Application of Ensemble Techniques for Flood Forecasting in India

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Abstract: Most of the techniques formulated for real-time flood forecasting in India, are based on statistical, and deterministic approach. Any error in the observations, model structure, model parameters, and initial conditions, which are unknown initially, propagates through the flood forecasting system to produce uncertain prediction of flood values. Deterministic forecasting method ignores these uncertainties, and also it cannot account for them during flood forecasting. Hence, identifying the source of uncertainty, focusing on the way the uncertainties cascade through the flood modelling system, and its quantification is of primary importance in operational flood forecasting. This can be achieved by running multiple simulations of forecast, with slight variations in its initial conditions, and slightly perturbing the model parameters, producing an ensemble (or suite) of forecasts. Such a technique is called as "Ensemble forecasting", a method used in Numerical Weather Prediction (NWP). This type of approach is a probabilistic approach, and has the ability to provide information on indication and probability of occurrence of extreme events. Also, the advances in remote sensing, data collection, monitoring systems, and hydrologic models, along with the improvement in weather prediction skills has led to improvement in the flood forecasting skills. Hence, shift of approach from deterministic to probabilistic by flood forecasting agencies can be helpful in developing reliable flood prediction systems, as the conventional flood prediction systems are less reliable in predicting floods which are less frequent and catastrophic, resulting from extreme rainfall events. Since there is a lot of progress in the development of ensemble forecasting techniques, and are adopted successfully by various flood forecasting agencies around the world, which produces satisfactory results, there is an urgent need for adopting this technique for producing operational hydrological forecasts in India.

Keywords: Deterministic, probabilistic, ensemble, operational flood forecasting, NWP, EPS, uncertainty, lead-time, reliable flood prediction systems.

1. Introduction

As flood is a natural phenomenon, it is usually difficult to predict a definite trend especially with regard to the time and place of its occurrence (CWC, 2019). India has experienced an increase in the frequency of extreme flood events due to increase in the frequency of extreme rainfall, which can be observed in the recent past (Ray et al., 2019). Almost 12% of India (40 million ha) is prone to flooding (National Disaster Management Plan, 2019). The long, wide, and flashy rivers with high discharge potential, in the Indo-Gangetic-Brahmaputra plains, have posed a greater flood risk, during the monsoon season, since time immemorial. The states like Rajasthan and Gujarat too have reported losses due to floods, because of poor urban drainage infrastructure.

The rise in flood magnitude has caused a rise in human, animal, and economic losses, and will keep on rising if adequate and necessary preventive measures are not taken, and therefore a large compensation will have to be made. The damages and losses by disasters largely result from the failures of development policies and practices, affecting the poorest sections the most (GOI-UNDP, 2019). Not only India, other countries in the world too have experienced many catastrophic flood events in last two decades. Scientists have predicted that floods will become more frequent in India, considering the fact that India is among the countries most affected by global warming and climate change. The data for the last 65 years, from the CWC's annual report "Water and Related Statistics, 2019", supports the above statement.

These damages can be minimized if the extreme events are predicted several days prior to their occurrence. Hence, forecasting the extreme events in advance, could eventually reduce loss of lives, infrastructure, and expenditure. In connection to this, as India is a country with a huge water resource potential, management of water is very much necessary for agriculture, hydropower, water supply, etc., if the rainfall and flood forecasts are made many days ahead.

The minimum period of advance warning necessary for preparatory action to be taken effectively (WMO-No.1072, 2011) is called lead-time. The lead-time of deterministic forecasts is short when compared to the probabilistic forecasts. Increasing lead-time and reducing uncertainty (the error or bias associated with the observations and/or models) is the prime focus of any flood forecast organization. The uncertainties propagate through the inputs and model equations and finally gives uncertain output, which when disseminated without proper processing techniques, could lead to chaos and disaster. Also, deterministic forecasting does not account for uncertainty. Therefore, major operational flood forecasting agencies in the world have adopted ensemble prediction systems (EPS), which are the ensembles of NWP, to extend the lead-time and also to quantify the uncertainty associated with the observations and forecast models.

The objective of this paper is to make the reader understand the importance of ensemble techniques, and to make/encourage the researchers and operational flood forecasters of India, to implement, research, and adopt this technique for flood forecasting in India, by discussing the following topics in the upcoming sections: Brief review on the history of extreme flood events in India; statistics of damages; operational flood forecasting agencies around the world; review of existing FF systems; issues and challenges associated with Ensemble flood forecasting; and need for adoption of this technique in India.

The components of a flood forecasting system such as pre-processing, data assimilation, hydrologic modelling, post-processing, and verification techniques are not discussed in detail in this paper.

1.1 History of severe floods in India

In recent years, extreme rainfall has caused flash floods in India's major cities - Mumbai (2005), Bihar (2007 & 2008), Brahmaputra Flood (2012), Uttarakhand (2013), Srinagar (2014), Gujarat and Chennai (2015), Assam (2016), Gujarat, Bihar, and West Bengal (2017), and Kerala (2018). The impact of climate change, rapid and unregulated urban growth has also worsened the risk of floods in urban areas of India.

1.2 Statistics of damages due to floods

The 1970s was the decade in terms of huge loss to human and cattle lives due to floods in India. These losses have come down since then. Floods resulted in loss of 0.86% of the total GDP in the 1970s and 1980s. This share has come down to 0.1% of the GDP in the present decade (i.e. from 2011-2018). Until 1970s, the biggest component of economic loss, due to floods, is the damage to crops. Since 1980s, damage to public utilities has acquired the biggest share in flood-related losses. The last two decades have shown an exponential increase in the scale of destruction in the list of annual damages for the past 65 years. CWC has given detailed estimates of damage to crops, cattle, and human lives in area, numbers and economic loss due to floods from 1953-2018 in its annual report "Water and Related Statistics" published in October 2019.

1.3 Need for adoption of new FF techniques in India

Sometimes, predictions by deterministic forecasting could also go wrong. It may over-estimate or under-estimate the required hydrological parameters. On May 8th, 2018, the IMD had issued an alert of thunderstorm in Delhi. However, there was no extreme weather activity as predicted (Hindustan Times, May 20, 2018). Communicating such uncertain forecasts, by government, may raise doubts in the general public on the forecasting potential of the research organisations. Such experiences are driving the operational flood forecasters to increase the flood forecasting potential by improving the accuracy of flood forecasts. The World Meteorological Organization (WMO) has published a manual, that provides the basic knowledge and guidance to develop or to set up an appropriate and tailored system for any case in which a flood forecasting and warning system is required (WMO-No.1072, 2011).

In order to improve the warning time and the accuracy of the forecast, the adoption of techniques that integrates meteorological data into hydrological models to generate flood forecasts, is considered necessary. Also, it involves usage of high performance computers for dealing such heavy data and computations. Meteorologists have attained greater skill in the prediction of weather components by adopting Numerical Weather Prediction (NWP) systems. This skill is reflected in increase in forecast lead-time, and reduction of uncertainty. This skill was achieved due to improvement in data collection, increase in computational facilities, man-power, and support from the government - in terms of allocation of budget, keeping in mind the necessity and urgency of forecasting the extreme events such as weather, precipitation, floods, and droughts for early preparedness.

The Ministry of Earth Science (MoES), India, on 1st June, 2018, has adopted the ensemble prediction systems (EPS) for weather forecasting, which can forecast the weather with a longer lead-time. To facilitate the modelling, MoES has also augmented its High Performance Computing (HPC) facility by 6.8 Peta Flops. The HPC has been installed at two of its constituent units, namely (i) Indian Institute of Tropical Meteorology (IITM), Pune with 4.0 Peta Flops capacity – named as 'PRATYUSH', and (ii) National Centre for Medium Range Weather Forecasting (NCMRWF), Noida with 2.8 Peta Flops capacity – named as 'MIHIR'. With this facility, a paradigm shift in weather and climate modeling activity for operational weather forecast has been achieved. Weather forecasting includes the meteorological parameters such as rainfall, temperature, wind, humidity, and others.

Since we have our own resource of ensemble weather forecasts, which are now easily available, we can develop a new FF system for India by integrating fine scale weather forecast models with high resolution distributed hydrological models to improve our flood forecasts. Hence, shifting from traditional (or conventional) FF approaches to new FF approaches, can minimize the losses (quantifiable and inestimable) due to floods, and also gives a chance to stand forefront alongside the current operational FF agencies in the world.

2. Flood Forecasting Services in India

The FF services in India are provided by Central Water Commission (CWC) - a premier technical organization of India in the field of Water Resources and is presently functioning as an attached office of the Ministry of Jal Shakti, Department of Water Resources, River Development and Ganga Rejuvenation, Government of India. The forecasting is performed on major rivers and their important tributaries.

2.1 Flood Forecasting Network of India

The present FF network of CWC has 13 regional field offices, installed over 19 major river basins, varying across 24 States & UTs, with a total of 325 FF stations (197 water level forecasting towns/important villages, and 128 inflow forecasting for Dams/Reservoirs) ("Flood Forecast", n.d.). For major rivers, the forecast is issued once in a day at 1000 hrs with advance warning time from 24 to 36 hrs. For medium rivers, the forecast is issued twice in a day at 0700 hrs and 1900 hrs with advance warning time from 12 to 24 hrs. For flashy rivers, the forecast is issued multiple times (more than twice) in a day with advance warning time less than 12 hrs.

2.2 Role of IMD in Management of Hydro-Meteorological Services

Indian Meteorological Department (IMD) renders assistance and advice on the meteorological aspects of hydrology, water management and multipurpose river valley projects management. These services are utilised by the CWC, Ministry of Agriculture, Ministry of Water Resources (MoWR), Railways, Damodar Valley Corporation Flood Control Authorities, and the State Governments. "Hydromet Division" of IMD caters the information on various rainfall products through its 'Customised Rainfall Information System (CRIS)', in form of reports and maps on the CRIS portal.

2.3 Flood Forecasting Methods Presently Used in India

The flood forecasting agency, CWC, uses only real-time observed data i.e. precipitation and streamflow data from its network of gauging stations to provide the flood forecast using statistical methods like (i) statistical correlations using gauge to gauge; (ii) gauge-discharge data; (iii) multiple coaxial correlations using gauge, rainfall, and antecedent precipitation index (API) data. In addition to the data collected from the network of CWC stations, the meteorological data and Quantitative Precipitation Forecast (QPF) received from IMD are also utilized in formulation of flood forecast having 3-day lead-time.

CWC divided the country into 7 zones, and further into 26 hydro–meteorologically homogeneous sub-zones, to develop the flood estimation models for computing the design flood in ungauged catchments (Ministry of Water Resources, Annual Report 2018-19, n.d.). CWC published the reports namely "RBF-16" and "Flood Estimation Reports (FER)" based upon the catchment area. The "Rational formula" for catchment area < 25 sq.km for estimation of peak runoff, and "Synthetic Unit Hydrograph (SUH) method" for catchment area > 25 km^2 and up to 5000 km^2 for the estimation of flood peak and time distribution of surface runoff. These methods comes under deterministic forecasting. Deterministic methods pertains to the transformation of the time distribution of rainfall on the catchment to the time distribution of runoff. So far, flood estimation reports covering 24 sub-zones have been published.

CWC is currently doing rainfall-based mathematical modelling for flood forecasting which uses both the hydrologic (rainfall-runoff) and hydrodynamic modelling technique for real-time water level and inflow prediction in the river and reservoirs respectively. The models like MIKE-11, and HEC-HMS are being used for flood forecasting.

2.4 Limitations in the Present FF Techniques

Till 2016, CWC disseminated flood levels with maximum lead-time of 1-day. During the flood season of 2017, the CWC resorted to rainfall-based modelling and issued flood advisories on a trial basis with 3 days lead-time (Press Information Bureau, 18 June 2018). The prediction of flood in exact quantities i.e. peak flow, and time of occurrence of peak, many days in advance, is really a difficult task with the present flood forecasting techniques. Present FF techniques does not quantify the uncertainty associated with the inputs and models. Forecasting floods with shorter lead-time is also of primary concern for decision making and issuing flood alerts and warnings. Though floods occur annually, only little improvements are achieved in the lead-time of operational flood forecasting.

A single value of flood peak and time distribution of surface runoff estimated by CWC's Flood Estimation Reports (FER) comes under deterministic forecasting. In India, very few attempts have been made to develop flood forecasting systems which integrates weather forecast systems with hydrological models. Till date, the operational hydrologists/practitioners in India haven't made use of meteorological forecasts for generating flood forecasts. Despite the advancements made in Indian Monsoon weather forecast by the Indian meteorologists, parallel progress in the development of ensemble hydrological forecasts have not taken place. Assimilating satellite observations such as streamflow, soil moisture, snowpack measurements, surface water elevation, terrestrial water storage, and land surface temperature with hydrological models also improves the prediction and reliability of flood forecasts.

3. Forecasting Agencies Around the World

3.1 Operational Weather Forecasting Agencies

The major operational weather prediction facilities worldwide are as follows: (i) National Centres for Environmental Prediction (NCEP of the US), (ii) European Centre for Medium-Range Weather Forecasts (ECMWF), (iii) United Kingdom Met Office (UKMO), (iv) Météo-France, (v) Environment Canada, (vi) Japan Meteorological Agency, (vii) Bureau of Meteorology (Australia), (viii) China Meteorological Administration (CMA), (ix) Korea Meteorological Administration, (x) CPTEC (Brazil), and (xi) Ministry of Earth Sciences (IMD, IITM & NCMRWF) (India).

3.2 Operational Flood Forecasting Systems

(1) European Flood Awareness System (EFAS) - An operational continental-scale flood forecasting system of the European Commission (EC), (2) Global Flood Awareness System (GloFAS) developed jointly by the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF), provides countries with information on upstream river conditions as well as continental and global overviews, (3) European HYdrological Predictions for the Environment (E-HYPE) model of the Swedish Meteorological and Hydrological Institute (SMHI), (4) The Flood Forecasting and Warning Service (FFWS) for Australia by Bureau of Meteorology (BoM), (5) Hydrologic Ensemble Forecasting Service (HEFS) for USA by U.S. National Weather Service (NWS), (6) Global

Flood Monitoring System (GFMS) is an experimental system, funded by the NASA, which uses real-time Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) precipitation information as input to a quasi-global hydrological runoff and routing model, (7) The Global Flood Forecasting Information System (GLOFFIS) is a research-oriented operational system based on Delft-FEWS, are the flood forecasting that are presently operational around the world (Emerton *et al.*, 2016).

All the above operational flood forecasting centres use ensembles of NWP for flood forecasting. Thielen *et al.* (2009) & Bartholmes *et al.*, (2009) have presented the development and skill assessment of EFAS. Emerton *et al.* (2016) has reviewed six state-of-the-art operational large-scale flood forecasting systems. Models and inputs used by various operational FF systems in the world, for real-time flood forecasting, were reviewed presented in detail by S.K.Jain et al. (2018). 14 forecast centres in Europe alone, use ensemble weather predictions to drive operational and pre-operational flood forecasting systems (Cloke and Pappenberger, 2009). The majority of them uses ECMWF EPS as input.

4. Ensemble Forecasting

4.1 Deterministic vs Probabilistic Forecasting

Forecasting future events is a challenge in hydrometeorology. A forecast can be of two types: deterministic and probabilistic. An illusion of certainty is created in the user's mind when a deterministic forecast is disseminated, which when turns out to be wrong leads to immense losses (Krzysztofowicz, 2001). Probabilistic prediction takes into account the uncertainties present in the inputs and model equations and/or parameters during the modeling process (Liu and Gupta, 2007). Probabilistic (ensemble) forecasts are more valuable than single (deterministic) forecasts, because, apart from the most likely outcome, the probability of occurrence of extreme and rare events can also be identified (Demeritt *et al.*, (2010), Cloke and Pappenberger, (2008)).

A deterministic forecast is a point estimate of a variable while a probabilistic forecast specifies a probability distribution function (PDF) for the dependent variable (Araghinejad and Burn, 2005). To quantify the uncertainty, the best way is to represent the predictions in terms of a probability distribution (Liu and Gupta (2007), Du *et al.* (2019)). This is the basic concept of ensemble forecasting.

4.2 Uncertainty associated with the forecasts

One of the top issues in current hydrological science is uncertainty. This fundamental issue of flood forecasting needs to be dealt with at the different spatial and temporal scales, and also at different stages of the flood generating processes (Cloke et al., 2009). This uncertainty from the inputs (i.e. rainfall) is cascaded through the model (model structure and parameters) of the flood forecasting system to produce an uncertain prediction of flooding (output). This evolving uncertainty in the predicted river flows could be displayed through "spaghetti diagrams" (plotting values for every member of the forecast ensemble with discharge on Y-axis, and time on X-axis).

During the process of flood forecasting, we can expect significant sources of uncertainty due to (i) corrections and downscaling, (ii) spatial and temporal uncertainties as input into the hydrological antecedent conditions of the system, (iii) data assimilation, (iv) geometry of the system, (v) characteristics of the system in the form of model parameters, and (vi) in the limitations of the models (Liu and Gupta (2007), Cloke and Pappenberger, (2008)).

To reduce the uncertainty in hydrologic modeling, proper understanding, and quantification of uncertainty is required (Liu and Gupta, 2007). Hence, for the purpose of research and operational modeling, proper consideration of uncertainty is to be done. Increase in the resolution of the model, and the amount of data being assimilated, and improvements in data assimilation techniques and model physics/dynamics reduces the error in the flood modelling.

4.3 Ensemble Prediction Systems (EPS)

Ensemble forecasting is a method used in Numerical Weather Prediction (NWP). Ensembles of NWPs, known as Ensemble Prediction Systems (EPS), are used as an input to a hydrological and/or hydraulic model to produce river discharge predictions. Such predictions are called as Hydrological Ensemble Prediction Systems (HEPS)-based forecasts, and are discussed in the special issue by Cloke et al. (2013). In the past decade, the operational flood forecasting community has increasingly used HEPS to drive their forecasts. The Hydrologic Ensemble Prediction Experiment (HEPEX) is a project designed to promote the use of HEPS internationally with the aim to investigate how best to produce, communicate and use hydrologic ensemble forecasts in hydrological short, medium, and long-term prediction of hydrological processes.

EPS has the capability to make the uncertainty of flood forecasts more transparent to their recipients (Demeritt et al., 2010). Cloke et al., (2013) in his paper described about the added value of forecasts, particularly in increasing warning lead-times, when HEPS based forecasts are used. Ensemble forecasting is a form of Monte-Carlo analysis. Multiple simulations are run, each with a slight variation of its initial conditions and with slightly perturbed model parameters, which results in multiple predictions of weather or flood for the same location and time. These variations represent the inevitable uncertainty in the initial conditions and approximations in mathematical models to solve equations. Therefore, instead of making a single forecast, a set (or ensemble or suite) of forecasts is produced to capture the uncertainty in NWPs. This set of flow forecasts could be displayed through spaghetti diagrams (Demeritt et al., 2010).

This suite of forecasts gives an indication of the range of possible future states of the variable, and how long into the future the forecasts are useful. The smaller the range, the sharper is the forecast, and also reliable. For example: If a reliable forecast says that there is a 85% chance of flood rising above a certain threshold, then in 85% of cases, the flood will surely rise above that threshold. WMO provides guidelines with an intention to provide some general advice to forecasters and forecast providers on the effective use of EPS (WMO-No.1091, 2012).

4.4 Advantages of using ensembles in operational flood forecasting

The ensemble approach can be used to make probabilistic forecasts of any dynamical system, and not only for weather prediction. EPS forecasts also has the potential to create and disseminate probabilistic forecasts, extend lead-time, and also for quantification of predictability. For the medium-range flood forecasting, the FF agencies are using Ensemble Prediction Systems (EPS) to drive their predictions. Cloke and Pappenberger (2009) gave a detailed review of the benefits of ensemble over deterministic flood forecasts, particularly looking at the increased capability for issuing flood alerts and warnings.

Apart from forecasting of floods, ensemble forecasting can also be used for reservoir operation, estimation of droughts, hydropower, and water management. Improvements in weather forecasts, combined with advances in monitoring, remote sensing, data collection, and computational power, have led to simultaneous improvements in the flood forecasting skill. Ensemble forecasts are scientifically more honest, enable risk-based warnings of floods, enable rational decision making, and offer additional economic benefits (Araghinejad and Burn, 2005). Cloke and Pappenberger (2008, 2009) listed a large number of case studies evaluating ensemble flood forecasting.

5. Communicating EPS

Unbiased weather forecasts are critical to the success of flood forecast models. The single-valued deterministic flood forecasts, based on uncertain rainfall predictions, have posed operational difficulties during the communication of flood risk to different end users. Ensemble forecasting also provides a basis to communicate forecasts, with confidence, to end users who can then be better prepared (Du et al., 2019). Ensemble forecasts produces large amounts of information, and the whole of this information should be conveyed appropriately to the end users for appropriate decision making (Emerton et al., 2016).

Better training and closer contacts between operational flood forecasters, EPS system designers, and users is required for communicating the uncertainty associated with the EPS products to be understood by the intended consumers. Also, this is the area where still significant amount of research has to be done to come out with methods for better communication of the probabilistic forecasts to various end users.

6. Conclusions

The previous sections have shown the importance of addressing, quantifying, and reducing the uncertainty associated with the forecasts, with an overall aim to improve the forecast skill and lead-time. This can be achieved by shifting the flood forecasting approach from deterministic to probabilistic. A parallel progress in the development of ensemble hydrological forecasts along with the development in ensemble weather forecasts will be highly appreciated.

CWC disseminates forecasts only 3 days in advance, whose short lead-time is very short, when compared to the lead-time of FF agencies of other countries. India is heading into a future of climatic uncertainty, where the damages due to floods will continue to hamper the growth of the country unless an efficient flood management mechanism is adopted. Hence, there is an immediate need for adopting the ensemble techniques for producing operational hydrological forecasts in India.

Having an own space research organization (ISRO), high-resolution remotely sensed satellite observations are available for free in the BHUVAN and India-WRIS portals, which can be used for assimilating data into the FF system to develop reliable flood forecasts. CWC has been making continuous endeavour for modernization and expansion of its flood forecasting network in order to have desired automatic system of data collection and real time data transmission.

Developing a new FF system will be the new challenge for our operational hydrologists and researchers. Along with developing and using the Ensemble techniques, the following questions are also to be addressed: “How to build confidence in the people on our hydro-meteorological forecasting potential?” “How should the uncertainty results be conveyed to the decision makers?” “How to make sound decisions before disseminating the ensemble forecasts?”

A rapid progress in the development of ensemble forecasting techniques have produced satisfactory results by various flood forecasting agencies around the world. Countries like United States, Australia, Canada, and few European countries have fully adopted ensemble forecasting techniques into its hydro-meteorological services, for the development, operation, and implementation of meteorological, and hydrological forecasts. Now it is time for India to compete with the operational flood forecasting agencies around the world, as we have tremendous scope for research and development to develop a highly reliable flood forecasting system.

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