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Urban Floods : An Evolving Engineering Challenge

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Abstract : Globally, urban flooding is the biggest and severest natural disaster faced year after year. Managing floods in cities is evolving as an engineering challenge due to several factors. Urban flooding cannot be managed in isolation and responses to potential impacts of floods are complicated by interlinked environmental and socio-economic changes. To manage flooding, an integrated framework is required in which a leap from the current, poorly managed system to a highly efficient and technology-driven automated management is achieved. Such an integrated approach should provide clarity regarding the flood management, risk, vulnerability and resilience as well, and how the interactions across various systems can be achieved. This paper discusses about challenges and various sights in modelling, managing floods and lists different structural and structural measures to attain a sustainable urban drainage system. An integrated approach is shown for urban planning and water management for a viable and sustainable environment, bringing together researchers, government agencies, policy makers and stake holders. A city scale pioneering and experimentation are essential to build resilience through bottom-up initiatives that can shape strategy and policy development.

Keywords: urban flooding, integrated approach, flood risk management, sustainability.

1 Introduction

The global population is increasingly getting concentrated in cities, with more than 50% of the world's population currently living in urban areas (UN, 2011). The United Nations urbanization prospects (2005) reported that twentieth century is observing rapid urbanization, globally. This population growth has led to urban sprawl with rapid increase in urban areas. Urbanization, leading to changes in land use/land cover, has created substantial contrasts in land surface characteristics between urban areas and surrounding rural areas, manifesting in different hydrologic signatures. Advances in the science and practice of urban hydrology have therefore been significant over the last two decades. New methodologies for modelling urban precipitation have emerged, with the aim of addressing the challenges of modelling urban flooding precisely. Despite these advances, management of flood in urban areas is still a challenge to policy makers in many countries. This paper discusses on the issues why management of urban flooding is an engineering challenge and give insights of an integrated approach to manage flooding in cities.

2 Why Urban Flooding is a Challenge?

It is well understood that urbanization alters the hydrologic response of a catchment. However, precise modeling of the hydrologic response and then the assessment of the flooded areas, including the management of flooding in cities is still a major challenge for various reasons. Following are some of the challenges in modeling and management of urban flooding.

2.1 Availability of data

Flood and environmental risks are always dependent on correct designs, which in turn depend on the quality and quantity of data. Data requirements for urban applications are different

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compared to applications in rural catchments (Schilling, 1991). Especially, fine resolution data in both temporal and spatial scales are required. Urban infrastructure design and evaluation is in general based on hydraulic simulations using short-duration, local precipitation data as input. For example, a sustainable urban storm water drainage system requires handling a short duration, low frequency precipitation event without excessive flooding or other problems (Olsson et al., 2012). Most urbanized catchments are relatively small, with low catchment response times, typically of hourly to sub-hourly scales. Therefore, the precipitation data from sub-hourly to hourly time scales are required for assessing urban runoff behavior. However, the availability of precipitation time series recorded at such short time steps is in general sparse leading to uncertainties.

In the urban designs, it is also important to consider the spatial variability of short duration high intensity precipitation events. The areal extent of such events is in general limited, and the events evolve as a nature of convective storms, where, the precipitation producing cells are typically of the order of a few square kilometres in areal coverage and have durations of between 10 and 40 min (Patrick and Stephenson, 1990). However, the data is not recorded at a high spatial resolution leading to high uncertainties in estimations of the spatial variation of precipitation in urban areas. Therefore, understanding spatial variation of short duration events along with uncertainty quantification is also crucial in the urban hydrologic designs.

New research methods have been emerging to quantify the uncertainties due to insufficient quantity and quality of data and propagate the uncertainties in the urban hydrologic designs. For example, methods like Monte Carlo simulations, Bayesian techniques are incorporated to quantify the uncertainties due to insufficient quantity of data in the design precipitation intensities. Fig. 1 shows the Intensity Duration Frequency (IDF) relationships for the Bangalore City obtained from the classical approaches using standard statistical techniques (Maximum Likelihood Estimation (MLE) approach) and from the Bayesian method. It should be noted that the uncertainties in the short duration (at sub-hourly scales) precipitation events are high when compared to that of the high duration, of order daily.

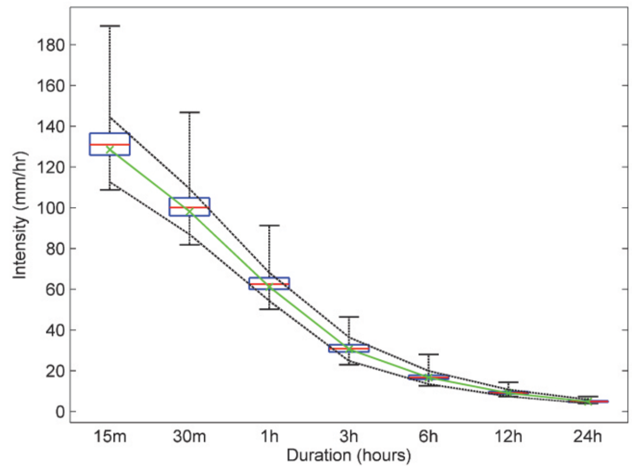

Figure 1: Variation in return levels for 10-year return period for different durations (historical period, 1969-2003) for Bangalore City. Boxplot gives the uncertainty in return levels obtained from Bayesian analysis. Intensity using Classical approach (MLE method) is shown in solid green line; black dashed lines give the uncertainty band using delta method

2.2 Climate change impacts

Although it is evident that urbanization significantly influences the local climate, the climate change also effects the extreme precipitation, adding further complications in modeling the extremes in urban areas. According to IPCC (2012), climate change is believed to increase the frequency and magnitude of the extreme precipitation events. As growing urban communities seek to minimize their impact on already stressed water resources, an emerging challenge is to design for resilience to the impact of climate change, particularly in regard to ensuring secure water supplies and the protection of water environments. For the Bangalore City, short duration precipitation increases considerably in future (Chandra Rupa et al., 2015). Fig. 2 shows the

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

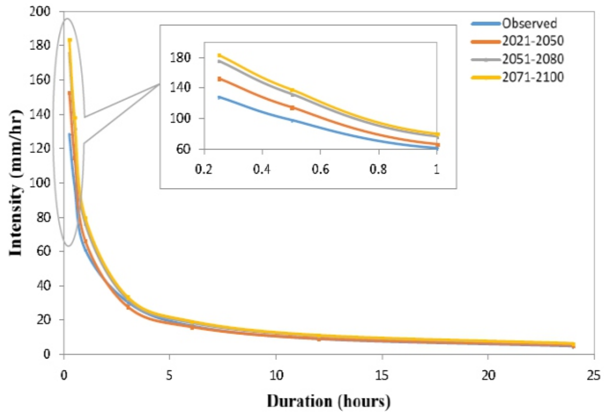

Figure 2: Projected IDF relationships for Bangalore City for RCP 8.5 scenario for 10-year return period (Chandra Rupa et al., 2015)

2.3 Reliable forecasts

Simulating emergent behaviors and predicting precipitation extremes are significant research challenges because the interactions between drivers are highly complex and uncertain. 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.

Therefore, the objective should be to develop components for community NWP forecasting models that can be applied for cities. The widely-used Weather Research Forecasting (WRF) model is considered as the base, and the challenge is to adapt the model for high resolution (sub km) grid spacing runs. For developing urban scale NWP forecasts, 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 models (Mujumdar et al., 2017).

Current approach used in weather models for representing urban areas have been 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. Further, since urbanization also implies increasing population, the flood risk, vulnerability and consequence of such events should they occur, drastically increases (Mujumdar et al., 2017). Therefore, a critical factor in developing high-resolution urban weather prediction model is the representation of land surface and the associated parameters This challenge of representing the land surface that can be linked within high-resolution WRF needs to be undertaken for urban areas.

2.4 Management of urban infrastructure

Despite research issues like assessing the climate change impacts and modelling reliable forecasts, poor maintenance and management of urban water infrastructure is a major cause for flooding in cities. Though reliable forecasts are available, if the drainage system cannot cater the needs of the storm, flooding is inevitable. Besides poor maintenance, some of the other factors which causes flooding are listed in the following sub-sections.

2.4.1 Encroachments

Storm water channels overtops their banks if developments encroach floodplains, obstructing floodways and causing loss of natural flood storage. Drainage systems back up because they cannot cope with the volume of water or are blocked by urban waste. Also, there could be cases where the sewer systems obstruct the natural flow in the drains.

2.4.2 Unplanned urbanization

Over a longer historical period, cities have always successfully adapted to changing environmental conditions and thus have been extremely resilient. Due to the unprecedented growth of population in urban areas in the recent past, cities couldn't adapt to the quick changes. This increase in population has led to unplanned urbanization in most of the cities. Research work by Sheppard (2007) revealed that the spatial distribution of urban population in nearly all 90 cities surveyed is by and large not the result of conscientious planning. This lack of careful planning, or even uncontrolled urbanization, will exacerbate the trend of increasing flood vulnerability of cities due to a combination a) development in areas previously in nonurban use, leading to encroachment and expansion onto flood-prone areas b) redevelopment of built-up areas and infill of the remaining open spaces in already built-up areas, leading to an overall density increase and subsequent increase of surface imperviousness and disruption of natural drainage channels and c) conversion of water bodies (lakes, ponds in low lying areas) to residential layouts (Zevenbergen et al., 2008).

2.5 Extended events of precipitation

The worst flooding occurs after prolonged rainfall when the soil is saturated and the water levels in drains, lakes rise. Then, if an intense rainfall burst occurs, causing a large amount of rain within a brief period, flash flooding may occur with little or no warning. This is one of the reasons for devastating flooding in the Bangalore City during September 1st – 10th, 2017.

3 Integrated Urban Flood Management

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. Consequently, cities losing their capacity to deal with quick changes (like changes in extreme rainfall events) and the ability to anticipate and adapt to slow changes and trends (population increase, climate change) pose new challenges for urban flood management research and touch upon various disciplines (e.g. urban planning, regional economy, etc.). Because urban floods cannot be managed in isolation, there is a need for integrated approaches that address the problem of urban flooding.

Best management techniques and practices are required to achieve a leapfrog from the current, poorly managed state to a highly efficient, technology-driven automated end-to-end management of urban flood, thus overcoming the institutional constraints to a significant extent. An innovative use of sensor and communication technologies coupled with ultra-high resolution real-time nested forecasts of high intensity rainfall, state-of-the-art hydrologic models, GIS and control systems are required for implementable operational decisions in real time. Hydro-meteorological forecasts with sufficient lead times of a few hours to a day or more, need to be developed using a suite of data driven, pattern recognition models as well as process based numerical urban weather prediction models. Forecasts of high intensity rainfall should be converted to flood forecasts with in-situ as well as remote sensed measured data. Measurements from in-situ sensors provide information on rainfall intensity, and geospatial location of water levels, which should be assimilated within the hydrologic models.

A comprehensive GIS driven data base, integrated with the flood forecast models is required to graphically depict flooding in real time at various locations in the city. Control systems algorithms should be developed to provide operational decisions, communicated instantly through internet and/or mobile technologies. Long term adjustments in the hydrologic designs for urban flooding are to be recommended based on likely changes in frequencies of high intensity rainfall. To achieve this, cross-sectional collaborations between hydrologists, climatologists, government agencies and policy makers is required. Through involvement of government agencies, policy makers and with the support of NGOs implementing post-flood management solutions is possible. Involvement of stakeholders is also crucial in achieving a flood free city. A citizen driven portal should be developed to upload digital pictures or tweets on the flood levels, which provides visual, numerical input to complement the sensor data in a bi-directional information flow mode.

A collaborative project titled "Integrated Urban Flood Management in India: Technology driven Solutions" by Indian Institute of Science, Bangalore with other partners from Karnataka Natural Disaster Monitoring Center (KSNDMC), NIT Warngal, ITS Pilani Hyderabad Campus and C-DAC Trivendrum aims at an integrated urban flood management in urban areas (Mujumdar et al., 2017). The project has its focus set on two cities: Bangalore and Hyderabad, and on a controlled watershed in Bangalore. The graphical overview of the project is shown in Fig. 3

Figure 3: Graphical overview of "Integrated Urban Flood Management in India – Technology Driven Solutions"

The key activities carried out towards this project are summarized in following points.

- 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 spatial distribution of return levels of extreme rainfall, are studied. Fig. 4 shows the variation in return levels in and around the Bangalore City. The return levels and the associated uncertainty on the western part of the Bangalore City are higher by 10% compared to the other parts for annual maxima (Chandra Rupa and Mujumdar, 2017). In addition, temporal non-stationarity in the extreme rainfall series is studied. Fig. 5 shows the methodology developed for obtaining the non-stationary rainfall IDF curves by modelling non-linear trend in the extreme rainfall series (Agilan and Umamahesh, 2017).

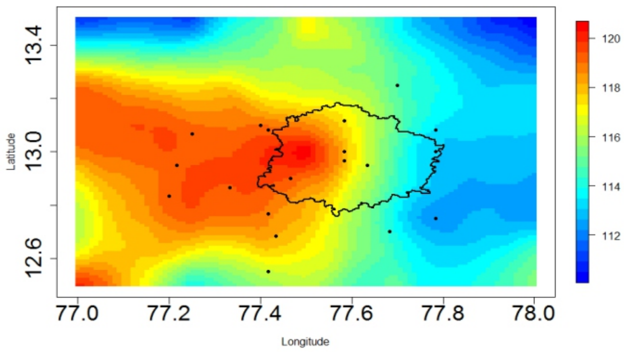

Figure 4: Spatial map of mean return levels (mm) for 10-year return period for Bangalore City. The city boundary is marked, and the stations used for modelling are shown as black dots (Chandra Rupa and Mujumdar, 2017)

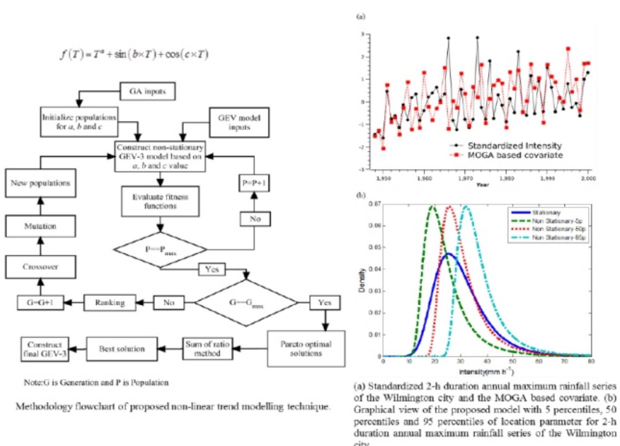

Figure 5: Proposed methodology for developing non-stationary rainfall IDF curves for Hyderabad City by modelling non-linear trend in the extreme rainfall series. Results of the proposed methodology are shown on the right panel of the Figure (Source: Agilan and Umamahesh, 2017)

- The climate change impacts on hydro-climatic variables and its extremes are projected for the future time periods. Solving research problems like - 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 etc.
- 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.

Figure 6: Experimental setup and facilities

Implementation on ground:

- Flow level sensors are installed in pilot study areas. Fig. 7 shows the flow level sensor installed in the storm water drain in IISc campus and Fig. 8 shows the flow level sensors installed in a storm water drain and in a lake (Gottigere Kere) in Bangalore City.
- 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.

Figure 7: Water level sensor installed at the outlet of the drainage network inside the IISc Catchment

- Flood maps are created by combining hydrological simulations with GIS environment. Fig. 9 shows the flood inundation map of a catchment in Bangalore City.
- 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

Figure 8: Water level sensor installed in a storm water drain and in a lake – Bangalore City case study

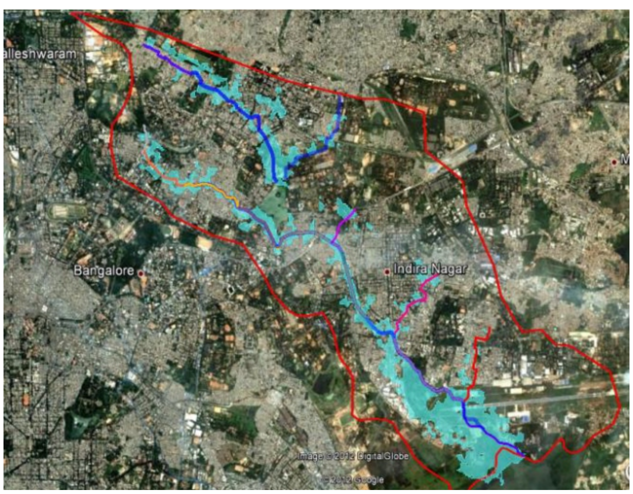

Figure 9: A flood inundation map superimposed over the Google map for a valley in Bangalore City

In addition to research and modelling, a few value additions are made in the project – a) revised urban landcover and climate zone maps of Bangalore city are created for accurate meteorological forecasts using weather research forecast model, b) 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 and c) 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 has organized three Monsoon schools, two short-term courses, two workshops and a training program.

The disaster management i.e., emergency preparedness and response activity, is also planned in the project. As the response to a natural disaster warning must be immediate, comprehensive, and demonstrate very clear lines of command, the hierarchy in the chain of command was established for all responsible personnel. Further to the specification of roles and responsibilities for those involved in disaster management activities, the main tasks responding to different disaster scenarios were identified. Fig. 10 shows the summary of disaster management activities.

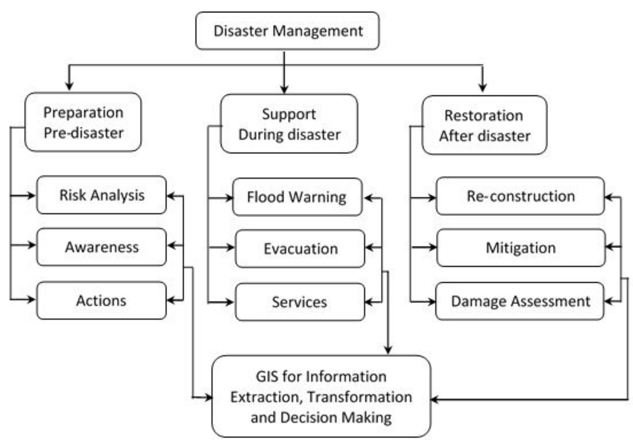

Figure 10: Disaster management framework (Modified from Price and Vojinovic, 2008)

4 Flood Risk Management

It is unrealistic to expect a no flooding scenario in urban areas and therefore risk management in case of flooding is a must. Flood risk management requires the holistic development of a long-term strategy, balancing current needs with future sustainability. Integrated flood risk management also includes the recognition that flood risk can never be fully eliminated and that resilience to flood risk can include enhancing the capacity of people and communities to adapt to and cope with flooding. Four capacities for reduced vulnerability and increased resilience are illustrated in Fig. 11.

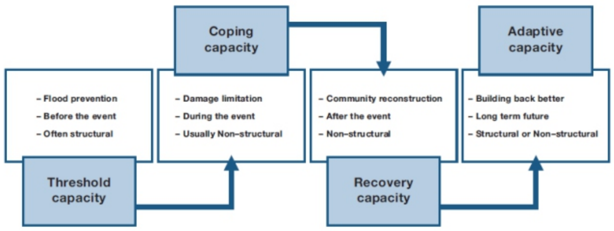

Figure 11: The four capacities towards increased resilience (Source: Jha et al., 2012)

An integrated strategy usually requires the use of both structural and non-structural solutions. It is important to recognize the level and characteristics of existing risk and likely future changes in risk.

4.1 Structural and non-structural measures

Structural measures range from heavily-engineered interventions, such as floodways and reservoirs, to more natural approaches like wetlands and greening measures. They cover water management at the catchment and urban level. A few structural measures are:

- Providing temporary storage for storm water in urban areas by making use of areas with other primary functions, for example, parkland, play grounds or car parks
- Increasing the drainage capacity or altering the line
- Reopening culverts
- Floodplain restoration
- Relief channels - re-direct some of the flow at flooded areas, by using an off-take structure, to an area where water can be safely discharged without adverse impacts
- Protecting the banks from erosion
- Introduce flood mitigation structural measures, (restriction removal, widening/deepening)

Non-structural measures do not require extensive investment in hard-engineered infrastructures, but rely instead on a good understanding of flood hazard and adequate forecasting systems. There are four main categories are i) increased preparedness, ii) flood avoidance iii) emergency planning and management and iv) speeding up recovery and using recovery to increase resilience.

Many of the measures, such as early warning systems, will form part of any flood risk management scheme. They can be seen as a first step in protecting people in the absence of more expensive structural measures, but they will also be needed to manage residual risk where such schemes have been constructed.

Engagement of the community at risk and encouragement of citizen preparedness is critical to the success of non-structural flood risk management. Communication is, therefore, a key element. Develop and implement awareness programs. Land use planning and regulation of new development is a central measure for reducing future flood risk, particularly in rapidly urbanizing emerging economies. Control land use/development.

Heavily-engineered structural measures can be highly effective when used appropriately, but they share one characteristic: that they tend to transfer flood risk from one location only to increase it in another. In some circumstances this is acceptable and appropriate, while in others it may not be. Therefore, a careful study of the area is required before implementing a solution.

4.2 Sustainable drainage

It is possible to return the catchment response to a more natural state by using natural methods of drainage. The use the infiltration and storage properties of semi-natural devices such as infiltration trenches and ponds, not only help in preventing floods, but also improve water quality. In addition, they can enhance the physical environment and in urban areas. These techniques are term 'best management practices' (BMPs), or the Sustainable Urban Drainage Systems (SUDS) (Woods-Ballard et al. 2007; Butler and Davies 2011). There is growing awareness that sustainable urban drainage systems can offer a more sustainable option for the management of storm water runoff than conventional drainage systems.

SUDS devices are most effective in avoiding flooding. Like all drainage systems, SUDS are designed to provide capacity for a storm event of a particular frequency. For more extreme events, exceedance flows are likely to be generated and must be carried by the major drainage system. Many SUDS devices are based on infiltration to the ground, the risk of groundwater pollution is an important consideration, especially where surface runoff is likely to be polluted and the groundwater is used for drinking supplies. The design of a permeable pavement system, for example, can be adjusted to allow infiltration, or not, in order to account for this.

The main types of SUDS devices can be listed as: Inlet control - Inlet control devices provide storage close to the point where the rainfall is first collected.

Green roofs/vegetated surfaces - Rooftop ponding uses the storage potential of flat roofs; as this creates an additional load there is an increased need for water tightness, as well as good maintenance of outlet control devices. A green roof is a planted area that provides storage, encourages evapo-transpiration and improves water quality.

Infiltration devices - Instead of connection to the drainage system, water collected from roofs can be diverted at the bottom of the downpipe to in filtrate in nearby stable pervious areas. Paved area ponding, to accommodate heavy rainfall, can be achieved by restricting in flow to the piped drainage system, thereby reducing flood risk downstream.

Detention ponds - Detention basins are storage facilities formed from the landscape with controlled outflow. They store stormwater temporarily, and are dry between storms.

Retention ponds - They provide storage within a permanent body of water. They allow natural treatment of the water and provide environmental and amenity benefits.

Constructed wetlands - A water store, consisting of a water butt or a tank near to ground level, can store rainwater and make it available for garden use, though some outflow must be assured to provide capacity for subsequent rainfall.

Permeable paving - Permeable paving (also known as pervious or porous pavement) are surfaces that allow water to pass through voids in the paving material or between pavers while providing a stable, load-bearing surface. This allows storm water to filter through the soil below the paved surface, reducing the numerous environmental issues associated with water runoff.

5 Concluding Remarks

Historically, disasters were viewed as 'act of God', but, floods in the recent past can be viewed as 'negligence of man'.

Establishing healthy urban conditions through planning, design, and management, while ensuring a resilient future for people in cities, requires a novel understanding of how numerous elements converge and interact to form and influence urban functions and dynamics (McPhearson et al., 2016, Alberti, 2017). Given the uncertainties surrounding these complex interactions, urban policy makers need reliable empirical evidence, innovative decision-making tools, and novel approaches (Rosenzweig et al., 2010).

Strategic decisions about urban planning and investments in infrastructure require synthesis of the complex and evolving knowledge of how coupled human–natural systems work. Only a new collaboration among scholars from diverse disciplines can develop a research agenda that will deliver a shared framework and generate a productive knowledge synthesis, connecting recent advancements in complex systems science, engineering, and urban design and planning. Such synthesis is essential to transforming the study of cities into an integrative urban science to address the challenges confronting humanity in an urbanizing world. Therefore, an integrated urban planning and water management, bringing together researchers, government agencies, policy makers and stake holders is required for a more viable and sustainable urban environment.

Cities are becoming smarter and huge amount of information flowing in an urban network must be used for multiple purposes. So, investing in a 'digital city' is another way of improving the preparation for natural disasters. In this respect, the application of hydroinformatics technologies in urban water systems plays a vital role. Increasingly, urban policy makers are turning to the collection, archiving and analysis of data for their cities, especially through facilities like advanced geographic information systems (GIS) and remote sensing. Properly presented GIS maps of flooded areas, and areas at risk become important means of communicating information on potential natural disasters.

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