# Development of Flood Forecasting System for Middle Mahanadi Basin

**Archana R. Mohite, Chandranath Chatterjee, Rajendra Singh**
*Agricultural and Food Engineering. Department., IIT Kharagpur, West Bengal, India*
*Correspondence author email: archanamohite@agfe.iitkgp.ac.in

**Abstract:** Flood forecasting, with sufficient lead time and accuracy, has great significance for effective flood warning and emergency response. In the present study, discharge forecasting system is developed for Mundali gauging station, which is located at the head of the delta region in the Mahanadi River basin, in eastern India. Integrated MIKE 11 Nedbore Afstromnings Model (NAM) rainfall-runoff (RR) and MIKE 11 hydrodynamic (HD) model is used for the development of Flood Forecast System (FFS). Initial RR modeling is carried out using India Meteorological Department (IMD) station-based observed rainfall data. River channel cross-sections extracted from SRTM 30 DEM are used as input to the MIKE 11 HD module. Integrated MIKE 11 NAM-HD model is calibrated and validated with the monsoon (June-October) period data for the years 2000-2007 and 2008-11, respectively. The calibrated MIKE 11 NAM-HD model is applied for flood forecasting using multistep-ahead rainfall forecasts from numerical weather prediction (NWP) model data. In this study, the IMD Multi Model Ensemble (MME) and European Centre for Medium-Range Weather Forecasts (ECMWF), each separately, are verified for the development of flood forecasting system (FFS). Aim of the present study is to evaluate performance of freely available IMD MME forecast data in the application of flood forecasting in comparison to widely used ECMWF data. Performance evaluation of FFS developed using both NWP model forecast data are analyzed for 1- to 3-day lead time using Nash-Sutcliff efficiency (NSE) index, coefficient of determination ($R^2$), percentage bias (PBias), RMSE-observations standard deviation ratio (RSR) and error in peak flow values ($E_{peak}$). The forecasting results obtained in the present study show satisfactory performance in terms of reliable streamflow forecasting for a sufficient lead time.

**Keywords:** Flood forecasting; Integrated MIKE 11 NAM-HD, ECMWF; IMD MME

## 1. Introduction

Flooding is one of the prominent water based natural hazards (about 50%) across the globe, which accounts for 15% of all deaths related to natural disasters. As per the statistics reported by Planning Commission India (2013), about 7.2 Mha area and a population of 3.2 million were affected on an average every year during the period of 1953-2010. Different structural and non-structural measures of flood management are used to minimize the damages due to flood havoc. Among different non-structural measures, flood forecasting is considered as an important tool for reducing the vulnerabilities and flood risks in flood prone areas (Rahman et al., 2012). Technical aspects considered in the development of a flood forecasting system are: (i) data collection, (ii) transmission, and (iii) analysis for developing a forecasting model (Perumal and Sahoo, 2010). In most of the countries, the deterministic models being used for operational flood forecasting are of three types: (i) rainfall-runoff models, (ii) flood routing models and (iii) integrated rainfall-runoff and flood routing models. The integrated rainfall-runoff and flood routing models are generally used in large basins to increase the forecast lead time using the forcing data from real-time rainfall observations to rainfall-runoff model. (Bartholmes and Todini, 2005). Recent advances in the Numerical Weather Predictions

(NWPs) model forecasts at various time ranges and spatial resolutions has opened a scope for extending the forecast lead time. Therefore, coupling the hydrological models with these NWP model outputs can be useful for flood forecasting at higher lead times. European Centre for Medium-Range Weather Forecasts (ECMWF) provides NWP model forecasts across the world and has been used in the operational flood forecasting in different world river basins (Rahman et al., 2012; Pattanaik and Das, 2015; Tomasella et al., 2018) Similarly, in India the operational distict-wise and block-wise multi-model ensemble (MME) of NWP forecasts are issued by the India Meteorological Department (IMD) since 2008. This product has been made available for real-time application, which is freely accessible in public domain (Bhowmik and Durai, 2012; Das and Kaur, 2013, 2016).

The importance of flood forecasting is crucial for many river basins in India which are being managed by the Central Water Commission (CWC), New Delhi, India. Odisha state in India ranks seventh for flood vulnerability. The contribution of flood flow of the Mahanadi river severely affects the delta region of the river basin (Planning Commission India, 2011). A critical study of historic flood events in the Mahanadi delta (1969 to 2011) reveals that, about 69% major floods are due to the contribution from downstream uncontrolled catchment beyond the Hirakud reservoir up to Mundali (head of the Mahanadi delta). It shows that the contribution from uncontrolled catchments beyond the Hirakud dam up to delta alone is sufficient to create flood havoc in the downstream. (Parhi et al., 2012). Currently, CWC is managing a water level forecasting station in the middle Mahanadi basin at the head of delta i.e., at Naraj gauging station.

In recent past, different research studies have been conducted for developing flood forecasting models in the Middle Mahanadi basin (MMB), based on data driven models (Kar and Lohani, 2010;Tiwari and Chatterjee, 2010a, 2010b, 2011; Tiwari et al., 2012, 2013; Kant et al., 2013; Sehgal et al., 2014). However, the operational use of data-driven models has limitations due to the lack of physical processes involved.

Therefore, the present study is taken up to develop a discharge forecasting system for the MMB using the MIKE 11 modules (rainfall-runoff model, MIKE 11 NAM and river routing model, MIKE 11 HD) for the Mundali gauging station (just about 3.5 km upstream to that of Naraj). The forecast system is developed using observed (IMD station) rainfall along with the NWP forecasts (IMD MME) and ECMWF) rainfall data. Flood in the year 2008 was occurred mainly due to contribution from uncontrolled catchments in the MMB. Hence, retrospective analysis for the same monsoon season is carried out using the developed flood forecasting system. The objective of this study is to investigate how well the developed flood forecasting system performs with observed and NWP forecast rainfall data to provide accurate flood forecasts at higher lead times.

## 2. Materials and Methodology

### *Study Area*

Middle Mahanadi basin (MMB) selected for this study is shown in Fig. 1. This basin lies in between 82° E-86° E longitudes and 19° N-22° N latitudes. It has a total basin area of 48,700 km$^2$. The Mahanadi river extends from the Hirakud dam to delta head (Mundali) having a length of 315 km. Lateral tributaries Ong, Sukhtel, and Tel joining the Mahanadi river in the middle reaches are mainly responsible for uncontrolled flood flow from catchments. The main soil types found in the study area are red and yellow soils. The normal annual rainfall is about 1458 mm and the temperature in this region varies from 14 $^{\circ}$C to 40 $^{\circ}$C. The average monthly pan evaporation of the area varies from 2.4 cm to 14.6 cm. Mundali station, located at delta head is considered as a discharge forecast station in the present study, which is also the forecast station under CWC (Central Water Commission) Bhubaneswar and HDC (Hirakud Dam Circle) Burla, Odisha. Hirakud dam is world's longest earthen dam and mainly constructed to control flood in delta region of the Mahanadi basin.

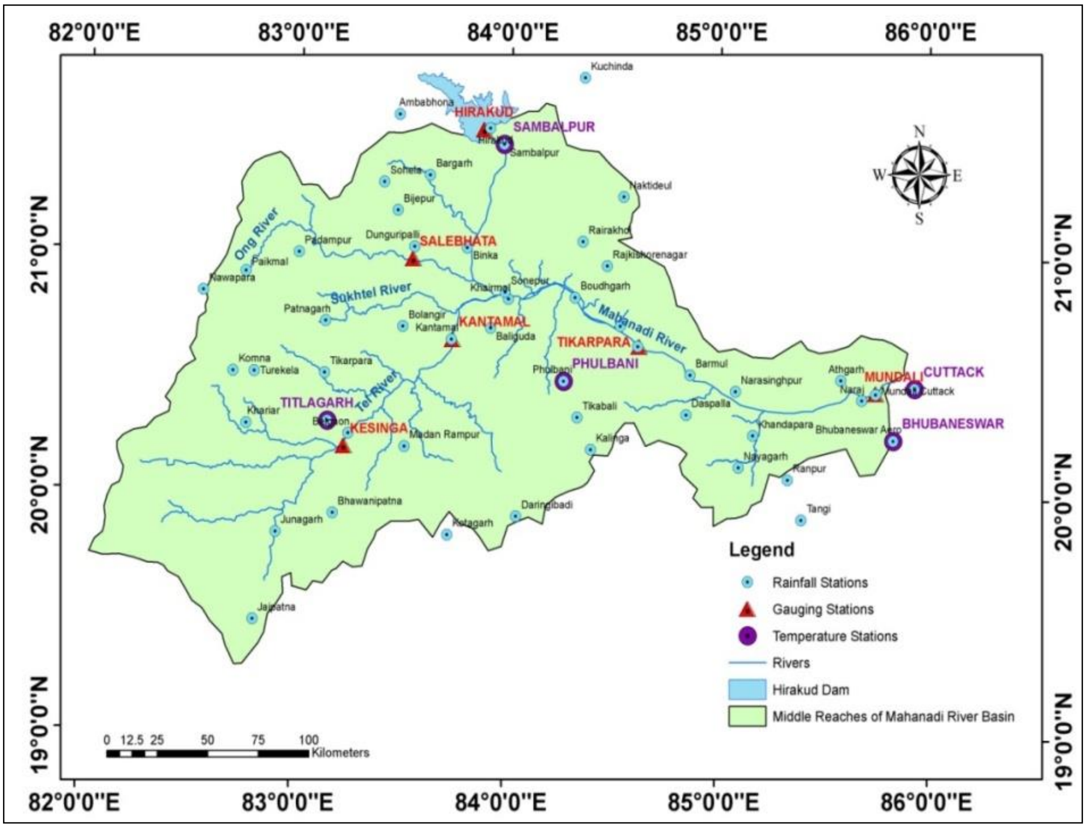


Fig. 1: Middle reaches of the Mahanadi river basin showing hydro-meteorological gauging stations

***Data Used***

The present study is carried out to develop discharge forecast system at Mundali gauging station (downstream boundary of MMB). MIKE 11 software with NAM (Nedbør Afstrømnings Model i.e., rainfall-runoff model and HD (Hydrodynamic) modules are used for the development of flood forecasting system. Rainfall-runoff process for the catchments in the MMB is modeled using MIKE 11 NAM model.

NAM model is a lumped conceptual model. Input data to the model is given in the form of average time series of hydro-meteorological data over the catchment area. Figure 1 shows detailed map of hydro-meteorological gauging stations considered in the present study. Station rainfall data is used to prepare catchment-wise average rainfall time series. Station daily

maximum and minimum temperature data is converted to potential evapotranspiration (ET) using Hargreaves equation (Hargreaves and Samani, 1985), and then to catchment-wise mean areal values of ET.
Table 1 shows the spatial and temporal resolution and sources of the hydro-meteorological data used in the NAM model setup.

Table 1: Details of the data used in the NAM model setup

| Sl. No. | Data | Spatial resolution | Temporal resolution | Data period (Year) | Source |
|---|---|---|---|---|---|
| 1 | Rainfall: 59 stations | Station | Daily | 2000-2011 | IMD Pune |
| 2 | Temperature: 5 stations | Station | Daily | 2000-2011 | IMD Pune |
| 3 | Gauging stations: 4 | Station | Daily | 2000-2011 | CWC, Bhubaneswar; India-WRIS (www.indiawris.nrsc.gov.in/); HDC, Burla; DoWR, Bhubaneswar, Odisha. |
| 4 | SRTM 90m DEM | 90 m × 90 m | | | https://earthexplorer.usgs.gov/ |

Channel routing of flood flow is carried out using MIKE 11 HD model. Model setup is prepared using river network details, river cross-section data, flow data, lateral flow link from R-R model and Manning's roughness coefficient. Details of data collected for HD model setup is given in Table 2.

Table 2: Details of data used in the HD model setup for the MMB

| Sl. No. | Data | Spatial resolution | Temporal resolution | Data period (Year) | Source |
|---|---|---|---|---|---|
| 1 | Gauging station data: Discharge | Station | Daily | 2000-2011 | India-WRIS (www.india-wris.nrsc.gov.in/), HDC Burla |
| 2 | SRTM 30m DEM (Cross-section extraction) | 30 m × 30 m | - | - | https://earthexplorer.usgs.gov |

After initial calibration and validation, integrated NAM-HD model is used for development of flood forecasting system. ECMWF and IMD MME NWP forecast data products are used in the present study. Details are given in Table 3.

Table 3: Details of the NWP forecast data used for development of flood forecasting systems in MMB

| Sl. No. | Data | Spatial resolution | Data interval | Data period (Year) | Source |
|---|---|---|---|---|---|
| 1 | ECMWF data: Rainfall and Temperature | 0.5° × 0.5° grid | Daily | 2008 | Institute of Earth and Environmental Sciences, University of Potsdam, Germany |
| 2 | IMD multi-model ensemble (MME) forecast data: Rainfall and temperature | Centroid of district administrative boundary | Daily | 2008 | ftp://125.21.185.50/ |

***Methodology***

Operational CWC Flood Forecasting Network (CFFN) for the MMB (India-WRIS, 2016) comprises of one base station, viz. Tikarpara located on the Mahanadi river and a water level forecast station, viz. Naraj on the Mahanadi river. Travel time of flood flow from the base station to forecast station in CFFN varies from 18-20 h (India-WRIS, 2016). In the present study, gauging stations, viz. Salebhata and Kantamal located on the Ong, and Tel river, respectively, are considered as base stations and Mundali station (just 3 km upstream of Naraj gauging station) located on the Mahanadi river as discharge forecast station (Fig. 2).

Integrated MIKE 11 NAM-HD i.e., NAM-HD setup (Fig. 2) is developed considering R-R modeling for upstream catchments (i.e., Salebhata and Kantamal) to the base station and contributing catchment of Middle reaches of Mahanadi Basin (MMB-C1) coupled with river routing model (NAM-HD). As the Hirakud is a major reservoir in the Mahanadi basin, and controlled releases from it heavily influences streamflow values at Mundali station, observed outflow time series from Hirakud is considered as input (or inflow boundary) to NAM-HD setup. Downstream boundary at Mundali gauging station is specified with Q-h rating curve. Basic model layout considers reservoir outflow at a Hirakud base station (HD upstream boundary).

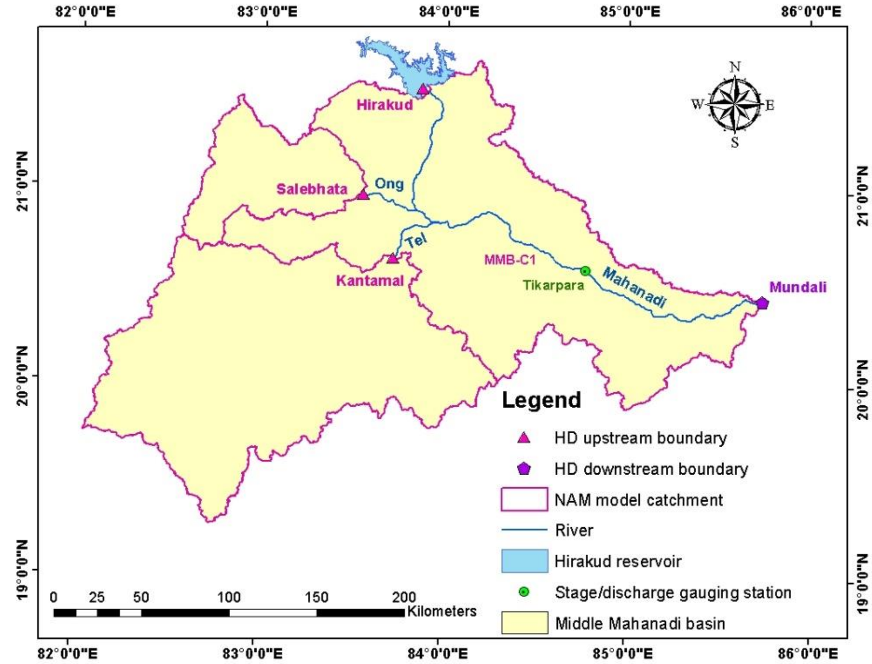


Fig. 2: NAM-HD Setup for Middle Mahanadi Basin

Calibration and validation of integrated NAM-HD model setup is carried out through two steps. First, calibration of MIKE 11 NAM model catchments using observed rainfall data is carried using autocalibration criteria. Second, integrated NAM-HD setup is again calibrated for the Manning's roughness coefficient, *n*, in the HD model setup. Integrated MIKE 11 NAM-HD model is calibrated and validated using only monsoon season (June-October) data for the years 2000-2007 and 2008-11, respectively. Calibration and validation results of integrated NAM-HD model are evaluated using the Nash-Sutcliffe Efficiency (*NSE*) index, Coefficient of determination ($R^2$), Percent error in volume/Percent Bias (*PBias*) and error in peak flow ($E_{peak}$) (Nash and Sutcliffe, 1970; Moriasi et al., 2007).

During forecasting mode, ECMWF and MME forecast rainfall data, each separately, is used as input to the calibrated NAM-HD model to obtain forecasting results for the flood event during the year 2008. Performance of the forecasting results is evaluated using above-mentioned performance indices. During flood forecasting, two case scenarios are considered for different data input structure into NAM-HD setup. In Case-I, NAM-HD is provided with observed hydro-meteorological data in the hindcast period and no data in the forecast period. Case-II is evaluated using observed hydro-meteorological data in the hindcast period and NWP model meteorological forecast (ECMWF or MME) in the forecast period. Here, hindcast period is the period between start of simulation and ToF, and forecast period is the period between ToF and end of the simulation period. Both the case scenarios are evaluated for 1- to 3-day lead time.

## 4. Results and Discussion

***Calibration and Validation of Integrated MIKE 11 NAM-HD Model***

Integrated NAM-HD model setup is calibrated using monsoon season data for the years 2000-07. Figure 3 (a) shows that, during calibration NAM-HD model performs with *NSE* = 0.96, $R^2$ = 0.97, │*PBias*│ = 4.86% and *RSR* = 0.19; whereas during validation it performs with *NSE* = 0.95, $R^2$ = 0.95, │*PBias*│ = 4.85% and *RSR* = 0.23. Results show that there is very good agreement between simulated and observed discharge for calibration and validation dataset and all peak flows are reproduced with $E_{peak}$ = ±20%. Here, it is to be noted that discharge at Mundali gauging station is heavily influenced by Hirakud releases.

***Evaluation of Forecasting System***

Performance of NAM-HD setup in Case-I forecasting scenario is analyzed with initial model conditions generated using observed hydro-meteorological input data in the hindcast period and no data during forecast period. Figure 4a-c show the forecasting results of NAM-HD setup for Case-I scenario, respectively for 1- to 3-day lead time. The performance of a model is judged as acceptable for flood forecasting if $NSE \geq 0.75$, $R^2 \geq 0.75$, *PBias* = ±20%, $RSR \leq 0.50$. For Case-I scenario (see Fig. 4), performance indices are *NSE* = 0.96, $R^2$ = 0.97, │*PBias*│ = 3.83% and *RSR* = 0.19 at 1-day lead time; whereas *NSE* = 0.86, $R^2$ = 0.93, │*PBias*│ = 11.95% and *RSR* = 0.37 at 2-day lead time. This shows that model setup with inclusion of rainfall-runoff modeling for upstream catchments play a crucial role in improving the flood forecasts by increasing the lead time of forecasts. Thus, it is observed that the performance of flood forecasting system under Case-I is found to be acceptable for 2-day lead time with $NSE \geq 0.75$, $R^2 \geq 0.75$, *PBias* = ±20%, $RSR \leq 0.50$.

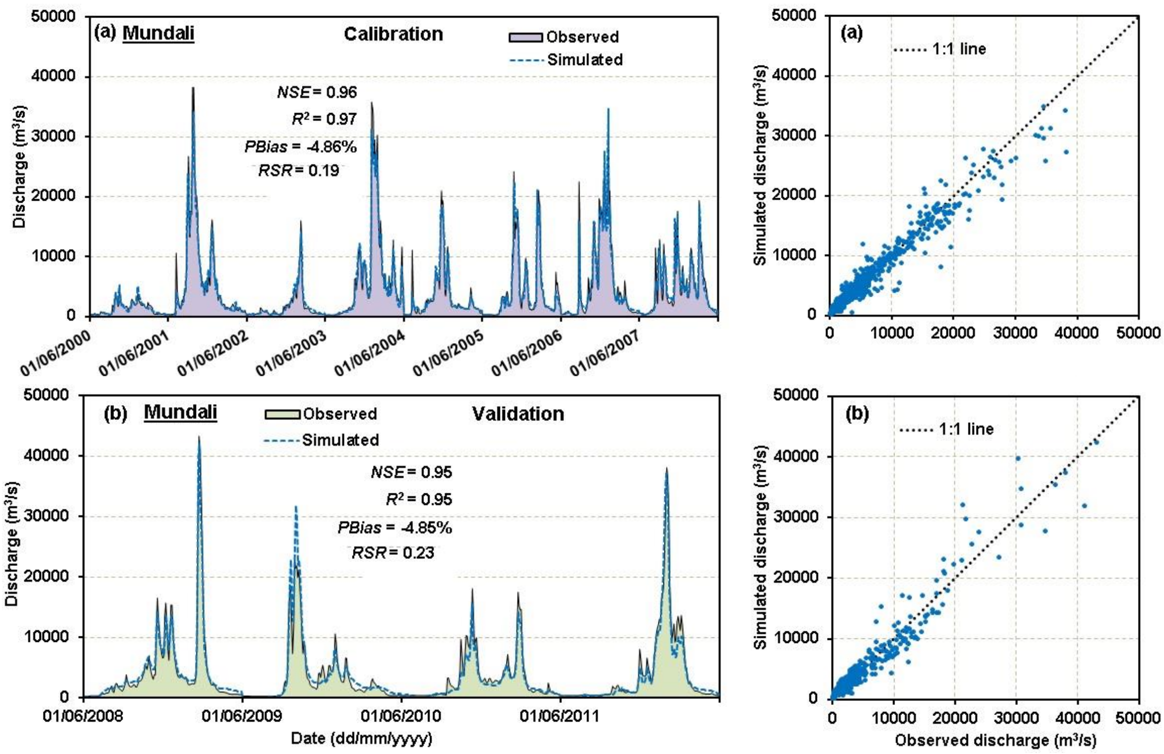

Fig. 3: Hydrographs and Scatter Plot for Simulated and Observed Discharge Values of NAM-HD model setup at Mundali Gauging Station during (a) Calibration and (b) Validation

In Case-II scenario, NAM-HD setup is evaluated for discharge forecasting at the Mundali gauging station using model initial condition genrated from observed hydro-meteorologial data coupled with NWP model meterological forecast data.

Figure 5a-c shows forecasting results in Case-II obtained from NAM-HD setup for 1- to 3-day lead time. At 1- and 2-day lead time, NAM-HD setup using ECMWF forecast rainfall performs with *NSE* = 0.90-0.96, $R^2$ = 0.97, $|PBias|$ = 4.57-5.15%, and *RSR* = 0.20-0.32; whereas for MME *NSE* = 0.89-0.96, $R^2$ = 0.97, $|PBias|$ = 4.54-7.39%, and *RSR* = 0.20-0.34. Overall performance of developed system is found to be acceptable for flood forecasting up to 2-day lead time and it deteriorates at higher lead times.

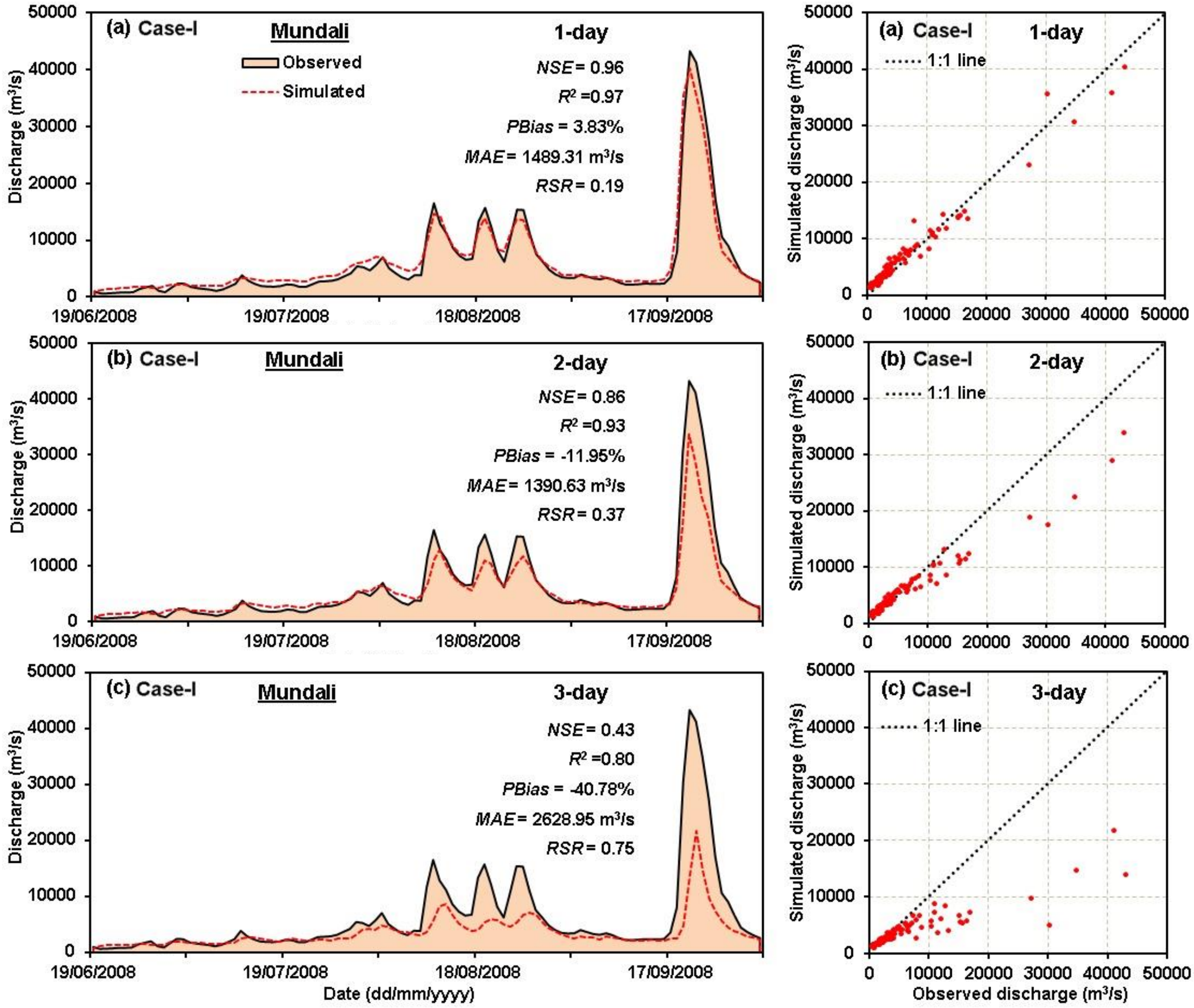


Fig. 4: Discharge forecast results of NAM-HD setup for Case-I for 1- to 3-day lead time

Following are the outcomes obtained for flood forecasting system:

1. From Case-I it is observed that integrated MIKE 11 NAM-HD model setup developed using rainfall-runoff modeling for upstream catchment provides acceptable performance up to 2-day lead time.
2. MIKE 11 NAM-HD setup provided with NWP model meteorological forecasts (ECMWF or MME) could not extend the acceptable performance beyond 2-day lead time. However, the performance at 2-day lead time improved with the use of NWP model meteorological forecasts
3. For Case-II, no significant difference in performance error measures is observed in forecasting results obtained using ECMWF and MME forecast for 1- and 2-day lead time.

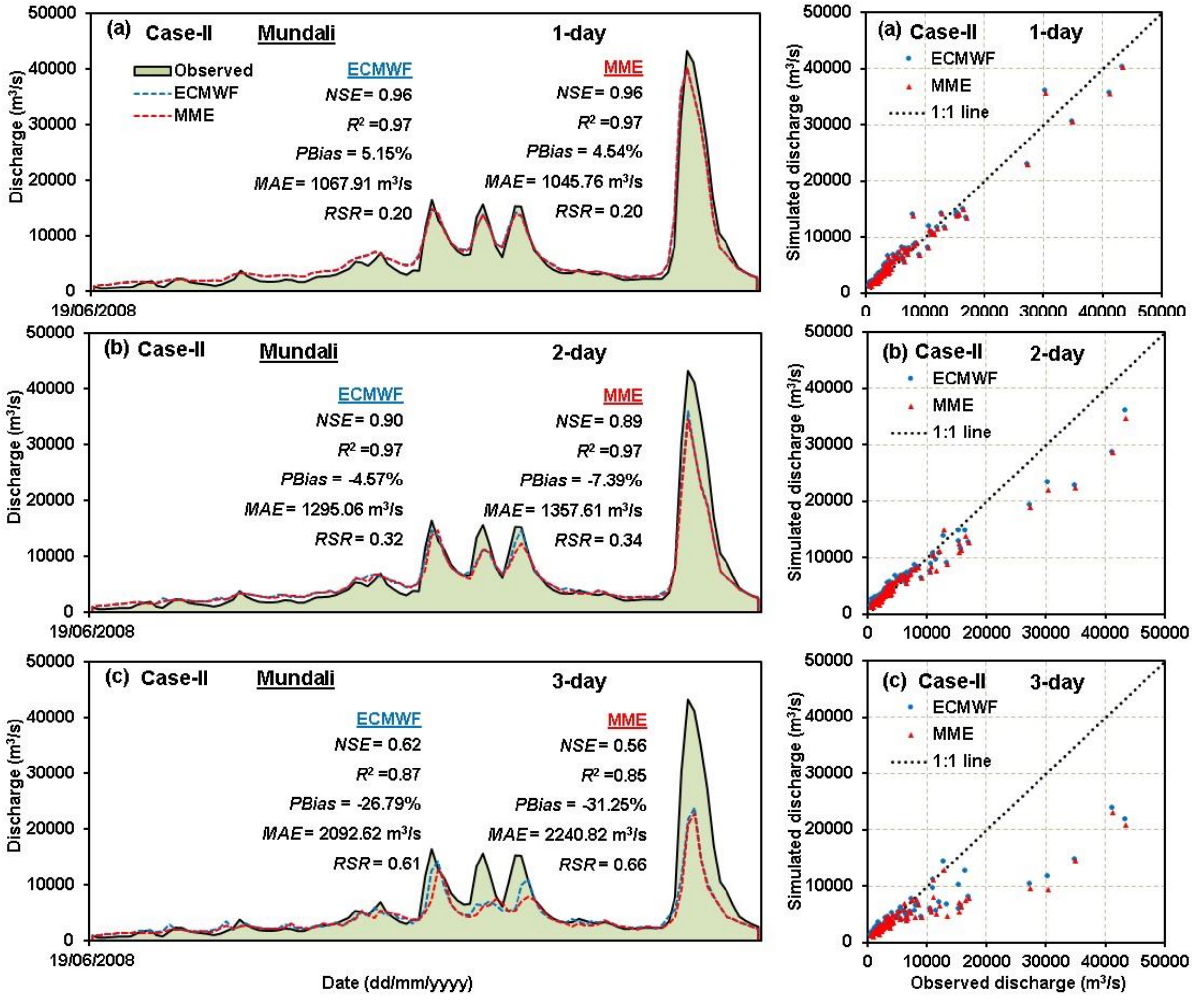


Fig. 5: Discharge forecast results of NAM-HD setup for Case-II for 1- to 3-day lead time.

Peak error ($E_{peak}$, %) statistics is also evaluated for 2008 flood event at Mundali gauging station. $E_{peak}$ criteria is considered acceptable when peak event is within ±20%. Table 4 shows the peak error statistics for forecasting results obtained for peak flow events (during years 2008-2011) for both the scenarios.

Thus, an overall comparison of NAM-HD setup under Case-II with either of the forecast data from ECMWF and MME revealed that modeling framework could be used operationally for 1- to 2-day lead time forecasting.

**Table 4**: $E_{peak}$ (%) values obtained using different model setups at 1- to 3- day lead times developed for the MMB for Case-I and Case-II

| Date | Observed discharge ($m^3/s$) | $E_{peak}$ (%) | | |
|---|---|---|---|---|
| | | Case-I | Case-II | |
| | | | ECMWF | MME |
| | | 1-day | | |
| 20/09/2008 | 44781.9 | -7.05 | -7.08 | -7.09 |
| | | 2-day | | |
| | | -22.04 | -16.62 | -19.89 |
| | | 3-day | | |
| | | -68.29 | -49.68 | -51.83 |

## 5. Conclusions

This study is carried to develop flood forecasting system for middle Mahanadi basin (MMB). Travel time of flood flow from the base station to forecast station in CFFN varies from 18-20 h. With the extended flood forecasting network, in order to obtain increased lead time from base station to forecast station, developed modelling system resulted in following conclusions:

1. Calibration and validation of the MIKE 11 NAM-HD model developed for the middle Mahanadi basin using observed hydro-meteorological data shows very good agreement between observed and simulated streamflows.
2. The performance of MIKE 11 NAM-HD model for flood forecasting with CWC network for middle Mahanadi basin is found to be acceptable for 1-day lead time.
3. Incorporation of rainfall-runoff modeling of the upstream catchments in MIKE 11 NAM-HD model improves the flood forecasts at higher lead times. This could extend the acceptable flood forecasts from 1-day to 2-day lead time in the middle Mahanadi basin.
4. The use of NWP model meteorological forecasts (ECMWF and MME) in MIKE 11 NAM-HD model improves the flood forecasts. This could extend the acceptable flood forecasts at 2-day lead time in the middle Mahanadi basin. The performance of ECMWF and MME meteorological forecasts in flood forecasting is similar.

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