and computational time step was set in control specification. Control specifications for calibration and validation of bath basins are tabulated in *Table 4.7.*

Table 4.7:Control Specification for calibration and validation of both models

Control Specification	Kävlinge River Basin	Kankai River Basin
Calibration period	2008-2011	2000-2003
Calibration time step	30 minutes	30 minutes
Validation period	2012-2014	2004-2006
Validation time step	30 minutes	30 minutes

After completion of building and parameterizing the model components, following operations were performed.

1. Sensitivity Analysis
2. Calibration and validation

Sensitivity Analysis

Sensitivity analysis was carried out for 14 SMA parameters. The parameters evaluated are lag time, canopy storage, surface storage, maximum infiltration, impervious, soil storage, tension storage, soil percolation, GW1 storage, GW1 percolation, GW1 coefficient, GW2 storage, GW2 percolation and GW2 coefficient. The initially calculated and assumed values of the parameters were kept as base value for the evaluation and one parameter at a time was analysed from -50% to +50% with increment of 10% keeping all other parameters constant. The sensitivity of SMA parameters defining the initial condition were not evaluated. The percentage change in simulated volume and peak flow due to percentage variation in each parameter was plotted in separate graphs. The parameters that showed greater variation in simulated volume and peak flow were considered as most sensitive for each case. The parameters were ranked from most to least sensitive based on the plotted graph. The result of sensitivity analysis is shown and discussed in Section 5.1.

Calibration and Validation

Calibration of the models was performed to obtain the outflow volume, peak flow and time of peak as closely as possible to the observed ones at the discharge gauges. However, the primary objective of this project was to simulate the volume of the basin accurately. Therefore, calibration was done mainly considering the simulated outflow volume. In case of Kävlinge, it was carried out at four stations and in case of Kankai, at two discharge stations. Description of the discharge stations has been done in Chapter 4 of this report. Calibration procedure undertaken involved combination of automated calibration provided by the software and manual calibration. At first automated calibration was done, however, the results obtained from it was not satisfactory, so it was followed by manual calibration. Manual calibration was done by optimizing the initially set values of different parameters until a good calibrated model was obtained. Optimization of parameters were first done considering their physical relevance; however, the model could not be calibrated accurately. So, the final values of parameters that were taken to obtain calibrated model did not have any physical relevance to the process.

After calibration, the models were validated using the same input parameters as determined by the calibration process but with different simulation time. Models for both Kävlinge and Kankai were calibrated for four years and validated for 3 years. The detail information regarding time span and run time is provided in *Table 4.7.*

4.3 Hydraulic Model Development

Hydraulic analysis of the river system was performed with the help of HEC-RAS along with HEC-GeoRAS, an extension in ArcGIS. Schematic diagram of modelling approach for performing hydraulic analysis is as shown in *Figure 4.17* below:

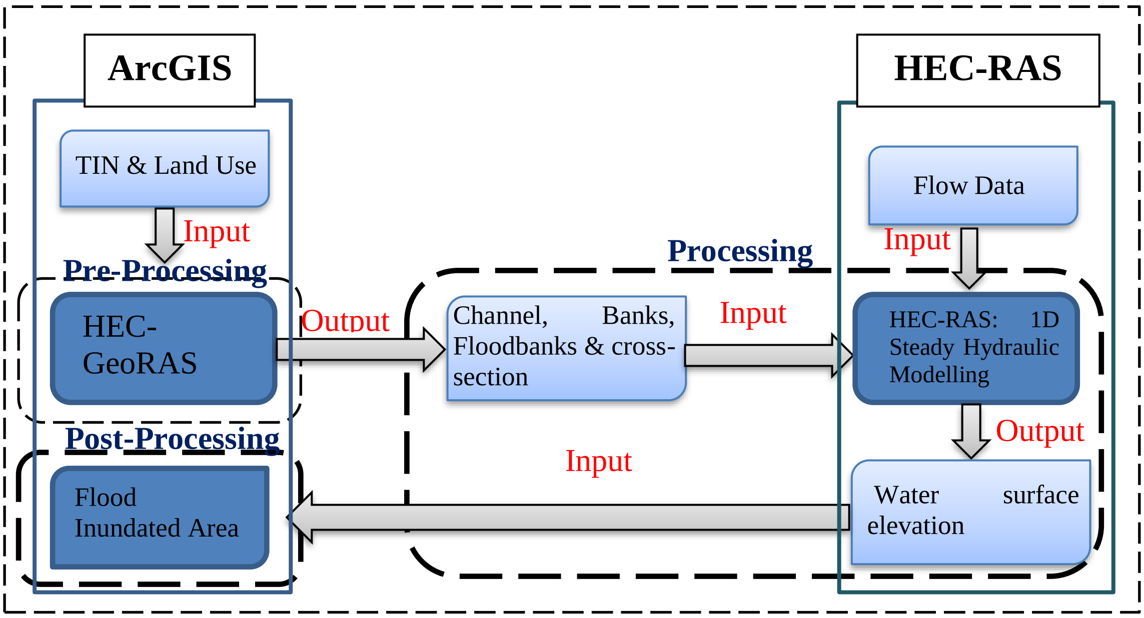


Figure 4.17: Modelling approach for Flood Inundation Mapping

The methodology used for performing hydraulic analysis can be diving into three parts which are as follows:

- Pre-processing: Developing geometry of river in ArcGIS
- Processing: Performing hydraulic computation in HEC-RAS
- Post-processing: Processing RAS results in ArcGIS

4.3.1 Pre-processing: Developing geometry of river in ArcGIS

Firstly, TIN was generated based on the DEM available for two study areas. Both DEM were refined using pre-processing tools (DEM reconditioning and fill sink) available in HEC-GeoHMS. Based on the generated TIN and aerial photograph of the study area, geometric layers like stream centreline, bank lines, flow path centrelines and cross section cut lines were created. These layers represented the actual river system. Other than these basic geometric features, additional features like bridges, blocked obstruction, ineffective areas were also created which are present along river for making the analysis more realistic. Stream centreline, bank lines, flow path centrelines, cross-section cut lines and bridges were created as polylines while blocked obstruction and ineffective areas around bridges were created as polygons. The cross-sectional cut lines were generated automatically in HEC-GeoRAS at a regular interval which were further refined manually based on their necessity. All the layers were to generate their attributes like name, length, topology, elevation, positioning for them to be identified while importing them to HEC-RAS. Further, land use layer was also used to generate the values for Manning's coefficient on all the cross-sections.

4.3.2 Processing: Performing hydraulic computation in HEC-RAS

All the geometric data were imported into HEC-RAS and the verification of quality of data was done. To run the flood analysis, 1D Steady flow simulation was carried out under subcritical flow regime. Flood values for 5, 25,100 and 500 return periods were calculated using Gumbel Distribution Method, as explained in Section 3.2.1 above. The Gumbel distribution graph plotted for both the basins have been included in Appendix C. These flood values along with suitable boundary conditions were used as input for steady flow data. Since the selected flow regime was subcritical, boundary condition was defined only at the downstream end of the river. It was defined by the normal depth which is the slope of the river bed. The boundary condition at the junction were predefined by the software. The output of the simulation was water level for all the flood values. The water level can be viewed in cross-sections or longitudinal section of the river. Water surfaces for 5, 25, 100 and 500-year flood and river centreline were exported back to ArcGIS. The file exported from HEC-RAS to ArcGIS was in spatial data format (SDF).

In case of Kävlinge, flood mapping of river basin after Vomb was carried out i.e. hydraulic computation was performed only on Kävlinge river which starts after the lake. As mentioned earlier in Section 2.3, discharge in Kävlinge river is contributed by two major tributaries apart from Vomb which are Klingavalsan and Braan. To represent the flow from these tributaries Kävlinge river was further divided into two reaches: Upper Kävlinge and Lower Kävlinge. For the upstream reach, combined flow data of stations 2018 and 2116 were used while for the downstream reach, the flow data of stations 2018, 2116 and 2126 were used. And in case of Kankai, flood mapping of river stretch after Mainachuli gauging station was done using flow data of that station. These data were calculated from the yearly maximum instantaneous discharge values. One highest discharge from the daily discharge per year was taken as maximum instantaneous discharge. Using the maximum discharge data and applying flood probability frequency analysis, values for different year return period flood were predicted. In this case Gumbel distribution method was used to predict future flood. The values of predicted floods for Kävlinge and Kankai are shown in *Table 4.8* and *Table 4.9* below.

Table 4.8 : Flood discharges for different return periods in Kävlinge river

Return Period (year)	**Discharge (m^3/s)**	
	Upper Kävlinge	**Lower Kävlinge**
5	37.69	57.46
25	54.49	80.71
100	68.35	99.89
500	84.31	121.97

Table 4.9: Flood discharges for different return periods in Kankai river

Return Period (year)	**Discharge (m3/s)**	
	Rajdwali	**Mainachuli**
5	612.19	5234.64
25	1091.66	7444.64
100	1487.30	8845.17
500	1942.74	10940.36

4.3.3 Post-processing: Processing RAS results in ArcGIS

The file exported from HEC-RAS in SDF was first converted to XML which is readable by ArcGIS. In this step, mapping of flood inundated area, depths and velocity of inundation were carried out. Firstly, before processing the outputs from HEC-RAS, a new set of layers were created and terrain model (TIN) generated in pre-processing step was specified for performing the floodplain delineation. The rasterization cell size for output DEM was also specified in this step. Then, the outputs from HEC-RAS previously converted to XML was imported into ArcGIS. While doing so stream centrelines, cross-section cut lines, bank points, velocity points and bounding polygon were created in ArcMap. The software creates different bounding polygons, the spatial limit for floods, based on the water surface elevation at cross-section cut lines for different year floods.

Finally, inundation mapping was carried out in two steps: water surface generation and floodplain delineation using raster. In water surface generation, TINs for water surface for 5, 25, 100 and 500-year floods were created from the altitude of water surface in each cross-section. Floodplain delineation was carried out using water surface that TINs generated in previous step and terrain model TIN. Thus, floodplain boundaries and their depths were calculated. The flood inundation areas for different flood values were represented by polygons while their respective depths were represented by DEM (raster format). In this project for both study area, rasterization cell size was set as 20 map units.

Flood maps were created with 2m resolution DEM for Kävlinge basin and 30m resolution DEM for Kankai basin. In case of Kävlinge basin, flood mapping has been done for Kävlinge river after Vomb lake. And, as the major flood plain area for Kankai lies at the lower part of the basin which is the terai (flat) region of Nepal, flood mapping of lower flat plain has been done.

CHAPTER 5. RESULTS AND DISCUSSIONS

5.1 Sensitivity Analysis

Figure 5.1 and *Figure 5.2* below are sensitivity plots of SMA loss parameters for Kävlinge and Kankai river basin.

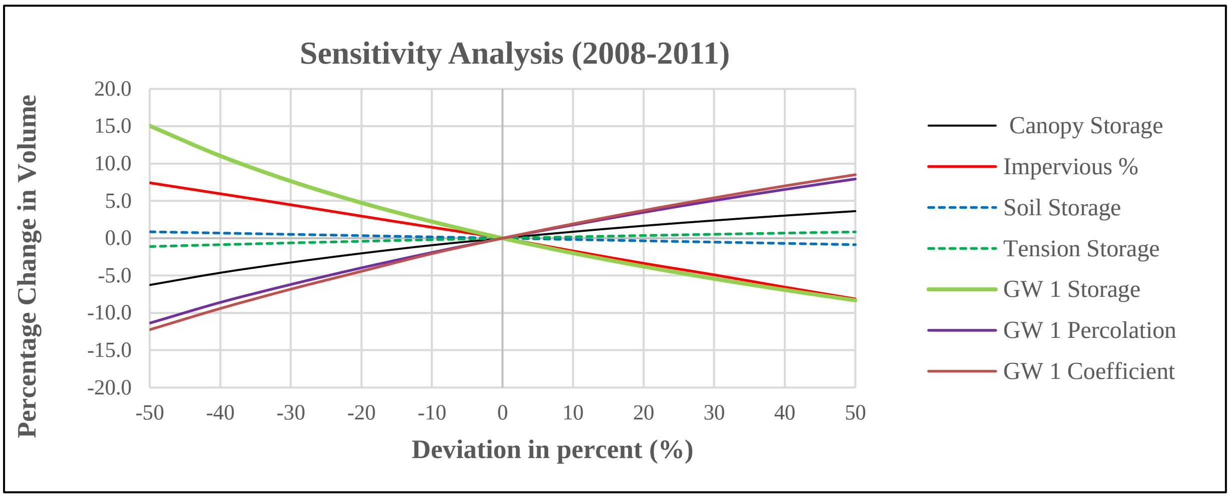


Figure 5.1: Sensitivity Analysis of HEC-HMS model of Kävlinge River Basin for % change in Volume for the Calibration Period.

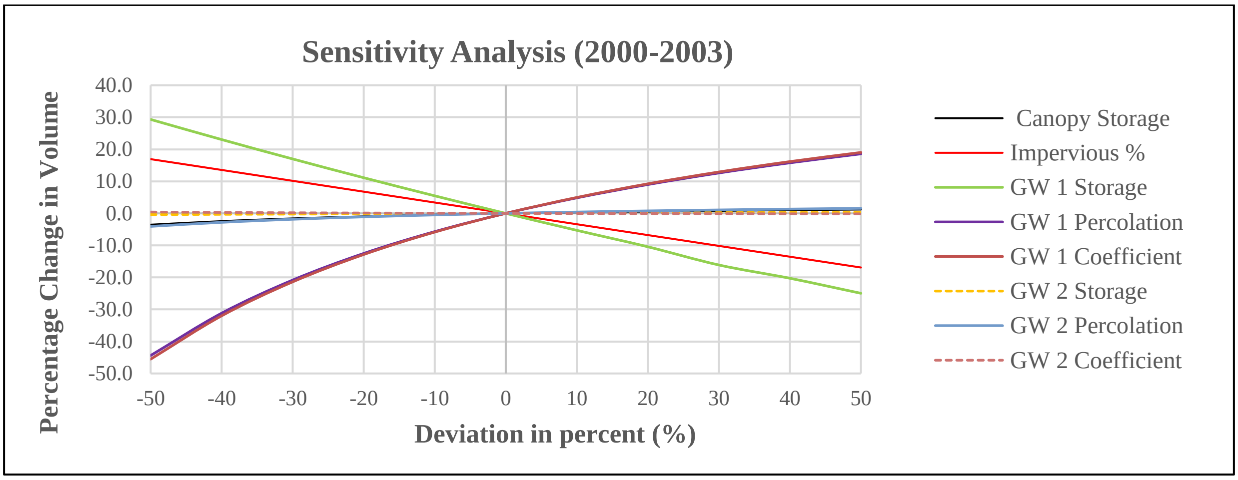


Figure 5.2: Sensitivity Analysis of HEC-HMS model of Kankai River Basin for % change in Volume for the Calibration Period.

By performing sensitivity analysis as explained in *section 4.2.1*, GW 1 storage, GW 1 Percolation and GW 1 Coefficient are found to be the most sensitive parameters for simulated stream flow during the calibration period for both river basins. It is also evident from the graphs in *Figure 5.1* and *Figure 5.2* that the models are highly sensitive of two other parameters, viz Impervious percentage, and Canopy storage.

Kävlinge river basin is found to be slightly sensitive to Soil Storage and Tension Storage unlike Kankai River basin where these parameters have negligible effect on the simulated stream flow. In Kankai basin, loss parameters for GW 2 layer: GW 2 Storage and GW 2 Coefficient have considerable effect on simulated stream flow whereas these parameters cause insignificant effect on Kävlinge river basin. Even though the two basins lie in different climatic region with distinct catchment characteristics, the main reason for having similar result is because the land use type in the basin area. The dominant and influencing form of land use type for parameter sensitivity in both basins is agricultural land. This shows that more than climatic factors, sensitivity of parameters are influenced by land use in the basin area thus giving similar results for sensitivity analysis. In case of Kankai, parameters are also slightly sensitive towards GW2 parameters (storage, percolation and coefficient). Volume of water is altered (mainly decreases) as water moves from upper hilly part to lower flat plains of basin area because of contribution water to GW2 layer due to highly active tectonic plate that runs between upper hilly part and lower plains and weak geology prevail in the basin area. (Khanal, 1998). Based on the sensitivity analysis, ranking of the model parameters is given in *Table 5.1* below.

Table 5.1: Sensitivity ranking of model parameters.

S.N.	Kävlinge River Basin	Kankai River Basin
1	GW1 Storage	GW1 Coefficient
2	GW1 Coefficient	GW1 Percolation
3	GW1 Percolation	GW1 Storage
4	Impervious%	Impervious%
5	Max. Canopy Storage	Max. Canopy Storage
6	Tension Storage	GW2 coefficient
7	Soil Storage	GW2 storage

5.2 Calibration and Validation

5.2.1 Calibration and Validation for Kävlinge River Basin

Calibration

Figures 5.3, 5.4, 5.5, 5.6 are the graphs that compare observed flow to simulated flow for the calibrated years, 2008 to 2011. The black dotted lines denote observed outflow measured at gauge station, at the respective junctions. The blue solid line denotes the total simulated outflow at that junction and blue dashed line denotes the outflow from upstream reach of the junction.

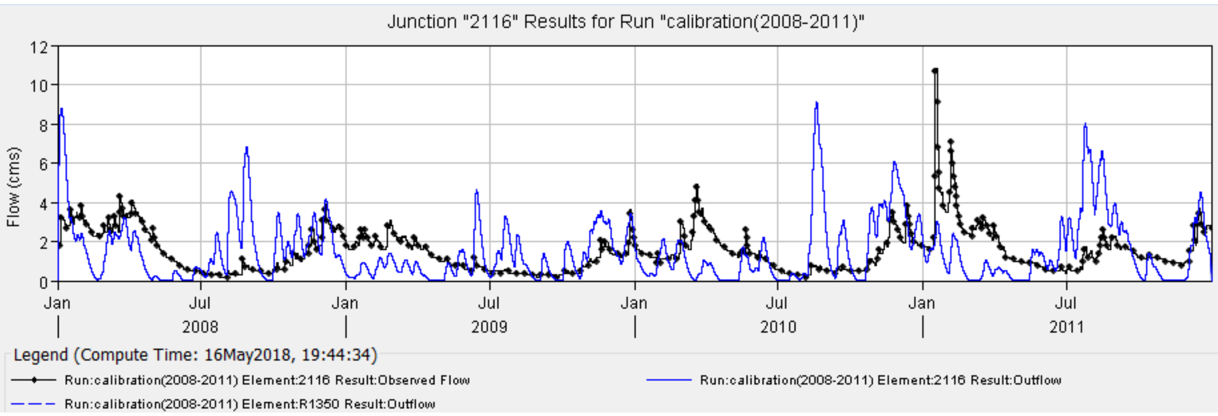


Figure 5.3: Observed and Simulated flow of Kävlinge River at 2116 for Calibrated years

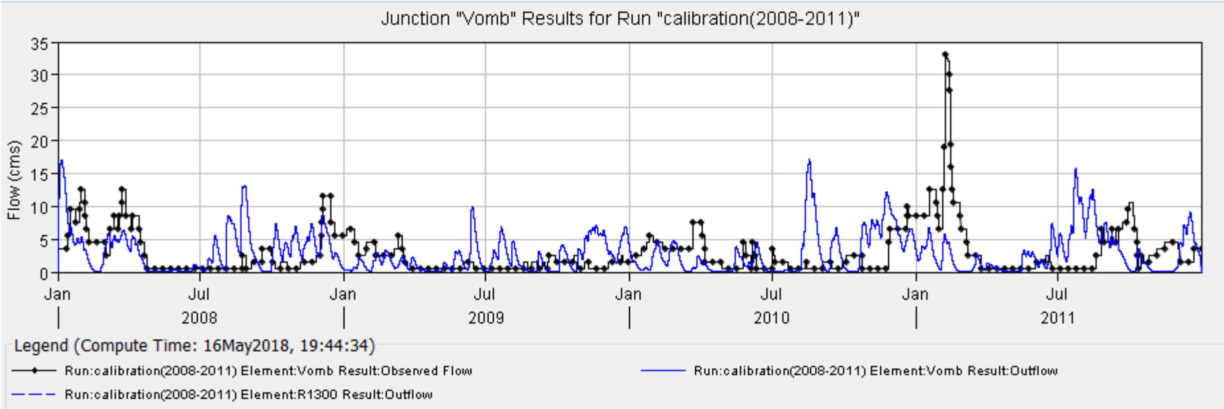


Figure 5.4: Observed and Simulated flow of Kävlinge River at Vomb for Calibrated years.

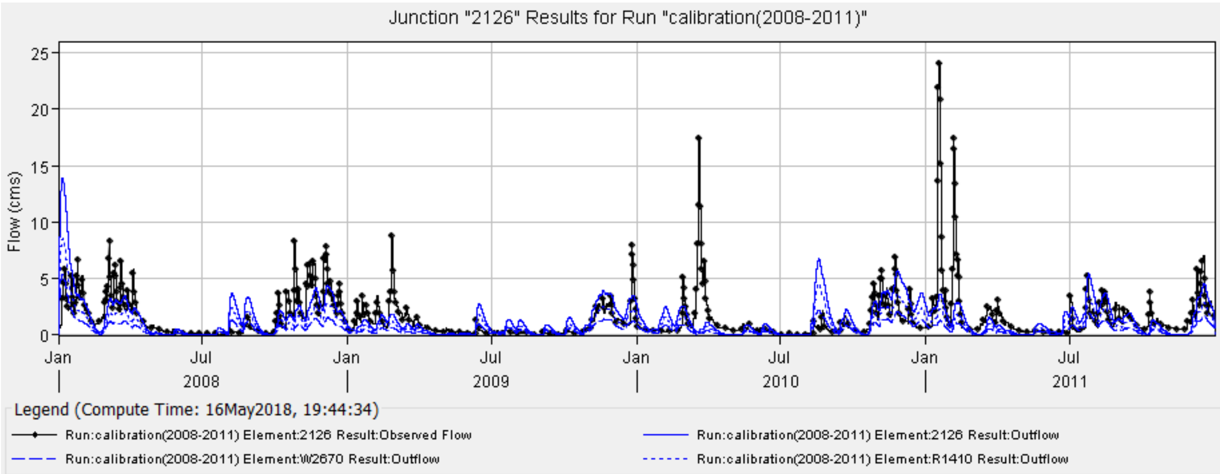


Figure 5.5: Observed and Simulated flow of Kävlinge River at 2126 for Calibrated years.

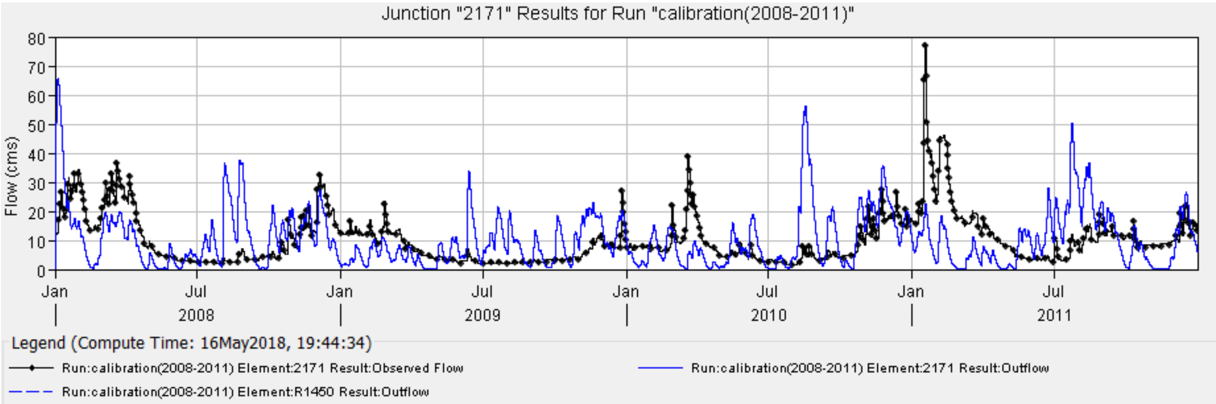


Figure 5.6: Observed and Simulated flow of Kävlinge River at 2171 for Calibrated years.

The calibration at all the junctions resulted with simulated outflow volume almost same as observed volume. At all the junctions, PEV for calibrated years is zero as shown in *Table 5.2.*

Since the model was mainly calibrated considering the outflow volume, the calibrated flow pattern poorly represented the observed flow for junctions 2116 and 2171 which is seen in *Figure 5.3* and *Figure 5.4*. Also, in case of Vomb refer to *Figure 5.4*, the flow pattern could not be calibrated accurately as the outflow at Vomb is regulated. Whereas, the flow trend is similar to observed flow at junction 2126 as seen in *Figure 5.5.* At all the junctions the observed peaks occur during winter which is likely to have resulted from snow melt, but the model fails to represent this effect. The observed peaks at junction 2126 during late winter and early spring i.e. Jan, Feb and March seem to result due to event based flow as these peaks are very sharp with sharp recession curves (refer *Figure 5.5*). Hence, the model is unable to simulate the short-term events accurately at this junction. To model such short-term events, separate model must be developed. The initial peaks seen in the calibrated flow at all the junctions are due to model warmup period and thus can be ignored. Failure to simulate the peak flow and time of peak could also be due to ambiguity in the precipitation data. Apart from this, some important meteorological parameters such as wind speed and air pressure has not been included in the model whereas wind plays an important role in hydrological cycle. The computational time step for simulation was set for 30 minutes therefore, the computed outflow data were also for 30 minutes interval. Whereas the precipitation and discharge data were daily averaged data. This mismatch between the time interval of input data and the output also created some level of error. *Table 5.2* helps to evaluate the model performance for calibration.

Table 5.2: Percentage error in simulated volume (PEV) of the model for calibration years

Hydro meteorological Station	Observed Volume (mm)	Calibrated Volume (mm)	PEV (%)
2126	1724.98	1725	0
2116	1211.99	1211.96	0
2171	1204.81	1204.53	0
Vomb	984.69	984.67	0

Validation

To verify the output of this model, validation was also performed at all four discharge stations from year 2012- 2014. This was performed to check if the models were able to predict the runoff at the discharge stations for the period other than calibrated one or not. The resulting graphs for validation period are shown in figures below.

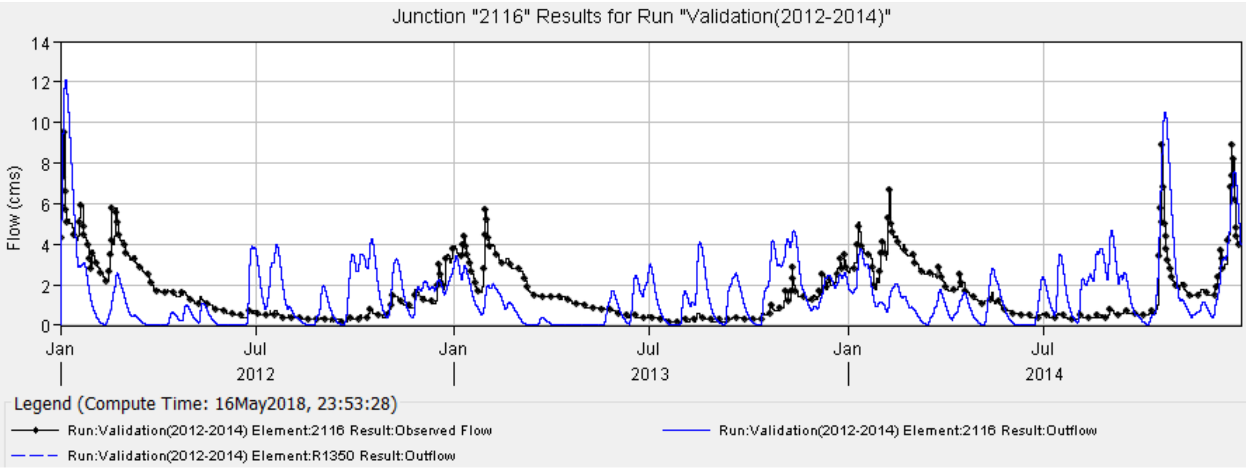


Figure 5.7: Observed and Simulated flow of Kävlinge at 2116 for Validated years

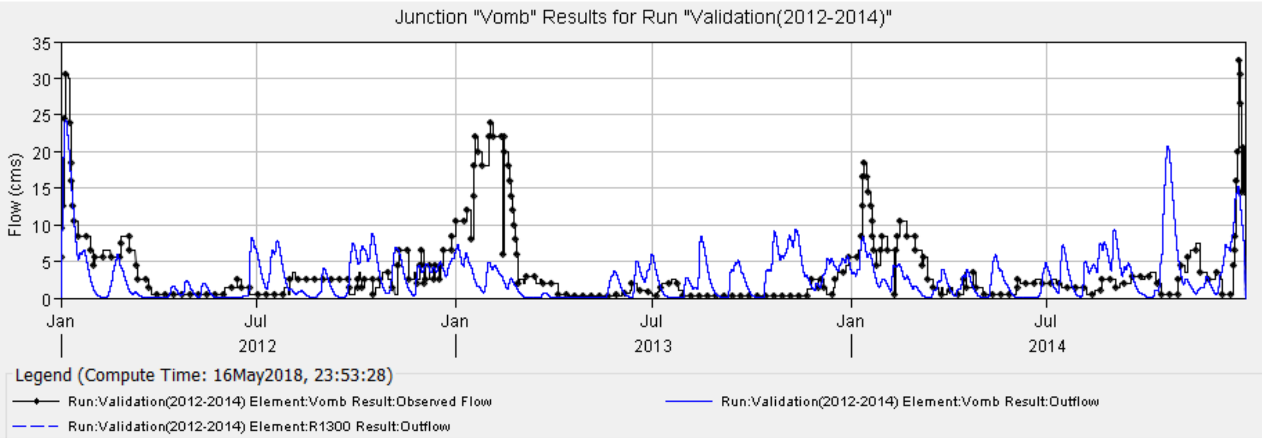


Figure 5.8: Observed and Simulated flow of Kävlinge at Vomb for Validated years

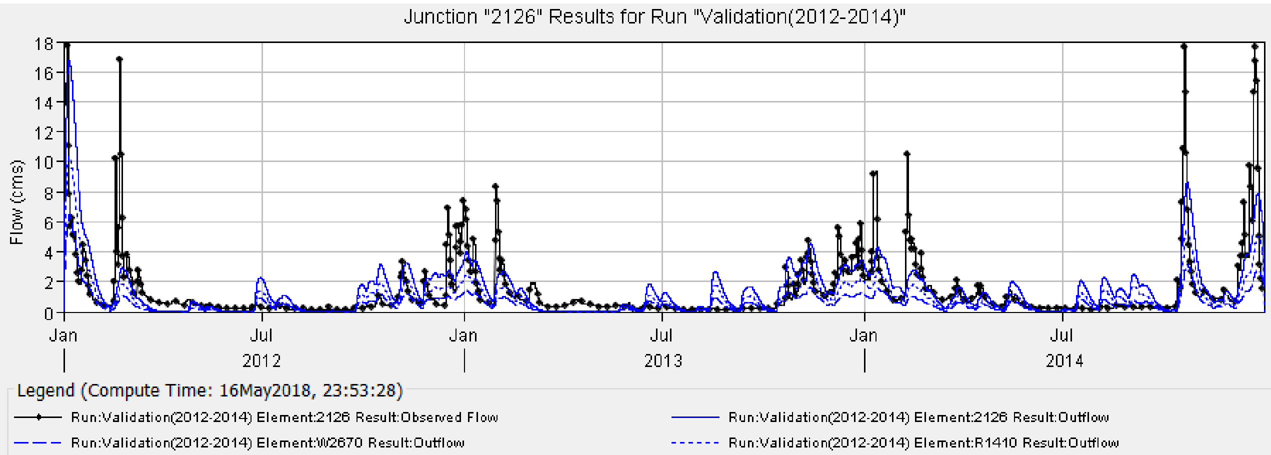


Figure 5.9: Observed and Simulated flow of Kävlinge at 2126 for Validated years

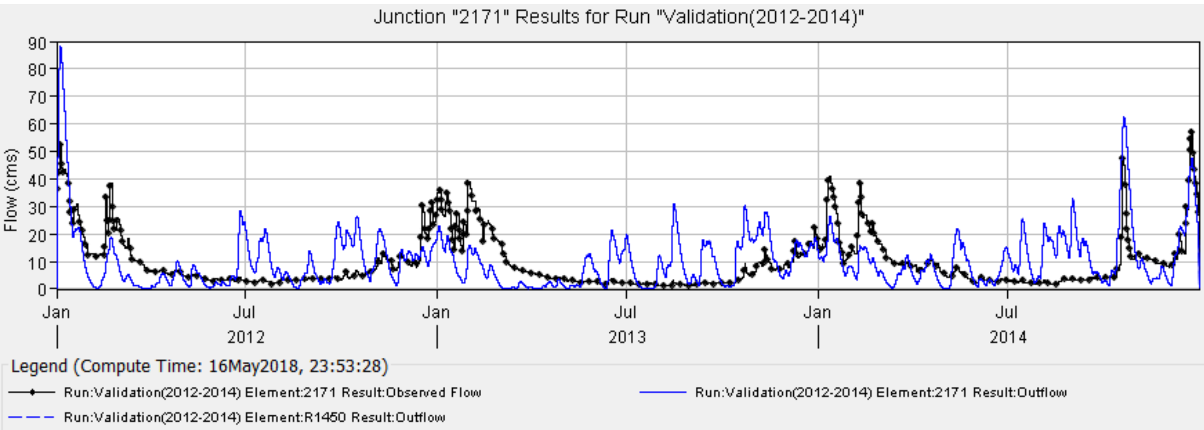


Figure 5.10: Observed and Simulated flow of Kävlinge at 2171 for Validated years

The flow pattern of simulated flow at all stations during validation resembled with that of calibration. However, the percentage error in volume escalated drastically. After validation, the maximum difference in volume was seen at station 2126 with 14% error while it was least for station 2171 with 6.5% error. The area simulated by 2126 is very small which is about

10% of the total area due to which the model could not replicate the actual hydrological situation of the basin, thus validation results were unsatisfactory in this station. While area covered by station 2171 is about 90% of the basin due to which actual hydrological situation of the basin could be modelled, thus validation results were better at this station. Although peak flows could not be modelled properly, the model is able to resemble time of peak very well which is seen around January and February for each year.

The best validated flow that represented basin outflow pattern was at junction 2126 while the most downstream junction, 2171 validated best for outflow volume. *Table 5.3* below helps to evaluate the model performance for validation period of the basin at all the junctions.

Table 5.3: Percentage error in simulated volume (PEV) of the model for validation years

Hydro meteorological Station	Observed Volume (mm)	Calibrated Volume (mm)	PEV (%)
2126	1150.53	1319.48	14.5
2116	963.56	913.54	5.2
2171	845.33	901	6.6
Vomb	907.66	752.96	17

The validated model was further evaluated using scatter plot between simulated and observed flow. *Figure 5.11* shows the scatter plot of the validated year, 2012 of junction 2126.

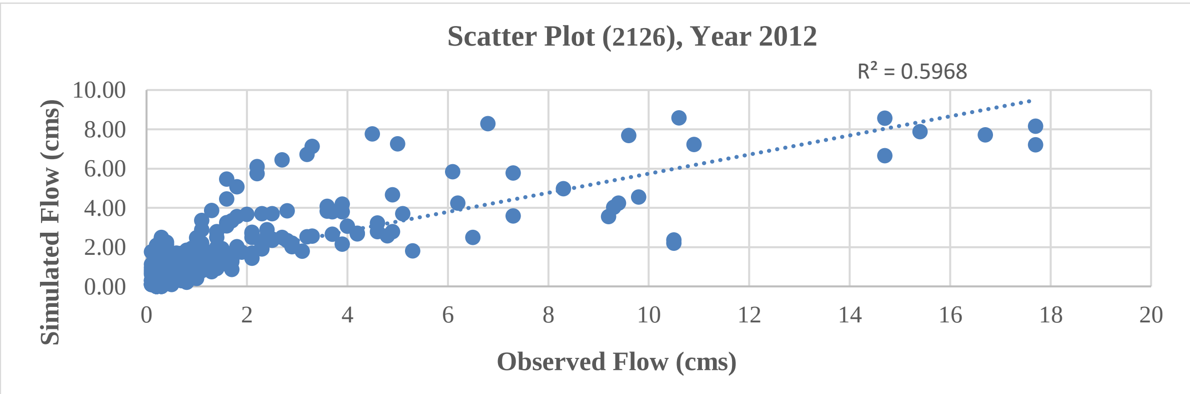


Figure 5.11: Comparison between the observed and simulated flow for the validated year 2012 at Junction 2126

In the graph, the straight dotted line denotes equality line and the dots denote flow. The accuracy of prediction of runoff is close to 0.6 which hardly gives satisfactory result for flow pattern. The value of R^2 varies from 0 to 1 and higher values of R^2 indicated less error in variance. Generally, value greater than 0.5 are considered acceptable (Moriasi, et al., 2007). More points fall above the equality line, which signifies that the model tends to over predict the flow.

5.2.2 Calibration and Validation for Kankai River Basin

Calibration

Figure 5.12 and *Figure 5.13* below are the graphs comparing observed flow to the simulated flow for the calibrated years, 2000 to 2003. The black dotted lines denote observed outflow measured at gauge stations, at the respective junctions. The blue solid line denotes the total simulated outflow at that junction and blue dashed line denotes the outflow from upstream reach of the junction.

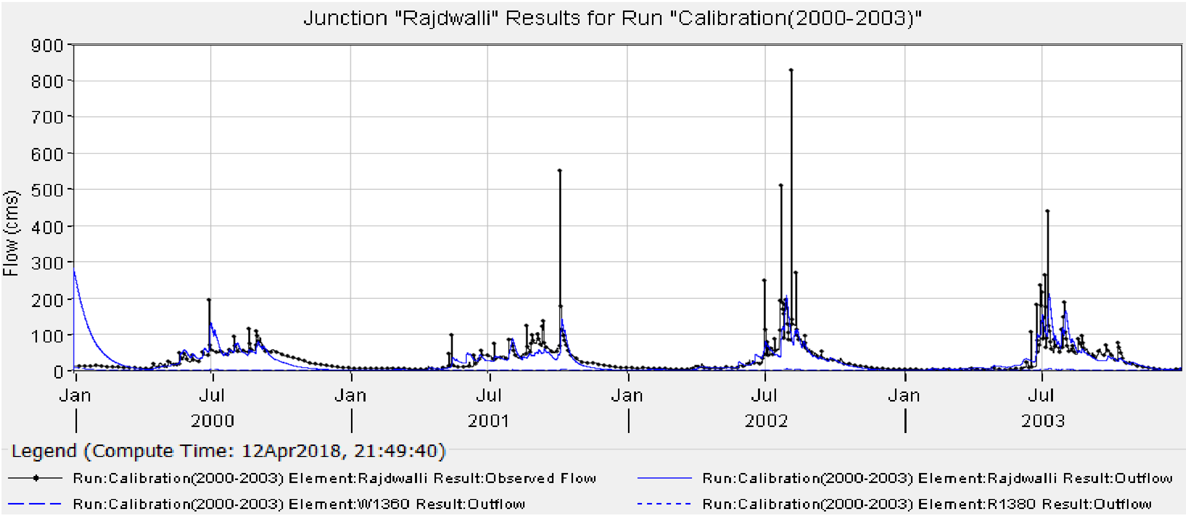


Figure 5.12: Observed and Simulated flow of Kankai River at Rajdwali for Calibrated years.

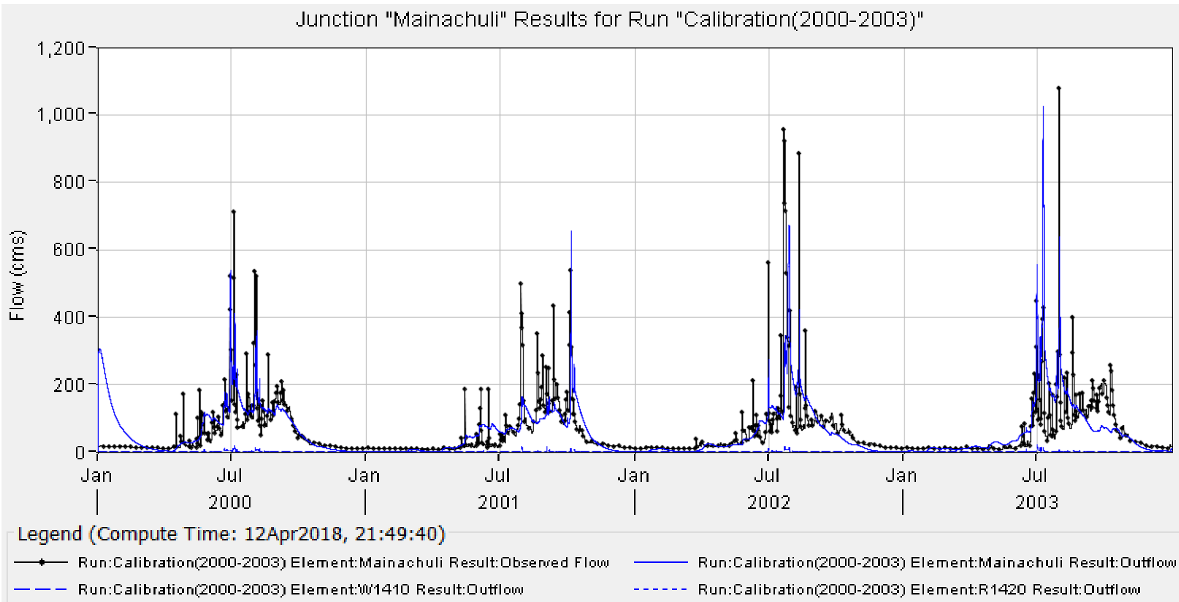


Figure 5.13: Observed and Simulated flow of Kankai River at Mainachuli for Calibrated years.

Calibration at both Rajdwali and Mainachuli junctions resulted with simulated outflow volume almost same as observed volume. At all the junctions, Percentage Error in Volume (PEV) for calibrated years is zero as shown in *Table 5.4.*

In reference to *Figure 5.12* and *Figure 5.13*, the outflow pattern for calibrated years in both junctions almost accurately represent the observed flow. The initial peaks in calibrated flow, as stated earlier in section 5.2.1, are due to model warmup period and thus can be ignored.

The extreme peaks seen in observed flow at both junctions are due to flash floods i.e. for a very short period and are underestimated by the model. Except those peaks, the HMS model is able to represent almost all the peaks at Rajdwali and Mainachuli. An early peak in simulated flow at Mainachuli can be noticed in the year 2003 instead of late July 2003 as in observed flow. This early peak could be due to the contribution of groundwater flow as GW loss parameters are highly sensitive in Kankai basin model. GW flow being the main long-term component of total runoff (Ward and Robinson, 2011) may have resulted in slightly early peak over the calibration span.

Failure to capture all the peak flows is mainly due to sparsely distributed precipitation gauging station and inability to feature varying climatic scenario within the basin. Unlike Kävlinge, Kankai basin has highly varying topographical and climatic features. The upstream part of basin has high hills with temperate climatic condition while the downstream part has flat terrain with tropical climatic condition. However, the whole basin has been represented by single set of meteorological components which seems to be unrealistic. Thiessen Polygon Method is used for spatial distribution of rainfall in this model. However, this method was more suitable for flat terrain rather than hilly areas. Therefore, some ambiguities in the simulated flow might be due to error in spatial distribution of rainfall.

Table 5.4 below helps to evaluate the model performance for calibration period of the basin at all the junctions for Kankai River Basin.

Table 5.4 : Percentage error in simulated volume (PEV) of the model for calibration years

Hydro meteorological Station	Observed Volume (mm)	Calibrated Volume (mm)	PEV (%)
Rajdwali	9263.64	9263.71	0
Mainachuli	6426.03	6426.05	0

Validation

Validation of the model was performed at both discharge stations from year 2004 - 2006. The resulting graphs for validation period are shown in *Figure 5.14* and *Figure 5.15* below.

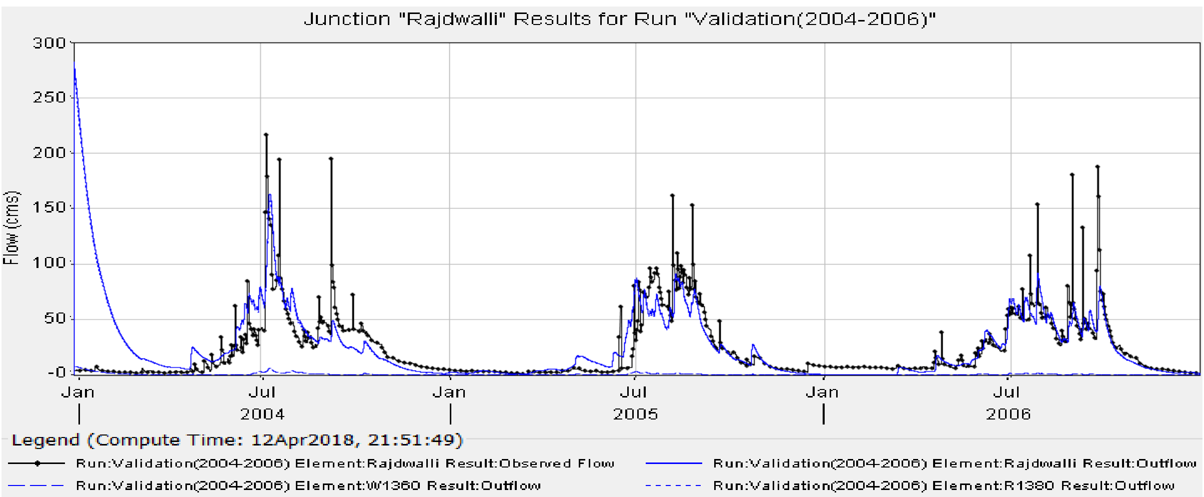


Figure 5.14: Observed and Simulated flow of Kankai River at Rajdwali for Validated years

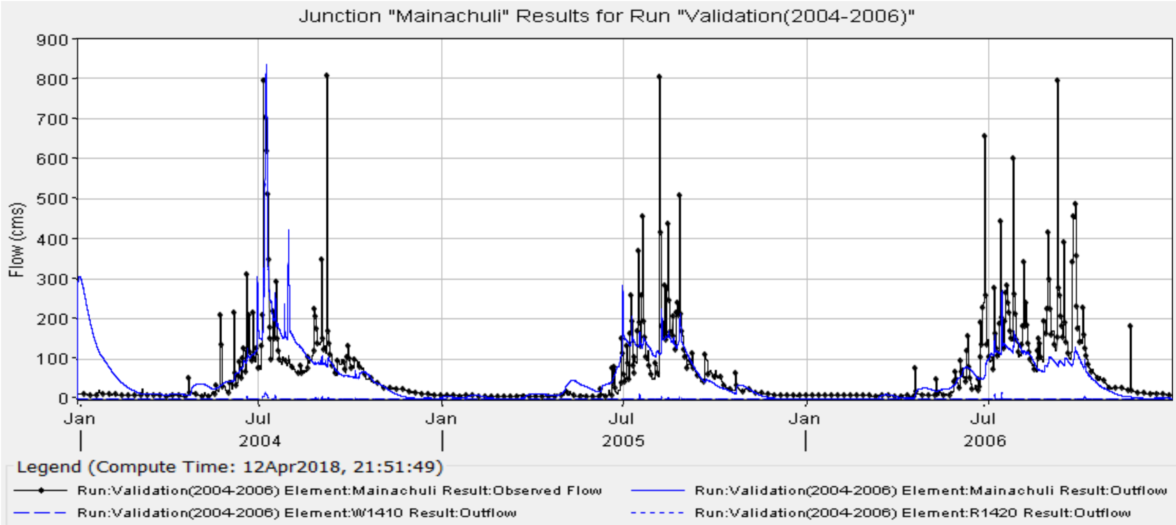


Figure 5.15: Observed and Simulated flow of Kankai River at Mainachuli for Validated years

As can be seen from the figures above, the pattern of simulated and observed flow is almost identical to each other except at the peaks. Mainachuli is the downstream gauge station at Kankai basin and has least volume error of 11.6 %. The maximum volume error was at the Rajdwali junction with 17.5 % during validation. The validated flow at both the junctions fairly represent the basin outflow pattern as seen in *Figure 5.14* and *Figure 5.15*. However, the simulated flow under predicts the peaks at both junctions because the model is calibrated for continuous event and is unable to represent short term events and flash floods accurately. *Table 5.5* below helps to evaluate the model performance for validation period of the basin at all the junctions for Kankai river basin.

Table 5.5: Percentage error in simulated volume (PEV) of the model for calibration years

Hydro meteorological Station	Observed Volume (mm)	Calibrated Volume (mm)	PEV (%)
Rajdwali	5683.78	6678.07	17.5
Mainachuli	4958.62	4383.25	11.6

The validated model was further evaluated using scatter plot between simulated and observed *Figure 5.16* shows the scatter plot of the validated year, 2006 at Rajdwali.

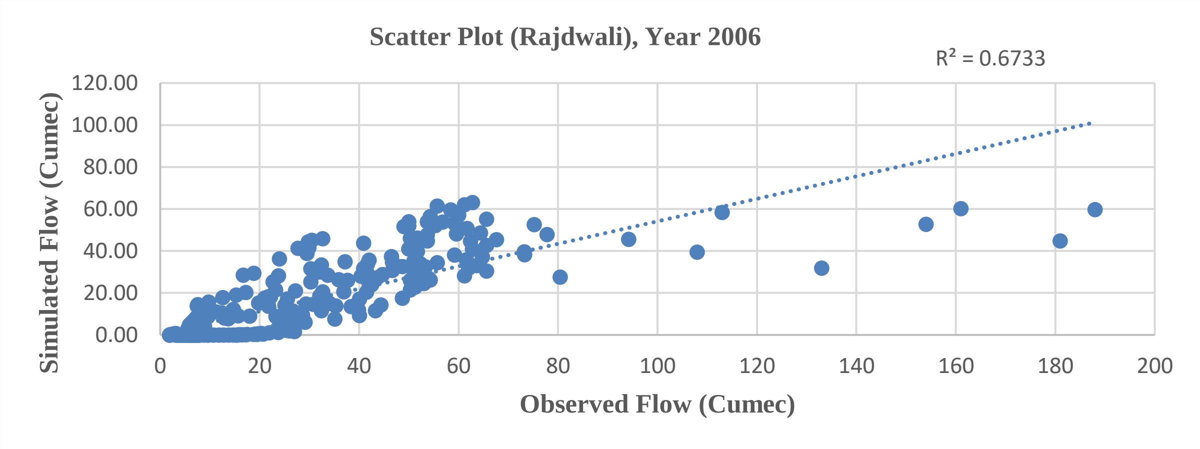


Figure 5.16 Comparison between the observed and simulated flow for the validated year 2006 at Rajdwali

In the graph, the straight dotted line denotes equality line and the dots denote flow. The accuracy of prediction of runoff is 0.67 which is fairly satisfactory. The significance of value of R^2 has been described in section 5.2.1 above. The discharge values above the equality lines are more so the model tends to under predict higher flows whereas lower flows are well represented.

From the above results, some similarities and differences between these basin models can be extracted and discussed herewith. There is no certainty for assigning values of parameters in HMS. Any value can be assigned to parameter to get a good calibrated model. Therefore, even a set of values that does not have any physical relevance can result in a good calibrated model. This could be possible in model of both Kankai and Kävlinge river basin.

Even though outflow volume has been calibrated properly for both basins, the flow pattern of simulated and observed flow were almost identical in case of Kankai basin except for some extreme peaks while it deviated for Kävlinge river basin. The main source of water in Kävlinge river is Vomb lake and the river runoff has more influence of groundwater than rainfall. There is availability of groundwater throughout the river stretch in the basin (VISS, 2018). This could be the reason for differences in simulated and observed flow and its pattern. The map of groundwater availability is given in Appendix D. While Kankai River is a rain fed river due to which surface runoff and the peak discharges simulated by the model from rainfall was closer to the observed flow. However, the result could have been even better had there been enough precipitation gauges in the basin area and meteorological condition could be defined separately for upper hilly part and lower flat plains. Having same parameter values for the whole year is also not good representation of the basin. Both basin have two distinct climates as dry and wet. Therefore, seasonal parameterization may improve the model performance.

Simulation of rainfall runoff modelling for both basins were performed based on historical timeseries data and were calibrated and validated with the observed flow in this project. With the ongoing global warming and climate change effects, the precipitation and temperature are in increasing trend which implies higher runoff in the future. However, simulation of rainfall runoff for future scenario was not in the scope of this project and has not been performed.

5.3 Hydraulic / Flood Inundation Modelling Results

5.3.1 Flood Inundation map of Kävlinge River Basin

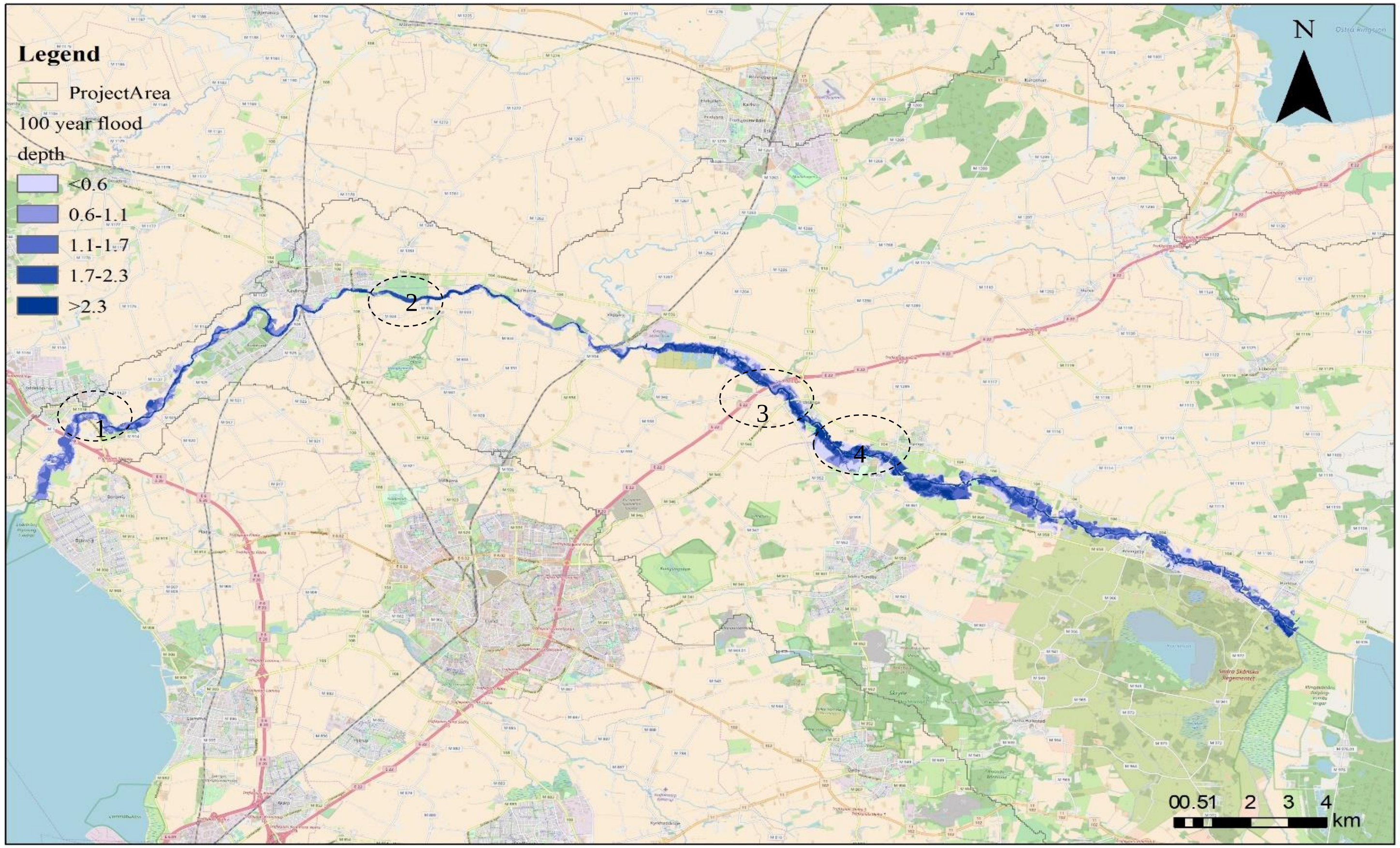


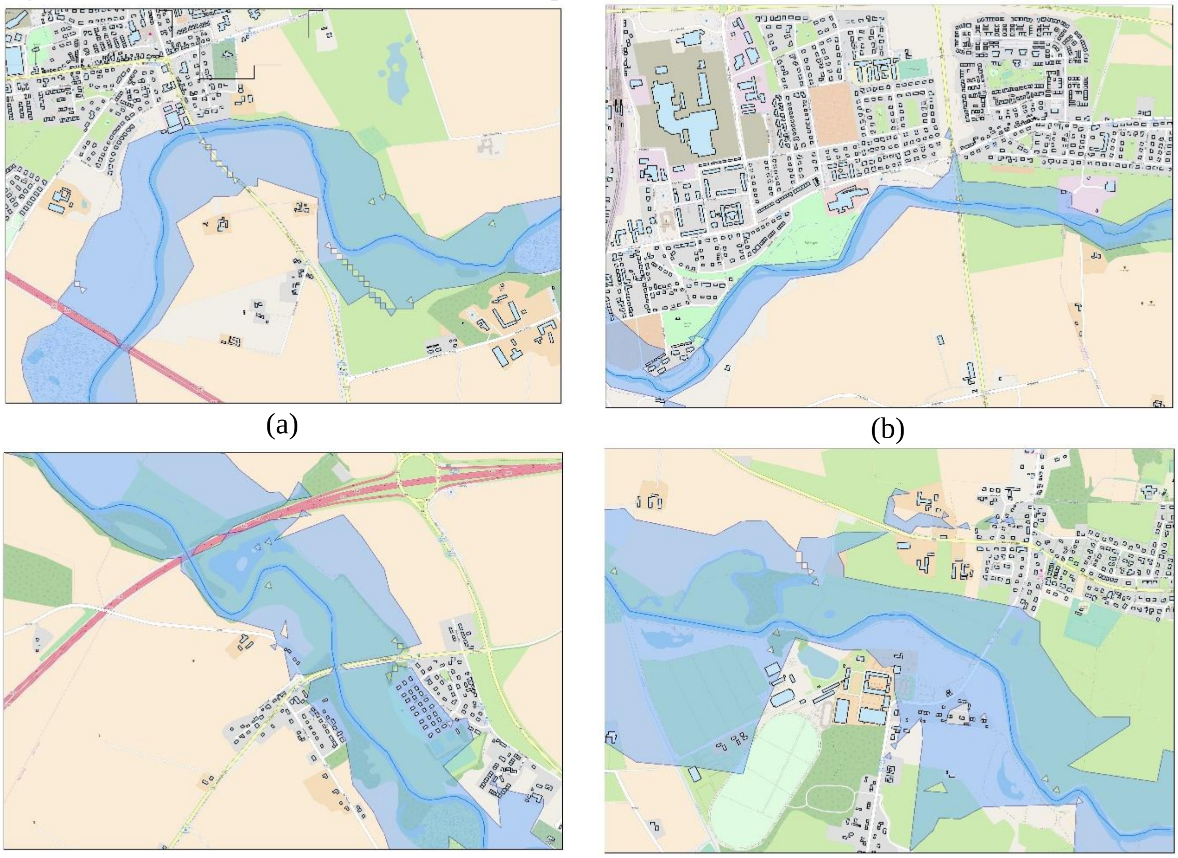
Figure 5.17: Plan view of inundated area of Kävlinge River during 100-year flood event

The flood values for different return periods were calculated using the maximum instantaneous flow from station Eggelstad which lies upstream of Vomb. There is only one discharge station at the immediate downstream of Vomb lake which is regulated. Therefore, flow measured at Egglestad was considered as a suitable representative of the outflow occurring in the basin. The inundation map of Kävlinge river due to 100-year return flood is shown in the *Figure 5.17*. The flow value for this 100 year flood has been obtained from Gumbel distribution method which has been explained in Section 3.2.1. Approximately, 12.9 square kilometre of the lower basin area is inundated by this flood. The highest value of water depth during 100-year flood in this river is 3.8 m. The inundated area and maximum water level given by HEC-RAS during 5, 25, 100 and 500-year flood is tabulated in *Table 5.6*

Table 5.6: Area inundated and Maximum water level in Kävlinge River Basin during 5,25,100,500-year floods

Return Period (year)	Inundated area (km^2)	Max. Water level (m)
5	9.95	3.3
25	11.64	3.6
100	**12.88**	**3.8**
500	13.85	4.0

Some major inundated areas in the basin have been marked with black dashed line in the *Figure 5.17* and their detailed view with exposure in those areas are shown in *Figure 5.18*.



(a) (b) (c) (d)

Figure 5.18: Inundated areas in Kävlinge river basin: Flood hazard mapping (a. Location 1, b. Location 2, c. Location 3, d. Location 4)

There are many settlement areas especially at the downstream of Kävlinge river basin. If a 100-year flood comes, nearly 165 buildings in the surrounding area are at the risk of getting affected.

Some cross sections of the river are shown in *Figure 5.19* and *Figure 5.20* below to visualize the effect of flood in the banks. In addition to 100-year flood level, 5, 25 and 500-year flood level are also shown in the figures to see how the water level varies with different flood values. The effect of flood on both banks of the river is almost equal in area. The schematic view of flood map of Kävlinge river basin with river stations is shown in Appendix E.

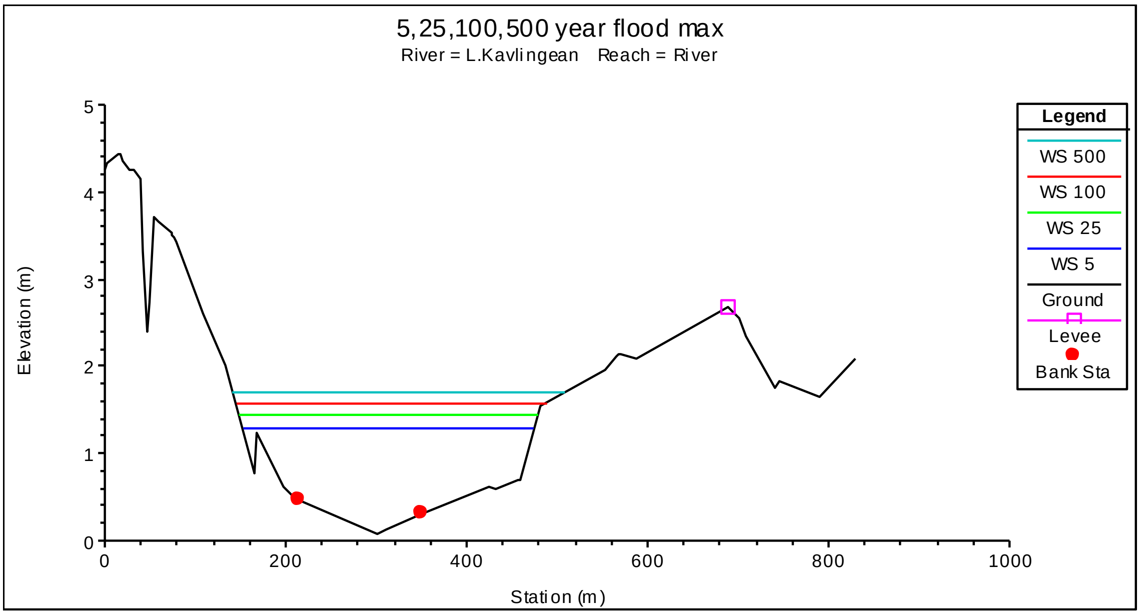


Figure 5.19: 5,25,100,500-year flood Max. water level at Kävlinge River at Location 1

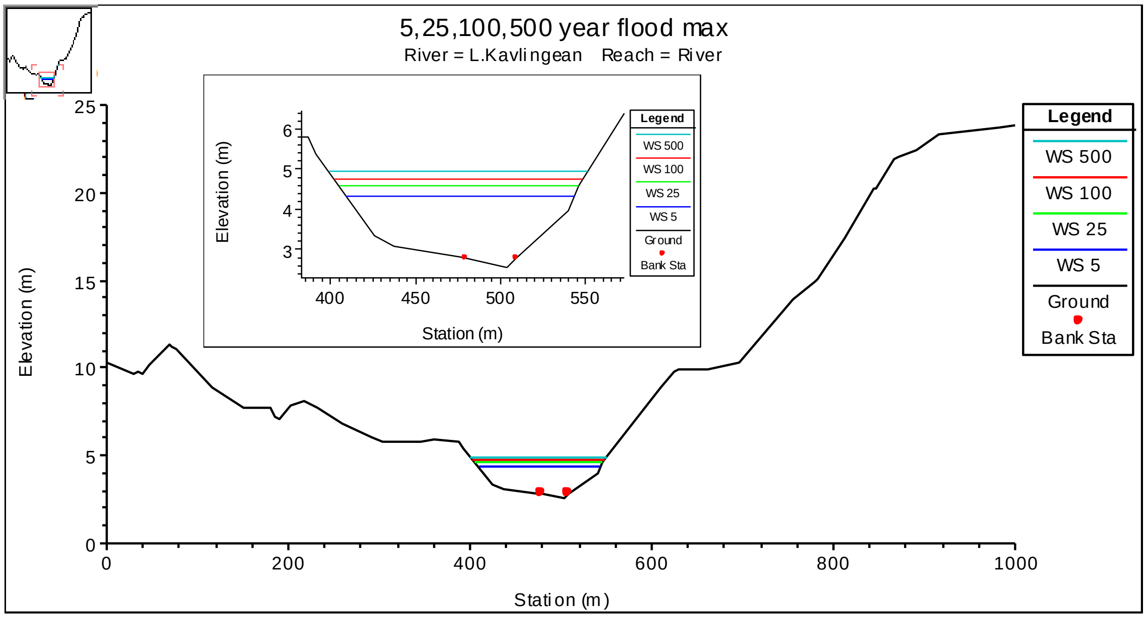


Figure 5.20: 5,25,100,500-year flood Max. water level at Kävlinge River at Location 4

5.3.2 Flood Inundation map of Kankai River Basin

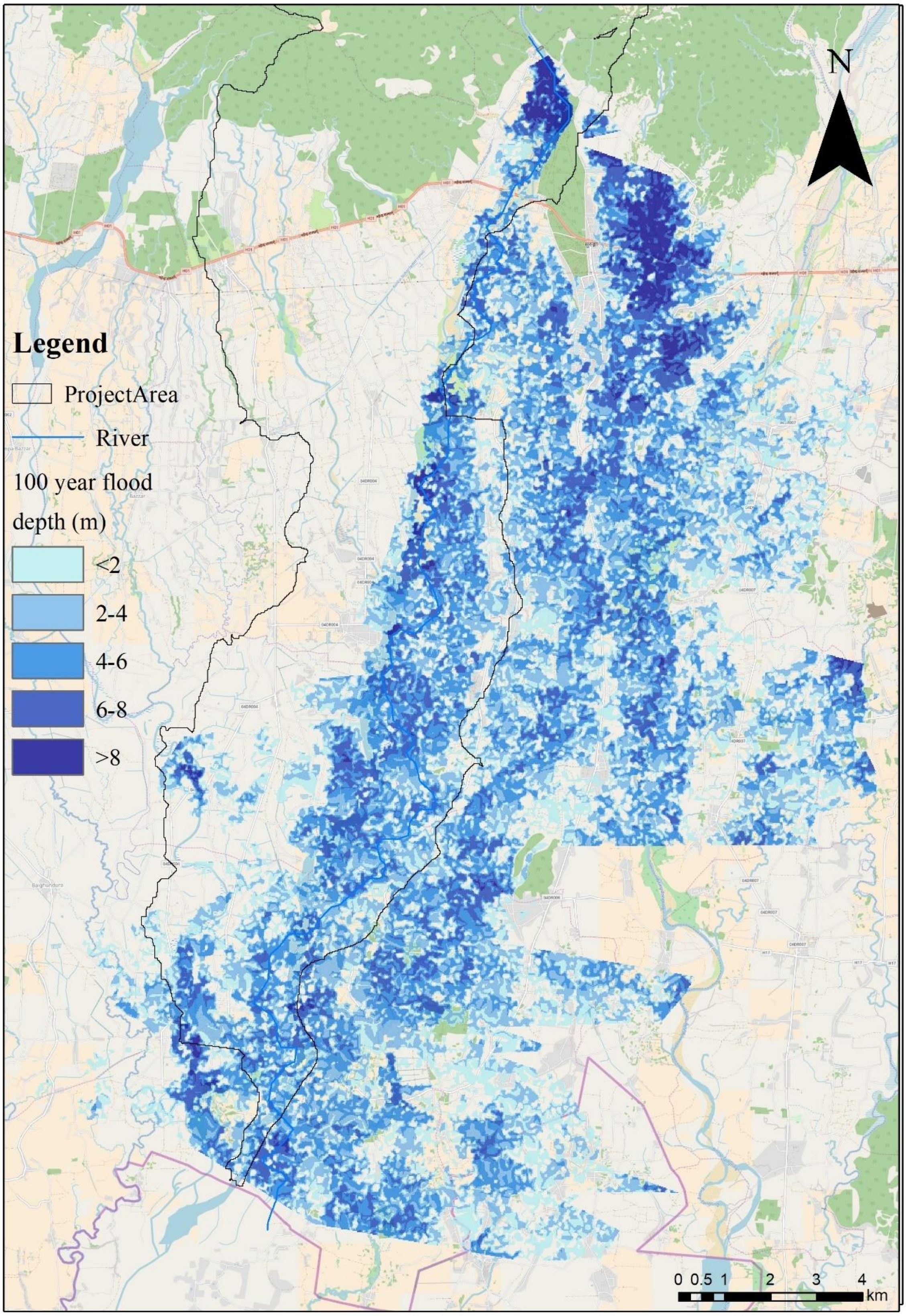


Figure 5.21: Plan view of inundated area of lower Kankai Basin during 100-year flood event.

Figure 5.21 above shows the inundated area during 100-year flood in the lower region of Kankai basin which is created using 30m resolution DEM. This lower part of the basin is the actual flood plain of Kankai basin. Approximately 157 square kilometres of the lower basin area is inundated during this flood. Actual exposure data was not available to indicate number of buildings inundated in case of Kankai basin. But a heavy settlement and large agricultural area are present around the flood zone which has been inundated by a 100-year flood. The water depth extends to maximum value of 8.5 m. This water depth is present only in a very short stretch at the top most region which a very narrow reach compared to rest of the basin area. Whereas, the water depth at all the remaining basin does not exceed 5m. The effect of flood is seen mainly at the left bank of the basin. Some discontinuities can be seen in the above flood map because in HEC-RAS the computed flow goes to the lowest elevation within the cross-section rather than following the river flow path. This is due to limitation of the selected modelling approach which is 1-D steady flow.

The inundated area and maximum water level given by HEC-RAS during 5, 25, 100 and 500-year flood in Kankai basin is tabulated in *Table 5.7* below to have an idea of water level in different design floods.

Table 5.7: Area inundated and Maximum water level in Kankai River Basin during 5,25,100,500-year floods

Return Period	Area inundated km^2	Max. Water level, m
5 Year	127.88	6.65
25 Year	146.16	7.3
100 Year	**157.16**	**8.47**
500 Year	167.71	9.1

Cross sections representing the top and middle region of Lower Kankai River are shown in *Figure 5.22* and *Figure 5.23* respectively. The schematic plan of Kankai flood plain with river stations is shown in Appendix E.

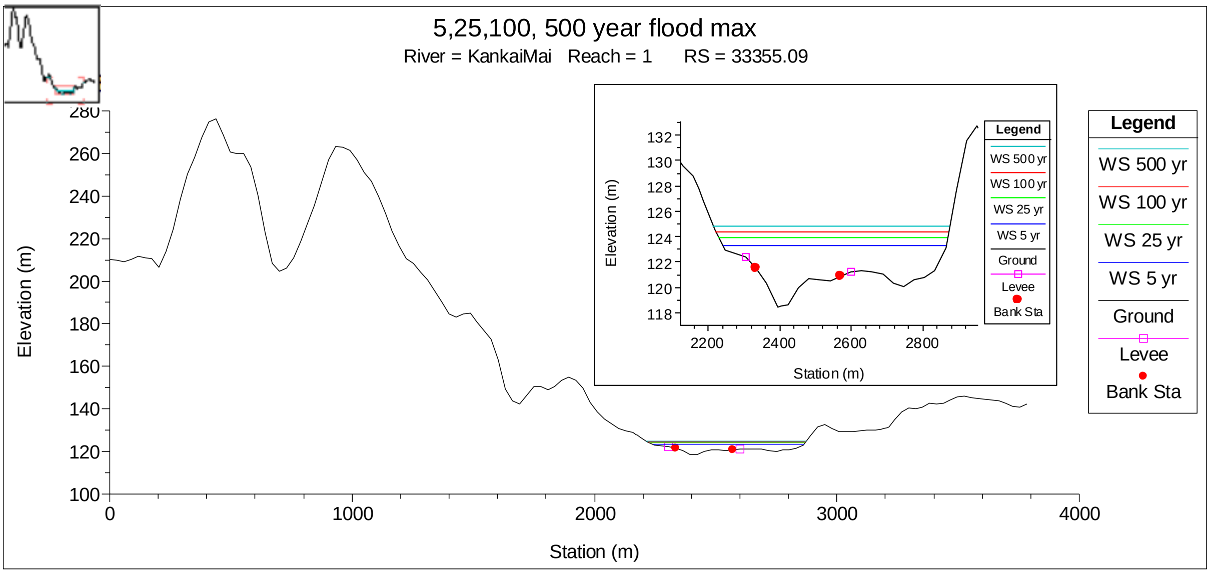


Figure 5.22: 5, 25, 100, 500-year flood max. water level at lower Kankai (River Stn. 33355.09)

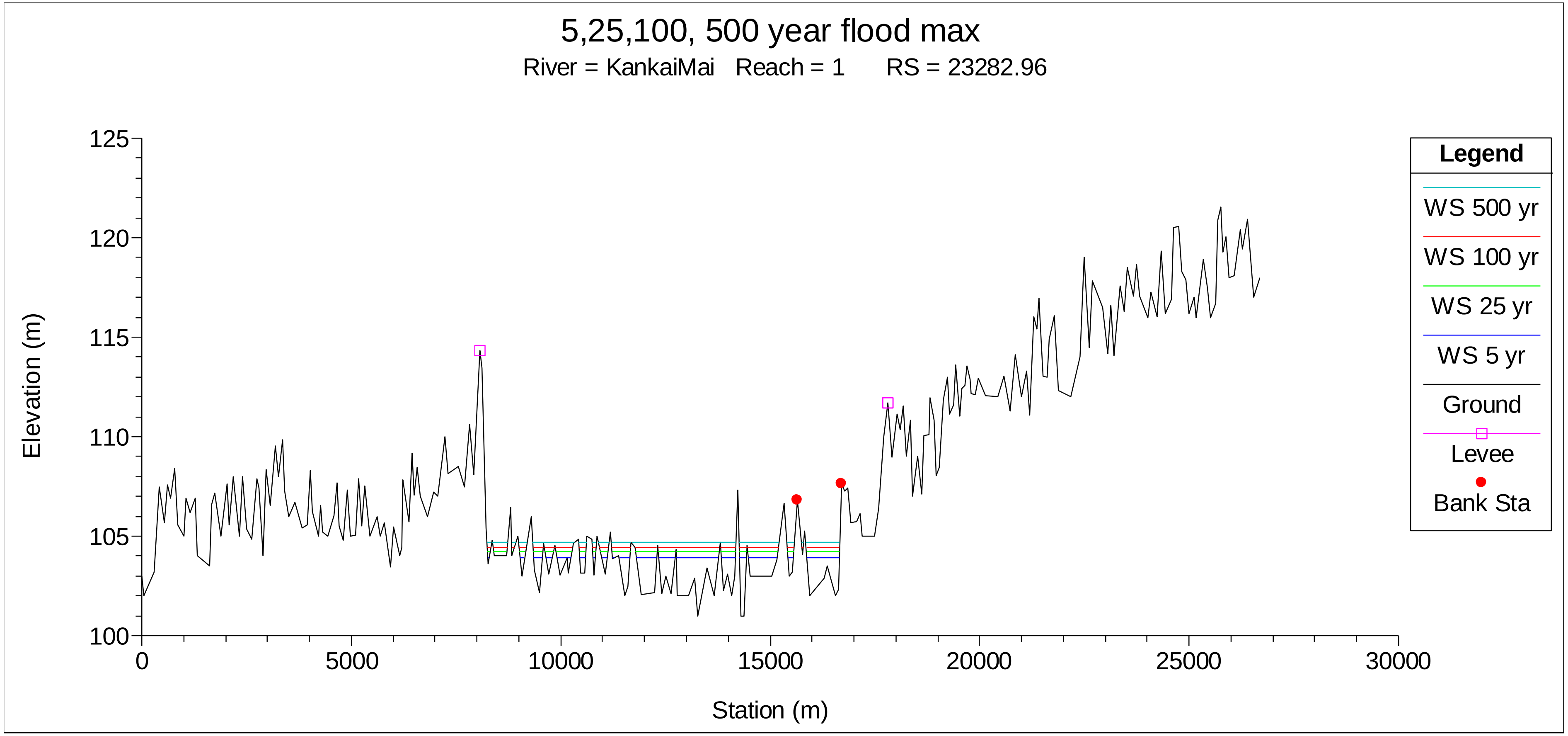


Figure 5.23: 5, 25, 100, 500-year flood max. water level at lower Kankai (River Stn. 23282.96)

Based on these results, some important abstractions have been made. Flood discharges at Kankai basin are huge compared to Kävlinge basin. Hence, for a 100-year flood, the flood plain of Kankai River basin is thirteen times larger than Kävlinge river basin. To represent such flood extent, flood maps can be produced either using deterministic or probabilistic approaches. The potential flood extent maps in this report have been presented as deterministic flood maps for both the basins. Deterministic flood maps classify floodplains into two distinct regions of wet and dry area (Alfonso, 2016). Kävlinge river basin has a defined and a fixed route of flow for which deterministic flood inundation maps can be used for flood hazard mapping. While lower Kankai River basin which has braided rivers and where flash floods are occurring frequently, needs to adopt probabilistic representation of flood extent to account for uncertainties. (Alfonso, 2016)

Sweden has planned settlements where there is lesser chance of floods affecting residential areas. Whereas, implementation of land use policy and planning is still lacking in many parts of Nepal with no proper control over land management and building construction. Hence, for Kankai basin, there exists the need to preparing land use maps that focuses on urban and urbanizing areas and using it for land use planning. Also, infrastructure development planning should integrate the consideration of flood hazard and risk reduction. The periodic updating of such maps is important for both cases. Based on the flood maps produced in this study, in Kankai basin, heavy settlement is present in the vicinity of flood prone area and Kävlinge basin also has some households at the risk of flooding. In such cases, development and implementation of flood management strategies for raising awareness, preparedness and developing coping strategies are of greatest importance. Such non-structural measures at community level should be conducted to strengthen the capacity of communities against flood. A network of emergency operation centres could be established at district and municipal levels to ensure flood risk and flood hazard reduction. Structural flood management works such as building dams, levees, embankments, barrage etc. should also be carried out to protect the residential and agricultural areas during floods. However, the design of such structure is usually carried out for 1 in 10 years flood. Designing such protection works for higher floods may not be economically feasible (Hossain, 2003).

CHAPTER 6. LIMITATIONS AND UNCERTAINTIES

- The quality of data collected, and the time span they covered has been the biggest limitation of produced work in this report. The discharge and precipitation data used in hydrologic modelling were daily, and many data series had gaps (in case of Kankai). The accuracy of study would have increased significantly if the data series were complete. The quality of DEM for Kankai basin was another limitation in producing a correct flood map.
- The SMA method adopted for rainfall runoff modelling in both basins is a data intensive conceptual model. The data involved in it should come from thorough observations and field surveys to calibrate the model well and predict runoff accurately. However, no such observations and surveys have been conducted and data were acquired from secondary sources. The results obtained from such data are highly unsatisfactory.
- The spatial distribution of gage stations for collection of climate and meteorological data was poor (in case of Kankai). This has resulted in lots of approximations in the analysis.
- In HEC-HMS, different set of parameter values can give similar results during calibration of a model. The values chosen for the calibrated parameters may not necessarily have a physical reflection on the basin.
- For given cross-sections where river channel is perfectly defined, 1D HEC-RAS model simulated well. But with wider cross-sections and lower elevated terrain where channel shape is not perfect, 1D HEC-RAS couldn’t perform well. For instance, the flow computed goes to the lowest elevation within the cross-section resulting discontinuity on river flow.
- Introducing levees probably is not the best idea to take advantage over 1D model. However, to constrain the flow within the river section during low flow, levees were introduced. It was found that the performance of the model was improved.

CHAPTER 7. CONCLUSION AND RECOMMENDATION

In this study, hydrological and hydraulic models of two different basins with different climatic and geographical characteristics were developed. The hydrological model using HEC-HMS was developed to study the effect of rainfall on surface runoff and peak discharges. And flood inundation maps produced through HEC-RAS were used to study the flood extent and its characteristics. Case study of Kävlinge basin of Sweden and Kankai basin of Nepal were considered to analyse the similarities and differences in these models.

Kävlinge and Kankai basin lies in completely different climatic zone. Kankai basin has temperate climate in upper hilly part and tropical climate in the lower flat plains with concentrated precipitation in summer months whereas Kävlinge basin has temperate climate with precipitation occurring throughout the year. Unlike Kävlinge basin, Kankai basin does not have precipitation in the form of snow and the average evapotranspiration in Kankai basin is more than twice compared to Kävlinge basin. Kävlinge basin is dominated with agricultural area with till as the most common landform. Whereas apart from agricultural land, Kankai basin has major area covered with forest and human settlement is dense compared to Kävlinge basin with clay as the most common landform.

To conclude this study as clearly as possible, the research questions have been answered thoroughly in the order they have been stated in section 1.4.

HEC-HMS modelling using SMA loss method was found to be more suitable for Kankai River basin than Kävlinge as Kankai Mai is a rainfed river while Kävlinge river has more influence of groundwater. Both the basin models were calibrated well for outflow volume, but the pattern of flow was identical only in case Kankai except for some extreme peaks which were created due to short-term event. A separate model must be created to capture those peaks. Snow has higher impact on rainfall runoff modelling of Kävlinge river basin while there is no snow in Kankai River basin. On the other hand, due to higher temperature in Kankai basin, there is higher loss of water through evapotranspiration than in Kävlinge. In both models, the final calibrated set of parameter values may not have any physical relevance due to which the models could not be validated well. Further, HEC-HMS describes rainfall runoff process as a linear algorithm while the natural hydrological cycle is a non-linear process. Hence, the hydrological cycle cannot be represented accurately by such modelling.

Almost similar conclusion could be derived from the sensitivity analysis of Kävlinge and Kankai River basin with the highest influence of GW1 parameters (storage, coefficient and percolation). Base flow generated from groundwater layer seems to control the surface runoff for both basins. The two different hydrological models created for this project also showed that there was more influence of land use type than climatic condition for determining the sensitivity of parameters. However, climatic condition too influences the sensitivity of parameter which these models failed to display. Therefore, to show the significance of climatic condition on parameter sensitivity, seasonal parameterization should be done as both basins have two distinct climatic conditions.

Impacts of flood are seen in both the catchments with larger effect in Kankai River basin. River discharges of this watershed being much higher compared to Kävlinge basin, the area inundated by 100-year flood in Kankai basin is almost 13 times bigger. There is a thin settlement in Kävlinge basin with some communities located in the surrounding of Kävlinge river. The risk of inundating approximately 165 buildings exists during a 100-year flood in those area. Whereas, huge human settlement and households are present in the surrounding of Kankai basin. However, due to the lack of exposure data, number of inundated households could not be extracted. The basin is also dominated by agricultural fields and forest lands. Around 157 square kilometres of area gets inundated in Kankai basin by a 100-year flood. The deterministic model adopted to represent flood maps for these basins seemed to work well for Kävlinge basin where the river morphology is more certain. In case of Kankai basin, rivers are braided, and the river morphology may change during flooding events. To represent such cases, probabilistic approach could be preferred as flood zones are developed based on probability which allows for uncertainties. Also, one-dimension model, HEC-RAS can provide good result in case of proper defined river course. Once it overtops the channel top level, two-dimensional model is required to compute the spread water over flood plain zone. Hence, for both basins, it is recommended to select 2D model. Flood hazard management can be carried out with two different approaches: soft and hard approach. The soft approach includes planning and policy making, strategy development, creating awareness and preparedness. These seem more effective in long perspective to reduce the effects of flood hazard. Infrastructural development for flood protection which comes under structural or hard approach is a comparatively quick solution but are expensive measures. Thus, thorough planning and implementation of policies and strategies should be integrated with effective structural measures for proper flood risk reduction and protection.

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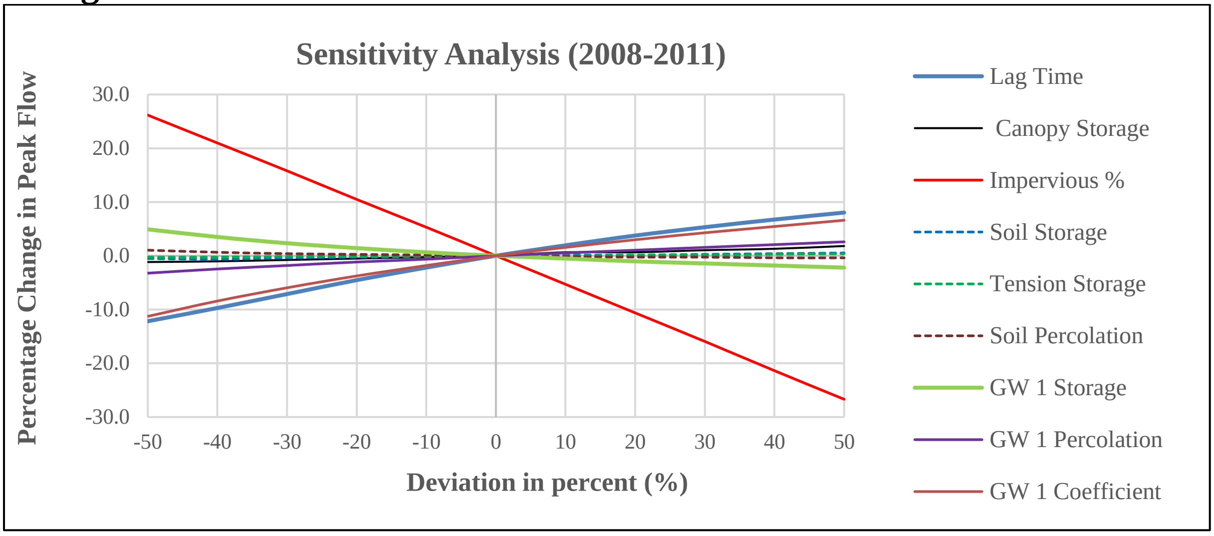
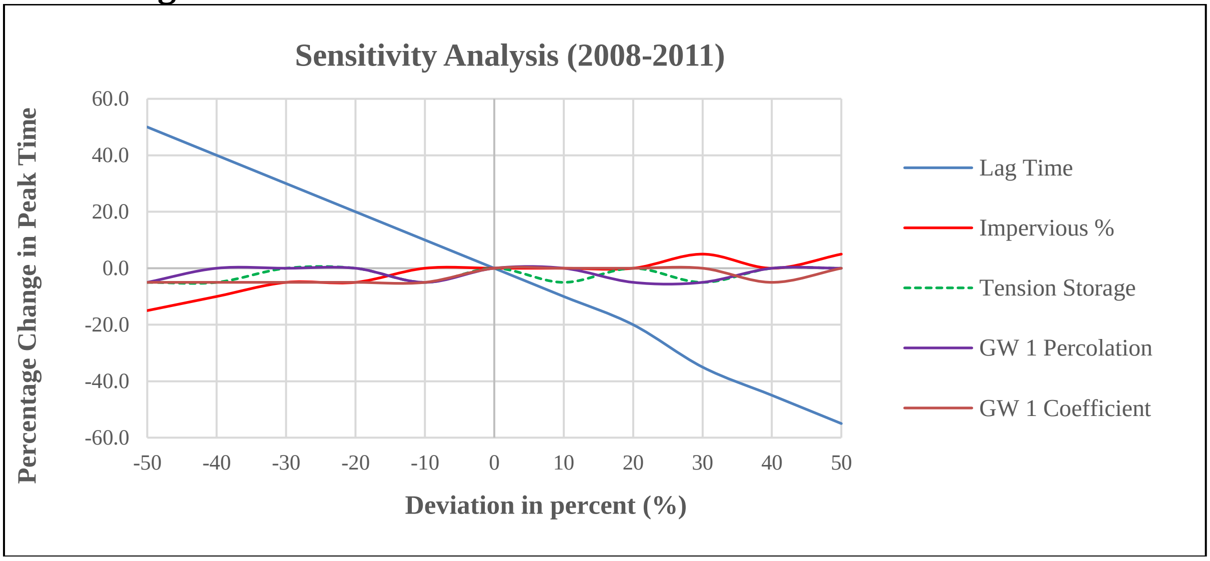
APPENDIX A:

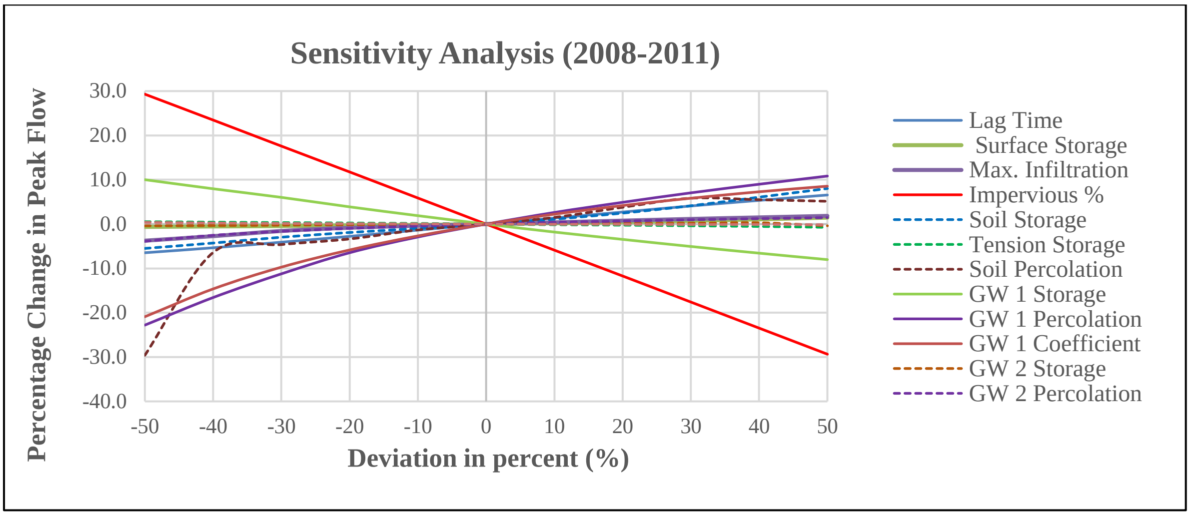
A.1 Sensitivity Analysis of HEC-HMS model of Kävlinge River Basin for % change in Peak Flow



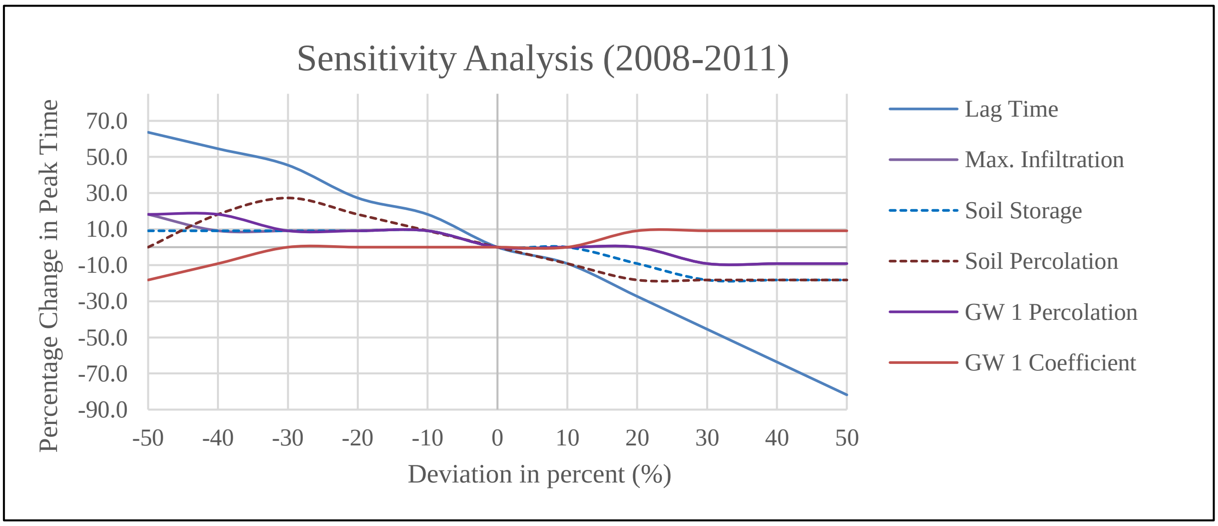
A.2 Sensitivity Analysis of HEC-HMS model of Kävlinge River Basin for % change in Peak Time



A.3 Sensitivity Analysis of HEC-HMS model of Kankai river basin for % change in Peak flow.

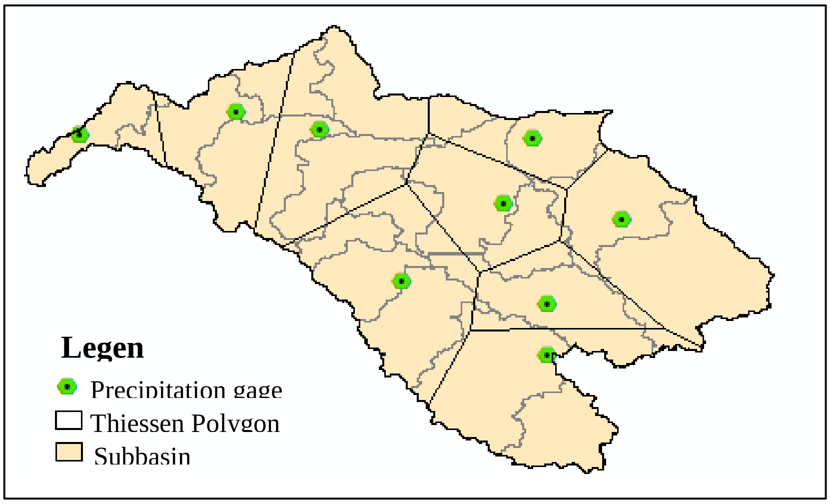


A.4. Sensitivity Analysis of HEC-HMS model of Kankai river basin for % change in Peak time .

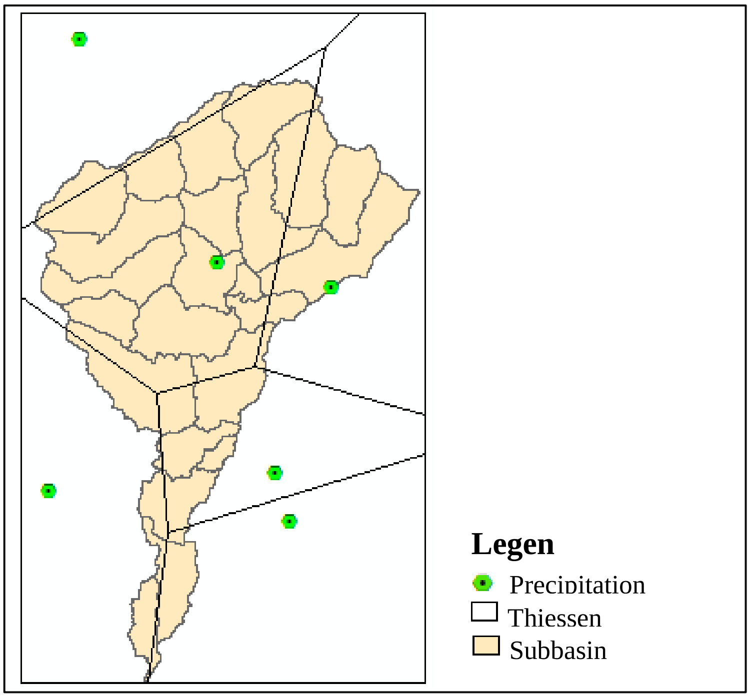


APPENDIX B

B.1 Thiessen polygon in Kävlinge river basin

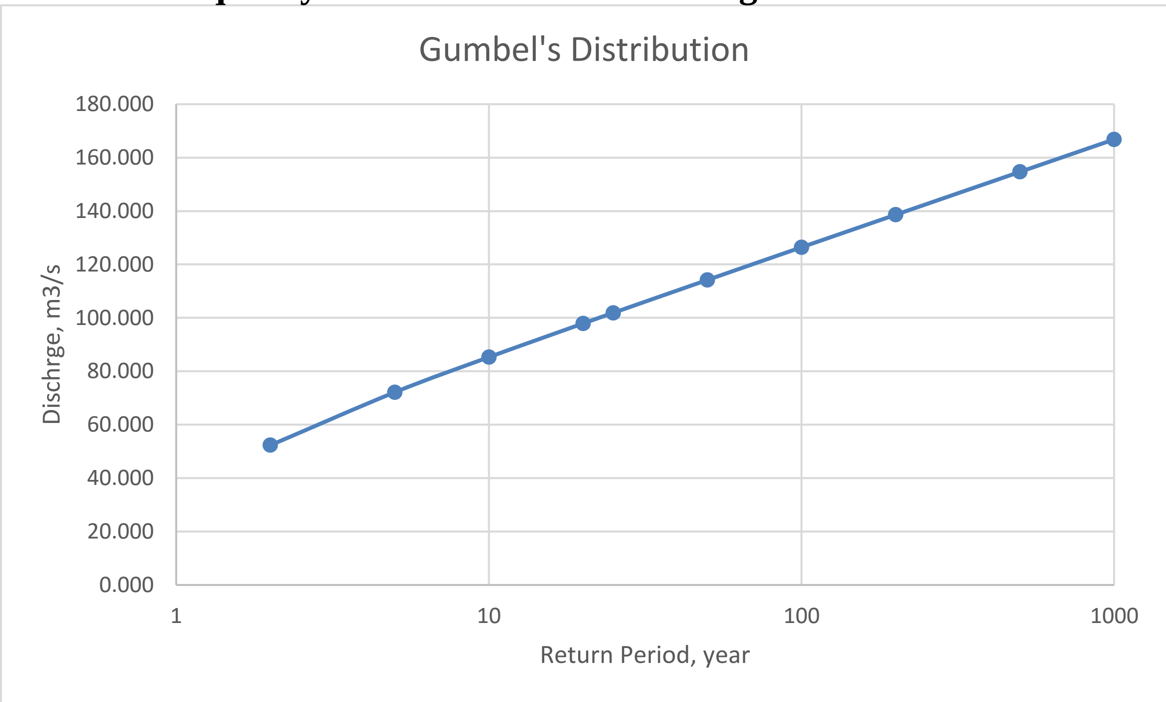


B.2 Thiessen polygon in Kankai river basin

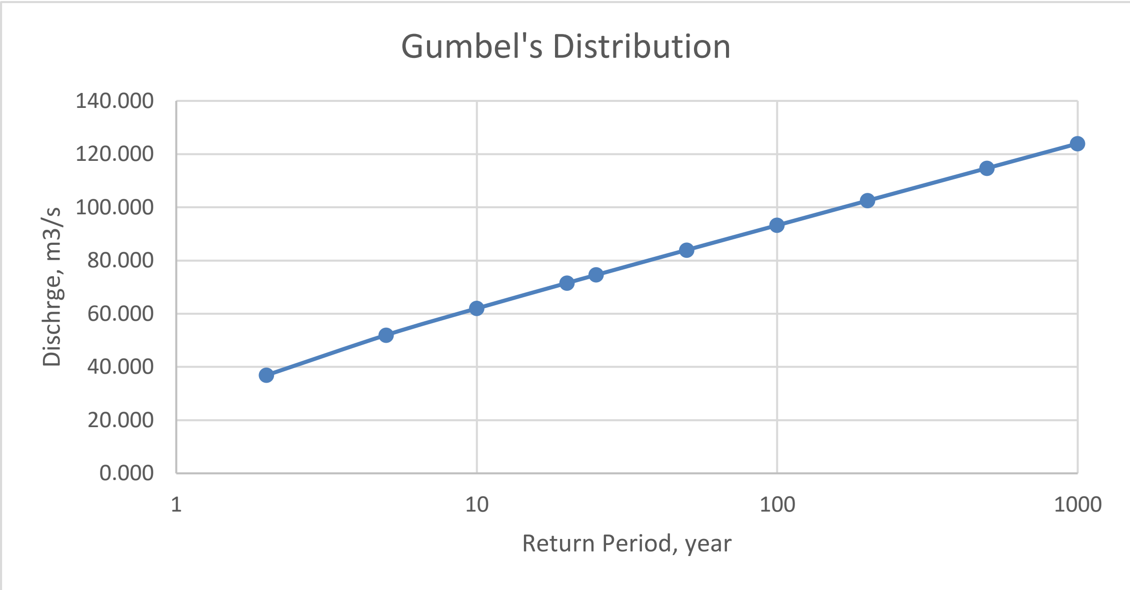


APPENDIX C

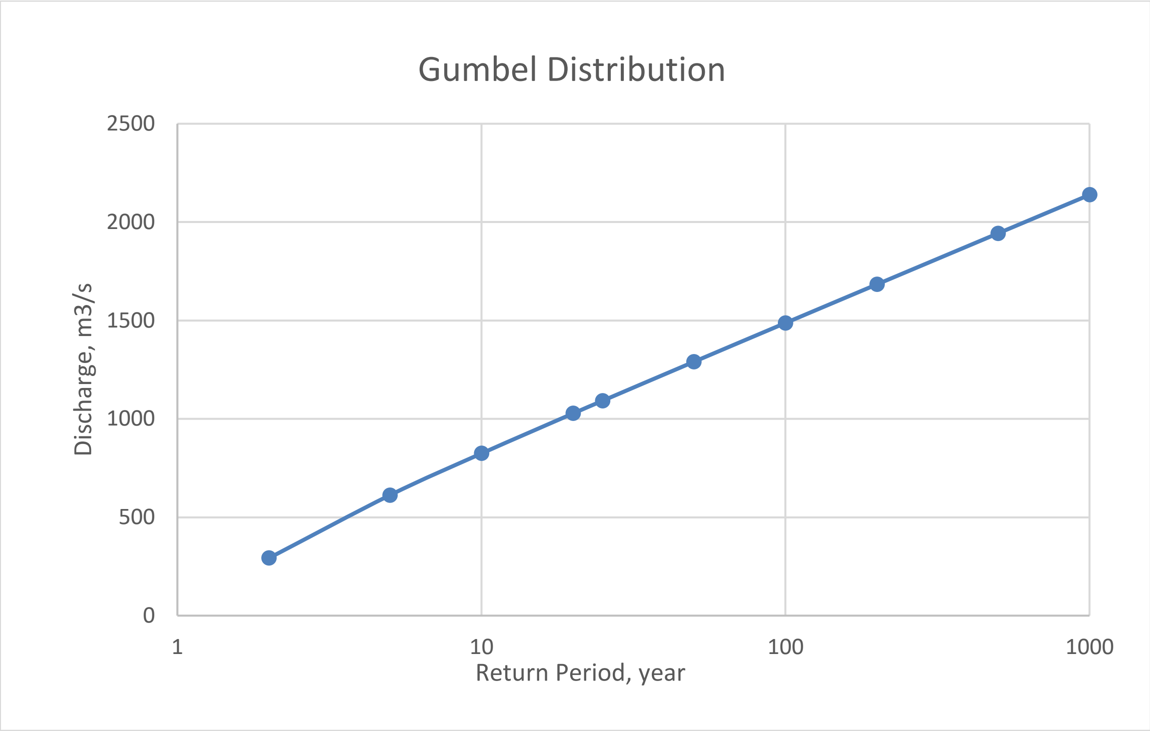
C.1 Flood frequency of Lower Reach in Kävlinge river



C.2 Flood frequency of Upper Reach in Kävlinge river

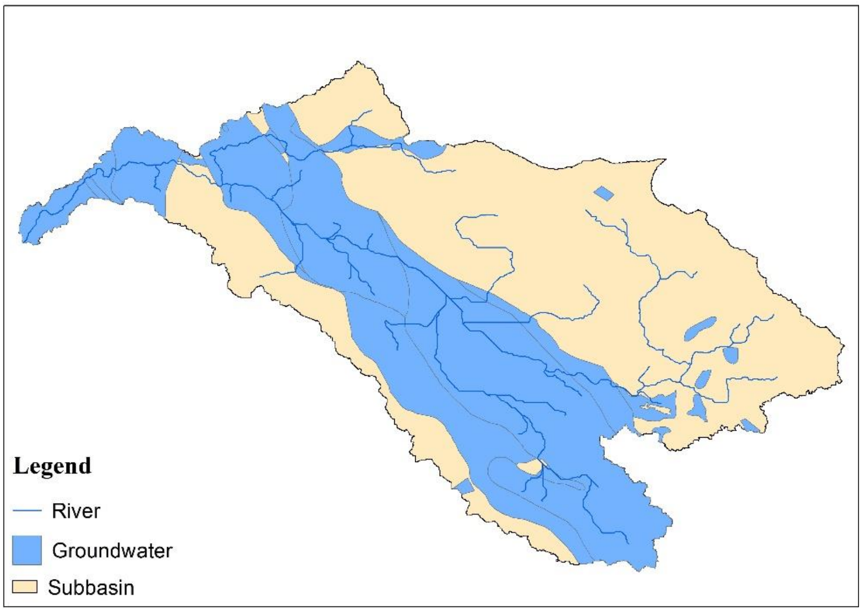


C.3 Flood frequency of Kankai Mai river



APPENDIX D

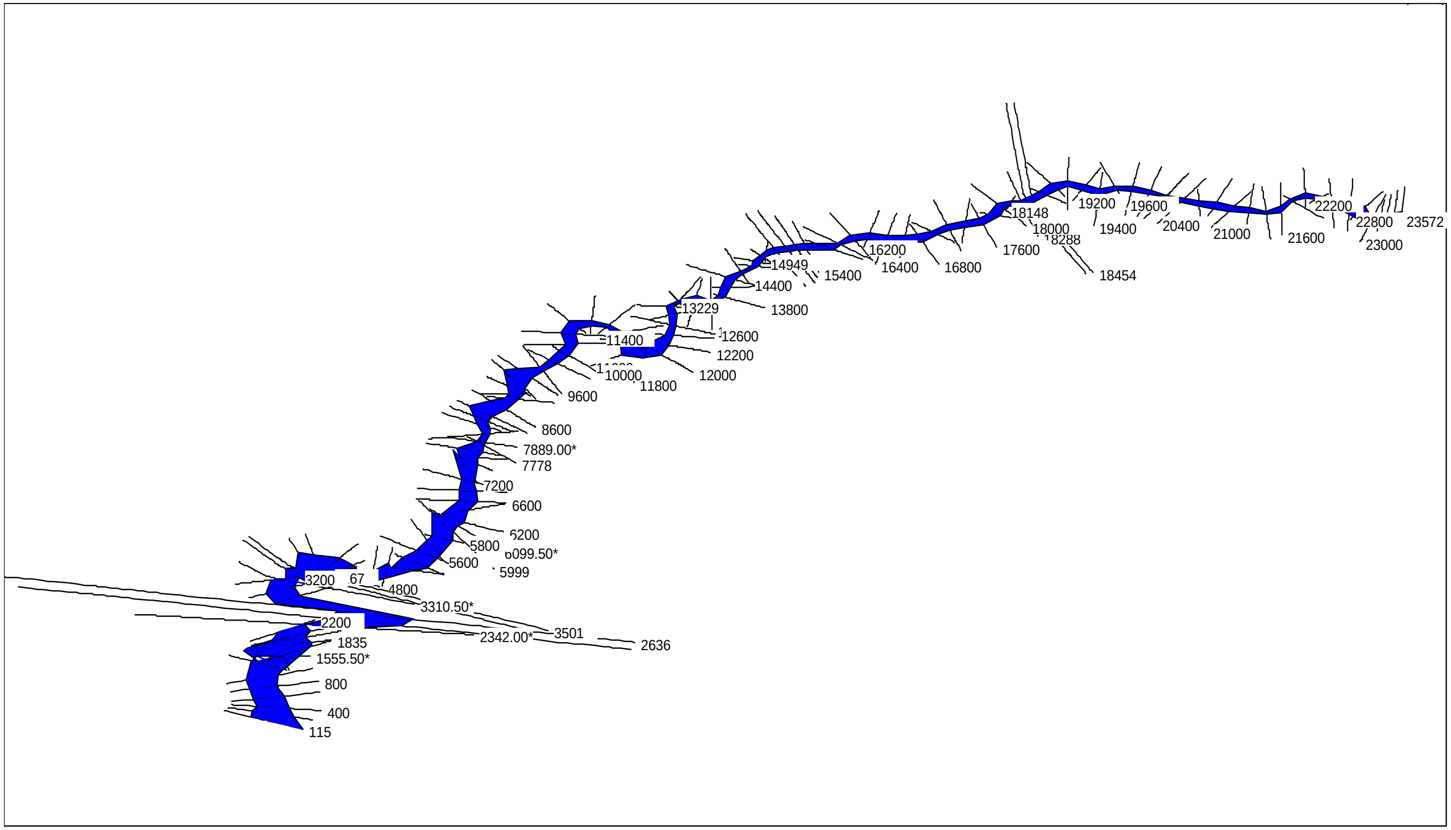
D.1 Groundwater map of Kävlinge river basin (VISS,2018)



APPENDIX E

Figure E.1 and *Figure E.2* are results from HEC-RAS (3D multiple cross-section viewer for Kävlinge basin and Kankai basin respectively).

E.1 Schematic map of Kävlinge river during 100-year flood with river stations



E.2 Schematic map of Schematic map of Kankai river during 100-year flood with river stations