Integrated Urban Flood Management in India – Technology Driven Solutions

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1.1 Overview

Floods are one of the biggest and the most severe, widespread and frequent natural disasters faced by the society. Floods result in loss of life and property, and in some cases, may lead to health emergencies too. Floods in urban areas are devastating, and cripple the economy of a much larger region than where the flood occurs. Ironically, most floods are triggered by weather, but human activities like deforestation and urbanisation, which have stripped away some of the essential services provided by the environment have become a dominant reason for the exacerbation of the flooding issue. Indian cities have witnessed tremendous growth in the last few decades, as a result of the rise in urban population. Unfortunately, infrastructure development has lagged with the economic and population growth, resulting in mismanagement of resources. Changing rainfall patterns, due to both natural and anthropogenic causes, have made the flooding problem more exaggerated, frequent, and widespread. Cities' drainage infrastructure, coupled with soil erosion, have proved ineffective in the face of intense rainfall, making flash floods a common occurrence. An interdisciplinary, collaborative project titled **'Integrated Urban Flood Management in India – Technology Driven Solutions' worked towards the objective of changing this situation by leapfrogging from**

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the current, poorly managed state to a highly efficient, technology-driven automated end-to-end management of urban floods. The project was motivated by the end goal to develop solutions by taking into account various ground conditions including clogging, sewerage in drains, and space constraints. It also leads to developing the foundation and implementation of a real-time flood forecasting model, with inputs from sensors placed at different parts of the city. As a result, presently urban flooding situation can be displayed on a computer screen using the geographical information systems (GIS) in real time. The system also incorporates appropriate algorithms and scientific advancements related to the science of the urban flooding that help expedite operational decisions, and enable faster communication to the stakeholders using a mobile phone and the internet. The project objectives can be summarised as follows.

- To develop real-time flood forecasting models that can be used for urban areas in India, assimilating data and information from remotely sensed products, automatic weather stations and state-of-the-art numerical weather prediction and hydrological models.
- To develop operational models for real-time management of urban drainage systems using water level sensors and control systems algorithms integrated with GIS.
- To develop models and methodologies for communicating the forecasts to different levels of decision-making mechanisms.
- To investigate the likely changes in the frequencies of high-intensity rainfall using extreme value theory and stochastic weather generators and to examine the adequacy of capacity of the existing structural measures to cope with the changing climate.
- To demonstrate the application of the models and the end-to-end implementation integrating the models-sensors-decision framework through a pilot project.
- To lead the development of flood management training and educational material.
- To create public awareness programs and involve communities in preparedness and flood rescue and recovery process.

Fig. 1.1: Photograph of recent floods in Indian metro cities (Chennai, Bangalore and Hyderabad). Sources: Multiple (NRSC, KSNDMC, Media, etc.)

The consortium for the project Integrated Urban Flood Management in India-Technology Driven Solutions consists of Indian Institute of Science (IISc) as Lead Institution (LIN) with Partnering Institutes (PIN) National Institute of Technology-Warangal (NITW), Birla Institute of Technology & Science, Pilani - Hyderabad (BITS Pilani), CDAC – Trivandrum. Purdue University and UNESCO Paris are a part of the project as research collaborators. Government organisations like Karnataka State Natural Disaster Monitoring Centre, Bruhat Bangalore Mahanagara Palike, MS University, Baroda and Greater Hyderabad Municipal Corporation are few other collaborators for the ITRA project. The list of institutes and peoples involved in the project is given in Table 1.1.

The Project “Integrated Urban Flood Management in India: Technology driven Solutions” has its focus set on two cities: Bangalore and Hyderabad, with the following study areas:

- Bangalore Pilot Study Area
- Hyderabad Pilot Study Area
- Controlled Watershed in IISc Campus, Bangalore

The Bangalore Pilot Study Area and the Controlled Watershed in IISc Campus is led by Indian Institute of Science, Bangalore with collaborative partners as Karnataka State Natural Disaster Monitoring Centre (KSNDMC) and Bruhat Bangalore Mahanagara Palike (BBMP). The Hyderabad Pilot Study Area is led by the teams from National Institute of Technology, Warangal (NITW) and BITS Pilani Hyderabad Campus having the collaborators from Greater Hyderabad Municipal Corporation (GHMC).

Table 1.1: The list of institutes and peoples involved in the project.

Institute	Member	Member role
Indian Institute of Science, Bangalore	Prof. P. P. Mujumdar	Principal Investigator (PI)
	Prof. M. S. Mohan Kumar	Co-PI
	Ms. Chandra Rupa R	Research Scholar
	Ms. Sudarshana	Project Staff
	Ms. Lubna	Project Staff
	Ms. Vijitha Babu	Project Staff
	Ms. Srivani	Project Staff
	Mr. Milind Sharma	Masters Students
	Mr. Mahadev Devale	Masters Students
BITS Pilani, Hyderabad	Prof. K. Srinivasa Raju	PI
	Ms Vemula Swathi	Research Scholar
	Ms Rampalli Madhuri	Research Scholar
	Ms. Sai Veena	Undergraduate Student
	Mr. Vem Anirud Reddy	Undergraduate Student
NIT Warangal	Prof. N V Umamahesh	PI
	Dr. Ajey Kumar Patel	Co-PI
	Dr. Agilan	Research Scholar
	Mr. Rangari Vinay Ashok	Research Scholar
CDAC, Trivandrum	Dr. R Valsalam	PI
	Mr. Abhir Raj Metkar	Collaborator
	Ms. Sindhu	Collaborator
Purdue University	Prof. Dev Niyogi	Mentor and Collaborator
UNESCO, Paris	Dr. Bhanu Neupane	Mentor
KSNDMC, Bangalore	Dr. G.S. Srinivasa Reddy	Collaborator
	Ms. Shubha Avinash	Collaborator
MS University, Baroda	Dr. Sanskriti Mujumdar	Collaborator

Fig. 1.2: The graphical overview of "Integrated Urban Flood Management in India – Technology Driven Solutions"

The graphical overview of "Integrated Urban Flood Management in India – Technology Driven Solutions" is shown in Fig. 1.1. The key activities carried out towards this project are summarised in following points.

<u>Hydrological models & lab setup:</u>

- The changes in the hydro-climatic variables' extremes (which are the main causes of floods) are analysed using historical observed data for Bangalore and Hyderabad city. Especially, the following aspects are deeply studied.
    - Spatial distribution of return levels of extreme rainfall, with spatial dependence structure built in – in and around the cityscapes
    - The temporal non-stationarity in the extreme rainfall series.

  The R&D results obtained and the proposed new models in these directions are discussed in Section 1.2.

- The climate change impacts on hydro-climatic variables and its extremes are projected for the future time periods. Solved research problems are as follows.
    - Model and Parameter Uncertainty in IDF Relationships under Climate Change.
    - The capability of covariate based non-stationary rainfall IDF curve in encompassing future rainfall changes.
- 2D overland flow models are built for the study regions to simulate the flood event accurately. The developed two-dimensional overland flow model is capable of simulating floods with obstructions due to buildings and other structures.
- The adequacy of capacity of the existing structural measures to cope with the changing climate is studied for Bangalore and Hyderabad city.
- Enhanced laboratory setup is created and experiments are conducted to reproduce the field situations under floods.

Implementation on ground:

- Flow level sensors are installed in pilot study areas.
- LiDAR survey is carried out in IISc Campus for obtaining very high resolution (0.2m resolution) terrain information that will eventually help in producing accurate flood forecast and inundation maps.
- The flow level and weather sensors are connected to wireless communication systems for getting hydro-meteorological data in real-time.
- Flood maps are created by combining hydrological simulations with GIS environment.
- Flood events are characterised into different classes for management activities.
- Flood management decision support system is developed by integrating Rainfall Forecast-Hydrologic Models-Flood Forecast on Real time

Value addition:

- Revised urban landcover and climate zone maps of Bangalore city are created for accurate meteorological forecasts using weather research forecast model.
- Communication systems such as WhatsApp Group, Website, Twitter page, Facebook page, e-mails and customised mobile SMS are created to disseminate flood forecast to administrative departments and public.

- A number of outreach activities are conducted during the project period to train faculty members of premier institutes of India, engineers from different municipalities, scientists and research scholars. In particular, the team is already organised three Monsoon schools, two short-term courses, two workshops and training program. See Section 1.3.2 for more details.

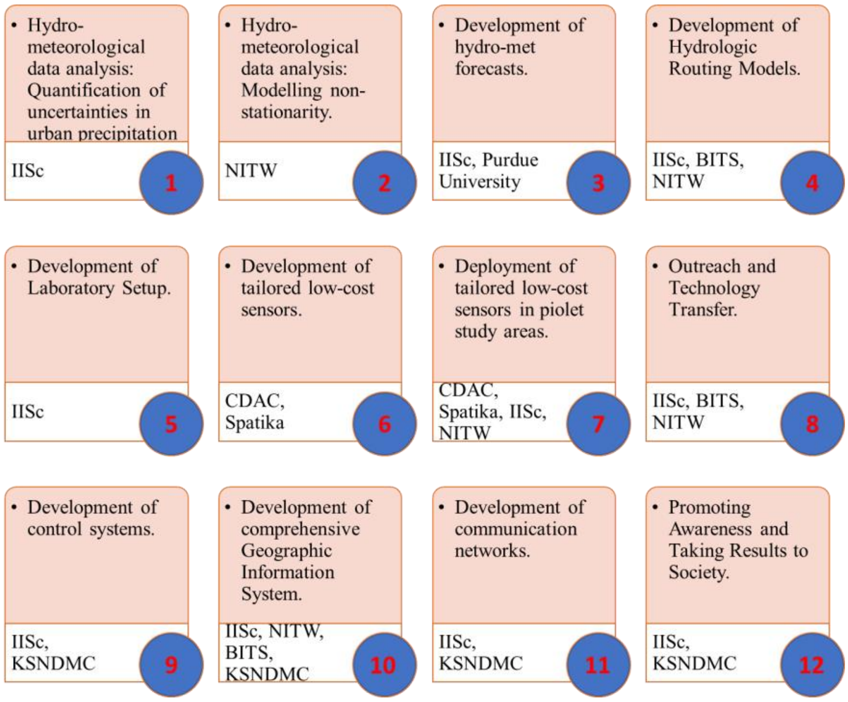


Fig. 1.3: The achievements from the project.

1.2 R&D Results Obtained, and their Impact on the Evolution of the Field

1.2.1 Quantification of uncertainties in urban precipitation extremes

Growth in population, along with industrial and economic development, has led to urban sprawl (UN, 2011). The process of urbanisation impacts hydrologic response of a catchment, resulting in increased runoff rates and volumes, concentration times, losses of infiltration and base flow (Randolph 2004; Dougherty et al. 2006). Quantifying the short duration high intensity precipitation is crucial in urban hydrology. However, the availability of precipitation data at short durations is lacking, leading to high uncertainties. Further, precipitation is expected to vary spatially in a rapid manner within the urban areas (Yang et al., 2015) due to non-uniformity in the spatiotemporal patterns of meteorological factors including convection, occurrence of updrafts, and aerosols. This work aims at quantifying uncertainty in precipitation extremes, both spatial and temporal, in urban areas.

Annual maximum precipitation series at different durations, starting from 15 min to 24 hour, for Bangalore city are considered in developing the IDF relationships along with uncertainty. Climate change is believed to cause variations in intensity, duration, and frequency of extreme precipitation events (IPCC 2014). Twenty-six Coupled Model Intercomparison Project – 5 (CMIP5) GCMs along with four Representative Concentration Pathway (RCP) scenarios are considered for studying the effects of climate change and to obtain projected IDF relationships for the Bangalore case study (Fig. 1.4). GCM uncertainty due to the use of multiple GCMs is treated using Reliability Ensemble Averaging (REA) technique along with the parameter uncertainty. It is noted that the uncertainty in short duration rainfall return levels is high when compared to the longer durations. Further, it is found that parameter uncertainty is large compared to the model uncertainty.

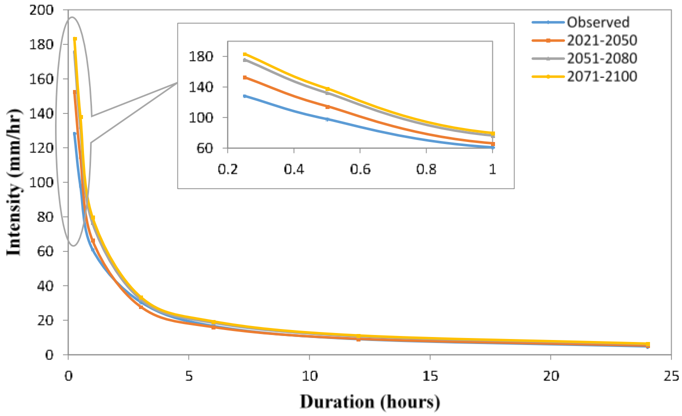


Fig. 1.4: IDF relationships for future time slices for RCP8.5 scenario for 10-year return period.

Precipitation extremes are often modelled with data from annual maximum series or peaks over threshold series. The Generalised Extreme Value (GEV) distribution is used to model the maxima of finite sized blocks. However, if hourly observations are available, GEV models using only one maxima per year (if annual) disregard other extreme data that could provide additional information. Therefore, considering this limitation, modelling extreme precipitation above a certain threshold following Generalized Pareto Distribution (GPD) model is generally proficient. Disaggregation of precipitation extremes from larger time scales to smaller time scales when the extremes are modelled with the GPD is burdened with difficulties arising from varying thresholds for different durations. The scale invariance theory is used to develop a disaggregation model for precipitation extremes exceeding specified thresholds. A scaling relationship is developed for a range of thresholds obtained from a set of quantiles of non-zero precipitation of different durations. A quantile-based modification in the scaling relationship is proposed for obtaining the varying thresholds and exceedance rate parameters for shorter durations. The disaggregation model is applied to precipitation datasets over Bangalore City, India (and also tested with Berlin, Germany where a higher density of observations was available to test the model). The developed disaggregation model is used to obtain projected IDF relationships for twenty-six CMIP5 GCMs with four RCP scenarios for the Bangalore case study.

The spatial variation of precipitation extremes in urban regions is significantly different from other areas (Shastri et al., 2015). Understanding of such spatial variations of extremes is critical for urban infrastructure design and operation. Bayesian hierarchical model is used to obtain spatial distribution of return levels of precipitation extremes in urban areas and quantify the associated uncertainty. The GEV distribution is used for modelling precipitation extremes. A spatial component is introduced in the parameters of the GEV through a latent spatial process by considering geographic and climatologic covariates. Applicability of the methodology is demonstrated with data from 19 telemetric rain gauge stations in Bangalore city, India (Fig. 1.5). From this case study, it is inferred that the elevation (where the observations are recorded geographically) and mean monsoon precipitation are the predominant covariates for annual maximum precipitation. Variation of seasonal extremes is also examined in this work. For the monsoon maximum precipitation, it is observed that the geographic covariates dominate while for the summer maximum precipitation, elevation and mean summer precipitation are the predominant covariates.

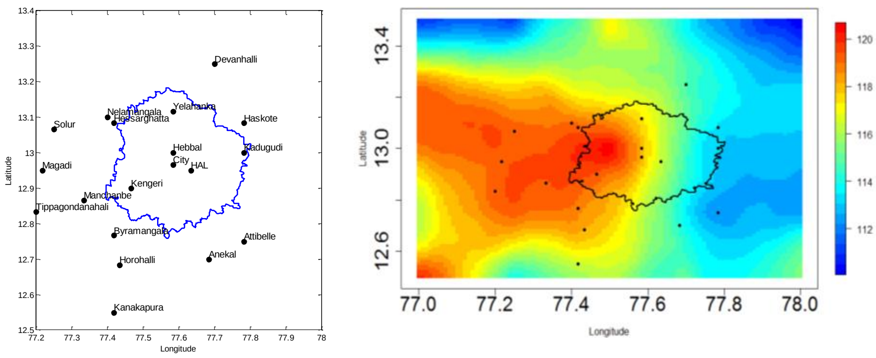


Fig. 1.5: Spatial map of mean return levels (mm) for 10-year return period for selected hierarchical model.

In the Bayesian hierarchical model, the precipitation is considered to be conditionally independent spatially. However, there could be some dependence among the observations, specifically at larger durations. To account this dependency in precipitation time series, the max-stable process is considered. In case of the Bangalore case study, similar results were obtained from both max-stable and Bayesian hierarchical models, due to the fact that less dependence (extremal coefficients of order 1.8) is observed in the data. Another case study, Berlin city, is considered in the analysis for checking the dependence structure at different accumulated durations within the city and its non-urban surroundings. The hourly precipitation shows independence within the city even at small distances, whereas the daily precipitation shows a high degree of dependence. This dependence structure of the daily precipitation gets masked as more and more surrounding non-urban areas are included in the analysis. Different geographical and climatological covariates are considered in the modelling of location and scale parameters of GEV distribution. The geographical covariates are predominant within the city and the climatological covariates are prevailing when non-urban areas are added. These results suggest the importance of quantification of dependence structure of spatial precipitation at the sub-daily timescales, as well as the need to more precisely model spatial extremes within the urban areas

<u>Impacts:</u>

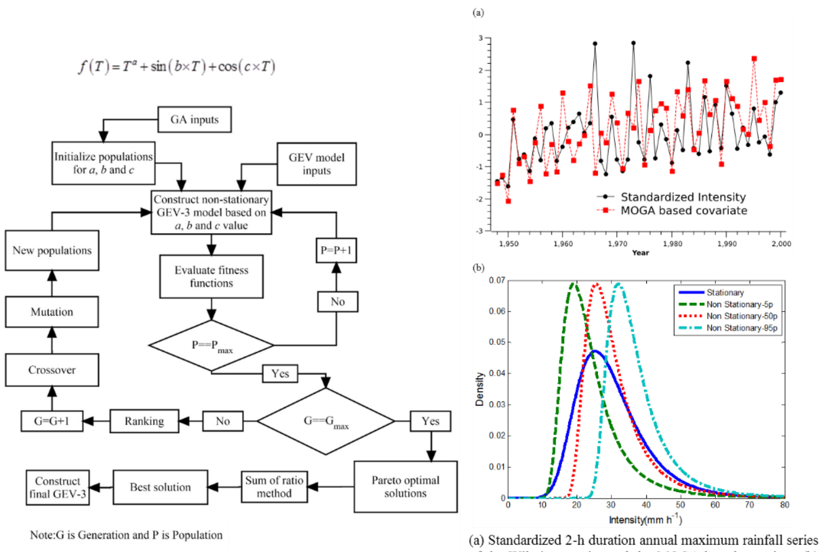
- Short duration, high intensity rains often cause notable impacts if the infrastructure, such as the storm water drains, detention ponds, does not cater the requirements especially in the low-lying areas. The data available for short duration rainfall is often limited, which introduces large uncertainties in GEV parameters. This work develops the probabilistic IDF relationships, which can be used in the designs of urban storm water infrastructure and risk assessment strategies.

- Climate change is expected to affect precipitation and therefore the use of robust and accurate techniques for projections of IDF relationships under changing climate are necessary for development of urban infrastructure to adapt to the likely changes in flood frequencies. Projected probabilistic IDF relationships are developed as a part of this research work.
- A reliable disaggregation model is required to obtain shorter duration precipitation extremes as downscaling the GCM outputs directly to small-time scales is generally not reliable. A quantile based disaggregation model is developed based on scale invariance theory for disaggregating parameters of GPD and exceedance rate parameters.
- In urban areas, spatial variation in rainfall is observed, and it is important to understand the space-time behaviour of extreme precipitation for effective infrastructure design and operation. The spatial and temporal data in urban areas, is in general sparse leading to high uncertainties in estimating the return levels of extreme precipitation. This research work presents a methodology to obtain the spatial distribution of return levels of precipitation extremes in urban areas and quantify the associated uncertainty, considering both dependence and independence in the observations.

1.2.2 Modelling non-stationary in extreme rainfall

Since the extreme rainfall of most part of the world is increasing due to climate change and various physical feedbacks including urbanization (Trenberth, et al., 2003; Emori & Brown, 2005; Trenberth, 2011; Berg, et al., 2013; Kunkel, et al., 2013; Cavanaugh, et al., 2015; Xu, et al., 2015; Niyogi et al. 2017), developing rainfall IDF curve under the non-stationary condition is one of the current realms of hydrologic research. In studies to date, for developing non-stationary rainfall IDF curves, researchers directly used Time as a covariate to introduce time-varying component in the parameters of probability distributions which are fitted with the extreme rainfall series. But, just because the extreme rainfall series has a non-stationary component in it, directly using any single covariate (such as Time) to introduce time-varying component in the probability distributions' parameters leads to an increased non-stationarity bias in modelling. Therefore, the optimal physical covariates for developing non-stationary rainfall IDF curve need to be identified. In particular, among different physical processes and Time covariate, the optimal physical covariates for modelling non-stationarity in the different duration extreme rainfall series are analysed using non-stationary extreme value theory. The study was conducted using data from Hyderabad city. Results indicate that the local processes (i.e., urbanization, local temperature changes) are the 'best' covariates for the short duration extreme rainfall series and global processes (i.e., global warming, and climate variability due to El Nino-Southern Oscillations and Indian Ocean Dipole) are the best covariates for the long-duration extreme rainfall series of Hyderabad city. Furthermore, from the results, it is also concluded that the covariate Time is never qualified as the best covariate and, as hypothesised directly using it increases bias in the non-stationary model. These results will help the hydrologic community in analysing the influence of covariate in the non-stationary rainfall IDF curve.

For developing non-stationary rainfall IDF curves in the absence of the best covariates, Multi-Objective Genetic Algorithm (MOGA) based method for modelling non-linear trend in the extreme rainfall series is developed. In particular, MOGA based methodology has been developed to generate time-based covariate which will produce robust non-stationary models without increasing the complexity of the models by considering non-linear trends in the time series. This proposed method will help the hydrologic community in developing non-stationary rainfall IDF curve of any part of the world.



Methodology flowchart of proposed non-linear trend modelling technique.

(a) Standardized 2-h duration annual maximum rainfall series of the Wilmington city and the MOGA based covariate. (b) Graphical view of the proposed model with 5 percentiles, 50 percentiles and 95 percentiles of location parameter for 2-h duration annual maximum rainfall series of the Wilmington city.

Fig. 1.6: Proposed methodology for developing non-stationary rainfall IDF curves by modelling non-linear trend in the extreme rainfall series. Results of the proposed methodology are shown on the right panel of the Figure.

The significance of finding the best covariates for developing non-stationary rainfall IDF curve is also studied. In particular, the uncertainty in non-stationary rainfall return levels due to the choice of the covariate (covariate uncertainty) is analysed. Also, the relative significance of covariate uncertainty when compared to the uncertainty in parameter estimates due to insufficient quantity and quality of data is explored. The results of this study revealed that the covariate uncertainty is significant, especially when a number of covariates produce a significantly superior nonstationary model and, remarkably, it is nearly equivalent to the parameter uncertainty in such cases. Further, it is observed that the covariate uncertainties are due to the inability of the covariate to capture all quantiles of extreme rainfall, though the chosen covariate can produce a statistically significant non-stationary model. Accordingly, the study cautions the hydrologic community that the non-stationary GEV distribution should not be constructed with any covariate with the sole criteria that the extreme rainfall series has a non-stationary component.

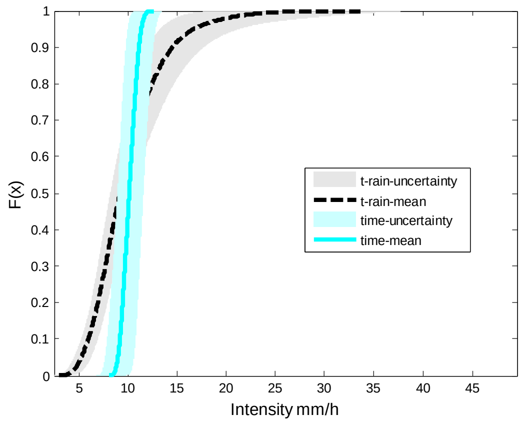


Fig. 1.7: The covariate and parameter uncertainty in Hyderabad city 12-h duration extreme rainfall 10-year non-stationary return levels.

Most of the published prior studies related to the rainfall IDF curves assumed stationarity and the stationary extreme value theory is not capable of encompassing future rainfall changes (due to climate change). The capability of covariate based non-stationary rainfall IDF curves in encompassing future rainfall changes is studied using CMIP5 RCP scenarios. The results indicate that the return period of an extreme rainfall for a city such as Hyderabad is reducing. In other words, if the IDF curve developed from the stationary model is used for an infrastructure design, the drainage networks will fail more frequently than its actual design. The non-stationary IDF curves developed by modelling trends in the observed extreme rainfall estimate return levels reasonably well for at least the next fifty years and can be used to design adaptation strategies. Therefore, it is suggested that the IDF curve developed by modelling trend in the observed rainfall is an appropriate choice for designing infrastructures which have a design life of less than 50 years.

The issue of stationarity is also embedded in most of the available weather generators that consider the extreme rainfall series. To incorporate non-stationarity in the extreme rainfall series while simulating long record of rainfall series for hydrological modelling and water resources planning applications, a semi-parametric stochastic weather generator is developed. The proposed weather generator can simulate rainfall for contemporary and the future by extrapolating non-stationary statistical model parameters. This new weather generator also aims at generating extreme rainfall conditions adequately. Therefore, the developed weather generator is useful for flood risk management decisions, and urban flood assessments.

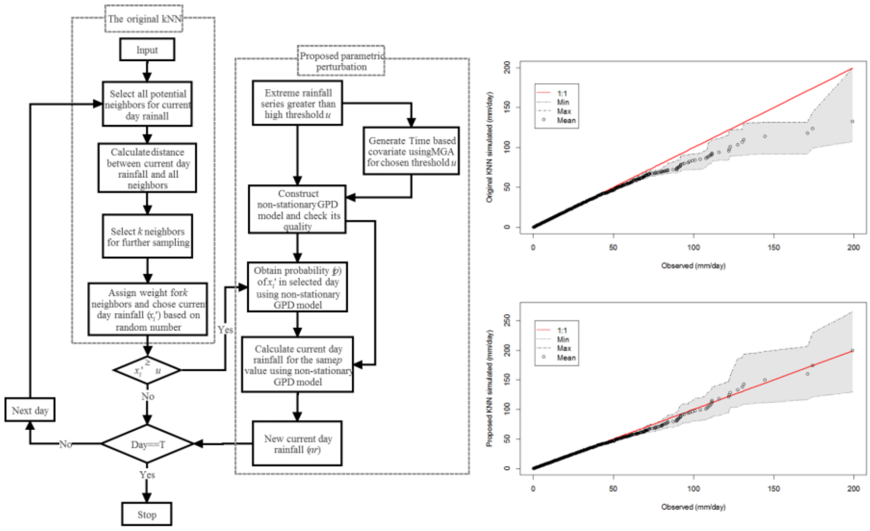


Fig. 1.8: The methodology of the proposed weather generator. Results of available and proposed weather generator are shown in the right-top and right-bottom panels respectively.

1.2.3 Controlled Watershed in IISc Campus, Bangalore

IISc being the lead institute for this project has a controlled watershed within which the development, calibration and validation of a hydrological model is carried out for half of its total area (192 acres). Fine resolution (0.2 m x 0.2 m) terrain data is acquired using LiDAR technology and the calibration of the models is achieved by the sensors installed at the outlet of the drainage network. The LiDAR survey outputs are shown in Fig 1.9. The SWMM of controlled catchment in IISc is shown in Fig. 1.10. Water level sensor installed at the outlet of the drainage network which is used for the rainfall runoff modelling of the IISc Catchment is shown in Fig. 1.11.

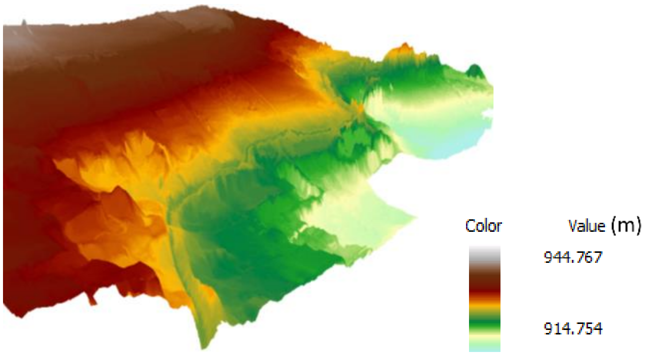


Fig. 1.9: The LiDAR data of resolution 0.2x0.2 m of the controlled watershed in IISc. The data is processed and incorporated into the 2D Overland flow and SWMM Model.

Fig. 1.10: The SWMM of controlled catchment in IISc

Fig. 1.11: Water level sensor installed at the outlet of the drainage network which is used for the rainfall runoff modelling of the IISc Catchment.

1.2.4 2D Overland flow model

For the controlled watershed in IISc, the hydrodynamics of overland flows are modelled as 2D shallow flows using the diffusive waveform of St. Venants equations. The irregular shape of the overland flow surface is represented by an approximate shape that resembles the actual shape of the catchment, square grids of uniform size. This often results in discontinuities in spatial lattice along the principal directions. Numerical solutions for the finite volume formulation of partial differential equations are obtained by finite difference method. Since the governing equation is based on conservation principles, a finite volume type formulation is used. In addition, the effects of land use land cover pattern in overland routing is explicitly studied. For example, the change in overland routing pattern due to the change in terrain is illustrated in Fig. 1.12.

Illustration of overland routing modified by highly pervious areas

Illustration of overland routing modified by highly impervious areas

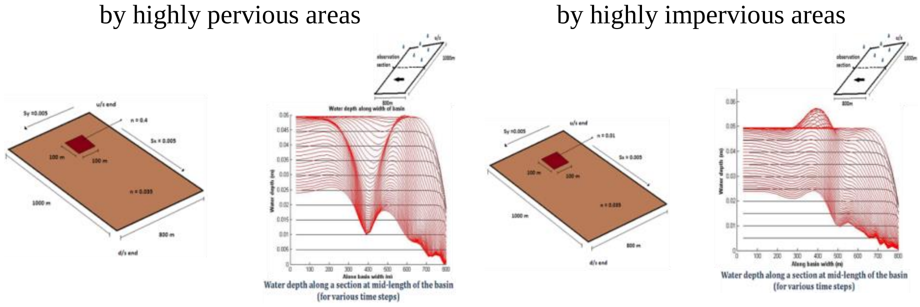


Fig. 1.12: Illustration of the change in overland routing pattern due to the change in terrain.

1.2.5 Laboratory Setup

The upstream section of MadivalaKere is modelled in the Experimental Laboratory Setup. Total storm runoff of AreKere catchment, HulimavuKere catchment and Gottigere catchment contributes to MadiwalaKere catchment, which has high turbulent flow and gravity flow. The flow analysis in prototype (BH554) is carried out using Experimental data obtained from model and numerical (CFD) flow analysis. The experimental model results are converted into prototype by using scale ratio parameter. The scaled model is consisting of a rectangular drain of 10 m x 0.5 m and height of 0.61m. The rectangular drain is of tilting type. A tank and a reservoir arrangement are provided for re-circulation of water in the drain. Two baffles are provided in the tank to minimise unsteadiness of water. In order to prevent flow separation, curvature is provided in the tank near the drain approach. From the drain, water finally drains into the reservoir located at the extreme end of the drain. The water is fed to the tank with the help of a 0.1 m diameter delivery pipe. A 15HP centrifugal pump is used for delivery in the pipe. The flow rate is regulated by means of a valve located on the delivery line. A sharp-edged orifice meter is installed in the delivery line. For the orifice, standard D-D/2 tapings are used for pressure drop measurements. A mercury-water manometer is provided for pressure drop measurement across the orifice. The details of experimental setup are shown in Fig. 1.13.

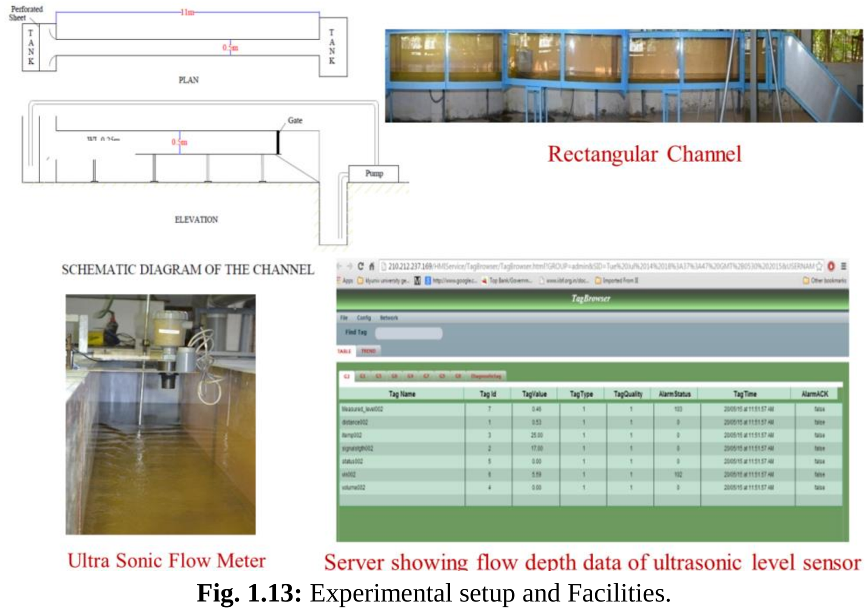


Fig. 1.13: Experimental setup and Facilities.

1.2.6 Hydrologic modelling of Bangalore and Hyderabad cities

Different hydrological models such as SWMM, HEC-RAS and MIKE Flood/ MIKE Urban models are developed (setup) for the Bangalore and Hyderabad cities. Key results of hydrological modelling are as follows.

- Flood inundation maps created using 2D routing for various intensities of rainfall that typically occur for different durations. A prototypical flood inundation map of Bangalore and Hyderabad cities are shown in Figs. 1.14 and 1.15 respectively.
- Critical overflowing drains are identified in the storm network in turn to identify the flood-prone localities.
- Peak runoff and depth of runoff from each catchment is obtained to identify the most vulnerable catchment and to suggest necessary mitigation measures.

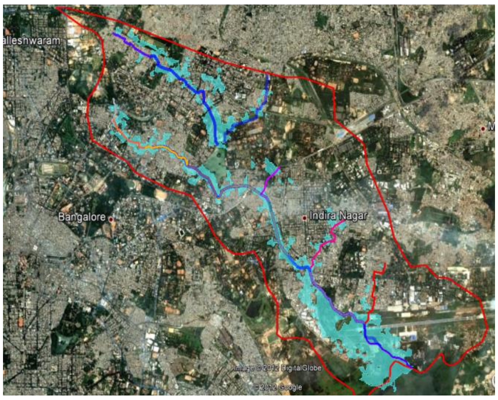


Fig. 1.14: A flood inundation map of Bangalore city superimposed over the Google map.

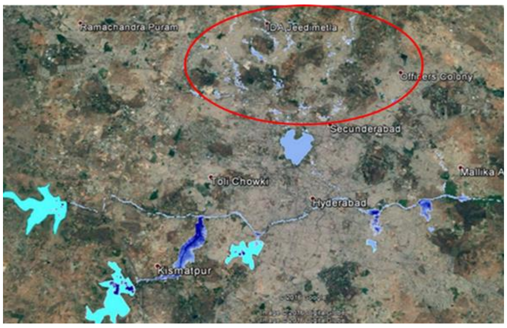


Fig. 1.15: A flood inundation map of Hyderabad city superimposed over the Google map.

1.2.7 A tailor made hydrological model

The hydrologic models are used as tools for various applications of watershed management. However, not many models are designed for Indian catchments. As a part of this project, a tailor-made model is developed aimed to suit Indian conditions at BITS, Pilani- Hyderabad campus. Computer program HYDROL in PYTHON environment for Indian conditions is developed and is dynamic in nature, Screenshot of the model are shown in Fig. 1.15. The code has the flexibility to handle multiple catchments. Computer program is developed for two modules; runoff, infiltration and routing. HYDROL was developed to accommodate different methods of rainfall- runoff processes, where each method has its own pros and cons and can be optimally used based on user's need and catchment conditions. A user manual and technical manual is developed to enable the user for model application. The model has flexibility so as to be adapted for any Indian catchment.

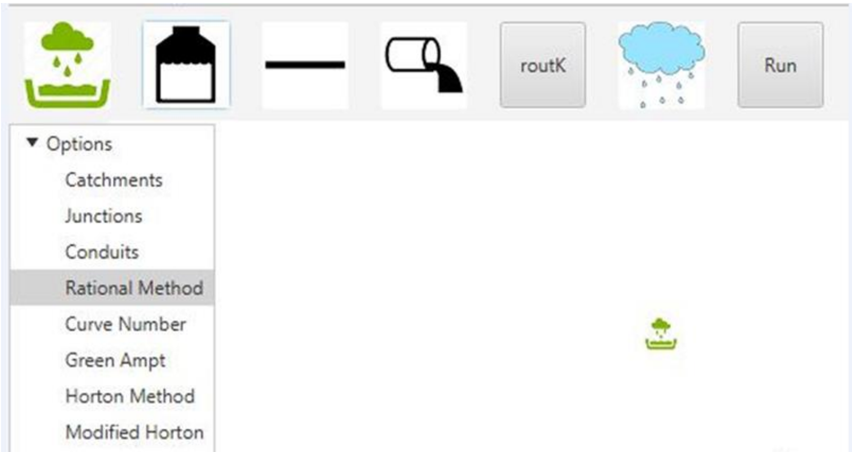


Fig. 1. 16: The drawing window of HYDROL model.

1.2.8 Local Climate Zone (LCZ) classification for Hydromet forecasting

The Challenge: A major challenge of extreme weather forecasting in urban areas is the underrepresentation of the local or regional influences of the urban areas of interest. Weather forecasting is essentially an initial value problem, and misrepresentation of the regional heterogeneities in land use and land cover (LULC), and the consequent land-atmospheric feedback, cascades to errors in local and regional extreme rainfall prediction. Currently, most numerical weather prediction (NWP) models are good for developing regional and large simulations but for urban flooding, urban scale weather forecasts are needed which have been lacking for the Indian conditions.

The objective, therefore, was to develop components for community NWP forecasting models that can be applied for Indian cities. Taking the widely-used Weather Research Forecasting (WRF) model as the base, the challenge was to adapt the model for high resolution (sub km) grid spacing runs. For developing urban scale NWP forecasts, even with the availability of high-resolution LULC or LiDAR datasets, there is a need for a robust methodology to incorporate these datasets as an input into (NWP)/mesoscale weather forecasting models. Additionally, the corresponding dynamic, thermal and radiative properties (e.g. albedo, emissivity, roughness length, specific heat capacity etc.) of the land cover types from these datasets need to be parameterized into the model.

Current approach used in weather models for representing urban areas such Bangalore City have been to based on a simple parametrization that alters surface albedo, thermal capacity, hydraulic conductivity, and roughness. These variables and the corresponding parameterizations are embedded within appropriate land surface models (LSMs) which have water, temperature, radiation, balance and predictions in a prognostic manner. That is, the atmospheric information such radiation, winds, temperature, humidity, and rainfall are needed as inputs to the LSM to generate surface energy balance, and hydrological responses such as surface and deeper soil moisture/ temperature fields. These surface variables in turn modulate the development of boundary layer, regional thermals, winds, cloud convection and ultimately the rainfall timing, amount, location, and intensity. Changes in LULC, impact the hydrological balance of the region and could potentially result in urban flooding. The removal of vegetation and soil in the process of urbanisation results in modified evaporation, reduced percolation and ultimately, increased runoff. Thus, variability in the intensity and duration of rainfall impacts the peak discharge, inundation and soil erosion levels. Further, since urbanisation also implies increasing population, the flood risk, vulnerability and consequence of such events should they occur, drastically increases. Therefore, a critical factor in developing high-resolution urban NWP is the representation of landsurface and the associated parameters.

This challenge of representing the landsurface that can be linked within high-resolution WRF was undertaken using Bangalore City as the prototype. Over the years, Bangalore has overseen unprecedented urbanisation and increase in anthropogenic activity. Observations conducted across the city for the past three decades have indicated an increase in the variability in the intensity, duration, frequency and spatial occurrence in rainfall- and hence flooding.

What was done? World Urban Database and Access Portal Tools (WUDAPT) facilitates a globally accepted standard of representing the LULC as local climate zones (LCZs or Urban Climate Zones/UCZs for urban areas). This classification comes with a coherent and consistent description of the range building, canopy and vegetative parameters pertinent to the form and function of urban regions. WUDAPT is community driven, where researchers across the world can generate and submit these UCZ maps to an openly accessible portal. In addition to the datasets and associated parameters of the classified types, recently, a structured methodology has been developed to incorporate the LCZ types into WRF. Further, the development of urban canopy models such as the Building Effect Parameterization/ Building Energy Model (BEP-BEM) within WRF parameterizes the sub-grid scale impacts of the urban regions of interest on to mesoscale weather forecasts. Through this project, the Indian cities were linked in with the WUDAPT team, and a new urban WUDAPT map for Bangalore was created.

How? A brief description of the methodology of generation of LCZ maps is summarised here. First, Landsat satellite imageries for the Bangalore and neighbouring region were obtained from US Geological Services website. Using Google Earth, a handful of sample polygons where the trainer is confident that the region belongs a specific LCZ type, These polygons are used as training areas and defined over the Landsat imagery for each of the LCZ types based on the description provided in Stewart and Oke (2012). Using an iterative process, the entire region of interest is classified into LCZs using SAGA-GIS using a clustering algorithm that learns from the training areas provided.

Fig. 1.17 highlights the difference between the default land cover type used currently in WRF and the LCZ WUDAPT map generated for Bangalore. As can be noted, the default landcover map captures the broad land features that are sufficient for conducting regional scale forecasting. The newly developed WUDAPT LCZ map shows the granularity of the urban landcover and the different land classes that capture the urban morphological variability realistically.

The next aspect was to link this land map within the NWP framework. This meant, that within the WRF model, the number of urban classes are increased from the default to ten UCZs. The information from the LCZ map generated using SAGA-GIS is used to modify the default land use indices in WRF. Further, the urban parameter table in WRF is used to specify parameters such as urban fraction, building heights, heat capacity, thermal conductivity and anthropogenic flux pertinent to the region of interest. The data compiled in Stewart and Oke (2012) offered a range of values for each of these LCZ types and the median value of the same was used if local information on the parameters could not be estimated with high subjective confidence. WRF was then used with the Noah LSM or in conjunction with BEP-BEM where the subgrid scale urban impacts are parameterized based on the input provided the urban parameter table.

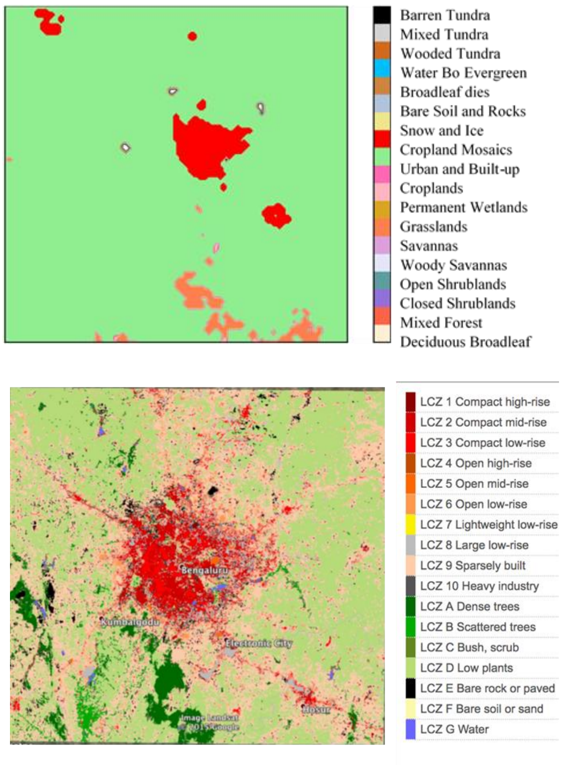


Fig. 1.17: (a) The default representation of Bangalore's land cover in WRF. Urban areas are represented by a single category with this representation. (b) The classification of Bangalore using the Local Climate Zone classification. Ten different urban climate zones are used to describe the city.

Implications

- Introduction of WUADPT LCZ mapping for Indian cities and the interface for WRF has opened an avenue for city scale NWP and rainfall forecasts. The project and efforts which have been started with Bangalore as a prototype have been since replicated for other cities across India including Hyderabad, Chennai, and Delhi.
- The improved model and the model representation has higher fidelity in simulating rainfall over urban regions and thus assists urban flood forecasting efforts.
- A related effort undertaken was to understand the spatial patterns of heavy rainfall around Bangalore and developing a climatology and morphologic analysis regarding which type of rain systems affect the city and the heavy rain or storm intensification are expected.

1.2.9 Development of sensors

As a part of the project, CDAC, Thiruvananthapuram developed rainfall and water level measurement sensors. The rainfall sensor and level sensor are tested at Indian Meteorological Department (IMD) Thiruvananthapuram (Fig. 1.18) and Kerala Water Authority-Thiruvananthapuram respectively. These developed sensors were installed at NIT Warangal for two months (July-August 2016).

Rainfall Sensor testing at IMD | Level and Rainfall Sensor testing at NIT Warangal

Fig. 1.18: The rainfall and level sensors developed by CDAC, Thiruvananthapuram.

Similarly, Spatika, one of the project partners, developed a tailored low-cost level sensors. These sensors are currently installed in the Bangalore pilot study area (Fig. 1.19). Data from these installed sensors being acquired on a real-time basis.

Gottikere Inlet | Hullimavu kere Inlet | Hullimavu kere Outlet

Fig. 1.19: Sensors installed in the Bangalore pilot study area.

1.3 Other Notable Results

1.3.1 Curricular Impact

Prof. P. P. Mujumdar has been offering the course "Urban Hydrology" as an elective for the Masters and Research Scholars at IISc, Bangalore, India. As a part of this course the students were taken to KSNDMC for a field visit.

New modules on simulation of urban drainage system and design of urban drainage design are included in the Hydraulic and Hydrologic Design Laboratory Course of M.Tech program in Water Resources Engineering at NIT, Warangal, India.

In BITS-Pilani, Hyderabad campus, Urban Hydrology course has been approved by the Senate and will be offered in the coming semesters. In addition, new modules on urban flood forecasting and mitigation strategies; urban flood planning in changing climate; description of general circulation models and downscaling approaches are introduced in the existing courses in BITS-Pilani, Hyderabad campus.

1.3.2 Outreach

A rapid assessment report on Chennai Floods is published and available online at http://www.icwar.iisc.ernet.in/chennai-floods-2015/. Further, as a part of this project, the team is organised four Monsoon schools, two short-term courses, two workshops and training program. In addition, one more Monsoon school is scheduled during July 3 – 8, 2017 at IISc, Bangalore. Following is list of outreach activities conducted by different institutes of the team.

1. Monsoon School on Urban Floods- August 4-9, 2014 at IISc, Bangalore.
2. Monsoon School on Urban Floods-August 24-29, 2015 at IISc, Bangalore.
3. Workshop on Integrated Urban Flood Management in Hyderabad: Technology Driven Solutions, October 31, 2015 at BITS-Pilani, Hyderabad Campus.
4. Training Program on Integrated Urban Flood Management: Technology Driven Solutions, November 20-21, 2015 at BITS-Pilani, Hyderabad Campus.
5. Short Term Course on Urban Flood Modelling, December 10-12, 2015 at NIT Warangal.
6. Monsoon School on Urban Floods- August 22-27, 2016 at IISc, Bangalore.

7. Short Term Course on Urban Flood Modelling- November 21-26, 2016 at NIT Warangal.
8. Workshop-cum-Training Program on Urban Flood Management: Technology Driven Solutions, during March 3-4, 2017 at BITS-Pilani, Hyderabad Campus.
9. Monsoon School on Urban Floods- July 3-8, 2017 at IISc, Bangalore.

1.3.3 Contributions to relevant United Nations' Sustainable Development Goals

Goal 11: Make cities and human settlements inclusive, safe, resilient and sustainable: This project recognises the importance of sustainable development and management of urban infrastructure, viz. storm water drains, lakes/reservoirs, infiltration ponds etc. The adequacy analysis of the storm water drains was performed in the pilot study areas and the measures to avoid flooding are listed. Long term adjustments in the hydrologic designs for urban flooding are recommended based on likely changes in frequencies of high intensity precipitation. The project also aims at understanding the resilience of the infrastructure and the community in case of heavy flooding in the cities and the lists of post flood response measures are developed. We have partnership with the Government authorities, local authorities and communities to implement the strategies and sustainable measures which are developed as a part of the research work carried out in this project. For example, with the research outputs from IISc, KSMDC has carried out detailed watershed analysis for all the major three watersheds in Bangalore viz., Koramangala Chellagatta Valley, Vrishabhavathi Valley and Hebbal Valley. And, the SWMM hydrological model outputs were mapped for flood inundation maps using Inp.Pins, a tool to integrate GIS and SWMM model and to get a flood map. These flood maps were considered as input for Flood forecast and early warning in the city. With all the technical inputs available from the model outputs, a good network of information dissemination system has been established at KSNDMC. The information about the rainfall forecast for the city and respective flood forecast and dynamic flood early warnings is being given to all the administrative Departments like BBMP, BESCOM, BMTC, BWSSB, TRAFFIC POLICE, CIVIL DEFENCE and NDRF. From the administrative officers the flood early warning will be shared with the field level officers to take better action and control over the upcoming flood disaster in the city. The Rain /flood forecast and an early warning will be given to all the concerned administrative departments 8 hours in prior which make the system to have preparedness measures and better handle the flood disaster situations in the city. Currently, the dissemination is being carried through

- Website: www.bengaluruvarunmitra.info
- WhatsApp Group: Be ready Bengaluru (with all the officers from all line department in the city including the chief secretary of Government of Karnataka).
- Twitter – https://twitter.com/karnatakasndmc
- Facebook- https://www.facebook.com/KSNDMC/
- E-Mails - dmc.kar@gmail.com
- Customised mobile SMS: Rain Forecast & Daily Rainfall SMS to customised Mobile numbers.

Goal 13. Take urgent action to combat climate change and its impacts: As a part of research work, out team has worked on assessing the impacts of climate change on flooding and on the urban infrastructure. Expected changes in the frequencies and magnitudes of high intensity precipitation are assessed using climate models. Different methods are used in downscaling and disaggregating the climate model outputs to bring down to the urban scale as a part of research work. These likely changes in the extreme precipitation are used in flood routing models to examine the adequacy of the existing infrastructure, and adaptive measures are recommended to cope with the changing frequencies of extreme events.

1.4 How have the following aspects of your team changed during the ITRA project period:

1.4.1 Average work quality and quantity of participating groups from different institutions

This project has given an opportunity to both faculty and students to interact with other members of the team, other ITRA teams and mentors. This has enhanced both the quality and quantity of the research work of participating groups from different institutions.

1.4.2 Variance of work qualities and quantities of participating groups from different institutions

The rigorous evaluation of the project and the constructive feedback that we received from the mentors provided the driving force to the team to do better. In addition, these comments also expanded the research interest of participating groups from different institutions.

1.4.3 Interest shown by students/others in your group's activities

As a team, students were interested to discuss their research problem among teams and with panel members. Poster presentation inculcated more interest to present their work. Students from both undergraduate and postgraduate level were involved in the project. Eight M.Tech. students and two B.Tech. students have shown interest in the project and have carried out their dissertation work in urban flood modelling and management. Three undergraduate students of NIT Warangal have worked on the problem of developing level sensors for monitoring water levels in urban storm water drains. Notably, Dr. M. Sanskriti attended the Monsoon school organised by IISc, Bangalore during August 4-9, 2014. Later, she got motivated in working on the project and joined as one of the collaborators.

1.4.4 Teamwork

One of the major contributions of this ITRA project is that it brought together students and faculty from various Institutions to work as one team. The bond that developed between the all the members in the team will continue beyond the ITRA project. Following are some of the key activities that happened during the ITRA project period.

- Skype meeting among all team members is regularly conducted at every 3 months.
- A webinar training program was conducted by IISc on 28th April 2016 to train KSNDMC, BITS Pilani Hyderabad and NIT Warangal on floodplain mapping using the software like SWMM, ArcGIS and inp.PINS Extension.
- With the help of IISc, the KSNDMC developed a SWMM model for the Bangalore city and it is currently being used in giving flood warning through WhatsApp group to administrators.
- A workshop on "Integrated Urban Flood Management: Technology Driven Solutions" was held on September 20th, 2016 at IISc Bangalore where Prof. Mujumdar presented the works done in IUFM Project.
- Three days training program on Mike zero, Mike Flood and Mike Urban is organised during July 11-13, 2016 at NIT Warangal to train project associates and research scholars of the project.
- Seminars by the PhD students among IISc, NIT Warangal and BITS Hyderabad are conducted every month over Skype to discuss their respective research works which help in improving the quality of work.

1.4.5 Research drive

ITRA inculcated research drive by regular meetings, panel suggestions and discussion with mentors. Discussion and sharing knowledge among teams also created research interest.

1.4.6 Linkages with industry/other users

During the ITRA project period, following linkages has happened between ITRA institutes and other government organisation.

- IISc, Bangalore has entered into MoU with Karnataka State Natural Disaster Monitoring Centre (KSNDMC) as part of this project.
- IISc, Bangalore has entered into MoU with Bruhat Bengaluru Mahanagara Palike (BBMP) as part of this project.
- NIT Warangal has entered into MoU with Greater Hyderabad Municipal Corporation (GHMC) as part of this project.

1.4.7 Work environment/culture

Good access between research scholar and PIs of the project are created. Necessary models, computing facilities and laboratory facilities are made available.

1.5 How has the ITRA project affected your team's vision and strategies? What lessons have you learnt? How has the project been different from others that you have been involved in? How do you feel you could sustain the team or and any other momentum you may have built, and influence larger research community in India? What is the Road Ahead for your project and the field?

ITRA extended the scope of the project in multi dimensions involving institutions and experts from various specialisation, where urban flooding could be addressed in all the aspects. One of the main strength of the ITRA project is the periodic evaluations that were conducted every six months. The Review and Evaluation Workshop meetings were very different from other project related reviews. These meetings have a good technical exchange from professors and industrial experts from different parts of the world. The rigorous evaluation of the project and the constructive feedback that we received from the mentors provided the driving force to the team to do better. It helped the team to develop real time flood forecasting and flood alert system by collaborating with government agencies. ITRA learned to work as a team with different people from the various institution on a same platform. As a team, different aspects of urban flooding are addressed and extensive research takes places in the area, resulting in outreach activities, training programs and publications which may influence larger research community in India. We look forward to sustaining this momentum and continue to work with the other team members.

1.6 What aspects of the ITRA model or its implementation so far could be improved and how?

The poster sessions are meant for providing an opportunity to the research scholars to present their work. However, these poster sessions were not effective. Awards like the best poster, the best researcher could be introduced to motivate the students to do better.

1.7 Description of Data Produced/Demos/Field Tests/Other results and how to access them

Details of the project, work done by various teams, student poster, presentation and any necessary data can be accessed from urban flood official website http://itraurbanfloods.in/.

1.8 10 most representative and noteworthy publications.

1. Chandra Rupa, Ujjwal S. and Mujumdar P.P. (2015) Model and Parameter Uncertainty in IDF Relationships under Climate Change, Advances in Water Resources, 79:127-139.
2. Agilan V. and Umamahesh N. V. (2015). "Detection and attribution of non-stationarity in intensity and frequency of daily and 4-hour extreme rainfall of Hyderabad, India", Journal of Hydrology, 530: 677-697.
3. Agilan V. and Umamahesh N. V. (2016) Is the covariate based non-stationary rainfall IDF curve capable of encompassing future rainfall changes? Journal of Hydrology, 541-Part B:1441–1455.
4. Agilan V. and Umamahesh N. V. (2017) What are the best covariates for developing non-stationary rainfall intensity-duration-frequency Relationship? Advances in Water Resources, 101:11–22.
5. Agilan V. and Umamahesh N. V. (2017) Non-Stationary Rainfall Intensity-Duration-Frequency Relationship: a Comparison between Annual Maximum and Partial Duration Series. Water Resources Management, 31(6):1825–1841.
6. Agilan V. and Umamahesh N. V. (2017) Modelling nonlinear trend for developing non-stationary rainfall intensity–duration–frequency curve. International Journal of Climatology, 37(3):1265–1281.

7. Chandra Rupa and Mujumdar P.P. (2017), Quantification of Uncertainty in Spatial Return Levels of Urban Precipitation Extremes, ASCE Journal of Hydrologic Engineering, In Press.
8. Agilan V. and Umamahesh N. V. (2017) Covariate and parameter uncertainty in non-stationary rainfall IDF curve, International Journal of Climatology, In Press.
9. Chandra Rupa and P.P. Mujumdar (2017), Disaggregation of Precipitation Extremes Modelled by Generalized Pareto Distribution, Submitted to Advances in Water Resources (under review, manuscript number: ADWR_2017_230).
10. Chandra Rupa and P. P. Mujumdar (2017), Dependence structure of urban precipitation extremes, Submitted to Advances in Water Resources (manuscript number: ADWR_2017_458).

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1.10 Biographical Sketches of each author

Prof. P P Mujumdar is currently serving as a Professor in the Department of Civil Engineering and as Chairman, Interdisciplinary Centre for Water Research at Indian Institute of Science, Bangalore. He has earlier served as the Chairman of the Department from November 2006 to December 2010 and as KSIIDC Chair Professor from August 2012 to July 2015. He holds Associate Faculty positions in the Divecha Center for Climate Change and Center for Earth Sciences at IISc Bangalore. He has served as the Chairman of the Water Resources Management section of the International Association for Hydro-Environment Engineering and Research (IAHR), and as a reviewer for the Assessment Report 5 (AR5) of the IPCC. Prof. P P Mujumdar is a recipient of the Alexander von Humboldt Medal of the European Geosciences Union (EGU), the Distinguished Visiting Fellowship of the Royal Academy of Engineering, UK and the CSIR-NGRI-AHI Indian National Hydrology Lecture Award. He is a member of the Editorial Board of the journal Advances in Water Resources, has served as a member of the Editorial Board of the journal Water International, and has been a member of several state- and national- committees dealing with urban flooding, and operational and environmental aspects of water resources in India. His Research interests include Stochastic Hydrology, Water Resources Systems, Surface Water Hydrology and Urban Hydrology. His areas of professional consultancy include urban storm water drainage, floodplain management, river basin planning, reservoir operations, lift irrigation, hydropower development and impact assessment of water resources projects. He is a Fellow of the Indian National Academy of Engineering (INAE), a Fellow of the Indian Academy of Sciences (IASc) and a Fellow of the Indian National Science Academy (INSA). He has more than 100 papers in international/ national journals and conferences.

Prof. M. S. Mohan Kumar is currently serving as a Professor in the Department of Civil Engineering and as Chairman in Indo-French Cell for Water Sciences at Indian Institute of Science, Bangalore. He holds Associate Faculty positions in The Center for infrastructure, Sustainable Transportation and Urban Planning (CiSTUP), Robert Bosch Centre for Cyber Physical Systems and Interdisciplinary Centre for Water Research (ICWaR) at IISc Bangalore. His research areas are Ground water flow modeling, Flow through vadose zone Contaminant transport modelling in porous media, Flow in canal networks Multiphase flow modeling Water quantity / quality modeling in distribution networks etc. Prof. M. S. Mohan Kumar is a recipient of the Alexander von Humboldt Medal of the European Geosciences Union (EGU), Indian National Science Academy and Japanese Society for Promotion of Science Fellowship, IBM faculty award. Amulya & Vimala Reddy Lecture Award conferred by Indian Institute of Science in the field of sustainable technology and Prof N C Modak Memorial Lecture award by Institution of Engineers (India). He has more than 100 papers in international/ national journals and conferences.

Prof. K. Srinivasa Raju is Professor, Department of Civil Engineering, Birla Institute of Technology and Science, Pilani Hyderabad Campus. He completed M.Tech from IIT Chennai and Ph.D from IIT Kharagpur in water resources engineering. He worked with Prof Lucien Duckstein in the field of Multicriterion Decision Making (MCDM) with reference to Water Resources Planning during his post-doctoral programme. His research interests include Climate Hydrology, Water Resources Systems, MCDM and soft computing applications in Water Resources Engineering. He has published more than 100 papers in various reputed journals and conferences and reviewed numerous papers for various international journals of repute and listed among 150 most cited civil engineering authors.

Prof. N. V. Umamahesh is currently serving as a Professor in the Department of Civil Engineering at National Institute of Technology, Warangal, Telangana, India. He has earlier served as the Head of the Department from July 2008 to June 2010, as Dean, Students' Welfare from July 2012 to March 2013 and as Dean, Planning & Development from April 2013 to June 2014. His area of specialization is Water Resources with a focus on Water Resources Systems, Hydrologic Modelling, Irrigation Management, Water Quality Modelling and Management, Applications of Soft Computing Techniques and Modelling Impacts of Climate Change. Prof. N. V. Umamahesh is a recipient of the Jalamitra award by the Govt. of AP in 2003 for successful implementation of Watershed Development Project in Warangal District, G M Nawathe award for the paper presented at Hydro 2004 (annual conference of the Indian Society for Hydraulics) and Central Board of Irrigation and Power (CBIP) award. 7 Ph.D. students have graduated with Prof. N. V. Umamahesh as their advisor. He is currently advising 7 Ph.D. students at NIT Warangal. He has published more than 50 papers in various reputed journals and conferences.

Dr. S. Rominus Valsalam is currently working as the Associate Director & Head of the Department of Control and Instrumentation in the Centre for Development of Advanced Computing (CDAC), Thiruvananthapuram. His R&D experience encompasses System Design & Development, Engineering, Installation and Commissioning of Computerised Control and Instrumentation and SCADA systems for Thermal Power Plants, Hydroelectric Power Plants, Oil Installations, Integrated Steel Plants, Cement Plants, Process and Petrochemical Industries. He has published 45 papers in International and National journals and conferences. He is a Member of Institution of Electrical and Electronics Engineers (IEEE) and a fellow of The Institution of Engineers (India).

Dr. G S Srinivasa Reddy is currently serving as Director of Karnataka State Natural Disaster Monitoring Center (KSNDMC) since January 2015. He has earlier served as scientific officer in KSNDMC from 2008-2015. He holds Junior scientific officer position in KSNDMC from 1996-2008. He joined Drought monitoring center now KSNDMC as Project scientist from 1990-1996. He was being Junior and Senior Research fellow under UGC NET scheme for 5 years (1985-1990) Dr. G S Srinivasa Reddy is serving as member of Geological society of India. Member in state level weather watch committee, state level coordination committee for crop insurance, state level technical committee on sujala watershed, Technical committee on climate change initiatives (EMPRI). His area of professional consultancy includes Hydro geological studies for many private and Government projects all over India.

Dr. Dev Niyogi is a Professor with joint appointment in departments of Agronomy and Earth, Atmospheric and planetary Science at Purdue University, USA; and Visiting appointment with Indian Institute of Technology, Bombay. Dr. Niyogi teaches an undergraduate Weather and Climate course for non-meteorology majors and an advanced Land Surface Modeling course at Purdue, and as a State Climatologist is actively engaged in helping decision makers work with different climate and climate change related issues. Dr. Niyogi's research is funded through a variety of competitive federal research grants- NSF, NASA, Joint Center for Satellite Data Assimilation, DOE, and USDA/NIFA. He has developed over 30 successful research grants. Since 2009, Dr. Niyogi received Purdue 'Seeds for Success' award, Million Dollar research award, and the University Faculty Scholar recognition, the NSF's CAREER award, the USDA NIFA Partnership Award. 9 Ph D and 15 MS students have graduated with Dr Niyogi as their advisor or coadviser. He is currently advising or coadvising/mentoring 1 Postdoctoral Student, 6 Graduate Students (4 female, 2 male), 2 Undergraduate Students, 1 Technician/ Scientific Associate, 2 International Visitors. Dr. Niyogi has coauthored over 150 papers for peer – reviewed international journals, 13 book chapters, and over 150 conference proceedings or abstracts for professional conferences such as the AMS and AGU annual meetings.