Study Project Report

Online flood forecasting tool using a coupled Hydrological-Hydraulic model: LARSIM & HEC-RAS

Case Study: Upper Main Catchment

Author:
Mohsin Saeed
Matriculation number: 03675621

Supervision:
M.Sc. Punit Bholo

Date of Submission: 06-06-2018
Declaration of Authorship

I, hereby confirm that the presented project work has been done independently and using only the sources and resources as are listed. This work has not previously been submitted elsewhere for purposes of assessment.

Munich, June 6th, 2018

__________________________
Mohsin Saeed
Abstract

The task of this study project is to develop the 1-D hydrodynamic model along with the flood forecasting tool which can forecast the water levels and velocities at the infrastructure objects i.e. bridges and weirs of the Upper Main catchment. This study is part of FloodEvac project, which is cooperative research project between India and Germany and it aims to improve the forecast of extreme flood events. The HEC-RAS model is developed by converting the existing MIKE 11 model over the four flood events occurred in February 2005, May 2006, January 2011 and May 2013. The input data (discharges m$^3$/s) for the HEC-RAS model is extracted from the LARSIM (hydrological model) for all the sub catchments. After stabilizing the HEC-RAS model, calibration of the model is performed by the Manning’s roughness parameter.

The HEC-RAS model is automated by the flood forecasting tool developed over the MATLAB. The tool has the capability to extract the observed and LARSIM simulated data, to write the HEC-RAS input files, to run and calibrate the model with randomly generated Manning’s values and finally to plot the water levels at the user specified bridges. With all the descriptions and supported instructions, the tool is user friendly and can be operated by the less experienced modeler too.

The calibration results showed that the model performed better with roughness parameter of 0.027 for main channel and 0.029 for flood plain except for January 2011 event, where parameters changed to 0.032. The accuracy of the hydraulic model results is highly dependent over the output of hydrological model results and model reacts to be sensitive against the changes in the Manning’s value. The overall model performance is good with the obtained NSE values and validation results along with other parametric findings i.e. peak errors (m), time to peak (Hrs.) and travelling time of flood wave from one calibration gauge to the next one.
Acknowledgment

I would like to express my gratitude to Punit Bhola from the Chair of Hydrology and River Basin Management, Technical University of Munich, for introducing the fundamental theories and aspects of flood modelling and for his contribution and advices as a supervisor during this study project.

Additionally, I want to thank the Wasserwirtschaftsamt Hof (WWA) and Bayerisches Landsamt für Umwelt (LfU) for providing the valuable information about the study catchment and complementary observed data. This report has also benefited from the valuable lessons provided in the lecture “Flood Risk and Flood Management” by Prof. Dr.-Ing. Markus Disse & Dr.-Ing. Olga Spackova held in 2017 at the Technical University Munich.
CONTENTS

DECLARATION OF AUTHORSHIP ................................................................. I

ABSTRACT ............................................................................................... II

ACKNOWLEDGMENT ............................................................................... III

LIST OF FIGURES .................................................................................. VII

LIST OF TABLES ..................................................................................... VIII

ABBREVIATIONS .................................................................................... IX

1 INTRODUCTION ................................................................................... 1

1.1 Work Structure .................................................................................. 3

1.2 Report Organization .......................................................................... 3

2 MODEL AND SOFTWARE DESCRIPTION ........................................... 3

2.1 Introduction ....................................................................................... 3

2.2 ArcGIS .............................................................................................. 3

2.3 Hydrology and hydrological modelling ............................................. 3

2.3.1 LARSIM ....................................................................................... 3

2.4 Hydraulic modelling .......................................................................... 4

2.4.1 Fundamentals of hydrodynamic modelling ..................................... 5

2.4.2 1-D flow hydrodynamics ................................................................. 5

2.4.2.1 Continuity equation ................................................................. 6

2.4.2.2 Momentum equation .................................................................. 7

2.4.2.3 Saint Venant Equation ............................................................. 8

2.4.2.4 Bed resistance ............................................................................ 8

2.4.3 Numerical discretization ............................................................... 8

2.4.4 Implicit finite difference scheme .................................................. 9

2.4.5 Properties of numerical solution ................................................... 10

2.4.5.1 Stability ................................................................................... 10

2.4.5.2 Consistency .............................................................................. 11
2.4.5.3 Convergence.................................................................................................................. 11

2.5 Software packages.................................................................................................................. 11
  2.5.1 MIKE 11.......................................................................................................................... 11
  2.5.2 HEC-RAS........................................................................................................................ 12

3 STUDY AREA DESCRIPTION.................................................................................................... 14
  3.1 Kulmbach............................................................................................................................. 14
    3.1.1 Characteristics of study area......................................................................................... 14
    3.1.2 Flood mitigation measures ......................................................................................... 15

4 MODEL DEVELOPMENT.......................................................................................................... 17
  4.1 Introduction.......................................................................................................................... 17

  4.2 HEC-RAS development ....................................................................................................... 17
    4.2.1 Network ....................................................................................................................... 18
    4.2.2 Hydrological model (LARSIM) .................................................................................... 20
    4.2.3 Conversion from MIKE 11 to HEC-RAS ..................................................................... 20
    4.2.4 Analysis of cross-sectional data .................................................................................. 20
    4.2.5 Initial conditions........................................................................................................... 21
    4.2.6 Boundary conditions .................................................................................................... 21
    4.2.7 Hydraulic roughness parameter .................................................................................... 23
    4.2.8 Expansion and contraction coefficients ........................................................................ 23
    4.2.9 Unsteady simulation runs ............................................................................................ 24
    4.2.10 Post processing ........................................................................................................... 24

  4.3 Model stability ....................................................................................................................... 24

  4.4 Automating with MATLAB .................................................................................................. 25
    4.4.1 Flow chart of MATLAB Script .................................................................................... 25
    4.4.2 HEC-RAS controller setting ......................................................................................... 25
      4.4.2.1 Basic functions ....................................................................................................... 26
      4.4.2.2 Writing input files ................................................................................................. 26
      4.4.2.3 Unsteady flow file ............................................................................................... 26
      4.4.2.4 Geometry file ........................................................................................................ 26
      4.4.2.5 Reading output files ............................................................................................. 27

  4.5 Historical events .................................................................................................................... 27

  4.6 Calibration ............................................................................................................................. 27
    4.6.1 Generation of Random Samples .................................................................................... 28

  4.7 Validation ............................................................................................................................... 30
5 RESULTS AND DISCUSSION ........................................................................................................ 33

5.1 February 2005 event ........................................................................................................... 33
   5.1.1 Discussion ..................................................................................................................... 34

5.2 May 2006 Event .................................................................................................................. 35
   5.2.1 Discussion ..................................................................................................................... 37

5.3 January 2011 event ............................................................................................................ 39
   5.3.1 Discussion ..................................................................................................................... 40

5.4 May 2013 event ................................................................................................................. 42
   5.4.1 Discussion ..................................................................................................................... 44

5.5 Results validation .............................................................................................................. 46

5.6 Bridges and Weirs .......................................................................................................... 47

6 SUMMARY AND OUTLOOK ................................................................................................. 50

6.1 Outlook ............................................................................................................................. 51

7 REFERENCES ....................................................................................................................... 53

8 APPENDIX ............................................................................................................................ 56

A MATLAB Code .................................................................................................................. 56

B HEC-RAS Stabilization Flow Chart ....................................................................................... 64
List of Figures

Figure 2.3-1 Water Balance components (Wohlrab, Ernstberger, Meuser, & Sokollek, 1992) ..................4
Figure 2.4-1 Elementary control volume for derivation of continuity and Momentum equations (US Army Corps of Engineers, 2016b) ..............................................................6
Figure 2.4-2 Typical finite difference cell (US Army Corps of Engineers, 2016b) .................................10
Figure 2.5-1 6-Point Abbott Scheme (DHI, 2012a) .............................................................................12
Figure 3.1-1 River catchment along with full network (Bhola et al., 2016) ...........................................15
Figure 4.2-1 HEC-RAS file system ..................................................................................................18
Figure 4.2-2 A screenshot of GUI of HEC-RAS with River Network ..................................................19
Figure 4.2-3 Sub-Catchments of Study Area (Wasserwirtschaftsamt Hof, 2018) .................................19
Figure 4.2-4 Input hydrographs for the January 2011 Event ..............................................................23
Figure 4.4-1 MATLAB script flow chart ..........................................................................................25
Figure 4.6-1 MATLAB calibration scheme .......................................................................................29
Figure 4.7-1 Validation points (Wasserwirtschaftsamt Hof, 2018) .....................................................30
Figure 5.1-1 Comparison between simulated and observed water level at three calibration gauges for Feb 2005 event for scenario 5 ..................................................................................34
Figure 5.1-2 Comparison between observed and LARSIM simulated discharges for February 2005 event at (a) Kaurendorf, (b) Ködnitz, (c) Unterzettlitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern .......35
Figure 5.2-1 Comparison between simulated and observed water level at three calibration gauges for May 2006 event for scenario 5 ..................................................................................36
Figure 5.2-2 Comparison between observed and LARSIM simulated discharges for May 2006 event at (a) Kaurendorf, (b) Ködnitz, (c) Unterzettlitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern ...............38
Figure 5.2-3 Comparison between observed and LARSIM simulated discharges for May 2006 event at KEMM ............................................................................................................38
Figure 5.3-1 Comparison between simulated and observed water level at three calibration gauges for Jan-2011 event for scenario 10 ..................................................................................40
Figure 5.3-2 Comparison between observed and LARSIM simulated discharges for January 2011 event at (a) Kaurendorf, (b) Ködnitz, (c) Unterzettlitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern ......41
Figure 5.3-3 Comparison between Observed and LARSIM simulated discharges for January 2011 event at KEMM ............................................................................................................42
Figure 5.4-1 Comparison between simulated and observed water level at three calibration gauges for May-2013 event for scenario 12 ..................................................................................43
Figure 5.4-2 Comparison between observed and LARSIM simulated discharges for May 2013 event at KARD (a), KOD(b), UZET (c), MLEU (d), SWBI (e), KEMM (f) .........................................................45
Figure 5.4-3 Comparison between Observed and LARSIM simulated discharges at KEMM for May 2013 ...............................................................45
List of tables

Table 4.2-1  Inflow discharges.............................................................................................................. 22
Table 4.6-1  Performance rating for NSE (Moriasi et al., 2007) ......................................................... 28
Table 4.7-1  Water levels for validation .................................................................................................. 31
Table 4.7-2  Flood wave travel duration (Bayerisches Landesamt Für Umwelt, 2018b) ................. 31
Table 5.1-1  Performance criteria of the HEC-RAS model for Feb-2005 event ............................ 33
Table 5.1-2  The time to peak, peak errors and travelling time of flood wave for February 2005
 event.................................................................................................................................................... 34
Table 5.2-1  Performance criteria of the HEC-RAS model for May 2006 event ........................... 36
Table 5.2-2  The time to peak, peak errors and travelling time of flood wave for May 2006 event
 ............................................................................................................................................................ 37
Table 5.3-1  Performance criteria of the HEC-RAS model for Jan-2011 event ............................ 39
Table 5.3-2  The time to peak, peak errors and travelling time of flood wave for January 2011
 event ..................................................................................................................................................... 40
Table 5.4-1  Performance criteria of the HEC-RAS model for May 2013 event ........................... 43
Table 5.4-2  The time to peak, peak errors and travelling time of flood wave for May 2013 event
 ............................................................................................................................................................ 44
Table 5.5-1  Validation of model results with LARSIM discharge .................................................. 46
Table 5.5-2  Validation of model results with observed discharge KOED & KEMM ................. 46
Table 5.6-1  Location of bridges and weirs in Upper Main catchment with Model ID’s ............. 49
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 D</td>
<td>One Dimensional</td>
</tr>
<tr>
<td>2 D</td>
<td>Two Dimensional</td>
</tr>
<tr>
<td>St. Venant Eq.</td>
<td>Saint Venant Equation</td>
</tr>
<tr>
<td>NSE</td>
<td>Nash Sutcliffe Efficiency</td>
</tr>
<tr>
<td>LARSIM</td>
<td>Large Area Runoff Simulation Model</td>
</tr>
<tr>
<td>MLEU</td>
<td>Mainleus</td>
</tr>
<tr>
<td>SWBI</td>
<td>Schwürbitz</td>
</tr>
<tr>
<td>KEMM</td>
<td>Kemmern</td>
</tr>
<tr>
<td>Avg.</td>
<td>Average</td>
</tr>
<tr>
<td>Obs.</td>
<td>Observed</td>
</tr>
<tr>
<td>Sim.</td>
<td>Simulated</td>
</tr>
<tr>
<td>n</td>
<td>Manning’s Value</td>
</tr>
<tr>
<td>KARD</td>
<td>Kaurndorf</td>
</tr>
<tr>
<td>KOED</td>
<td>Ködnitz</td>
</tr>
<tr>
<td>UZET</td>
<td>Unterzettlitz</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

This study project is the part of research collaborative project FloodEvac between India and Germany, which focuses on the ‘Vulnerability of transportation structures, warning and evacuation in case of major inland flooding’. It is a bilateral research project between the two countries with the goal to improve the flood forecasting methods. FloodEvac has a sub-project ‘Flood Modelling and Flooded areas’ which aims to develop an effective management tool for flood forecast in mesoscale catchments. The tool gives the flood warning in a sharp and reliable way as compared to conventional way. This research based on the analysis of the related processes through relevant modelling tools i.e. rainfall runoff modelling (hydrological modelling) and finding of water level through hydrodynamic modelling (FloodEvac, 2016).

Floods are considered among the extreme natural hazards which mainly caused by the anthropogenic changes in atmospheric composition which leads to the climate change resulting with the increase in flood risk (Milly, Wetherald, Dunne, & Delworth, 2002). With the different types of floods like river floods, urban floods, flash floods etc., flash floods are one of the most prominent natural hazards which have the high probability of risking the life and destruction of buildings and infrastructure (Gaume et al., 2009). Climate change which has affected the rain pattern and increased snow melting process have forced the leading stakeholders to work over the flood mitigation policies which based over the timely prediction of any type of floods which ultimately increased the demand of flood forecasting tools. Flood forecasting tools are based over the river flood modelling, which is a tool for assessment, evaluation and prediction of river flood in different scenarios. A successful river model required a sufficient representation of the river channel and flood plain geometries, with an accurate description of the model parameters, to make it possible to predict the flow magnitude and water levels along the reach accurately (Alaghmand, bin Abdullah, Abustan, & Eslamian, 2012).

Flood forecasting tools worked over the output of the hydrological and hydrodynamic models, simultaneously these both models’ outputs are dependent over the correct input data to provide reliable warnings. A flood forecasting tool will comprise of the hydrological model output in which flood discharges are estimated through rainfall measurements and forecasts, and with the hydrodynamic component in which the water levels along the whole river network are calculated.

Real-time flood forecasting is an integral part of flood warning system and can help to provide more accurate warnings to reduce the both tangible and intangible damage due to flooding, including loss of life, damage to property (buildings and transportation infrastructure), and reduction of negative health and social impacts (Werner, Cranston, Harrison, Whitfield, & Schellekens, 2009). Considering the importance of flood warning systems, the flood forecasting tools based on different methods are developed subsequently over the years. As the Doswell III, Brooks, & Maddox, (1996) introduced the ingredient based methodology for the timely flood
forecasting of flash floods which based over the basic ingredients i.e. rainfall rates, precipitation efficiency and air contained substantial water vapors. The Gouweleeuw, Thielen, Franchello, De Roo, & Buizza, (2005) used the medium-range probabilistic weather prediction method which obtained the results by combination of probabilistic approach and Ensemble Prediction Systems (EPS). Probabilistic approaches are widely used in the flood forecasting systems which deals with the effects of the meteorological uncertainty on the flood warnings, while the EPS systems are based on the Numerical Weather Prediction (NWP) models.

Accuracy, reliability and timeliness are an essential prerequisite for an efficient flood forecasting system. The translation of all available information (prior knowledge and model forecast) into reality, through the estimation of predictive uncertainty is necessary for the decision makers to make most effective decisions. Bogner & Pappenberger, (2011) enhanced the efficiency of a hydrological forecasting system by reducing the prior uncertainty through analysis and correction of the error of the predictions and by providing the decision maker with estimates of the predictive uncertainty. The wavelet based method was used to determine and correction of error between the observed and simulated discharges. The recent developments in the flood forecasting based on the artificial intelligence technology. Some of the models based over this technology developed by Chau, Wu, & Li, (2005) with the names of genetic algorithm-based artificial neural network (ANN-GA) and the adaptive-network-based fuzzy inference system (ANFIS) for the quick and accurate flood forecasting. Along with that real-time-satellite-based rainfall products i.e. TRMM (Tropical Rainfall Measuring Mission) and GPM (Global Precipitation Measurement) can be effectively used for the real-time flood forecasting (Nanda, Sahoo, Beria, & Chatterjee, 2016).

Reliable river flow forecast plays a key role in the flood risk mitigation and infrastructure is the important part of flood risk management plans. For that reason, the systematic analysis of infrastructure is necessary considering the risk of flood events. Since bridges and roads are necessary in evacuating the people at such extreme events, the flood forecasting tools should be developed where the early warnings can be released by estimating the water levels and velocities at the bridges and weirs.

The main objective of the study is to develop the 1-D hydrodynamic model ‘HEC-RAS’ along with the flood forecasting tool which can forecast the flooding event and help to release the early warnings based over the estimated water levels at bridges and weirs. The task of the study project includes to examine the existing MIKE 11 model developed by Bhola et al., (2016) and to prepare the HEC-RAS model. Furthermore, it includes the automation of the HEC-RAS model by the flood forecasting tool developed over the MATALB, which can forecast the water levels at user specified infrastructural objects in upper main catchment.
1.1 Work Structure

- Hydrological analysis through LARSIM (Large-area run off Simulation Model).
- Conversion of MIKE 11 model to HEC-RAS.
- Setting-up and stabilizing the HEC-RAS model.
- Development of MATLAB HEC-RAS Controlling tool.
- Writing the input files i.e. discharge or hydrographs obtained through LARSIM, geometrical data (roughness parameter), plan and project files.
- Run the HEC-RAS model for the stated scenarios.
- Calibration and validation of the model.
- Plotting of the graphs at the required locations.

1.2 Report Organization

This study project organized in six chapters which are:

- Chapter 2 describes the theory behind the models applied in this study. It includes the study of basic principles of Hydrodynamic modelling.
- Chapter 3 briefly explains about the study area and its hydrological characteristics. Furthermore, the flood mitigation works of the area are also being discussed.
- Chapter 4 explains in detail about the development of HEC-RAS model along with the steps of automating it with MATLAB. A brief overview of the MATLAB code is also presented, along with the explanation of calibration & validation process.
- Chapter 5 discuss the results of model simulations.
- In the last chapter, the summary and outlook of the whole study project is presented.
2 MODEL AND SOFTWARE DESCRIPTION

2.1 Introduction

This chapter provides the theoretical background for understanding of the data processing and modeling procedures used in this study. The three software solutions and the mathematical models used in this study are presented in detail. ArcMap is used for all GIS related tasks, LARSIM for hydrologic- and HEC-RAS for hydraulic modeling. Furthermore, MATLAB is used to develop the forecasting tool to extract water levels at user defined infrastructure objects.

2.2 ArcGIS

The Environmental System Research Institute’s (ESRI) developed ArcMap software is used for all the GIS related tasks. ArcMap is the main component of ESRI’s ArcGIS. ArcMap and Arc toolbox are mainly used for geospatial processing. ArcGIS provides the range of extension software to prepare a consistent model input files. One of these applications for pre- and post-processing data is HEC-GeoRAS, which serve as a port of link to ArcGIS. For this project ArcMap is used to get the necessary data, while Hec-GeoRAS is not utilized in this study, since river network is imported from the already developed MIKE 11 model.

2.3 Hydrology and hydrological modelling

The study of movement of water through the atmosphere, over and beneath the earth’s surface, along with its distribution on the surface is called as Hydrology. Hydrological processes such as precipitation, evaporation and subsurface and surface runoff represent represents the fundamental model in hydrology and plays an pivot role in the future predictions (Davie, 2008).

The development of the good hydrological model at the catchment level requires the sound simulation of hydrological processes including careful parametrization, calibration and evaluation (Viviroli, Gurtz, & Zappa, 2007).

2.3.1 LARSIM

LARSIM is an acronym for Large Area Runoff Simulation Model, which is a hydrologic basis water balance model. Water balance models are programmed to quantify the spatial and temporal distribution of important hydrologic conditions like evaporation, precipitation, seepage, water storage in the catchment and runoff (Ludwig & Bremicker, 2006).
LARSIM allows the process-and area-detailed simulation of water cycle including hydrologic sub processes: interception, actual evapotranspiration, snow accumulation, metamorphosis of snow and snow melt, soil water and groundwater storage, lateral water transport to stream, water temperature and routing in channel networks. It simulates the hydrologic processes on the meso-scale level for the defined time to give the resulting hydrograph which serves as the input information for the next element as per the general model structure (Ludwig & Bremicker, 2006).

2.4 Hydraulic modelling

The recurrent occurrence of flood around the world, hydraulic modelling plays pivot role in providing the reliable and accurate results for the alert methods developed to reduce the risk and damage. The study of motion of water consists of simulating the river flows is regarded as hydraulic modelling or simply flood plain modelling (Gharbi, Soualmia, Dartus, & Masbernat, 2016).

Numerical modelling of flood plain is mostly done for two reasons. Firstly, to use it as an alternative way of laboratory experiments to improve process understanding. Secondly, to get
predictions of quantities which are related to management of floodplain systems, i.e. water surface elevation, flow velocity and discharge (Bates, Horritt, Hunter, Mason, & Cobby, 2005).

2.4.1 Fundamentals of hydrodynamic modelling

Many hydrodynamic models are available comprised over the differentials or algebraic equations. The selection of suitable model depended over the many assumptions and requirements. Typically, there are three types of hydrodynamic modelling, one-dimensional, two-dimensional, and three-dimensional. One-dimension model consider the flow in one dimension (uni-directional) i.e. $V_x=V$, while $V_y=V_z=0$. The mean flow velocity is calculated only in flow direction. Two and three-dimensional modelling allows the numerical simulation to take account to the expansion of the river in two or three dimensions respectively (Gharbi et al., 2016). In this study 1-D unsteady approach is used.

2.4.2 1-D flow hydrodynamics

One-dimensional modelling can be done in steady and unsteady conditions. 1-D unsteady flow engine combines the properties of the left and right overbank into a single flow compartment called the floodplain. Hydraulic properties for the flood plain are computed by combining the left and right overbank elevation vs Area into a single set of relationships for the flood plain portion of the cross section. While in steady flow conditions the left and right overbank treated completely separately (US Army Corps of Engineers, 2016b).

An equation for 1D channel flow can be derived from the governing physical laws of flow of water in stream:

- Conservation of mass (continuity)
- Conservation of momentum

The principle of conservation of momentum yields towards the well know 1D St. Venant or Shallow Water Equations (derived from Navier-Stokes-Equations). In river sections, typically the vertical dimensions (water depths) are much smaller than the horizontal expansion in x & y direction of river, so the velocity in the vertical dimension can be neglected. Therefore, the Navier-Stokes-Equation can be reduced (integrated over depth) to 1D St. Venant Equation (US Army Corps of Engineers, 2016b).

A more detailed explanation about the set of equations used are presented below, based over the literature of (Bates et al., 2005),(Gharbi et al., 2016) and (US Army Corps of Engineers, 2016b).
2.4.2.1 Continuity equation

Continuity equation describes the conservation of mass in one dimensional system. It means that the inflow at the control volume equals the outflow, given that there is no additional inflow or outflow at certain time \( t \).

Consider the elementary control volume shown in Figure 2.4-1, the distance \( x \) is measured along the channel, while the flow and total flow area is denoted by \( Q(x, t) \) and \( A \), respectively. The total flow area is the sum of active area \( A \) and off-channel storage area \( S \).

![Elementary control volume for derivation of continuity and Momentum equations (US Army Corps of Engineers, 2016b)](image)

- The rate of inflow into the control volume may be written as:

  \[
  Q - \frac{\partial Q}{\partial x} \Delta x / 2
  \]  

- The rate of outflow as:

  \[
  Q + \frac{\partial Q}{\partial x} \Delta x / 2
  \]  

- The rate of change in storage as:

  \[
  \frac{\partial A}{\partial t} \Delta x
  \]  

- The final simplified form of continuity equation is
\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q = 0
\]  \hspace{1cm} (4)

Where \( q \) is the lateral inflow per unit length.

With the addition of storage term (\( S \)), the continuity equation looks like

\[
\frac{\partial A}{\partial t} + \frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} - q = 0
\]  \hspace{1cm} (5)

### 2.4.2.2 Momentum equation

The conservation of momentum equation is expressed by the Newton’s second law as:

\[
\sum F_x = \frac{d\bar{M}}{dt}
\]  \hspace{1cm} (6)

The conservation of momentum for a control volume states that the rate of change in momentum is equal to the external forces acting upon the system. The considered three external forces are: pressure, gravity and boundary drag or friction force. These forces are given by the following equations

- **Pressure Force**

\[
F_P = \rho g A \frac{\partial h}{\partial x} \Delta x
\]  \hspace{1cm} (7)

- **Gravitational Force**

\[
F_g = -\rho g A \sin \theta \Delta x
\]  \hspace{1cm} (8)

- **Friction Force**

\[
F_f = -\rho g A S_f \Delta x
\]  \hspace{1cm} (9)

By inserting the all three external forces in the equation, the final form of momentum equation is obtained as:

\[
\frac{\partial Q}{\partial t} + \frac{\partial (QV)}{\partial x} + gA \left( \frac{\partial z}{\partial x} + S_f - S_o \right) = 0
\]  \hspace{1cm} (10)

Where \( S_f \) is the friction slope, \( \frac{\partial z}{\partial x} \) is water surface slope, \( S_o \) is channel bed slope and \( V \) is velocity.
2.4.2.3 Saint Venant Equation

The Shallow Water Equations (SWE) or St. Venant Equation is the simplified form of one-dimensional momentum equation along with the continuity equation. Based on the assumption that the vertical momentum is small as compared to the horizontal momentum, St. Venant equation is obtained after integration over the river cross section.

\[
\frac{\partial Q}{\partial t} + \frac{\partial (QV)}{\partial x} + gA \left( \frac{\partial z}{\partial x} + S_f - S_o \right) = 0
\]  
(11)

2.4.2.4 Bed resistance

To describe the bed resistance, the Chezy equation is used. The chezy coefficient is approximated by the Gaukler-Manning-Strickler Equation (Manning’s Equation). The Manning’s equation is an empirical formula used to calculate the average velocity of a liquid flowing in a conduit that does not completely enclose the liquid, such as open channel flow (Mustaffa, Ahmad, & Razi, 2016).

The Manning’s equation is:

\[
n = \frac{A}{Q} \frac{2}{R^3} \frac{1}{S^\frac{1}{2}}
\]  
(12)

Where

- n = Manning's roughness coefficient
- A= cross-sectional area (m²)
- Q=flow discharge (m³/s)
- R= hydraulic radius (m)
- S= longitudinal slope

2.4.3 Numerical discretization

The derived St. Venant equation doesn’t have the exact analytical solution, but with appropriate boundary and initial conditions they can be solved using numerical techniques (Bates et al., 2005).

The solution is to discretize the variable in space and time, which approximates the differential equations to a system of algebraic equations. These determine the values of the solution at only finite number of points of the domain on which the solution is sought. The finer this discretization
is, the more exact the solution is, but it will relatively increase the computation efforts (Griebel, Dornseifer, & Neunhoeffer, 1997).

There are many approaches available for the discretization in space, but the most important are:

- The finite difference method (FDM)
- The finite volume method (FVM)
- The finite element method (FEM)

While for the discretization in time the implicit and explicit scheme can be differentiated:

- Explicit scheme is considered as the simplest discretization method. This scheme used the current state of the system to calculate the next step i.e. solution values at time $t_{n+1}$ are computed from the values of time $t_n$. Therefore, it is possible to do direct computations without solving a system of equations but it required the smaller time step which could possibly leads towards system stability issues.

- Implicit scheme used a system of equations which requires the both, current and next time step, to be solved i.e. all fluxes and source terms are evaluated at time $t_{n+1}$ in terms of unknown variable values at new time $t_{n+1}$. In implicit scheme, much larger time steps are possible which increases the possibility of stable model while every time step requires the solution of system of equations (de Mier Torrecilla, n.d.).

### 2.4.4 Implicit finite difference scheme

The discussed software, HEC-RAS is based on the implicit, finite difference scheme. The first step in obtaining a numerical solution is to discretize the geometric domain i.e. a numerical grid must be defined. In finite difference discretization method, the mathematical background is the Taylor function, which approximates the differential form up to difference quotient. The difference quotient is a measure of the average rate of change of function over an interval (Ferziger & Peric, 2012).

The most successful and accepted procedure for solving the one-dimensional unsteady flow equations is the four-point implicit scheme, also known as the box scheme, as shown in Figure 2.4-2. Under this scheme, space derivatives and function values are evaluated at an interior point, $(n+\theta)\Delta t$. Thus, values at $(n+1)\Delta t$ enter the all terms present in the equations. For a reach river, a system of simultaneous equations is used. The simultaneous solution is an important aspect of the scheme because it allows information from the entire reach to influence the solution at any one point (US Army Corps of Engineers, 2016b).
Figure 2.4-2 Typical finite difference cell (US Army Corps of Engineers, 2016b)

The general implicit finite difference forms are:

**Time derivative**

\[
\frac{\partial f}{\partial t} \approx \frac{\Delta f}{\Delta t} = \frac{0.5(\Delta f_{j+1} + \Delta f_j)}{\Delta t}
\]  

(13)

**Space derivative**

\[
\frac{\partial f}{\partial x} \approx \frac{\Delta f}{\Delta x} = \frac{\left(f_{j+1} - f_j\right) + \theta(\Delta f_{j+1} - \Delta f_j)}{\Delta x}
\]  

(14)

**Function Value**

\[
f = 0.5\left(f_j + f_{j+1}\right) + 0.5 \theta(\Delta f_j + \Delta f_{j+1})
\]

(15)

### 2.4.5 Properties of numerical solution

Every numerical solution method has certain properties which are used to analyze the method. The properties of numerical solution include consistency, stability, convergence, conservation, boundedness, realizability and accuracy (Ferziger & Peric, 2012).

#### 2.4.5.1 Stability

A numerical solution is said to be stable if it does not magnify the errors that appear during numerical solution process. Stability is difficult to investigate, especially when complicated...
boundary conditions and non-linearities are present. In that case, modeler must rely over the experience and intuition.

### 2.4.5.2 Consistency

A numerical solution is said to be consistent when discretization become exact as grid spacing tends to zero. The difference between the discretized equation and the exact one is called the truncation error. Even if the approximations are consistent, it does not necessarily mean that the solution of the discretized equation system will become the exact solution of the differential equation in the limit of the small step size.

### 2.4.5.3 Convergence

A numerical method is said to be convergent if the solution of the discretized equation is tended to the exact solution of differential equation as the grid spacing tends to zero. A consistent and stable scheme is useless unless the solution method converges.

### 2.5 Software packages

In this study project, two hydrodynamic models are being discussed which are Mike 11 and HEC-RAS. General overview of both the models are described below.

#### 2.5.1 MIKE 11

MIKE 11 is a modelling system for rivers and channels developed by Danish Hydraulic Institute (DHI). It is a professional software engineering package for simulating flows, water quality and sediment transport in estuaries, rivers, irrigation channels and other water bodies (DHI, 2012b).

MIKE 11 can simulate unsteady stream flows for the specified time durations and time steps, which makes it a powerful graphic tool. The hydrodynamic module (HD) is the core of MIKE 11. It provides the library of computation methods for steady and unsteady flow in branched and looped channel networks. Typical application areas for MIKE 11 include flood risk analysis, real-time flood forecasting, dam break analysis, optimisation of reservoir and canal structure operations and integrated surface and ground water (Alaghmand et al., 2012).

MIKE 11 based over the implicit finite difference method with the staggered grid of 6-point Abbott scheme for the computation of unsteady flows in river. A staggered computational grid of alternating discharge and water level points is used and solved, while the space and time
derivatives of variables $h$ and $Q$ are not computed at the same grid point. The solution scheme of 6-point Abbott is presented below (DHI, 2012a).

![Figure 2.5-1 6-Point Abbott Scheme (DHI, 2012a)](image)

### 2.5.2 HEC-RAS

HEC-RAS is a freeware software developed by the Hydrologic Engineering Centre of the U.S. Army Corps of Engineers. It is an integrated system of software, designed for interactive use in multi-tasking environment. The system is comprised of a graphical user interface (GUI), separate analysis components, data storage and management capabilities, graphics and reporting facilities. HEC-RAS is designed to perform one dimensional (1D), two dimensional (2D), or combined 1D and 2D hydraulic calculations for a full network of natural and constructed channels (US Army Corps of Engineers, 2016b).

The HEC-RAS model was initially used for calculating water surface profiles for 1D steady state flow. From the version 4.0, it has incorporated an unsteady flow model also. Now recent versions of HEC-RAS provide the modeller with an option to use either the steady flow or unsteady flow option.

HEC-RAS is currently capable of performing one dimensional water surface profile calculation for steady gradually varied flow in natural or constructed channels. Subcritical, super critical and mixed regime water surface profile can be calculated. Along with the unsteady and steady flow options, the HEC-RAS model also provides the following capabilities:
Model and Software description

- Modelling of open channel networks and single rivers (both unsteady and steady flow options).
- Analysis of bridges, weirs and culverts (unsteady and steady flow options).
- Modelling of storage area, navigation dams, tunnels, pumping stations, and levee failures (unsteady flow option only).
- Handling of sub-critical, super-critical and mixed flow regimes (Alaghmand et al., 2012).

In the computational modelling procedure, HEC-RAS use an implicit difference scheme which is explained under the section 2.4.4. Since this scheme is used to overcome the problem of non-existence of analytical solution of St. Venant equations, the derivations of complete St. Venant equations are based over the following assumptions.

- The flow is one dimensional so the velocity component in other directions than the direction of flow is neglected.
- The water lengths are large as compared to water depths (vertical accelerations are neglected and the pressure is assumed to be hydrostatic).
- The water level across the cross-section is horizontal.
- The channel bed and banks are fixed and not mobile.
- The average channel bed slope is small (less than 1:10) (Maidment & others, 1993).
3 STUDY AREA DESCRIPTION

The study project focuses over the river catchment of Upper Main which is in North east of the Bavaria federal state in Germany. This catchment is part of Rhine river Basin with the approximate area of 4646 km². The area spread over the horizontal distance of 90 km, which is covered by the Thuringen forests from the North. In the south, it is enclosed by the Franconian Switzerland, west with the Haßberge, south-east with the Franconian Forest and east with the Fichtelgebrige (Pakosch, 2011).

The river Upper Main results from the two head streams, the White Main (Weißer Main) with the flow length of 45 km and the Red Main (Roter Main) with the flow length of 55 km near the gauge station of Mainleus. The Upper Main itself is 70 km long and flows down to the city Kemmern. The white main river originates in the Fichtelgebirge and merges with the several tributaries. Schorgast is the most important tributary regarding the flood region around Kulmbach which is the main point of interest in the upper main catchment.

3.1 Kulmbach

The city of Kulmbach which is situated bit after the confluence of White Main and Schorgast also contributed by the smaller tributaries of Kohlenbach and the Kinzelsbach. While the Dobrachbach from the Northern side of the city also joins the White Main from the its right. Though these three rivers are very small but still contribute to the flooding of the White Main and hence these are considered in the modelling steps. To protect the city of Kulmbach from the flooding, a flood basin (Mühlkanal) was built in 1930s that flows through the city. The built weirs ensure that not more than 5m³/s discharge passes through the city center, while the rest of the water goes through the flood channel (Flutmulde) (Wasserwirtschaftsamt Hof., 2016). The river catchment along with the network is shown in Figure 3.1-1.

3.1.1 Characteristics of study area

The characteristics of the river course are affected by the climatic differences and ultimately puts the region at risk of the flash floods. The Kulmbach city gets more affected by this difference i.e. the upper main valley and its tributaries has less precipitation as compared to low mountain ranges which has tendency of high precipitation in combination of snow melt in spring time(Pakosch, 2011). This poses the city of Kulmbach at the high risk of flooding in downstream. The main land use type of the catchment area is agriculture with around 50 % while 30% is covered with the forests. The rest of the area is covered with grass land.
Mainleus gauge is taken as the most important gauge since it is located direct after the Kulmbach. It is considered as the first calibration point followed by Schwürbitz and Kemmern. The gauge station Kemmern is situated close to the area outlet with the altitude of 230.20 m a.s.l. It is located at the river kilometer 390.93 km with the area catchment of 4,249.80 km² (Bayerisches Landesamt Für Umwelt, 2018a). The similar information for other gauge points can also be collected from the Bavarian Ministry of Environment.

Figure 3.1-1 River catchment along with full network (Bhola et al., 2016)

3.1.2 Flood mitigation measures

Kulmbach is the city with around 26,567 inhabitants, till date January 1st 2018, with about population density of 285 inhabitants per km² (Stadt Kulmbach, 2018). Regarding the flood mitigation measures, it was started in 1930s when a flood channel was built north of the city center. Two weirs system were built to control the stream of the river, so that only 5m³/s could flow through the original path of white main, which is passing through the city center of Kulmbach. The rest of the water flows through the flood channel.
Considering the past events, when the water exceeds the riverbed and overflows the city and channels, it was decided to plan for a new flood protection strategy in 2009 with the estimated costs around 11.5 mio. Euro (Wasserwirtschaftsamt Hof., 2016). In 2014, the renovation of the original path of the White Main was also being done. In March 2017 the construction work for the flood channel has started again to make sure that it can drain floods. The timeline of construction work goes as follows.

- March 2017 Start of construction work
- October 2017 Completion of the flood protection walls
- End of 2017 Completion of all flood protection walls and temporary dike filling.
- Mid 2018 Completion of overall measures (Wasserwirtschaftsamt Hof., 2016).
4 MODEL DEVELOPMENT

4.1 Introduction

In this chapter, the methodology that was applied to prepare the hydrodynamic model, ‘HEC-RAS’ is described in detail. The detailed steps of developing the flood forecast tool over MATLAB are also presented along with the schematic plots, which explains the processes of calibration and validation of the model.

4.2 HEC-RAS development

There are five main steps in creating a hydraulic model with HEC-RAS:

1) Starting a new project
2) Entering geometric data
3) Entering flow data and boundary conditions
4) Performing hydraulic calculations
5) Viewing and printing results

The above described general steps leads towards the important file system of HEC-RAS, which stores information in specific file formats. A detailed overview of the file system is described in US Army Corps of Engineers,(2016b).

- **.prj file**: Stores the project name, current plan files and units.
- **.g01 to .g99**: is the geometry file which stores all the information related to network i.e. cross-sectional data, Manning’s values, hydraulic structures etc.
- **.u01 to u99**: is the unsteady flow file which stores the information about the boundary conditions (flow hydrographs) and initial conditions along with the any user specified flow information like the path of Hot Start file.
- **.p01 to p99** is the plan file which contains the list of all input files along with all simulation options.
- **.p01.hdf to p99.hdf**: is the one HDF binary output file for each plan. This file stores all the information of model ranging from geometric data to simulation results i.e. discharge, water levels etc. It can be used in RAS Mapper to get computed results to visualize as inundation maps.
- **.com msgs.txt**: HEC-RAS computes log file for every simulation run providing detailed information about the problems that occurred in the solution.

A general schematic sketch of file system is presented below.
4.2.1 Network

Accurate terrain data in the form of high resolution Digital Elevation Models (DEM.s) is the most crucial input for hydrological modelling. In this case study, the DEM was developed by Kammereck, (2016) by drawing an inaccurate line in google earth and then importing from KML to shape file of ArcGIS. For the more detailed fitting of the river branches, maps of the geoportal Bayern were used and converted into the shape files. The start and end of the rivers were adjusted to the measurement points of the ‘‘Hochwassernachrichtendienst Bayern’, which were given by the point shape file. In case of HEC-RAS, HEC-GEORAS can be used as port of link to ArcGIS.

Since the model network is already developed for MIKE 11 working, it is directly imported to HEC-RAS. A detailed overview about the working and factors to be considered after the import are explained below in this chapter.

A general GUI of HEC-RAS model and DEM of the catchment along with the sub-catchments required for the hydrological model LARSIM is presented in Figure 4.2-2 & Figure 4.2-3.
Figure 4.2-2 A screenshot of GUI of HEC-RAS with River Network

Figure 4.2-3 Sub-Catchments of Study Area (Wasserwirtschaftsamt Hof, 2018)
4.2.2 Hydrological model (LARSIM)

Since, the main input data for hydraulic modelling is the runoff hydrograph of the river basin, so LARSIM hydrological model is utilised to generate the runoff hydrographs for various scenarios. The development of hydrological model is not included in the scope of study, only the brief overview of the model was carried out during the process. The hydrological model results are extracted and sorted out through MATLAB generated code at the required chainages, showed in the Table 4.2-1. Later it is incorporated in HEC-RAS as upstream boundary conditions i.e. flow hydrograph, lateral inflow hydrograph and uniform lateral inflow hydrograph based over the sub-catchments generated for the hydrological model. An overview of sub-catchments generated is shown in above Figure 4.2-3.

4.2.3 Conversion from MIKE 11 to HEC-RAS

An important feature of HEC-RAS is the ability to import different format of data in HEC-RAS environment. Under the geometry editor of HEC-RAS, it can import the network from GIS format, USACE format (standard survey data file format developed by U.S. Army Corps of Engineers), HEC-2, UNET geometric data format, CSV format (comma separated value) and MIKE 11 cross sections file.

To import the MIKE 11 data into HEC-RAS includes the following steps:

- Raw cross section data must be exported from within MIKE 11 to a text file, which is then imported into the HEC-RAS.
- Rest of the geometry data including System Branches and system points (coordinates) can be entered manually by copying from the MIKE 11 software directly.

4.2.4 Analysis of cross-sectional data

The detailed overview of cross sections is carried out, as the accurate representation of the stream channel and the overbank area (floodplain) is necessary to create an accurate hydraulic model. Cross section location, direction and distance are the most important aspects in the analysis. According to the (US Army Corps of Engineers, 2016b), following general guidelines should be followed by the modeller for the placement of cross sections.

- Cross sections are required at representative locations along the modelled reach and at the locations where changes occur in discharge, slope, shape and roughness.
- Cross section should span across the flow channel and the entire flood plains.
• Cross sections should be placed close enough where the abrupt changes occur in the channel geometry to describe the changes accurately.
• Cross section should be placed perpendicular to the expected flow paths in the channel as well as in the left and right overbanks.

4.2.5 Initial conditions

Initial conditions are needed for each model dependent variable at time t=0 for each computational node. Usually the system starts the simulation at low flows and it is important that the initial conditions are consistent with the first time-step flow from the unsteady flow boundary conditions. Initial conditions can be set by creating the ‘Restart file’ in which values of stages or flows are being read from the previous simulation run. These techniques are useful in real time forecasting. HEC-RAS provides the built-in key function which creates the Restart file or Hot start file either during the simulation or at the end of simulation (US Army Corps of Engineers, 2016c).

4.2.6 Boundary conditions

Boundary conditions are necessary to establish the starting water surface at the ends of river system (upstream and downstream). A starting water surface is necessary for the program to begin the calculations. The flow hydrographs resulting from the hydrologic modelling are used as the upstream boundary conditions. There are several different kinds of boundary conditions available in HEC-RAS. In this project, the open boundary conditions at the main tributaries i.e. Ködnitz (Upper Main), Kaurndorf (Schorgast), Unterzetlitz (Red Main) are utilized along with Branch Main which has constant discharge of 5m³/sec.

The flow hydrographs are entered at the corresponding cross sections of the network. The selection of the cross sections is based on the coordinates obtained through DEM and existing MIKE 11 model. Moreover, chainage values are also utilized to avoid wrong allocation of the data.

Q-h relation (rating curve) is used in this work as downstream boundary condition. For the sub-catchments, which were created during the process the hydrological modelling i.e. FLEN, ULGU, FLEH etc., are entered with the boundary condition type of ‘Lateral Inflow Hydrographs or Uniform Lateral Inflow Hydrographs’ at their corresponding cross sections. The allocation of boundary conditions of sub-catchments along with the river chainages and HEC-RAS cross section numbers are showed in the following Table 4.2-1.
<table>
<thead>
<tr>
<th>Sr. #</th>
<th>Branch Name</th>
<th>Catchment ID</th>
<th>River chainage [meter]</th>
<th>HEC-RAS Cross-section</th>
<th>Boundary Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schorgast</td>
<td>KARD</td>
<td>850</td>
<td>-850</td>
<td>Flow Hydrograph</td>
</tr>
<tr>
<td>2</td>
<td>Upper Main</td>
<td>KOED</td>
<td>479920</td>
<td>476521</td>
<td>Flow Hydrograph</td>
</tr>
<tr>
<td>3</td>
<td>Dobrachbach</td>
<td>FLDO</td>
<td>470790</td>
<td>470970</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>4</td>
<td>Roter Main</td>
<td>UZET</td>
<td>3880</td>
<td>-5560</td>
<td>Flow Hydrograph</td>
</tr>
<tr>
<td>5</td>
<td>Branch Main</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>Constant Flow Hydrograph</td>
</tr>
<tr>
<td>6</td>
<td>Kohlenbach</td>
<td>FLKO</td>
<td>1350</td>
<td>-1350</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>7</td>
<td>Kinzelbach</td>
<td>FLKI</td>
<td>2450</td>
<td>-2450</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>8</td>
<td>Roter Main</td>
<td>RMVZ</td>
<td>7794</td>
<td>-7160</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>9</td>
<td>Upper Main</td>
<td>MLEU</td>
<td>46114</td>
<td>458900.9</td>
<td>Uniform Lateral Inflow</td>
</tr>
<tr>
<td>10</td>
<td>Upper Main</td>
<td>ULMO</td>
<td>458032</td>
<td>458101.6</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>11</td>
<td>Upper Main</td>
<td>FLEA</td>
<td>457765.67</td>
<td>457700.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>12</td>
<td>Upper Main</td>
<td>FLEC</td>
<td>452414.36</td>
<td>452358.6</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>13</td>
<td>Upper Main</td>
<td>FLEQ</td>
<td>448414.68</td>
<td>448401</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>14</td>
<td>Upper Main</td>
<td>ULWE</td>
<td>447682.35</td>
<td>447608.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>15</td>
<td>Upper Main</td>
<td>ROMA</td>
<td>439718.66</td>
<td>439683.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>16</td>
<td>Upper Main</td>
<td>SWBI</td>
<td>438215.97</td>
<td>435606.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>17</td>
<td>Upper Main</td>
<td>ULEH</td>
<td>435358.27</td>
<td>435526.3</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>18</td>
<td>Upper Main</td>
<td>FLEH</td>
<td>430749.62</td>
<td>430748.2</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>19</td>
<td>Upper Main</td>
<td>ULEH</td>
<td>429197.95</td>
<td>429177.1</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>20</td>
<td>Upper Main</td>
<td>FLER</td>
<td>428050.51</td>
<td>427989.9</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>21</td>
<td>Upper Main</td>
<td>ULLA</td>
<td>418945.03</td>
<td>418884.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>22</td>
<td>Upper Main</td>
<td>FLEK</td>
<td>411979.39</td>
<td>411974.5</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>23</td>
<td>Upper Main</td>
<td>ULKE</td>
<td>410801.99</td>
<td>410754.5</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>24</td>
<td>Upper Main</td>
<td>FLEM</td>
<td>405451.86</td>
<td>405455.1</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>25</td>
<td>Upper Main</td>
<td>FLEN</td>
<td>403632.25</td>
<td>403696.4</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>26</td>
<td>Upper Main</td>
<td>ULIT</td>
<td>396211.34</td>
<td>396188.1</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>27</td>
<td>Upper Main</td>
<td>FLEU</td>
<td>394796.71</td>
<td>394756.7</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>28</td>
<td>Upper Main</td>
<td>FLEP</td>
<td>394579.15</td>
<td>394610.1</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>29</td>
<td>Upper Main</td>
<td>ULGU</td>
<td>394292.01</td>
<td>394219.1</td>
<td>Lateral Inflow Hydrograph</td>
</tr>
<tr>
<td>30</td>
<td>Upper Main</td>
<td>KEMM</td>
<td>389917</td>
<td>389836.9</td>
<td>Uniform Lateral Inflow</td>
</tr>
<tr>
<td>31</td>
<td>Upper Main</td>
<td>-</td>
<td>-</td>
<td>389730</td>
<td>Rating Curve</td>
</tr>
</tbody>
</table>

Table 4.2-1 Inflow discharges
The example of entered hydrographs used as the open boundary conditions for the gauges KOED, KARD and UZET are shown in Figure 4.2-4.

Figure 4.2-4 Input hydrographs for the January 2011 Event

### 4.2.7 Hydraulic roughness parameter

Hydraulic roughness is the amount of frictional resistance water experiences when passing overland and channel features (Mustaffa et al., 2016). Manning’s value ‘n’ is considered in this study as roughness parameter and these are the main calibration parameter in hydrodynamic modelling (US Army Corps of Engineers, 2016c).

### 4.2.8 Expansion and contraction coefficients

These loss coefficients are applied in the hydraulic computations to account for the energy losses resulting from contraction and expansion of flow due to changes in cross section geometry along the reach. The energy loss caused by a transition in channel geometry is calculated by the absolute difference in velocity head between one cross section and next downstream, cross section. (US Army Corps of Engineers, 2016c). For the supercritical flow, it is suggested by the US Army Corps of Engineers,(2016b) that to use the value of 0.01 for contraction parameter and 0.03 for expansion parameter. In this study both these default values are used in all simulations.
4.2.9 Unsteady simulation runs

Once all the geometry and unsteady flow data is entered, unsteady simulation can run by defining few parameters i.e. simulation time and computation time. These settings can be saved in the plan, called as simulation plan.

4.2.10 Post processing

The post processor used to compute detailed hydraulic information during the unsteady flow simulation period. The purpose is to compute hydraulic output variables that are not computed by the unsteady flow computation engine i.e. the unsteady flow computations only compute the stage and flow hydrographs. By running the post processor, all the available features of HEC-RAS are accessed and simulation results in HDF format can be added in RAS Mapper for flood mapping.

4.3 Model stability

An unstable model is one for which certain types of numerical errors grow to the extent at which the solution begins to oscillate, or the errors become so large that the computations cannot continue. The stability of the resulting solution depends on following factors.

- Cross section spacing
- Computation time step
- Drastic changes in changes in channel geometry
- Theta weighting factor for numerical solution
- Characteristics of flood wave itself
- Manning’s value
- HTab parameters
- Initial/low flow conditions
- Downstream boundary conditions

These stability problems lead to the inaccuracies in the simulated results. Model accuracy can be defined as the degree of closeness of the numerical solution to the true solution. To avoid the inaccuracy of the model, HEC-RAS computes log file for every simulation run providing detailed information about the problems that occurred in the solution. Nevertheless, it is suggested that every unsteady model application should be analysed in detail regarding the accuracy and stability of the solution (US Army Corps of Engineers, 2016c). The stabilization process of the model is explained in Appendix B.
4.4 Automating with MATLAB

MATLAB of Math Works Inc. and its toolboxes provides the option of integration in the form of computation, visualization in an easy to use environment. In the field of hydrology and hydraulic engineering, number of researchers are using the MATLAB for the automation of respective software. In this study HEC-RAS is controlled by the MATLAB to save time and efforts and to serve as online forecast tool as part of FloodEvac tool (Leandro et al., 2017). For that reason, MATLAB script has been developed to write Input files, read output files, make plots and perform fully automated functions of HEC-RAS.

4.4.1 Flow chart of MATLAB Script

```
| LARSIM data extraction           |
| (Discharges)                     |
|                                 |
| Writing HEC-RAS input files      |
| *u.## *g.## *p.## *prj          |
|                                 |
| Simulated data extraction        |
| for calibration, validation and  |
| at bridges with best NSE value   |
| At MLEU, SWBI, KEMM, 8 city      |
| locations and at bridges         |
|                                 |
| Plot                             |
| Simulated Vs Measured            |
```

Figure 4.4-1 MATLAB script flow chart

4.4.2 HEC-RAS controller setting

This section provides the brief description of about the working of MATLAB controlled HEC-RAS (HEC-RAS Controller). The detailed code of MATLAB consisted of six functions is presented in Appendix A. Some important functional parts of the controller are explained below. The controller setting is based over the Leon & Goodell, (2016) work.
4.4.2.1 Basic functions

The function ‘run_ras’, contains the ‘actxserver’, which will create a new, invisible copy of HEC-RAS with the text ‘RAS504.HECRASCONTROLLER’. RAS504 depicts the HEC-RAS version which is used. The other important functions called are for ‘computing the current plans’, open and saving the respective project.

4.4.2.2 Writing input files

As described in Leon & Goodell (2016), the most important HEC-RAS input text files are:

- Unsteady flow file (*.u##)
- Geometry file (*.g##)
- Plan file (*.p##)
- Project file (*.prj)

4.4.2.3 Unsteady flow file

After extracting the flow discharges from LARISM, it is loaded in the unsteady text files in the same order as it is saved by default in HEC-RAS at their corresponding cross-section number. The inflow discharges along with the boundary conditions are presented in Table 4.2-1.

Firstly, all the input data from the default unsteady flow file is being deleted, so the new input data taken from the LARSIM can be entered. The stated script ‘Unsteady_Qinflow’, first prepares the lines of data to be written in the unsteady file. In this case number of lines of data is 10.

Once the data is prepared, the script ‘ChangeInlineStruct_Data’, read the key variables i.e. ‘Flow Hydrograph’, ‘Lateral Inflow Hydrograph’ and ‘Uniform Lateral Inflow Hydrograph’. With these scripts, the extracted data can be successfully entered and changed at their corresponding locations.

4.4.2.4 Geometry file

The geometry file contained the information about the information about Manning’s value, which is the main parameter in calibration of the model. To read out the Manning’s value from the text file, the key variable is being called i.e. ‘#Mann=’, through the script ‘Change_Geometry’. Now the desired the Manning’s value can be entered in the project.

Similarly, the project title is changed through ‘Change_Project’ and the simulation date can be changed through ‘Change_Plan’ scripts, which are presented in Appendix A.
4.4.2.5 Reading output files

The output of simulated HEC-RAS is stored in .hdf format. To extract the relevant water levels and velocities from the output files, a MATLAB function ‘createtext’ is implemented in the loop. This function imports the ‘.hdf’ output file and extract the water level at desired location in text format, which is then utilized for calibration and validation of the model. Furthermore, the water level at the bridges and weirs is also extracted through this function for the forecasting.

4.5 Historical events

Four historical events were hindcasted using HEC-RAS in this study, covering from the year 2005 in the catchment.

- Event 1: February 2005
- Event 2: May 2006
- Event 3: January 2011
- Event 4: May 2013

4.6 Calibration

Model calibration is the process of estimating the model parameters by comparing model predictions (output) for a given set of assumed conditions with the observed data for the same conditions (Moriaisi et al., 2007). It is the adjustment of a model’s parameters, such as roughness and hydraulic structure coefficients, so that it reproduces observed data to an acceptable accuracy.

The gauge stations Mainleus (MLEU), Schwürbitz (SWBI) and Kemmern (KEMM) are considered as the calibration points for all the events. Out of them, Mainleus is the most important calibration point as it is located directly after the Kulmbach, which is the main area of most interest. For the calibration of the hydrodynamic model, roughness parameterization is very important, as it represents the land use types and distinguished the river bed and flood plains.

To start the calibration, as realistic values for the flood plains and river bed must be selected. The value of Manning’s ‘n’ is highly variable and depends on many factors including, surface roughness, vegetation, channel irregularities, channel alignment, obstructions, size and shape of the channel. Since, it is an empirical value and getting the exact value is not possible, so starting values selected for main channel (river bed) is taken as 0.029 and for flood plain 0.033. The values are extracted from the (US Army Corps of Engineers, 2016b) which provides the review of Manning’s values for different type of streams and flood plains. These excerpts are collected from
the Te Chow, (1959). Furthermore, the author’s visit of the site and previous work done over the same catchment by Seubert, (2017) and Kammereck, (2016) helps to select the suitable range for the calibration.

The prediction performance of the model is evaluated by the comparison between observed and corresponding predicted simulated water levels at different Manning’s values for four different events at the described three-gauge stations. These graphs are compared by the Nash-Sutcliffe Efficiency (NSE) criteria, which is a normalized statistics that determines the closeness of the simulated behaviour to the observed measurements (Moriasi et al., 2007).

\[
NSE = 1 - \frac{\sum_{i=1}^{n}(Y_{i}^{obs} - Y_{i}^{sim})^2}{\sum_{i=1}^{n}(Y_{i}^{obs} - Y_{i}^{mean})^2}
\]  

Where

\(Y_{i}^{obs}\) is the \(i\)th observed value

\(Y_{i}^{sim}\) is the \(i\)th simulated value

\(Y_{i}^{mean}\) is the observed mean values

The NSE values ranges from -infinity to 1 (1 inclusive). NSE value =1 is considered as the best value, while negative values indicate that the mean observed value is the better predictor of the model rather than simulated value. The value ranges from 0.0 to 1.0 are viewed as the acceptable ranges for the model which are showed in Table 4.6-1 (Moriasi et al., 2007).

<table>
<thead>
<tr>
<th>Performance Rating</th>
<th>NSE [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Good</td>
<td>0.75 &lt; NSE ≤ 1.0</td>
</tr>
<tr>
<td>Good</td>
<td>0.65 &lt; NSE ≤ 0.75</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>0.50 &lt; NSE ≤ 0.65</td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>NSE ≤ 0.50</td>
</tr>
</tbody>
</table>

Table 4.6-1 Performance rating for NSE (Moriasi et al., 2007)

Since, the flash flood modelling is the major concern in this study, therefore more attention in calibration is given to fitting of high peaks. Moreover, NSE is not very sensitive for low flows while it shows better fitting at peak values, for that reason it is perfectly fit for this model.

### 4.6.1 Generation of Random Samples

Initially the model calibration was done manually by adjusting the Manning’s coefficients of the river reaches. After getting the nearest possible values and to ensure the results, the 100 random
values are generated for the main channel and flood plain separately. An advantage of HEC-RAS is the possibility to write/change the Manning’s value in text file for both channel and flood plains separately. It can be done through MATLAB automation whose process is explained under the section 4.4.2.4. The following Figure 4.6-1 explained the process the calibration process through MATLAB.

Figure 4.6-1 MATLAB calibration scheme
To run the 100 simulations of HEC-RAS in loop, the geometry file is accessed through MATLAB for each run and it is updated for each set of generated Manning’s values in loop. Afterwards HEC-RAS simulation proceeds to end for each single roughness value. The result files for each run is saved in HDF file format. Only the successful stable run values at the calibration gauge points are separated through MATLAB function which is implemented in the loop. The detailed code is presented in the Appendix A.

4.7 Validation

The validation of the model is performed to check the selected hydraulic roughness parameters are perfectly fit for the model and provide suitable results for the different simulation period. For validation, the observed water level at 8 locations at their respective date and time are compared with the simulated water levels. One important key in the validation is to keep all the parameters at the same values which are obtained in the calibration process. The validation points in the catchment with ‘IDs’ are shown in the following Figure 4.7-1.

Figure 4.7-1 Validation points (Wasserwirtschaftsamt Hof, 2018)
The measured water levels are provided from Wasserwirtschaftsamt Hof (Wasserwirtschaftsamt Hof, 2018). The corresponding cross-sections in HEC-RAS along with the MATLAB find_ID are listed below.

<table>
<thead>
<tr>
<th>ID</th>
<th>Recorded Date &amp; Time</th>
<th>Measured Water Level</th>
<th>River</th>
<th>HEC-RAS Cross-section</th>
<th>MATLAB find_ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14-01-2011 14:09</td>
<td>304.06</td>
<td>White Main</td>
<td>Upper Main 472458</td>
<td>195</td>
</tr>
<tr>
<td>2</td>
<td>14-01-2011 14:18</td>
<td>303.35</td>
<td>White Main</td>
<td>Upper Main 471943</td>
<td>204</td>
</tr>
<tr>
<td>3</td>
<td>14-01-2011 14:23</td>
<td>302.02</td>
<td>White Main</td>
<td>Upper Main 470870</td>
<td>216</td>
</tr>
<tr>
<td>4</td>
<td>14-01-2011 14:26</td>
<td>301.99</td>
<td>Dobrachbach</td>
<td>Upper Main 470770</td>
<td>217</td>
</tr>
<tr>
<td>5</td>
<td>14-01-2011 13:27</td>
<td>297.12</td>
<td>Side canal</td>
<td>Upper Main 468800</td>
<td>238</td>
</tr>
<tr>
<td>6</td>
<td>14-01-2011 14:01</td>
<td>301.35</td>
<td>Mühlkanal</td>
<td>Branch Main -1800</td>
<td>39</td>
</tr>
<tr>
<td>7</td>
<td>14-01-2011 14:35</td>
<td>300.06</td>
<td>Mühlkanal</td>
<td>Branch Main -2750</td>
<td>58</td>
</tr>
<tr>
<td>8</td>
<td>14-01-2011 14:35</td>
<td>300.04</td>
<td>Mühlkanal</td>
<td>Branch Main -2850</td>
<td>61</td>
</tr>
</tbody>
</table>

Table 4.7-1 Water levels for validation

Furthermore, time to peak and peak errors are also calculated along with the travelling time of flood wave reaching from Mainleus to Schwürbitz to Kemmern to get the best fit model.

The travelling times of unreformed flood waves are retrieved from Bayerisches Landesamt Für Umwelt, (2018b) with the approximate travelling distance from gauge to gauge. Since, the study area is limited till Kemmern, so travelling time of flood wave from Kemmern to downstream is not considered for the results.

<table>
<thead>
<tr>
<th>Gauging station</th>
<th>Approx. time (Hrs)</th>
<th>Average time (Hrs)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>From MLEU to SWBI</td>
<td>3.0 to 6.0</td>
<td>4.5</td>
<td>22.81</td>
</tr>
<tr>
<td>From SWBI to KEMM</td>
<td>10 to 20</td>
<td>15</td>
<td>47</td>
</tr>
<tr>
<td>From KEMM to downstream</td>
<td>5</td>
<td>-</td>
<td>12.49</td>
</tr>
</tbody>
</table>

Table 4.7-2 Flood wave travel duration (Bayerisches Landesamt Für Umwelt, 2018b)
The peak error and time to peak are calculated by taking a difference between the observed and simulated values at the same gauging stations i.e. both values (sim. & obs.) of MLEU station are utilized. While to calculate the flood wave travelling time, the difference between the occurring time of peak water levels at MLEU and SWBI is calculated which should be in the range of values provided by Bayerisches Landesamt Für Umwelt, (2018b), presented in Table 4.7-2.
5 RESULTS AND DISCUSSION

The model calibration is initially done for the very coarse range starting from 0.038 \((n_1)\) for flood plains and 0.035 \((n_2)\) for the main channel. The results show the calibration values are somewhere around 0.033 for \(n_1\) and 0.029 for \(n_2\) as described in section 4.6. After the manual calibration MATLAB automated calibration is also performed to confirm the results. Furthermore, it is also being analysed that the HEC-RAS model is very sensitive to changes in Manning’s value, as it also leads to model instability for different values and scenarios. Manual and automated calibration results showed that model gets unstable every time for each scenario whenever either \(n_1 < 0.029\) or \(n_2 < 0.027\). The calibration results and discussion for each event is explained below. The blanked space in the tables represents the model instability.

5.1 February 2005 event

The simulation time for this event is from 11/02/2005 till 20/02/2005. The selection of time is based over the simulated hydrograph obtained after LARSIM simulation. The peak of discharges at different river chainages, mentioned in Table 4.2-1, noted from 13/02/2005 till 14/02/2005. The calibration results for the event are presented in Table 5.1-1.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Manning’s</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n_1)</td>
<td>(n_2)</td>
</tr>
<tr>
<td>1</td>
<td>0.033</td>
<td>0.029</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
<td>0.029</td>
</tr>
<tr>
<td>3</td>
<td>0.030</td>
<td>0.028</td>
</tr>
<tr>
<td>4</td>
<td>0.028</td>
<td>0.027</td>
</tr>
<tr>
<td>5</td>
<td>0.029</td>
<td>0.027</td>
</tr>
<tr>
<td>6</td>
<td>0.030</td>
<td>0.027</td>
</tr>
<tr>
<td>7</td>
<td>0.033</td>
<td>0.027</td>
</tr>
<tr>
<td>8</td>
<td>0.029</td>
<td>0.026</td>
</tr>
<tr>
<td>9</td>
<td>0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>10</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>11</td>
<td>0.029</td>
<td>0.029</td>
</tr>
<tr>
<td>12</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>13</td>
<td>0.033</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Table 5.1-1 Performance criteria of the HEC-RAS model for Feb-2005 event

The obtained Manning’s value is 0.029 for flood plain \((n_1)\) and 0.027 for main channel \((n_2)\) with the best NSE values. The result of calibration at the obtained Manning’s values is shown in the following Figure 5.1-1.
Results and Discussion

Figure 5.1-1 Comparison between simulated and observed water level at three calibration gauges for Feb 2005 event for scenario 5

The results of peak errors, time to peak and travelling time of simulated flood wave are listed below.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Max. Water level (m)</th>
<th>Time to peak (Hrs)</th>
<th>Peak Time</th>
<th>Travelling Time (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLEU</td>
<td>288.21</td>
<td>288.20</td>
<td>-0.01</td>
<td>54.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWBI</td>
<td>268.43</td>
<td>268.23</td>
<td>-0.2</td>
<td>58.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KEMM</td>
<td>236.61</td>
<td>237.07</td>
<td>-0.46</td>
<td>78.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1-2 The time to peak, peak errors and travelling time of flood wave for February 2005 event

5.1.1 Discussion

The outcome of the model is the satisfactory approximation of the measured data with the NSE values presented in Table 5.1-1, along with the simulated flood wave travelling times which also validates the values presented by Bayerisches Landesamt Für Umwelt, (2018b) in Table 4.7-2.
The negative values in the Table 5.1-2 show the over estimation while positive values reflect the under estimation. The possible reason of this over estimation is the difference between LARSIM simulated and observed discharges which prevails from the start of the studied catchment i.e. KOED and goes till end of catchment KEMM as shown in the following Figure 5.1-2 (b).

![Comparison between observed and LARSIM simulated discharges for February 2005 event at (a) Kauerndorf, (b) Ködnitz, (c) Unterzettlitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern](image)

**5.2 May 2006 Event**

The simulation time for this event is from 24/05/2006 till 04/06/2006. The peak of discharges observed from 27/05/2006 till 01/06/2006. The calibration results at different Manning’s values are presented below.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Manning’s</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n₁</td>
<td>n₂</td>
<td>MLEU</td>
<td>SWBI</td>
<td>KEMM</td>
</tr>
<tr>
<td>1</td>
<td>0.033</td>
<td>0.029</td>
<td>0.04</td>
<td>0.46</td>
<td>0.29</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
<td>0.029</td>
<td>0.06</td>
<td>0.47</td>
<td>0.29</td>
</tr>
<tr>
<td>3</td>
<td>0.030</td>
<td>0.028</td>
<td>0.18</td>
<td>0.51</td>
<td>0.27</td>
</tr>
<tr>
<td>4</td>
<td>0.028</td>
<td>0.027</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.029</td>
<td>0.027</td>
<td>0.30</td>
<td>0.53</td>
<td>0.29</td>
</tr>
</tbody>
</table>
Results and Discussion

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0.030</td>
<td>0.027</td>
<td>0.29</td>
<td>0.53</td>
<td>0.29</td>
</tr>
<tr>
<td>7</td>
<td>0.033</td>
<td>0.027</td>
<td>0.28</td>
<td>0.53</td>
<td>0.29</td>
</tr>
<tr>
<td>8</td>
<td>0.029</td>
<td>0.026</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>0.027</td>
<td>0.027</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.028</td>
<td>0.028</td>
<td>0.07</td>
<td>0.47</td>
<td>0.29</td>
</tr>
<tr>
<td>11</td>
<td>0.029</td>
<td>0.029</td>
<td>0.28</td>
<td>0.35</td>
<td>0.29</td>
</tr>
<tr>
<td>12</td>
<td>0.032</td>
<td>0.032</td>
<td>-0.5</td>
<td>0.16</td>
<td>0.29</td>
</tr>
<tr>
<td>13</td>
<td>0.033</td>
<td>0.033</td>
<td>-0.5</td>
<td>0.16</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 5.2-1 Performance criteria of the HEC-RAS model for May 2006 event

The obtained Manning’s value is 0.029 for flood plain (\(n_1\)) and 0.027 for main channel (\(n_2\)) with the best NSE values. The results of calibration at the obtained Manning’s values are shown in the following Figure 5.2-1.

Figure 5.2-1Comparison between simulated and observed water level at three calibration gauges for May 2006 event for scenario 5
Results and Discussion

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Max. Water level (m)</th>
<th>Time to peak (Hrs)</th>
<th>Peak Time</th>
<th>Travelling Time (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLEU</td>
<td>288.12</td>
<td>288.94</td>
<td>111</td>
<td>109.75</td>
</tr>
<tr>
<td>SWBI</td>
<td>267.16</td>
<td>267.99</td>
<td>124.5</td>
<td>113</td>
</tr>
<tr>
<td>KEMM</td>
<td>235.26</td>
<td>236.05</td>
<td>151.25</td>
<td>121</td>
</tr>
</tbody>
</table>

Table 5.2-2 The time to peak, peak errors and travelling time of flood wave for May 2006 event

5.2.1 Discussion

The outcome of the model for this event is a satisfactory approximation of measured data with the NSE values presented in Table 5.2-1. With the comparison of simulated travelling time of flood wave with the values presented in Table 4.7-2, it is cleared that time of flood wave from MLEU to SWBI is well in the range with the value of 3.25 Hrs with the minimum travelling time of 3 hours. On the other hand, the travelling time from SWBI to KEMM is 8 hours showing under estimation of 2 hours in comparison to the measured minimum travelling time of 10 hours. Along with that there is overestimation of peak water level at all the calibration gauges.

The possible reason of this behaviour is the under estimation of peak in LARSIM simulated data in comparison to the measured data starting from KOED till KEMM as shown in Figure 5.2-2. Since, KEMM is last study point of the projected catchment, so it’s good overview point to show the difference between the observed and LARSIM simulated data (HEC-RAS input). The difference at KEMM is shown separately in Figure 5.2-3. LARSIM peak discharge (228.6 m$^3$/s) is observed at May 30, 2006 10:00, while the measured peak discharge (278.3 m$^3$/s) occurred at May 30, 2006 08:00. The difference between the peak discharge and in occurring time is 50 m$^3$/s and 2 hrs respectively, which is the possible reason of flood wave reaching 2 hours earlier than expected.
Results and Discussion

Figure 5.2-2 Comparison between observed and LARSIM simulated discharges for May 2006 event at (a) Kauendorf, (b) Ködnitz, (c) Unterzettltitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern

Figure 5.2-3 Comparison between observed and LARSIM simulated discharges for May 2006 event at KEMM
5.3 January 2011 event

The simulation time for this event is from 07/01/2011 till 20/01/2011. In this event two peaks are noticed. The first smaller peak noted from 08/01/2011 till 10/01/2011, while the other peak observed from 12/01/2011 till 14/01/2011. This event appeared to be most sensitive to the changes in the Manning’s values. Model gets unstable for every value lower than 0.32 either for main channel or flood plain. The abrupt and high change in the input data is the possible reason of instability of the model. The calibration results at different Manning’s values are presented below.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Manning’s</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n₁</td>
<td>n₂</td>
</tr>
<tr>
<td>1</td>
<td>0.033</td>
<td>0.029</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
<td>0.029</td>
</tr>
<tr>
<td>3</td>
<td>0.030</td>
<td>0.028</td>
</tr>
<tr>
<td>4</td>
<td>0.028</td>
<td>0.027</td>
</tr>
<tr>
<td>5</td>
<td>0.029</td>
<td>0.027</td>
</tr>
<tr>
<td>6</td>
<td>0.030</td>
<td>0.027</td>
</tr>
<tr>
<td>7</td>
<td>0.033</td>
<td>0.027</td>
</tr>
<tr>
<td>8</td>
<td>0.029</td>
<td>0.026</td>
</tr>
<tr>
<td>9</td>
<td>0.027</td>
<td>0.027</td>
</tr>
<tr>
<td>10</td>
<td>0.028</td>
<td>0.028</td>
</tr>
<tr>
<td>11</td>
<td>0.029</td>
<td>0.029</td>
</tr>
<tr>
<td>12</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>13</td>
<td>0.033</td>
<td>0.033</td>
</tr>
</tbody>
</table>

Table 5.3-1 Performance criteria of the HEC-RAS model for Jan-2011 event

The obtained Manning’s value is 0.032 for flood plain n₁ and 0.032 for main channel n₂ with the best possible NSE values. The results of calibration at the obtained Manning’s values are shown in the following Figure 5.3-1.
Results and Discussion

Similarly, the peak errors, time to peak and flood wave travelling time are presented below.

<table>
<thead>
<tr>
<th>Gauge</th>
<th>Max. Water level (m)</th>
<th>Time to peak (Hrs)</th>
<th>Peak Time</th>
<th>Travelling Time (Hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLEU</td>
<td>288.19</td>
<td>292.95</td>
<td>-4.76</td>
<td>177.5</td>
</tr>
<tr>
<td>SWBI</td>
<td>268.44</td>
<td>272.78</td>
<td>-4.34</td>
<td>189.25</td>
</tr>
<tr>
<td>KEMM</td>
<td>236.88</td>
<td>245.04</td>
<td>-8.16</td>
<td>202</td>
</tr>
</tbody>
</table>

Table 5.3-2 The time to peak, peak errors and travelling time of flood wave for January 2011 event

5.3.1 Discussion

The outcome of the model for this event is not a good approximation of measured data with the NSE values presented in Table 5.3-1. Though the simulated flood wave travelling time is well in the range of average values (Table 4.7-2), but there is big difference in the observed and simulated peak water levels. The peak errors observed to be maximum at the gauging station KEMM. Since the output of LARSIM is the input of HEC-RAS model, so the bad estimation LARSIM simulated...
Results and Discussion

data in comparison to the measured data, is the possible reason of high peak errors which prevails from the starting gauge KOED. The difference between the discharges is observed at the same rate in the coming gauges too i.e. UZET, MLEU, SWBI and KEMM as shown in Figure 5.3-2. Since, KEMM is last study point of the projected catchment, so it’s good overview point to show the difference between the observed and LARSIM simulated data (HEC-RAS input). The difference at KEMM is shown separately in Figure 5.3-3.

As there are two peaks in the simulation period, it can be seen from the following Figure 5.3-3 that LARSIM maximum discharge at smaller peak is 337.4 m$^3$/s, observed at Jan 11, 2011 01:00. While the observed maximum discharge is 513 m$^3$/s, noted at Jan 10, 2011 01:00, which shows the under estimation of simulated discharges by 175.6 m$^3$/s. This under estimation of discharges surely contributes in the peak difference that started from Jan 14, 2011 as shown in Figure 5.3-1 and in Table 5.3-2.

The LARSIM maximum discharge at the higher peak is 891.1 m$^3$/s at Jan 15, 2011, 23:00 in comparison to the maximum discharge of 577 m$^3$/s in the observed data at Jan 15, 2011 10:00. This over estimation of 314.1 m$^3$/sec resulted the high peak errors. The abrupt and high changes in the input data also causes to get model unstable at lower Manning’ value. The comparison between observed and LARSIM simulated discharges at KEMM is shown in Figure 5.3-3.

![Figure 5.3-2 Comparison between observed and LARSIM simulated discharges for January 2011 event at (a) Kauernordorf, (b) Ködnitz, (c) Unterzettlitz, (d) Mainleus, (e) Schwürbitz, (f) Kemmern](image-url)
Results and Discussion

Figure 5.3-3 Comparison between Observed and LARSIM simulated discharges for January 2011 event at KEMM

Furthermore, the travelling distance between the gauges increase the possibility of getting numerical and measured data errors, which ultimately contributes in the peak errors. As the travelling distance of flood wave from SWBI to KEMM is almost the double of MLEU to SWBI distance (Table 4.7-2), it also increases the sources of uncertainty in the input data coming in the form of lateral inflows from the sub-catchments. The total number of lateral inflows from MLEU to SWBI is 7, while from SWBI to KEMM the number increases to 14 (Table 4.2-1). The peak water level error at KEMM station is also observed almost the double of MLEU station. It can be deduced from the scenario that the HEC-RAS output highly depends over the input coming from hydrological model (LARSIM).

5.4 May 2013 event

The simulation time for this event is from 24/05/2013 till 31/05/2013. The peak of discharges observed from 28/05/2013 till 30/05/2013. The calibration results at different Manning’s values are presented below Table 5.4-1.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Manning’s</th>
<th>NSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n1</td>
<td>n2</td>
</tr>
<tr>
<td>1</td>
<td>0.033</td>
<td>0.029</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
<td>0.029</td>
</tr>
<tr>
<td>3</td>
<td>0.030</td>
<td>0.028</td>
</tr>
</tbody>
</table>
Results and Discussion

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.028</td>
<td>0.027</td>
<td>0.31</td>
<td>0.54</td>
<td>0.46</td>
</tr>
<tr>
<td>5</td>
<td>0.029</td>
<td>0.027</td>
<td>0.33</td>
<td>0.56</td>
<td>0.46</td>
</tr>
<tr>
<td>6</td>
<td>0.030</td>
<td>0.027</td>
<td>0.33</td>
<td>0.56</td>
<td>0.44</td>
</tr>
<tr>
<td>7</td>
<td>0.033</td>
<td>0.027</td>
<td>0.33</td>
<td>0.56</td>
<td>0.46</td>
</tr>
<tr>
<td>8</td>
<td>0.029</td>
<td>0.026</td>
<td>-0.01</td>
<td>0.36</td>
<td>0.46</td>
</tr>
<tr>
<td>9</td>
<td>0.027</td>
<td>0.027</td>
<td>0.01</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>10</td>
<td>0.028</td>
<td>0.028</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>0.029</td>
<td>0.029</td>
<td>0.33</td>
<td>0.63</td>
<td>0.47</td>
</tr>
<tr>
<td>12</td>
<td>0.032</td>
<td>0.032</td>
<td>0.52</td>
<td>0.77</td>
<td>0.47</td>
</tr>
<tr>
<td>13</td>
<td>0.033</td>
<td>0.033</td>
<td>0.51</td>
<td>0.77</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Table 5.4-1 Performance criteria of the HEC-RAS model for May 2013 event

The results of calibration at the obtained Manning’s values are shown in the following Figure 5.4-1.

![Figure 5.4-1 Comparison between simulated and observed water level at three calibration gauges for May-2013 event for scenario 12](image)

Similarly, time to peak, peak errors and flood wave travelling time are also calculated for this event and presented in Table 5.4-2.
### 5.4.1 Discussion

The outcome of the model for this event is satisfactory approximation of measured data with the NSE values presented in Table 5.4-1. With the comparison of simulated travelling time of flood wave with the measured values presented in Table 4.7-2, it is cleared that travelling time of flood wave from MLEU to SWBI is well in the range while for SWBI to KEMM it is under estimated by 3.5 hours from minimum and by 9.5 hours from the average travelling time. The possible reason of this behaviour is the under estimation of peak in LARSIM simulated data in comparison to the measured data which starts from KOED and goes till KEMM which is shown in Figure 5.4-2.

Since, KEMM is considered as the over view point. The LARSIM peak discharge (182 m³/s) is observed at May 29, 2013 04:00, while the measured peak discharge (246.5 m³/s) occurred at May 29, 2013 13:00. The difference between the peak discharge and in occurring time shows the under estimation of 64.5 m³/s and 9 Hrs respectively. This under estimation of the simulated wave reflected in the results of travelling time from SWBI to KEMM, where it is under estimated by 9.5 hours from the average travelling time. From this scenario and May 2006 scenario, it can be seen that the under estimation of peak discharges, effects the flood wave travelling time. The comparison of observed discharges and LARSIM simulated discharges at KEMM are shown below in Figure 5.4-3.
Results and Discussion

Figure 5.4-2 Comparison between observed and LARSIM simulated discharges for May 2013 event at KARD (a), KOD (b), UZET (c), MLEU (d), SWBI (e), KEMM (f)

Figure 5.4-3 Comparison between Observed and LARSIM simulated discharges at KEMM for May 2013
Results and Discussion

5.5 Results validation

For the validation of the model, the comparison of measured water level and simulated water level is done at the respective date and time. Some of the validation values shows big difference because of the explained reasons under the sections 5.2.1, 5.3.1 & 5.4.1. The points of validation and process is explained under the section 4.7. The validation of the model is done against the LARSIM discharge as well as with the observed discharge of ködnitz and kaurendorf. This is done to validate the assumption that most of the errors are coming from hydrological model. For that purpose, the input data (discharge) of KOED and KARD is changed to observed values, while the uniform lateral inflows (MLEU) coming from LARSIM are also removed to get better approximation about the performance of hydraulic model.

<table>
<thead>
<tr>
<th>ID</th>
<th>Recorded Date &amp; Time</th>
<th>Measured Water Level (m)</th>
<th>HEC-RAS Water Level (m)</th>
<th>Difference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14-01-2011 14:09</td>
<td>304.06</td>
<td>305.01</td>
<td>-95</td>
</tr>
<tr>
<td>2</td>
<td>14-01-2011 14:18</td>
<td>303.35</td>
<td>304.12</td>
<td>-77</td>
</tr>
<tr>
<td>3</td>
<td>14-01-2011 14:23</td>
<td>302.02</td>
<td>302.84</td>
<td>-82</td>
</tr>
<tr>
<td>4</td>
<td>14-01-2011 14:26</td>
<td>301.99</td>
<td>302.72</td>
<td>-73</td>
</tr>
<tr>
<td>5</td>
<td>14-01-2011 13:27</td>
<td>297.12</td>
<td>299.67</td>
<td>-255</td>
</tr>
<tr>
<td>6</td>
<td>14-01-2011 14:01</td>
<td>301.35</td>
<td>301.20</td>
<td>15</td>
</tr>
<tr>
<td>7</td>
<td>14-01-2011 14:35</td>
<td>300.06</td>
<td>300.93</td>
<td>-87</td>
</tr>
<tr>
<td>8</td>
<td>14-01-2011 14:35</td>
<td>300.04</td>
<td>300.93</td>
<td>-89</td>
</tr>
</tbody>
</table>

Table 5.5-1 Validation of model results with LARSIM discharge

<table>
<thead>
<tr>
<th>ID</th>
<th>Recorded Date &amp; Time</th>
<th>Measured Water Level (m)</th>
<th>HEC-RAS Water Level (m)</th>
<th>Difference (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14-01-2011 14:09</td>
<td>304.06</td>
<td>304.18</td>
<td>-12</td>
</tr>
<tr>
<td>2</td>
<td>14-01-2011 14:18</td>
<td>303.35</td>
<td>303.37</td>
<td>-2</td>
</tr>
<tr>
<td>3</td>
<td>14-01-2011 14:23</td>
<td>302.02</td>
<td>302.11</td>
<td>-9</td>
</tr>
<tr>
<td>4</td>
<td>14-01-2011 14:26</td>
<td>301.99</td>
<td>302.03</td>
<td>-4</td>
</tr>
<tr>
<td>5</td>
<td>14-01-2011 13:27</td>
<td>297.12</td>
<td>298.45</td>
<td>-133</td>
</tr>
<tr>
<td>6</td>
<td>14-01-2011 14:01</td>
<td>301.35</td>
<td>301.15</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>14-01-2011 14:35</td>
<td>300.06</td>
<td>300.22</td>
<td>-16</td>
</tr>
<tr>
<td>8</td>
<td>14-01-2011 14:35</td>
<td>300.04</td>
<td>300.21</td>
<td>-17</td>
</tr>
</tbody>
</table>

Table 5.5-2 Validation of model results with observed discharge KOED & KEMM
Results and Discussion

From the comparison of Table 5.5-1 & Table 5.5-2, there is significant improvement in validation values and it can be deduced that main reason of high differences between the measured and simulated water levels is due to the hydrological model results. In the meanwhile, it is not recommended to use only observed discharge values to fetch the water level through HEC-RAS as it doesn’t include the many hydrological factors that affect the water balance of the catchment.

5.6 Bridges and Weirs

The flood forecasting tool developed over MATLAB, as explained under the section 4.4, further extended over the infrastructural objects of the catchment i.e. weirs and bridges. This extension enables the user to get the water level at the selected bridges or weirs. The location of bridges is incorporated in the same function ‘createtext’, where location of calibration and validation points are specified. As per schematic plots shown in Figure 4.4-1 and Figure 4.6-1, the water level at the selected bridges can be plotted with best NSE valued Manning’s numbers.

The following table depicted about all the weirs and bridges present in the area along with the relative location in the HEC-RAS model with cross-section name and MATLAB Find_ID. The location of bridges and weirs are pointed out through their coordinates. Relative river chainages are also presented in the table, which may or may not be same as HEC-RAS cross section number. The cross-section ID/Find_ID, is important to extract the data through MATLAB from HEC_RAS HDF system file. A detailed code is presented in Appendix A which explained how to extract the water levels and velocities at the specific bridge or weir.

<table>
<thead>
<tr>
<th>ID</th>
<th>Category</th>
<th>River chainage [meter]</th>
<th>HEC-RAS Cross-section</th>
<th>MATLAB Find_ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Weir</td>
<td>1446</td>
<td>Schorgast, -1450</td>
<td>141</td>
</tr>
<tr>
<td>2</td>
<td>Weir</td>
<td>472256</td>
<td>Upper Main 472270</td>
<td>199</td>
</tr>
<tr>
<td>3</td>
<td>Weir</td>
<td>468446</td>
<td>Upper Main 468460</td>
<td>244</td>
</tr>
<tr>
<td>4</td>
<td>Weir</td>
<td>460770</td>
<td>Upper Main 460799</td>
<td>327</td>
</tr>
<tr>
<td>5</td>
<td>Weir</td>
<td>457062</td>
<td>Upper Main 457102.3</td>
<td>352</td>
</tr>
<tr>
<td>6</td>
<td>Weir</td>
<td>447958</td>
<td>Upper Main 447996.7</td>
<td>398</td>
</tr>
<tr>
<td>7</td>
<td>Weir</td>
<td>445227</td>
<td>Upper Main 445215.7</td>
<td>414</td>
</tr>
<tr>
<td>8</td>
<td>Weir</td>
<td>441825</td>
<td>Upper Main 441771.2</td>
<td>438</td>
</tr>
<tr>
<td>9</td>
<td>Weir</td>
<td>432636</td>
<td>Upper Main 432637.0</td>
<td>486</td>
</tr>
<tr>
<td>10</td>
<td>Weir</td>
<td>429899</td>
<td>Upper Main 429916.9</td>
<td>505</td>
</tr>
<tr>
<td>11</td>
<td>Weir</td>
<td>422218</td>
<td>Upper Main 422238.9</td>
<td>548</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>12</td>
<td>Bridge</td>
<td>466289</td>
<td>Upper Main 466300.0</td>
<td>272</td>
</tr>
<tr>
<td>13</td>
<td>Bridge</td>
<td>466897</td>
<td>Upper Main 466900.0</td>
<td>266</td>
</tr>
<tr>
<td>14</td>
<td>Bridge</td>
<td>467587</td>
<td>Upper Main 467600.0</td>
<td>259</td>
</tr>
<tr>
<td>15</td>
<td>Bridge</td>
<td>468793</td>
<td>Upper Main 468786.0</td>
<td>239</td>
</tr>
<tr>
<td>16</td>
<td>Bridge</td>
<td>470107</td>
<td>Upper Main 470170.0</td>
<td>223</td>
</tr>
<tr>
<td>17</td>
<td>Bridge</td>
<td>3178</td>
<td>Branch Main -3185</td>
<td>70</td>
</tr>
<tr>
<td>18</td>
<td>Bridge</td>
<td>471949</td>
<td>Upper Main 471957.0</td>
<td>203</td>
</tr>
<tr>
<td>19</td>
<td>Bridge</td>
<td>472386</td>
<td>Upper Main 472383.0</td>
<td>197</td>
</tr>
<tr>
<td>20</td>
<td>Bridge</td>
<td>472464</td>
<td>Upper Main 472458.0</td>
<td>195</td>
</tr>
<tr>
<td>21</td>
<td>Bridge</td>
<td>472484</td>
<td>Upper Main 472472.0</td>
<td>193</td>
</tr>
<tr>
<td>22</td>
<td>Bridge</td>
<td>472890</td>
<td>Upper Main 472870.0</td>
<td>190</td>
</tr>
<tr>
<td>23</td>
<td>Bridge</td>
<td>472975</td>
<td>Upper Main 472949.0</td>
<td>189</td>
</tr>
<tr>
<td>24</td>
<td>Bridge</td>
<td>473018</td>
<td>Upper Main 473028.0</td>
<td>187</td>
</tr>
<tr>
<td>25</td>
<td>Bridge</td>
<td>474611</td>
<td>Upper Main 474528.0</td>
<td>172</td>
</tr>
<tr>
<td>26</td>
<td>Bridge</td>
<td>476436</td>
<td>Upper Main 476078.</td>
<td>153</td>
</tr>
<tr>
<td>27</td>
<td>Bridge</td>
<td>478909</td>
<td>Upper Main 476228.0</td>
<td>150</td>
</tr>
<tr>
<td>28</td>
<td>Bridge</td>
<td>1350</td>
<td>Branch Main -1350</td>
<td>30</td>
</tr>
<tr>
<td>29</td>
<td>Bridge</td>
<td>1650</td>
<td>Branch Main -1650</td>
<td>36</td>
</tr>
<tr>
<td>30</td>
<td>Bridge</td>
<td>1800</td>
<td>Branch Main -1800</td>
<td>39</td>
</tr>
<tr>
<td>31</td>
<td>Bridge</td>
<td>2300</td>
<td>Branch Main -2300</td>
<td>50</td>
</tr>
<tr>
<td>32</td>
<td>Bridge</td>
<td>2500</td>
<td>Branch Main -2500</td>
<td>53</td>
</tr>
<tr>
<td>33</td>
<td>Bridge</td>
<td>2850</td>
<td>Branch Main -2850</td>
<td>61</td>
</tr>
<tr>
<td>34</td>
<td>Bridge</td>
<td>3091</td>
<td>Branch Main -3091</td>
<td>67</td>
</tr>
<tr>
<td>35</td>
<td>Bridge</td>
<td>850</td>
<td>Schorgast -850</td>
<td>126</td>
</tr>
<tr>
<td>36</td>
<td>Bridge</td>
<td>389956</td>
<td>Upper Main 390014.4</td>
<td>862</td>
</tr>
<tr>
<td>37</td>
<td>Bridge</td>
<td>391510</td>
<td>Upper Main 391248.8</td>
<td>849</td>
</tr>
<tr>
<td>38</td>
<td>Bridge</td>
<td>391520</td>
<td>Upper Main 391434.5</td>
<td>848</td>
</tr>
<tr>
<td>39</td>
<td>Bridge</td>
<td>397062</td>
<td>Upper Main 397068.2</td>
<td>784</td>
</tr>
<tr>
<td>40</td>
<td>Bridge</td>
<td>400436</td>
<td>Upper Main 400436.8</td>
<td>749</td>
</tr>
<tr>
<td>41</td>
<td>Bridge</td>
<td>403770</td>
<td>Upper Main 403774.0</td>
<td>719</td>
</tr>
<tr>
<td>42</td>
<td>Bridge</td>
<td>404690</td>
<td>Upper Main 404700.2</td>
<td>705</td>
</tr>
<tr>
<td>43</td>
<td>Bridge</td>
<td>408804</td>
<td>Upper Main 408856.3</td>
<td>654</td>
</tr>
<tr>
<td>44</td>
<td>Bridge</td>
<td>415550</td>
<td>Upper Main 415551.9</td>
<td>594</td>
</tr>
<tr>
<td>45</td>
<td>Bridge</td>
<td>415778</td>
<td>Upper Main 415695.7</td>
<td>592</td>
</tr>
<tr>
<td>46</td>
<td>Bridge</td>
<td>419805</td>
<td>Upper Main 419812.2</td>
<td>563</td>
</tr>
</tbody>
</table>
### Results and Discussion

<table>
<thead>
<tr>
<th>Location</th>
<th>Model ID</th>
<th>ID</th>
<th>Location</th>
<th>Model ID</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>Bridge</td>
<td>422228</td>
<td>Upper Main</td>
<td>42238.9</td>
<td>548</td>
</tr>
<tr>
<td>48</td>
<td>Bridge</td>
<td>425134</td>
<td>Upper Main</td>
<td>425014.8</td>
<td>533</td>
</tr>
<tr>
<td>49</td>
<td>Bridge</td>
<td>426024</td>
<td>Upper Main</td>
<td>425985.5</td>
<td>528</td>
</tr>
<tr>
<td>50</td>
<td>Bridge</td>
<td>429642</td>
<td>Upper Main</td>
<td>429645.9</td>
<td>509</td>
</tr>
<tr>
<td>51</td>
<td>Bridge</td>
<td>429771</td>
<td>Upper Main</td>
<td>429772.1</td>
<td>507</td>
</tr>
<tr>
<td>52</td>
<td>Bridge</td>
<td>431214</td>
<td>Upper Main</td>
<td>431167.3</td>
<td>497</td>
</tr>
<tr>
<td>53</td>
<td>Bridge</td>
<td>432547</td>
<td>Upper Main</td>
<td>432535.3</td>
<td>488</td>
</tr>
<tr>
<td>54</td>
<td>Bridge</td>
<td>438007</td>
<td>Upper Main</td>
<td>437907.4</td>
<td>457</td>
</tr>
<tr>
<td>55</td>
<td>Bridge</td>
<td>441617</td>
<td>Upper Main</td>
<td>441681.5</td>
<td>439</td>
</tr>
<tr>
<td>56</td>
<td>Bridge</td>
<td>443030</td>
<td>Upper Main</td>
<td>443044.5</td>
<td>431</td>
</tr>
<tr>
<td>57</td>
<td>Bridge</td>
<td>443208</td>
<td>Upper Main</td>
<td>443235.5</td>
<td>430</td>
</tr>
<tr>
<td>58</td>
<td>Bridge</td>
<td>444010</td>
<td>Upper Main</td>
<td>444024.7</td>
<td>426</td>
</tr>
<tr>
<td>59</td>
<td>Bridge</td>
<td>445009</td>
<td>Upper Main</td>
<td>445031.9</td>
<td>418</td>
</tr>
<tr>
<td>60</td>
<td>Bridge</td>
<td>446058</td>
<td>Upper Main</td>
<td>446026.7</td>
<td>409</td>
</tr>
<tr>
<td>61</td>
<td>Bridge</td>
<td>447612</td>
<td>Upper Main</td>
<td>447608.7</td>
<td>401</td>
</tr>
<tr>
<td>62</td>
<td>Bridge</td>
<td>451129</td>
<td>Upper Main</td>
<td>451173.9</td>
<td>379</td>
</tr>
<tr>
<td>63</td>
<td>Bridge</td>
<td>451969</td>
<td>Upper Main</td>
<td>451953.4</td>
<td>377</td>
</tr>
<tr>
<td>64</td>
<td>Bridge</td>
<td>453665</td>
<td>Upper Main</td>
<td>453618.5</td>
<td>368</td>
</tr>
<tr>
<td>65</td>
<td>Bridge</td>
<td>456834</td>
<td>Upper Main</td>
<td>456896.6</td>
<td>353</td>
</tr>
<tr>
<td>66</td>
<td>Bridge</td>
<td>459287</td>
<td>Upper Main</td>
<td>459241.6</td>
<td>341</td>
</tr>
<tr>
<td>67</td>
<td>Bridge</td>
<td>460631</td>
<td>Upper Main</td>
<td>460610</td>
<td>329</td>
</tr>
<tr>
<td>68</td>
<td>Bridge</td>
<td>460938</td>
<td>Upper Main</td>
<td>460924.6</td>
<td>326</td>
</tr>
<tr>
<td>69</td>
<td>Bridge</td>
<td>464475</td>
<td>Upper Main</td>
<td>464400.0</td>
<td>292</td>
</tr>
<tr>
<td>70</td>
<td>Bridge</td>
<td>464917</td>
<td>Upper Main</td>
<td>464880</td>
<td>288</td>
</tr>
<tr>
<td>71</td>
<td>Bridge</td>
<td>465172</td>
<td>Upper Main</td>
<td>465200.0</td>
<td>284</td>
</tr>
<tr>
<td>72</td>
<td>Bridge</td>
<td>465655</td>
<td>Upper Main</td>
<td>465700.0</td>
<td>279</td>
</tr>
<tr>
<td>73</td>
<td>Bridge</td>
<td>6918</td>
<td>Roter Main</td>
<td>-7110</td>
<td>105</td>
</tr>
<tr>
<td>74</td>
<td>Bridge</td>
<td>3880</td>
<td>Roter Main</td>
<td>-5560</td>
<td>71</td>
</tr>
</tbody>
</table>

Table 5.6-1 Location of bridges and weirs in Upper Main catchment with Model ID’s
6 SUMMARY AND OUTLOOK

In this study, the HEC-RAS model is developed through existing MIKE 11 model along with the flood forecasting tool over the MATLAB. Stable HEC-RAS model is necessary for all the events to get water level forecasting. Stability of the model is dependent over the many factors like cross-section spacing and numbers, hydraulic parameters, computation time step, type of flow (sub critical, super critical), ineffective flow areas and downstream boundary conditions. To get the stable model, modeller needs to understand the HEC-RAS background working, as sometimes it is necessary to change two or three parameters simultaneously.

The performance of the Hydraulic model is dependent over the provided data like boundary conditions, topographical data and highly over the simulated discharge data coming from the Hydrological model. The difference between the measured discharges and simulated discharges (LARSIM) leads to the various problems including model stability, model performance and less NSE value. HEC-RAS model is appeared to be sensitive with roughness parameters (Manning’s values). Too low Manning’s values cause the instabilities in the model because of rapid change in discharge and higher velocities. All these factors ultimately lead to model instability. Furthermore, the stability of model procedure change for events to events, as it is strongly dependent over the input which is different for each event. HEC-RAS likes things to change gradually, if something is changing drastically i.e. sudden increase or decrease in flow/stage over short time span or significant change in size and shape of main channel from cross-section to cross-section, it would lead to model instabilities and requires one or more steps to stabilize the model, as explained in B HEC-RAS Stabilization Flow Chart

The model performance is accessed with Nash-Sutcliffe Efficiency (NSE), which predicts the peak water level more accurately, which is utmost required for flash flood forecasting. Some other parameters like peak errors and travelling time of flood wave from one measuring station to next one is also measured. These factors are affected by the distance between the measuring stations and amount of lateral inflows coming from the sub-catchments. As these lateral inflows (discharges) are calculated through hydrological modelling, the model errors in the hydrological model makes difficult to get best-fit model. Furthermore, the travelling distance from gauge to gauge increase the possibility of getting numerical and measured data errors. It can be deduced from all the discussed scenarios that the performance of HEC-RAS model is highly dependent on the input coming from LARSIM (hydrological model).

Infrastructure of any city including bridges and weirs are the important part in the flood risk management plans, which is a process of decision making under uncertainty. The study is extended to develop the flood forecasting tool which can provide the water levels and velocities at all bridges of the catchment which would serve as an early warning system for the floods.
6.1 Outlook

There is scope of improvement in both the developed hydraulic model as well as flood forecasting tool, as the lot of experience is required in hydrodynamic modelling to fetch best possible results. Hydraulic model results can be improved by implementing the good hydrological model results. As from the results and validation section, it is recommended to check the LARSIM model from the Ködnitz (KOED) till Mainleus (MLEU), since it is the start of the catchment and prevailing differences between the discharges effects the validation results and causing instabilities in the hydraulic model. While the model for different events shows good approximation of NSE value as well as flood wave travelling time at gauge Schwürbitz (SWBI). Furthermore, the LARSIM model should be checked from SWBI till Kemmern (KEMM), because of the travelling distance and maximum number of lateral inflows which possibly leads towards the uncertainty in the model input data. The flood wave travelling distance analysis between the gauges encourages over the more calibration points between the gauges, as it will help to single out the problem area in the hydrological as well as in hydraulic modelling.

In one-dimensional flow routing, flow through the river channel and the floodplains is treated only in the longitudinal direction parallel to the conduit. Even though, the flow in a natural channel is never truly 1-D, these flow models were found to deliver acceptable results for predicted hydraulic parameters in many applications (Hu & Walton, 2008). This can create difficulties when multiple flow directions are required or when the flow exchange between the channel and the floodplain cannot be neglected. Since, the upper main passes through the urban areas like Kulmbach and consisted on many inline structures i.e. bridges and weirs. It is recommended to develop 1D-2D coupled model which consisted of 1-D channel with 2-D floodplain areas modelling. The coupled model allows the user to get the more parameters along with water surface elevations i.e. average velocities, detailed velocities in two dimensions at specific locations, which can further use for the analysis of the bridges present (US Army Corps of Engineers, 2016a).

In this study, constant Manning’s value is used for the entire reach which is a big assumption, as in reality it changes for different land-use types. In future varying Manning’s value for different reaches, based on the available land-use maps and detailed digital elevation model (DEM), can be accessed and utilized in the improvement of hydraulic model. Since, Manning’s is an empirical value, a correlation analysis can be carried out between the stable and field work Manning’s values along with the uncertainty analysis through GLUE method to find out best fit roughness parameter.

Inundation mapping through the water surface profile results from the flood event model provides a preliminary assessment of flood hazard and provides insight for the emergency preparedness, which can be compared with the flood inundation maps prepared through remote sensing. By the combination of these two approaches, the possible improvement in quality and accuracy of the
inundation maps can be achieved. While this comparison is subject to the availability of satellite data of the studied catchment. Furthermore, the inundation depth considered as the most important parameter for the damage estimation. As the next step flood depth-damage functions can be established which can determine the flood damage that would occur at specific water depths per asset or per land-use class using depth-damage curves. Later, the flood risk and flood hazard maps can be computed for the better overview.

Additionally, no structures have been implemented in the model. Only the bridge locations have been entered and results are extracted through the model. The modelling of the bridges and weirs can be done for more accurate results and to check the effects of them over flood wave i.e. back water effect. Furthermore, the velocity through the bridges and its consequential effects over the bridge piers can be investigated.

An GUI (Graphical User Interface) of flood forecasting tool can be implemented to make it easier for the future user. As the preparation of input data can be hard for the user with less experience with MATLAB interface. Though the MATLAB script is developed as user-friendly as it can be with the supported instructions. For the real-time forecasting, the MATLAB tool can be enhanced by which it can accessed directly the real-time input data (discharge) from the hydrological model. The MATLAB tool can be incorporated with parallel computing program to speed up the processing time with multiple runs.

Regarding the real-time flood forecasting at specified bridges, the forecasted results can be extracted by specifying the bridge location through ‘MATLAB_find_ID’, presented in Table 5.6-1, which would serve as the early warning system for the floods and help to find out the areas at risk and evacuate in time.
7 REFERENCES


Appendix


Appendix

8 Appendix

A MATLAB Code

FloodEvac tool: Run 1D hydraulic model HECRAS 5.04

%Problem in running on the server so please run local

%Workflow

%1. Assign right time and date for LARSIM model and get output Q1 and Out
%for each separate event
%2. Define all the inflows from LARSIM data (Q1 and out)
%3. Change unsteady, plan, geometry and project files and update it
%4. Define output list: Find chainages of Mainleus, Lichtenfels, Schwürbitz
%   Kemmern for calibration, along with Validation locations
%5. Change Manning’s ‘n’ in a range automatically and run Hecras in loop and compare results
%6. Load and extract observed relevant data
%6. Check NSE values and plot with best extracted NSE value against
%   observed data and compare
%7. Define output locations of all beidges and weirs.

% Events
%1. February 2005
%2. May 2006
%3. January 2011
%4. May 2013

%% Observed Data Extraction

[num,txt,raw] = xlsread('D:\Back_Up_Projekt\HEC-RAS_1D\Input_Data\pegel.xlsx'); %Load input data
x =txt(2:end,1);
x1=datestr(x); % convert into Char values
d = datetime(x1,'InputFormat','dd-MM-yyyy HH:mm:ss'); % Writing the homogenous format

%% Save and Load separated observed data
load('obs_data'); % To save time

%% Input parameters for LARSIM & HEC-RAS
filepath = 'F:\Study\study_projectFeb_2005_event\Hec_Ras\';
filepath_Larsim = 'F:\Study\study_projectFeb_2005_event\';
startdate_LARSIM = datetime(2005,2,01,0,0,0);  %startdate of LARSIM
enddate_LARSIM = datetime(2005,2,28,0,0,0);   %enddate of LARSIM
startdate = datetime(2005,2,11,0,0,0);   %startdate of HecRAS
enddate = datetime(2005,2,20,0,0,0);   %enddate of HecRAS
timestep_Larsim = 1;  %Default Parameter: 1 hour Output from LARSIM
time_step_hecRAS = 0.25; %Default Parameter: 15 Min Output time step to store the results
runs = 1; %Define number of runs for HecRAS
NSE_Mat = zeros(runs,3); % Initiating NSE Matrix to store NSE values at end

%% Generation of Uniform Random samples for Manning's Value
R = [unifrnd(0.027,0.035,runs,1) unifrnd(0.029,0.035,runs,1)] % First write the range for main channel, then for flood plains, starting from low to high value

for i = 1:runs

%% Define all the inflow and lateral boundary conditions from Q and Out, be extra careful in assigning

Q_inflow(:,1) = simulated(:,10);  %Schorgast - KOED -850
Q_inflow(:,2) = simulated(:,5);  % Kaurndorf - KARD 476521
.
.
.
Q_inflow(:,33)=simulated(:,22)/4; %UpperMain - MLEU  461100.8

%% Changing Unsteady Input file
%change unsteady file in 2 steps
%1st step: Assign the Q according to HECRAS
u01_input = [filepath_temp u01_temp];
u01_output1 = [filepath_temp sprintf('projekt_temp%1.0f.u01',i)];
Unsteady_Qinflow(filepath,u01_input,u01_output1,Q_inflow,total_timestep,i);  
%2nd step: Assign the dates and number
u01_output = [filepath_temp sprintf('projekt_%1.0f.u01',i)];
Change_unsteady_dates(filepath,u01_output1,u01_output,total_timestep,startdate_LARSIM_string);
copyfile(u01_output, [filepath 'projekt.u01']);
%% not done properly
% delete u01_output1;

%% Change Geometry file, Assigning Manning's value

n_channel=R(i,1);    % Assigning values from randomly generated 'n' values
n_floodplain=R(i,2);
%n_channel=0.027;    % For Manual calibration, assigning single value
%n_floodplain=0.029;
g01_input = [filepath_temp g01_temp];
g01_output = [filepath_temp sprintf('projekt_%1.0f.g01',i)];
Change_Geometry(g01_input,g01_output,n_channel,n_floodplain,i);
copyfile(g01_output,[filepath 'projekt.g01']);

%% Run Hec_RAS 1D

prj_name = [filepath 'projekt.prj'];
run_ras(prj_name);
%wait for controller till unsteady file is finished
pause_mat(Geom_writer_exe);
pause_mat(Unsteady_exe);
pause_mat(Steady_exe);
%in case you want to save the hdf file
% hdffile = [filepath sprintf('projekt_%1.0f.p01.hdf',i)];
%Extract data from the hdf file, extract points are defined in the function and it can be changed
% TODO : check the options here
%extract hdf file out, copy and change to somewhere else
copyfile([filepath hdffile], [filepath_results sprintf('projekt_%1.0f.p01.hdf',i)]);
%kill the hec ras
!taskkill /im ras.exe
creatatxt(filepath,hdffile,i,total_time_Hecras); % To separate calibration data in .txt
NSE_Mat(i,:) = Plot_NSE(filepath,hdffile,i,num,d,startdate,enddate,0); % To calculate NSE value

end
NSE_Mat;

%% Selection of Best NSE Value

OnesMat = ones(size(NSE_Mat));
DiffMat = (NSE_Mat-OnesMat).^2
% Based on all values
Appendix

\textbf{M = sum(DiffMat,2)} \% smallest distance is the best
\[ \text{[~}, \text{ind} \text{]} = \text{min(M)} \]
\textbf{Plot_NSE(filepath,hdffile,ind,num,d,startdate,enddate,1);} \% To plot with NSE values

%%% Change Geometry Function to assign Manning’s value

\begin{verbatim}
function Change_Geometry(filenameinput,filenameoutput,n_channel,n_floodplain,temp)
    fid = fopen (filenameinput, 'rt'); \%Open file for reading
    fout = fopen (filenameoutput, 'wt'); \%Open file for writing
    while ~feof(fid)
        strTextLine = fgetl(fid); \%To read one additional line
        if strfind(strTextLine, '#Mann='); \%Reading through geometry file
            B0string=strTextLine;
            strTextLine = fgetl(fid);
            a=str2num(strTextLine);
            a(1,2)=n_floodplain; a(1,8)=n_floodplain; a(1,5)= n_channel;
            strTextLine=num2str(a, '%8.4f'); \% default Geometry file with total 8 spaces & 4 decimal
            BinaryArray = isspace(strTextLine); \% Make binary array with space char
            Array2 = find(cumsum(BinaryArray)==0); \% Cummulative sum without space char
            len = Array2(end);
            B1string=sprintf(' %s',strTextLine);
            if(len==1) \%Defining all possible 8 scenarios with spaces
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==2)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==3)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==4)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==5)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==6)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            elseif(len==7)
                fprintf(fout,' %s
 %s
',B0string,B1string);
            else
                fprintf(fout,' %s
 %s
',B0string,B1string);
            end
        else
            fprintf(fout, '%s
',strTextLine);
        end
    end
end
\end{verbatim}
fclose (fid); %Close the text file
fclose (fout); %Close the text file

%% Create Text function to write calibration, validation and bridge data in text file

function createtxt(filepath, hdffile, i, total_time_Hecras)
% Default Inputs based on Main function

filepath = 'F:\Study\study_project\Feb_2005_event\Hec_Ras\';
hdffile = 'projekt.p01.hdf';
hdffile = [filepath hdffile];

% Extracting relevant data through .hdf Hec_RAS files
% Extracting water levels for bridges, calibration and validation
data1 = hdf5read(hdffile,'/Results/Unsteady/Output/Output Blocks/Base Output/Unsteady Time Series/Cross Sections/Water Surface');
findi1 = [343,469,497,864]; % For Calibration with sequence of MLEU,SWBII,ICT,KEMM
findi2 = [195,204,216,217,238,39,58,61]; % 8 locations of city for Validation
WL_final_calibration = data1(findi1,:);
WL_final_validation = data1(findi2,:);
WL_bridges = data1(findi3,:);

% Extracting velocities for bridges
data2 = hdf5read(hdffile,'/Results/Unsteady/Output/Output Blocks/Base Output/Unsteady Time Series/Cross Sections/Velosity Total');
Vel_bridges = data2(findi3,:);

% Write Water Level in text file in case of stable run

if(size(WL_final_calibration,2)==total_time_Hecras) % Stable run for the full time period
Water_Level_calibration = [filepath sprintf('WL_calibration_projekt_%1.0f.txt',i)];
    f = fopen( Water_Level_calibration, 'wt' );
    fprintf(f, '%f %f %f %f
', WL_final_calibration);
    fclose(f);
Water_Level_validation = [filepath sprintf('WL_validation_projekt_%1.0f.txt',i)];
    f = fopen( Water_Level_validation, 'wt' );
    fprintf(f, '%f %f %f %f
', WL_final_validation);
    fclose(f);
Water_Level_bridges = [filepath sprintf('WL_bridges_projekt_%1.0f.txt',i)];
    f = fopen( Water_Level_bridges, 'wt' );
    fprintf(f, '%f %f %f %f %f %f %f %f
', WL_bridges);
    fclose(f);
Velocity_bridges = [filepath sprintf('Vel_bridges_projekt_%1.0f.txt',i)];
    f = fopen( Velocity_bridges, 'wt' );
    fprintf(f, '%f %f %f %f %f %f %f %f
', Vel_bridges);
    fclose(f);
else
    % in case of unstable run i.e. not complete full simulation period
    Water_Level_calibration = [filepath sprintf('WL_calibration_projekt_%1.0f.txt',i)];
    delete(Water_Level_calibration);
    Water_Level_validation = [filepath sprintf('WL_validation_projekt_%1.0f.txt',i)];
    delete(Water_Level_validation);
    Water_Level_bridges = [filepath sprintf('WL_bridges_projekt_%1.0f.txt',i)];
    delete(Water_Level_bridges);
    Velocity_bridges = [filepath sprintf('Vel_bridges_projekt_%1.0f.txt',i)];
    delete(Velocity_bridges);
end
end

%%% Plot NSE function to Plot best NSE value

function [NSE] = Plot_NSE(filepath, hdffile, i,num,d,startdate,enddate,flag)
    % Separating and assigning observed data
    k1 = find(d==startdate);
    k2 = find(d==enddate);
\[ z = d(k1:k2); \]
\[ y1\_mleu\_obs=num(k1:k2,1); \% order of guages is Mainleus, Schwürbitz, Kemmern \]
\[ y2\_swb\_obs=num(k1:k2,2); \]
\[ y3\_kemm\_obs=num(k1:k2,3); \]
\[ t\_obs=datenum(z); \]

% Load Hec_RAS Simulated Data

Water\_Level\_calibration = [filepath sprintf('WL\_calibration\_projekt\_%1.0f.txt',i)];
fileID = fopen( Water\_Level\_calibration, 'r');

% In case of unstable Hec\_Ras run, NSE value is not calculated
if(fileID==-1)
    NSE = [inf inf inf];
    return; \% return to Main function for next Manning's value
end

% In case of stable Hec\_Ras run
formatSpec = '%f %f %f %f';
WL\_calibration\_projekt = fscanf(fileID,formatSpec);
WL\_calibration\_projekt = reshape(WL\_calibration\_projekt,4,[]);
y1\_mleu\_sim=WL\_calibration\_projekt(:,1);
y2\_swb\_sim=WL\_calibration\_projekt(:,2);
y3\_kemm\_sim=WL\_calibration\_projekt(:,4);
t\_sim=datenum(z);
NSE=zeros(1,3);

\%----------goodness of fit calculation, NSE------------------------
if(flag==0)
    \% gives the corresponding values
    [Rel\_Vol,b\_gradient,NSE(1), R2, Index\_d,R2\_adj]=nashsutcliffe\_value(y1\_mleu\_obs,y1\_mleu\_sim,t\_obs,t\_sim);
    [Rel\_Vol\_1,b\_gradient\_1,NSE(2), R2\_1, Index\_d\_1,R2\_adj\_1]=nashsutcliffe\_value(y2\_swb\_obs,y2\_swb\_sim,t\_obs,t\_sim);
    [Rel\_Vol\_2,b\_gradient\_2,NSE(3), R2\_2, Index\_d\_2,R2\_adj\_2]=nashsutcliffe\_value(y3\_kemm\_obs,y3\_kemm\_sim,t\_obs,t\_sim);
else
    \% Plotting with NSE value
    figure(1)
    set (0, 'defaultFigurecolor',[1 1 1]);
    subplot(3,1,1)
    plot(z,y1\_mleu\_obs,'g',z,y1\_mleu\_sim,'r','LineWidth',2);
ylabel('Mainleus');
    \% title ('11-Feb-2005 till 20-Feb-2005');
    legend('Observed','Simulated');
set(gca,'fontsize',15);
subplot(3,1,2);
plot(z,y2_swb_obs,'g',z,y2_swb_sim,'r','LineWidth',2);
ylabel('Schwürbitz');
legend('Observed','Simulated');
set(gca,'fontsize',15);
subplot(3,1,3);
plot(z,y3_kemm_obs,'g',z,y3_kemm_sim,'r','LineWidth',2);
ylabel('Kemmern');
xlabel('Date & Time');
legend('Observed','Simulated');
set(gca,'fontsize',15);
end
end
Appendix

B  HEC-RAS Stabilization Flow Chart

Run Hec-Ras Unsteady model

Immediately gives errors and does not run

Fix errors as listed

Add Cross sections points filter

Check Htab Parameters starting EI

Check Initial Conditions

Lists Large errors at cross sections and stops simulation

Check cross-section spacing with Samuel’s equation

Lower the computation time-step and repeat

Runs with not setup errors
Appendix

Turn on Mixed Flow regime and increase the warm-up time steps

Increase the No. of Cross sections where high slope present

Junction Modelling Errors

Cross-section should not overlap at junction
Assign distance around junction carefully
Energy Balance Method

List acceptable errors

Accept results

Figure-B HEC-RAS stabilization process