IMPACT ASSESSMENT OF CLIMATE CHANGE ON HYDROLOGICAL RESPONSE AND URBAN FLOODING FOR ADAPTATION STRATEGIES (CASE OF LAI NULLAH, PAKISTAN)

By

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2014-NUST-MS-WRE&M-63441

DEPARTMENT OF WATER RESOURCES ENGINEERING AND MANAGEMENT

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A thesis submitted in partial fulfillment of

the requirements for the degree of

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in

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(2016)

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by Mr Hammayun Zulfiqar Rana, Registration No. 2014-NUST-MS-WRE&M-63441, of MS WRE&M 2014 Batch (NICE) has been vetted by undersigned, found completed in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have been incorporated in the said thesis.

Signature___________________

Name of Supervisor Dr. Shakil Ahmad

Date:

Signature (HoD)__________________

Date:

Signature (Dean/Principal)_________________

Date:

DISCLAIMER

The views expressed in this work are those of the creators and do not necessarily represent those of the UK Government's Department for International Development, the International Development Research Centre, Canada or its Board of Governors.

DEDICATION

This work is dedicated to my beloved parents and family. It is their love and support that enabled me not only to complete this task but taught me to walk every step of life with confidence and commitment.

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ABSTRACT

Varying hydrological regimes caused due to intensive land use changes and high intensity rainfalls has significantly increased the frequency of extreme flood events in Lai Nullah, Pakistan. The current study involves application of a rainfall-runoff model through spatial modeling within GIS environment, frequency analysis for annual instantaneous peak flow and annual max daily rainfall series, estimation of Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF), development of rainfall intensity duration frequency (IDF) and depth duration frequency (DDF) curves, application of a suitable hydraulic model for flood plain inundation mapping, analysis of future climate scenarios and identification of various adaptation strategies. Rainfall-runoff model was successfully calibrated and validated using 10 mins interval rainfall data against stream flow gauge data at Kattarian and Gawalmandi. PMF values for Kattarian and Gawalmandi suggests an annual return period of 500 years. IDF curves based on 3 hr interval rainfall data showed credible results for use in design purposes. DDF curves represent efficient operational forecast guide for different storm durations for various stakeholder and policy makers. Delta downscaling technique was applied for bias correction for conversion from grid rainfall GCM data to point rainfall data. Frequency analysis was also carried out for projected annual maximum rainfall data under ensembled model conditions. Results of calibrated and validated hydraulic model showed good consistency with observed stage values. The integrated approach encompassing hydrological and hydraulic modelling under changing climate scenarios was used and it was found that 100 year return period flood expected to increase by 11% with flood extent increase of 0.506 Km^2. Further, adaptation strategies like ponds, flow diversion and forestation were also explored to mitigate the flood hazards impacts. This study will facilitate various policy makers and stakeholders in deciding and formulating the mitigation and adaptation strategies to improve the existing flood risk management and relief plans.

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LIST OF ABBREVIATIONS

AD	Anderson-Darling
AIPF	Annual Instantaneous Peak Flow
AMDR	Annual Maximum Daily Rainfall
ASTER	Advance Spaceborne Thermal Emission and Reflection
AWCI	Asia Water Cycle Initiative
CF	Correction Factor
CI	Confidence Interval
CN	Curve Number
DDF	Depth Duration Frequency
DEM	Digital Elevation Model
DHM	Distributed Hydrological Model
D/S	Downstream
FAO	Food and Agricultural Organization of United Nations
GCM	General Circulation Model
GEOSS	Global Earth Observation System of Systems
GIS	Geographic Information System
HEC	Hydrologic Engineering Center
HI-AWARE	Himalayan Adaptation Water and Resilience Research
HKH	Himalaya Karakoram Hindukush
HMS	Hydrologic Modeling System
HR	Hour
HSPF	Hydrological Simulation Program - Fortran
IDF	Intensity Duration Frequency

IGIS	Institute of Geographical Information System
IWRM	Integrated Water Resource Management
JICA	Japan International Cooperation Agency
MAE	Mean Absolute Error
Max	Maximum
MODFLOW	Modular Finite Difference Flow Model
NCEP	National Centers for Environmental Prediction
NS	Nash-Sutcliffe Coefficient
KS	Kolmogorov-Smirnov
PARC	Pakistan Agricultural Research Council
PMD	Pakistan Meteorological Department
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
RAMC	Rawalpindi Agromet Centre
RAS	River Analysis System
RDA	Rawalpindi Development Authority
RMSE	Root Mean Square Error
RS	Remote Sensing
SCS	Soil Conservation Service
SDO	Small Dams Organization
SPI	Standardized Precipitation Index
SPOT	Satellite Pour l'Observation de la Terre, lit
SUPARCO	Space and Upper Atmosphere Research Commission
SWAT	Soil and Water Assessment Tool
TIN	Triangular Irregular Network

TMA	Tehsil Municipal Administration
UH	Unit Hydrograph
USGS	United States Geological Survey
U/S	Upstream
WAPDA	Water and Power Development Authority
WASA	Water And Sanitation Agency
WEB	Water and Energy Budget
WEST	Water Environmental Sedimentation Technology
WMO	World Meteorological Organization
WSE	Water Surface Elevation
WSM	Water Shed Management
YR	Year

Chapter 1

INTRODUCTION

1.1 GENERAL

Impact of climate change has not only significantly altered hydrologic process but will also continue to influence events of extreme flood disasters in future. Rainfall-runoff models which simulate the catchment responses are frequently used to study prediction of flooding events and future hydrological scenario. Owing to profound impact of climate change and the extensive flood events, formulation of effective flood mitigation & adaptation strategies has assumed added significance. Lai Nullah which originates from the foothills of Margalla flows through the heart of Islamabad and Rawalpindi and falls into Soan River has historically remained flood vulnerable specially during monsoons. In view of intensive land use changes due to rapid economic growth and urbanization in recent past and high intensity rainfalls, frequency of flood disaster in Lai Nullah has been higher than ever before (Q. T. M. Siddiqui *et al.*, 2010). Existing data also reveals that flood damages broke out almost once in every three years in twin cities of Islamabad & Rawalpindi inflicting huge losses to human lives and property (JICA, 2003).

1.2 PROBLEM STATEMENT

Rawalpindi and Islamabad Metropolis is frequently faced with the issue of flood disaster in Nullah Lai causing significant damages. Flood event of 2001 being the worst of its kind experienced in Lai Nullah so far bears ample testimony to this very fact. Inspite of considerable time lapse and repeated studies on the subject, no concrete steps in terms of flood adaptation and mitigation strategies have been executed by policy makers and stake holders thus maintaining very much status quo on the issue.

It is thus imperative that a comprehensive study may be undertaken on the subject involving integrated modeling approach using hydrological and hydraulic models of Lai Nullah Basin for future flood plain inundation mapping & adaptation measures. The study dictates use of a suitable rainfall-run off simulation model with reliable storm data for future scenario of complete basin. Fine resolution DEM is thus required for accurate spatial modeling in GIS environment. Urban change detection information along nullah banks will be useful for ascertaining future rainfall peaks and standard flood discharges. Observed annual maximum daily and 3 hr interval rainfall data required to be analyzed for frequency analysis, determination of PMP / PMF values and subsequently IDF / DDF curves. Flood plains inundation maps to be analyzed using 2D hydraulic model for the identification of suitable adaptation strategies. Integrated modeling technique based on hydrological & hydraulic models will also required to be used for future assessment of extreme precipitation events using fine resolution statistically downscaled GCM data.

1.3 RATIONALE OF THE STUDY

Lai Nullah has remained the focus of attention for hydrological and hydraulic researchers in recent past. While these studies provides a useful insight to the hydrological variations of Lai Nullah Basin, a comprehensive study focused on assessment of climate change impact on hydrological response of Lai Basin being a major challenge was still an unfamiliar avenue thus leaving a huge gap between climate change impact and variation in hydrological regimes. The current research is one such endeavour to bridge this gap and encompasses application of a rainfall-runoff model integrated with suitable hydraulic model thoroughly incorporating the aspects of climate and land use change, frequency analysis, PMP / PMF, IDF & DDF curves and future assessment so as to come up with viable and feasible adaptation strategies.

1.4 OBJECTIVES OF THE STUDY

Following are the major objectives of the study;

i. Application of a rainfall-runoff model for the assessment of hydrological response.

ii. Evaluation of urban flood extent by the integration of a rainfall-runoff model with a hydraulic model.

iii. Impact assessment of climate & land use changes on the hydrological response and urban flood extent.

iv. Identification of various possible adaptation strategies to reduce the urban flood extent.

1.5 SCOPE OF THE RESEARCH WORK

During the course of this study, following tasks were undertaken;

i. Thorough review of the literature to understand the approaches and techniques of hydrological and hydraulic modeling.

ii. Examining and reviewing the existing studies on Lai Watershed.

iii. Data acquisition involving satellite / remote sensing spatial data, rainfall & stream flow data for extreme events, channel cross sections, flood plain topography, water levels and discharge data from various agencies including PMD & RDA.

iv. Urban change detection using supervised image classification technique.

v. Application of a suitable rainfall - run off hydrological model for suitable storm events involving model calibration and validation.

vi. Frequency analysis of standard flood discharges based on annual instantaneous peak flows and annual maximum daily rainfall data, determination of PMP / PMF and development of IDF / DDF curves.

vii. Setting up of hydraulic model using river cross sections and flood plain terrain data, model calibration / validation and simulation for various return periods.

viii. Assessment of future scenarios using 8 GCM models and comparison with observed / base line data.

ix. Identification of various adaptation strategies using peak flows for 100 year return period.

1.6 BENEFITS OF THE RESEARCH WORK

Current research will bring following benefits to all concerned:

i. To facilitate various policy makers and stakeholders while deciding mitigation and adaptation strategies ahead of time.

ii. To provide useful information on land use policy and buffer zones.

iii. To improve existing flood risk management and relief plans.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Lai Nullah flowing through the heart of twin cities of Islamabad & Rawalpindi has remained the focus of attention with regards to flood disasters during recent past. Increased frequency of flood during monsoon, increased urbanization along its banks, environmental pollution with regards to addition of effluents and solid waste and lack of concrete steps for flood mitigation and adaptation by all stake holders has further compounded the problem of floods in Lai Nullah. Complicated problem of Lai Nullah floods has attracted the attention of researchers in recent past and quite a number of studies covering various aspects have been conducted on the subject.

2.2 Previous Studies on Lai Nullah

Japan International Cooperation Agency (JICA) carried out a comprehensive study for formulation of a master plan for flood mitigation and environmental improvement of Lai Nullah during 2002 - 2003. It was a detailed study which modeled and simulated flood event of 2001 in Lai Nullah using 1 D computer model i.e. MIKE 11. Moreover, detailed surveys were also conducted in flood affected areas for validating the model and generating flood hazard map from the results of survey (JICA, 2003).

(Hayat, 2003) used a hydro-meteorological model MIKE 11 to develop a flood forecasting system for providing pre-alerts and warnings from flash floods in Lai Nullah. System used 10 minute interval rainfall data as automated weather product for anticipating flash flood hazards in Lai Nullah. This system, combined runoff and point rainfall recorded data, produced 2 to 6 hour precipitation rate and accumulation forecasts for every 10 minutes for both meteorological and hydrological purposes. Efficiency of the model was ascertained in extreme precipitation event of March 2007 and model reported corresponding alerts well and confidence on the system was established.

(Kamal, 2004) suggested an integrated flood management with a view to effectively manage and mitigate flood with regards to flooding issues of Lai Nullah. The study encompassed catchment and administrative jurisdiction of Lai, its topography, present hydrological and land use patterns with specific reference to floods, various structural and non-structural measures in place and their efficacy with regards to 2001 flood event. Study also contained legal aspects of flood management with regard to land use, flood warning system, preparedness and response with special emphasis on stakeholder participation. The study concluded with emphasis on adopting integrated flood management approach by proposing certain recommendations both for the country as well as for the Lai Basin area for real time flood management.

(F. Khan *et al.,* 2008) proposed a proactive flood risk reduction approach using cost benefit analysis of flood damages in Lai Nullah Basin. The study was based on methodology that combines social science (cost benefit analysis) with natural science (hydrological and climate modelling) to evaluate various strategies for risk reduction in the Lai flood basin. The study incorporated probabilistic climatic risk in determining benefits of risk reduction. Findings and tools developed in this area were found to be highly replicable and relevant to developing world urban hazardscapes that have traditionally received lesser attention in the academic world but are omnipresent.

(Afzal *et al.*, 2010) carried out flood forecasting analysis in Lai Basin using NCEP reanalysis (2.5° × 2.5°) data sets based on extreme precipitation event of July 2008. Different meteorological fields were used to carry out comparison of both the observed and reanalysis data sets. NCEP reanalysis data set though of coarse resolution presented good picture of event in terms of interaction between two main weather systems. The analysis revealed that the south-easterly incursion from the Arabian Sea was activated due to the westerly trough approaching the HKH mountain ranges. The results showed that Vertical wind Velocity (omega) and constant pressure surfaces are good predictors for this particular study.

(Ahmad *et al.*, 2010) used an integrated modeling approach using HEC-GeoRAS & HEC-RAS model to delineate flood vulnerable areas at various discharge values. In this study HEC- RAS and HEC-GeoRAS models were used for estimation of flood zones and flood extent 2001 flood event. Different flood hazard maps were prepared with probable discharge values based on flood frequency analysis for 25, 50 and 100 years return period.

(Ali *et al.*, 2011) used an empirical land use change model and an event scale, rainfall-runoff HEC-HMS model to quantify the impacts of potential land use change on the storm-runoff generation in the Upper Lai Nullah Basin. This study incorporated the effects of land use changes on hydrological response of Lai Basin for different time periods with a view to assess the future land use scenarios.

(B. Khan, 2011) carried out a study to establish relationship between floods and droughts in context of climate change and exploring the options and practices to find better, sustainable and reliable solutions for the case of Lai Nullah. The study defines the integrated methodology for understanding relationships between different issues of interest and gives a detail analysis of importance to using structural and non structural measures together while planning or project design. Research found that rain water should be taken as an opportunity rather than threat in context of climate change and two options has been explained that deals with rain water harvesting in way that not only mitigates the flood impact but also recharge the ground water in Lai Basin.

(Hashmi *et al.*, 2012) carried out study on Lai flooding using one dimensional flood simulation model i.e. MIKE 11. The study involved flood simulation by calculating runoff from the sub-basins by Unit Hydrograph method, based on SCS curve number and flood routing along the river. Different flood scenarios with respect to recurrence period were also modeled and extent of flood was measured. River computational geometry was generated using available cross sectional data and flood flow was simulated. This study also suggests structural and non-structural measures for flood risk management.

(Umer, 2015) presented flood simulation study using two-dimensional hydrodynamic BASEMENT model, on Nullah Lai Catchment. Flood event of 2001 was simulated to visualize the propagation of flow in channel and over floodplains. Hydraulic model was developed by integration of river cross-section and floodplain topography to generate the 2D computational mesh. Simulated results showed close agreement with the results obtained by JICA.

2.3 Similar Studies on Other Basins

(Zainudini *et al.*, 2011) developed rainfall intensity-duration-frequency (IDF) curves using rainfall data from Sistan and Balochistan for different durations. The results were subsequently compared with analysis of data from other countries. The results based on shorter duration rainfall data were plausible and can potentially be useful for design purposes.

(Qaiser *et al.*, 2012) studied the impacts of urbanization and wetlands for mitigation through floodplain modeling in the Kansas River Basin using HEC-HMS & HEC-RAS Models. The study evaluated the impacts of future land use change in the backdrop of 100 year design storms on the peak runoff and flood inundation extents for the Kansas River and evaluated the potential role of wetlands in flood attenuation. Hydrological and hydraulic models were used to highlight the flooding potential for the Kansas River region as a result of urbanization and extreme rainfall events and evaluated the potential of using wetlands as a mitigation option. Study also analyzed the role of reservoirs and levees towards flood mitigation.

(R. SIDDIQUI *et al.*, 2012) used an integrated approach combining HSPF & HEC-RAS models to analyze scenarios and generate preventive measures for flood assessment of a northern watershed in Pakistan. HSPF model was calibrated and validated for Mangla watershed and HSPF generated stream flow was used as input to HEC-RAS model to simulate flood scenarios in the form of flood inundation maps. Water Shed Management System (WMS) Tool was also incorporated to analyze the two models. Study concluded that HSPF being a complex model may be used for planning of disaster management and mitigation measures.

(Malik *et al.*, 2014) used a hydrodynamic HEC-RAS model to determine areas inundated during heavy rainfall events in the Swat River Basin. The flood zones for floods with return periods of 5, 10 and 100 years were calculated. Results show the exact location of areas with high, moderate and low risk to be flooded at specific high flood events. It was found that the combination of GIS with the HEC-RAS model was very powerful and efficient approach in flood zone analysis and can also provide the location of high risk areas, so that an early warning system can easily be located. This study provided suitable information to inhabitants of the area who are at-risk and how to prevent and mitigate the effect of flood-related damages.

(Van Quan *et al.*, 2014) analyzed the effects of climate change on drought levels in the future by using both hydrological model (SWAT) and Standardized Precipitation Index (SPI) tools. Bench mark periods of climate change were compared with baseline periods in the basin. Results indicate that both the SWAT and SPI index showed a similar correlation in duration and density of the drought occurrence levels based on shortage of soil water content and values of drought spatial changes in the future.

(Koike *et al.*, 2014) developed an advanced river management system for supporting integrated water resources management practices in Asian river basins under the framework of GEOSS Asia water cycle initiative (AWCI). The system is based on integration of data from earth observation satellites and in-situ networks with other types of data, including numerical weather prediction model outputs, climate model outputs, geographical information, and socio-economic data. The study incorporated water and energy budget distributed hydrological model (WEB-DHM) and analyzed climate change impact assessment on hydrological regimes for Soan River Basin in Pakistan. Results of climate scenarios indicate substantial increase in magnitude of peak flows in future thus reinforcing the probability of increased flooding events in future.

(Boota *et al.*, 2015) used Hershfield Technique and Gumble distribution of annual maximum daily rainfall data of Gujjar khan for the estimation of 24 hr probable maximum precipitation based on frequency factor. The PMP for Gujjar khan was estimated to be 357.39 mm and the ratio of the 1-day PMP to highest 1-day precipitation was 1.19. The maximum daily precipitation for different return periods was also estimated. The estimated maximum rainfall and PMP values could be useful in designing of soil and water conservation practices, design of small dams in the study area.

(Azmat, 2015) studied the change in snow cover dynamics and its impact on the hydrological behaviour of the Jhelum River catchment, water availability under climate change scenarios in high-altitude scarcely gauged (transboundary nature) catchment and subsequently its impact on hydropower generation at Mangla Dam and downstream canal system through operational management of the Mangla Reservoir. The impact of climate change on hydropower generation at Mangla Dam and downstream canal system was computed by the utilization of hydrological outcomes under current and future water resources availability. The outcomes of this study will not only help to solve several complex problems related to practical designing and management issues of water resources and hydropower crises of Pakistan but also for future proposed studies.

(Sahu, 2016) used HEC-HMS model to analyze various extreme rainfall events in Kan Watershed, Iran. The study was an attempt to compare the results of Green & Ampt, Initial and constant loss rate and Deficit and Constant loss methods for estimation of runoff losses by consider to objective functions (percent error in peaks and volumes) for selection of best method. Results of simulation in six events and comparison of simulated and observed hydrographs showed that the model can applied for simulation of rainfall-runoff in study area.

Chapter 3

MATERIALS & METHODS

3.1 Study Area

Lai Nullah Basin is located in twin cities of Islamabad and Rawalpindi, between 33º33´ and 33º46´ N and 72º55´ and 73º06´ E and covering the area of about 217.36 Km^2 (150.05 Km^2 in Islamabad and 67.31 Km^2 in Rawalpindi) (Fig-3.1). Low lying areas of Lai Nullah in Rawalpindi City particularly between Kattarian to Gawalmandi are the most floods prone and vulnerable with main channel and tributaries suffer from even small floods (Ahmad, *et al.*, 2010) . Elevation range of the watershed varies from 1244 – 420 m during its course from Margalla foothills till its confluence with Soan River in Rawalpindi (Fig-3.2). There are 6 major tributaries joining the river system, 3 each in Islamabad and Rawalpindi jurisdiction areas (F. Khan, *et al.*, 2008).

The climate of the Study Area is classified as "Subtropical Triple Season Moderate Climate Zone", which is characterized by single rainfall season from July to September and its moderating influence on temperature. The Study Area has hot summers and cold winters. In June, the daily maximum temperature reaches 40°C, while the daily minimum temperature falls near 0℃ in December and January. Between July and September, the temperature is slightly moderate due to humidity (JICA, 2003).

Lai Nullah Basin receives a heavy rainfall of about 500 mm during monsoon from July to September, which results in large flood runoff discharge (JICA, 2003). Intensive urbanization and development along Lai Nullah and its tributaries increases runoff discharge and on the other hand flow capacity of river is reducing downstream in the area of Rawalpindi due to illegal encroachment of buildings and structures constructed over the river course and also due to the garbage piles indiscriminately dumped into the river. With increasing population rate, Rawalpindi is fully urbanized and densely populated relative to Islamabad (JICA, 2003).

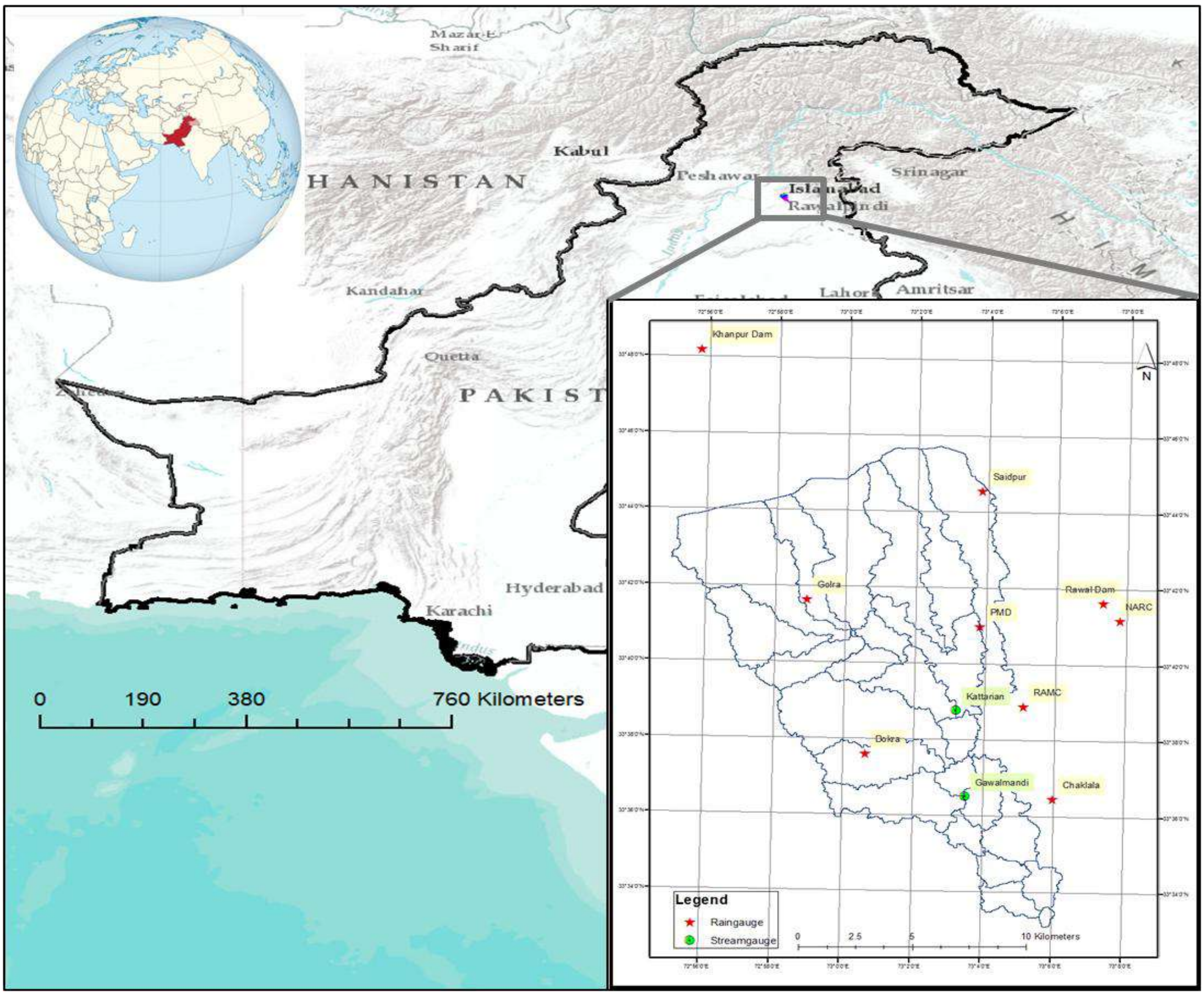


Fig-3.1 – Lai Nullah Basin

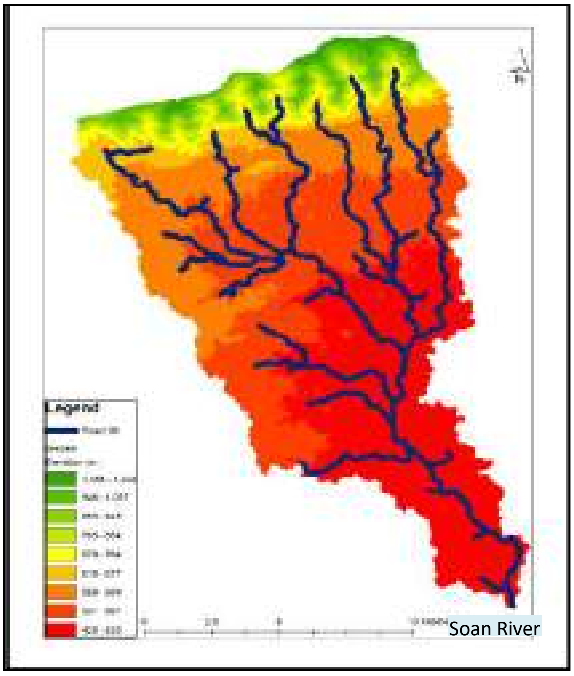


Fig-3.2 – Elevation Range – Lai Basin

3.2 Data

3.2.1 Precipitation Data (Table 3.1)

The precipitation data for current study pertaining to six rainfall gauging stations of Lai Nullah Basin was acquired from Pakistan Meteorological Department (PMD) (Ref to Fig 3.1). Moreover, rainfall data for Rawal Dam, NARC & Khanpur Dam rainfall gauging stations were also acquired from Small Dams Organization (SDO), Pakistan Agricultural Research Council (PARC) & Water and Power Development Authority (WAPDA) respectively. Details of precipitation data used are shown in Table 3.1.

<table>
<tr><th>S.No</th><th>Type</th><th>Station</th><th>Managed By</th><th>Coordinates (Lat / Long)</th><th>Installed in Year</th><th>Measurement Frequency</th></tr>
<tr><td>1</td><td rowspan="9">Rainfall</td><td>Chaklala*</td><td rowspan="6">PMD</td><td>33°36'27" / 73°06'00"</td><td>1944</td><td>Daily – 1944 - 2015
3 hr – 1970 - 2015</td></tr>
<tr><td>2</td><td>PMD*</td><td>33°40'59" / 73°03'51"</td><td>1983</td><td>Daily – 1983 - 2015
3 hr – 1983 - 2015</td></tr>
<tr><td>3</td><td>RAMC*</td><td>33°38'53" / 73°05'07"</td><td>1989</td><td>Daily – 1989 - 2015
3 hr – 1989 - 2015</td></tr>
<tr><td>4</td><td>Saidpur*</td><td>33°44'33" / 73°03'51"</td><td>1994</td><td>Daily – 1994 - 2015</td></tr>
<tr><td>5</td><td>Bokra*</td><td>33°37'38" / 73°00'39"</td><td>2007</td><td rowspan="2">*10 minutes data of six stations available since 2007 - 2015</td></tr>
<tr><td>6</td><td>Golra*</td><td>33°41'38" / 72°58'55"</td><td>2007</td></tr>
<tr><td>7</td><td>Rawal Dam</td><td>SDO</td><td>33°41'37" / 73°07'22"</td><td>1984</td><td>Daily – 1984 - 2015</td></tr>
<tr><td>8</td><td>NARC</td><td>PARC</td><td>33°41'13" / 73°07'52"</td><td>1988</td><td>Daily – 1988 - 2015</td></tr>
<tr><td>9</td><td>Khanpur Dam</td><td>WAPDA</td><td>33°48'10" / 72°55'46"</td><td>1988</td><td>Daily – 1988 - 2015</td></tr>
</table>

Table -3.1 – Precipitation Data

3.2.2 Stream Flow Data (Table 3.2)

Stream flow data for Kattarian and Gawalmandi Stream Gauges was acquired through Pakistan Meteorological Department (PMD). Details of stream flow data are shown in Table 3.2.

<table>
<tr><th>S.No</th><th>Type</th><th>Station</th><th>Managed By</th><th>Coordinates (Lat / Long)</th><th>Installed in Year</th><th>Measurement Frequency</th></tr>
<tr><td>1</td><td rowspan="2">Stream Flow</td><td>Kattarian</td><td rowspan="2">PMD</td><td>33°38'46" / 73°03'13"</td><td>2007</td><td>10 mins - 2007 - 2015</td></tr>
<tr><td>2</td><td>Gawalmandi</td><td>33°36'30" / 73°03'31"</td><td>2007</td><td>10 mins - 2007 - 2015</td></tr>
</table>

Table -3.2 – Stream Flow Data

3.2.3 Remote Sensing Data

As far as remote sensing data is concerned, 30 m ASTER Digital Elevation Model (DEM) was downloaded from USGS website (http://gdex.cr.usgs.gov/gdex/). 10 m spatial resolution multi-spectral (MS) SPOT-5 satellite imageries for the year 2005 & 2014 were procured from SUPARCO.

3.2.4 Soil Data

Owing to the absence of any reliable soil data with Soil Survey of Punjab and Soil Survey of Pakistan, FAO world soil dataset was extracted from FAO website (http://fao.org/home/en/) for the Lai Catchment.

3.2.5 Land Use Map & Urban Master Plan

Land Use Map for Rawalpindi & Urban Master Plan for the year 2030 for Islamabad City was acquired through Rawalpindi Development Authority (RDA) & Capital Development Authority (CDA) respectively.

3.2.6 Downscaled GCMs Dataset

Eight GCMs dataset was downloaded from HI-AWARE Server (http://futurewater.com). The grid data was statistically downscaled from mid hills and lower parts of Indus Basin based on spatial resolution of 10 km x 10 km.

3.2.7 Flood Plain Topography & Channel Geometry Data

As far as hydraulic data is concerned, accurate channel geometry and flood plain topography data was essentially required to develop the terrain. Acquisition of data was carried out from two major agencies i.e RDA & NESPAK. Details are as shown in Table-3.3.

S.No	Dataset	Source
1	Flood Plain Topography (9914 Elevation Points)	WASA / RDA Survey - 2007
2	River Geometry Survey – 250 X Sections (Kattarian – Marir Chowk)	WASA / RDA Survey - 2010
3	River Geometry Survey – Lai Express Way	NESPAK Survey - 2010

Table - 3.3 – Flood Plain Topography & Channel Geometry Data

3.3 Methodology

Conceptual flow chart of the study is shown in Fig-3.3.

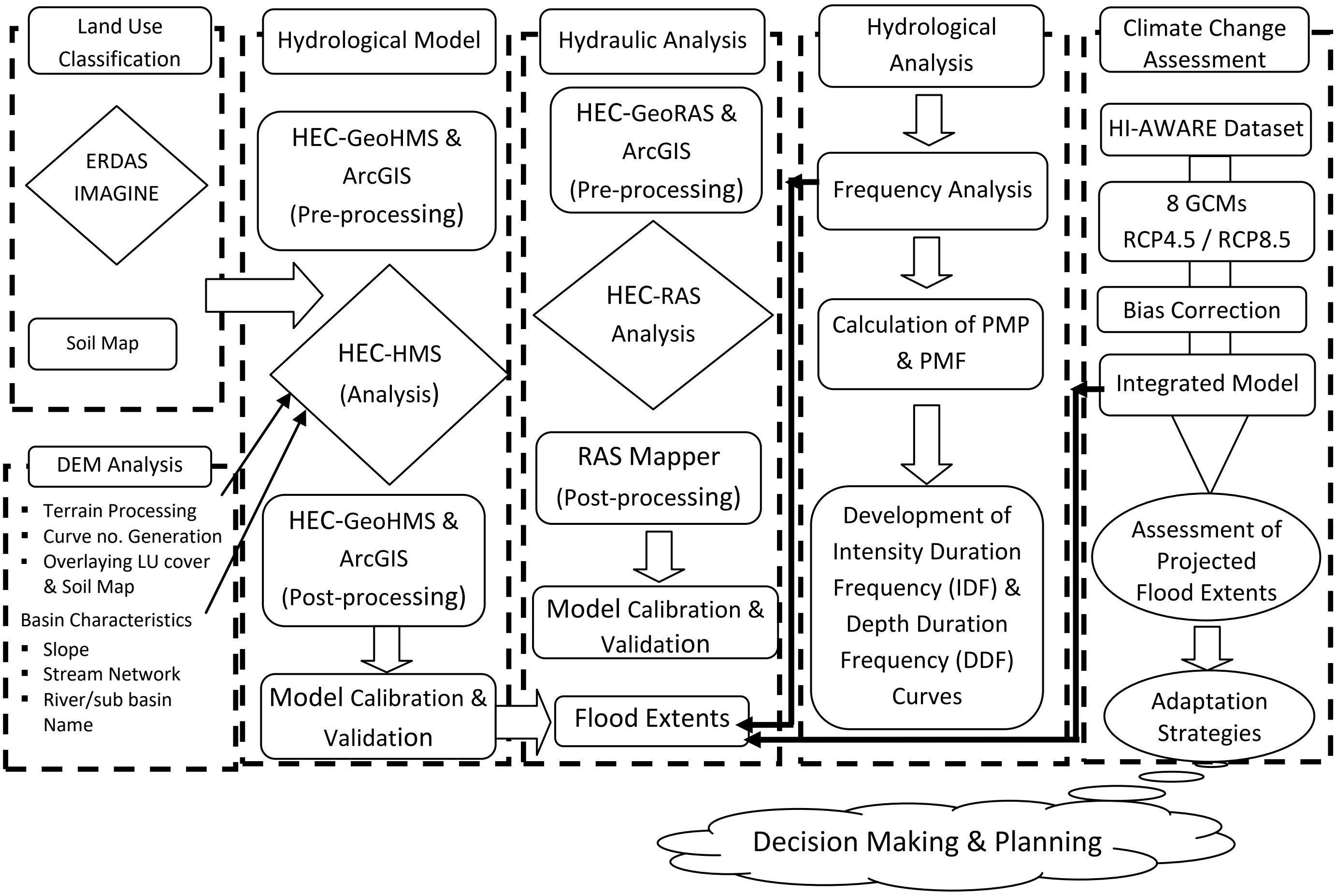


Fig-3.3 – Conceptual flow chart

3.3.1 Hydrological Modelling

3.3.1.1 Terrain Processing in ArcGIS / HEC-GeoHMS

Lai Basin DEM of 30 m spatial resolution was extracted from ASTER DEM Scene in ArcGIS environment. HEC-GeoHMS software was used to perform pre-processing, terrain processing and subbasins delineation of Lai Catchment. Lai Basin was delineated into twenty four sub-basins and various attributes including slope, stream network, sub-basin names were defined as shown in Fig-3.4. A HEC-HMS import file was created in HEC-GeoHMS containing attribute data from an existing digital elevation model (DEM) and complimentary data sets of Lai Catchment for subsequent hydrological modeling in HEC-HMS.

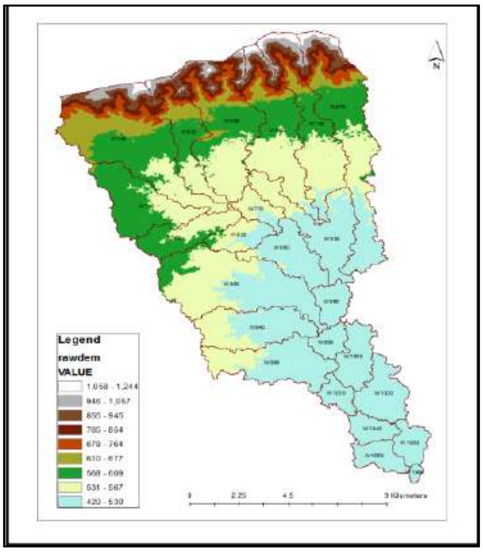


Fig-3.4 – Sub basins Delineation

3.3.1.2 Land Use Analysis

This phase involved extraction of Lai Catchment imagery from the SPOT-5 scene using ArcGIS. ERDAS IMAGINE software was applied for carrying out land use classification using supervised classification technique (Duda *et al.*, 2002). Lai Catchment was classified into six land use categories including residential high density, residential low density, forest, agriculture, green / bare land and water as shown in Fig-3.5. In order to ascertain the increase in urbanization pattern, two SPOT-5 imageries of different time frames (2005 & 2014) & same resolution were analyzed. Based on existing growth pattern & urban master plan 2030, future land scenario was also projected for year 2030.

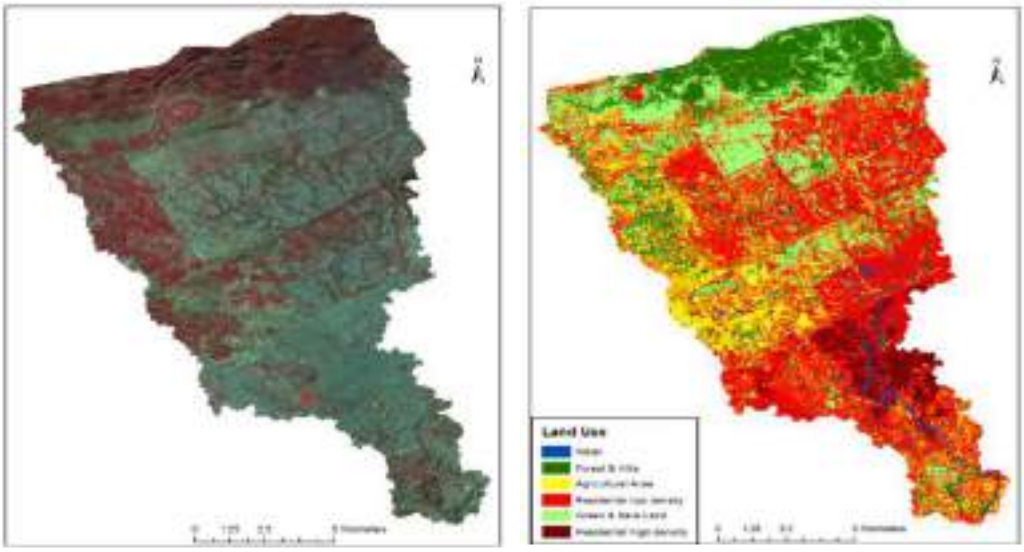


Fig-3.5 Land Use Classification

3.3.1.3 Preparation of Soil Map & Curve Number Grid

Soil classification map for Lai Catchment was extracted from FAO World Soil Map dataset (Fig-3.6). Based on the soil properties, soil was classified into two major hydrological groups B & C using the criteria defined by (Chow *et al.*, 1988; Debo *et al.*, 2002). Lumped Curve number, land use data and soil groups were merged to generate composite curve number grid shown in Fig-3.7.

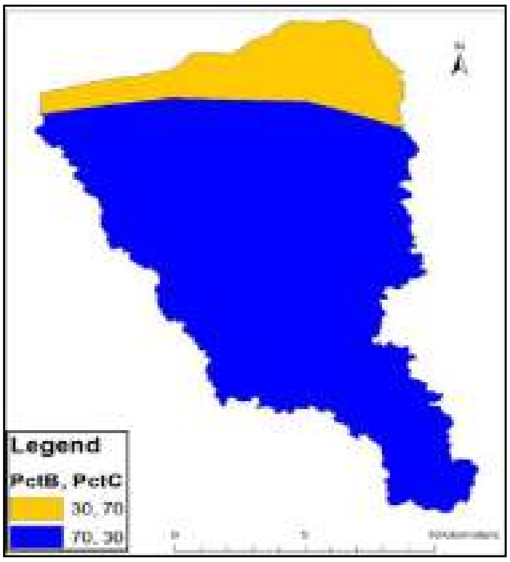


Fig-3.6 – Lai Soil Map

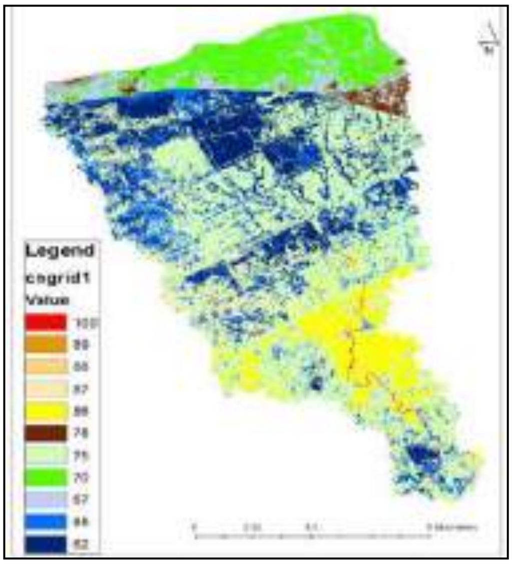


Fig-3.7 – Curve Number Grid

3.3.1.4 Preparation of Spatial Precipitation Data

In order to convert point rainfall data to average rainfall over a basin, Theissen Polygon or Weighted average rainfall values were computed (Earls *et al.*, 2007) as shown in the Fig-3.8.

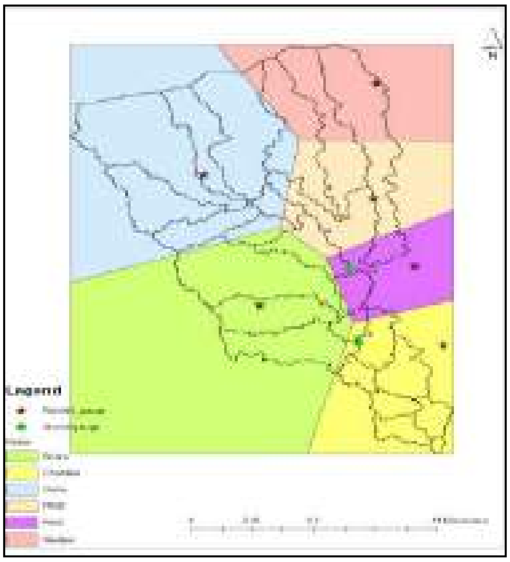


Fig-3.8 Division of Basin through Thiessen Polygons

3.3.1.5 Hydrological Modeling System

Hydrological modeling is slowly and gradually becoming integral part of water resources studies particularly in data scarce scenarios. Studies of un-gauged watersheds, environmental impacts of land use changes, conjunctive use of groundwater and surface water and climate impact studies concerned with effects on water resources of an anticipated climate change are a case in point.

A modeling system is a generalized software package, which can be used for different catchments without modifying the source code. Examples of hydrological modeling systems are MIKE SHE, HEC-HMS and MODFLOW. A model is a site-specific application of a modeling system, including given input data and specific parameter values.

3.3.1.6 HEC-HMS MODEL

HEC-HMS is one of the most widely used hydrological modeling software developed by US Army Corps of Engineers for simulation of rainfall - runoff process for urban and natural dendritic watersheds. The program is based on a powerful algorithm to simulate various hydrological processes using variety of infiltration, transformation of excess precipitation, base flow and routing methods. The program features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools. The model choices include gridded and area-averaged methods for event or continuous simulation. It is a semi-distributed hydrological model which can be used for event based and continuous rainfall - runoff simulation. HMS model comprises of basin model, meteorological model, control specifications and input data. The land use information, hydrological soil groups and rainfall information with spatial and temporal variations is used as model input for rainfall – runoff simulation of extreme events. The model is used for design and operation of flood control projects, regulating floodplain activities, monitoring water use, local and regional watershed planning, water availability studies, urban drainage design, flow forecasting, determining urbanization impacts on waterways, reservoir spillway design, determining flood damage reductions, and real-time system operation of flood events (Chen *et al.*, 2009; USACE, 2000).

An assortment of different methods is available to simulate infiltration losses, transformation and base flow. Options for event modeling include initial and constant, SCS curve number, gridded SCS curve number, exponential, Green Ampt, and Smith Parlange. Seven methods are included for transforming excess precipitation into surface runoff unit hydrograph methods includes the Clark, Snyder, and SCS techniques. User specified unit hydrograph or s-graph ordinates can also be used. Five methods are included for representing base flow contributions to sub-basin outflow whereas six hydrologic routing methods are included for simulating flow in open channels.

3.3.1.6.1 Loss Methods

3.3.1.6.1.1 SCS Curve Number

The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use and antecedent moisture, using the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Where,

Q = runoff (inches)

P = rainfall (inches)

S = potential maximum retention after runoff begins (inches) and

I_a= initial abstraction (inches)

3.3.1.6.1.2 Initial and Constant Rate

The concept of Initial and Constant Rate is that the maximum potential rate of precipitation loss, f_c is constant throughout an event. Thus if p_t is the mean aerial precipitation depth during a time interval t to $t+\Delta t$, the excess, pe_t during the interval is given by:

$$pe_t = \begin{Bmatrix} p_t - f_c & \text{if } p_t > f_c \\ 0 & \text{Otherwise} \end{Bmatrix}$$

3.3.1.6.1.3 Green and Ampt

The Green and Ampt Infiltration Loss Model is a conceptual model of precipitation in a watershed. The model computes the precipitation loss on the pervious area in time interval as:

$$f_t = \frac{K\left[1 + (\varphi - \theta_i)S_f\right]}{F_t}$$

Where,

f_t = Loss during period t

K = Saturated Hydraulic Conductivity

$\varphi - \theta_i$ = Volume moisture deficit

S_f = Wetting Front Suction

F_t = Commulative loss at time t

3.3.1.6.2 Transformation Methods

3.3.1.6.2.1 SCS Unit Hydrograph

The SCS Unit Hydrograph (UH) is a parametric model based on averages of UH derived from gauged rainfall and runoff for a large number of small agricultural watersheds. SCS UH Model is a dimensionless, single peak UH, expressing the UH discharge U_t, as a ratio to the UH peak discharge, U_p, for any time t, a fraction of T_p, the time to peak. UH peak discharge is given by following equation:

$$U_p = C \frac{A}{T_p}$$

A = watershed area

C = Conversion Constant (2.08 in SI and 484 in foot-pound system)

Time to peak (or time to rise), T_p is related to the duration of unit of excess precipitation as:

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

Δt = the excess precipitation duration

t_{lag} = the basin lag, time difference between center of mass of rainfall excess and peak of UH

UH lag time t_{lag} may be related to time of concentration t_c, by following relation:

$$t_{lag} = 0.6\, t_c$$

3.3.1.6.2.2 Clark Unit Hydrograph

The Clark unit hydrograph is a synthetic unit hydrograph method based on a time versus area curve built into the program to develop the transition hydrograph resulting from a burst of precipitation. The resulting transition hydrograph is routed through a linear reservoir to account for storage attenuation effects across the basin. Time of concentration is estimated via calibration using SCS equation while storage coefficient is also estimated via calibration.

3.3.1.6.2.3 Snyder Unit Hydrograph

The SCS Unit Hydrograph (UH) is a synthetic unit hydrograph method where all ordinates of the hydrograph are not computed. Lag time (basin lag) T_p is calculated using duration of net rain T_r by following equation:

$$T_p = 5.5T_r$$

If the actual duration of storm is not equal to T_r , then following equation can be used as well,

$$T_{pr} = T_p - \frac{T_r - T_R}{4}$$

Where T_R = Actual storm duration

3.3.1.6.3 Routing Methods

3.3.1.6.3.1 Muskingum Routing Method

The Muskingum Routing is a storage routing equation based on the storage routing equation which is an expression of continuity:

$$I - O = \frac{\Delta S}{\Delta t}$$

I = Inflow

O = Outflow

$\frac{\Delta S}{\Delta t}$ = Rate of change of storage

Expression for storage in a reach of a stream used in Muskingum method is :

$$S = K[XI + (1 - X)O]$$

K & X represent storage parameters.

3.3.1.6.3.2 Lag Routing Method

Lag methods assume that average inflows occur at a later time further downstream. The Successive Average and Progressive Average lag methods are the most common. The Successive Average method assumes that outflow is based on a specific number of averaged inflows within the reach. Outflow is computed by:

$$Q_{n+1} = C_1 I_1 + C_2 I_2 + C_3 I_3 + \dots \dots \dots \dots \dots . + C_{n+1} I_{n+1}$$

Where n equals the number of successive averages within the reach. The routing coefficients C_1, C_2, ... C_{n+1} can be calculated by trial and error using observed inflow and outflow hydrograph data.

3.3.1.7 Model Calibration & Validation

Various methods available in HEC-HMS for loss, transformation, base flow and routing were used in different combinations to select the best fit methods for model calibration as shown in Table-3.4.

Loss	**Transformation**	**Routing**	**Baseflow**
SCS Curve Number	SCS Unit Hydrograph	Muskingum	Recession (Initial Discharge & Threshold Flow)
Initial & Constant Rate	Clark Unit Hydrograph	Lag	Bounded Recession
Green & Ampt	Snyder Unit Hydrograph	-	-

Table -3.4 – Methods used in HEC-HMS

Various parameters including basing lag time, curve number, initial abstraction, Muskingum K and Muskingum X values were calibrated for extreme event of 23 Jul 2001 against JICA’s reproduced results and further three extreme storm events corresponding to 14 Jul 2007, 12 Aug 2007 & 28 Jun 2008. Values of initial discharge and threshold flow were calculated from observed stream flow values at Kattarian & Gawalmandi. Besides manual calibration of the model parameters, optimization trials using the objective function criteria (USACE, 2008) were also conducted in HEC-HMS to match the simulated results with the observed values as closely as possible. A unique aspect of this study is that HEC-HMS model was calibrated and validated for two stream gauging outlets at Kattarian & Gawalmandi simultaneously.

3.3.1.8 Model Performance

In order to assess goodness of fit between simulated results and observed values, various statistical parameters including coefficient of correlation (R^2), relative root mean square error (RRMSE), deviation of runoff volume (Dv), deviation of peak discharge (Dp), absolute error of time to peak (ΔT) & Nash-Sutcliffe Coefficient (E) were evaluated (Asadi *et al.*, 2013; Chen, *et al.*, 2009).

Calibrated parameters were used as input for model validation for three storm events corresponding to 3 Sep 2012, 6 Aug 2013 & 5 Sep 2014. Model performance was again evaluated using above mentioned statistical parameters for assessment criteria of its validation.

3.3.2 Frequency Analysis

Increased frequency of flood events in Lai Nullah Basin warranted a reliable frequency analysis study to ascertain the magnitude of standard flood discharges for various return periods. Thus, a comprehensive analytical frequency analysis was carried out based on annual instantaneous peak flows recorded at Kattarian & Gawalmandi outlets and annual max daily rainfall values recorded at all nine rainfall gauging stations. In order to assess the data, tests for high and low outliers (Chow, *et al.*, 1988) were performed initially for all types of data and outliers were removed accordingly. Frequency Analysis was carried using various types of distributions including Lognormal, Log Pearson Type III, Pearson Type III & Extreme Value Type I (Gumbel) distributions.

Three types of goodness of fit tests were applied using Easyfit statistical software to select the best fit distribution for prediction of magnitude of extreme events corresponding to various return periods. Goodness of fit tests can be reliably used in climate statistics to assist in finding the best distribution to use to fit the given data. These tests calculate test-statistics, used to analyze how well the data fits given distribution out of any possible distributions. The performances of the distribution fits are ranked using three goodness-of-fit test results: Kolmogorov-Smirnov test (KS), Anderson-Darling (AD) and Chi-Squared (x2) Test.

(Solaiman *et al.*, 2011) explains the details of all the three tests on goodness of fit criteria. The goodness of fit tests were executed in the downloadable software EasyFit, ***(http://www.mathwave.com/easyfit-distribution-fitting.html).*** All test values and statistics were produced from this program. Results of frequency analysis of annual instantaneous peak flows and flows generated from annual max daily rainfall series were compared with the results of JICA Study.

3.3.2.1 Annual Instantaneous Peak Flow Analysis

While analyzing the annual instantaneous peak flow series for both Kattarian and Gawalmandi Stream Gauges, a major constraint encountered was the non availability of discharge data prior to year 2007. Use of the available discharge data for Kattarian and Gawalmandi stream gauges for the period from 2007 – 2015 (nine years only) for frequency analysis would have led to erratic and non-reliable results. Using the 3 hr interval rainfall values for Chaklala, PMD & RAMC rainfall gauges for the period from 1986 - 2007 as input for the validated HEC-HMS model, peak flows were generated both for Kattarian and Gawalmandi stream gauging stations. In order to further validate the values of peak floods, peak flows at Gawalmandi Station were compared with available peak floods recorded by

TMA for some of the extreme events (JICA, 2003). The results showed strong correlation between simulated and observed values thus authenticating the validity of the model as shown in Appendix-2. Annual instantaneous peak flow values for Kattarian and Gawalmandi for the period from 1986 – 2015 are shown in Fig-3.9 while tabulated values are shown in Appendix-3. Regression analysis was carried out for annual instantaneous peak flow data series for both Kattarian and Gawalmandi gauges. Weibull formula was used to establish plotting position relationship by calculating probability of exceedence and recurrence intervals for both data samples as shown in Appendix-4.

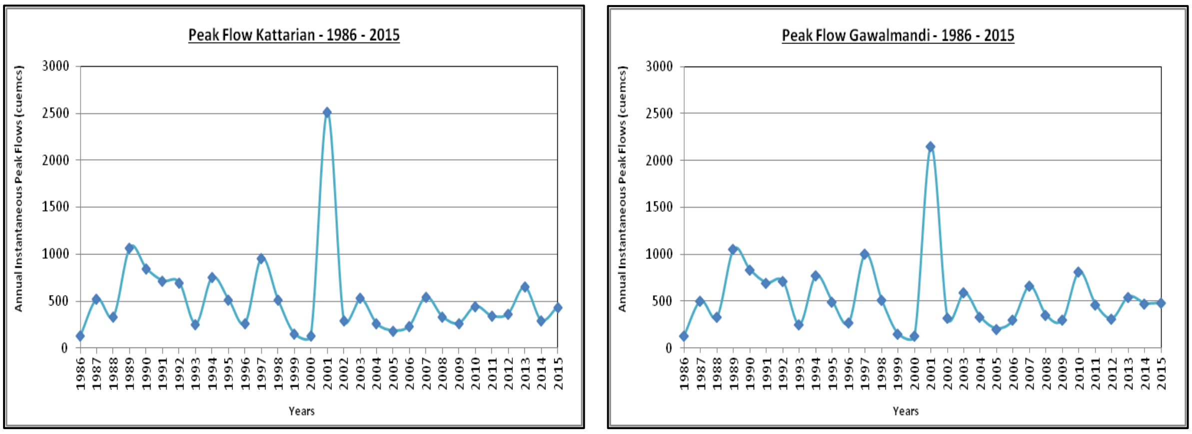
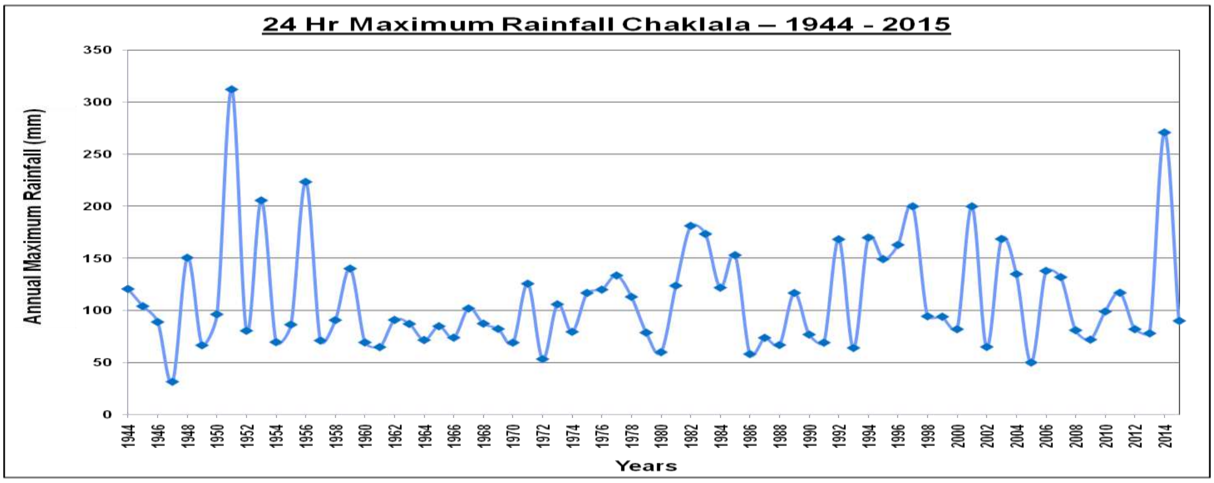


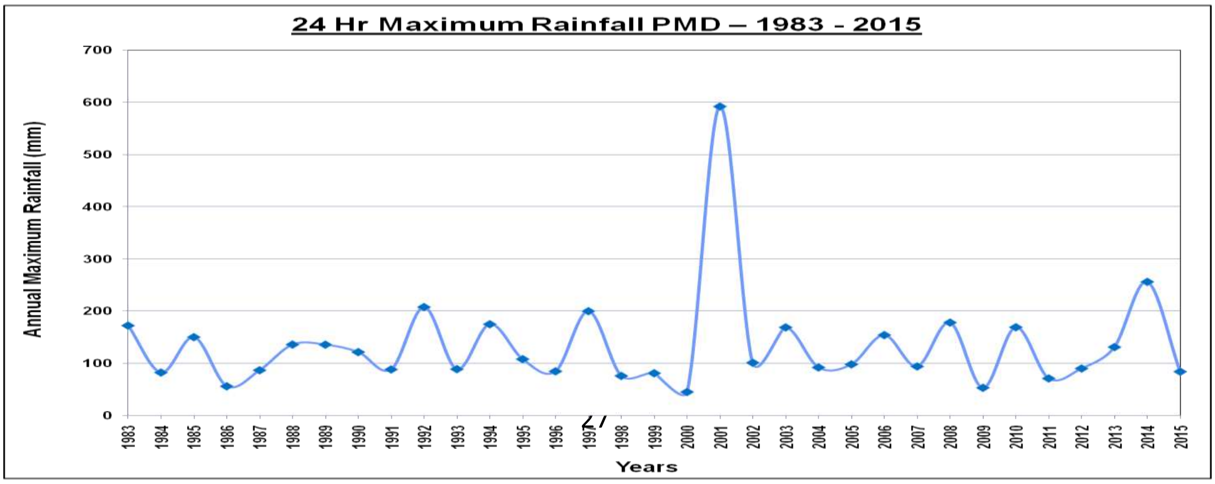
Fig-3.9 Annual Instantaneous Peak Flows – (1986 - 2015)

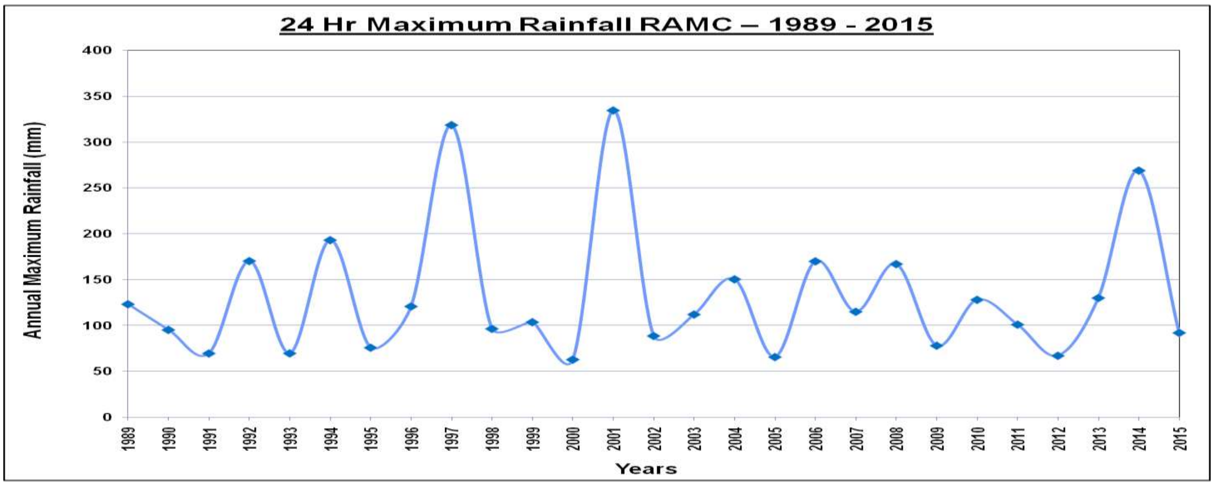
Four types of distributions (Log Normal, Log Pearson Type III, Pearson Type III & Extreme Value Type I (Gumbel) were applied to the peak flow data. Three types of goodness of fit tests including (Kolmogorov-Smirnov (KS), Anderson-Darling (AD) and Chi-Squared (x^2) (Solaiman, *et al.*, 2011) were applied to select the best fit distribution. The goodness of fit tests were performed in the freely available distribution fitting software EasyFit (Mehrannia *et al.*, 2014). Test results and statistics were generated from this software (Millington *et al.*, 2011). Coefficient of correlation (R^2) values were calculated for the best fit distribution. Trend line equation for the best fit distribution was also used to calculate magnitude of extreme flows corresponding to various return periods.

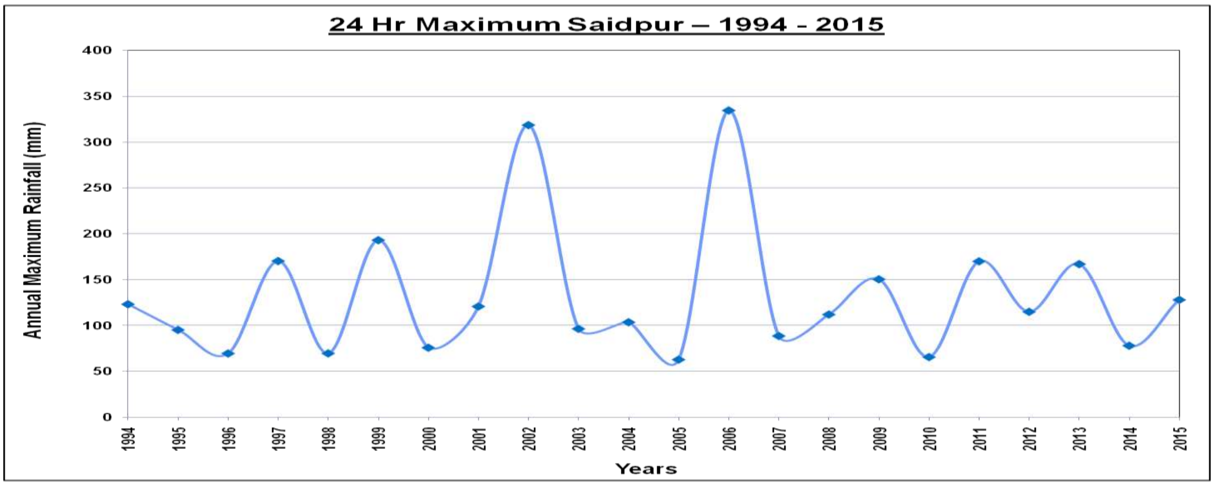
3.3.2.2 Annual Maximum Daily Rainfall Analysis

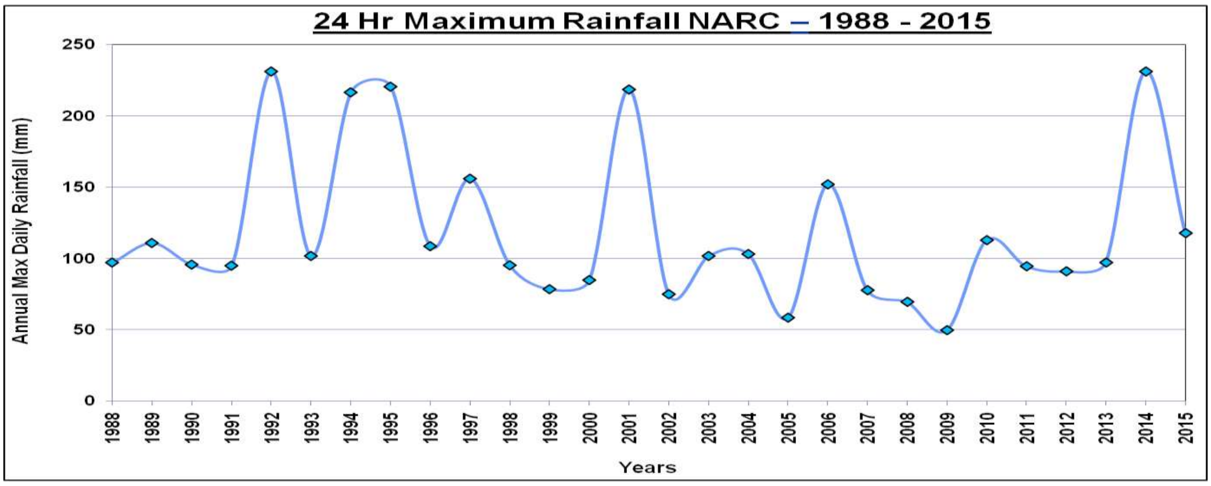
Annual maximum daily rainfall analysis was carried out for seven rainfall gauging stations including Chaklala, PMD, RAMC, Saidpur, Rawal Dam, NARC & Khanpur Dam. Rainfall data for Golra & Bokra stations with only 9 year rainfall data were not included in the analysis. Since there were no missing values, tests for high and low outliers were performed for each rainfall series and outliers removed accordingly. Annual maximum daily rainfall values for all seven rainfall gauging stations are shown in Fig-3.10. Four types of distributions already discussed were analyzed for each of the annual maximum daily rainfall data series. Goodness of fit tests through Easyfit software was executed to select the best fit distribution in each case. Rainfall values corresponding to various return periods were calculated through trend line equation. Validated HEC-HMS model was used to derive annual max peak flows for the period from 1986 – 2006 corresponding to annual max daily rainfall values.

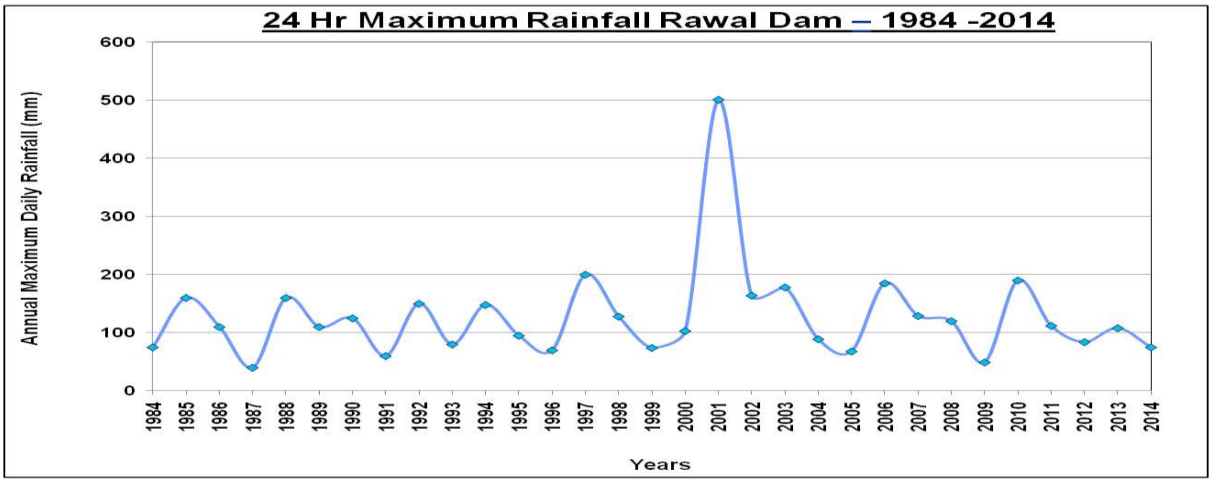





24 Hr Maximum Rainfall RAMC – 1989 - 2015
Annual Maximum Rainfall (mm)
Years


24 Hr Maximum Saidpur – 1994 - 2015
Annual Maximum Rainfall (mm)
Years


24 Hr Maximum Rainfall NARC – 1988 - 2015
Annual Max Daily Rainfall (mm)
Years



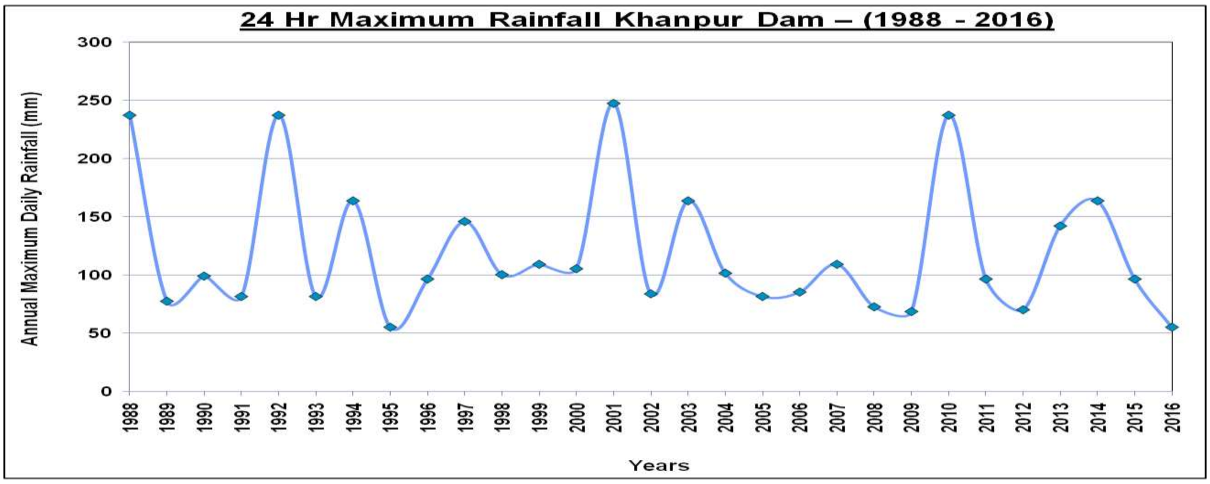


Fig-3.10 Annual Maximum Daily Rainfall Series

3.3.2.3 Comparison with JICA Study

Results of standard flood discharges calculated at various return periods through frequency analysis of annual instantaneous peak flows and annual maximum daily rainfall values were then compared with JICA Study conducted in 2003. JICA study involved calculation of standard flood discharges for various return periods through MIKE-11 Hydrological Model validated for 3 hour rainfall data of 2001 flood event using annual maximum daily rainfall data. Current study is based on calculation of standard flood discharges for various return periods through analysis of annual instantaneous peak flows and use of HEC-HMS model calibrated and validated on 10 minutes rainfall and stream flow data for six storm events using annual maximum daily rainfall values till 2015.

3.3.3 Calculation of Probable Maximum Precipitation (PMP)

According to (WMO, 2009), Probable Maximum Precipitation (PMP) is defined as the maximum depth of precipitation for a specified duration meteorologically possible for a specific watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends. Two main approaches are commonly in practice for calculation of PMP including physical approach and statistical approach (Casas *et al.*, 2011). Physical approach is based on meteorological analysis involves maximization and transposition of actual storms through storm classification and storm efficiency with the help of maximum observed rainfall & amount of precipitable water. This approach warrants availability of dew point temperature, dry and wet bulb temperature for calculation of precipitable water which is a major constraint. Statistical approach based on Hershfield technique is most widely used involving general frequency equation modified by (Chow, *et al.*, 1988) as;

$$PMP \ = X_n^- + \ (K_m \times S_n)$$

Where: X_n^-, S_n is the mean and standard deviation of maximum series of N years, and K_m is frequency factor. The empirically derived coefficient K_m is calculated by using formula (Boota, *et al.*, 2015) given as:

$$K_m \ = \frac{(X_m - \ X_{n-1}^-)}{S_{n-1}}$$

Where: X_m is the largest value of the annual series, X_{n-1}^- is Mean of the annual series omitting the largest value and S_{n-1} standard deviation of annual series omitting the largest value. (Ghahraman, 2008) shown that for number of stations within a catchment, highest value of K_m to be taken as standard for all stations for calculation of PMP.

Values of PMP calculated for all nine rainfall gauging stations were then interpolated through spline interpolation tool using ArcGIS to produce a continuous raster surface. Isohyetal lines were then generated using contour tool to spatially represent the PMP values across the watershed.

3.3.4 Calculation of Probable Maximum Flood (PMF)

Values of Probable Maximum Precipitation (PMP) were used as input for validated HEC-HMS model to generate values of Probable Maximum Flood (PMF) at Kattarian and Gawalmandi. PMF values were then compared with extreme event magnitudes of standard flood discharges through analysis of annual instantaneous peak flows and annual maximum daily rainfall values.

3.3.5 Intensity Duration Frequency (IDF) & Depth Duration Frequency (DDF) Curves

Quantification of rainfall is generally done using intensity-duration-frequency (IDF) curves (Chow, *et al.*, 1988). The Intensity Duration Frequency (IDF) relationship is a mathematical relationship between the rainfall intensity, the duration and the return period. The rainfall Intensity Duration Frequency (IDF) relationship is one of the most commonly used tools for the design of hydraulic and water resources engineering control structures. The establishment of such relationship was done as early as 1932 (Bernard, 1932). The rainfall intensity-duration-frequency (IDF) relationship is commonly required for planning and designing of various water resource projects (El-Sayed, 2011). This relationship is determined through statistical analysis of data of meteorological stations.

Graphical method was used for development of Intensity Duration Frequency (IDF) relationship curves for 6 stations within Lai Catchment i.e Chaklala, PMD, RAMC, Saidpur, Golra & Bokra. Using 3 hr frequency data for the above mentioned stations, max rainfall intensities for different storm durations of 3, 6, 9, 12 & 24 hr duration were calculated for each year as shown in Appendices 4-8. The maximum intensities from data were collated and arranged in descending order of magnitude. Values are ranked in descending order, probability & recurrence interval calculated using Weibull Formula. Following steps were involved in the development of IDF Curves:-

i. Rainfall data intensity was regressed against specified duration for each year using probability density functions.
ii. Best fit function ascertained through goodness of fit tests using Easy fit statistical software.
iii. After fitting the regression, rainfall intensities for 3 hr, 6 hr, 9 hr, 12 hr & 24 hr were estimated for different return periods through trend line.
iv. The intensity duration frequency curves are obtained by plotting the rainfall intensity values against corresponding durations for different return periods.

Using the IDF curves, rainfall values were extracted for various storm durations for six rainfall gauging stations. These values were simulated as inputs for the validated HEC-HMS model to derive standard flood discharges for Kattarian and Gawalmandi gauges. With the help of standard flood discharges for corresponding storm durations at Kattarian and Gawalmandi, depth duration frequency (DDF) curves were developed for Kattarian and Gawalmandi gauges.

3.3.6 Hydraulic Modelling

3.3.6.1 General

HEC-RAS can perform 1-Dimensional (1D) modeling, 2-Dimensional (2D) modeling (no 1D elements), and combined 1D and 2D modeling. The ability to perform combined 1D and 2D modeling within the same unsteady flow model can work on larger river systems, utilizing 1D modeling where appropriate (for example: the main river system), and 2D modeling in areas that require a higher level of hydrodynamic fidelity.

3.3.6.2 Full Saint Venant or Diffusion Wave Equations in 2D

The software solves either the full 2D Saint Venant equations or the 2D Diffusion Wave equations. In general, the 2D Diffusion Wave equations allow the software to run faster, and have greater stability properties. While the 2D Full Saint Venant equations are more applicable to a wider range of problems. However, many modeling situations can be accurately modeled with the 2D Diffusion Wave equations. Diffusion Wave Equation is far more numerically stable and accurate as compared to 2D Saint Venant equation for solving the computational flow over 2D Mesh.

Full Saint Venant Equations can be given as:

$$C = V \times \left(\frac{\Delta T}{\Delta X}\right) \leq 1.0\ (with\ a \max C = 3.0)$$

Where: C = Courant Number

V = Velocity of the Flood Wave (ft/s)

ΔT = Computational Time Step (seconds)

ΔX = The Average Cell size (ft)

Diffusion Wave Equation can be described as:

$$C = V \times \left(\frac{\Delta T}{\Delta X}\right) \leq 2.0\ (with\ a \max C = 5.0)$$

3.3.6.3 Implicit Finite Volume Solution Algorithm

The 2D unsteady flow equations solver uses an Implicit Finite Volume algorithm. The implicit solution algorithm allows for larger computational time steps than explicit methods. The finite volume approach provides a measure of improved stability and robustness over traditional finite difference and finite element techniques. The wetting and drying of 2D elements is very robust with the finite volume solution algorithm in HEC-RAS. 2D Flow Areas can start completely dry, and handle a sudden rush of water into the area.

Additionally, the algorithm can handle subcritical, supercritical, and mixed flow regimes (flow passing through critical depth, such as a hydraulic jump).

3.3.6.4 Unstructured or Structured Computational Meshes

HEC-RAS can use structured or unstructured computational meshes. This means that computational cells can be triangles, squares, rectangles, or even five and six-sided elements (the model is limited to elements with up to eight sides). The mesh can be a mixture of cell shapes and sizes. The outer boundary of the computational mesh is defined with a polygon. The computational cells that form the outer boundary of the mesh can have very detailed multi-point lines that represent the outer face(s) of each cell.

3.3.6.5 Detailed Hydraulic Table Properties for Computational Cells and Cell Faces

Within HEC-RAS, computational cells do not have to have a flat bottom, and cell faces do not have to be straight line, with a single elevation. Instead, each computational cell and cell face is based on the details of the underlying terrain. Each cell, and cell face, of the computational mesh is pre-processed in order to develop detailed hydraulic property tables based on the underlying terrain used in the modeling process. Additionally, each computational cell face is evaluated similar to a cross section and is preprocessed into detailed hydraulic property tables (elevation versus - wetted perimeter, area, roughness, etc…). The flow moving across the face (between cells) is based on this detailed data. Additionally, the placement of cell faces along the top of controlling terrain features (roads, high ground, walls, etc…) can further improve the hydraulic calculations using fewer cells overall. The net effect of larger cells is less computations, which means much faster run times.

3.3.7 HEC-RAS Model

3.3.7.1 Terrain Processing

A major limitation encountered during hydraulic modeling was lack of suitable data to accurately depict the terrain. Moreover, the available channel geometry and flood plain data covers the portion from Kattarian till Marir Chowk only. Hydraulic Modelling of Lai Nullah Stream in HEC-GeoRAS & HEC-RAS dictates an accurate flood plain surface representing both channel geometry and flood plain spot elevations For this purpose, 3 types of data were used for generation of integrated surface as follows:-

i. The flood plain topography, which was generated from 9914 surface elevation points. This data was surveyed in 2007 by WASA-RDA. A major limitation of the data was the absence of drainage network and the densely populated residential and commercial zones.

ii. River geometry survey consists of 250 cross sections from Kattarian – Marir Chowk, in year 2010 by the WASA-RDA.

iii. River geometry survey conducted by NESPAK in connection with Lai Expressway during 2010.

Merging 3 data sets of different time durations, with different bench marks and different coordinate systems was a quite laborious and time consuming task. Moreover most of the data was generated in Auto-CAD which was imported in ArcGIS and appropriated projection systems were defined. Using 3D Analyst & spatial analyst tools in ArcGIS, an integrated triangular irregular network (TIN) surface was generated using Delaunay Triangulation which was quite accurate representative of the channel geometry and spot elevations. Channel geometry was derived from 1m contours, stream centre line and embankments 3D polylines extracted from AutoCAD file of RDA Survey. Resulting generated TIN was accurate by 1m & far more accurate and realistic when compared with 30m DEM & google earth elevations points as shown in Fig-3.11.

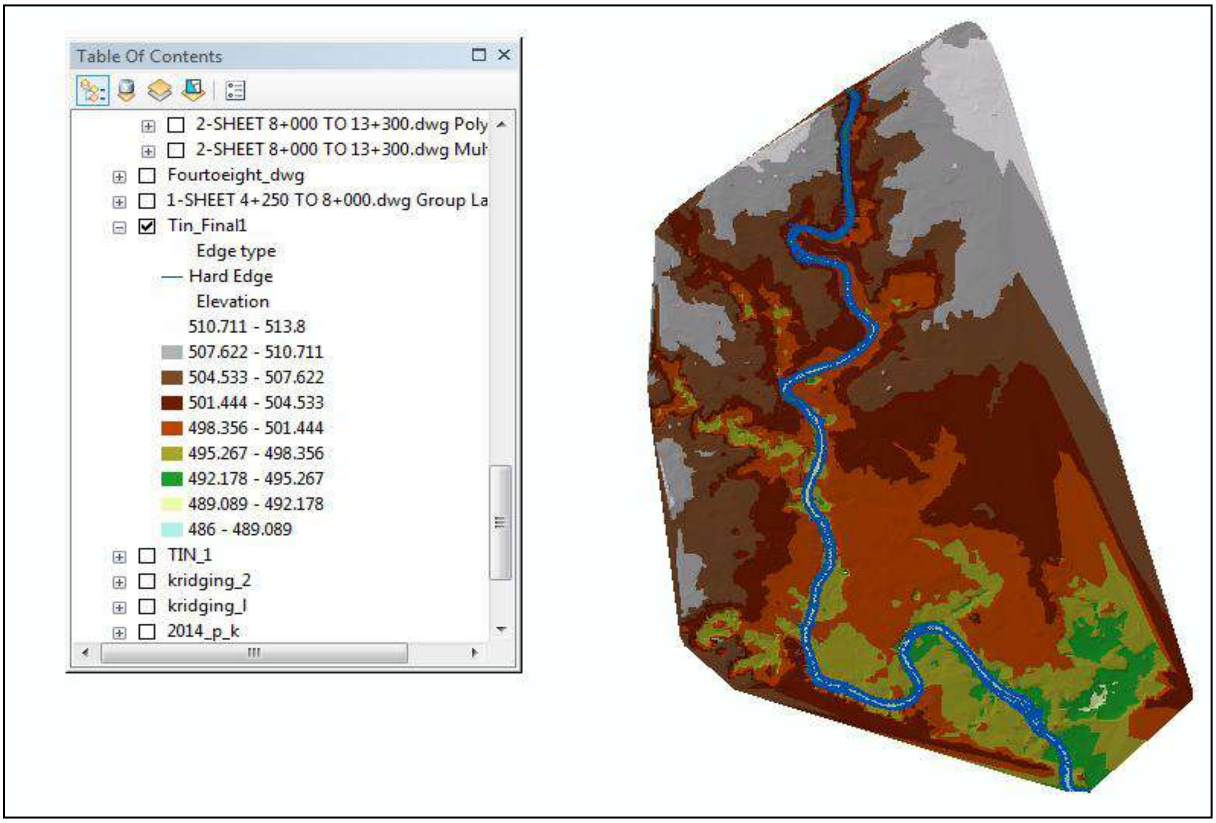


Fig-3.11 Triangular Irregular Network (TIN) – Lai Basin

3.3.7.2 Addition of Structure Elevation Data

In order to accurately represent the surface, addition of structural data including bridges, roads and railway lines was again a difficult and tricky job. Separate elevation layers were extracted each for roads, bridges and railway lines using RDA/WASA & NESPAK survey data. In case of bridges, accurate information including length, width, no of piers, pier width, spacing b/w piers, roadway width and elevation was required for modelling in HEC-RAS. Total of 9 bridges with approach roads and exits, corresponding roads and railway lines were added in existing TIN to generate an accurate continuous flood plain surface for subsequent analysis in HEC-GeoRAS & HEC-RAS. It is pertinent to mention here that in version of HEC-RAS 5.0.1 for 2D modeling, there are no direct provisions for addition of bridges information. Therefore, indirect technique using SA/2D Area Connection with culverts was adopted for addition of bridges (Goodell, 2016). Refined TIN model with addition of roads and bridges is as shown in Fig-3.12

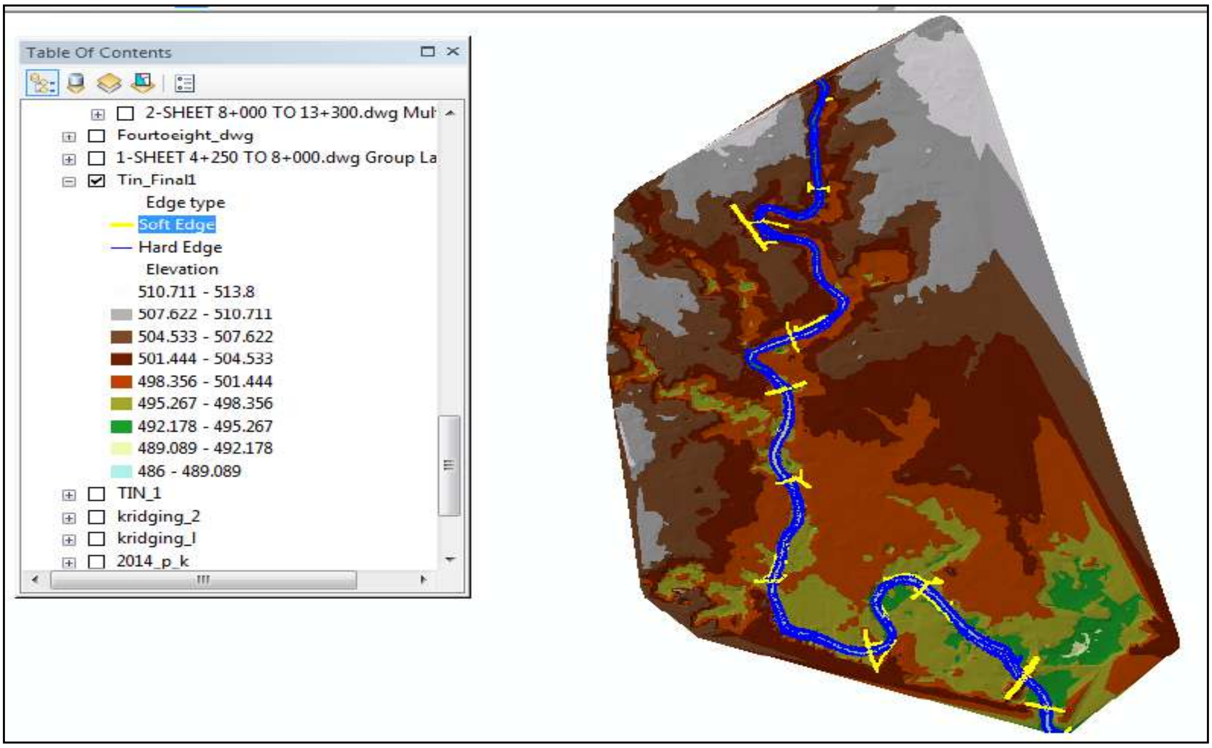


Fig-3.12 Refined TIN – Lai Basin

3.3.14.3 Generation of 2D Computational Mesh

HEC-RAS geometric editor provides 2D flow area geometric tool for generation of 2D Computational meshes. For the purpose of this study, regular computational grid cells of 25m x 25m were generated and a total of 20944 cells were generated as shown below in Fig-3.13 & Fig-3.14.

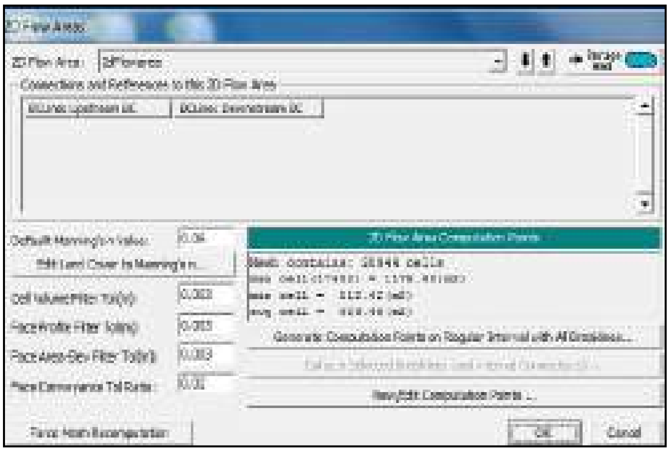


Fig-3.13 Generation of a 2D Computational Mesh

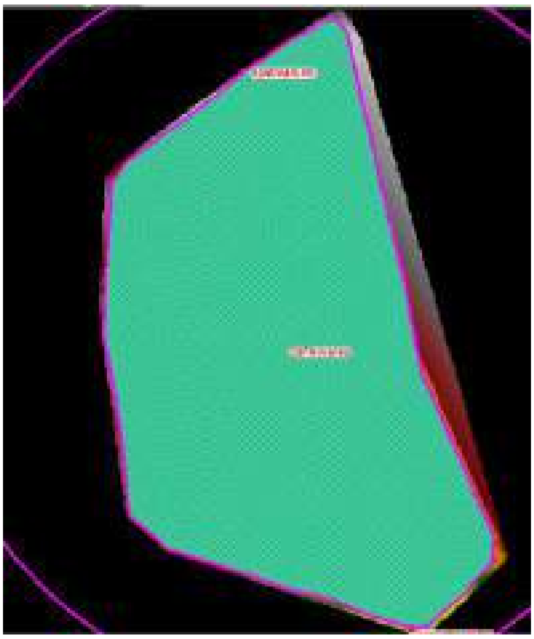
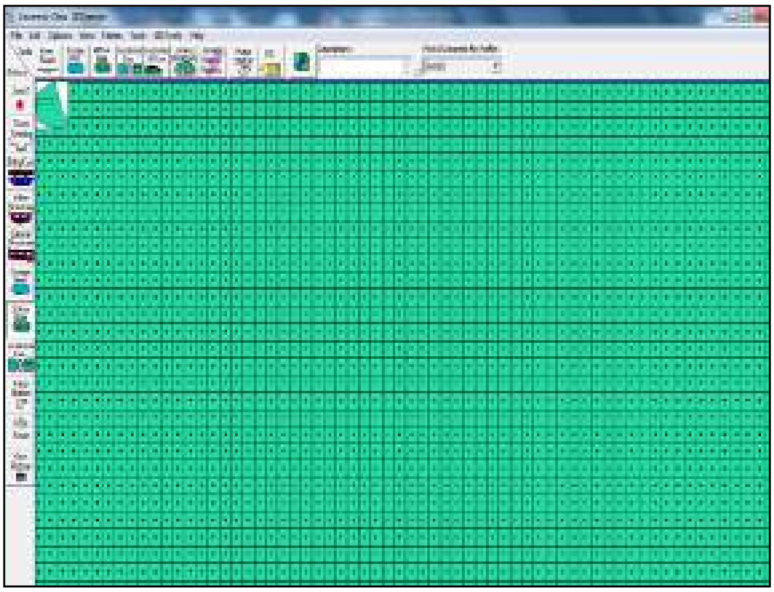
 

Fig-3.14 Computational Grid Cells of 2D Mesh

3.3.7.4 Analysis in RAS Mapper

After completion of integrated TIN, RAS Mapper tools in HEC-RAS 5.0.1 were used to generate accurate terrain model fully representative of channel geometry and flood plain. Effect of lateral structures including bridges/roads as well as high grounds was duly incorporated in the terrain model. Terrain model generated in RAS Mapper is shown in Fig-3.15.

Output of RAS Mapper results involves depth, velocity and WSE layers. An interesting feature of RAS Mapper is the inclusion of particle tracing and static velocity arrows which clearly defines the flow path and the arrows of velocities corresponding to their relative magnitude. These tools proved very helpful while understanding the concept of overbank and overtopping of flow, movement of flow over 2D computational mesh, visualizing where water is flowing and relative magnitude of the velocity.

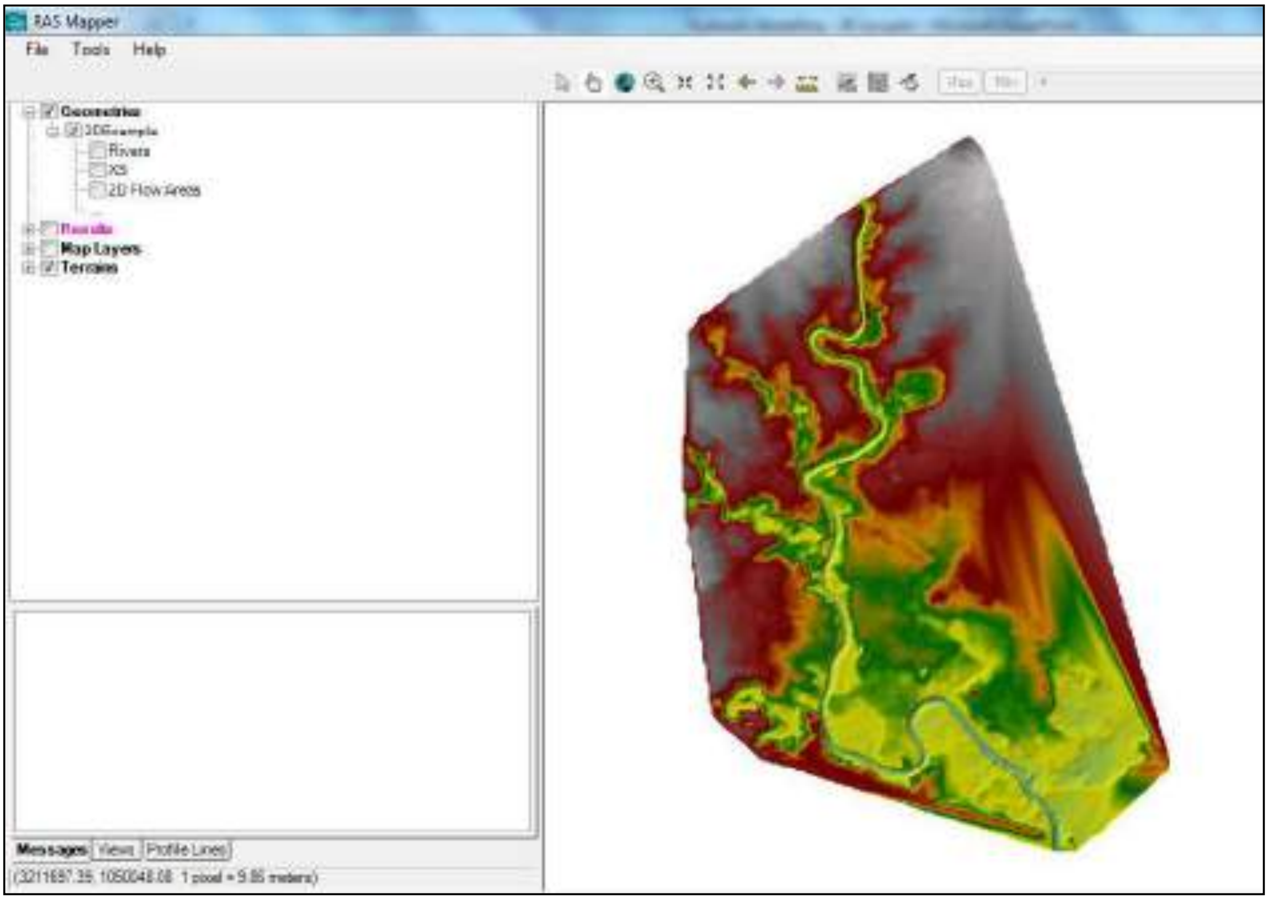


Fig-3.15 RAS Mapper Terrain

3.3.7.5 Model Calibration & Validation

Different upstream (U/S) and downstream (D/S) boundary conditions including flow hydrograph, stage hydrograph, rating curve and normal depth were tried during model calibration for unsteady flow. Basing on the trial results, inflow hydrograph was used as U/S boundary condition at Kattarian while stage hydrograph was used as D/S boundary condition near Marir Chowk. Stage hydrograph was developed with the help of discharge data extracted from hydrological model using rating curve at Gawalmandi, stage values derived from corresponding discharge at Marir Chowk. Calibration was carried out against observed data at Gawalmandi Stream Gauge against simulated data. 10 min interval recorded discharge and stage data was used for model calibration and validation. Selected events of 14 Jul 2007 & 12 Aug 2007 were used for model calibration while events of 28 Jun 2008 & 13 Aug 2013 were used for model validation.

In order to assess the model efficiency, various statistical parameters were used find the agreement between observed and simulated Water surface elevation (WSE). These parameters include Coefficient of Correlation – R, Coefficient of Determination – R^2, Relative Root Mean Square Error (%) – RRMSE and Nash-Sutcliffe Coefficient – E. As far as computation equation is concerned, 2D Diffusion wave equation being more stable and accurate was used for computation.

3.3.7.6 Manning's n Roughness Coefficient

During model calibration, calibration of Manning coefficient assumes vital significance. HEC-RAS 5.0.1 version provides model calibration provision through addition of spatially varying manning layer. By making use of spatially varying land use layer, manning coefficients were calibrated for different land use classes. As far as channel roughness coefficient is concerned, value of 0.35 was optimized during model calibration. This value of 0.35 was also using during hydraulic modeling by JICA authorities. Calibrated spatially varying roughness values are shown in Fig-3.16.

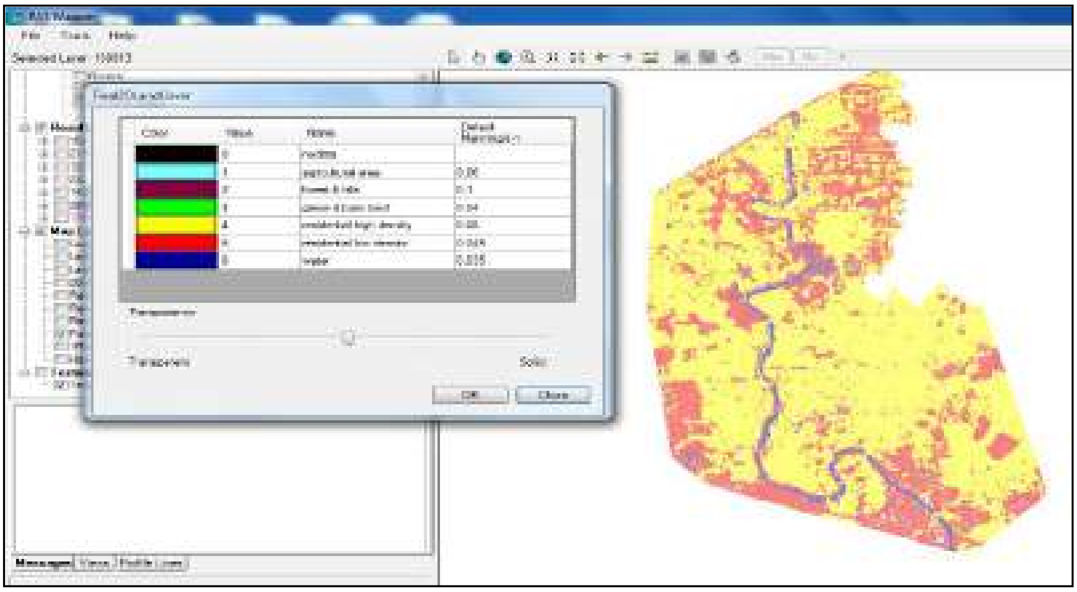


Fig-3.16 Spatially Varying Manning Layer

3.3.7.7 Simulation for Future Scenarios

Calibrated & validated hydraulic model was used for simulation of peak floods at various return periods. Different return periods i.e 2 yr, 5 yr, 10 yr, 25 yr, 50 yr, 100 yr, 200 yr, 500 yr (PMP) & 1000 yr were simulated using validated model. Different scenarios were mapped and results of RAS Mapper were imported in ArcGIS for generation of flood inundation mapping. Latest 2m resolution Google Earth satellite imagery was used as a backdrop to study to effects of spread and carry out flood plain damage assessment. Results of 100 yr return period simulation were quite consistent with results of JICA study for same return period. This further validates the model for its subsequent use for future assessment.

3.3.8 Assessment of Climate Change Scenarios

In order to assess the climate change scenarios, HI-AWARE Climate dataset based on output of 8 GCMs statistically downscaled and bias corrected at 10 km x 10 km grid resolution was used (Lutz *et al.*, 2016). Details of GCMs used in current study are shown in Table-3.5.

Type of GCMs	RCP4.5	RCP8.5	Climate Conditions
BNU-ESM_r1i1p1	X		cold, wet
inmcm4_r1i1p1	X		cold, dry
CMCC-CMS_r1i1p1	X		warm, dry
CSIRO-Mk3-6-0_r4i1p1	X		warm, wet
inmcm4_r1i1p1		X	cold, dry
CMCC-CMS_r1i1p1		X	warm, dry
bcc-csm1-1_r1i1p1		X	cold, wet
CanESM2_r3i1p1		X	warm, wet

Table-3.5 Details of HI-AWARE GCMs

Since this climate data was based on 10 km x 10 km grid resolution, where as the HEC-HMS hydrological model was calibrated and validated using rainfall station data as inputs. Therefore, bias correction was needed to be applied to convert grid data to station data. Delta downscaling technique was used to apply bias correction for all 8 models data using baseline data of 1981 – 2010 and corresponding observed station data. Delta Method is conceptually very simple and widely used in water planning studies (Hamlet *et al.*, 2010). Simplest equation of Delta Method may be given as:

$$X_{F.i} = X_{C.i} + \Delta X_{I.i}$$

$X_{F.i}$ = Future value of the cell for the variable X (precipitation, temperature) for month *i*

$X_{C.i}$ = Current value of the cell for the variable X (precipitation, temperature) for month *i*

$\Delta X_{I.i}$ = Interpolated value of the delta or anomaly corresponding to the cell for the variable X for the month *i*

As far as Delta downscaling with mean and variability change is concerned, following set of equations are used:

$$i.\quad V_{tuned} = \frac{V_{obs}^{-}}{V_{ref}^{-}}$$

$$ii.\quad S_{tuned} = \frac{S_{obs}^{-}}{S_{ref}^{-}}$$

$$iii.\quad E_s = \left(V_{proj} - V_{ref}^{-}\right) * S_{tuned}$$

$$iv.\quad E_{proj} = E_s + (V_{ref}^{-} * V_{tuned})$$

V_{obs}^{-} = Observed Climatology

V_{ref}^{-} = Reference Climatology for GCM/RCM baseline

V_{tuned} = Adjusted factor for mean climate

S_{obs}^{-} = Standard deviation of the monthly observed dataset

S_{ref}^{-} = Standard deviation of the GCM/RCM

S_{tuned} = Signal to noise ratio

V_{proj} = Particular projected month that needs correction

E_s = Signal enhanced or signal dampened for a particular projection month

E_{proj} = Bias corrected climatic variable for that particular month

This method apply monthly changes in temperature and precipitation from a GCM, calculated at the global/regional scale, to an observed set of station or gridded temperature and precipitation records that are the inputs to a hydrologic model (Onyutha *et al.*, 2016). By comparing baseline data with corresponding observed station data, Correction Factor (CF) is ascertained which is then subsequently applied to model outputs to train the model for future series. Overlapping historical period (1981–2010) was used to compare observed annual maximum daily rainfall data for 4 rainfall stations (Chaklala, PMD, RAMC & Saidpur) with base line data of GCMs. For the purpose of current study, 3 future time slices i.e (2011 – 2040 (2025s), 2041 – 2070 (2055s) & 2071 – 2100 (2085s) were selected for each of the models.

Top-30 peak rainfall values for each model for each time slice were ranked and compared with the observed rainfall data. Moreover, in order to assess the impact of climate change, frequency analysis for projected data averaged for 8 climate models 3 future time slices i.e 2025s, 2055s & 2085s was carried out and then compared with results frequency analysis of observed data. Rainfall values for 100 yrs return period based on projected average conditions were simulated in validated hydrological model. Simulated hydrographs were then used as input in validated hydraulic model. Flood extent maps for projected 100 yr return period were finally compared with current 100 yr return period map based on observed data frequency analysis.

3.3.9 Identification of Various Adaptation Strategies

In order to restrict the flood damages, various adaptation strategies including structural and non-structural measures were analyzed so as to study the most viable and feasible adaptation strategies. In connection with JICA study and discussions with RDA representatives, following structural and non structural measures were identified as likely adaptation strategies and their effects were simulated using validated hydraulic model:-

Structural Measures

i. Formation of a community pond located at Fatima Jinnah Park in Islamabad.
ii. Construction of flood mitigation dam which is to be placed in the area administratively called Block E-11 of Islamabad.
iii. Flood diversion channel to divert the flow of eastern tributary i.e Saidpur Kas joining at Kattarian to Korang River.
iv. Combination of community pond and mitigation dam in totality.

Non Structural Measures

i. Watershed management through forestation programme in foothills of Margalla so as to alter the land use scenario.
ii. Increase the channel conveyance capacity by eliminating the dumpage of solid waste and effluents in various reaches of Lai Nullah.

Chapter 4

RESULTS & DISCUSSIONS

4.1 Land Use Analysis

The results of land use analysis for Lai Nullah Basin are shown in Table-4.1. Projected land use assessment for year 2030 indicate that residential areas specially along the Lai Banks will increase owing to increase in population with corresponding decrease in agriculture, forest and green land areas classes accordingly. Fig-4.1 shows comparison of land use assessment with that of JICA Study 2003.

Land Use	**2005**		**2014**		**2025**	
	km^2	%	**km^2**	%	**km^2**	%
Water	1.85	0.85	1.82	0.84	1.75	0.81
Forest	36.29	16.70	32.06	14.75	26.89	12.37
Residential High Density	26.6	12.24	31.08	14.30	36.54	16.81
Residential Low Density	54.53	25.09	70.50	32.44	90.03	41.42
Agriculture	26.08	12.00	23.41	10.77	20.13	9.26
Green Land	72.01	33.13	58.49	26.91	42.04	19.34
Total	**217.36**	**100**	**217.36**	**100**	**217.36**	**100**

Table-4.1 Land Use Classification – Lai Basin

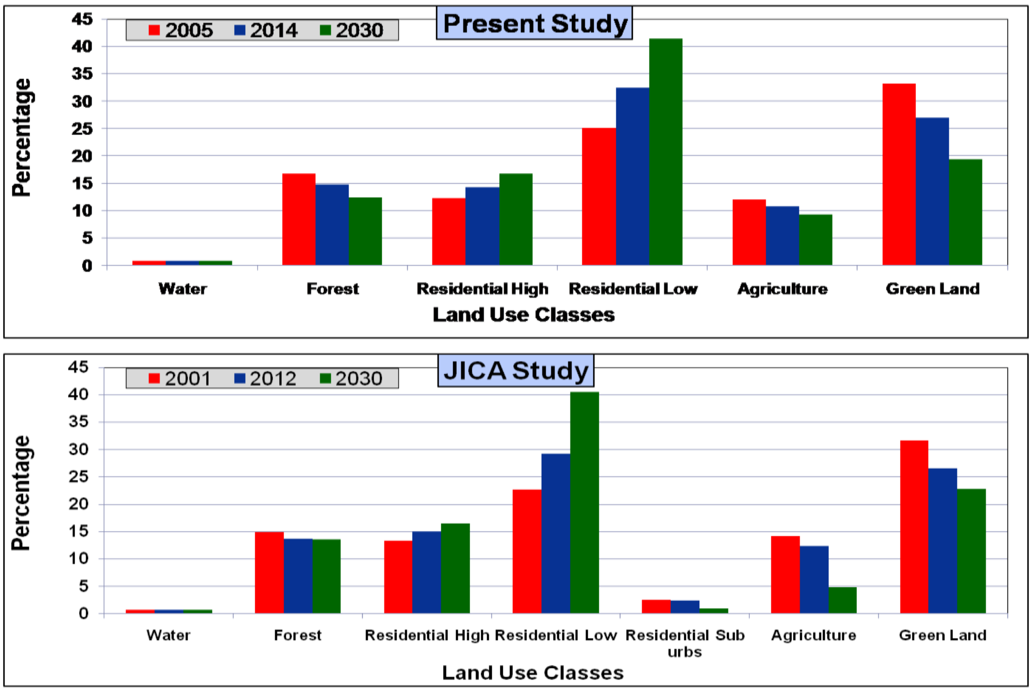


Fig-4.1 Comparison of Land Use Assessment

Comparison of land use assessment carried out in present study with results of JICA Study conducted showed strong correlation with minor variations particularly in land use class categories of agriculture, forest and green/bare land. These differences can be attributed to the use of better resolution multi-spectral satellite images (10m SPOT-5) of period pertaining to 2005 & 2014 as compared to single 30m Landsat imagery of 2001 used in JICA Study where projected land use situation of 2012 & 2030 was based on existing growth pattern and Urban Master Plan 2030. However, both studies projected an increase in urbanization pattern in future which is going to be the case owing to increasing population.

Increase in urbanization pattern predicted in both studies will also have profound impact on increase in runoff/ flood. Change in land use with time will alter the curve number (CN) thus reducing the time to peak and increase in magnitude of runoff/flood. Apropos, it can be stated the analysis of future landuse pattern of Lai Nullah Catchment reveals an increasing trend in extreme urban flooding events.

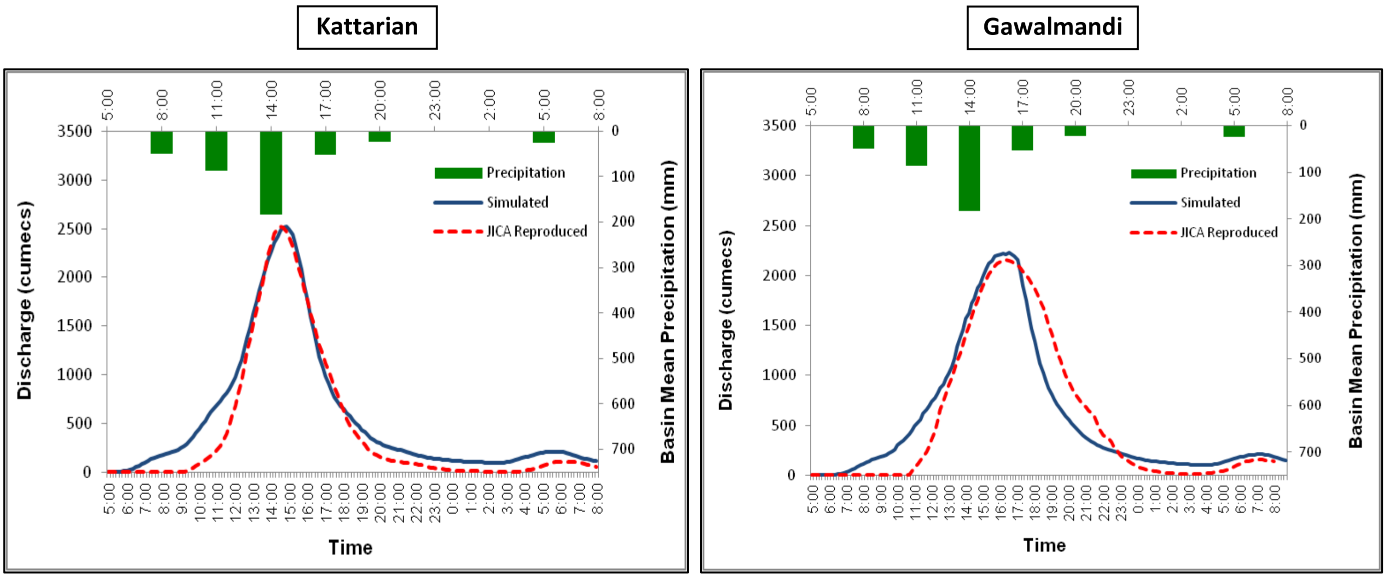
4.2 Hydrological Analysis

4.2.1 Model Calibration and Validation

Based on the results of all different methods, SCS Curve Number, SCS Unit Hydrograph, Muskingum and Recession Methods were finally selected for loss, transformation, base flow and routing respectively. Performance indicators of different methods are shown in Appendix-1. Values of impervious and basin lag time for each sub basin computed in HEC-GeoHMS were used as initial estimates for model calibration as shown in Appendix-2. Initial value for initial abstraction for each sub basin was estimated at 25 mm.

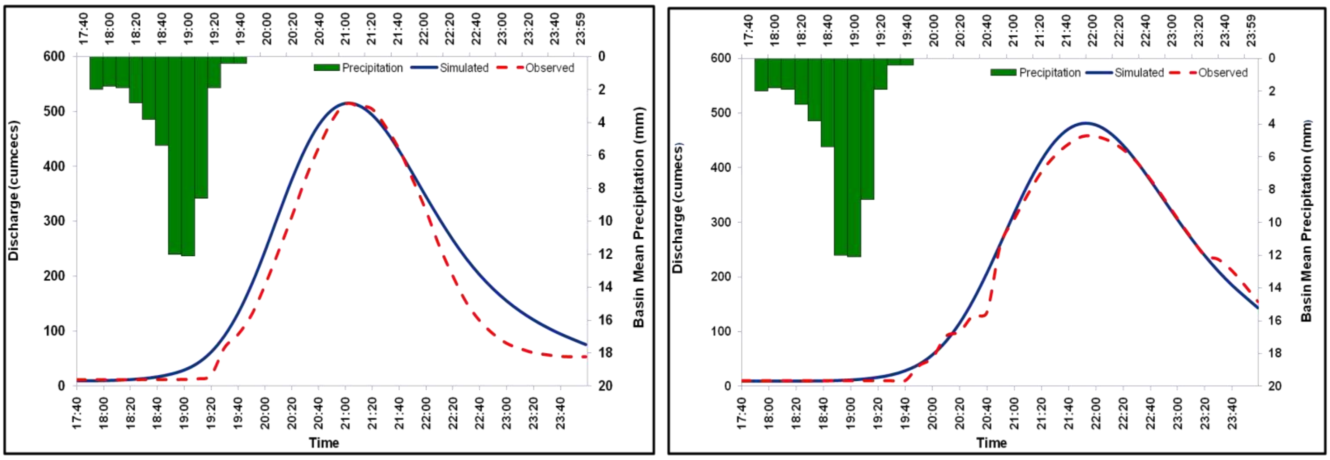
The hydrographs of rainfall-runoff analysis generated by HEC-HMS along with observed discharge values measure both at Kattarian and Gawalmandi gauges during model calibration and validation for 23 Jul 2001 event and six storm events for the period from 2007

– 2014 are shown in Fig-4.2 & Fig-4.3. Statistical performance during model calibration and validation are shown in Table-4.2 & Table-4.3. Major performance evaluation criteria include average values of coefficient of correlation (R^2) which varied from 0.972 – 0.98 and Nash-Sutcliffe Coefficient (E) which remained from 0.884 – 0.939 thus depicting a strong correlation between observed values and simulated results. Since HEC-HMS model displayed good consistent results as shown in Table-4.2 & Table-4.3 during calibration and validation against observed flows at two stream gauges using 10 mins interval rainfall data, use of validated model for the assessment of climate change, generation of past flows before 2001 period, calculation of annual peak flows from annual maximum daily rainfall values and calculation of Probable Maximum Flood (PMF) can be considered as valid, authentic and nearest representative of actual basin.

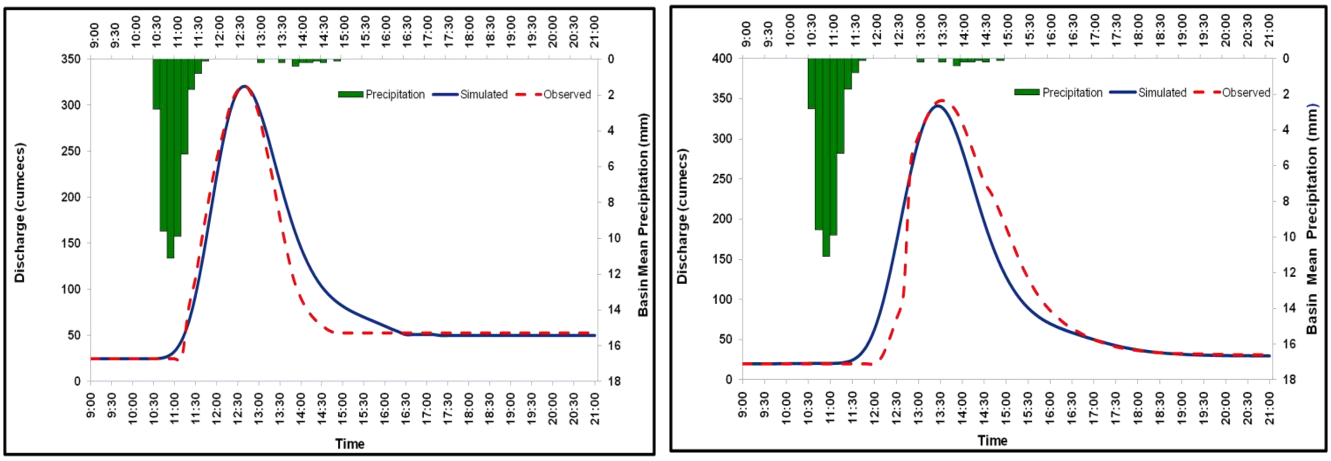


23 Jul 2001

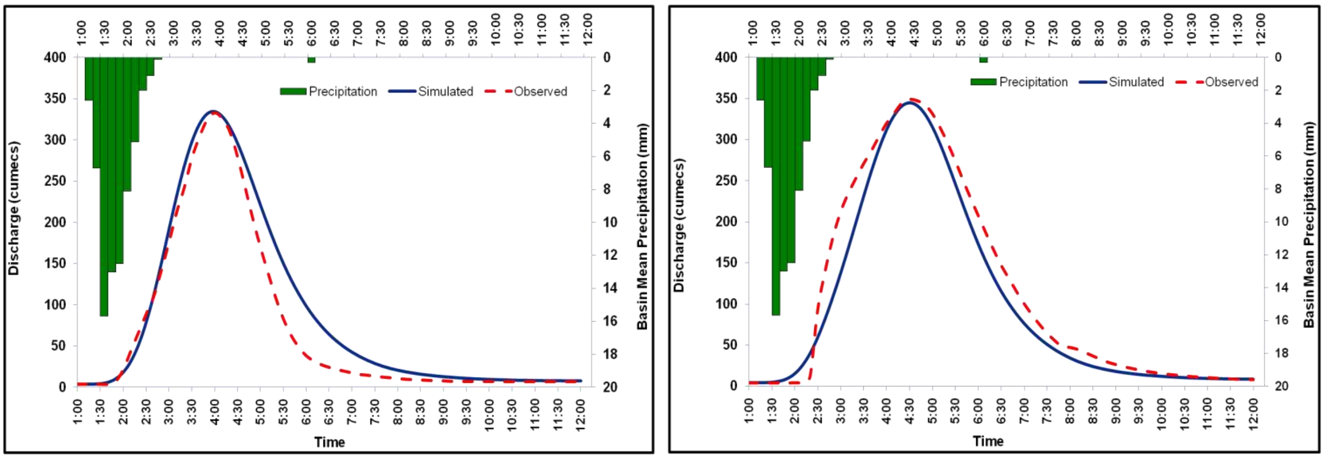
Kattarian **Gawalmandi**



14 Jul 2007



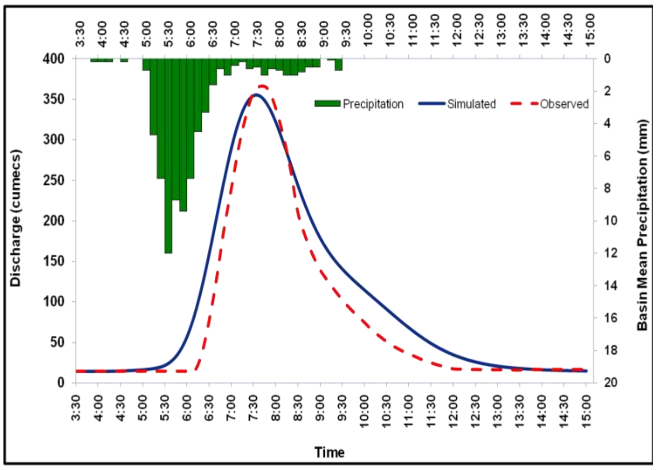
12 Aug 2007

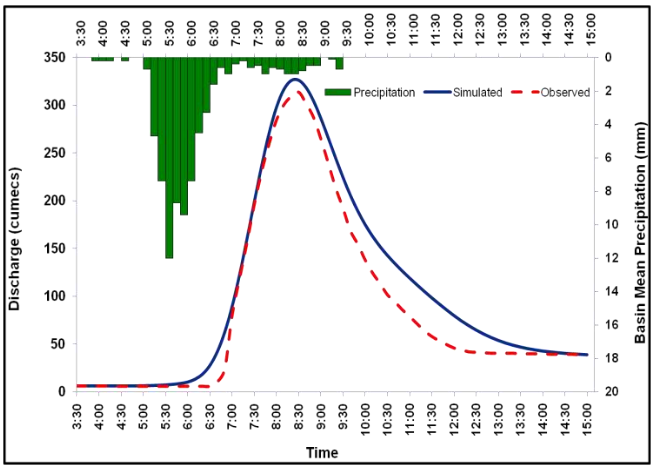


28 Jun 2008

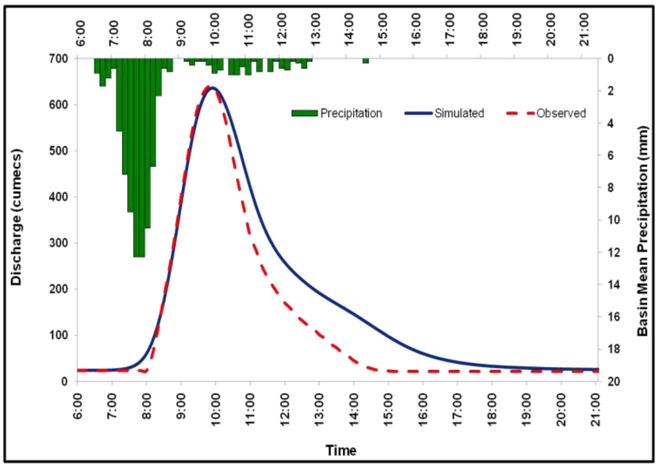
Fig-4.2 Hydrological Model Calibration

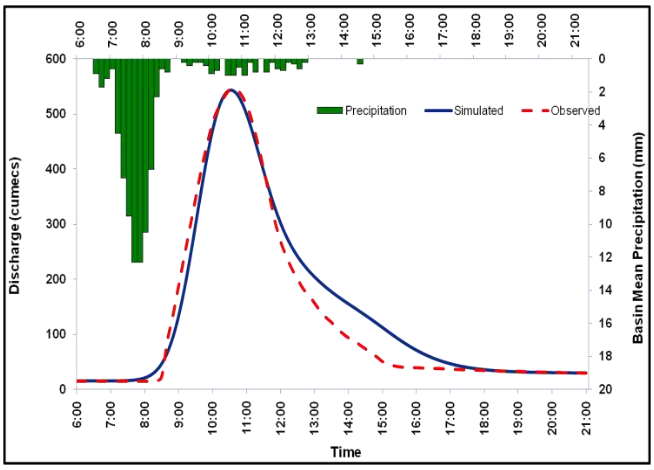
Kattarian | Gawalmandi



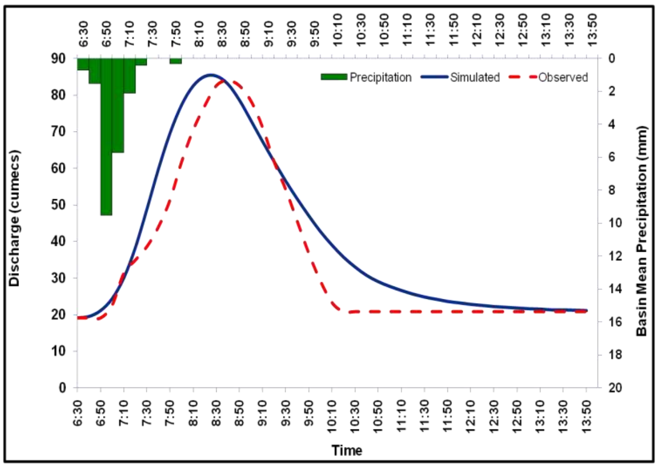


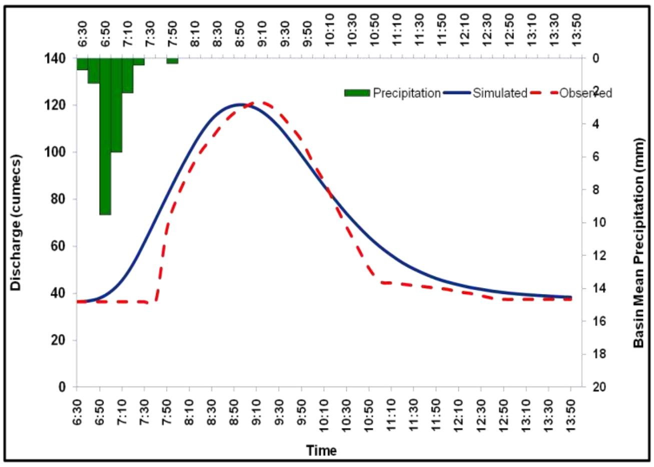
3 Sep 2012





13 Aug 2013





14 Sep 2014

Fig-4.3 Hydrological Model Validation

S.No	Event	Gauge	Volume (mm)	Observed Peak (cumecs)	Evaluation Criteria					
					R^2	RRMSE (%)	Dv %	Dp %	ΔT	E
1	23 Jul 2001	Kattarian	398.93	2517.46	0.966	1.645	1.14	0.132	0	0.943
		Gawalmandi	303.06	2152.98	0.963	2.317	3.83	2.91	10	0.878
2	14 Jul 2007	Kattarian	35.86	514	0.973	2.243	11.5	0.116	0	0.939
		Gawalmandi	24.56	457.2	0.965	0.383	1.39	5.16	0	0.989
3	12 Aug 2007	Kattarian	27.68	321.7	0.976	0.798	5.83	3.32	0	0.944
		Gawalmandi	22.31	347.2	0.960	0.411	-4.51	-1.90	0	0.921
4	28 Jun 2008	Kattarian	21.36	333.1	0.981	1.316	11.91	0.420	0	0.937
		Gawalmandi	25.76	349.2	0.988	1.569	-14.88	-1.173	0	0.959
Average			**107.44**	**874.11**	**0.972**	**1.335**	**2.026**	**1.123**	**10**	**0.939**
5	3 Sep 2012	Kattarian	21.72	366.0	0.992	1.346	8.26	-3.06	0	0.915
		Gawalmandi	18.73	314.0	0.976	1.857	12.54	3.82	0	0.873
6	13 Aug 2013	Kattarian	42.2	640.3	0.975	2.46	11.26	-0.827	0	0.885
		Gawalmandi	37.08	546.3	0.984	0.894	7.63	-0.512	10	0.835
7	14 Sep 2014	Kattarian	7.12	84.0	0.982	1.98	9.87	-1.42	10	0.882
		Gawalmandi	11.08	142.2	0.971	1.21	5.92	-0.989	10	0.914
Average			**22.98**	**348.8**	**0.98**	**1.624**	**9.24**	**-0.498**	**5**	**0.884**

Table-4.2 Performance Evaluation – Calibration & Validation

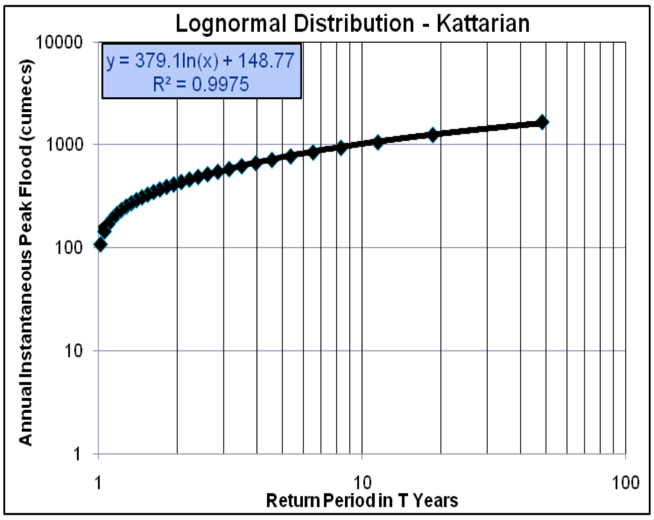
4.3 Frequency Analysis

4.3.1 Annual Instantaneous Peak Flows (AIPF)

Based on the results of goodness of fit tests (Table-4.3) performed in distribution fitting Easyfit statistical software, Lognormal distribution was found to have the optimum score in all three tests. Thus, Lognormal distribution was selected as most optimum distribution for analysis of annual instantaneous peak flows both for Kattarian and Gawalmandi (Fig-4.4). Coefficient of correlation values in both cases was 0.9975 which was quite satisfactory. Trend line equation was used for generation of future flows at various return periods. Values of standard flood discharges corresponding to various return periods is shown in Table-4.4.

S.No	Distribution	Kolmogorov – Smirnov		Anderson – Darling		Chi – Squared	
		Statistics	Rank	Statistics	Rank	Statistics	Rank
				Kattarian			
1	Gumbel	0.21564	4	1.9378	4	1.3552	2
2	Log-Pearson	0.0933	2	0.26742	3	1.2369	1
3	Log-Normal	0.08169	1	0.26049	1	2.3255	4
4	Pearson-III	0.09539	3	0.26612	2	1.5981	3
				Gawalmandi			
1	Gumbel	0.18486	4	1.6549	4	2.8385	4
2	Log-Pearson	0.11486	2	0.34978	2	1.2825	3
3	Log-Normal	0.09284	1	0.29897	1	0.47431	1
4	Pearson-III	0.13475	3	0.4571	3	1.1135	2

Table – 4.3 Results - Goodness of Fit Tests



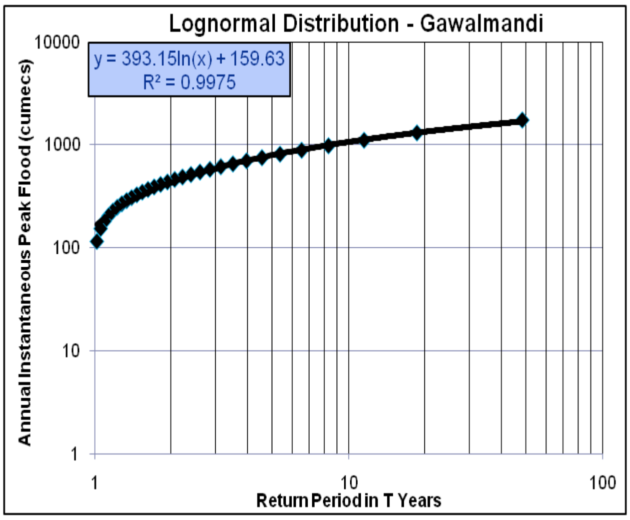


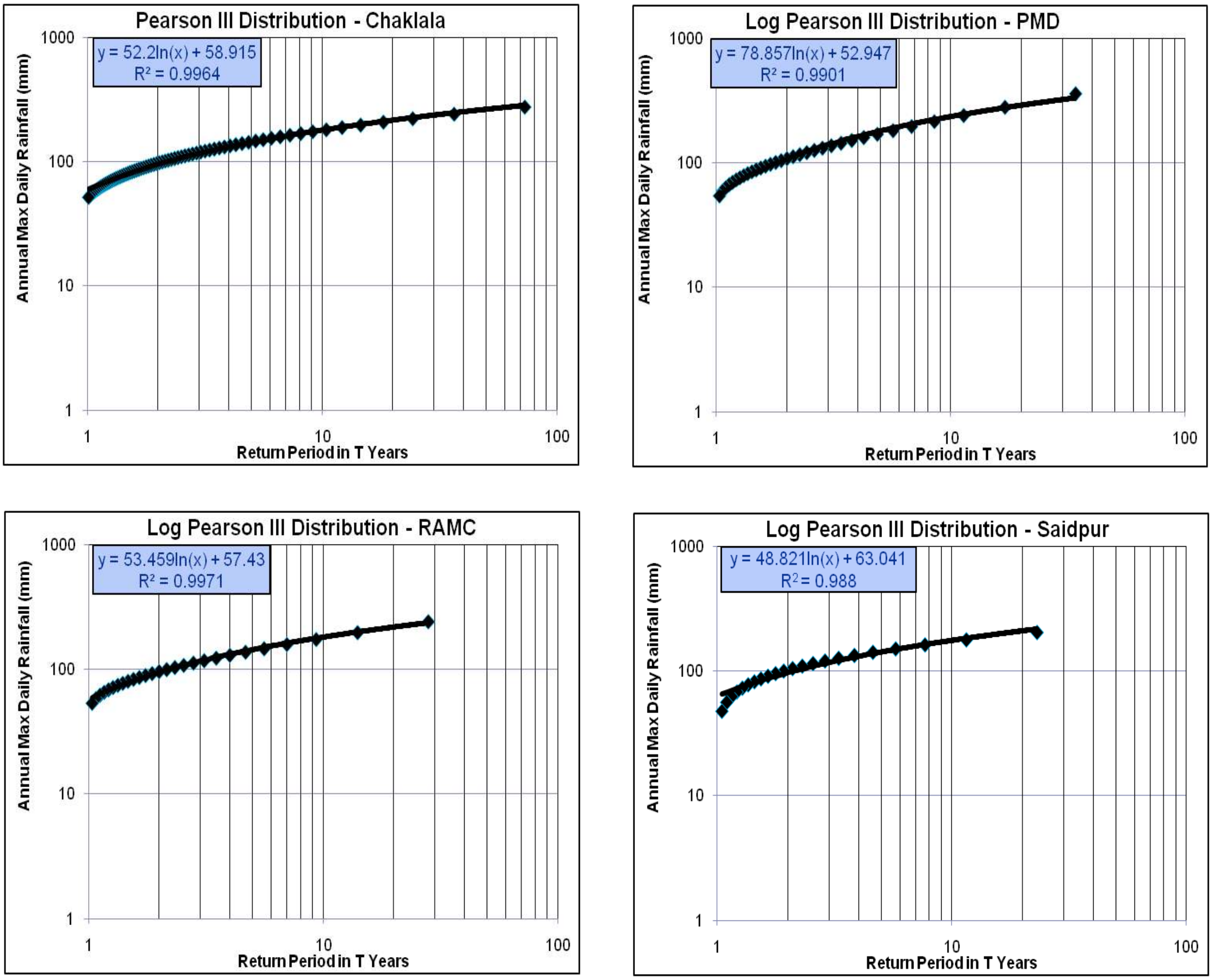
Fig-4.4 Best Fit Distribution

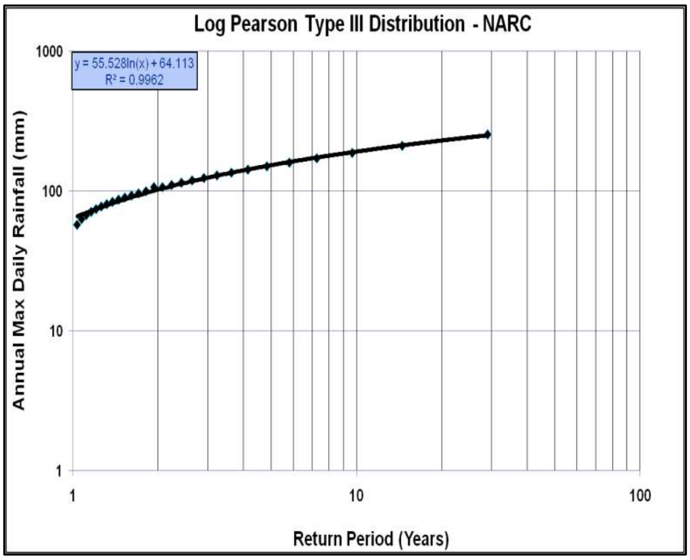
Return Period	Standard Flood Discharge Kattarian (cumecs)	Standard Flood Discharge Gawalmandi (cumecs)
2	411.54	432.14
5	758.91	792.38
10	1021.68	1064.89
25	1369.05	1425.13
50	1631.82	1697.64
100	1894.59	1970.15
200	2157.36	2242.66
500	2504.73	2602.90
1000	2767.50	2875.41

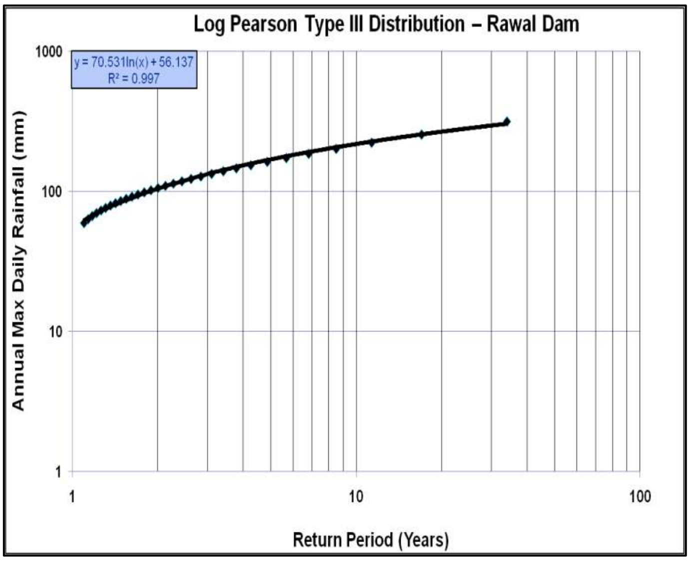
Table-4.4 Standard Flood Discharges - AIPF

4.3.2 Annual Maximum Daily Rainfall (AMDR)

Pearson Type III was found most fit distribution for Chaklala Station while Log Pearson Type III distribution was found best for rest of six stations including PMD, RAMC & Saidpur, Rawal Dam, NARC & Khanpur Dam. Trend analysis was also carried out and logarithmic trend line gave satisfactory coefficient of correlation values R^2 of 0.9964, 0.9901, 0.9971, 0.9921, 0.997, 0.9962 & 0.997 for Chaklala, PMD, RAMC, Saidpur, Rawal Dam, NARC & Khanpur Dam respectively (Fig-4.5).







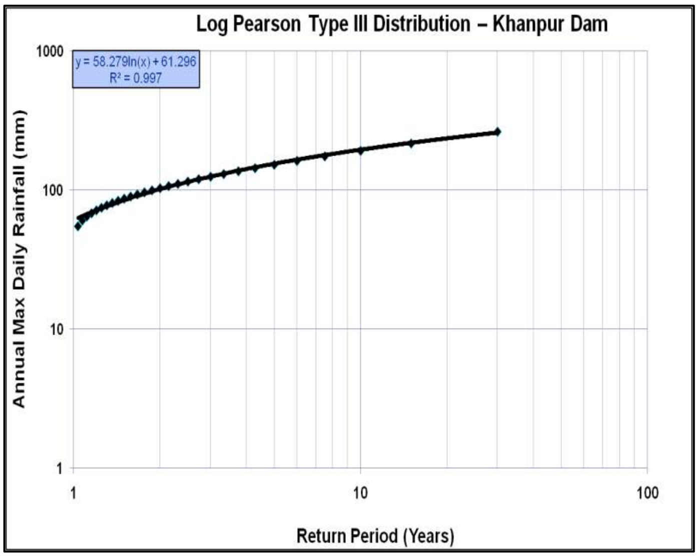


Fig-4.5 Best Fit Distribution

Trend line equation was used for generation of extreme magnitude rainfall for Chaklala, PMD, RAMC & Saidpur stations at various return periods. Values of annual maximum daily rainfall (AMDR) corresponding to various return periods for all 4 stations are shown in Table-4.5.

Return Period	Chaklala (mm)	PMD (mm)	RAMC (mm)	Saidpur (mm)
2	95.10	107.59	94.48	96.88
5	142.93	178.99	143.47	141.62
10	179.11	233.01	180.52	175.46
25	226.94	304.41	229.51	220.19
50	263.12	358.42	266.56	254.03
100	299.30	412.44	303.62	287.87
200	335.49	466.45	340.67	321.71
500	383.32	542.58	389.66	366.44
1000	419.50	597.19	426.71	400.28

Table-4.5 AMDR Values at Various Return Periods

Using the rainfall magnitudes of Chaklala, PMD, RAMC & Saidpur stations from Table-4.6 as input for validated HEC-HMS model, standard flood discharges were derived at Kattarian and Gawalmandi (Table-4.6).

Return Period	Standard Flood Discharge Kattarian (cumecs)	Standard Flood Discharge Gawalmandi (cumecs)
2	196.75	220.62
5	395.1	474.6
10	651.4	779.8
25	1161.2	1312.5
50	1620.1	1830.8
100	2197.35	2421.57
200	2760	3021
500	3450.2	3721.4
1000	3935.8	4227.1

Table-4.6 Standard Flood Discharges - AMDR

4.3.3 Comparison of Standard Flood Discharges

Standard Flood Discharges computed through frequency analysis of annual instantaneous peak flows and annual maximum daily rainfall values at Kattarian and Gawalmandi were compared against results of JICA Study of 2003 (Fig-4.6). Results indicate that values of standard flood discharges derived through annual maximum rainfall were consistent with JICA Study both for Kattarian and Gawalmandi. As far as JICA Study is concerned, values of annual maximum daily rainfall data till 2001 were analyzed and Log Pearson III distribution was used as optimum distribution.

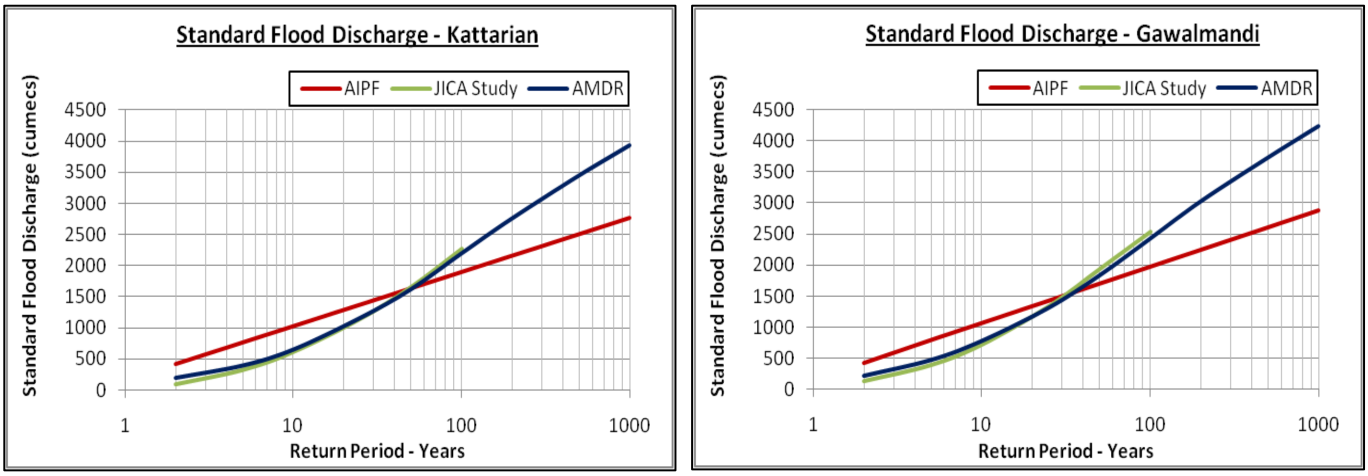


Fig-4.6 Comparison of Standard Flood Discharges

4.3.4 Probable Maximum Precipitation (PMP) & Probable Maximum Flood (PMF)

Values of PMP were calculated using statistical approach through Hershfield formula. For calculation purpose, all 9 stations data were used for PMP calculation. K_m factor was calculated for various stations and values are shown in Table – 4.7.

Station	K_m **Factor (mm)**
Chaklala	4.40
PMD	9.31
RAMC	3.38
Saidpur	2.75
Golra	2.45
Bokra	3.68
Rawal Dam	4.74
NARC	2.29
Khanpur Dam	2.13

Table - 4.7 Values of K_m Factor

Using the highest value of K_m factor standard as 9.315 as, 24-hr PMP values were computed for all 9 stations along with ratio of PMP value to highest observed value as shown in Table-4.8 below.

Station	**One Day Highest Observed Rainfall (mm)**	**Mean $\bar{X}_n$ (mm)**	**Standard Deviation S_n**	**Coefficient of Variation Cv = S_n / $\bar{X}_n$**	**24-hr PMP (mm)**	**24-hr PMP / highest observation**
Chaklala	312.4	110.9	51.92	0.46	594.62	1.90
PMD	591.9	134.1	96.13	0.71	1029.63	1.73
RAMC	334.6	132.1	73.1	0.6	813.01	2.43
Saidpur	292	153.7	59.9	0.38	711.32	2.43
Rawal	501	127.1	81.86	0.64	843.04	1.68
NARC	231.26	119.4	54.40	0.45	626.14	2.70
Khanpur	247.65	119.6	57.46	0.48	654.81	2.64
Bokra	192	94.1	33.47	0.35	503.77	2.62
Golra	237	124.7	69.84	0.56	765.32	3.22

Table 4.8 – 24-Hr PMP Values

After estimation of PMP values, these values were required to be spatially represented by using ArcGIS. For this purpose, both Kriging and Spline interpolation techniques were tried. However, Spline Interpolation method gave much better results. Spatial representation of PMP values with 30m and 50m interval is as shown in Fig-4.7.

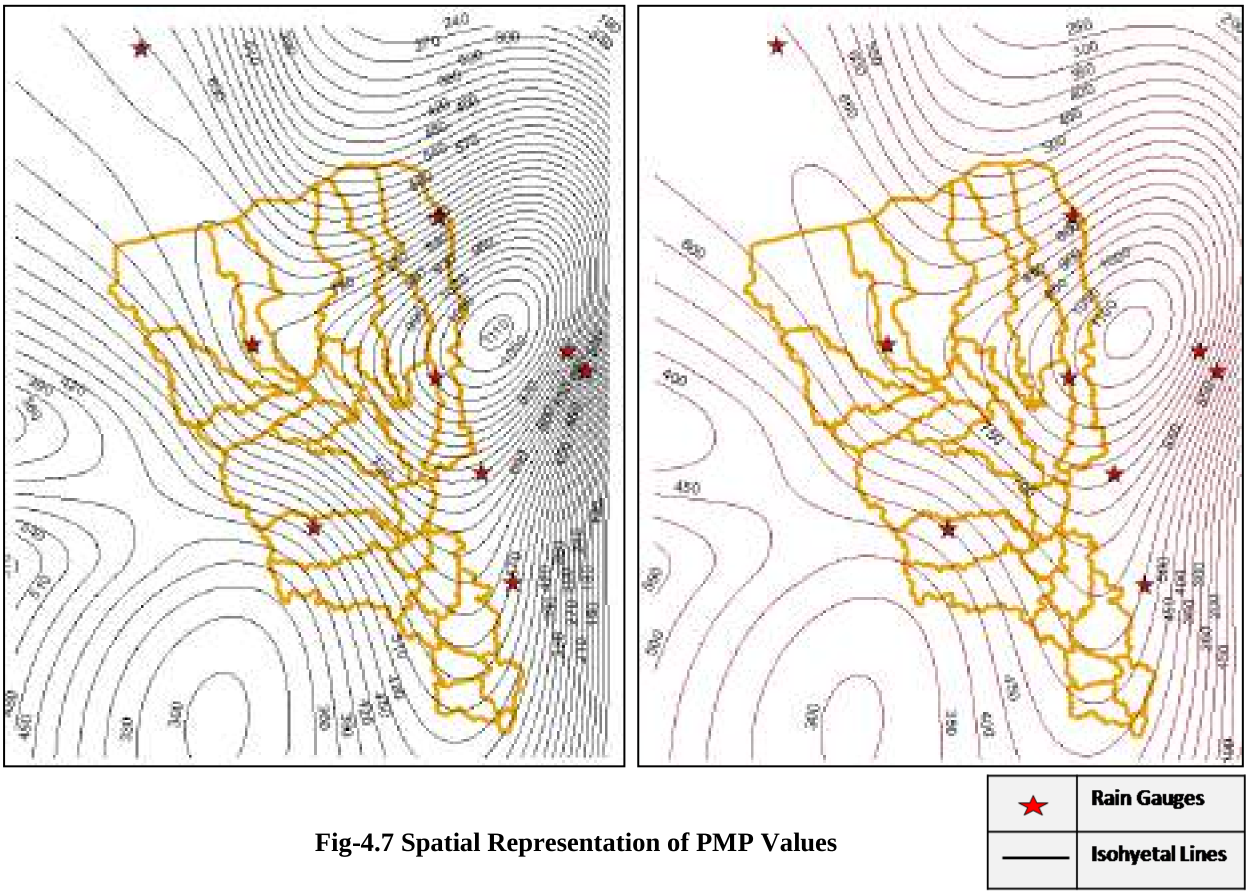


Fig-4.7 Spatial Representation of PMP Values

Using the values of PMP, as inputs for validated HEC-HMS model, PMF values were calculated for both Kattarian and Gawalmandi gauges. Values of PMF for Kattarian & Gawalmandi are 3440.15 & 3553.1 cumecs respectively. These values almost correspond to 500 year return period for annual maximum daily rainfall frequency analysis.

4.3.5 Intensity Duration and Depth Duration Frequency Curves

Using regression analysis, IDF curves for all 6 rainfall gauging stations were obtained by plotting the rainfall intensity values against corresponding durations for different return periods. Appendix-10 & Figs 4.8 shows the values and curves of IDF for corresponding 6 stations.

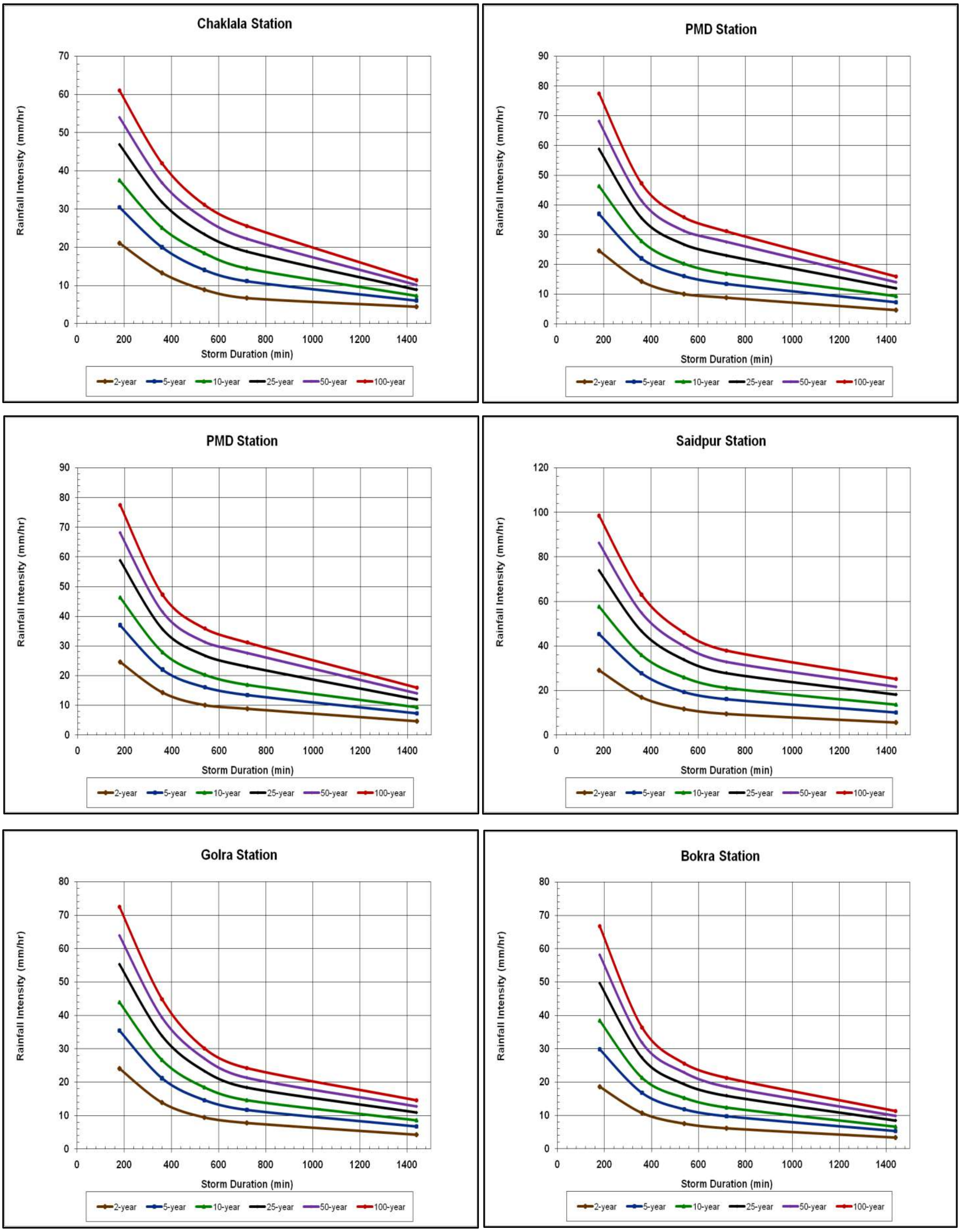
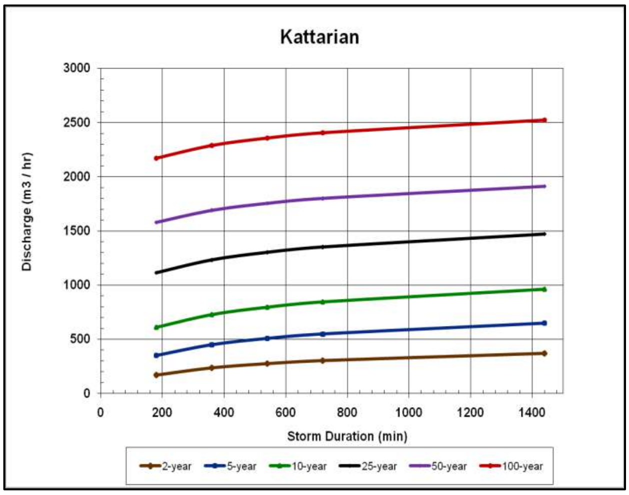


Fig 4-8 Rainfall Intensity Duration Frequency Curves – 6 Stations

Using the IDF curves, rainfall values were derived for all six stations corresponding to different storm durations as shown in Appednix-11. Derived rainfall was used as input for validated HEC-HMS model to calculate the standard flood discharges for Kattarian and Gawalmandi corresponding to various storm durations respectively as shown in Appendix-12. Depth Duration Frequency (DDF) curves generated by using standard flood discharges against various storm durations were plotted against different return periods as shown in Fig 4.9. These DDF curves can be used as operational forecast tables for different storm durations.



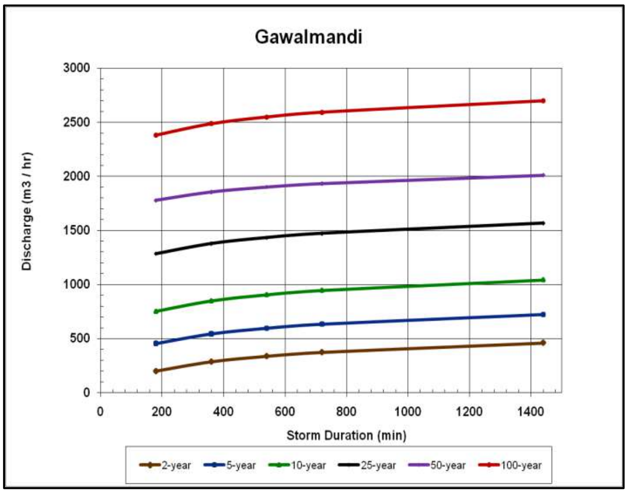


Fig-4.9 Rainfall Depth Duration Frequency Curves

4.4 Hydraulic Modelling and Flood Extents

4.4.1 Model Calibration & Validation

HEC-RAS model was initially calibrated for extreme event of 23 Jul 2001 where simulated values were compared against JICA's rainfall runoff model reproduced results (Hashmi, *et al.*, 2012; JICA, 2003; Q. T. M. Siddiqui, *et al.*, 2010). HEC-RAS hydraulic model was subsequently validated for 4 extreme events during period 2007 – 2013 using 10 mins interval observed flow hydrograph at Kattarian as U/S boundary condition while stage hydrograph condition at Marir Chowk derived from rating curve at Gawalmandi was used as D/S boundary condition. Observed and simulated WSE at Gawalmandi for all 5 events are shown in Fig-4.10 & Fig-4.11. Various statistical parameters were used to check the model efficiency during calibration and validation by comparing observed WSE with simulated results at Gawalmandi. Average values of Nash Schutcliffe Coefficient (E) remained between 0.834 – 0.908 during model calibration & validation which confirms the correlation as strong between simulated and observed data as shown in Table-4.9. Flood extent maps for all 4 events are shown in Fig-4.12. Moreover, flood extent map for event of 23 Jul 2001 was also compared against JICA Ground Survey Map as shown in Fig-4.13.

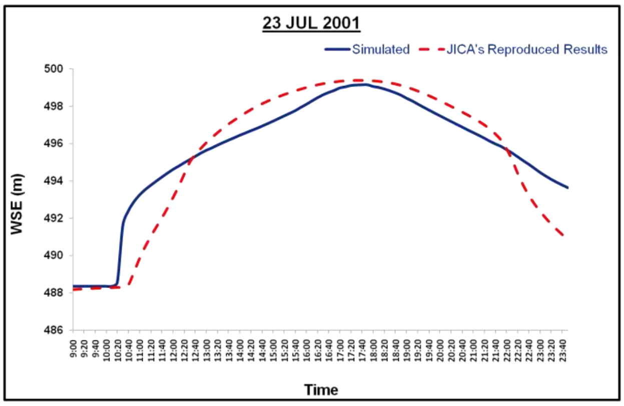


Fig-4.10 Model Calibration – 2001 Event

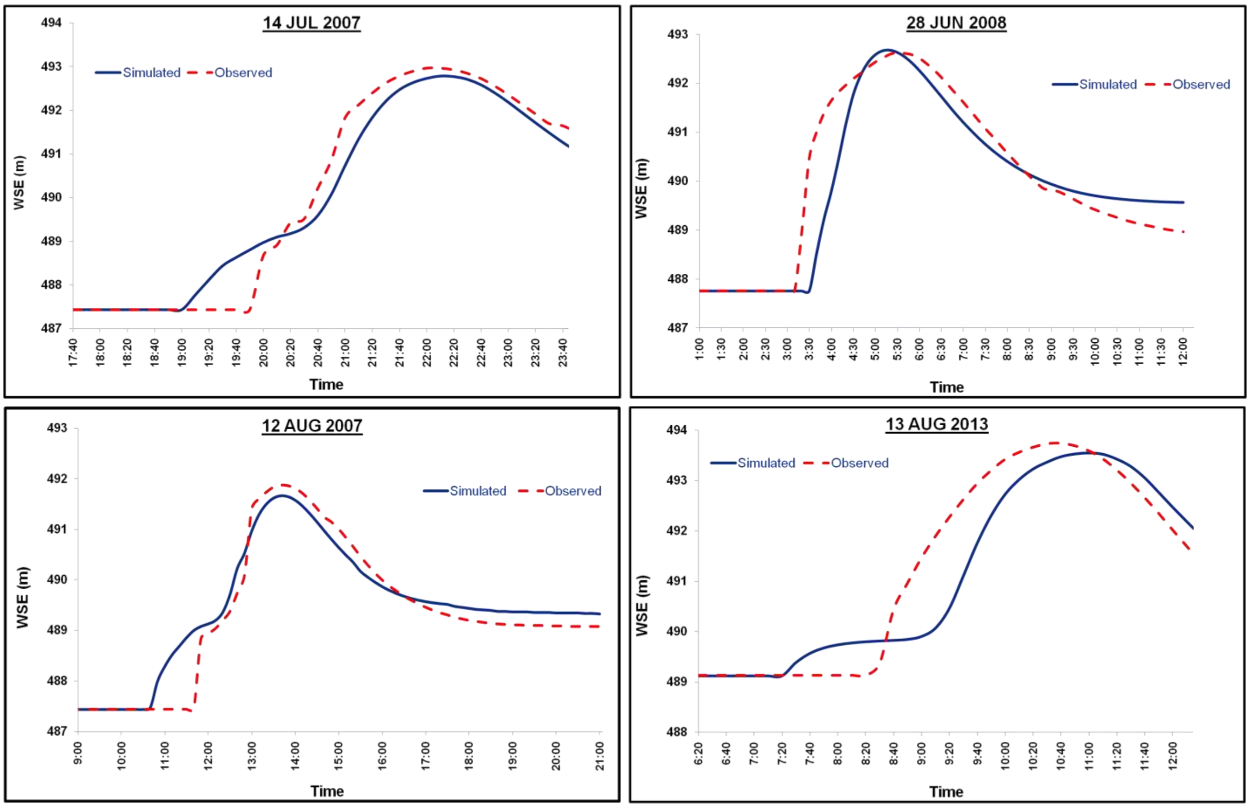


Fig-4.11 Model Validation Results

S.No	Event	Gauge	Evaluation Criteria			
			R	R^2	RRMSE (%)	E
1	23 Jul 2001	Gawalmandi	0.964	0.929	1.91	0.816
2	14 Jul 2007	Gawalmandi	0.952	0.906	2.08	0.911
3	12 Aug 2007	Gawalmandi	0.910	0.826	1.05	0.905
4	28 Jun2008	Gawalmandi	0.919	0.844	1.67	0.836
5	13 Aug 2013	Gawalmandi	0.929	0.863	3.55	0.849
Average			**0.9348**	**0.8736**	**2.052**	**0.8634**

Table-4.9 Performance Evaluation – Calibration & Validation

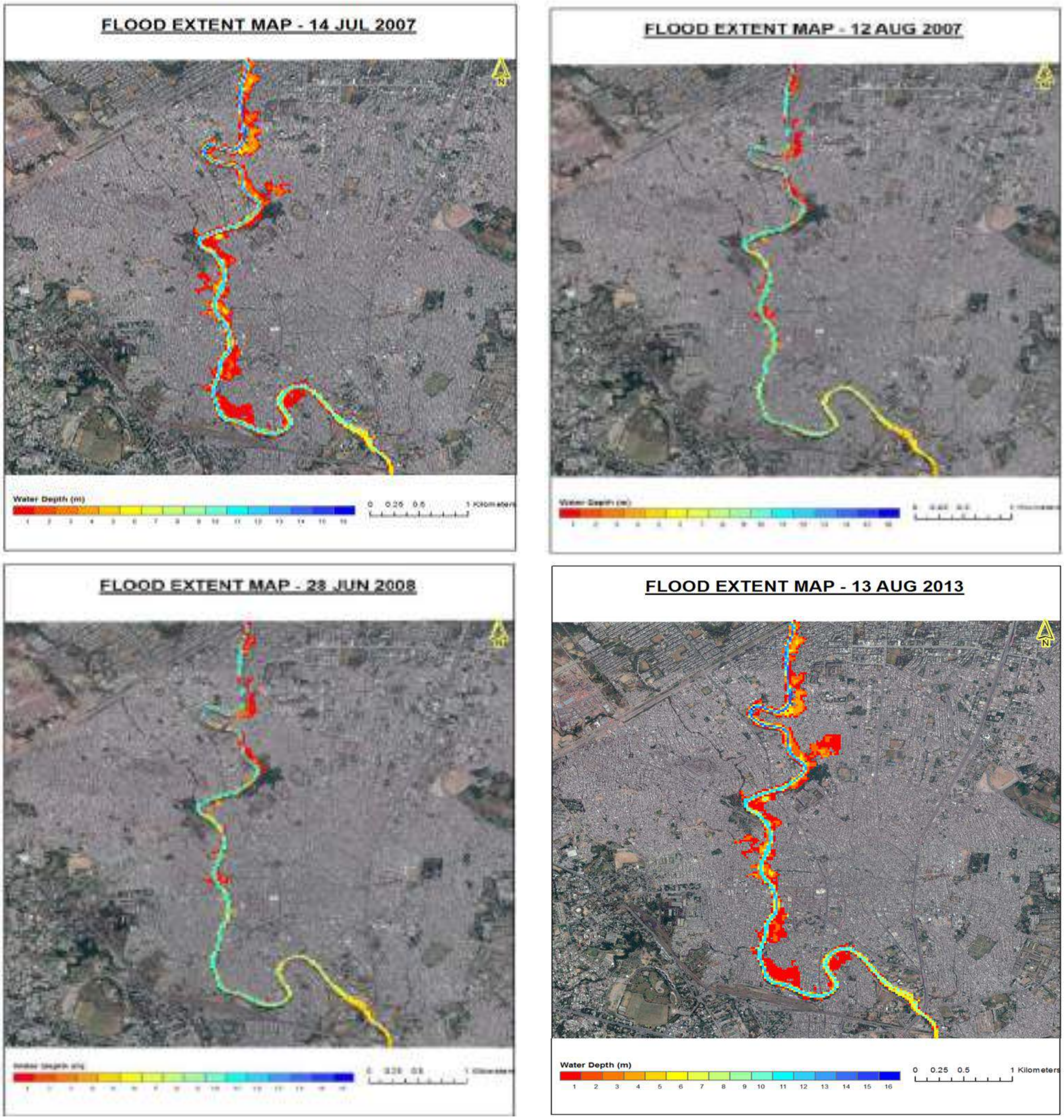


Fig-4.12 Flood Extent Maps

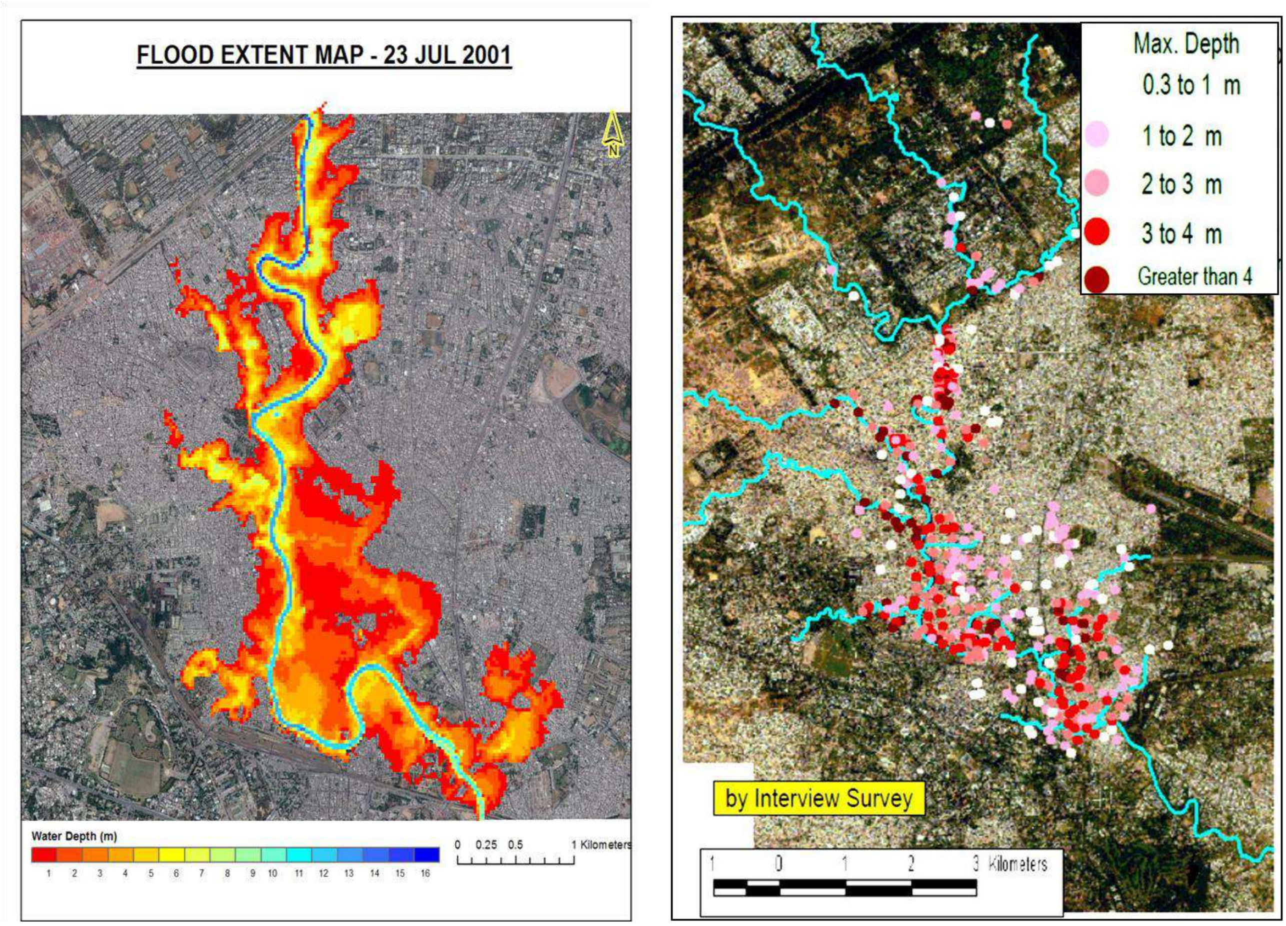


Fig-4.13 Comparison of 2001 Flood Extent Map & JICA Map

4.4.2 Simulation for Various Return Periods

Validated HEC-RAS model was used to model flood inundation for standard flood discharges at various return periods estimated through AMDR (ref Table-4.6). Areas inundated due to flood spread in various return periods were also estimated to determine the change in inundation extents with increase in return periods as shown in Table-4.10. Flood extent maps for various return periods are shown in Figs-4.14 – 4.22.

Return Period	Flood Inundated Area (km^2)
2	0.021844
5	0.551035
10	0.91978
25	1.905703
50	4.910648
100	5.25756
200	5.986571
500	6.15547
1000	6.312341

Table – 4.10 Flood Inundated Areas

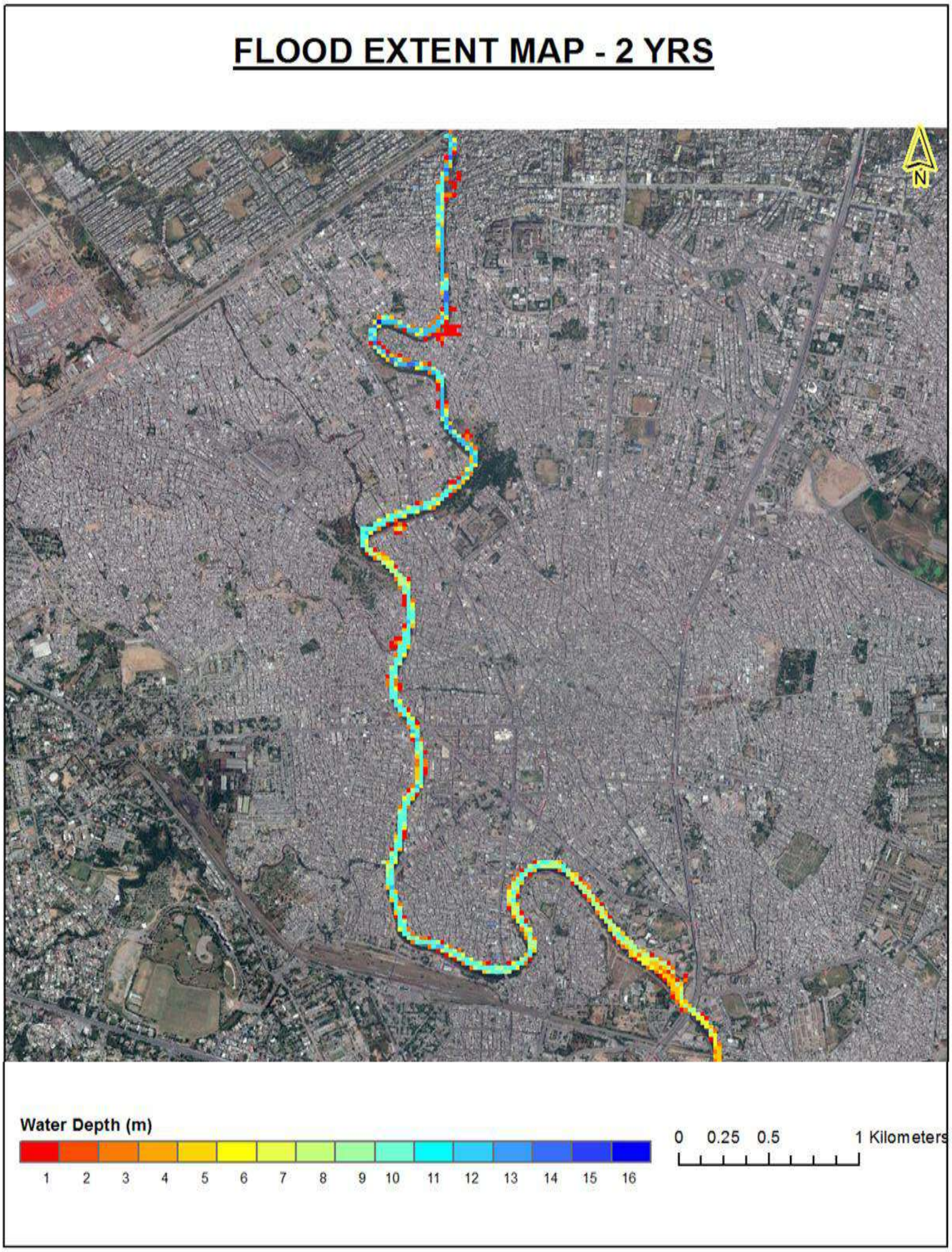


Fig-4.14 Flood Extent Map – 2 Year Return Period

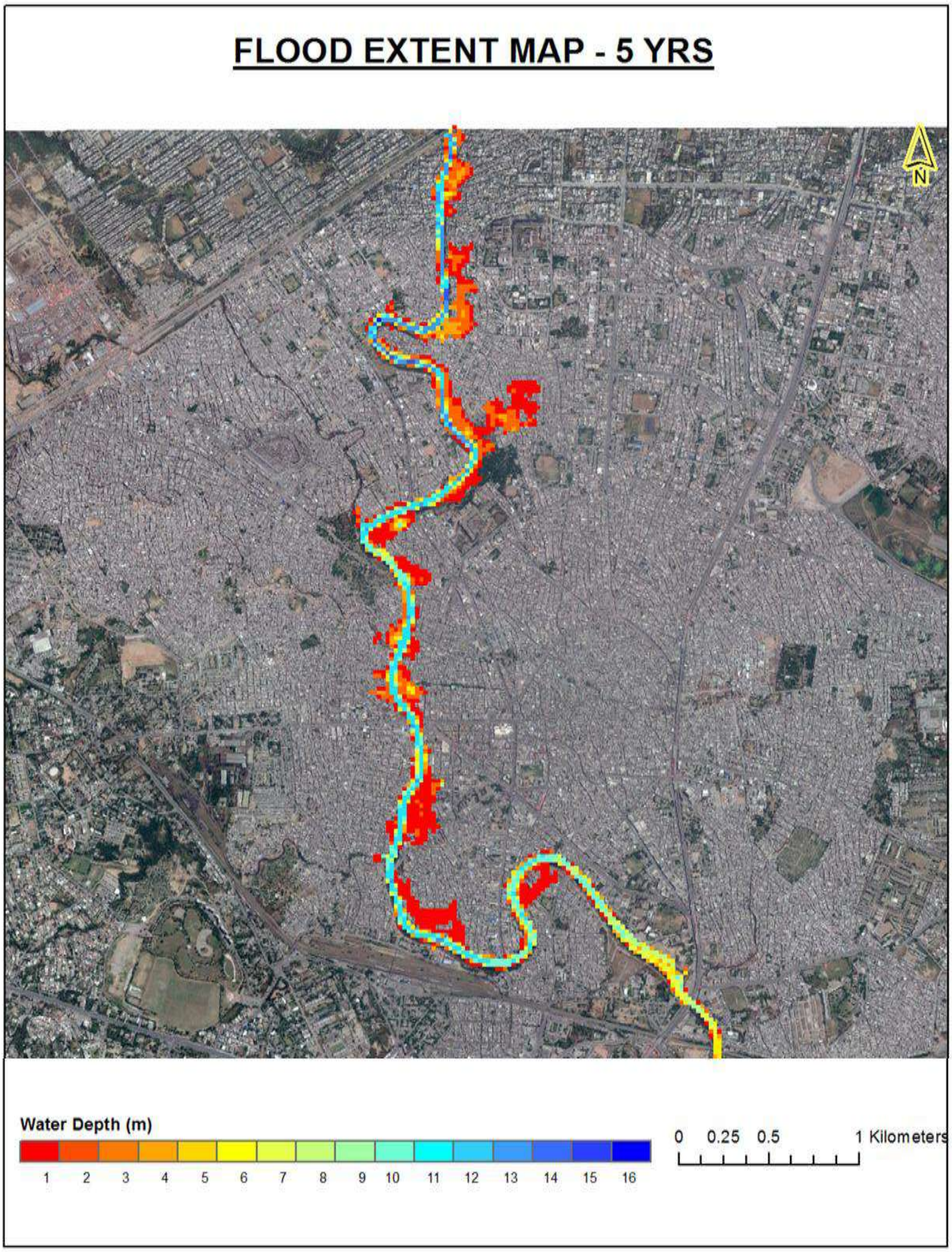


Fig-4.15 Flood Extent Map – 5 Year Return Period

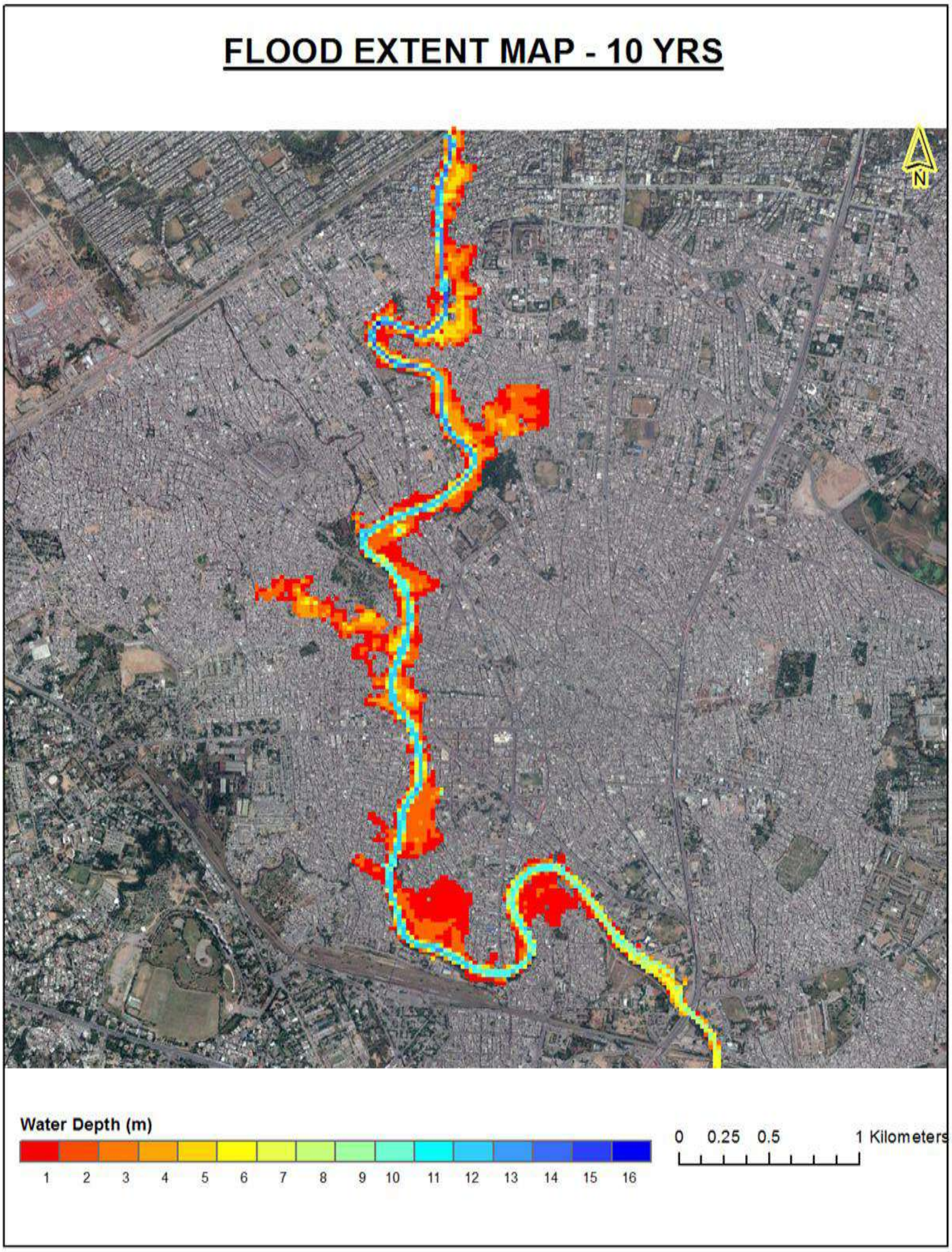


Fig-4.16 Flood Extent Map – 10 Year Return Period

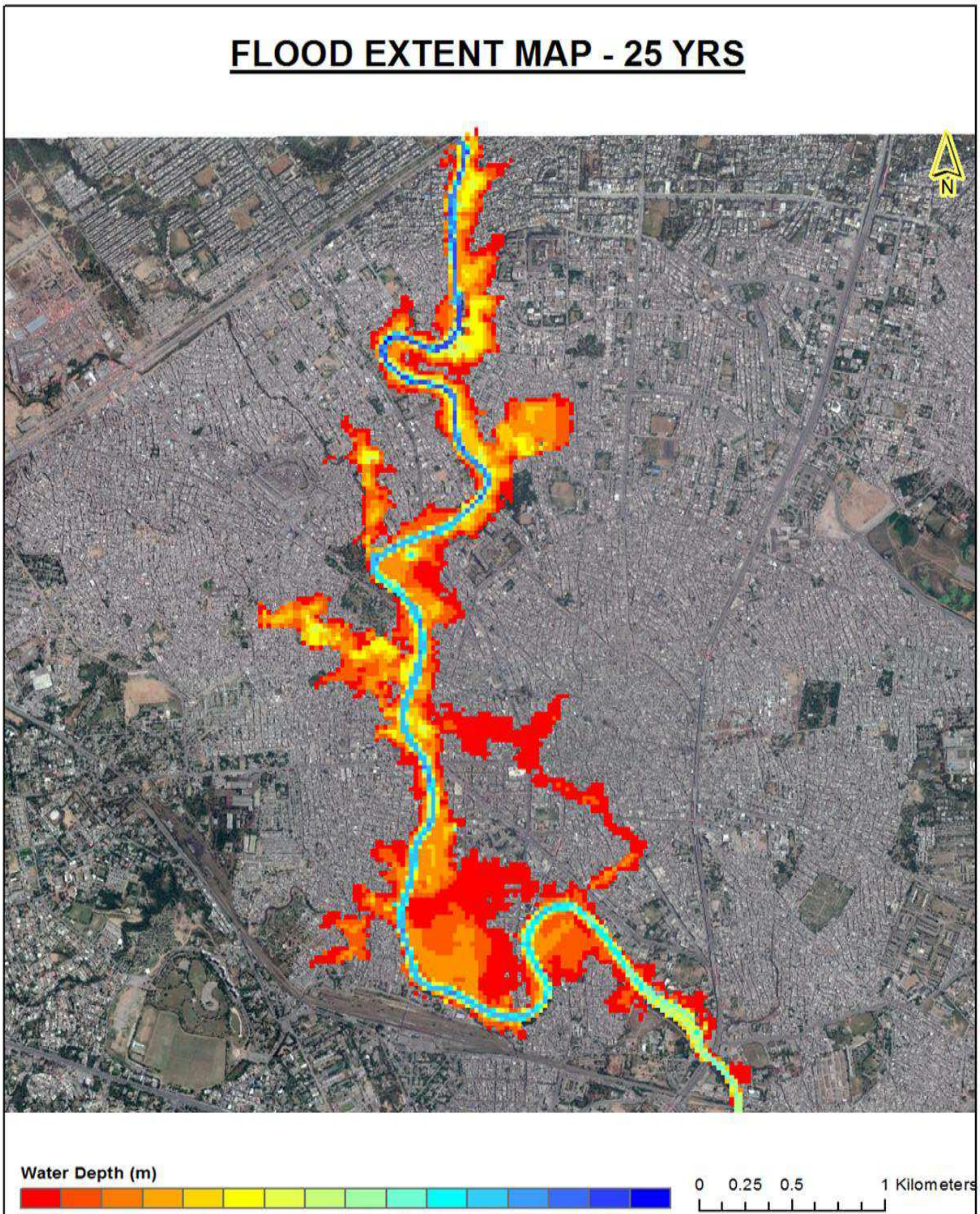


Fig-4.17 Flood Extent Map – 25 Year Return Period

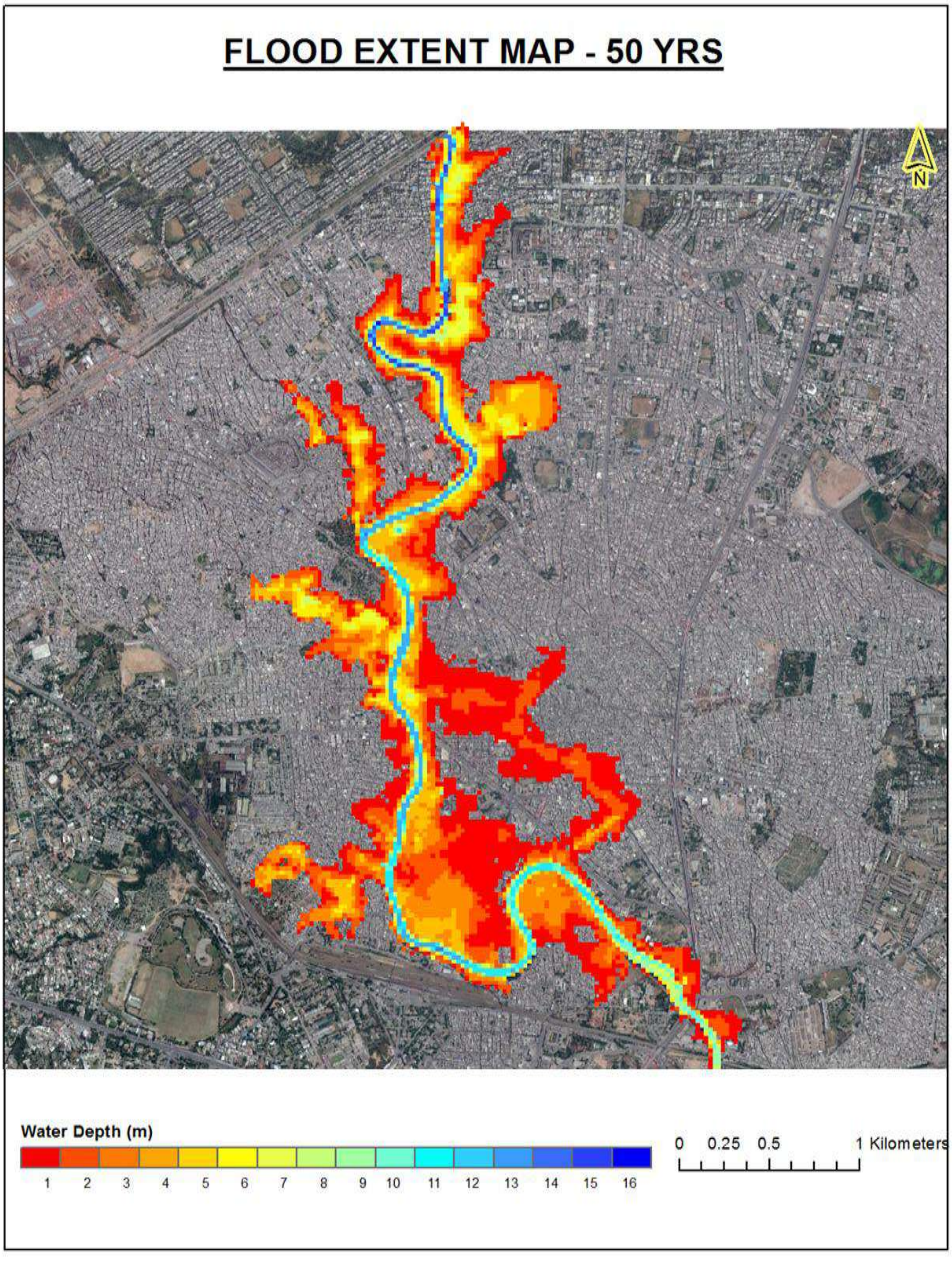


Fig-4.18 Flood Extent Map – 50 Year Return Period

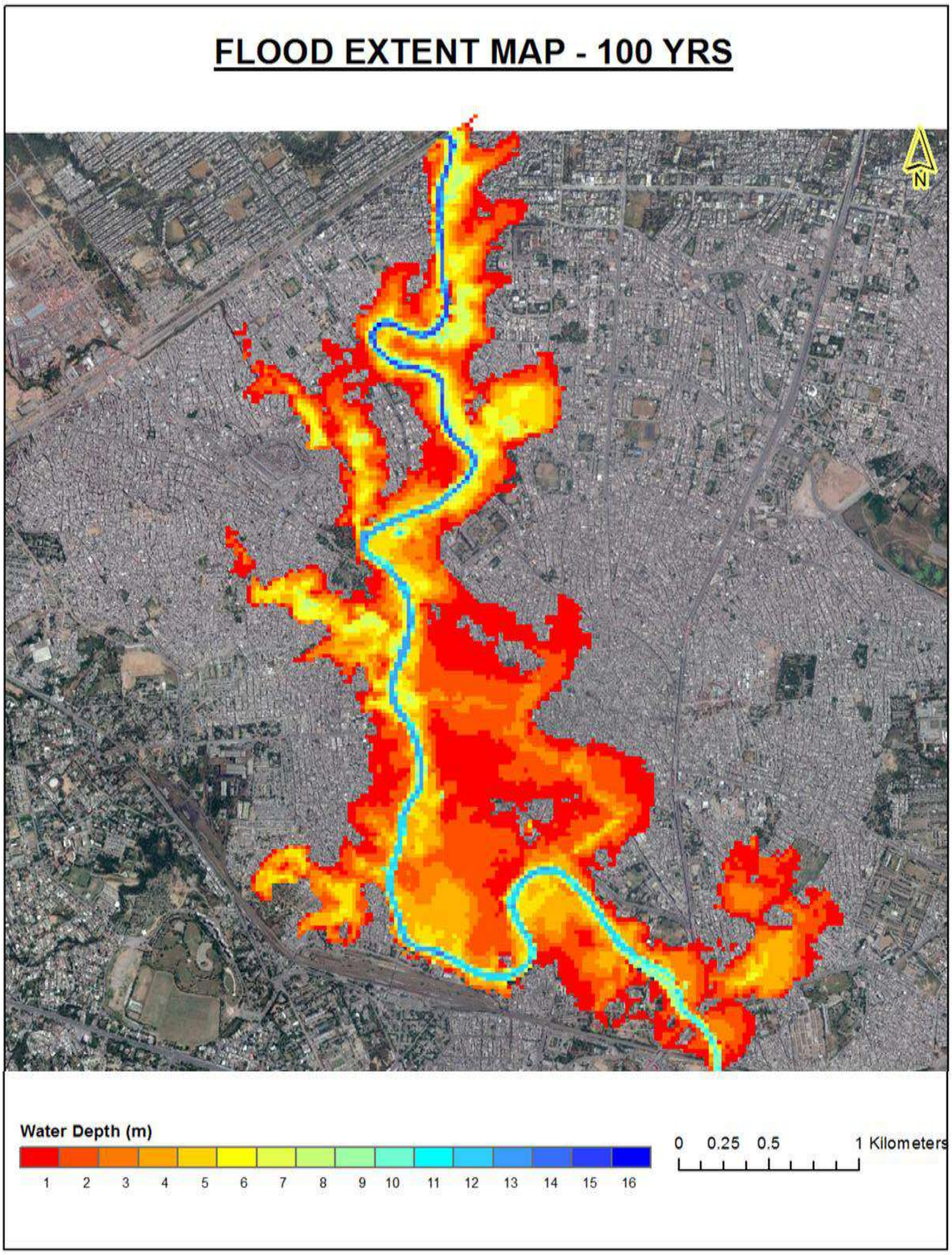


Fig-4.19 Flood Extent Map – 100 Year Return Period

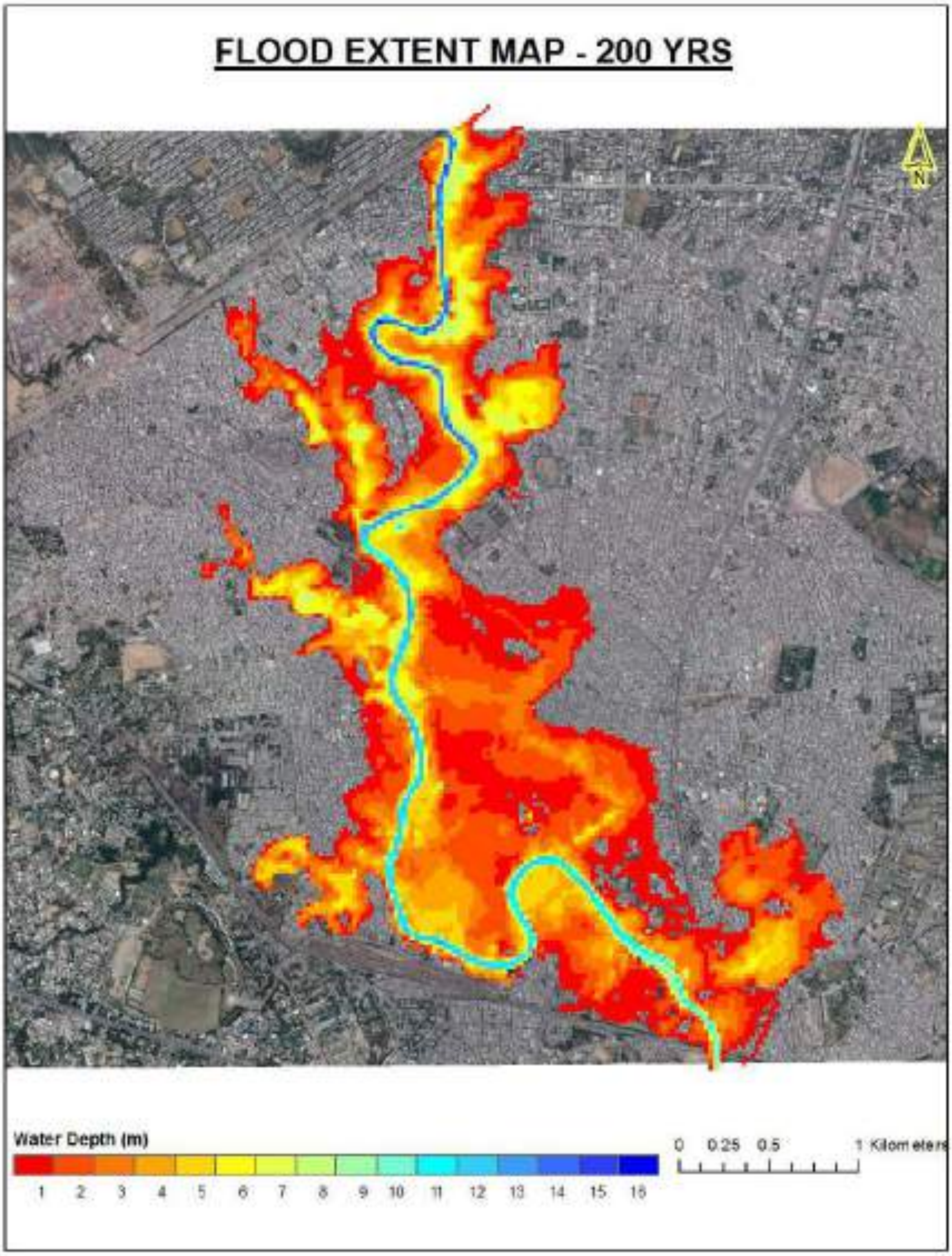


Fig-4.20 Flood Extent Map – 200 Year Return Period

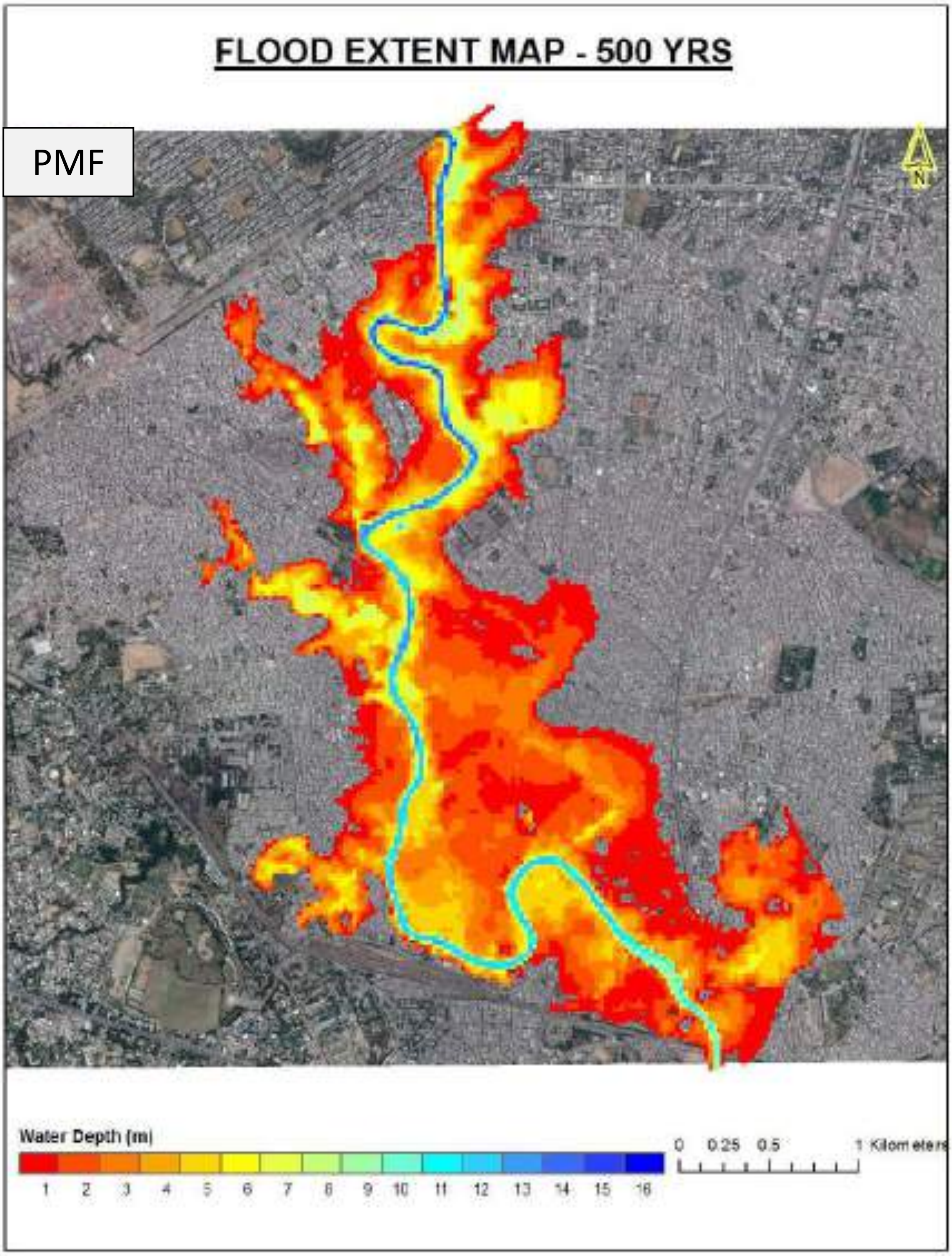


Fig-4.21 Flood Extent Map – 500 Year Return Period

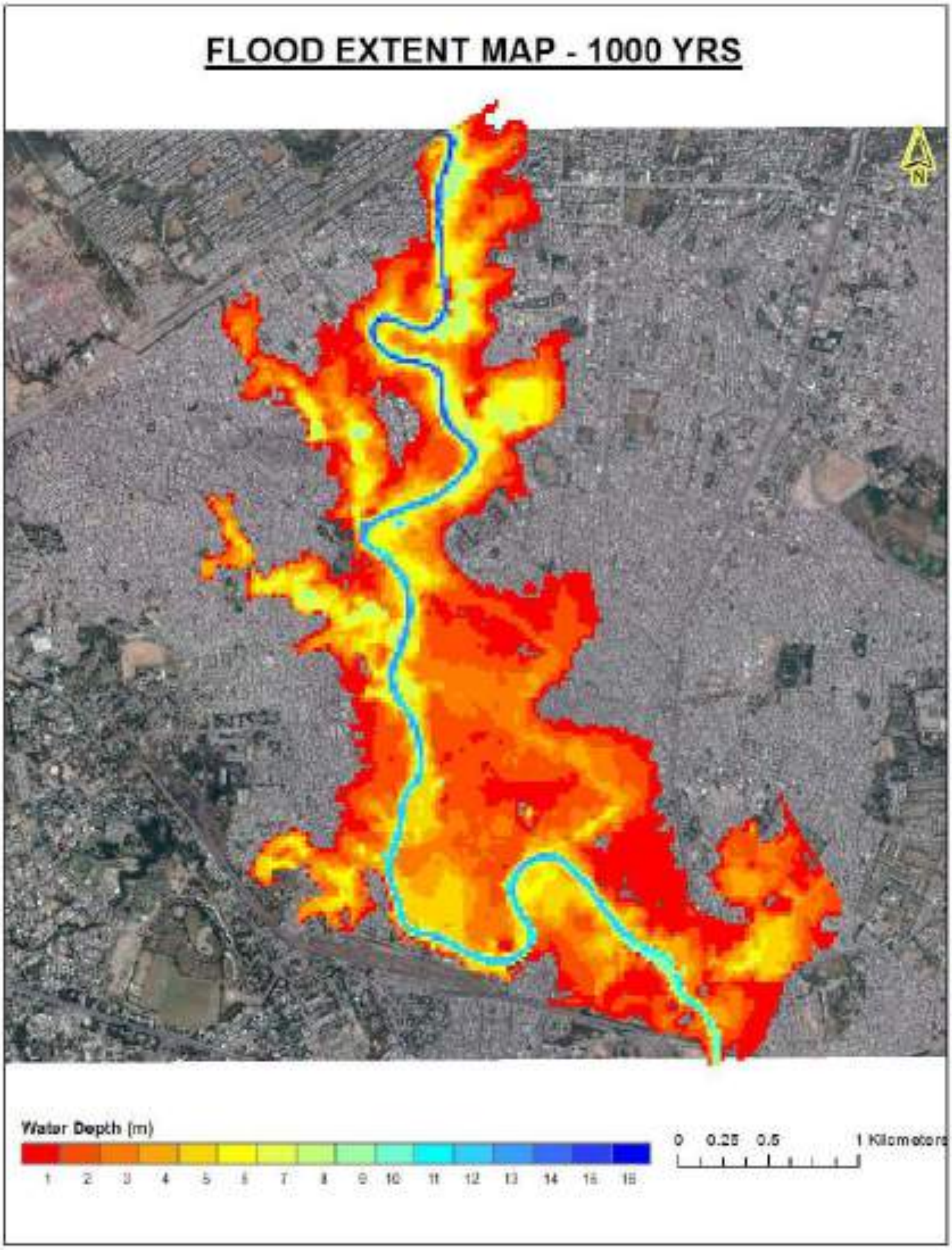


Fig-4.22 Flood Extent Map – 1000 Year Return Period

4.4.3 Climate Change Assessment

4.4.3.1 Bias Correction

Observed and Baseline Data for the period from 1981 – 2010 was compared initially for all the 4 stations as shown in Fig-4.23. All the outputs of 8 GCMs were bias corrected through Delta downscaling technique and then compared with observed data for 3 different time slices i.e 2025s (2011 – 2040), 2055s (2041 – 2070) & 2085s (2071 – 2100) for all 4 stations. 95% Confidence Interval (CI) were also plotted to show variation between observed data and average model conditions as shown in Fig-4.24, 4.25 & 4.26. Moreover, uncorrected data for all GCMs was also compared with observed data and average model conditions as shown in above mentioned figures. Corrected climate data of 4 GCMs each of RCP-4.5 and RCP-8.5 for all 4 stations for all 3 time slices (2025s, 2055s and 2085s) are also shown in Fig-4.27 and Fig-4.28 respectively.

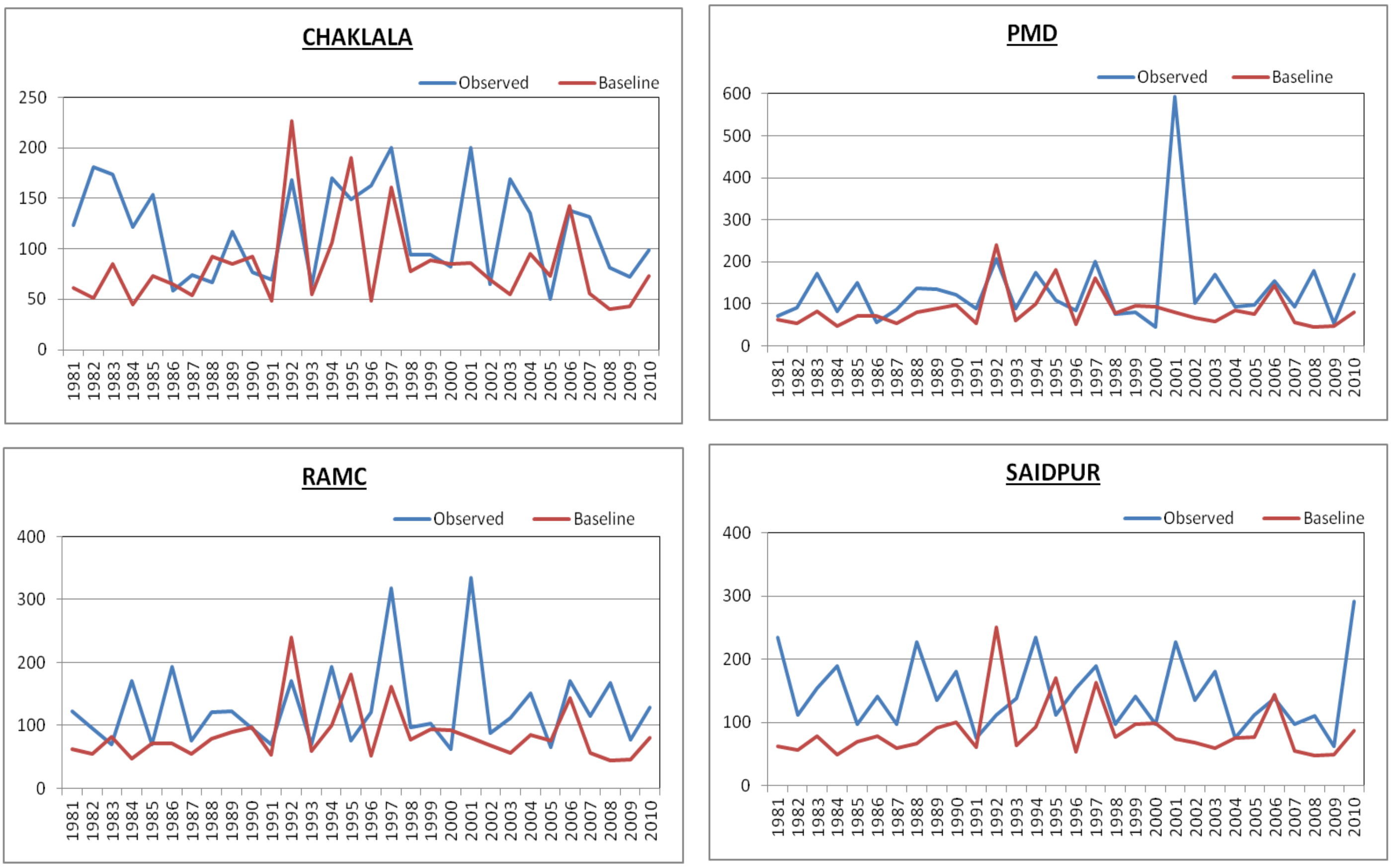
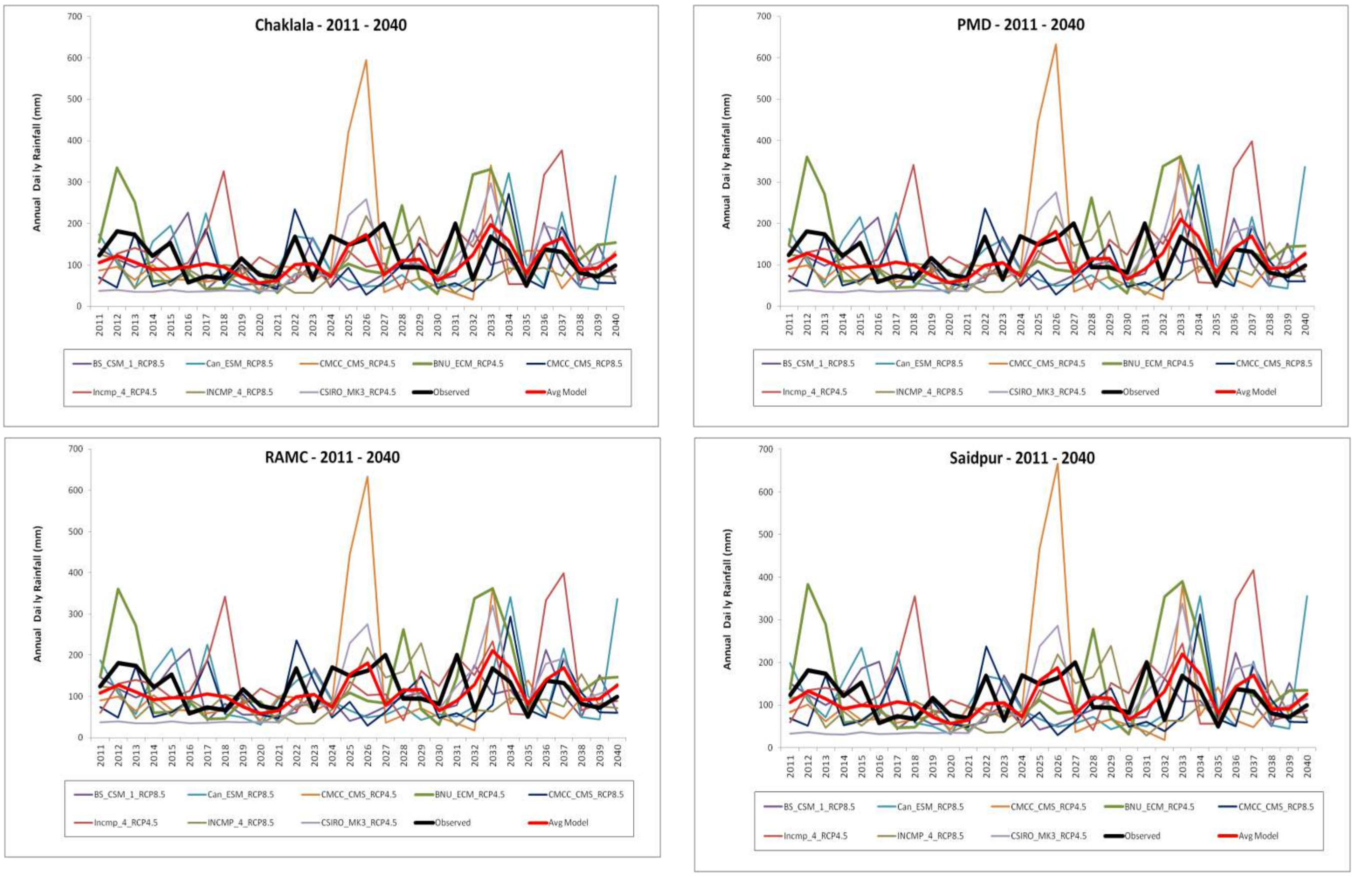


Fig 4.23 – Comparison of Observed Vs Baseline Data

(2025s)



Uncorrected Data

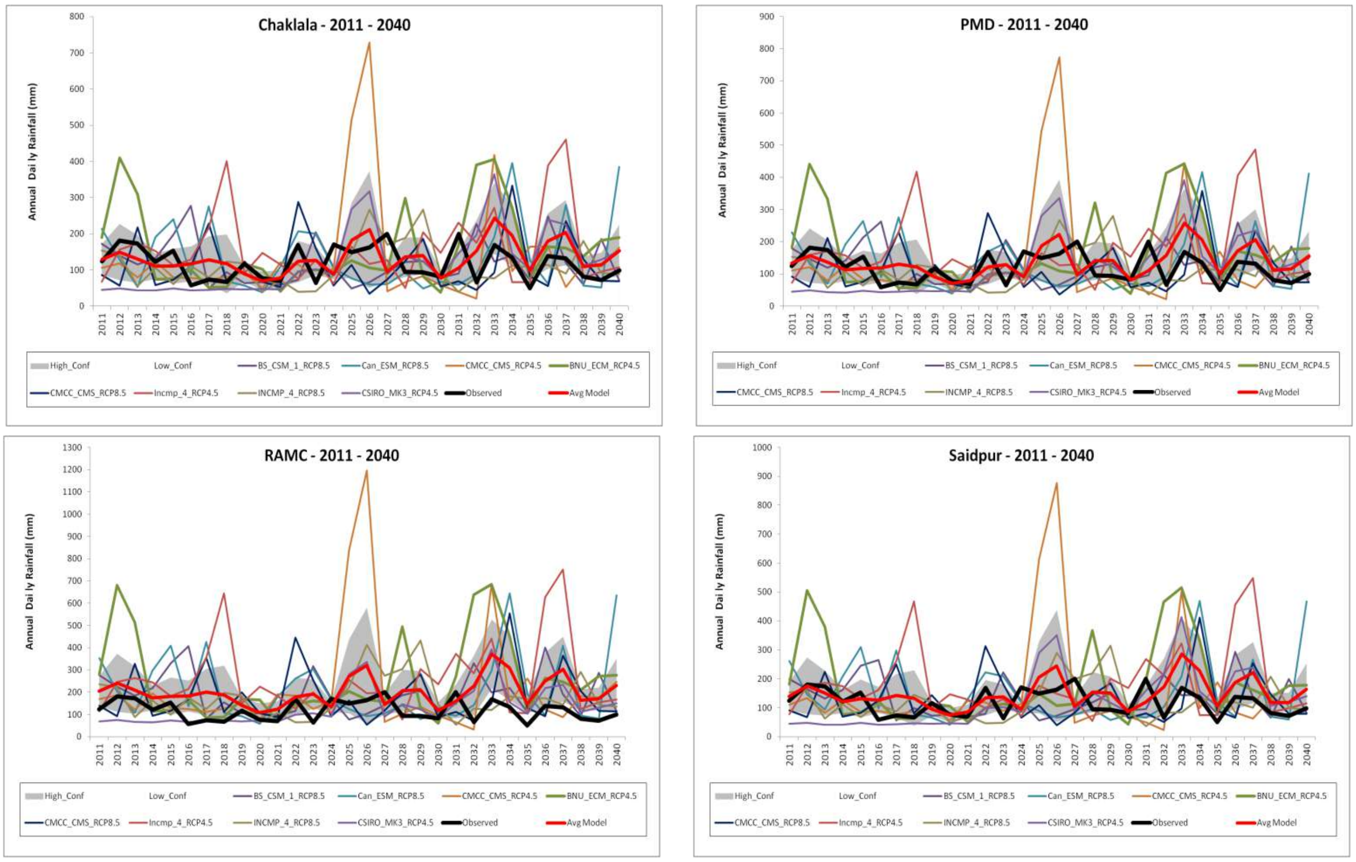
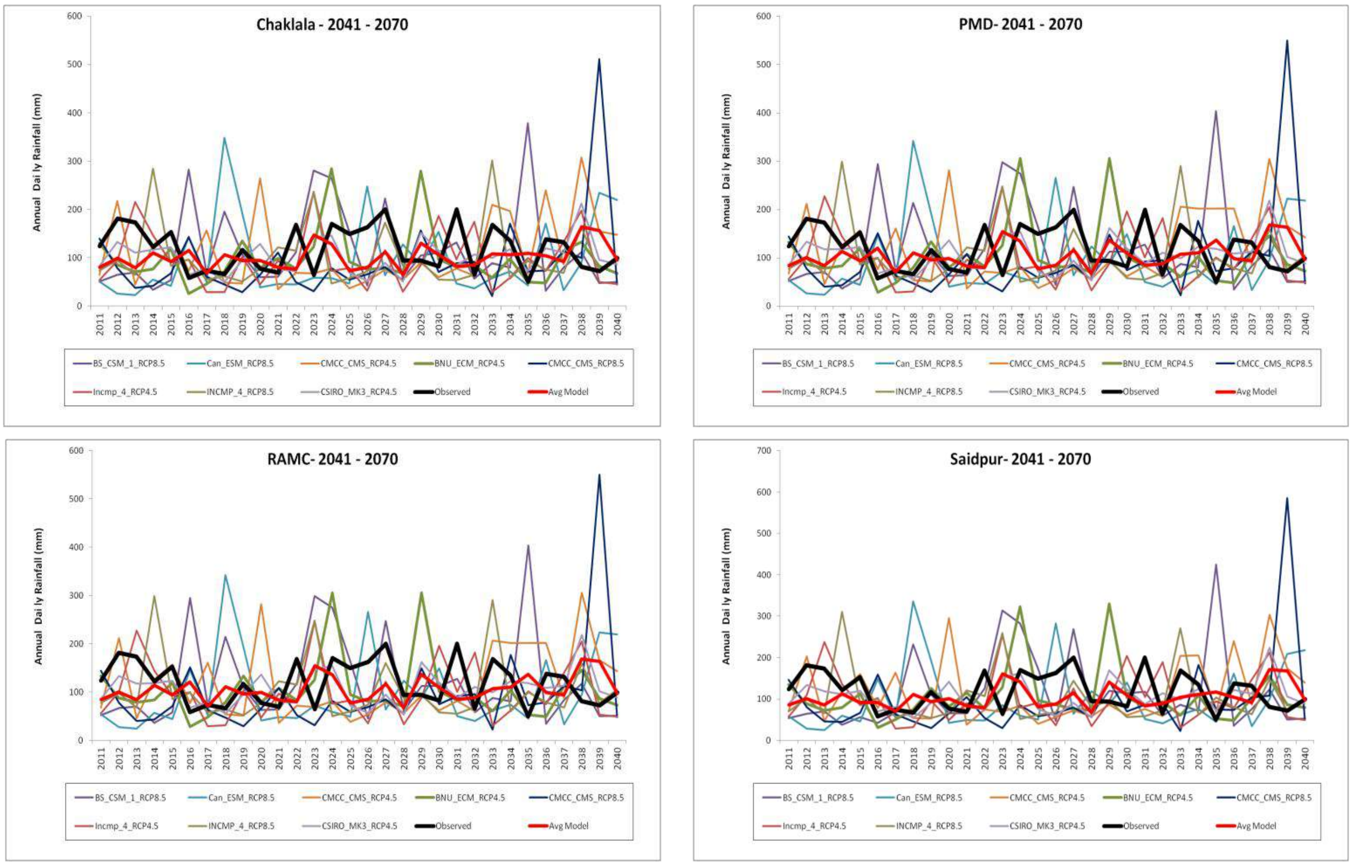


Fig-4.24 Bias Corrected Data – 2025s

(2055s)



Uncorrected Data

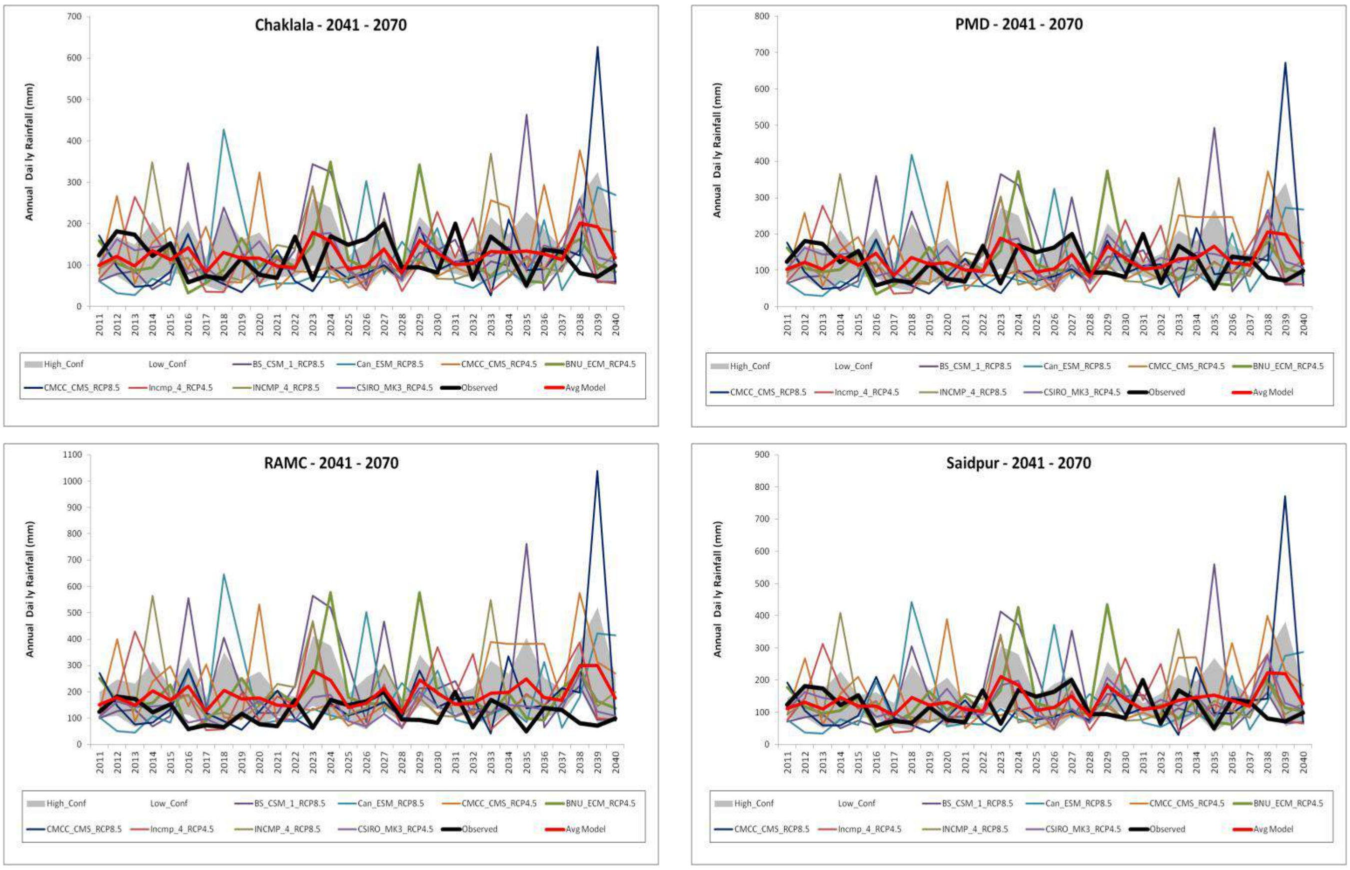
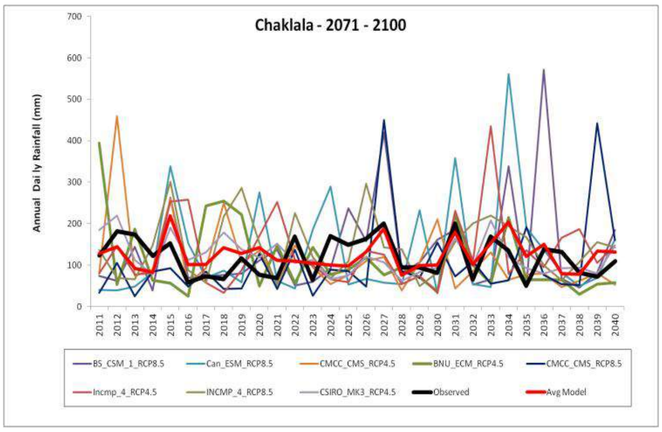
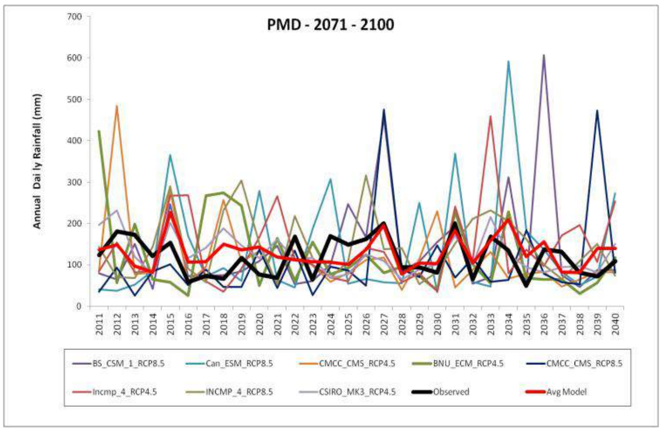
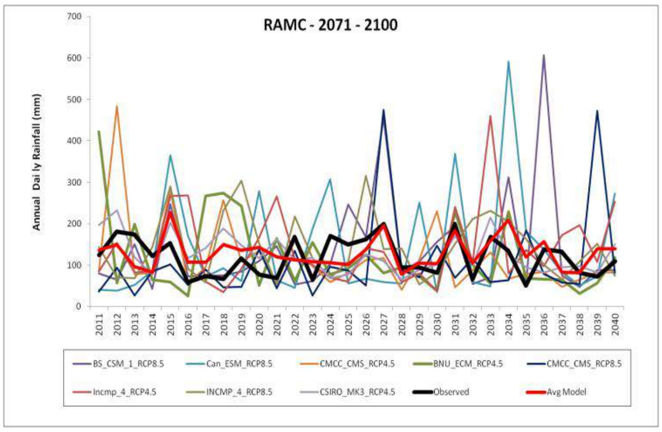


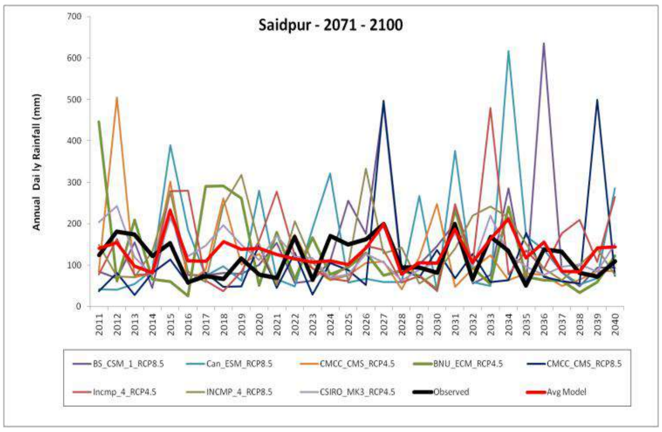
Fig-4.25 – Bias Corrected Data – 2055s

(2085s)

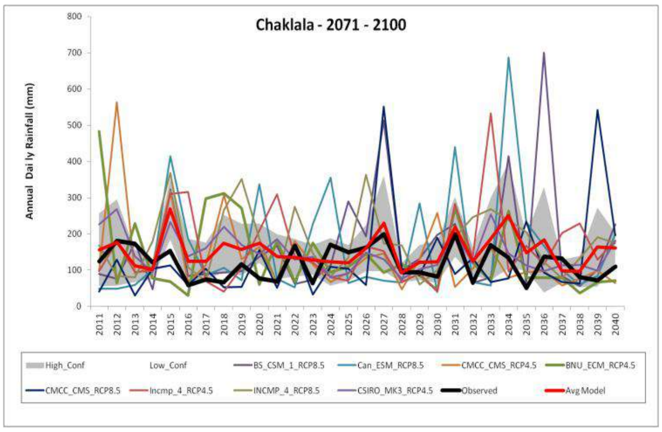


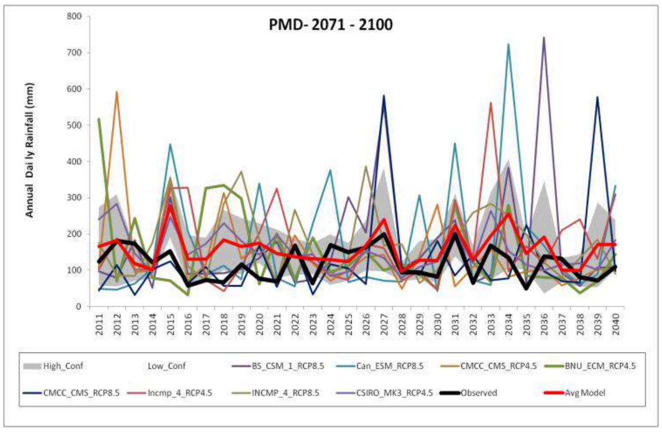


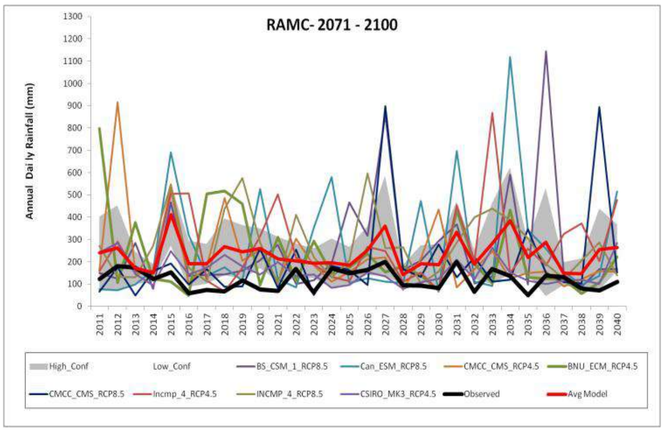




Uncorrected Data







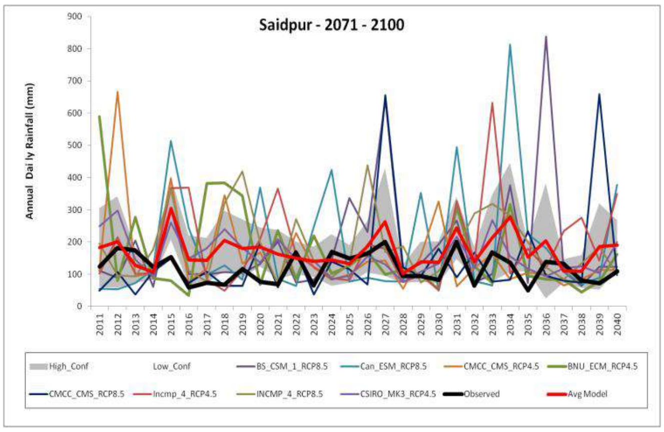


Fig-4.26 – Bias Corrected Data – 2085s

Fig-4.27 – Bias Corrected Data (RCP - 4.5)

Fig- 4.28 – Bias Corrected Data (RCP-8.5)

4.4.3.2 Comparison of Top-30 Annual Maximum Daily Rainfall (AMDR) Values

Top 30 AMDR values for all the models for 3 time slices were sorted and assigned rank numbers. These values were then compared with top 30 AMDR values for observed data for each station to have a fair idea about the impact of climate change. It is pertinent to mention here that projected values are showing minor deviations with regards to observed rainfall data. Comparison of top 30 peak rainfall values for all 4 stations for 3 time slices are shown in Fig-4.29, 4.30, 4.31 & 4.32.

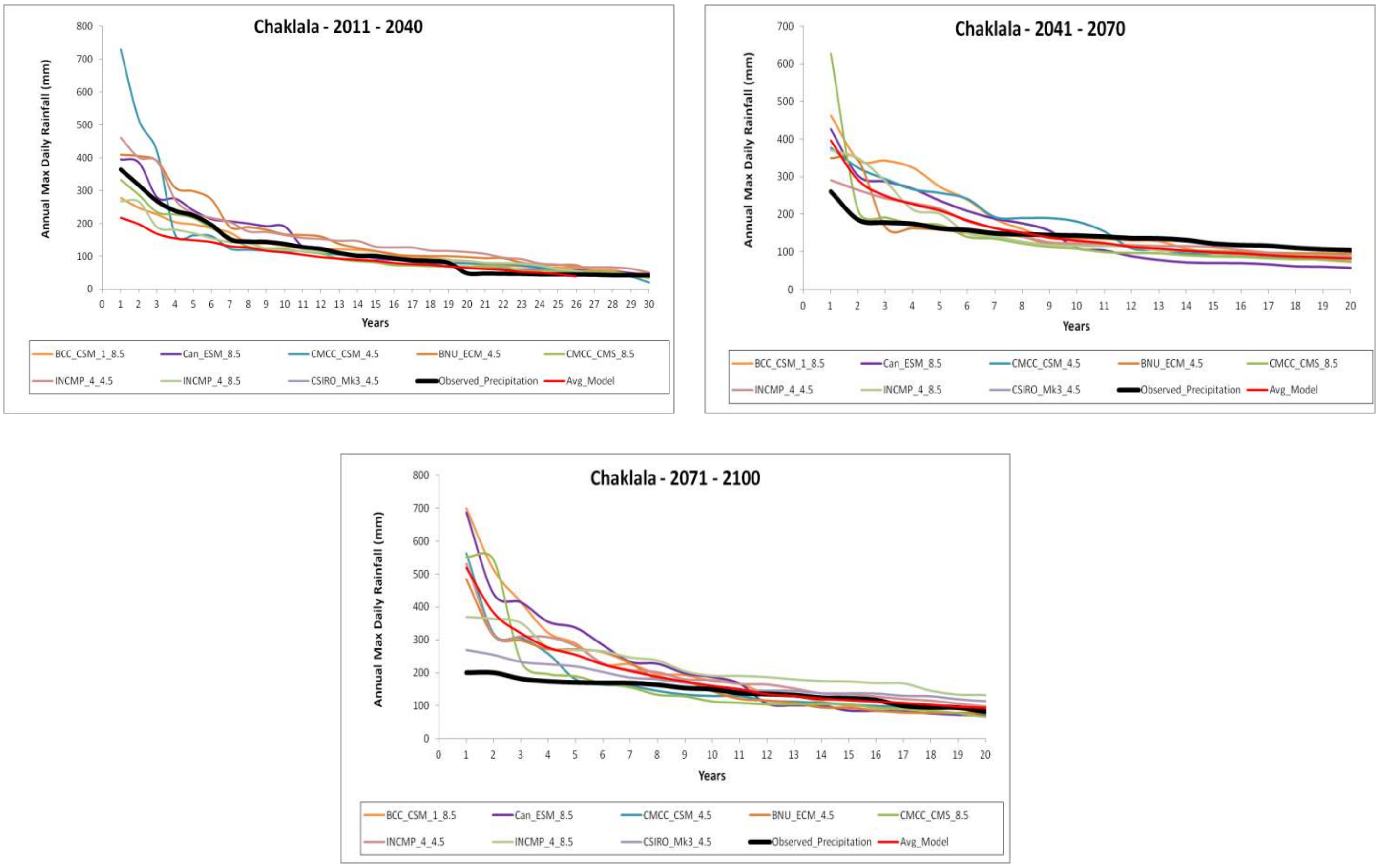


Fig-4.29 Comparison Top 30 AMDR Values - Chaklala

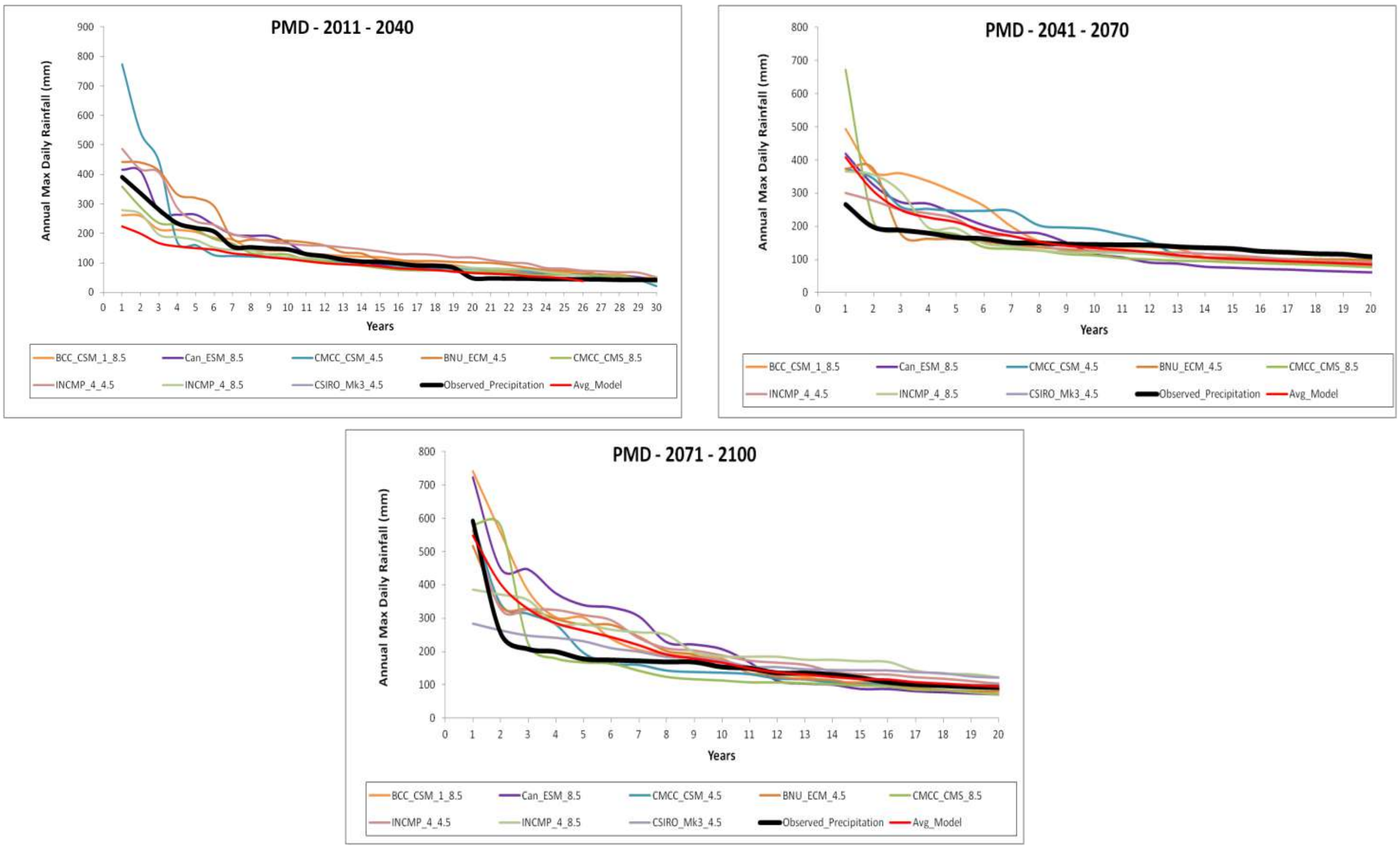


Fig-4.30 Comparison Top 30 AMDR Values - PMD

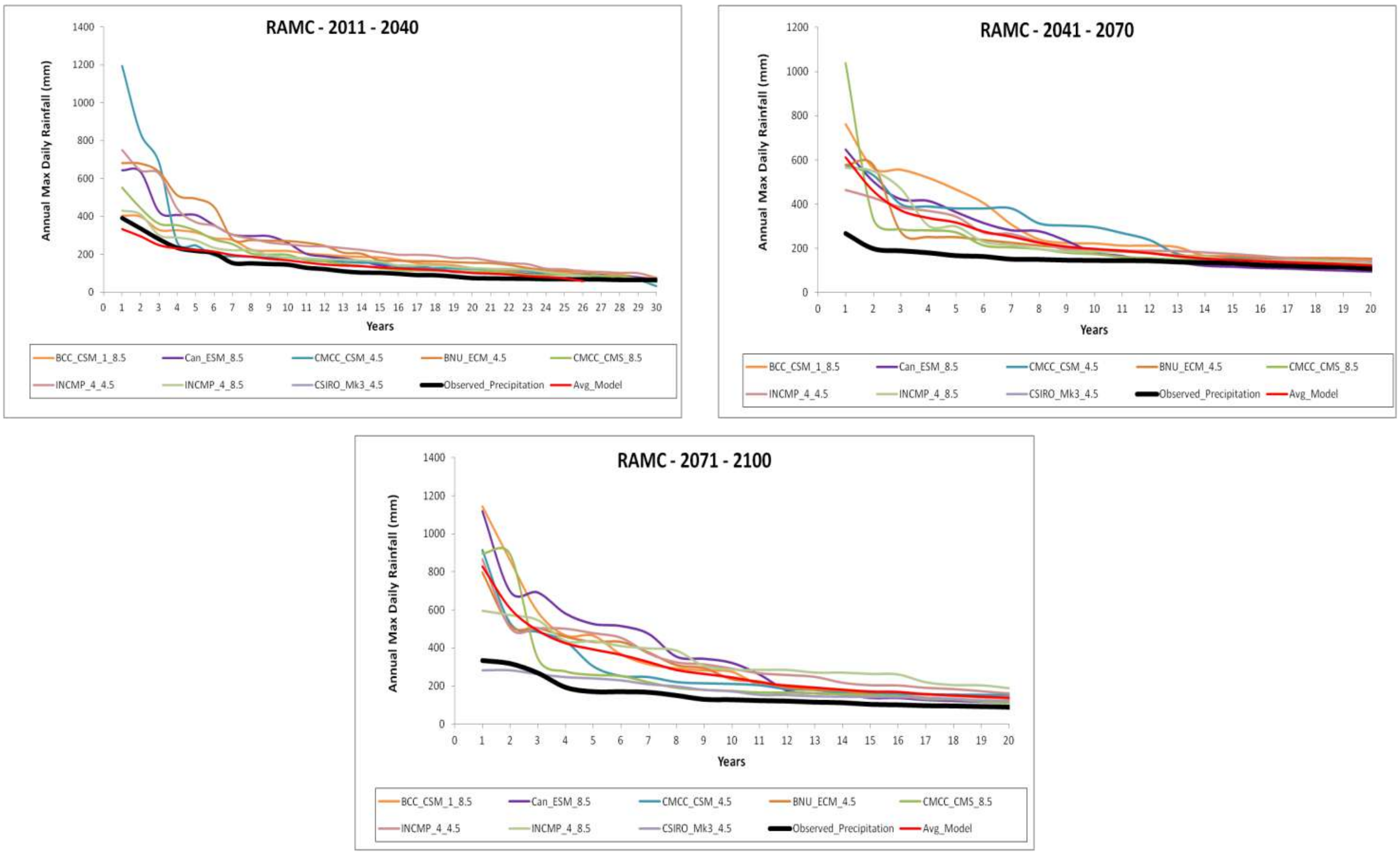


Fig-4.31 Comparison Top 30 AMDR Values - RAMC

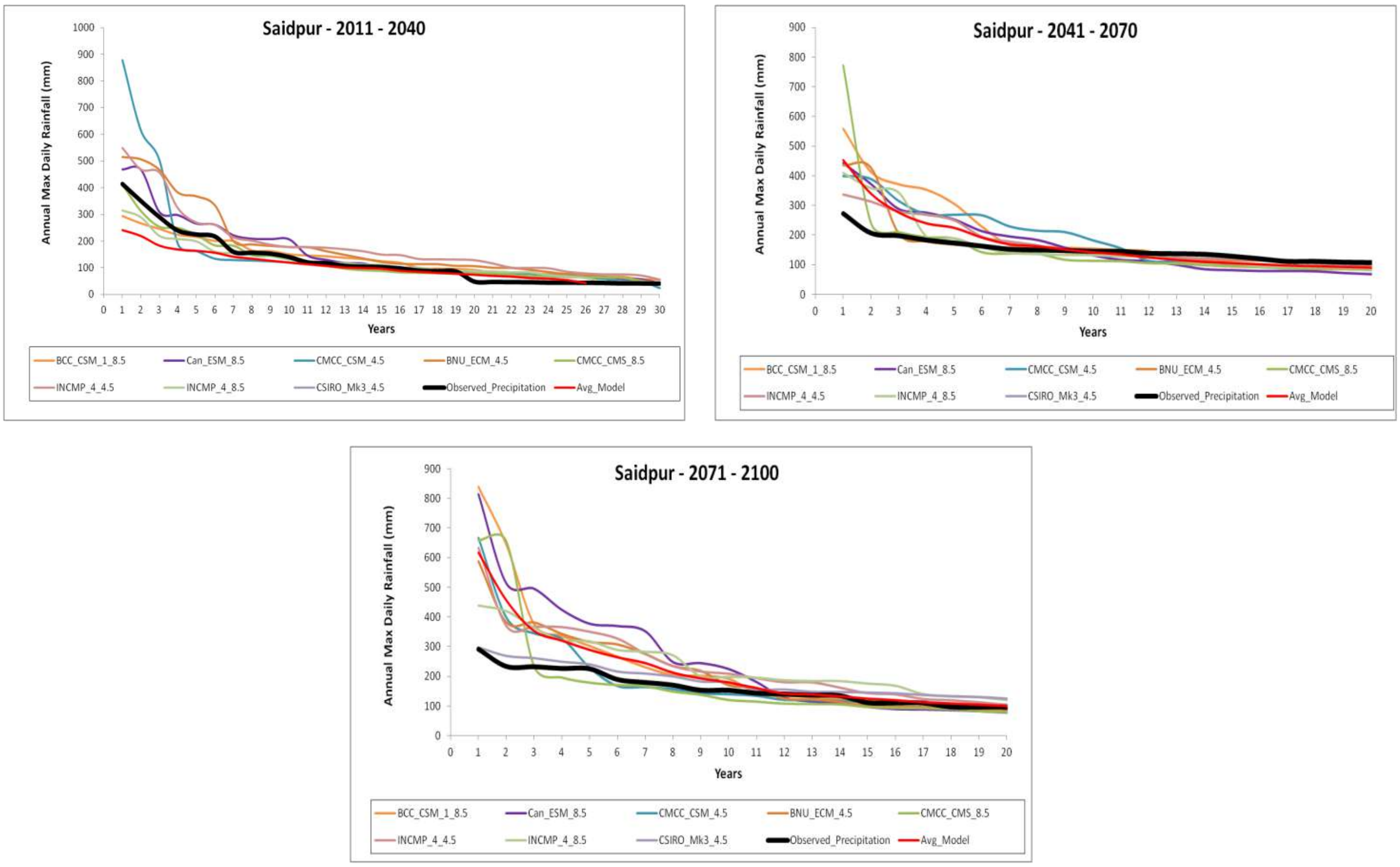


Fig-4.32 Comparison Top 30 AMDR Values - Saidpur

4.4.3.3 Frequency Analysis of Projected AMDR Data

Using the average model conditions for each time slice of all 4 stations i.e Chaklala, PMD, RAMC & Saidpur, frequency analysis based on 30 years projected annual maximum daily rainfall (AMDR) data was carried out. AMDR values for 100 year return period for all 4 stations are estimated & percentage increase with respect to observed data was computed as shown in Table-4.11. Moreover, AMDR values for different return periods for all 4 stations were also estimated as shown in Appnedix-13. Average rainfall values for 100 year return period were calculated for each time slice to be subsequently used as input for HEC-HMS Hydrological model.

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	321.17	299.3	7.30	318.38	6.37
	2055s	314.11		4.94		
	2085s	319.87		6.87		
PMD	2025s	467.93	412.44	13.45	459.12	11.32
	2055s	453.07		9.85		
	2085s	456.37		10.65		
RAMC	2025s	413.52	303.62	36.19	402.22	32.47
	2055s	399.09		31.44		
	2085s	394.05		29.78		
Saidpur	2025s	380.48	287.87	32.17	368.35	27.95
	2055s	371.00		28.87		
	2085s	353.57		22.82		

Table-4.11 Frequency Analysis Projected AMDR Values – 100 Year Return Period

Comparison for 100 year recurrence interval projected and observed rainfall data frequency analysis shows an average increase of 6.38 %, 11.32 %, 32.48 % & 27.96 % for Chaklala, PMD, RAMC & Saidpur stations over the period from 2011 to 2100. Variation in rainfall increase pattern for different stations may be attributed to various parameters associated with climate change including land use, temperature, rainfall patterns etc. which needs to be investigated.

4.4.3.4 Climate Models Efficiency Analysis

Various statistical efficiency parameters including Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Coefficient of Correlation (R^2) and Nash-Sutcliffe Coefficient (E) were used in order to ascertain efficiency criteria of different climate models for the overlapping observed and forecasted model data. Results of model efficiency analysis are shown in Table-4.12. Results indicate that BNU-EMS4.5, CSIRO-Mk-4.5, BS-CMS8.5 and CMCC-CMS8.5 were found relatively more efficient as compared to other GCMs including INMCM4.5, INMCM8.5, CMCC-CMS4.5 and Can-ESM8.5.

Stations	Efficiency Parameters	BS-CMS8.5	Can-ESM8.5	CMCC-CMS4.5	BNU-EMS4.5	CMCC-CMS8.5	INMCM 4.5	INMCM 8.5	CSIRO-MK_4.5
Chaklala	MAE	2.36	13.49	16.52	8.24	10.10	17.26	19.15	8.02
	RMSE	4.86	11.62	12.86	9.08	10.05	13.14	14.54	8.96
	R^2	0.121	1.172	1.264	0.065	0.025	1.121	1.091	0.052
	NS	-0.423	-0.503	0.142	2.53	-1.455	0.166	-0.225	1.256
PMD	MAE	3.34	14.51	17.74	8.50	10.40	18.08	17.11	8.15
	RMSE	5.78	12.05	13.32	9.22	10.20	13.45	14.87	9.03
	R^2	0.043	0.004	0.017	0.013	0.018	0.021	0.016	0.018
	NS	-0.942	1.907	0.041	3.086	-0.963	-0.225	0.661	1.487
RAMC	MAE	8.03	9.68	18.27	5.67	10.71	12.06	15.77	5.43
	RMSE	4.35	11.46	12.31	4.46	6.64	14.58	10.39	6.04
	R^2	0.186	0.154	0.910	1.059	0.901	0.869	1.213	1.013
	NS	-0.083	-2.725	1.816	1.300	1.181	-0.842	-3.398	1.531
Saidpur	MAE	3.61	10.31	13.59	5.44	7.17	12.43	16.38	5.42
	RMSE	4.81	9.41	6.04	4.07	6.38	16.30	5.08	5.76
	R^2	0.134	0.141	0.600	0.959	0.819	1.037	1.139	0.984
	NS	-1.417	-0.047	0.093	3.124	-1.432	-1.229	-0.019	1.472

Table-4.12 Model Efficiency Results

4.4.3.5 Simulation in HEC-HMS & HEC-RAS

Average rainfall values based on projected AMDR for various return periods calculated for each time slice were used as input in validated HEC-HMS model. Values of standard flood discharge for 100 year return period at Kattarian & Gawalmandi were computed as 2436.8 & 2714.4 cumecs. Thus, an increase of 10.90 % was observed for 100 yearr return period flood discharge at Kattarian. Simulated hydrograph for projected 100 year return period at Kattarian was simulated in validated HEC-RAS model and flood extent map was developed and compared with existing 100 year return period flood extent map (ref Fig-4.33). Projected flows using HEC-HMS for various return periods is shown in Table-4.13.

Return Period	Standard Flood Discharges AMDR (cumecs)		Projected Flood Discharges AMDR (cumecs)		% Increase	
	Kattarian	Gawalmandi	Kattarian	Gawalmandi	Kattarian	Gawalmandi
2	196.75	220.62	208.6	236.4	6.01	7.14
5	395.1	474.6	429.1	521.9	8.61	9.97
10	651.4	779.8	715.3	859.8	9.80	10.25
25	1161.2	1312.5	1285.7	1463.5	10.72	11.50
50	1620.1	1830.8	1797.2	2035.7	10.92	11.19
100	2197.35	2421.57	2436.8	2714.4	10.90	12.09
200	2760	3021	3070.3	3398.5	11.24	12.50
500	3450.2	3721.4	3811.8	4160.2	10.48	11.79
1000	3935.8	4227.1	4349.5	4726.8	10.51	11.82

Table-4.13 Projected Flows - AMDR

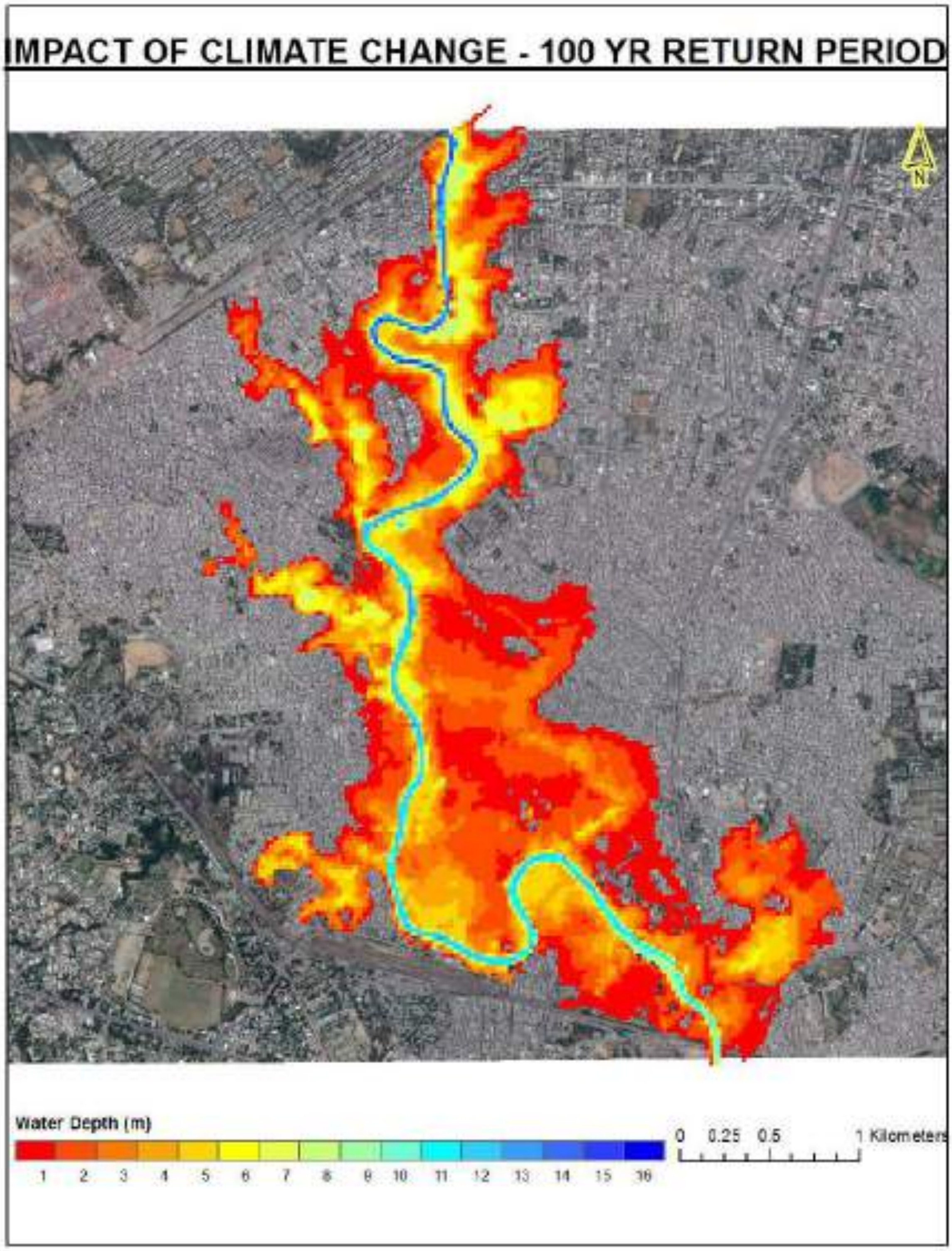


Fig-4.33 Impact of Climate Change – 100 Yr Return Period

4.4.4 Simulation for various Adaptation Strategies

4.4.4.1 Formulation of Community Pond

Reference to JICA Study, a community pond was suggested in Fatima Jinnah Park (F-9 Park) located in Islamabad as shown in Fig-4.34 with a view to flatten the hydrograph and attenuate the peak. JICA Study proposed that a fully functional community pond of size 26.5 km^2 will reduce the peak inflow hydrograph at Kattarian by 35%.

Thus, inflow hydrograph for 100 year return period was reduced by 35% & simulated using validated HEC-RAS model. The covered area of flood spread came out to be 3.0258 km^2, thus reducing the original flood spread by 42.43% and reducing the inundation depth from 5m to approx 1-2 m near low lying areas of Gawalmandi. Simulation map of impact of community pond is shown in Fig-4.35. Therefore, introduction of community pond will significantly reduce the flood hazard specially D/S of Gawalmandi.

4.4.4.2 Impact of Flood Mitigation Dam

Flood mitigation is an effective adaptation measure which serves to delay the flood peak besides reducing its magnitude by acting as temporary storage area. As far as Lai Nullah is concerned, area D/S of Kattarian hardly allows any structural measures which may serve as adaptation measure. Therefore, area upstream of Kattarian is the only possible option where control of inflow may be checked. JICA Study proposed a flood mitigation dam of area 19.7 km^2 in general area Block E-11 as shown in Fig-4.34. As per JICA Study, flood mitigation dam at proposed site will reduce the peak inflow hydrogprah by 44 %.

Inflow hydrograph for 100 year return period was reduced by 44 % & simulated using validated HEC-RAS model. The covered area of flood spread came out to be 2.75 km^2, thus reducing the original flood spread by 45.74 % and reducing the inundation depth from 5m to approx 1m near low lying areas of Gawalmandi. Simulation map of impact of flood mitigation dam is shown in Fig-4.36.

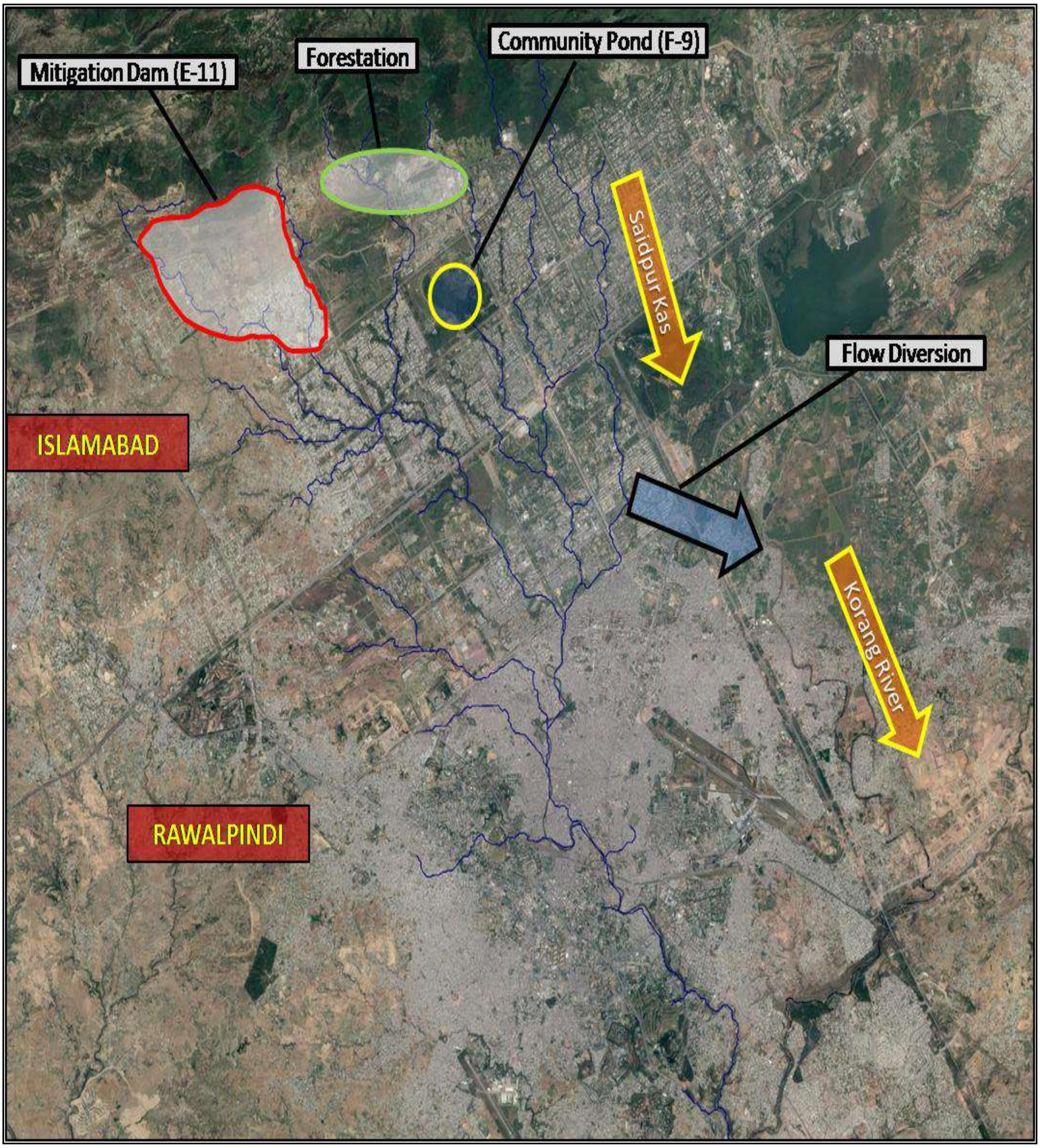


Fig-4.34 Adaptation Strategies

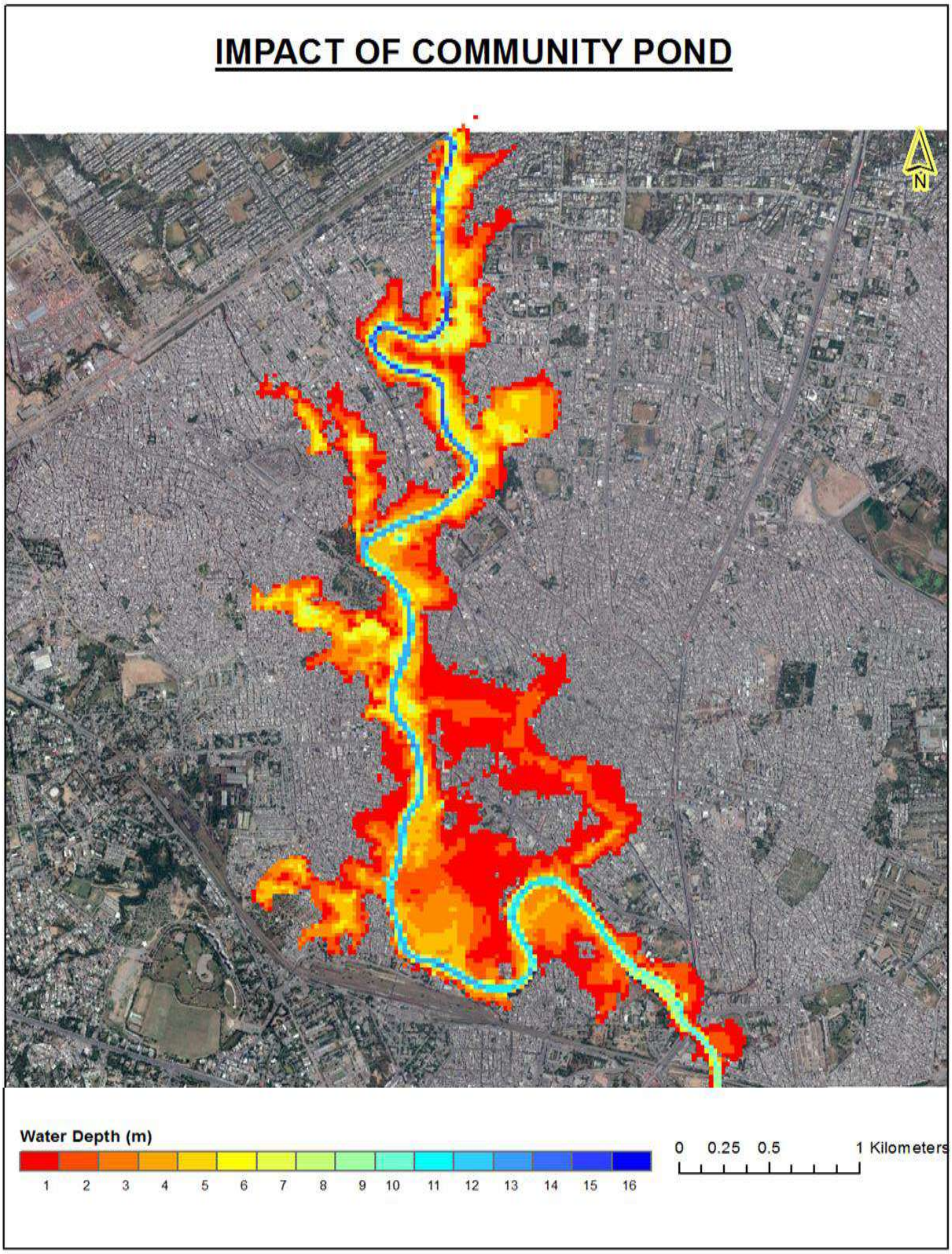


Fig-4.35 Impact of Community Pond

4.4.4.3 Impact of Flow Diversion

There are various tributaries contributing to the combined inflow at Kattarian downstream. Possibility of flow diversion from Eastern Tributary Saidpur Kas (refer to Fig-4.34) and its possible impact was analyzed in consultation with RDA Lai Division. The proposal involved, diverting the flow of Saidpur Kas towards Korang River flowing almost parallel to Lai Nullah towards the Eastern side. It was estimated that diversion of flow from Saidpur Kas towards Korang River will reduce the inflow hydrograph by approximately 23 %.

Inflow hydrograph for 100 year return period was reduce by 23% & simulated using validated HEC-RAS model. The covered area of flood spread came out to be 3.704 km^2, thus reducing the original flood spread by 29.54 %. Simulation map of impact of flow diversion is shown in Fig-4.37.

4.4.4.4 Impact of Forestation

Change in land use pattern through plantation / forestation alters the curve number and inturn the runoff potential of the surface. Increase in plantation in general area of Margalla Foothills (refer to Fig-4.34) was one such option which is considered and analyzed in the current study. In the absence of any tangible parameters to assess the net impact on inflow hydrograph, it was approximated that effective plantation and afforestation campaign in Islamabad area of Lai Watershed will reduce the peak hydrograph by 18 %.

Accordingly, inflow hydrograph for 100 year return period was reduced by 18 % & simulated using validated HEC-RAS model. The covered area of flood spread came out to be 4.068 km^2, thus reducing the original flood spread by 22.61 %. Simulation map of impact of forestation is shown in Fig-4.38.

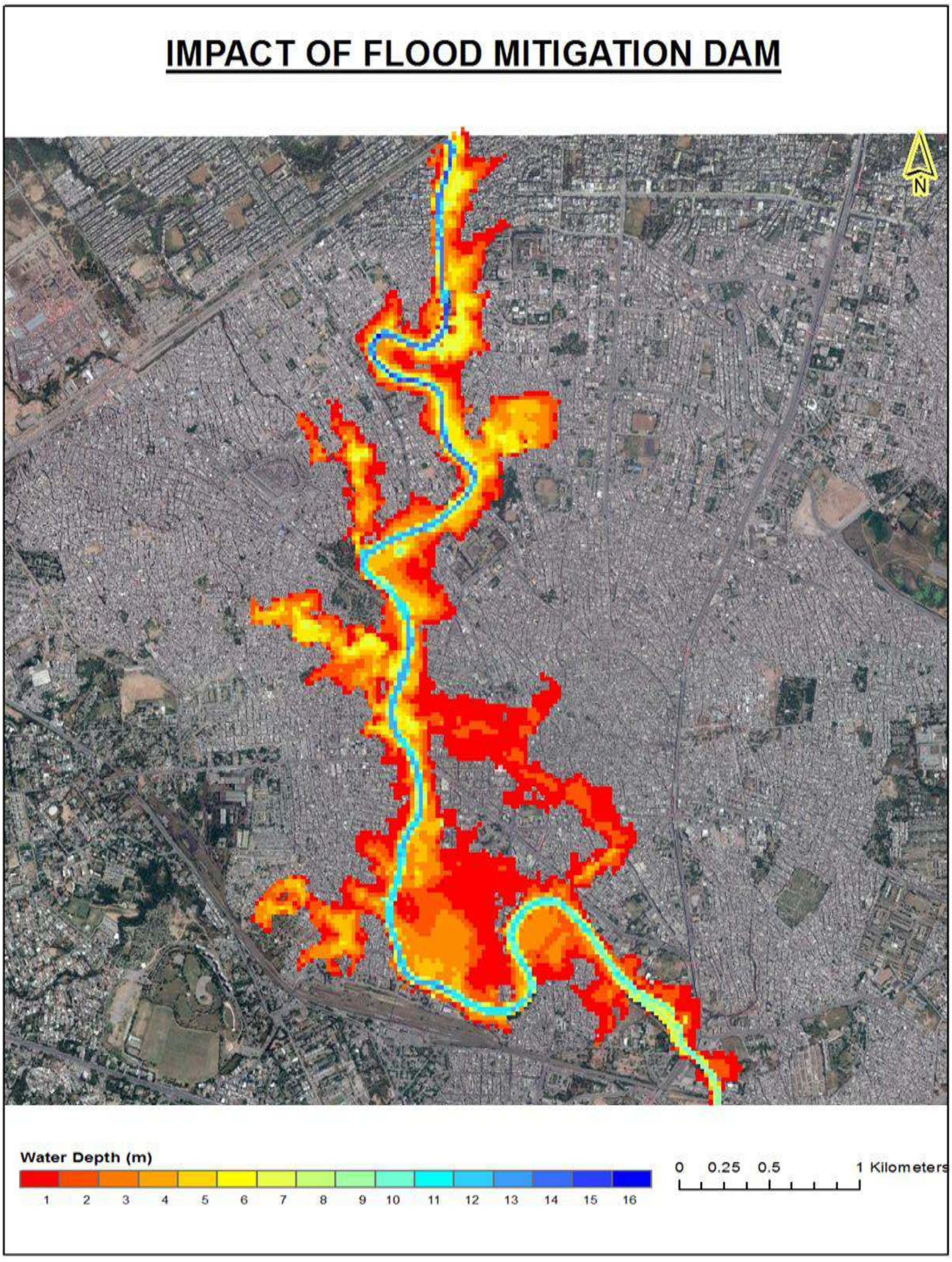


Fig-4.36 Impact of Flood Mitigation Dam

4.4.4.5 Combined Effect of Community Pond & Flood Mitigation Dam

As community pond and flood mitigation dam significantly reduces the inflow hydrograph as compared to other adaptation measures, it was worth noting the combined effect of both on overall flooding situation of Lai Nullah. Moreover, both community pond and flood mitigation being feasible and effective will permanently address the flooding issues of Lai Nullah.

Inflow hydrograph for 100 year return period was reduced by 79 % & simulated using validated HEC-RAS model. The covered area of flood spread came out to be 0.893 km^2, thus reducing the original flood spread by 83.1 %. Simulation map of combined impact of community pond and flood mitigation dam is shown in Fig-4.39.

4.4.4.6 Analysis of Various Adaptation Strategies

Effects of various adaptation strategies in terms of % reduction in inflow hydrograph, % reduction on flood extent and % reduction in inundation depth in ms were summarized in Table-4.14. Results indicate that combined effect of community pond and mitigation dam was found most effective in terms of controlling flood extents and maximum inundation depth reduction.

Adaptation Strategies	Reduction in Inflow Hydrograph (%)	Inundation Extent Area (km^2)	Reduction in Original Flood Extent (%)	Max Reduction in Inundation Depth (m)
100 Yr Return Period	-	5.257	-	-
Community Pond	35	3.025	42.43	2
Flood Mitigation Dam	44	2.752	45.74	3
Flow Diversion	23	3.704	29.54	1.5
Forestation	18	4.068	22.61	1
Community Pond & Mitigation Dam	79	0.893	83.1	4.5

Table-4.14 Effects of Adaptation Strategies

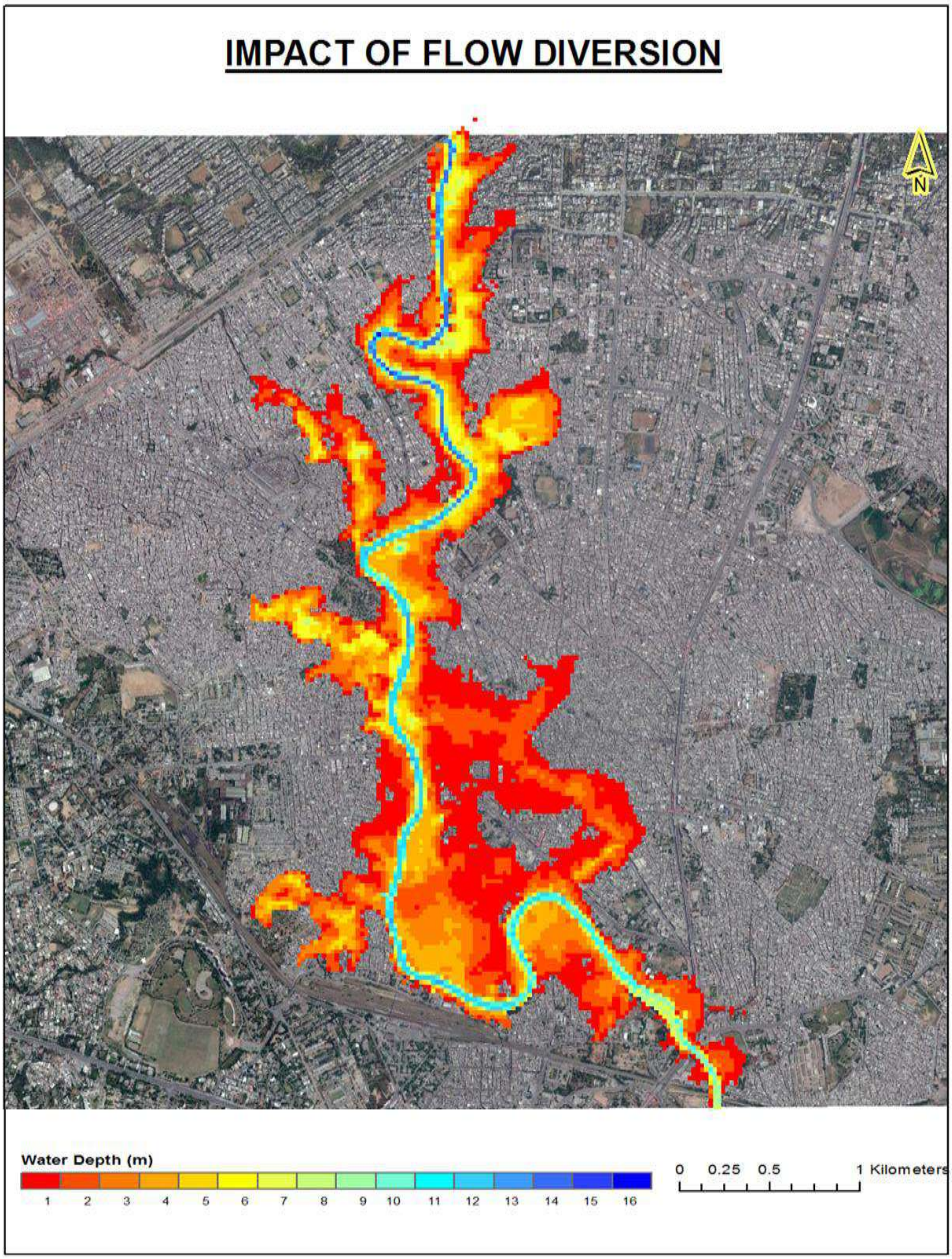


Fig-4.37 Impact of Flow Diversion

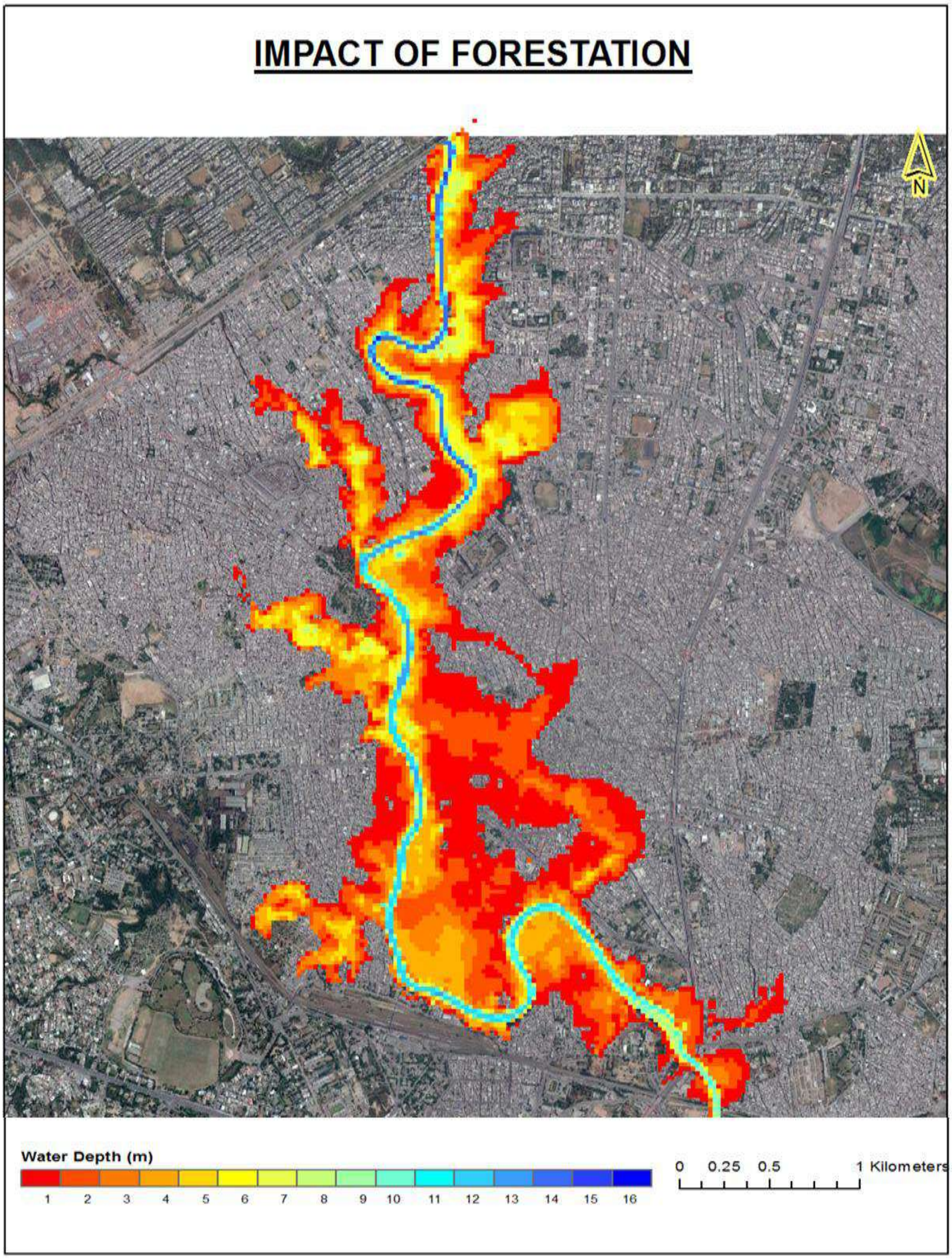


Fig-4.38 Impact of Forestation

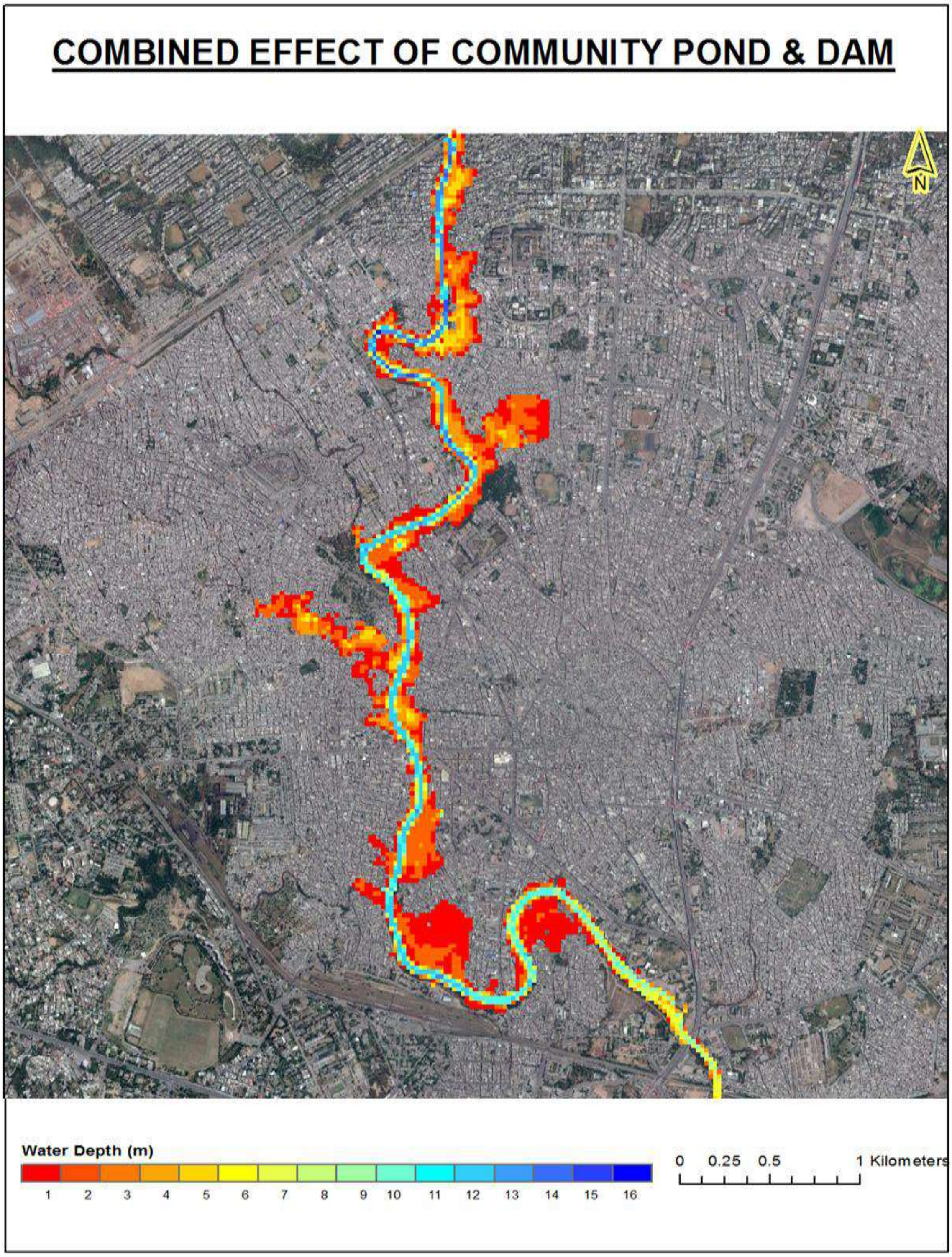


Fig-4.39 Combined Effect of Community Pond & Flood Mitigation Dam

4.4.4.7 Other Possible Adaptation Measures

In addition to above mentioned measures, various other adaptation measures including construction of flood protection bund /embankment, increasing channel conveyance capacity by channel widening, lining of channel and checking the malpractices of dumping of solid waste including garbage, debris and other effluents was also studied / analyzed.

As far options of flood protection bunds, channel lining and channel widening are concerned, rapid urbanization along Lai banks leaves very little cushion for any such structural measures. In order to undertake any such measures, availability of additional land along nullah banks is major obstruction besides exorbitant cost effects which negates both these options. However, malpractices of dumping solid wastes in Lai Nullah specially in Rawalpindi areas needs to be checked / curbed. This will not only increase the channel capacity but also will reduce the environmental pollution concerns caused by the nullah. Lai Division RDA undertakes nullah cleaning measures after regular intervals but these measures needs to be expedited.

Chapter 5

CONCLUSION & RECOMMENDATIONS

5.1 CONCLUSIONS

The present study encompasses an integrated modeling approach based on hydrological and hydraulic model with a view to assess the impact of climate and land use change on hydrological response of Lai Nullah Basin. Assessment of climate change impact lead towards identification of feasible adaptation strategies. Following are the major conclusions drawn from the present study:

- Land use assessment of Lai Nullah Basin for 3 different periods i.e 2005, 2014 & 2025 using 10m resolution SPOT imagery showed strong correlation with the corresponding JICA Study. Land use classification trend showed decreasing trend of 1.99%, 1.19% & 6.16% in Forest, Agriculture & Green Bare land classes. However, Residential Low & High Density classes show increasing trend of 7.35 & 2.06% respectively indicating increasing urbanization trend in Lai Catchment. Increase in residential classes supports the argument of rapid urbanization specially in near vicinity of Nullah Banks.
- HEC-HMS Rainfall – runoff simulation model was calibrated and validated for 10 mins interval rainfall and stream flow data in addition to 2001 flood event. Statistical analysis showed good correlation between simulated & observed values. HEC-HMS model calibrated & validated on fine temporal resolution data was subsequently used for generation of standard flood discharges using 3 hr interval rainfall data which again showed good agreement with observed data where available.
- Validated HEC-HMS model was also used for calculation of standard flood discharges using annual maximum daily rainfall against various return periods,

calculation of PMF, calculation of standard flood discharges using rainfall intensities & generation of standard flood discharges against various return periods using projected GCMs annual maximum daily rainfall data.

- Hydrological Analysis was carried out for annual instantaneous peak flows for Kattarian & Gawalmandi gauges and annual maximum daily rainfall values for all rainfall stations less Golra & Bokra. Through application of Goodness of Fit Tests, Log Pearson Type III distribution was found optimum both for Annual Instantaneous Peak Flows & Annual Max Rainfall Analysis except Chaklala where Pearson type III was used. JICA Study also used Log Pearson Type III distribution for annual maximum daily rainfall analysis as optimum distribution. Results of frequency analysis for standard flood discharges estimated through annual max daily rainfall values were found close to corresponding JICA Study.
- Probable Maximum Precipitation (PMP) values were calculated using Hershfield statistical technique for all 9 rainfall stations. These values were spatially represented on the catchment using spline interpolation technique in ArcGIS. PMF values were calculated through validated HEC-HMS model as Kattarian – 3440.15 cumecs & Gawalmandi – 3553.31 cumecs.
- IDF Curves were generated for 6 rainfall stations including Chaklala, PMD, RAMC, Saidpur, Golra & Bokra using 3 hr interval frequency rainfall data. These curves will prove quite handy and useful for all stake holders specially for designers with regards to probable magnitude of rainfall intensity and rainfall for various storm durations at different stations.
- Corresponding DDF Curves were also generated for Kattarian & Gawalmandi basing on the data of IDF curves. These DDF curves will serve as operational forecast curves for policy makers while calculating design discharges for various storm durations.

- 2D hydraulic model using HEC-RAS 5.0.1 was developed through generation of computational meshes based on the terrain data developed from channel geometry and flood plains elevation data. HEC-RAS Model was calibrated and validated for 5 extreme storm events including 2001 flood event by using spatially varying land use manning's n layer. Statistical analysis showed strong agreement between simulated and observed WSE values at Gawalmandi.
- Flood Extent Maps were prepared using validated HEC-RAS model for standard flood discharges estimated through annual maximum daily rainfall data against different return periods i.e 2, 5, 10, 25, 50, 100, 200, 500 (PMP) & 1000 years. Flood Inundation extents were also computed for each recurrence interval.
- Assessment of climate change was done using HI-AWARE Climate dataset based on 8 GCMs statistically downscaled at 10 km x 10 km spatial grid resolution. Bias correction was applied using Delta downscaling technique based on observed and baseline overlapping historical data. Uncorrected and bias corrected data for 3 time slices i.e 2025s, 2055s and 2085s for 4 stations i.e Chaklala, PMD, RAMC & Saidpur was compared with observed data and average model conditions.
- Frequency analysis was carried out for average model conditions for each time slice for each station and annual maximum daily rainfall (AMDR) values for different return periods were derived. Comparison for 100 year recurrence interval for projected and observed AMDR data frequency analysis shows an average increase of 6.378 %, 11.320 %, 32.477 % & 27.957 % for Chaklala, PMD, RAMC & Saidpur stations over the period from 2011 to 2100.
- 100 Year Recurrence interval rainfall values average over the entire period from 2011 – 2100 for all 4 stations were used as input for validated HEC-HMS model. Values of standard flood discharges at Kattarian & Gawalmandi were computed as 2436.8 &

2714.4 cumecs respectively. Thus, an increase of 10.90 % was observed for peak inflow hydrograph at Kattarian.

- Various adaptation strategies were also proposed for flood mitigation and reducing the hydrograph peak. These strategies include community pond, flood mitigation dam, flow diversion from Saidpur Kas, increased plantation in upstream catchment and combination of community pond and flood mitigation dam. Effect of community pond and flood mitigation dam was found most pronounced reducing the flood spread by 42.43 % & 45.74 % respectively and reducing the maximum inundation depth from 5 m to approx 1 – 2 m in low lying areas of Gawalmandi. Moreover, both community pond and flood mitigation in combination proved far more effective reducing the overall water spread by 83 %. Impact of flow diversion from Saidpur Kas to Korang River was also considered a feasible option reducing the spread by 29.54 %.

5.2 RECOMMENDATIONS

A sincere and dedicated effort was made in the current study to incorporate all the possible aspects of hydrological and hydraulic modeling for Lai Basin as well as analyzing the possible impacts of climate change on hydrological response of Lai Nullah with a view to suggest suitable adaptation strategies. Present study also addresses the areas which were not touched upon during previous studies on Lai Basin including frequency analysis, calculation of PMP / PMF, generation of IDF / DDF curves, assessment of future climate scenarios and adaptation strategies. Following recommendations are proffered in this regard with regards to current research:

- Hydrological Modelling in HEC-HMS involved terrain processing using 30m DEM which was readily available through open source. It is strongly recommended that fine resolution DEM i.e 2.5m or 5m spatial resolution may be used in future studies for better results.

- As far as Hydraulic Modelling is concerned, accurate and authentic channel geometry and flood plains elevation data is recipe for efficient modeling. Current study incorporated different datasets of channel geometry and flood plain elevation surveys from Kattarian till Marir Chowk conducted by different agencies during period 2007 - 2010. It is strongly recommended that a detailed survey of channel geometry and flood plain topography for complete basin from Margalla foot hills till its confluence with Soan Basin including tributaries be undertaken by RDA so as to have a fair idea of changes occurred in post 2010 period besides increasing the accuracy of terrain model.
- HEC-RAS 5.0.1 2D hydraulic model allows partial incorporation of bridges, lateral structures and roads through indirect method as was done in the current work. It is strongly recommended that future hydraulic study on the subject should completely incorporate the effect of bridges, floating debris, roads, railway lines, residential areas and other structures to have a more realistic hydraulic assessment.
- Though effort was made in the current study to touch the aspects of flood zoning and flood risk damage assessment. However, owing to lack of reliable data these aspects were not completed and included in the thesis work. It is strongly recommended that future study on the subject may include the aspects flood zoning and flood risk damage assessment.
- Assessment of climate change impact was studied using HI-AWARE dataset based on statistically corrected 8 GCMs through delta downscaling bias correction technique which is relatively simpler and widely used. However, it is recommended other GCMs / RCMs data may also be considered for future studies. In this regard, dynamic downscaling techniques and quantile mapping methodology is also recommended to be included for future studies.

- As far as impact of climate change is concerned, variation in rainfall increase pattern for different stations are generally attributed to various parameters associated with climate change including land use, temperature, rainfall patterns etc. It is recommended that future studies should also encompass through investigation of all such factors with regards to climate change.
- While analyzing the adaptation strategies, a number of miscellaneous strategies including construction of flood protection bunds, channel widening, channel lining and checking the malpractices of solid waste dumping were proposed. Proposal for construction of Lai Expressway during 2010 was also one such study which was left untouched. It is highly recommended that future studies by carried out to explore the feasibility of these strategies in more detail.
- Present degradation of Lai Nullah with regards to environmental pollution was also a major concern for the residents of Rawalpindi and Islamabad being the direct affectees. It is recommended that a comprehensive environmental study may also be undertaken on the subject to address the problems of dumpage of solid wastes including garbage and effluents / sewage flow in the Nullah thus reducing its conveyance capacity besides causing serious environmental pollution.
- Acquisitions of data particularly channel geometry and flood plain elevation data from various sources was a time consuming and labourious process. It is strongly recommended that a central database may be established at Lai Division RDA or at Lai Division PMD where all the pertinent data of Lai Basin along with all relevant studies may be complied and archived. This practice will be highly beneficial for guidance of future researchers to undertake their research in a befitting manner.

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APPENDICES

Appendix 1

COMPARISON OF DIFFERENT METHODS – HEC-HMS

S.No	Loss, Transformation, Base Flow & Routing Methods	Event	Gauge	Performance Indicators					
				R^2	RRMSE (%)	Dv %	Dp %	ΔT	E
1	SCS Curve Number, SCS Unit Hydrograph, Muskingum and Recession	14 Jul 2007	Kattarian	0.973	2.243	11.5	0.116	0	0.939
			Gawalmandi	0.965	0.383	1.39	5.16	0	0.989
2	Initial & Constant Rate, Clarke Unit Hydrograph, Lag and Bounded Recession	“	Kattarian	0.821	4.365	14.8	7.8	5	0.897
			Gawalmandi	0.736	3.784	8.46	4.5	10	0.815
3	Green & Ampt, Snyder Unit Hydrograph, Lag & Recession	“	Kattarian	0.724	0.653	20.8	10.8	10	0.638
			Gawalmandi	0.694	0.627	15.4	8.3	10	0.592

Appendix 2

SUB BASIN ATTRIBUTES COMPUTED IN HEC-GEOHMS

Basin Name	Slope	Curve Number	Impervious (%)	Lag Time (hrs)
W570	16.56	71.92	20.74	2.48
W590	23.72	67.7 0	12.75	1.62
W630	20.80	68.28	15.81	1.60
W710	4.92	70.26	15.59	2.38
W720	19.80	70.83	4.03	1.90
W740	16.92	69.42	16.69	2.41
W760	5.51	72.58	5.25	1.94
W770	6.89	71.66	26.91	1.15
W800	16.81	69.01	16.83	2.07
W830	6.85	70.76	22.47	1.41
W850	5.14	72.10	6.86	2.79
W880	4.96	72.41	8.95	2.05
W890	5.78	81.49	50.21	0.89
W940	5.97	77.93	39.91	1.74
W950	5.63	75.87	13.59	2.74
W960	5.97	85.51	60.07	0.78
W990	5.94	77.17	18.06	2.08
W1000	5.89	82.62	48.13	1.23
W1010	6.27	76.30	37.75	0.76
W1020	5.54	76.59	12.16	1.39
W1030	9.85	75.14	5.81	0.89
W1040	5.82	69.83	6.73	1.12
W1050	7.16	71.81	23.46	1.13
W1060	17.63	72.38	19.51	1.11

Appendix 3

ANNUAL INSTANTANEOUS PEAK FLOWS
KATTARIAN & GAWALMANDI

Year	Simulated Flows		Observed Flow recorded by TMA at Gawalmandi (cumecs)
	Kattarian (cumecs)	Gawalmandi (cumecs)	
1986	135.9	135	-
1987	521.3	501.6	-
1988	336.6	331.8	-
1989	1071.7	1051.8	-
1990	846.3	834.9	-
1991	715.6	696.3	-
1992	697	711.9	-
1993	256.2	248	-
1994	751	773.4	770
1995	515.6	496.2	500
1996	263.8	269.6	270
1997	959.4	1005.4	-
1998	515.2	514	-
1999	149.5	148.6	-
2000	135.8	133.1	-
2001	2517.8	2190.4	2152.98
2002	297.13	327.73	320
2003	532.23	593.65	-
2004	259.49	328.63	-
2005	186.3	207.45	-
2006	237.69	298.8	-
2007	543.47	661.21	-
2008	333.07	349.32	-
2009	264.21	300.76	-
2010	444.68	813.42	-
2011	341.84	465.49	-
2012	366.03	313.99	-
2013	650.07	546.31	-
2014	296.35	477.62	-
2015	438.23	481.34	-

Appendix 4

USE OF WEIBULL FORMULA FOR PLOTTING POSITIONS

Rank	Peak Flood Kattarian (cumecs)	Probability P= m/(N+1)	Return Period T = (1/P)	Rank	Peak Flood Gawalmandi (cumecs)	Probability P = m/(N+1)	Return Period T = (1/P)
1	2517.46	0.032	31.00	1	2152.98	0.032	31.00
2	1071.7	0.065	15.50	2	1051.8	0.065	15.50
3	959.4	0.097	10.33	3	1005.4	0.097	10.33
4	846.3	0.129	7.75	4	834.9	0.129	7.75
5	751	0.161	6.20	5	813.42	0.161	6.20
6	715.6	0.194	5.16	6	773.4	0.194	5.16
7	697	0.226	4.42	7	711.9	0.226	4.42
8	650.07	0.258	3.87	8	696.3	0.258	3.87
9	543.47	0.290	3.44	9	661.21	0.290	3.44
10	532.23	0.323	3.10	10	593.65	0.323	3.10
11	521.3	0.355	2.81	11	546.31	0.355	2.81
12	515.6	0.387	2.58	12	514	0.387	2.58
13	515.2	0.419	2.38	13	501.6	0.419	2.38
14	444.68	0.452	2.21	14	496.2	0.452	2.21
15	438.23	0.484	2.06	15	481.34	0.484	2.06
16	366.03	0.516	1.938	16	477.62	0.516	1.938
17	341.845	0.548	1.824	17	465.496	0.548	1.824
18	336.6	0.581	1.722	18	349.32	0.581	1.722
19	333.07	0.613	1.632	19	331.8	0.613	1.632
20	297.13	0.645	1.550	20	328.63	0.645	1.550
21	296.35	0.677	1.476	21	327.73	0.677	1.476
22	264.21	0.710	1.409	22	313.99	0.710	1.409
23	263.8	0.742	1.348	23	300.76	0.742	1.348
24	259.49	0.774	1.292	24	298.8	0.774	1.292
25	256.2	0.806	1.240	25	269.6	0.806	1.240
26	237.69	0.839	1.192	26	248	0.839	1.192
27	186.3	0.871	1.148	27	207.45	0.871	1.148
28	149.5	0.903	1.107	28	148.6	0.903	1.107
29	135.9	0.935	1.069	29	135	0.935	1.069
30	135.8	0.968	1.033	30	133.1	0.968	1.033

Appendix 5

ANNUAL MAXIMUM RAINFALL INTENSITIES – CHAKLALA STATION

Year	Rainfall Intensity (mm / hr)					Year	Rainfall Intensity (mm / hr)				
	3 hr	6 hr	9 hr	12 hr	24 hr		3 hr	6 hr	9 hr	12 hr	24 hr
1970	0.680	0.455	0.309	0.236	0.118	1993	20.000	10.667	7.111	3.583	2.667
1971	1.517	0.868	0.584	0.354	0.177	1994	31.333	26.500	18.556	13.917	7.083
1972	0.607	0.317	0.125	0.110	0.055	1995	22.667	16.167	15.667	13.250	6.225
1973	1.367	0.695	0.096	0.072	0.036	1996	36.000	27.167	22.389	8.067	6.792
1974	42.867	23.967	17.244	13.375	3.313	1997	35.667	26.000	23.333	19.000	8.333
1975	19.467	9.950	7.478	5.608	4.867	1998	31.467	15.733	8.111	7.250	3.933
1976	33.867	19.000	13.111	9.833	5.000	1999	16.667	12.000	7.000	6.583	3.917
1977	27.100	22.267	17.478	13.108	5.567	2000	16.667	11.667	7.778	6.833	3.417
1978	23.300	12.667	12.567	10.800	4.713	2001	33.000	27.333	18.889	14.167	8.333
1979	20.000	10.333	7.089	4.642	3.279	2002	15.000	9.167	6.444	3.917	2.708
1980	15.833	9.867	5.622	4.575	2.496	2003	20.667	10.833	7.222	2.083	2.029
1981	33.933	20.633	13.756	10.000	5.158	2004	16.667	15.167	3.444	2.442	1.925
1982	52.033	29.867	29.478	22.658	7.554	2005	11.000	4.667	4.333	3.333	2.083
1983	35.000	25.967	19.056	14.458	7.229	2006	30.333	29.667	20.889	17.583	5.750
1984	33.867	20.317	8.267	6.200	5.079	2007	27.000	23.500	17.444	5.500	5.500
1985	33.867	17.133	11.900	7.825	6.379	2008	23.667	12.167	8.000	6.083	3.375
1986	10.233	6.133	4.089	2.658	2.421	2009	14.667	11.500	8.000	6.000	3.000
1987	18.967	9.783	6.522	3.908	3.071	2010	18.333	9.167	6.111	4.583	4.125
1988	18.300	11.133	5.956	4.992	2.783	2011	25.667	13.500	8.556	6.833	4.875
1989	25.400	13.500	8.489	6.792	4.867	2012	27.333	13.667	9.111	6.833	3.417
1990	21.833	13.883	9.933	4.842	3.204	2013	23.000	11.500	7.667	5.750	3.250
1991	16.933	10.400	6.456	5.008	2.879	2014	37.000	25.833	21.444	18.750	11.292
1992	25.567	15.050	12.178	11.008	7.017	2015	1.667	0.833	0.778	0.583	0.450

Appendix 6

ANNUAL MAXIMUM RAINFALL INTENSITIES – PMD STATION

Year	Rainfall Intensity (mm / hr)					Year	Rainfall Intensity (mm / hr)				
	3 hr	6 hr	9 hr	12 hr	24 hr		3 hr	6 hr	9 hr	12 hr	24 hr
1983	23.233	14.450	12.133	9.717	7.175	2000	17.467	9.233	7.156	3.433	1.875
1984	17.033	10.883	8.300	5.642	3.429	2001	29.000	15.167	10.111	4.433	4.208
1985	39.700	23.033	16.200	12.508	6.254	2002	24.333	15.667	11.778	11.917	7.029
1986	14.233	8.800	6.011	4.592	2.329	2003	16.000	8.167	5.444	4.083	3.833
1987	24.900	14.400	9.600	7.800	3.613	2004	29.000	14.833	9.889	7.417	4.079
1988	24.033	15.483	8.522	4.442	3.663	2005	39.700	23.033	16.200	12.508	6.417
1989	26.233	13.367	8.611	6.733	5.654	2006	29.000	14.833	9.889	7.417	3.917
1990	30.867	20.067	15.967	12.083	5.058	2007	41.000	26.500	18.111	13.750	7.417
1991	16.600	9.200	6.167	4.975	3.675	2008	11.667	6.167	4.111	3.083	2.208
1992	23.733	18.700	15.244	13.558	8.654	2009	24.333	15.667	11.778	11.917	7.042
1993	20.400	9.333	6.733	5.117	3.700	2010	17.667	11.833	8.000	5.917	2.958
1994	58.200	29.133	19.422	14.567	7.283	2011	16.000	8.167	5.444	4.083	3.750
1995	29.000	15.167	10.111	4.433	4.196	2012	39.000	21.000	14.111	10.667	5.458
1996	25.333	13.500	9.222	5.583	3.525	2013	28.000	20.833	19.889	16.917	10.667
1997	36.667	18.333	17.711	15.800	8.325	2014	19.667	9.833	6.556	5.500	3.500
1998	17.667	12.633	8.556	5.950	3.158	2015	133.367	88.683	64.178	51.650	24.663
1999	18.333	12.500	6.044	3.517	3.371	-	-	-	-	-	-

Appendix 7

ANNUAL MAXIMUM RAINFALL INTENSITIES – RAMC STATION

Year	Rainfall Intensity (mm / hr)					Year	Rainfall Intensity (mm / hr)				
	3 hr	6 hr	9 hr	12 hr	24 hr		3 hr	6 hr	9 hr	12 hr	24 hr
1989	38.567	19.717	13.689	10.267	5.133	2003	20.067	10.100	4.811	4.317	4.267
1990	36.000	15.867	10.578	7.933	3.967	2004	42.133	21.442	16.294	13.867	6.267
1991	22.867	11.583	8.256	6.375	2.896	2005	21.667	10.833	7.811	6.208	2.733
1992	50.600	26.050	21.367	24.233	7.096	2006	42.667	27.167	18.333	13.917	7.083
1993	23.200	11.317	4.211	4.783	2.900	2007	22.333	11.667	7.778	5.833	4.792
1994	58.367	31.800	21.456	16.092	8.046	2008	42.667	27.167	18.333	13.917	6.958
1995	23.533	11.833	8.433	7.875	3.158	2009	26.000	13.000	8.667	6.500	3.250
1996	38.000	20.133	10.311	4.650	4.033	2010	24.333	15.667	11.778	9.667	5.333
1997	69.000	50.500	35.400	26.550	13.275	2011	24.000	16.667	11.222	8.417	4.208
1998	32.133	13.417	10.000	9.217	4.017	2012	18.000	9.833	7.000	5.250	2.792
1999	20.067	10.100	4.811	4.317	4.317	2013	33.667	16.833	11.222	8.500	5.417
2000	21.667	10.833	6.978	5.758	2.617	2014	34.000	23.833	21.444	17.917	11.208
2001	94.200	55.100	39.889	30.633	13.942	2015	36.000	15.867	10.578	7.933	3.833
2002	29.533	14.767	9.844	7.383	3.692	-	-	-	-	-	-

Appendix 8

ANNUAL MAXIMUM RAINFALL INTENSITIES – SAIDPUR & BOKRA STATIONS

Year	Rainfall Intensity Saidpur (mm / hr)					Year	Rainfall Intensity Bokra (mm / hr)				
	3 hr	6 hr	9 hr	12 hr	24 hr		3 hr	6 hr	9 hr	12 hr	24 hr
2007	27.000	14.500	9.667	7.250	3.625	2007	16.000	8.167	5.444	4.083	2.042
2008	30.667	16.333	10.889	8.417	4.208	2008	32.333	17.000	11.333	8.500	4.250
2009	10.333	5.500	3.667	2.750	1.375	2009	6.667	4.000	2.889	2.667	1.875
2010	46.000	30.167	20.556	17.833	12.167	2010	16.333	10.500	7.556	7.083	4.500
2011	54.000	28.500	19.000	14.250	7.125	2011	21.667	11.833	8.222	6.167	3.125
2012	30.333	15.167	10.111	9.667	6.000	2012	14.333	9.167	6.111	4.583	2.375
2013	45.000	33.500	23.222	17.583	9.417	2013	26.000	15.000	10.889	8.333	4.208
2014	24.000	18.000	17.556	14.750	10.333	2014	22.667	15.667	15.889	13.167	8.000
2015	32.000	16.167	10.778	8.083	6.417	2015	38.667	19.500	13.000	9.917	5.083

Appendix 9

ANNUAL MAXIMUM RAINFALL INTENSITIES – GOLRA STATION

Year	**Rainfall Intensity (mm / hr)**				
	3 hr	**6 hr**	**9 hr**	**12 hr**	**24 hr**
2007	25.000	12.667	8.556	6.500	3.250
2008	22.333	11.167	7.444	5.583	2.792
2009	15.333	8.333	5.556	4.167	2.250
2010	54.000	31.000	21.444	16.333	9.875
2011	33.333	16.667	11.111	8.333	4.167
2012	14.333	7.833	5.444	7.167	3.875
2013	26.000	14.667	10.000	7.500	4.917
2014	20.667	18.000	15.556	12.833	8.000
2015	35.667	24.000	16.000	12.000	6.000

Appendix 10

IDF CURVES VALUES

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	21.04	30.40	37.48	46.85	53.93	61.01
360	13.28	20.00	25.09	31.81	36.90	41.98
540	8.89	14.06	18.45	23.42	27.51	31.10
720	6.72	11.14	14.48	18.90	22.24	25.58
1440	4.44	6.06	7.29	8.92	10.15	11.38

Chaklala Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	24.62	37.01	46.37	58.76	68.12	77.49
360	14.32	22.04	27.88	35.60	41.44	47.28
540	10.07	16.11	20.28	26.72	31.29	35.86
720	8.85	13.50	16.89	23.01	27.59	31.18
1440	4.66	7.31	9.32	11.97	13.98	15.99

PMD Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	31.78	44.45	54.03	66.69	76.28	85.86
360	17.01	25.21	31.42	39.62	45.83	52.04
540	11.23	18.03	22.82	29.12	34.11	39.11
720	8.96	14.48	18.65	24.16	28.34	32.51
1440	4.86	7.18	8.94	11.27	13.02	14.78

RAMC Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	29.01	45.28	57.59	73.87	86.18	98.49
360	16.90	27.71	35.88	46.69	54.86	63.04
540	11.66	19.35	25.89	33.88	39.93	45.97
720	9.47	16.14	21.18	27.84	32.88	37.92
1440	5.60	10.17	13.64	18.22	21.68	25.15

Saidpur Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	24.06	35.40	43.97	55.31	63.88	72.46
360	13.91	21.16	26.65	33.91	39.39	44.88
540	9.47	14.60	18.43	23.36	27.09	30.12
720	7.82	11.66	14.57	18.41	21.32	24.22
1440	4.30	6.70	8.52	10.92	12.74	14.56

Golra Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	72.18	106.2	131.91	165.93	191.64	217.38
360	83.46	126.96	159.9	203.46	236.34	269.28
540	87.03	135	171.27	219.24	255.51	291.78
720	93.84	139.92	174.84	220.92	255.84	290.64
1440	103.2	160.8	204.48	262.08	305.76	349.44

Bokra Station

Appendix 11

RAINFALL VALUES

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	63.12	91.2	112.44	140.55	161.79	183.03
360	79.68	120	150.54	190.86	221.4	251.88
540	80.01	126.54	166.05	210.78	247.59	279.9
720	80.64	133.68	173.76	226.8	266.88	306.96
1440	106.56	145.44	174.96	214.08	243.6	273.12

Chaklala Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	73.86	111.03	139.11	176.28	204.36	232.47
360	85.92	132.24	167.28	213.6	248.64	283.68
540	90.63	144.99	186.12	240.48	281.61	322.74
720	115.08	180	229.08	294	343.08	392.16
1440	111.84	175.44	223.68	287.28	335.52	383.76

PMD Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	73.86	111.03	139.11	176.28	204.36	232.47
360	85.92	132.24	167.28	213.6	248.64	283.68
540	90.63	144.99	186.12	240.48	281.61	322.74
720	115.08	180	229.08	294	343.08	392.16
1440	111.84	175.44	223.68	287.28	335.52	383.76

RAMC Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	29.01	45.28	57.59	73.87	86.18	98.49
360	16.90	27.71	35.88	46.69	54.86	63.04
540	11.66	19.35	25.89	33.88	39.93	45.97
720	9.47	16.14	21.18	27.84	32.88	37.92
1440	5.60	10.17	13.64	18.22	21.68	25.15

Saidpur Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	72.18	106.2	131.91	165.93	191.64	217.38
360	83.46	126.96	159.9	203.46	236.34	269.28
540	87.03	135	171.27	219.24	255.51	291.78
720	93.84	139.92	174.84	220.92	255.84	290.64
1440	103.2	160.8	204.48	262.08	305.76	349.44

Golra Station

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	18.60	29.87	38.40	49.67	58.20	66.73
360	10.74	16.75	21.30	27.31	31.86	36.41
540	7.56	11.79	15.27	19.38	22.89	25.57
720	6.18	9.72	12.39	15.93	18.60	21.27
1440	3.40	5.25	6.65	8.50	9.90	11.30

Bokra Station

Appendix 12

STANDARD FLOOD DISCHARGES

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	170.75	350.09	609.73	1113.85	1579.77	2170.75
360	236.52	449.20	727.48	1232.60	1689.83	2287.84
540	274.99	507.17	796.28	1302.06	1754.26	2356.33
720	302.28	548.30	845.13	1351.35	1799.91	2404.95
1440	368.05	647.41	962.84	1470.10	1910.07	2522.03

Kattarian

Storm Duration (min)	2 YEAR	5 YEAR	10 YEAR	25 YEAR	50 YEAR	100 YEAR
0						
180	199.23	455.66	752.83	1283.44	1777.09	2380.44
360	286.35	544.13	849.52	1377.82	1855.21	2486.91
540	337.32	595.89	906.08	1433.03	1900.90	2549.19
720	373.48	632.61	946.21	1472.20	1933.32	2593.37
1440	460.60	721.08	1042.91	1566.58	2011.43	2699.84

Gawalmandi

Appendix 13

FREQUENCY ANALYSIS – PROJECTED DATA AMDR

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	108.02	95.1	13.59	109.84	15.50
	2055s	111.07		16.80		
	2085s	110.41		16.10		
PMD	2025s	111.41	107.59	3.55	114.00	5.95
	2055s	116.97		8.72		
	2085s	113.60		5.59		
RAMC	2025s	106.79	94.48	13.03	107.68	13.98
	2055s	108.25		14.58		
	2085s	108.01		14.32		
Saidpur	2025s	133.42	96.88	37.72	135.40	39.76
	2055s	136.30		40.69		
	2085s	136.46		40.86		

2 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	157.95	142.93	10.51	158.68	11.02
	2055s	158.63		10.98		
	2085s	159.47		11.57		
PMD	2025s	194.92	178.99	8.90	194.52	8.68
	2055s	195.70		9.34		
	2085s	192.94		7.79		
RAMC	2025s	178.63	143.47	24.51	176.67	23.14
	2055s	176.38		22.94		
	2085s	175.01		21.98		
Saidpur	2025s	191.29	141.62	35.07	185.30	30.84
	2055s	191.28		35.07		
	2085s	173.32		22.38		

5 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	195.72	179.11	9.27	195.64	9.23
	2055s	194.61		8.65		
	2085s	196.59		9.76		
PMD	2025s	258.09	233.01	10.76	255.43	9.62
	2055s	255.25		9.55		
	2085s	252.96		8.56		
RAMC	2025s	232.98	180.52	29.06	228.86	26.78
	2055s	227.91		26.25		
	2085s	225.69		25.02		
Saidpur	2025s	235.06	175.46	33.97	231.24	31.79
	2055s	232.86		32.71		
	2085s	225.78		28.68		

10 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	245.64	226.94	8.24	244.49	7.73
	2055s	242.16		6.71		
	2085s	245.65		8.24		
PMD	2025s	341.59	304.41	12.21	335.95	10.36
	2055s	333.97		9.71		
	2085s	332.30		9.16		
RAMC	2025s	304.83	229.51	32.82	297.85	29.78
	2055s	296.03		28.98		
	2085s	292.69		27.53		
Saidpur	2025s	292.93	220.19	33.04	285.80	29.80
	2055s	287.83		30.72		
	2085s	276.63		25.63		

25 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	283.41	263.12	7.71	281.44	6.96
	2055s	278.14		5.71		
	2085s	282.76		7.47		
PMD	2025s	404.76	358.42	12.93	396.87	10.73
	2055s	393.53		9.80		
	2085s	392.31		9.46		
RAMC	2025s	359.18	266.56	34.75	350.04	31.32
	2055s	347.57		30.39		
	2085s	343.37		28.82		
Saidpur	2025s	336.71	254.03	32.55	327.08	28.76
	2055s	329.42		29.68		
	2085s	315.10		24.04		

50 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	358.95	335.49	6.99	355.34	5.92
	2055s	350.09		4.35		
	2085s	356.99		6.41		
PMD	2025s	531.10	466.45	13.86	518.69	11.20
	2055s	512.63		9.90		
	2085s	512.35		9.84		
RAMC	2025s	467.88	340.67	37.34	454.42	33.39
	2055s	450.63		32.28		
	2085s	444.74		30.55		
Saidpur	2025s	424.26	321.71	31.88	409.63	27.33
	2055s	412.59		28.25		
	2085s	392.04		21.86		

200 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	408.87	383.32	6.67	404.19	5.44
	2055s	397.65		3.74		
	2085s	406.05		5.93		
PMD	2025s	614.61	542.58	13.28	599.22	10.44
	2055s	591.36		8.99		
	2085s	591.69		9.05		
RAMC	2025s	539.72	389.66	38.51	523.41	34.32
	2055s	518.76		33.13		
	2085s	511.74		31.33		
Saidpur	2025s	482.13	366.44	31.57	464.19	26.68
	2055s	467.56		27.60		
	2085s	442.89		20.86		

500 Year Return Period

Gauge	Time Slice	Projected Rainfall	Observed Data	% Increase	Average	Average % Increase
Chaklala	2025s	446.64	419.5	6.47	441.14	5.16
	2055s	433.62		3.37		
	2085s	443.17		5.64		
PMD	2025s	677.78	597.19	13.49	660.13	10.54
	2055s	650.91		9.00		
	2085s	651.70		9.13		
RAMC	2025s	594.07	426.71	39.22	575.59	34.89
	2055s	570.29		33.65		
	2085s	562.42		31.80		
Saidpur	2025s	525.92	400.28	31.39	505.47	26.28
	2055s	509.14		27.20		
	2085s	481.36		20.26		

1000 Year Return Period