1D AND 2D COUPLED HYDRODYNAMIC MODEL OF NULLAH LAI FLOODING USING SAINT -VENANT EQUATIONS

By

Farman Ali Mirza
(NUST201260992MSCEE15312F)

A Thesis submitted in partial fulfillment of
the requirements for the degree of

Master of Science
in
Water Resources Engineering and Management

DEPARTMENT OF WATER RESOURCES ENGINEERING AND MANAGEMENT
NUST INSTITUTE OF CIVIL ENGINEERING
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
SECTOR H-12, ISLAMABAD, PAKISTAN

(2016)

This is to certify that the
Thesis entitled

1D AND 2D COUPLED HYDRODYNAMIC MODEL OF NULLAH LAI FLOODING USING SAINT -VENANT EQUATIONS

Submitted by

Farman Ali Mirza

(2012-NUST-MS-WRE&M-05)

Has been accepted in partial fulfillment of the requirements
Towards the award of the degree of

Master of Science in Water Resources Engineering and Management
(2016)

Dr. SAJJAD HAIDER
Associate Professor

NUST Institute of Civil Engineering (NICE)
School of Civil & Environmental Engineering
National University of Sciences & Technology, Islamabad

DEDICATED TO

MY PARENTS

ACKNOWLEDGEMENTS

This acknowledgment will hardly justify my sense of profound veneration for revered supervisor Dr. Sajjad Haider for his indelible help, unprecedented enthusiasm, constructive criticism, and perceptive encouragement.

I am highly honored to Dr. Hamza Farooq Gabriel for his expert guidance during my research. I sincerely thank him for his valuable suggestions, thoughtful criticism, and sustained encouragement during pursuance of my MS program.

No words can suffice my feelings of immense gratitude to my MS colleague Mr. M. Umer for their whole hearted, ever available help, technical acumen, moral support, and comradeship.

I am grateful to all the Faculty and staff at Department of Water Resources Engineering and Management for their guidance and support in every aspect for the completion of this thesis. I am grateful to National University of Sciences and Technology for the financial support of the complete research work.

I extend special thanks to my parents and family for their help and strength owing to which I could work peacefully.

ABSTRACT

Floods are among the most devastating natural hazards in the world causing huge losses of lives and infrastructure. Floods can be predicted but it's very hard to make its effects less severe. Flood can destroy human life, destroy the homes, infrastructure, buildings, and everything that comes in its way. Poor prediction of the flood can lead to a widespread damages.

Pakistan is an underdeveloped country that has seen an increasing number of floods in the last couple of decades. Lai Nullah is situated in Rawalpindi district of Pakistan, twin city of capital Islamabad. It has basin area of 235 km2. It has a history of flood after every three years. In 2001 there was a huge flood in Nullah which claims 74 people and affected 400,000 people, 742 cattle head perished, 1,087 houses completely damaged and 2,448 partially damaged, inflicting a capital loss of US$ 250 million to infrastructure, government and private property.

In this study, the flood of 2001 has been simulated using a technique called 1D-2D coupling. Two software have been used for this study; one is BASEMENT which calculates the flood extends velocity, water depth and water surface elevation. The other software is Surface-Water Modeling System (SMS) and Fudaa-Prepro, which are used for visualization of results.

The results have been verified with an already carried out study by Japan International Cooperation Agency (JICA, 2003) and fully 2D model (Umer, M. 2015). The 5.91 km2 extent has been calculated which is very close to the 6.01 Km2 calculated by JICA with a water depth of 5-6 meters in a low lying area called Naya Mohalla near Liaquat Road and Gawalmandi Bridge.

Simulated results are in close agreement with the JICA results as far as the floodplain is concerned but deviations are observed over the main channel due to the non-availability of reliable data for the cross sections. In the current study, the input hydrological data has been only taken at Katarian Bridge. It is suggested that if the hydrological data may be taken for the main Lai Nullah along with all of its tributaries like Niki Lai and Dhok Hassu Nullah which join the Lai below the Khabane-Sir-syed bridge and Peerwadi bridge respectively, the results may be better.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADB	Asian Development Bank
BASEMENT	Basic Simulation Environment for Computation of Environmental Flow & Natural Hazard
CUMEC	Cubic Meter per Second
DEM	Digital Elevation Model
FDM	Finite Difference Method
FEM	Finite Element Method
FVM	Finite Volume Method
GIS	Geographic Information System
GUI	Graphical User Interface
JICA	Japan International Cooperation Agency
WASA	Water and Sanitation Agency
WMO	World Meteorological Organization
PMD	Pakistan Meteorological Department
RDA	Rawalpindi Development Authority
SMS	Surface Water Modeling System
HEC-RAS	Hydrologic Engineering Centers River Analysis System
NAM	The North American Mesoscale Forecast System
IHACRES	Component Flows from Rainfall, Evaporation and Stream Flow Data
DHSVM	Distributed Hydrology Soil Vegetation Model

USACE	U.S. Army Corps of Engineers
HEC-HMS	Hydrologic Modeling System
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
FFWS	Flood Forecasting and Warning System

LIST OF NOTATIONS

Symbol	**Unit**	**Description**
A	m^2	Flow x-sectional area
C	$m^{1/2} / s$	Chezy resistance coefficient
g	m/ s^2	Acceleration due to gravity
H	m	Stage above horizontal reference level
Q	m^3 / s	Discharge
n	$s/m^{1/3}$	Manning coefficient
R_h	m	Hydraulic radius
S	Ratio	Slope of the hydraulic grade line
h	m	Water depth
u	m/s	Depth averaged velocity in x-direction
v	m/s	Depth averaged velocity in y-direction
z_B	m	Bottom elevation
$\tau_{\mathrm{b}x}$	N/m^2	Bed shear stress in x direction
$\tau_{\mathrm{b}y}$	N/m^2	Bed shear stress in y direction
τ_{xx}, τ_{xy},	N/m^2	Depth averaged viscous and Turbulent stresses
τ_{yx}, τ_{yy}	N/m^2	Depth averaged viscous and Turbulent stresses
D_{xx}, D_{xy},	N/m^2	Momentum dispersion terms
D_{yx}, D_{yy}	N/m^2	Momentum dispersion terms

Chapter 1

INTRODUCTION

1.1 GENERAL

Pakistan is an agricultural and under developed country with little emphasize on flood management. Pakistan has a varied topography with mountains in the northern areas and plain, sandy desert in its central and southern areas. There are four main rivers flowing through it, i.e. Sutlaj, Sindh, Chanab, and Jhelum. The Indus River is the biggest river of Pakistan. Its total length is 3180 km making it the largest river of Asia. The annual flow of the river is around 207 km3, making it the 21st largest river in the world. The Indus starts from Tibet; the Indus takes off at the convergence of the Sengge and Gar, that comes from the Nganglong Kangri and Gangdise Shan hills. After that the river flow north-west throughout the Ladakh and Baltistan into Gilgit, south of the Karakoram (Khalid et al., 2013).

Floods are very common in Pakistan. In 2010 Pakistan experienced the biggest flood in its history, which caused huge damage to the economy of the country and affected around 20 million and over 2000 people died with great loss of livelihood and infrastructure (Ali, 2009).

Floods are among the world greatest hazards. Pakistan is experiencing floods that are mostly owing to substantial south-westerly rainy season rain and speedy ice melting in the north region. Flash floods are defined as the flood due to the high intensity rain in short time. These inundations are very common in the Pothohar zone. Inundations could be somewhat remedied but inundation dangers could not be ended.

In Monsoon which is the main season of rain in Pakistan, these Nulls often get filled up with rain water then it floods. Pakistan has a number of nullahs which flow through the major cities of the country like Nullah Lai in Rawalpindi.

Due to climatic change globally and locally these flashy rivers are often flooded. But due to government’s main focus on predicting and avoiding the flooding in, the main rivers of

Pakistan these flashy rivers often remain neglected. As some of these flashy rivers lie right in the heart of the city so they can sometimes produce more destruction than main rivers.

Five components influence each flood. The main and first one are recognized as meteorological components (e.g. temperature, precipitation, vaporization, winds, and so on.). The second category contains the soil data (e.g. soil, hydraulic conductivity and so on.). The third component is identified as topographical components (surface slope, stream longitudinal slope). The fourth is area use (land cover), and the last one is river system components. Topographical components impact, area utilization, and waste system components. For example, farmhouse area and settlement zones are normally situated on the low slopes, while hilly area's catchments have steep slopes and have furthermore complex drainage system (Masoudian and Theobald, 2011).

The water of the natural streams normally goes into man-made channels. Generally, all the materials (garbage or sediments) of natural streams also come along the water to the artificial channels. The materials coming to the man made channel may be produced at the source and reach the channel due to the flood. There are many reasons for blockage of the natural/artificial channel such as construction material which is deposited along the road, washed into the channel and household garbage is dumped into the channels. These are the factors which play an important role in flooding of artificial and natural channels (Jimoh, 2008).

1.2 SIGNIFICANCE OF THE ISSUE

There are 19 major floods in Lai catchment from 1960 to till now which have been tabulated in Table 1.1 shown below.

Table 1.1: Flood Record of Nullah Lai

YEAR	DATE	YEAR	DATE
1944	August 13	1994	July 3
1957	Record not available	1995	July 24
1966	July 31	1996	July 29

YEAR	DATE	YEAR	DATE
1970	Record not available	1997	August 27
1972	Record not available	2001	July 23
1976	Record not available	2002	August 13
1977	Record not available	2008	August 3
1978	Record not available	2012	September 4
1982	August 10	2013	August 13
1990	Record not available		

On 23 July 2001, an unprecedented rain occurred for 10 hours in Lai catchment area amounting to 620 mm. The flood claimed lives of 74 people and affected 400,000 people, 742 cattle head perished, 1,087 houses completely damaged and 2,448 partially damaged, inflicting a capital loss of US$ 250 million to infrastructure, government and private property. Apart from this event, there was also flooding in 1981, 1988, and 1997 in Lai but 2001's flood is considered as the worst.

1.3 AIMS AND OBJECTIVES OF THE RESEARCH

This research has the following objectives.

1. To simulate the 2001 flood using 1D-2D coupling technique using BASEMENT
2. Calibration of the model with 2001's flood data
3. To compare the outputs of the 1 D-2 D model with a completely 2 D model outputs

1.4 RATIONALE OF THE STUDY

There are many attempts to reproduce the 2001's flood by using models e.g. MIKE 11 (Tallat et al., 2011)and HEC-RAS and HEC-GeoRAS (Ahmad et al., 2010) and 2D flood modeling (Umer, 2015).

In 1-D methodology where results (water levels and discharge and water surface elevation) can be calculated at points where cross-section data is available, 2-D model results can be calculated at each grid point in the specified domain. Discharge and velocity can also be calculated in a 2D model, i.e. along the flow and in the lateral direction.

Over floodplains having complex topography, the flood cannot be calculated in one-dimension. To precisely predict the lateral flow, a two-dimensional methodology is needed. 2-D Saint Venant equations is used in 2D models. A fine spatial resolution has to be utilized that slows down the calculation and use considerable machine memory.

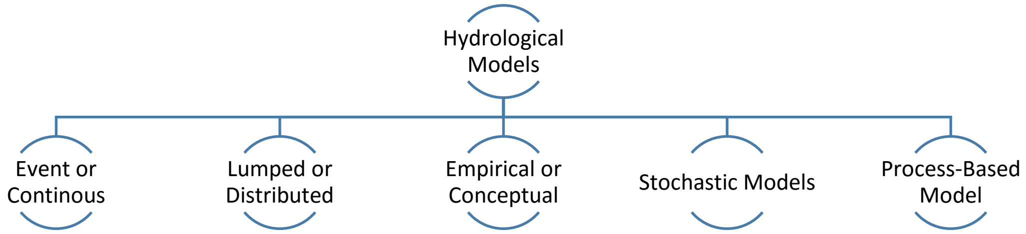
In 1D-2D coupling, both 1D and 2D approaches are used together. The channel is represented in 1D and floodplain is represented in 2D. Channel data is interpolated by different methods. For 2D representation, a mesh is developed from topographical data over an area. Then 1D and 2D data are joined by different coupling techniques. The fluxes between two components are characterized by their connecting edges (Faeh et al., 2011).

Chapter 2

LITERATURE REVIEW

2.1 HYDROLOGICAL MODELS

The literature contains a range of definitions for hydrologic models. Hydrologic models are rearranged, applied representations of a piece of the hydrologic cycle. A hydrologic model may be a simplification of complicated hydrological processes. At every modeling step, some approximations are made: perception of the phenomenon, formalization during a conceptual framework and eventually the interpretation through a programming language. Watershed models are basic to water resources assessment, development, and management. They analyze the amount and quality of streamflow, reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use management, water distribution systems and a variety of alternative water resource management activities. They're basically used for hydrologic expectation and for comprehending hydrologic procedures. Distinctive orders of the hydrologic models are proposed by totally different researchers to characterize the hydrologic models in five distinct categories. (Ford and Hamilton, 1996).



2.1.1 Event or Continuous

This distinction applies primarily to models of watershed runoff processes. An event model simulates one storm. The period of the storm could vary from a number of hours to a number of days. Thus, event hydrologic modeling is helpful for a higher understanding of the underlying hydrologic processes and in distinguishing the relevant parameters. Also, intensive fine-scale hydrologic observation data of precipitation events, that are essential to the calibration of the event hydrologic model, are similarly obtained. A continuous model simulates an extended amount, reducing watershed response both throughout and between precipitation events. Continuous hydrologic modeling synthesizes hydrologic processes and phenomena i.e., artificial responses of the basin to a variety of rain events and their accumulative effects over an extended period of time that has both wet and dry conditions. Additionally, calibration and verification of a continuous hydrologic model over an extended period of time typically need significant observation data. For several little watersheds, however, such long-term observation data might not be available, might not be ‘continuous,’ or might not have sufficient resolution. Thus, a mixture of the event and continuous hydrologic modeling takes advantage of the two modeling strategies and data availability, particularly, the parameters that are well calibrated in event models can facilitate to improve the continuous hydrologic modeling (Chu et al., 2009).

2.1.2 Lmped or Distributed

A distributed model is one within which the spatial (geographic) variations of characteristics and processes are considered explicitly, whereas, during a lumped model, these spatial variations are averaged or neglected. These models aim to represent the processes that occur within the watershed with a lot of solid physical base. These models encompass a series of conceptual components; interconnected, every part represents a system among the hydrologic cycle (evaporation, surface runoff once the profile is saturated, surface runoff). However, even if the quantity of parameters is sufficient, the processes description remains quite simplified. Samples of lumped conceptual rainfall-runoff modeling system are, North American Mesoscale Forecast System (NAM) and Identification of unit Hydrographs And Component Flows from Rainfall, Evaporation and Stream Flow Data (IHACRES) and distributed physically primarily based hydrological modeling system are MIKE 11 and Distributed Hydrology Soil Vegetation Model (DHSVM) (USACE, 2000).

2.1.3 Empirical or Conceptual

A conceptual model is made of data of the pertinent physical, chemical and biological processes that act on the input to provide the output. An empirical model, on the other hand, is based on observation of input and output, without seeking to represent explicitly the process of conversion. Hydrologic Engineering Centers River Analysis System (HEC-HMS) includes each empirical and conceptual models, for instance, Snyder’s unit hydrograph model is empirical. The model is calibrated with observed precipitation and runoff. The kinematic-wave runoff model is conceptually based upon basic principles of shallow free surface flow (USACE, 2000).

2.1.4 Stochastic Models

A stochastic model could be a tool for estimating probability distributions of potential outcomes by allowing random variation in one or additional inputs over time. The random variation is usually based on fluctuations determined in historical data for a specific period using standard time-series techniques. Distributions of potential outcomes are derived from an oversized range of simulations that reflect the random variation within the input(s). These models are a system, taking into consideration data and utilizing numerical and factual concepts to attach a particular data e.g. precipitation to the model yield e.g. rainfall. Often used methods are a regression, exchange capacities, neural systems, and ID. These models are referred to as random hydrology models (USACE, 2000).

2.1.5 Process-Based Model

A process-based model is the mathematical (and usually computer-based) representation of one or many processes characterizing the functioning of well-delimited biological systems of basic or economic interest. Examples of these models are organic chemistry pathways or population dynamics models (single species or mixed). Usually, such models carry with it a collection of standard partial differential equations that define the essence of every method (temporal patterns of key parameters). Outputs of one method will serve as input to different processes. Such a modeling paradigm was heavily used within the case of crop modeling (Buck-Sorlin, 2013). This model presents physical techniques. Normally, such models contain representations of surface runoff, evapotranspiration, and channel runoff. These models are called deterministic hydrology models. deterministic hydrology models may be divided into single-occasion models and continuous simulation models (USACE, 2000).

2.2 HYDROLOGICAL MODELING SYSTEM

In recent years, water resource management studies have increasingly been involved with elements where direct information isn't accessible. For instance, the estimation of flow for those areas where no hydrological gauges are put in, atmosphere impact from the utilization of land and combined effects of surface and ground water use.

A hydrological modeling system is common software system, which may be used for typical catchments without alteration of basic code. Examples of modeling system are HEC-HMS, and Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) (Refsgaard and Knudsen, 1996).

2.3 CLASSIFICATION OF MODEL TYPES FOR FLOOD RISK MANAGEMENT

Modeling strategies can be isolated into various methodologies exhibited in Table 2.1 (Néelz and Pender, 2009), described by their dimensionality or the way they consolidate methodologies of distinctive dimensionalities. Table 2.1 gives a rundown of the routines and scope of uses for every system. Those most prominent and present in the Table are 1D, 1D+, 2D- and 2D strategies. These modeling techniques cover most of the applications used in the study of flood risk management studies.

Table 2.1: Types of Models (Néelz and Pender, 2009)

Method	Description	Application	Outputs	Example Models
1D	Solution of the 1-D St-Venant equation.	Simulation which could be of the order of 10s to 100s of km	Water depth, cross-section averaged velocity and discharge at each cross section. Flood extent if flood-plains are portion of the 1-D simulation.	Mike 11, HEC-RAS, ISIS, Info Works.
1D+	1-D + a storage cell method to model the flood-plain flow.	Simulation which could be of the order of 10s to 100s of km depends on catchment area.	Water depth, cross-sections averaged velocity and discharge at each cross section. Flood extent if flood-plains are portion of the 1-D simulation and inundation extent in floodplain storage cells	Mike 11, HEC-RAS, ISIS, Info Works, RS.
2D-	2D- the conservation of momentum for the flood-plain flow.	Broad-scale simulation, used where inertial affects are not significant.	Inundation extent, water depths,	LISFLOOD-FP, JFLOW.

Method	Description	Application	Outputs	Example Models
2D	A solution of the 2D shallow water equations.	Simulation of the order of 10s of km. Might be used in broad-scale simuation if used for very coarse grids.	Inundation extent, water depths, depth-averaged velocities	TUFLOW, Mike 21, TELEMAC, SOBEK, Info Works 2D.
2D+	2D + a solution for vertical velocities using continuity only.	Mainly for coastal uses wherever 3-D velocity profiles are imperative. Has also been used to reach scale river simulation in investigation studies.	Inundation extent, water depth, 3D velocities	TELEMAC-3D
3D	A solution of the 3D Reynolds-averaged Navier-Stokes equations.	Local estimates of the 3D velocity field in conduits and flood-plains.	Inundation extent, water depths, 3D velocities	CFX

2.3.1 1D Models

One-dimensional models take into account some form of the one-dimensional St-Venant or Shallow Water Equation, which can be determined by averaging the Navier-Stokes mathematical statements over the cross-sectional surface of the channel. The assumptions of Saint-Venant equation confine its usage to the center line of the channel. Throughout the years, its utilization has been extended to complex channels, i.e. channel with floodplain. For this model, the floodplain flow is a part of the one-dimensional channel. The method has two advantages:

- Flow in the floodplain is assumed to be parallel to the channel.
- The cross-sectional velocity calculated by the St-Venant equation has a less physical importance in circumstances where substantial variation in velocity exists over the floodplain.

This methodology has been upgraded due to critical advances in parameterization through the improvement of the conveyance estimation system (Néelz and Pender, 2009).

2.3.2 1D+

In the 1D+ methodology floodplains are modeled as storage cells that can fill a few sq.km and are categorized by a water level/volume correlation. The flow between the 1D conduit and the floodplain cells is achieved through called ‘spill units’. These might also be employed to attach storage cells to one another. The discharge mark in every storage cell is then treated employing volume conservation. In any case, these models do not observe momentum conservation on the floodplains implying that water can travel rapidly from one end of the storage cell to the next. The calculation of cell flow might be in error due to the inflexible application of the spill flow equations. Errors in calculated water levels can also arise if the storage cells are too large and the assumptions of water level horizontality can't be met. The 1D+ methodology is additionally called to as ‘pseudo-2D’or ‘semi 2D’ (Néelz and Pender, 2009).

2.3.3 2D Models

Models which are based on 2D shallow water mathematical equations are classed as 2D methodologies. The 2D shallow water equation (2D St-Venant) can be inferred by integrating the Navier-Stokes equations over the flow depth. In its direction, a hydrostatic pressure distribution is assumed. The solution to these equations can be obtained by a mixture of numerical strategies, for example, finite difference, finite element or finite volume and utilization of a variety of numerical grids, (such as Cartesian or boundary fitted, structured or unstructured) all of which have advantages and disadvantages in view of the floodplain modeling.

The 2D- models have the following properties

- 2D- models are a depiction of the kinematic and diffusive wave equation which is acquired by ignoring selected terms of the 2D shallow water equations.
- Models are dependent on square-grid digital elevation models and a better 1D depiction of the flow between the raster DEM cells (LISFLOOD-FP).

2.3.4 3D Models

3D method is obtained by 3D Reynolds averaging of the Navier-Stokes Equations, which can be employed to predict water levels and 3D velocity in channels and floodplains. Their usage, at the present time, is limited due to numerical challenges and large computer resources for implementation. (Néelz and Pender, 2009).

2.3.5 1D-2D Coupling

Number of choices exists on an elementary level to couple 1D and 2D modeling approach. This approach allows to combine advantages already existing 1D model for channel the to advantages of the 2D floodplain models. There are numerous models which link 1D and 2D. The most model connect 1D and 2D model through sideways, where the exchange of flow is usually modeled with the help of the weir equations or depth-discharge relations. A limitation of this approach is that the complex momentum exchange between channel and floodplain is not modeled.

Other approaches are the longitudinal connection, which is used to model a channel mostly in 1D (upstream) and generally in 2D (downstream), or to combine the downstream end of a 1D model to a 2D system. In this method, the flow from the 1D enters the 2D model as a "source", and the water level in the 2D model at the junction is used as a downstream condition in the 1D model.

The procedure involved in coupling a 1D model and a 2D floodplain model using a vertical connection is most basic. This consists in identifying the floodplain using a persistent 2D grid overlying the 1D flow model. The 1D model works separately until the water level overtops the bankfull level, and enters into the 2D model.

A number of options exist to join 1D, 2D, and 3D modeling methodologies. Many software have the option to connect a 1D model to a 2D floodplain. These methodologies have become popular on the grounds that it permits the modeler to use the advantages of 1D flow modeling while treating the floodplains in 2D grid. This method saves computational time over the structured 2D grid.

A few models don't entirely fall in any of the classifications. This is the situation for the rapid flood propagation techniques which are the subject of some exploration in national-scale flood risk assessment for which simulation running times many orders of magnitudes shorter than routine 2D models are required. These procedures are established on much less difficult representations of the physical terrain than the 2D models and the elimination of the time discretization in the processing. Simple geometric strategies which extend water levels horizontally over a floodplain can likewise be termed 0D as far as modeling of the floodplain is concerned (Néelz and Pender, 2009).

2.4 PREVIOUS STUDIES OF 1D-2D COUPLED MODELING

Bladé et al., 2012, used the 1D method in river channels in addition the 2D one in floodplains and coupling of 1D and 2D flows by applying software MIKE 11 to river Ebro. In this method a completely conservative technique for the coupling of 1D and 2D areas is utilized using finite volumes. Manning *n*=0.030 has been used. The 1D-2D, based on finite volume approach is very useful for the inundation simulation. The 1D-2D methods reduce time and cost for calculation while preserving the accuracy of results.

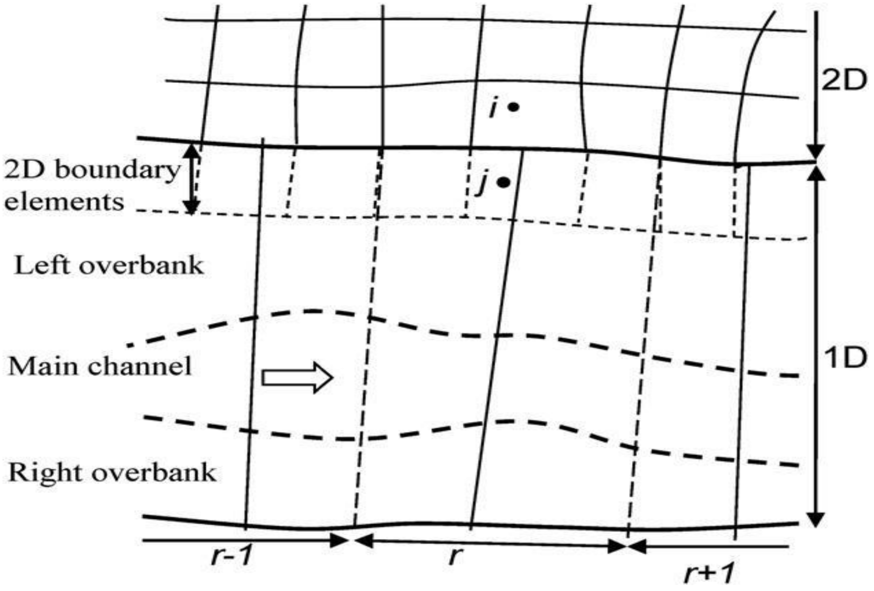


Figure 2.1: Depiction of lateral coupling (Bladé et al., 2012)

Morales-Hernández et al., 2013, utilized 1D and 2D models using conservative, upwind, cell-centered finite volume scheme. His technique applied to both the urban and rural flooding. His technique has both the sideways and parallel coupling. For the first trial Manning Coefficient n= 0.009 has been utilized on a flat bed. The discretization is applied to cross-sections of the 1D model and to a triangular unstructured grid of the 2D model.

Kuiry et al., 2010, studied the channel flow which is computed by solving the 1D Saint-Venant equation. Inundation extent above the embankment of the river onto the flood plains is computed using a storage cell model discretized over an unstructured triangular grid. Flow interchange among the one-dimensional river cells and the adjacent floodplain cells represented by the diffusive wave equation. The range of Manning's friction coefficient n_{ch} and n_{fp}, between 0.01 to 0.05 and 0.05 to 0.10 respectively were used for this study.

Ahmad et al., 2010, utilized hydrological models with GIS to evaluate the flood extent of Nullah Lai. HEC-RAS and HEC-GeoRAS models were utilized to demarcate the zones susceptible to flood at different discharges. A sufficient resolution DEM of the zone (Kattarian to Gawalmandi Bridges) was utilized. GIS were utilized to take into the consideration the variability of the topography and to calculate the inundation. Flood zone assessed at the discharge of 3000 m^3/sec is 3.4 km^2 out of which 2.96 km^2 is below the flood depth from 1 to 5 meters. Maximum inundation depth measured up to 20 meters for this discharge.

Tallat et al., 2011 worked on Lai with Mike 11 and developed rainfall–runoff model for the basin utilizing refined precipitation data and available cross-sections, and a simulation was carried out to simulate the 2001 flood. After that the model was somewhat changed to simulate typical flood discharges for a number of return periods. Flood extent was shown by producing flood maps for several return periods utilizing a GIS interface.

2.5 SUMMARY OF LITERATURE REVIEW

- 1D-2D coupling has the properties of both 1D and 2D and has not yet been applied to the Nullah Lai.
- The 1D approach is used for the main channel where the velocity is fast and the flow is 1D.

- 2D is used for the floodplain as velocity is small because water starts spreading out over the floodplain.
- Computer time and memory are saved because the number of channel x-sections in a 1-D model is drastically less in a 2-D model. While modeling a large domain the no of cells in 2D are going to be proportional to the area of the doamin whereas the no of cross sections in a 1-D simulation is proportional to the length of channel reach.
- Time differences between approaches can range from a few seconds to a few minutes in 1D to several hours, in 2D technique.
- Coupled models also have advantages when utilizing explicit methods in which the time step is restricted by the Courant condition. In a 2D model the river is typically the time step restrictive, as depths and velocities, are large than in the flood plain. If the similar zone is modeled in coupled, the value of the time periods can be increased due to the coupling.
- For 2D modeling, an accurate meshing of the river bed is obligatory to appropriately take the topography in consideration. Hence, mesh should be refined near to the channel floodplain interface and the time step must be reduced to guarantee the numerical stability. The coupled model, though, avoids such time step reduction at the interface.

Chapter 3

NULLAH LAI AND ITS FLOOD PLAINS

3.1 INTRODUCTION

The Lai Basin in from the Northern Pakistan at 33° 45′ 00″ and 33° 32′ 30″ North and 72° 57′ 30″ and 73° 07′ 30″ East, with a basin area of 235 km². The higher basin covers 161.3 km² (69%) is in Islamabad metropolitan and the other basin covers 73.6 km² is in Rawalpindi and outskirts. Its length is about 30 km from Margalla hills to Soan River and has six tributaries, three starting from hills of Islamabad at upper altitudes and three at lower elevations. The altitude of the Lai Basin fall in the range of 420 m at the connection with the Soan River to 1200 m in the Margala hill (Kamal, 2004) as shown in Figure 3.1. Four important branches are Saidpur Kas, Tenawali Kas, Bedarawali Kas and Johd Kas which meets Lai upstream of the Katarian bridge. Lai enters in Rawalpindi at Katarian Bridge. The low laying areas which frequently inundated mainly lie along the Lai is between Katarian bridge and Chaklala bridge (Ahmad et al., 2010)

Downstream of the Katarian bridge, in the densely populated area of Rawalpindi, three main tributaries are (i) Nikki Lai, (ii) Pir Wadhai Kas and (iii) Dhok Ratta Nullah, Lai Nullah passing through the down town Rawalpindi city and falls into Soan River.

3.2 CLIMATE

The climate of the Lai Basin is classified as ‘Subtropical Triple Season Moderate Climate Zone’. This zone is defined as a zone in which there is a sole rain period from July to September and it directly affects the temperature of the area. The subject area has hot summers and freezing winters. In June, the highest temperature is 40 °C, while minimum temperature is 0 °C in December and January. The precipitation falls throughout the monsoon season though, maximum precipitation falls from the middle of July to September. The overall precipitation throughout the rainy period is about 600 mm, which is 60% of the yearly precipitation of around 1,000mm (Hashmi et al., 2012).

3.3 TOPOGRAPHY

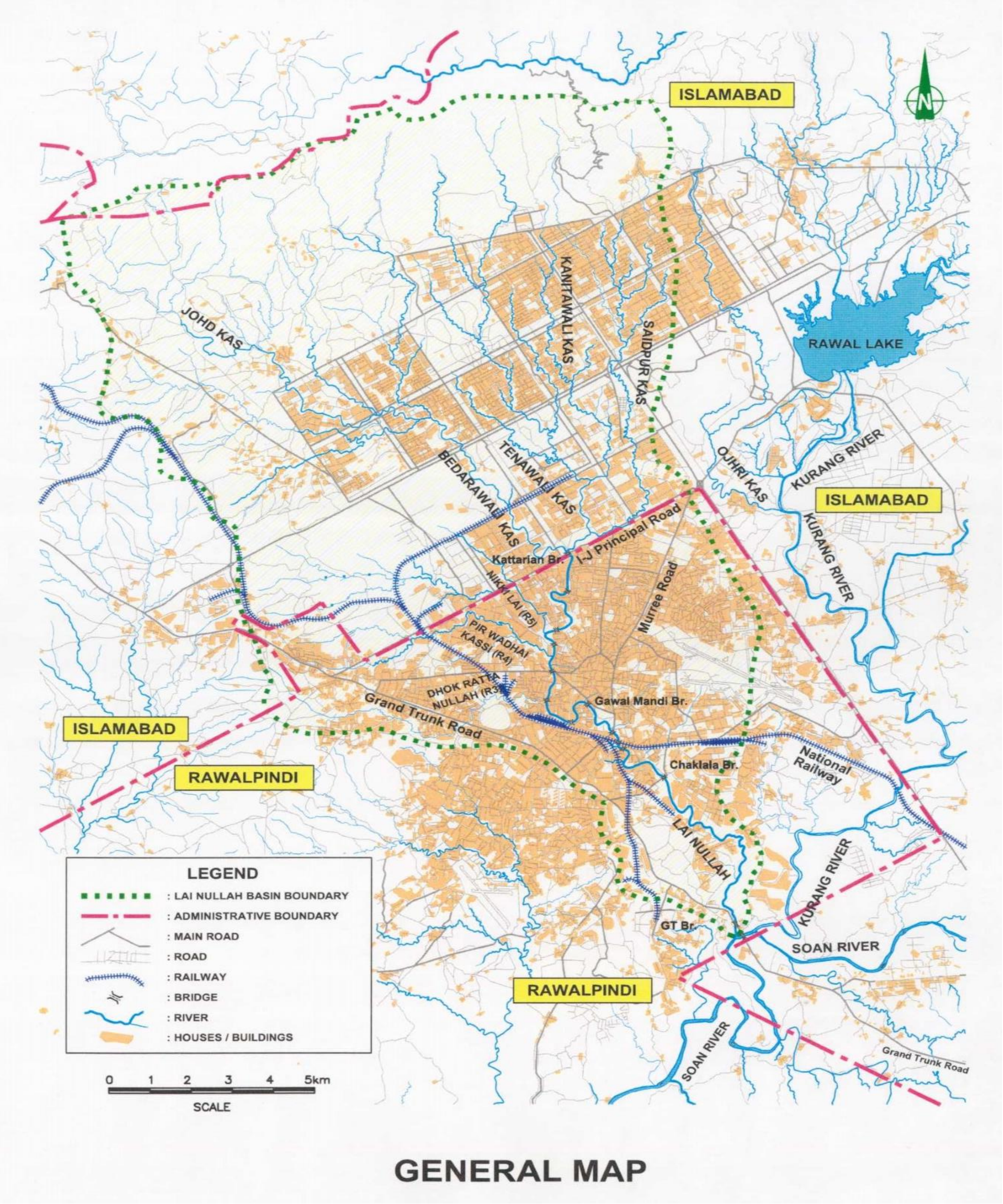


Figure 3.1: Location of Lai and Its tributaries in Rawalpindi and Islamabad (JICA, 2003)

The basin may be subdivided in four regions based on topography

- Margalla in Islamabad is the boundary on the North side. The foot of the Margalla is on an elevation of 620 m, whereas the highest elevation is at about 1,200m. Four tributaries take off from Margalla hill, having a slope of about 10% (JICA, 2003).
- The upper zone lies above the paved area of Islamabad with a mild slope from North to South.
- The Lower zone is the Rawalpindi municipal part lying upstream of the Chaklala Bridge.
- The zone downstream of the Chaklala Bridge, the nullah falls into the Soan River with frequenting cascading in between.

3.4 HYDROLOGY

Though there is precipitation in all seasons, the monsoon precipitation is significant and happens mid July to September. The entire precipitation throughout the rainy period is about 620 mm, accounting to 60% of the annual precipitation of around 1,000 mm. Monsoons carry substantial rainstorms to the Lai river basin, causing inundation of the Lai river and its tributeries (Tallat et al., 2011).

There are four rain-gauging stations of the Lai basin: Saidpur, Islamabad, Rawalpindi Agromet Center (RAMC) and Chaklala (JICA, 2003). The Chaklala and Islamabad stations are operational from last 35 years, Saidpur, and Rawalpindi Agromet Center (RAMC) stations were started since the last 13 and 18 years respectively (Tallat et al., 2011).

The Lai basin receiving considerable rainfall (average of 500 mm) in the monsoon period from July to September. During the 1944 - 2004 periods, a quantity of 19 precipitation events of major magnitude occurred at consistent interval. On July 23, 2001, an extraordinary rainfall took place above Islamabad-Rawalpindi carrying about 620 mm of precipitation in a time of round 10 hours. The resultant inundation caused the death of 74 persons and the entire or partial damage to about 3,000 dwellings (JICA, 2003).

3.5 STUDY AREA

The entire study area is 9.35 km^2 out of which 0.75 km^2 is the Lai channel area from Katarian Bridge to 2 km downstream of Chaklala Bridge. The higher area of Lai has typically built part and has north to south slope, in which the tributaries have a slope of 1/100 to 1/500 and join Lai upstream of the Katarian Bridge, which entrance point of Lai River into Rawalpindi. Downstream of the Chaklala bridge, the Lai join the Soan River at an elevation of 420 m above mean sea level at a point called Soan Adda (Tallat et al., 2011).

There is total 11 number of the bridge on Lai, linking the municipal area lying on the two sides. These bridges are Katarian bridge, New Katarian bridge, Sheik Rashid bridge, Khayaban-e-sir-Syed bridge, Pirwadi bridge, Ganj Mandi New bridge, Ganj Mandi Old bridge, Ratta bridge, City Sadar bridge, Gawal Mandi, and Murree Road bridge.

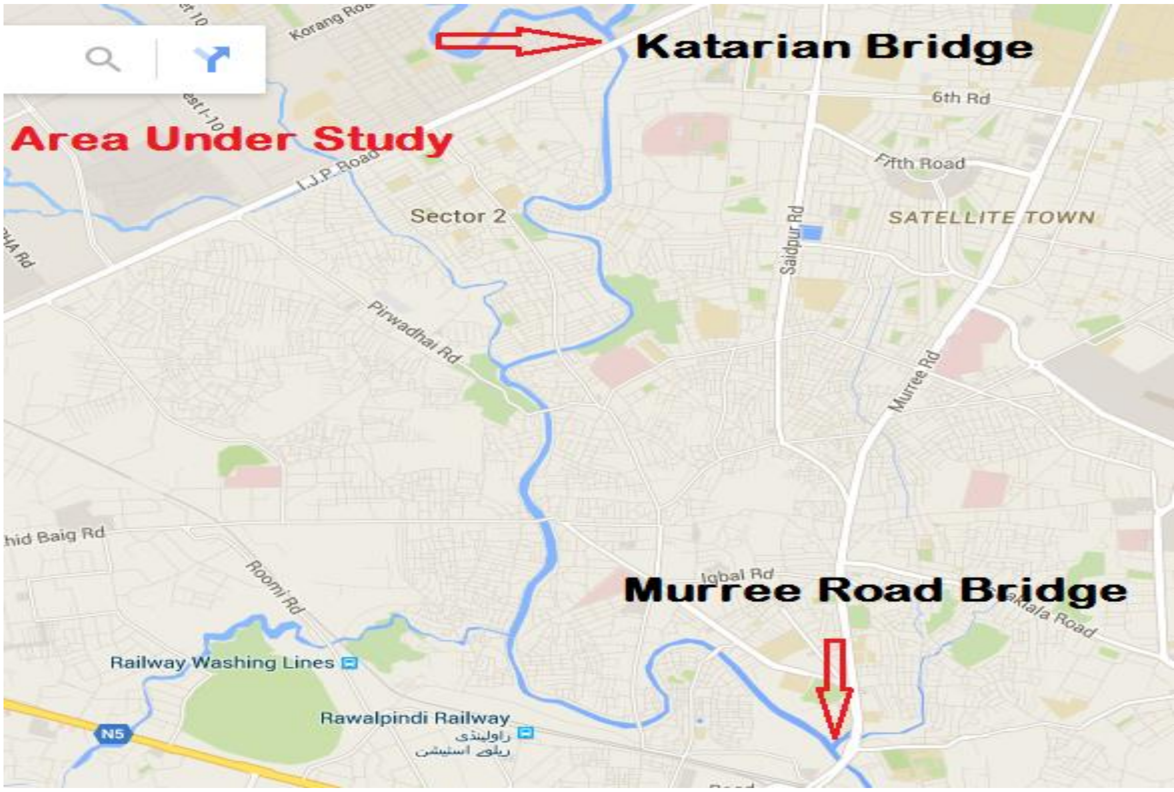


Figure 3.2: Study Area(Not to scale)

As the neighboring areas of Lai are the low lying than other parts of the town consequently once there is a flood of even minor scale the neighboring areas get inundated. The area between Ganj Mandi bridge and Railway bridge, and the branches of Arya Nullah, Dhok Rata Nullah, Dhok Charaghdin are severly affected by flood. Flooding starts in these areas when the channel level of Lai attains 18 feet mark (491.5 m) at Gawal Mandi bridge (Kamal, 2004).

Chapter 4

RESULTS & DISCUSSION

4.1 INTRODUCTION

An inundation is defined as any extraordinary stream flow that overtops the normal banks of a stream. Floods are amongst the world's greatest natural hazards, due to which many people die every year, triggering infrastructure damage than every other natural calamity. Pakistan's experience of flooding is largely owing to substantial south-westerly rainy season and quick snow melting in the north areas.

Number of models are employed for simulation e.g. one-dimensional (1D) (Samuels, 1990), two-dimensional (2D) (Hervouet, 1994), three-dimensional (3D), and coupled 1D-2D coupled model (Vojinovic and Tutulic, 2009). From various years, 1-D practice has been the usual exercise, the reason being that 1-D is not hard to setup, standardize and it gives reasonable results when linked to flow in the channel. The results are not very reasonable when connected to a 2 D flood-plain (USACE, 2000). For 2D flow simulation, a careful meshing of the channel is obligatory to represent the topography (USACE, 2000). The grid should be refined near to the channel banks and the time step essentially be reduced to guarantee the mathematical stability. In coupled simulation, 1-D and 2-D methodologies are joined into a single simulation. Computer time and memory are saved, as the number of points in a coupled model are lesser than 2-D simulation since in 2-D model calculation points are proportional to the model area (Bladé et al., 2012).

The hydrodynamic modeling software BASEMENT has been utilized for the solution of the Saint Venant Equations. In addition, Fudaa-Prepro has been utilized for the presentation of the results. The weir equation has been used for the flow exchanges between the river and the floodplain. The calculated depth and extent etc. of the 2001 flood in Nullah Lai has been compared with the already carried study carried out by JICA.

The results of a 1D-2D coupled modeling depend on different factors which include Manning coefficient (Kuiry et al., 2010) and quality of mesh (Umer, 2015). A combination of Manning's friction coefficient n_{ch} and n_{fp}, between 0.01 to 0.05 and 0.05 to 0.10 were used by (Kuiry et al., 2010).

Steps involved in this study are shown in Figure 4.1.

Figure 4.1: Step by Step depiction of the method used for the study.

4.2 DATA COLLECTION

The details of the spatial and hydrological data used in this study, as well as their sources, are shown in Table 4.1. The study utilized a number of spatial and hydrological data, peak discharge, cross-sections and cross-sectional profiles developed by RDA.

Table 4.1: Datatypes and source

Sr. No	Data Types	Source
1	250 channel cross-sections	From Rawalpindi Development Authority (RDA) which conducted topography survey in 2010.
2	Floodplain data (Elevations of floodplain) (Figure 4.2)	Surface elevation data for the flood plains of Nullah Lai was obtained from the Kattarian bridge to Railway bridge from Water And Sanitation Authority (WASA). Total numbers of survey points were 9941 from October 2006 to July 2007
3	2D Mesh of Nullah Lai	Mr. Umer (Umer, 2015)
4	Discharge hydrograph	Japan International Cooperation Agency (JICA, 2003)
5	Flood extent and water depth in the floodplain	6.01 Km^2 flood extent and water depth of more than 4 meters in the low-lying area of Ganjmandi, Raja Bazar, Naya Mohalla, Mohan Pura, Dhok Charaghdin and Ratta Amral.(JICA, 2003)

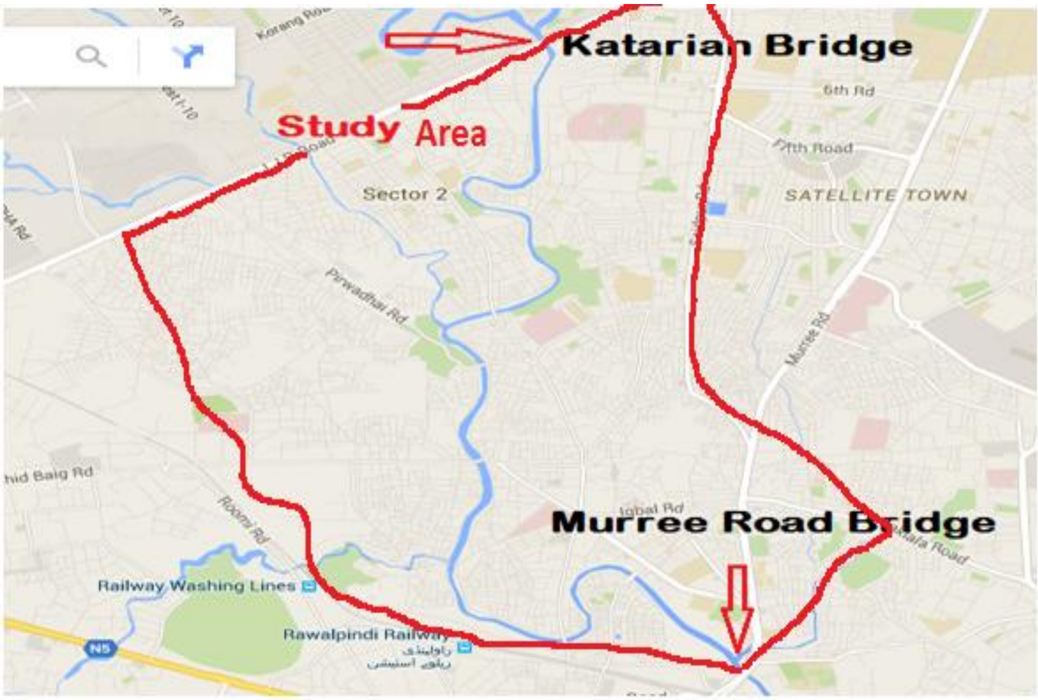
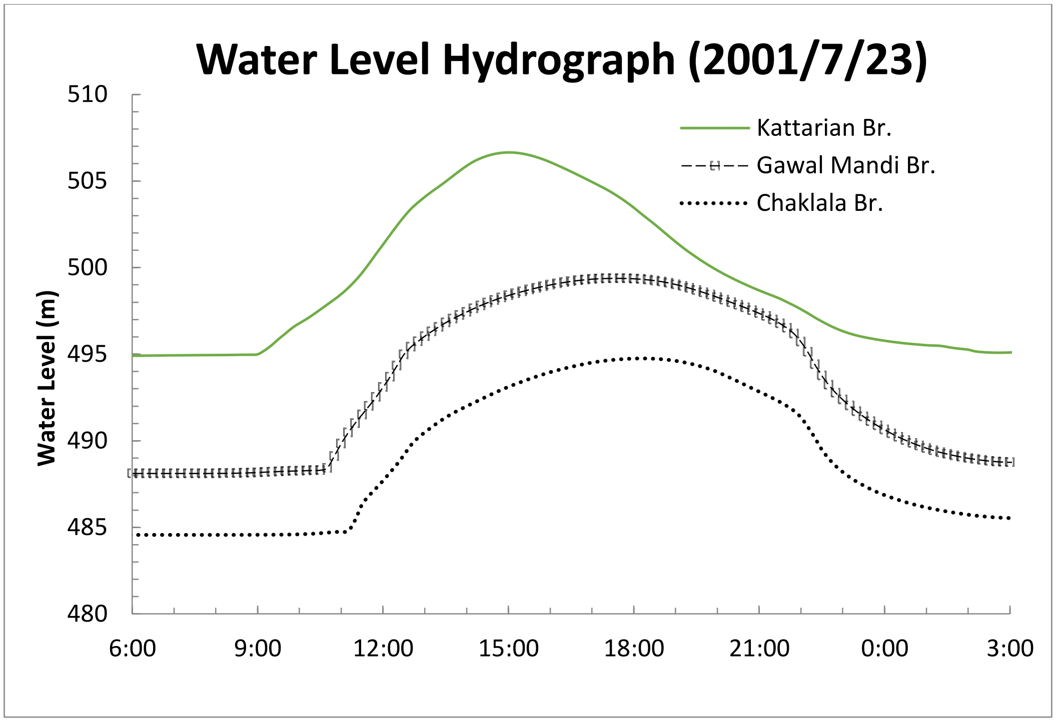


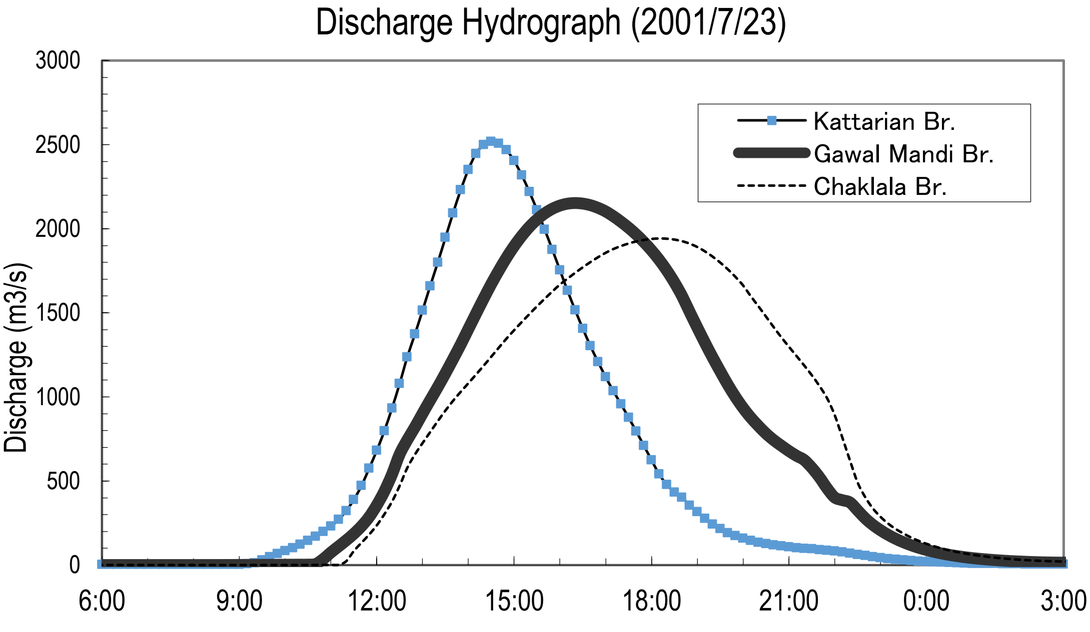
Figure 4.2: Study area (Not to scale)

Hydrological data is maintained by Pakistan Meteorological Department (PMD). Under PMD a project was run titled ‘Flood Forecasting and Warning System’, (FFWS) for the Nullah Lai basin. The primary purpose of this project was to establish a system that enables flood monitoring and mass evacuation during a flood event. Under this project, all hydrological data for the Lai stream was collected and maintained. Discharge data and hydrographs for the 2001 flood event were difficult to obtain as there were no gauging stations on the Lai stream. Therefore, after 2001 flood event, JICA conducted a survey and with the help of a hydrological rainfall-runoff model, excess precipitation was converted to runoff discharge by SCS Unit-Hydrograph using MIKE-11 and reproduced flood hydrograph of 2001 flood event. It is necessary to mention here that peak discharge estimated was based on an assumption that all flood water was confined in a river (JICA, 2003). JICA survey report and reproduced results were downloaded from the internet for the purpose of this study (Anonymous, 2002). Figure 4.3 shows a reproduced water level hydrograph and Figure 4.4 discharge hydrograph of 2001 flood event at the Kattarian Bridge, Gawal Mandi bridge, and the Chaklala bridge location.



Running time (hours)

Figure 4.3: Water level vs running time (JICA, 2003)



Running Time (hours)

Figure 4.4: Discharge vs Running time(JICA, 2003)

- There were many anomalies in Lai cross-section data e.g. many cross sections were missing, the coordinates of some cross-section were out of range. The missing cross-sections were added and coordinates were corrected by analyzing the raw data obtained from Rawalpindi Development Authority (RDA).
- After the 2001 flood, the work on the remodeling of Nullah Lai started, in which the illegal encroachments were removed and Nullah bed was dredged of sediments in order to increase the depth of Lai. Therefore elevation of many points has been changed since then and for the present simulation, post-remodeled Lai elevations have been used.
- The mesh created from the DEM and the topographic file does not incorporate the details regarding the buildings and bridges. In its place, increased value of roughness coefficient is used for the simulation which shows the same effect of slowing down the flood as exerted by the urban area on the flood.

4.3 PARAMETER SELECTION

Following is the main parameters which have been used in this study.

Manning coefficient 'n' for the main channel and floodplain.

4.3.1 Manning Coefficient '*n*' for the main channel and floodplains

The Manning's roughness coefficient "n" is used in the Manning's formula to calculate flow in open channels which is given below.

$$V = (1/n)R^{2/3}S^{1/2} \qquad \text{(Eq. 4.1)}$$

V = velocity in ft/sec

n = Manning coefficient is constant

R_h= hydraulic radius in ft

S= slope of the hydraulic grade line

It represents surface resistance to flow. It has a key role in this study and flood hydrodynamics. Many researchers have tried to develop a relation for velocity and flow resistance. Mainly two relations are used, which are Manning's, Chezy's or Darcy-Weisbach equations. For the purpose of modeling, Manning relation is mostly used. As the floodplain of Lai have buildings, streets, pavements, etc. which has been neglected for the purpose of this study and channel has stone, weeds in some area and in some areas silting and scouring occurs at meandering sections due to which two Manning coefficients were used, one for the main channel and second for the floodplain. Therefore increased value of roughness coefficient is used for the simulation which shows the same effect of slowing down the flood as exerted by the urban area on the flood. The use of the appropriate value of Manning coefficient was the most delicate step. Inappropriate selection of Manning coefficient may lead to errors in modeling for velocity and discharge calculation. Manning coefficient '*n*'=0.035 for Lai channel and 0.05 for floodplain respectively have been used for this study which had also been used in an earlier study (Tallat et al., 2011).

Connection points are those points where the discharge takes place from 1D channel to 2D floodplain and vice versa. For the purpose of this study, connection points have been defined on both sides of channel i.e. on the right and left side. Connection points are those points whose elevation is lower than its neighbor.

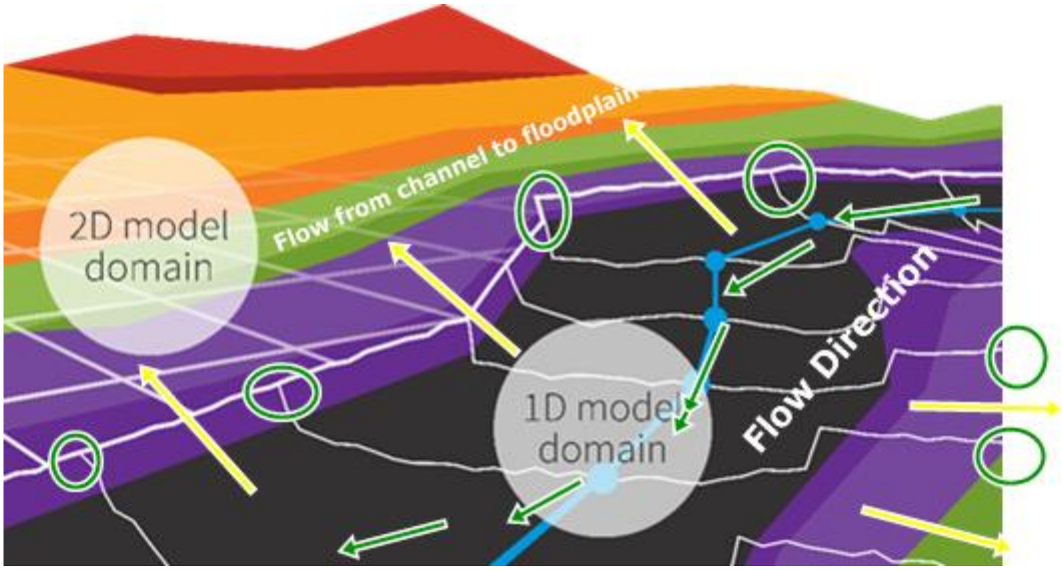


Figure 4.5: Conceptual view of 1D-2D coupled modeling (not to scale)

The idea behind making the connections is that when the water in the channel gets higher than a certain level it starts flowing onto the floodplain. The points of the flow exchange are taken as the connection point. A connection consists of three points or more. The center point is connected to its left and right side to make one connection. Connection point should be located at such place in channel and floodplain where the elevation is lower than neighbor points. In this way, the connection points are those points where water transfer occurs from the main channel to the floodplain. Both the right and left connection are defined as is clear from the Figure 4.5 and 4.6 respectively.

On the right floodplain, 36 numbers of connections have been defined. The point at which the elevation is low and has more chance that water will flow at this point from the main channel to the floodplain. In the same manner, a total of 16 number connections have been defined on the left floodplain.

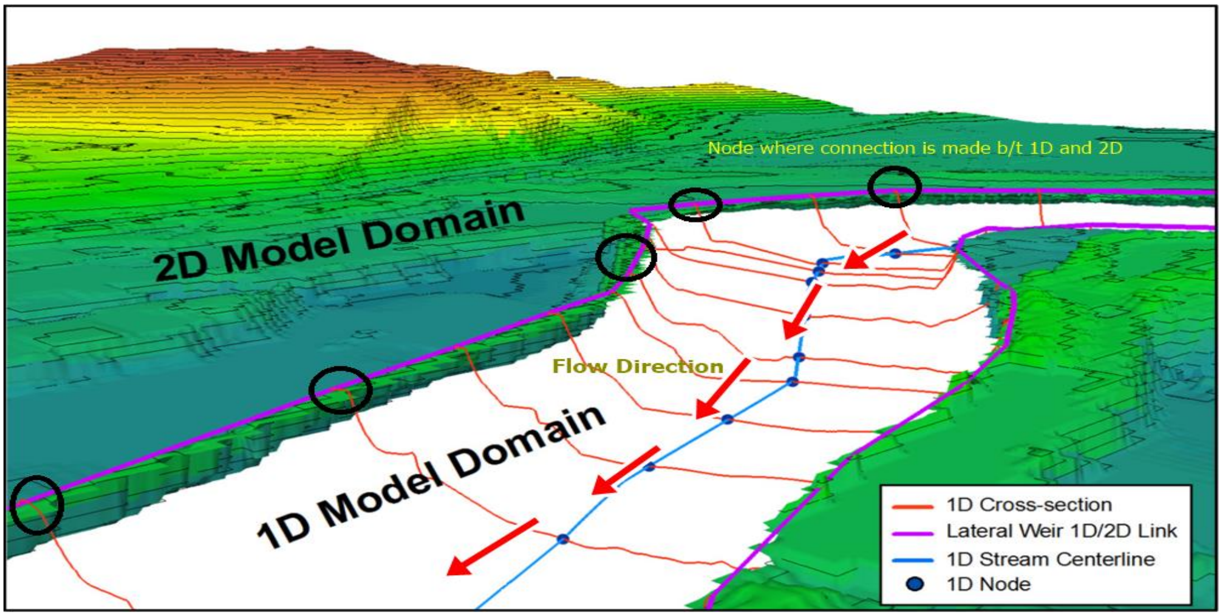


Figure 4.6: Conceptual view of 1D-2D coupled model (not to scale)

4.4 SIMULATION

A number of simulations were performed for the purpose of this study. At the initial stage, simulations were performed to remove errors in 1-D channel file and 2 D mesh. At the next level, 1D-2D coupled simulations were performed to get best results. During all simulations, some factors were kept constant which are given below.

- The floodplain has buildings, pavements, and other structures which have not been incorporated in the simulations due to insufficient topography details.
- The mesh used in all the coupling technique is same i.e. 18683 number of cells on left and 19232 number of cells are on right of floodplain are same.
- The length of 1D channel is 12.5 km from the Kattarian Bridge to Murree Road Bridge consisting of total 250 cross-sections at the distance of 50 meters apart.
- JICA prepared flood hydrograph of 2001 flood event by utilizing SCS Unit-hydrograph method in MIKE-11. This flood hydrograph has been used as the upstream boundary condition.

4.4.1 Runtime

The input hydrograph has flood discharge value for 15 hours on 23/7/2001 i.e. from 0900 hours to 00:00 hours as shown in Figure 4.7. Hydrograph has a time step of 1000 seconds against 54000 seconds total time. It means we have 54 values of flood discharge against 15 hours' time. Therefore simulation has been run for 54000 seconds.

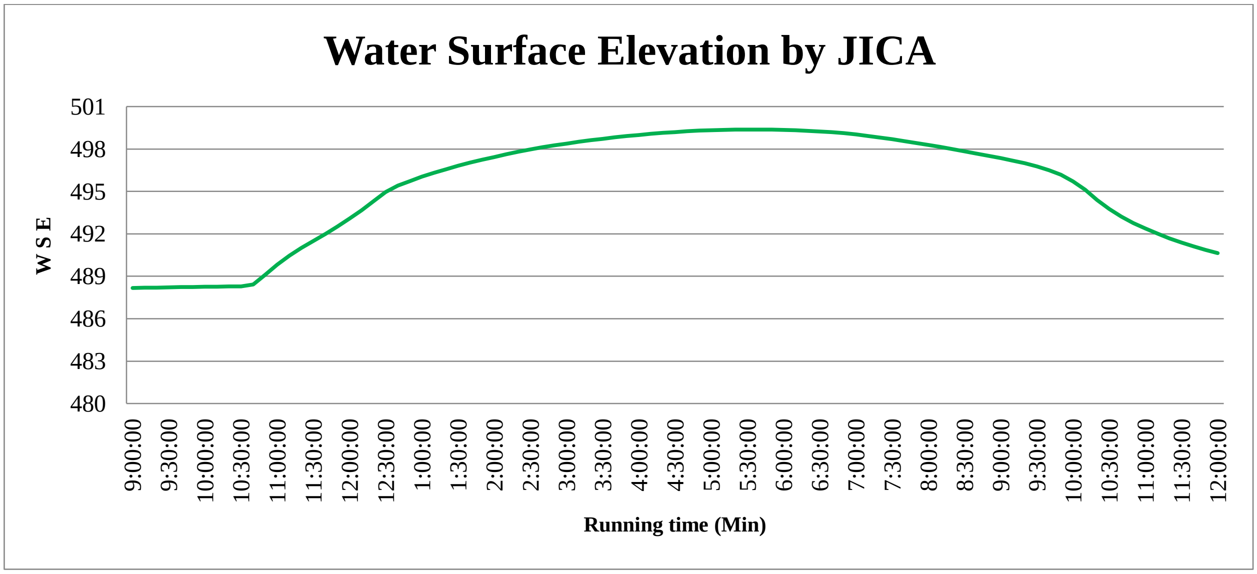


Figure 4.7: Input hydrograph from JICA at Gawalmandi bridge.

4.4.2 Boundary Conditions

In order to run 1D-2D coupled simulation by using BASEMENT, boundary conditions are needed both at the upstream and on the downstream for the channel. Different boundary conditions are available in BASEMENT, e.g. wall, weir, coupling weir, hydrograph, etc. For the 1D channel at the upstream a 'hydrograph' condition has been applied. Hydrograph condition required a file of two column containing discharge corresponding to the time (Faeh et al., 2011).

Discharge hydrograph of 2001 flood of the Kattarian Bridge has been taken as the inlet or upstream parameter of the model. Different options can be applied at the outlet boundary or downstream of the channel. For this study 'zero gradient' condition has been applied at the downstream end of the channel. 'Zero gradient' mean all the main variables remain constant in the last computational cell.

4.5 SIMULATION RESULTS

Different outputs are obtained by running the simulation in BASEMENT e.g. max depth, max velocity, the velocity with respect to time, depth with respect to time; discharge etc. for 1D channel and same can be obtained for the 2D floodplain. Following are the different results obtained from the simulation which has been analyzed and compared with an already carried out study about the Nullah Lai.

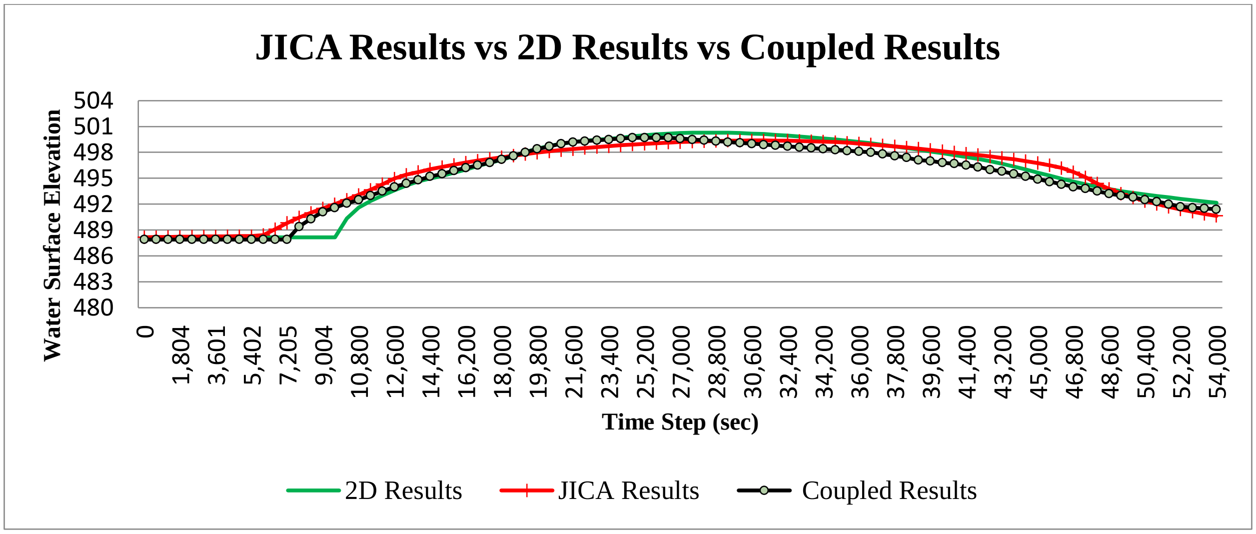


Figure 4.9: Comparison of JICA results, fully 2D model and 1D-2D coupled technique for Gawalmandi Bridge.

4.5.1 Discussion

For Gawalmandi Bridge the JICA highest value is 499.3 meters, 500.2 meters by fully 2D model while the calculated highest value is 499.7 meters as shown in Figure 4.9. There is a difference of 0.4 meters between coupled and JICA and 0.3 meters between coupled and fully 2D model. It has been observed that both the values of coupled and 2D model are more than the JICA values. The first reason is that in coupled model more discharge enter into the floodplain due to connection points at low elevation while in 2D model all the points are treated at same elevation. Second reason is non-availability of reliable data for cross sections.

The cross section data used in this simulation is developed in 2003 but in 2002 Lai channel was modified by digging and by widening. The discharge from two important tributaries one is Niki Lai and second Dhok Hassu Nullah both join the Lai below the Khayane-sir-syed bridge and Peerwadi bridge respectively has not been included in this study, therefore, the calculated peak value is less than the observed one. It is possible that if the discharge from these tributaries is included in the calculation we may get accurate results as shown in the Figure 4.10.

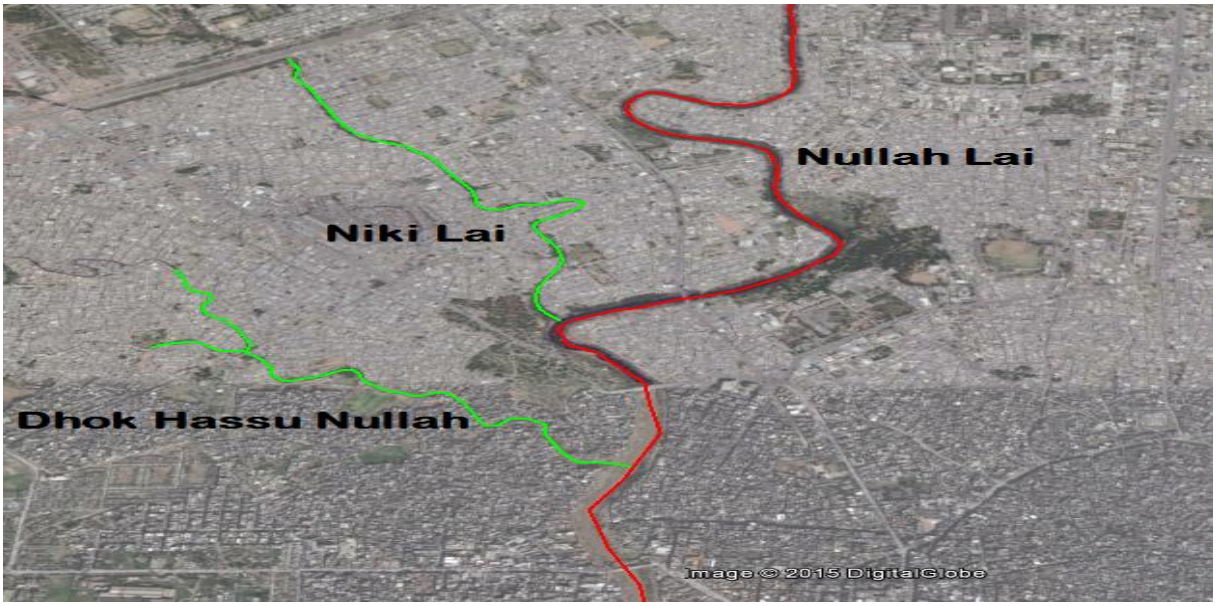


Figure 4.10: Niki Lai and Dhok Hassu Nullah Join main Lai channel at Khayane-sir-Syed bridge and Peerwadi Bridge (Not to scale)

4.5.2 Comparison of Water Depth in Channel

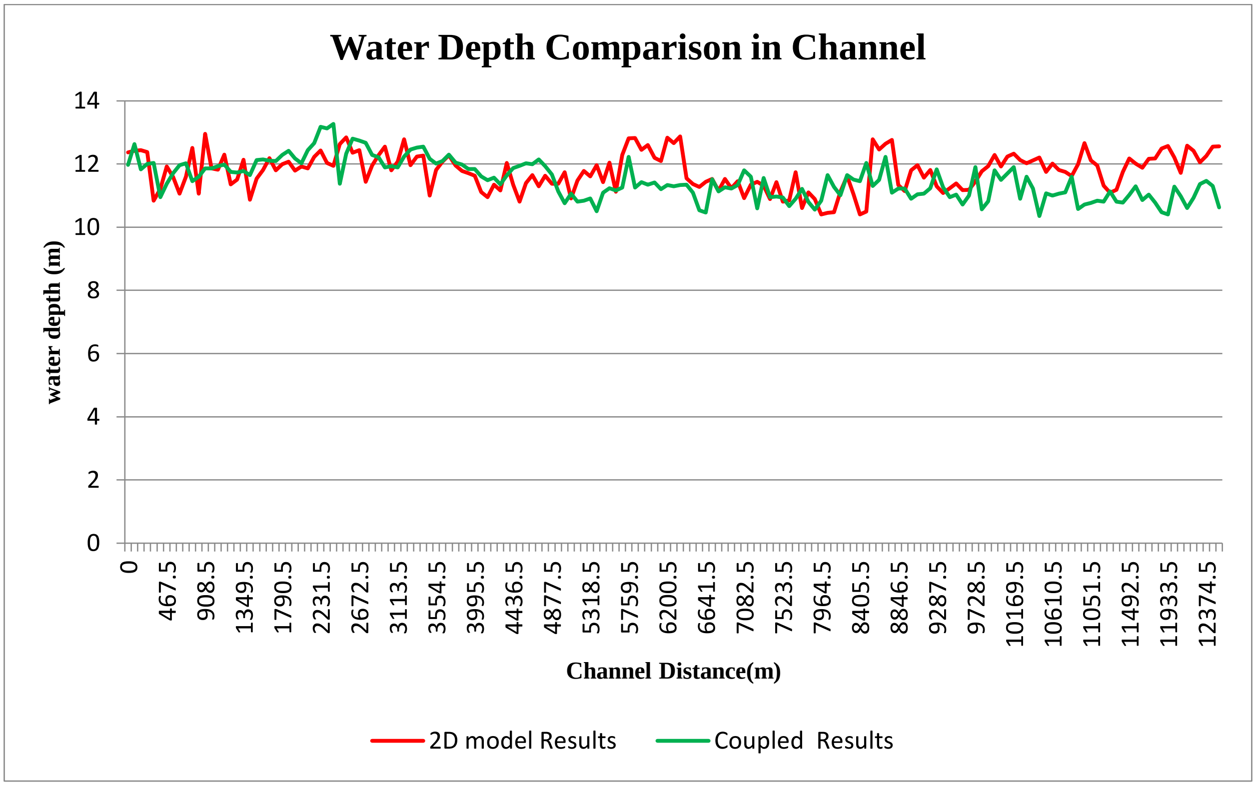


Figure 4.11: Water depth comparison for 1D-2D coupled and fully 2D model

4.5.3 Discussion

The Figure 4.11 shows the water depth comparison for 1D-2D coupled model and fully 2D model. From the figure, it is clear that water depth in the channel is almost same but deviate at the end points. At the end points, depth decrease for coupled model while for 2D model it increases slightly (Umer, 2015). As the WSE decreases for coupled model in the channel the depth also decreases. The reason for this decrease is again the same that more discharge enter into the floodplain for the coupled model due to the connection points at low elevations.

4.6 WATER DEPTH AND VELOCITY COMPARISON IN FLOODPLAIN

4.6.1 Water Depth Comparison for 1D-2D Coupled, 2D and JICA

The max depth obtained from the 1D-2D coupling is 6-7 meters in an area called Naya Mohalla near Liaquat Road and Gawalmandi bridge as shown below Figure 4.12. Depth calculated from the fully 2D is 5-6 meters in the same area (Umer, 2015). The 1D-2D coupled results agree with the observed value of Japan International Cooperation Agency (JICA, 2003) that max depth occurs in low lying area i.e. Ganjmandi, Raja Bazar, Naya Mohalla, Mohan Pura, Dhok Charaghdin and Ratta Amral as shown in the Figure 4.13. The reason for more water depth in the floodplain is due to more transfer of mass from channel to floodplain for coupled model. This phenomenon occurs due the better method of transferring mass from channel to floodplain in the coupled method.

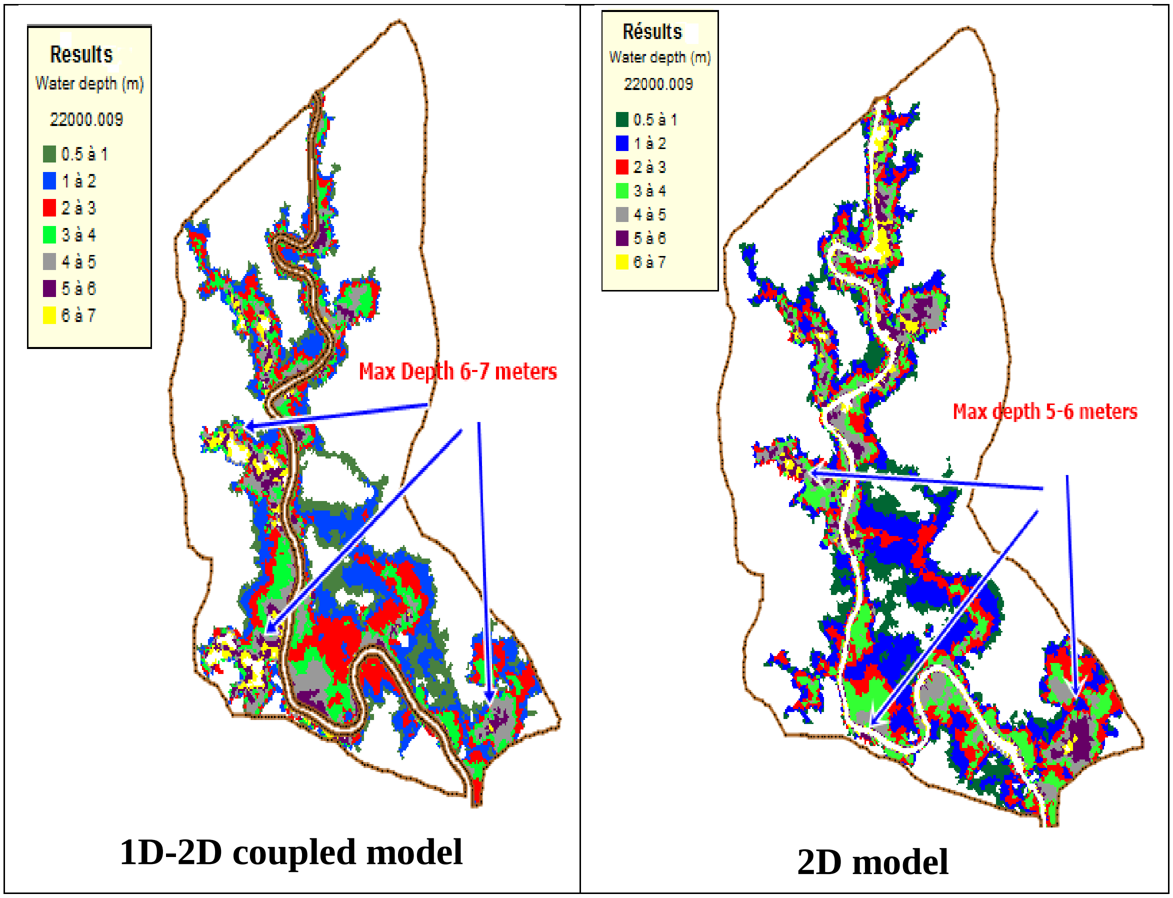


Figure 4.12: Flood extent map by1D-2D coupled and 2D modeling

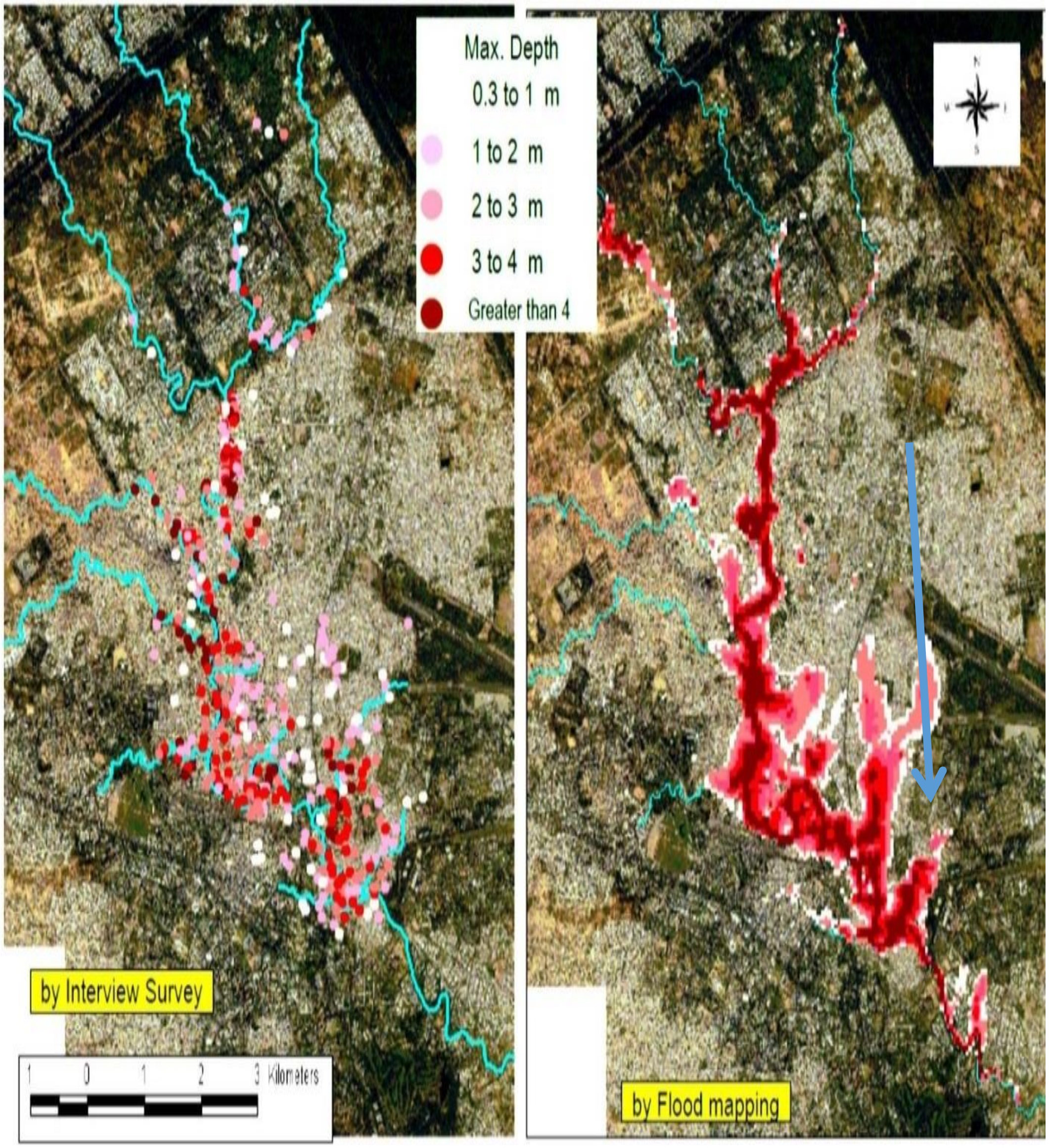
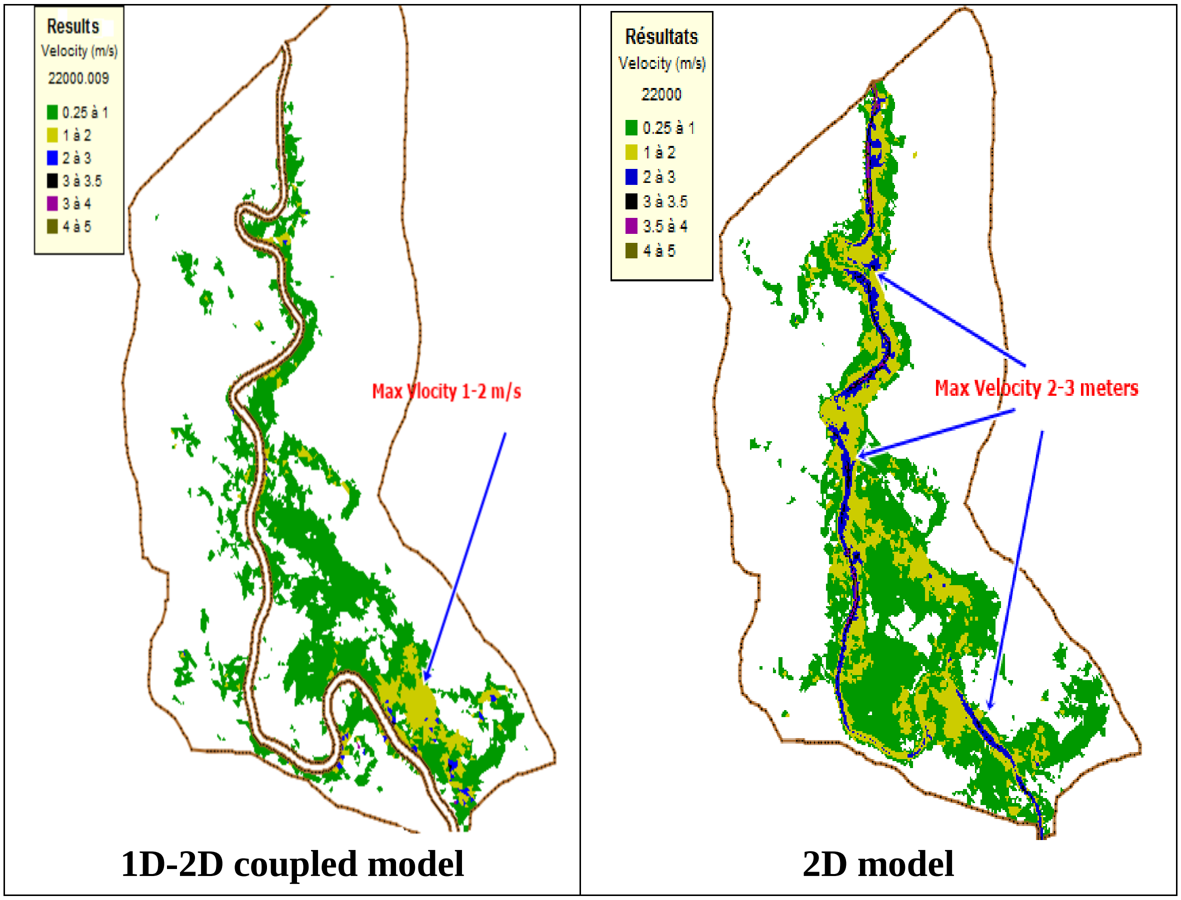


Figure 4.13: Flood map prepared by JICA

4.6.2 Velocity Comparison for 1D-2D Coupled and Fully 2D Technique

The Figure 4.14 shows the velocity comparison for 1D-2D coupled model and fully 2D model. From the comparison, it is clear that max velocity in the case of 1D-2D couple model is 1-2 m/s which occurs in a low lying area i.e. Ganjmandi, Raja Bazar, Naya Mohalla, Mohan Pura, Dhok Charaghdin and Ratta Amral. Fully 2D model produces the velocity of 2-3 m/s (Umer, 2015). The increased value of velocity in coupled model is due the frictional coefficient. The coefficient value of 0.03 has been used for coupled model and 0.05 for the 2D model.



1D-2D coupled model **2D model**

Figure 4.14: Velocity comparisons between 1D-2D coupled model and fully 2D model

4.7 FLOOD EXTENT COMPARISION

Table 5.3: Comparison of flood extent by JICA, 2D modeling, and coupled model

Inundated Area	**(Km^2)**
Flood extent by (JICA, 2003)	6.01
Flood extent by coupled model	5.92
Flood extent by fully 2D model (M.Umer, 2015)	5.69

Figure 4.12 and 4.13 is a visual comparison of flood extent calculated by JICA in 2002-2003. It is clear that JICA observed values and coupled model have a close relation. Table 5.3 is a numerical comparison of flood extent calculated by three different techniques. From this table, it is also clear that the flood extent 5.92 km^2 is near the 6.01 km^2 calculated by JICA. The reason for more water extent in the floodplain is due to more transfer of mass from channel to floodplain.

4.8 CONCLUSIONS

- Simulated results are in close agreement with the JICA model results as far as the floodplain is concerned but deviations are observed over the main channel due to the non-availability of reliable data for cross sections.
- The connection points are very important for the discharge value transferred from the channel to the floodplain and vice versa.
- On visual comparison of inundation extent, coupled model depicts strong correlation with JICA's flood map.
- The coupled model took 1.5 hours on Core i3 with 4 GB Ram while 2D model took 4.5 hours to run the same simulation (Umer, M. 2015).
- The coupled model has shown better results for the water depth in the floodplain and flood extent than the 2D model due to the better approach of connection points.
- The research showed the potential of the coupled simulation to predict the flooding extent and the wave propagation, highlighting its role in the rescue and relief efforts for the urban population living in flood-prone basins.
- Ease to calibrate and to run the model between 1D-2D coupled and fully 2D model depends on data availability, the complexity of topography and how much fine results are required.
- Velocity calculated in 1D-2D coupled model is 1 to 2 m/s while in the fully 2D model it is 2 to 3 m/s for the floodplain.
- The computational efficiency of coupled model is more in evidence when it is applied to large river reaches e.g. Indus river reach between two barrages.

REFERENCES

Ahmad, B., Kaleem, M. S., Butt, M. J., & Dahri, Z. H. (2010). Hydrological Modelling And Flood Hazard Mapping Of Nullah Lai. Proc. Pakistan Acad. Sci, 47(4), 215-226.

Ahmad, S. (1999). Comparison of One-Dimensional and Two-Dimensional Hydrodynamic Modeling Approaches For Red River Basin (pp. 51). International Joint Commission: Natural Resources Institute Facility for Intelligent Decision Support University of Manitoba Winnipeg, Manitoba Canada.

Ali, M. (2009). Impacts of Land Use Change on Surface Runoff of Lai Nullah Basin. M.S, National University of Sciences and Technology (NUST) Islamabad 44000, Pakistan

Bladé, E., Gómez-Valentín, M., Dolz, J., Aragón-Hernández, J. L., Corestein, G., & Sánchez-Juny, M. (2012). Integration of 1D and 2D finite volume schemes for computations of water flow in natural channels. Advances in Water Resources, 42, 17-29. doi: 10.1016/j.advwatres.2012.03.021

Chu, X., A.M.ASCE, & Steinman, A. (2009). Event and Continuous Hydrologic Modeling with HEC-HMS. JOURNAL OF IRRIGATION AND DRAINAGE ENGINEERING, 135, 119-124. doi: 10.1061/ASCE0733-94372009135:1119

Faeh, R., Muller, R., Rousselot, P., Vetsch, D., Volz, C., Vonwiller, L., . Farshi, a. D. (2011). System Manuals of BASEMENT version 2.1 (2.1 ed.). Zurich, Switzerland: (VAW) Laboratory of Hydraulics, Glaciology, and Hydrology. Swiss Federal Institute of Technology (ETH).

Ford, D. T., & Hamilton, D. (1996). Computer models for water-excess management Water resources handbook: McGraw-Hill, NY.

Hashmi, H. N., Siddiqui, Q. T. M., Kamal, M. A., Mughal, H. u. R., & Ghumman, A. R. (2012). Assessment of inundation extent for flash flood management. African Journal of Agricultural Research, 7(8), 1346-1357. doi: 10.5897/AJAR11.1394

Hervouet, J.-M., and Janin, J.-M., (1994). Finite element algorithms for modeling flood propagation, ASCE, 101–113.

Hydrologic Engineering Center, U. A. C. o. E. (2002). HEC-Ras, River Analysis System,

JICA. (2003). The Study on Comprehensive Flood Mitigation and Environmental Improvement Plan of Lai Nullah Basin in The Islamic Republic of Pakistan,submitted by CTI Engineering International Co Ltd. and Pacific Consultants International, Pakistan. (Vol. 2, pp. 296). Islamabad: JICA.

Jimoh, H. I. (2008). Drainage Problems in a Tropical Environment: Perspectives on Urban Quality Management. Journal of Human Ecology, 4.

Kamal, A. (2004). Lai nullah basin flood problem Islamabad – Rawalpindi cities World Meteorological Organization Global Water Partnership, 27.

Kuiry, S. N., Sen, D., & Bates, P. D. (2010). Coupled 1D–Quasi-2D Flood Inundation Model with Unstructured Grids. Journal of Hydraulic Engineering, Vol. 136,No. 8, 13. doi: 10.1061/(ASCE) HY.1943-7900.0000211

Masoudian, M., & Theobald, S. (2011). Influence of land surfaces topography on flood hydrograph Journal of American Science, 7.

Morales-Hernández, M., García-Navarro, P., Burguete, J., & Brufau, P. (2013). A conservative strategy to couple 1D and 2D models for shallow water flow simulation. Computers & Fluids, 81, 26–44.

Néelz, S., & Pender, G. (2009). Desktop Review of 2D hydraulic modeling packages (pp. 63): Environment Agency's Science Department Environment Agency/Defra Flood Coastal Erosion Risk Management Research and Development Program.

Refsgaard, J. C., & Knudsen, J. (1996). Operational validation and intercomparison of different types of hydrological models. Water Resources Research, 32. doi: 10.1029/96WR00896

Samuels, P. G. (1990). Cross-section location in one-dimensional models. Int. Conf. on River Flood Hydraulics, 339–350.

Tallat, Q., Siddiqui, M., Hashmi, H. N., Ghumman, A. R., & Mughal, H. u. R. (2011). Flood Inundation Modeling for a Watershed in the Pothowar region of Pakistan. Arab J Sci Eng, 36, 1203–1220. doi: 10.1007/s13369-011-0112-2

USACE, U. S. A. C. o. E. (2000). Hydrological Modeling System HEC-HMS. USACE, Washington, DC.

Umer, M. (2015). Two-Dimensional Flood inundation modeling. M.S, NUST, NUST.

Vojinovic, Z., & Tutulic, D. (2009). On the use of 1D and coupled 1D-2D modeling approaches for assessment of flood damage in urban areas. Urban Water Journal, 6(3), 16. doi: 10.1080/15730620802566877

APPENDICES

Appendix

A.1 BASEMENT

BASEMENT is a river engineering tool, which supports the engineer in the solution of tasks in the domain of river area modeling. The program permits reliable computations based on state of the art numerical tools, constant onward development and successive realization of case studies. Unlike currently used programs for the simulation of a specific flow behavior, BASEMENT intends the arrangement of many different problem types with one single tool to gain an integrated understanding for the initial position, the solution process and its results.

A.2 EMPLOYMENT DOMAINS

The aim of BASEMENT is to permit the solution of as many problems as possible in the domain of river engineering, especially in cases for which the traditional dimensioning tools are insufficient and studies including physical hydraulic models are not possible or too expensive.

Typical employment domains are:

- Several problems in relation with the sediment transport of water courses, for instance the future development of deltas and alluvial fans, the long term evolution of the bottom of channels, or the aggradations of storage spaces and the consequences of their scavenging;
- River engineering enterprises, which imply the modification of the channel geometry, as this can be the case for example for revitalizations or protection measures, where the consequences of the interventions have to be evaluated;
- Identification and quantification of dangers for the development of danger maps or of protection and emergency measures, considering the flow behavior and sediment deposition both inside and outside of the main channel, as well as erosion danger, and consequences of debris flows and dam breaks.

A.3 PROCESSED DATA TYPES

The raw data can be divided into three groups:

- topographic data, particularly elevation models and cross sections
- hydrologic data: time series of flow discharge, water levels or concentration of suspended sediments, velocity profiles;
- Granulometric data: grain size distributions from water-, sediment- or line samples.

A.4 CAPABILITIES

BASEMENT has the following fundamental capabilities:

- Simulation of flow behavior under steady and unsteady conditions in a channel as well as its transition.
- Simulation of sediment transport (both bed load and suspended load) under steady and unsteady conditions in a channel with arbitrary geometry.
- Simulation of erosion.
- Choose between different approaches (e.g. choice of problem matched solver-algorithms).

A.5 SYSTEM OVERVIEW

At the current stage of development, the software system consists of the numerical subsystems and the different interfaces to the infrastructural software, such as pre- and post-processors. The core of BASEMENT consists of the numerical solution algorithms comprised in the appropriate modules. Pre- and post-processing can be performed with independent products using a well-defined common interface. The flexible software design enables a future adoption to a common database for input- and output data.

A.6 NUMERICAL SUBSYSTEMS

The core of the software system consists of the numerical subsystems, which actually are:

A.6.1 BASE chain

The one dimensional numerical tool named BASE chain enables the simulation of river reaches (based on cross sections) with respect to sediment transport. BASE chain solves 1D Saint Venant Equations 1.1 to 1.2 which are given below.

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0 \qquad \text{(Eq. 1.1)}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g\frac{\partial y}{\partial x} - g(S_o - S_f) = 0 \qquad \text{(Eq. 1.2)}$$

Where

A = Flow x-sectional area (m^2)

C = Chezy's resistance coefficient ($m^{1/2}/s$)

g = Acceleration due to gravity (m/s^2)

h = Stage above horizontal reference level (m)

Q = discharge (m^3/s)

In one dimension, an element consists of two nodes with known cross-section. With a cell-centered discretization, all variables velocity, flow depth and cross-section geometry are defined at the location of the nodes. The midpoint of the connecting line between two nodes defines the common edge of the two elements.

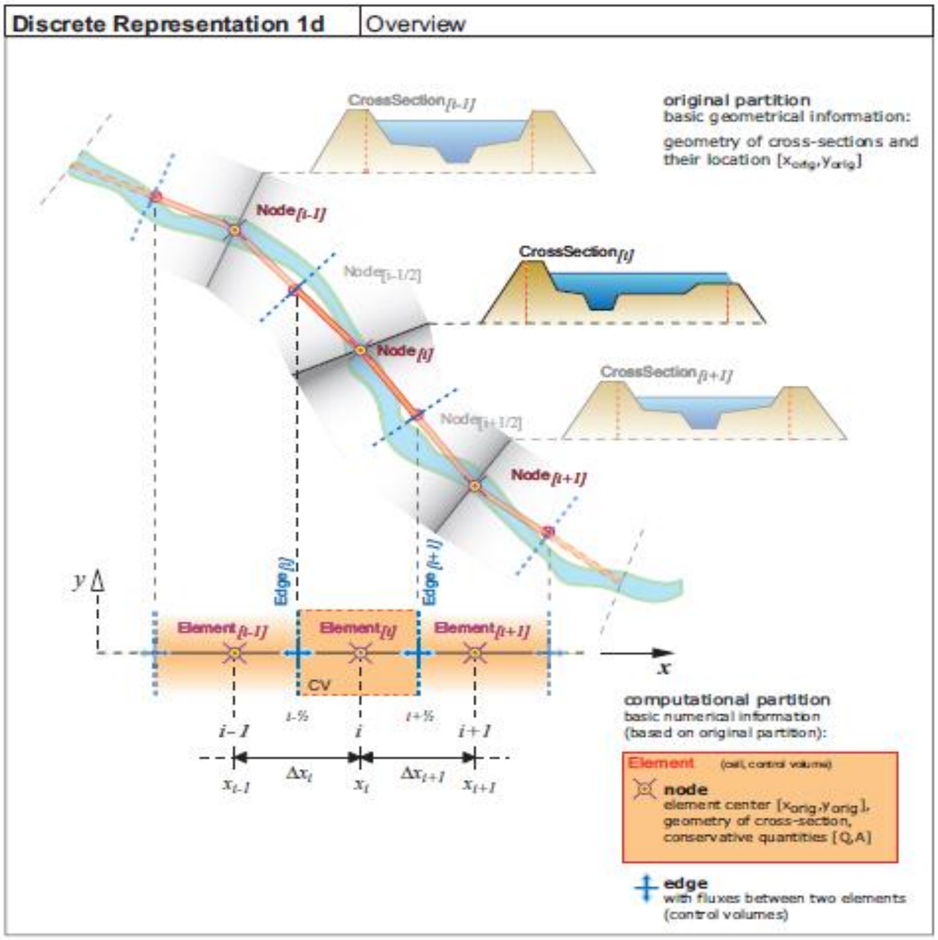


Figure 1: Dizcrete representation of the topography within BASE chain

A.6.2 BASE plane

The two dimensional numerical tool named BASE plane enables the simulation of river reaches as well as flood plains (bases on a digital terrain model) with respect to sediment transport. BASE plane solves 2D Saint Venant Equations 1.3 to 1.5 which are given below.

$$\frac{\partial h}{\partial t}+\frac{\partial(\bar{v}h)}{\partial x}+\frac{\partial(\bar{v}h)}{\partial y}=0$$

(Eq. 1.3)

$$\frac{\partial\bar{u}}{\partial t}+\bar{u}\frac{\partial(\,\bar{u})}{\partial x}+\bar{v}\frac{\partial(\,\bar{u})}{\partial y}+g\frac{\partial h}{\partial x} = -g\frac{\partial z_b}{\partial x}-\frac{1}{\rho h}\tau_{bx}+\frac{1}{\rho h}\frac{\partial\{h(\bar{\tau}_{xx}+D_{xx})}{\partial x}+1/\rho h\;(\frac{\partial\left\{h\left(\bar{\tau}_{xy}+D_{xy}\right)\right)}{\partial y}$$

(Eq. 1.4)

$$\frac{\partial\,\bar{v}}{\partial t}+u\frac{\partial(\;\bar{v})}{\partial x}+\frac{\bar{v}\partial(\;\bar{v})}{\partial y}+g\frac{\partial h}{\partial y} = -g\frac{\partial z_b}{\partial y}-\frac{1}{\rho h}\tau_{by}+1/\rho h\;(\frac{\partial\left\{h\left(\;\bar{\tau}_{yx}+D_{yx}\right)\right)}{\partial y}+1/\rho h\;(\frac{\partial\left\{h\left(\;\bar{\tau}_{xy}+D_{xy}\right)\right)}{\partial y}$$

(Eq. 1.5)

Where

h = water depth (m)

g = Gravity acceleration (m/s^2)

$\bar{\tau}_{xx,}\ \bar{\tau}_{yy}\bar{\tau}_{xy}\bar{\tau}_{yx}$ = depth average viscous and turbulence stresses (N/m^2)

z_b = Bottom elevation (m)

$\bar{v}$ = depth average velocity in y direction

D_{xy}, D_{yx}, D_{yy}, D_{xx} = Momentum dispersion terms (N/m^2)

$\bar{\tau}_{bx}$= bed shear stress in x direction (N/m^2)

In two dimensions, an element consists of three nodes with a known ground elevation. Usually, this real world height information is not given exactly at the desired node coordinates and therefore has to be interpolated. The primary variables are defined somewhere inside the element, e.g. the balance point. The fluxes between two elements are defined at their corresponding edges.

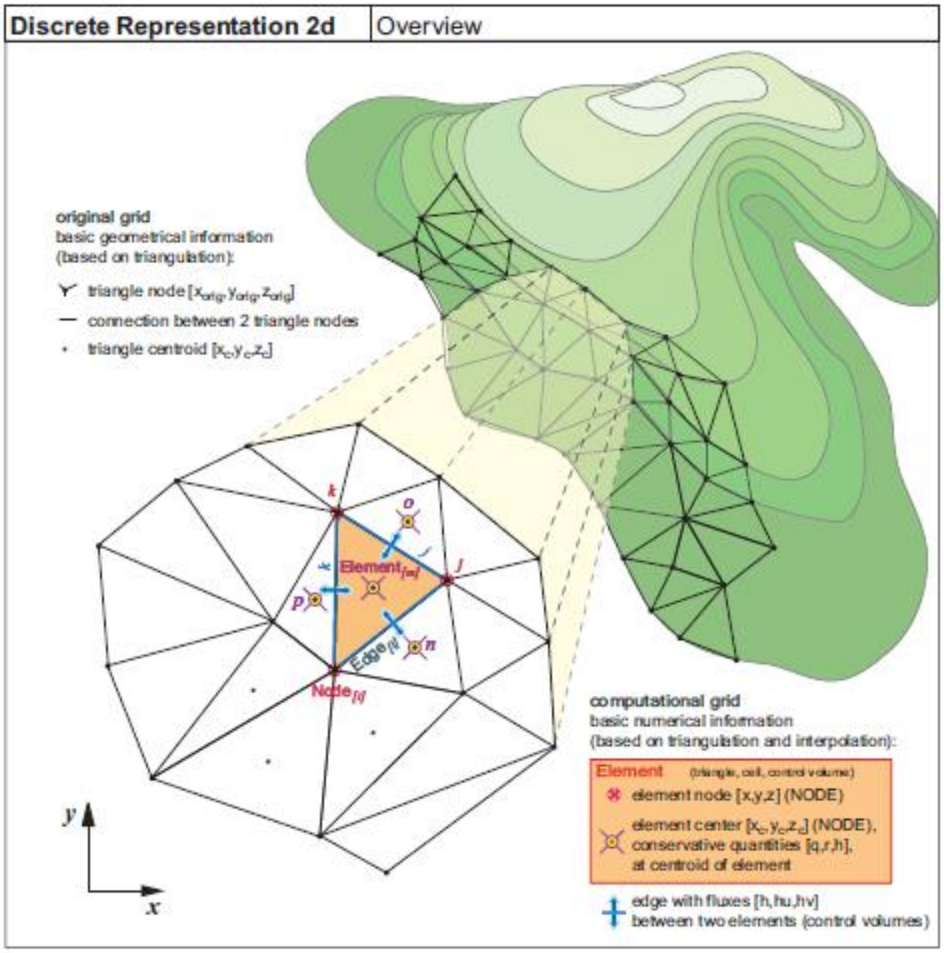


Figure 2: Dizcrete representation of the topography within BASE plan

A.7 COMPONENTS

To reveal the “black box” of the numerical models, Figure 3 gives a graphical insight. The simulation tools of BASEMENT can be subdivided into three different parts:

- The mathematical physical modules consisting of the governing flow equations
- The computational grid representing the discrete form of the topography
- The numerical modules with their methods for solving the equations

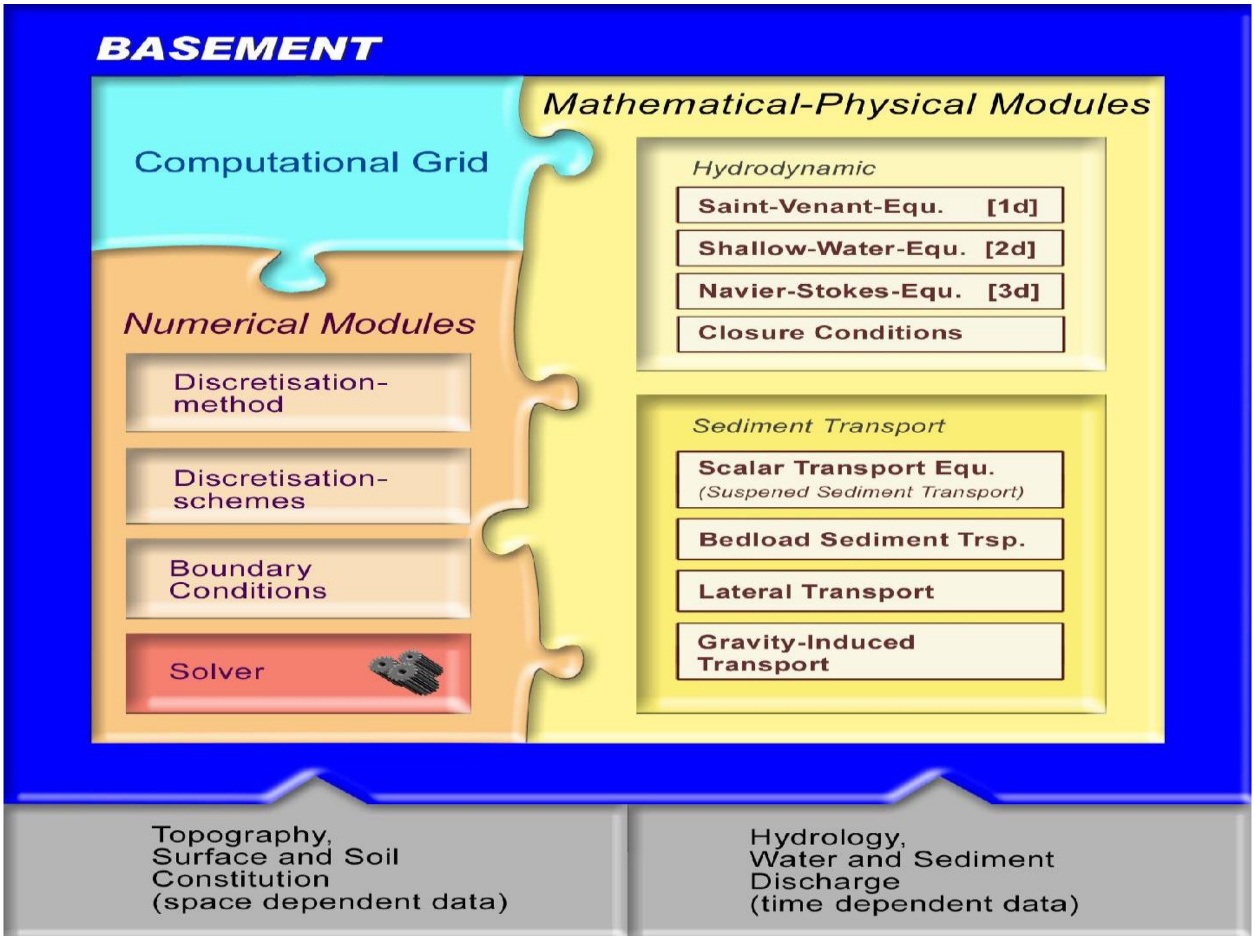


Figure 3: Modules and their Components

A.8 SIMULATION PROCEDURE

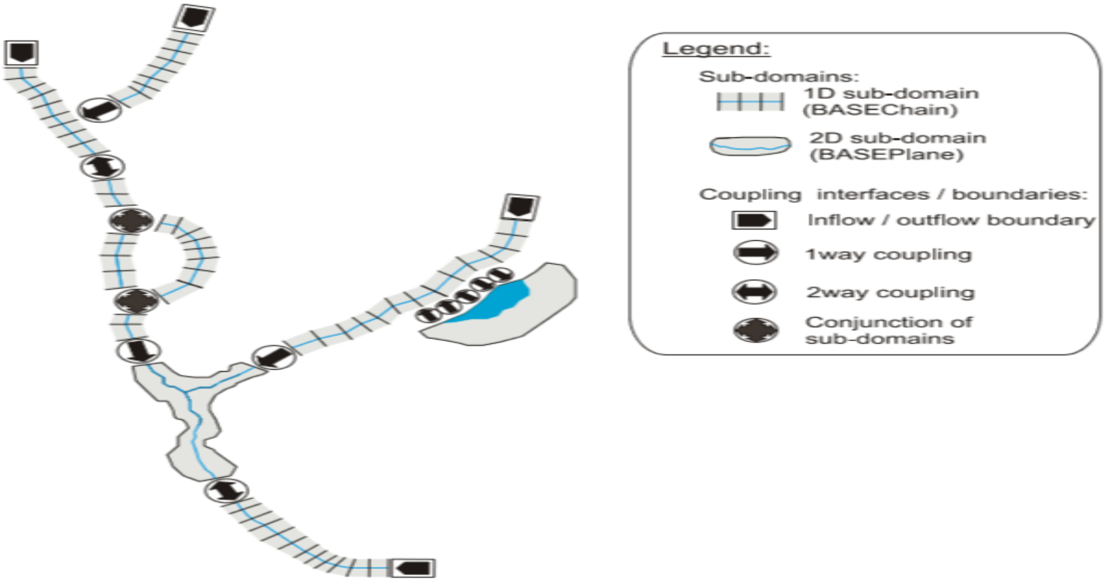
The procedure to simulate a concrete problem setup is not unique. BASEMENT is coded using an object-oriented design which allows for flexibility and interchange ability concerning different application problems. The possible combinations are manifold.

On the one hand, the governing equations may change dependent on simplifications or extensions of certain terms, use of sediment transport or pure hydraulics, etc. On the other hand, there are miscellaneous numerical methods, e.g. for time integration (implicit, semi-implicit, explicit) or computation of spatial fluxes. Therefore, the main variables of interest differ from one problem to the other.

It is of great importance, to plan carefully each simulation approach to a certain problem. The most difficult and time-consuming part is not the simulation itself but the acquisition of all needed data (topography, boundary- and initial conditions) and a proper setup of this data. This section describes the main activities performed to execute a simulation with BASEMENT in a very general case. In most problems, only a part of them are being used.

A.9 MODEL COUPLING

In addition to the simulation of single sub-domains using BASE chain (1-D) or BASE plane (2-D), the software BASEMENT also provides the possibility to connect sub-domains for combined numerical simulations. Such coupled simulations can range from simple configurations up to simulations of river networks with integrated river junctions bifurcations or integrated 1-D/2-D modeling. In Figure 4 a river network of multiple sub-domains with several coupling interfaces is illustrated. The coupling mechanisms thereby allow to couple hydrodynamic simulations as well as morphological simulations with sediment transport and suspended load.



River network with multiple BASEchain (1-D) and BASEplane (2-D) sub-domains and several coupling interfaces.

Figure 4: River network with multiple BASE chain (1-D) and BASE plane (2-D) sub-domains and several

A.10 Coupling Mechanisms

Coupling of sub-domains is implemented as an explicit coupling approach, which means that data is exchanged explicitly between the sub-domains at certain time intervals. This approach is simpler to implement than an implicit approach, especially regarding the coupling of sub-domains with mixed dimensionalities. However, in comparison to an implicit coupling approach, special care must be taken to achieve robust and stable combined simulations.

A.10.1 Exchange conditions for combined 1-d and 2-d modeling

The combined 1-D river flow and 2-D floodplain modeling bases mainly on the approach presented by Beffa. A conceptual overview is given in Figure 5 which illustrates river cross sections of the BASE chain sub-domain and the 2-D mesh of a floodplain modeled with a BASE plane sub-domain.

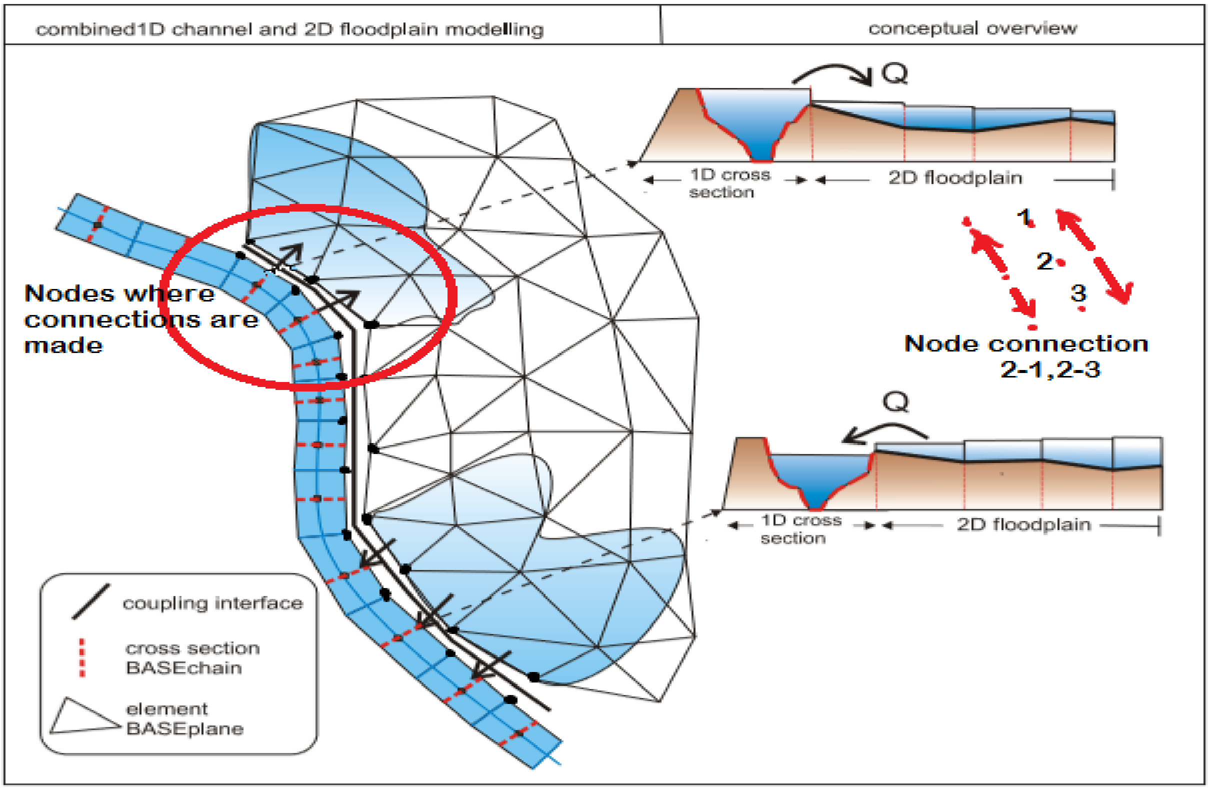


Figure 5: Conceptual over view of combined 1-D and 2-D floodplain modeling

A.11 LOCAL TIME STEPPING APPROACH

This approach bases on the method of local time stepping (LTS) as presented by Osher and Sanders (1983) and Sanders (2008). But in contrast to these methods, LTS is applied here to whole sub-domains instead of single grid elements. Different local time step sizes are allowed for the sub-domains instead of using one global time step for all sub-domains. This enables efficient computations by preventing very small time steps of single sub-domains to dominate the time step sizes of the other sub-domains. But restrictions are set for the time step sizes in a way to ensure that the sub-domains always reach common time levels. At these common time levels data can be exchanged easily without the need for interpolations.

A. 12 FUDAA-PREPRO

Fudaa-Prepro is 1 D, 2 D and 3 D hydrodynamic presenting program. It is employed before and after procedure of imitations. It could be employed for Imageries from GIS and when finished with procedure vertebral to GIS, mathematical simulation. The outputs might contain an exhibition of water surface elevation, flow yields.

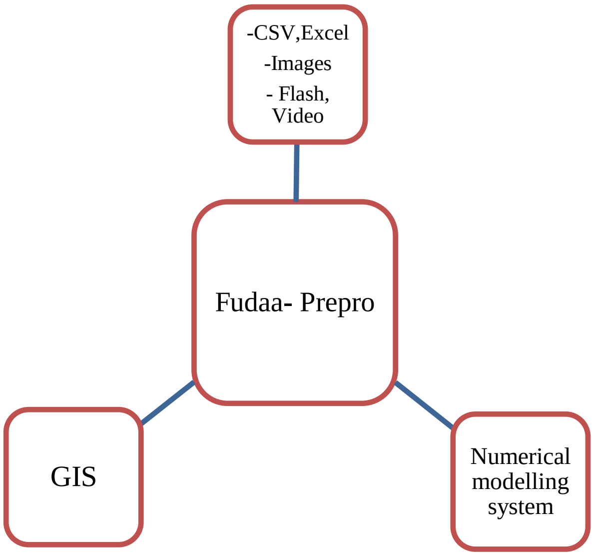
The software offers gears to work on a flow research. The gears are considered for the hydrodynamic methods like Reflux (CEREMA/DTecEMF), Rubar 20 (CEMAGREF) and Telemac (LNHE). The software is established by CEREMA/DTecEMF, based on Fudaa network.

Fudaa-Prepro provides tools to prepare and Launch a flow study. All the parameters can be easily edited thanks to interactive editors:

- Keywords / numerical parameters
- Nodal/mesh properties: bottom friction,
- Boundary conditions
- Liquid boundary conditions
- Initial conditions
- Transient curves
- Sources / culverts / weirs

- Structures / storm water
- Georeferenced images

Fudaa-Prepro uses a light GIS module allowing the user to create, use and share geographic data.



A.13 CAPABILITIES OF FUDAA-PREPRO

Produce graphs and animations in 1D, 2D and 3D

- Edit variables
- Compare with/import other results
- Perform advanced search
- Export to GIS format

A.14 COMPONENT OF FUDAA-PREPRO

A.14.1 Supervisor

- Files Explorer, codes launcher

A.14.2 Hydrodynamics projects Editor

- Keywords, boundary conditions, nodal parameters, initial conditions, sources, weirs, culverts.

A.14.3 Post-processor

- View results + exportation

A.14.4 Mesh View (under development)

- Check meshes