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Applicability of seasonal forecasts from dynamical models for reservoir management practices

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सार – भारतीय ग्रीष्मकालीन मॉनसून वर्षा (आईएसएमआर) के विश्वसनीय ऋतुनिष्ठ पूर्वानुमानों की उपलब्धता के बावजूद, जलाशय स्तर प्रबंधन के लिए इन पूर्वानुमानों द्वारा संचालित गतिकी मॉडल का उपयोग सीमित है। जलाशय जल प्रबंधन विशेष रूप से उपयोगी हो सकता है यदि यह आसन्न सूखे/बाढ़ की स्थिति को देखते हुए कई महीने पहले किया जा सके। उष्णकटिबंधीय भारतीय जलाशयों (मुला और कांगसबाती) के लिए ऋतुनिष्ठ और मासिक प्रवाह पूर्वानुमानों के लिए मॉनसून मिशन (एमएम) ऋतुनिष्ठ पूर्वानुमान मॉडल से ऋतुनिष्ठ पूर्वानुमानों की प्रयोज्यता का अध्ययन 3 महीने की लीड अवधि के लिए मृदा और जल मूल्यांकन उपकरण (एसडब्ल्यूएटी) हाइड्रोलॉजिकल मॉडल का उपयोग करके किया जाता है। दीर्घावधि प्रेक्षित इनफ्लो डेटासेट का उपयोग इन-सिटू मौसम संबंधी डेटा का उपयोग करके अनुक्रमिक अनिश्चितता फिटिंग (एसयूएफआई) - 2 एल्गोरिदम के साथ SWAT-अंशांकन और अनिश्चितता प्रक्रिया (सीयूपी) के अंशांकन और सत्यापन के लिए किया जाता है। प्रेक्षित अंतर्वाह और अंतर्वाह अनुकरण की तुलना समान कैलिब्रेटेड प्राचलों के साथ SWAT का उपयोग करके अनुकरित अंतर्वाह के साथ की जाती है, लेकिन एमएम मॉडल से पुन: पूर्वानुमान से प्राप्त फोर्सिंग के साथ। SWAT-कप दोनों जलाशयों के लिए उचित नैश सटक्लिफ दक्षता (एनएसई) (मुला = 0.75, कांगसाबाती = 0.79) और प्रतिशत पूर्वाग्रह (पीबीआईएएस) (मुला = -28%, कांगसाबाती = 17%) के साथ अच्छी तरह से कैलिब्रेट किया गया। मॉनसून ऋतु के दौरान धारा प्रवाह के अनुमान के लिए कौशल स्कोर 0.6-0.70 तक भिन्न होता है, जो इन अनुमानों के लिए उचित सटीकता का संकेत देता है। SWAT-MM मॉडल में 0.52-0.53 NSE और 26%-40% PBIAS के साथ उचित कौशल है। इसलिए, SWAT-MM- आधारित मॉडल में भारत के विभिन्न कृषि-जलवायविक क्षेत्रों के लिए मासिक और ऋतुनिष्ठ जलाशय प्रवाह का पूर्वानुमान लगाने की अच्छी क्षमता है। ये पूर्वानुमान जब वास्तविक समय में उपयोग किए जाते हैं, तो जलाशय के भंडारण और निर्गमन के प्रबंधन के लिए एक दिशानिर्देश के रूप में काम कर सकते हैं, और इसलिए यह विशेष सामाजिक-आर्थिक महत्व का साबित होता है।

ABSTRACT. Despite the availability of reliable seasonal forecasts of Indian Summer Monsoon Rainfall (ISMR), the use of dynamical models driven by these forecasts for reservoir level management is limited. Reservoir water management can specially be useful if it can be done several months in advance, in view of an impending drought/flood scenario. The applicability of seasonal forecasts from the Monsoon Mission (MM) seasonal forecast model for seasonal and monthly inflow forecasts for tropical Indian reservoirs (Mula and Kangsabati) is studied using the Soil and Water Assessment Tool (SWAT) hydrological model, at a lead time of 3 months. Long-term observed inflow datasets are used for calibration and validation of SWAT-Calibration and Uncertainty Procedure (CUP) with Sequential Uncertainty Fitting (SUFI)-2 algorithm using insitumeteorological data. Observed inflows and inflow simulations are compared with simulated inflow using SWAT with same calibrated parameters, but with forcing derived from reforecasts from the MM model. The SWAT-CUP calibrated well with reasonable Nash Sutcliffe Efficiency (NSE) (Mula = 0.75, Kangsabati = 0.79) and Percentage Bias (PBIAS) (Mula = -28%, Kangsabati = 17%) for both reservoirs. The skill scores for streamflow predictions vary from 0.6-0.70 during the monsoon season, indicating reasonable accuracy for these predictions. The SWAT-MM model has a reasonable skill with 0.52-0.53 NSE and 26%-40% PBIAS. Therefore, SWAT-MM-based model has a good potential to forecast monthly and seasonal reservoir inflow for various agro-climatic zones of India. These forecasts when used in real-time, can serve as a guideline for managing the reservoir storage and release, and hence proving to be of great socio-economic importance.

Key words – SWAT, Indian summer monsoon rainfall, Reservoir management, Seasonal inflow forecast, Climate forecast system.

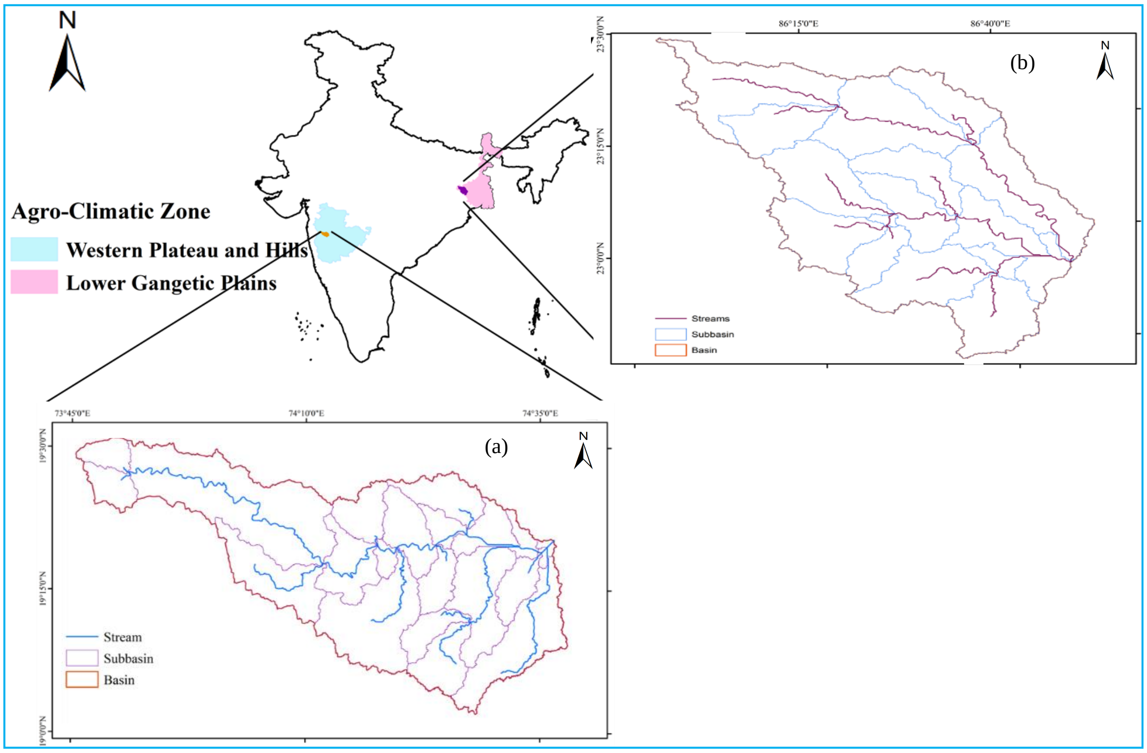
1. Introduction

Water is an important natural resource on the earth's surface that has a strong association with the earth system. The weather at any place is modulated by the myriad atmospheric and oceanic phenomenon and the redistribution of water through the hydrological cycle forms an important component of the complex earth system (Subramanya, 2008). The water balance parameters in a river basin are mainly influenced by physical characteristics of a watershed like morphology, soil, land use, *etc*. influence the components of water balance in a basin. Due to the climate variability, extreme weather events (*i.e*., tropical cyclones, flood, droughts and forest fire) in developing countries like India cause significant economic loss (Gadgil and Gadgil, 2006; Monirul and Mirza, 2003; Wallemacq & House, 2018). The terrestrial hydrological system is primarily driven by precipitation, and its variations could have a direct influence on water resources, such as, runoff (Chen *et al*., 2012; Zabaleta *et al*., 2014), reservoir performance (Raje & Mujumdar, 2010) and water resources management (Kundzewicz & Stakhiv, 2010; Dawadi & Ahmad, 2012; Vaghefi *et al*., 2015).

The rainfall-runoff interaction is a complex problem. In India, approximately 49% of precipitation over land gets converted into runoff during the monsoon season (Gupta *et al*., 2011). Managing reservoir releases for various purposes such as irrigation, drinking, industries, *etc*. is challenging due to reservoir runoff variations. As a result, most of the major irrigation projects perform unevenly, with an average overall efficiency of 35-38% (National water use efficiency improvement support program, 2014). Therefore, adaptive reservoir management based on reservoir inflow (runoff from reservoir catchment) forecast can mitigate the effect of climatic variability and extreme hydrological events, such as droughts and floods (Renard & Lall, 2014; Sharma *et al*., 2018).

To assess the socio-economic importance and climate variability impact on the water resources, it is crucial to simulate the hydrological components. The primary objective of any hydrological modeling framework is to predict the streamflow at the outlet of the catchment/reservoir. In India, distributed and semi-distributed models are commonly used to simulate hydrologic parameters over the watershed catchments due to heterogeneity in soil, vegetation, and land use land cover characteristics (Hegade *et al*., 2017). Generally, models perform best when the input datasets are available at the same spatial-scale as that of the model (Colby, 2001; Miller *et al*., 2002). Distributed hydrological models have become effective tools to investigate the intricate nature of the process that influences hydrological processes and physical characteristics of watershed (Meng *et al*., 2014). In recent years, several hydrological models have been developed to assess the hydrological components at watershed-scale. The most commonly used models include MIKE Système Hydrologique Européen (SHE) (Refsgaard & Storm, 1995), Hydrologic Simulation Program-Fortran (HSPF) (Donigian *et al*., 1995), Agricultural Non-Point Source Pollution (AGNPS) (Young *et al*., 1989) and Soil and Water Assessment Tool (SWAT) (Arnold *et al*., 1998). Among all these hydrological models, SWAT model has gained significant importance over the past few decades for simulations in agricultural watershed catchments (van Griensven *et al*., 2012). The model can compute hydrologic fluxes and stores for each Hydrological Response Unit (HRU) (Netnapa & Pongthep, 2013; Manaswi & Thawati, 2014).

In order to calibrate and validate the model outputs such as runoff, SWAT model utilizes the observed estimates of meteorological parameters (reanalysis data) as forcing datasets. However, the use of such models can be beneficial for water planners and decision-makers in improving preparedness for water management, only when they can provide reliable forecasts (Hansen, 2005). For such forecasts, reliable forecasts of meteorological parameters are vital. ECMWF's seasonal climate forecasts can predict the dry spell for the Limpopo basin well with a lead time of 0 to 4 months, which is useful in improving water resources management for mitigating adversities linked to climate extremes (Wetterhall *et al*., 2015). Skillful prediction of inflow to the reservoir is essential to decide reservoir release and canal irrigation scheduling. Recently, Zhang *et al*. (2017) integrated a general circulation model with the Variable Infiltration Capacity (VIC) model and satellite data to predict drought in Southwestern China. The seasonal forecasts of Indian Summer Monsoon Rainfall (ISMR) had remained a challenging problem since decades (Gadgil *et al*., 2005, Rajeevan *et al*., 2012). Identifying the urgent need for implementing a dynamical prediction system, Ministry of Earth Sciences, Government of India launched "Monsoon Mission" to operationalize and improve monsoon forecasts in the country at different time scales. Due to the concerted efforts by the monsoon community under Monsoon Mission (MM), seasonal prediction skill of ISMR has improved considerably (Rao *et al*., 2019). Since the launch of MM, a high resolution (~38 km) seasonal forecasting is now operational in India with high skill of 0.63 for Indian Monsoon for the period of 1981-2010 (Pillai *et al*., 2017). It is, therefore, worthwhile to assess the usability of these skillful seasonal monsoon predictions for hydrological purposes. These forecasts are available at three-month lead time. Consequently, they can have enormous usability for water management if the



Figs. 1(a&b). Map of the study area shows generated stream network and delineated sub-basins of (a) Mula and (b) Kangsabati reservoir catchments from different agro-climatic zones of India

hydrological forecasts derived from these numerical weather prediction (NWP) models turn out to be skillful.

Improved assessment of ISMR is important for water resource management at river basin scale. Not with standing their importance, accurate estimates of hydro-meteorological data (*i.e*., rainfall, temperature and stream flow) (Lopez *et al*., 2017) are quite difficult to obtain. In tropical regions, particularly in developing countries, field-based or *in situ* rainfall measurements are often sparse and inadequately distributed due to economic, methodological, or geographical constraints. This situation is unlikely to improve in the near future (Hughes, 2006). In the absence of such ground-based observations, reanalysis data serves as an observed estimate of meteorological parameters for hydrological modeling. Gosh *et al*. (2012) reported significant contrasting trends between the mean (a decrease) and extremes (an increase) of ISMR which posesa challenge to stakeholders who have to make decisions about water resource management.

The objectives of this study are two-fold. The first objective is to evaluate the application of SWAT models in two different agro-climatic zones of India (Maharashtra and West Bengal) for simulating reservoir inflow and, secondly, to assess the usability of skillful seasonal forecasts from Monsoon Mission model for reservoir management purposes. To achieve these objectives, seasonal reforecasts/hindcasts from the MM model for the period 1981-2017 is employed. The hydrological processes (runoff, evapotranspiration, groundwater flow) of Mula and Kangsabati reservoir catchments are quite complicated due to heterogeneities in topography, land use land and cover pattern, and other catchment characteristics. The Government of West Bengal (2010) reported a decrease in post-monsoon (Oct-Dec) rainfall, increase in pre-monsoon (Mar-May) rainfall and a delay in onset of the monsoon during the period of 1990-2008 in West Bengal. According to the World Bank (2013), Maharashtra's hydrological systems and agricultural activity could be impacted by rising temperatures and changed seasonal precipitation patterns (both in amount and timing).

Further, the Government of Maharashtra (2002) affirmed that a significant declining trend for Mula reservoir inflow over the last 30 years. Shah and Mishra (2016) noticed a significant decline in availability of surface water storage during monsoon season over the Ganga (8%) and Godavari (3%) basins from 1948 through 2012. Gupta *et al*. (2011) also pointed out that there might be a shortage in the surface water availability during the *Kharif* (July-Nov) season in the Ganga and Godavari basins in future. Consequently, it is expected that the Mula and Kangsabati catchments, located in the lower Ganga and upper Godavari basins, respectively might mainly be susceptible to climate. Thus, in turn, it might impact the water availability in the Mula and Kangsabati reservoirs considerably. However, this study does not dwell upon the climatic trends in reservoirs inflow but focuses on re-forecasting river basin inflows in such a scenario.

2. Material and methods

2.1. *Study area*

In this study, two different reservoir catchments are selected from different agro-climatic zones of India namely, Mula reservoir in the Western Plateau and Hills of Maharashtra and Kangsabati reservoir in the Lower Gangetic Plain Region of West Bengal (Fig. 1). The selection of the study area is based on different climatic conditions, geographical conditions, crop type and catchment area type and availability of data. Brief descriptions of both the catchments are given in Fig. 1.

Mula catchment present in upper Godavari basin covers approximately 2300 km^{2}and lies between 19.5°-18° N latitudes and 73°-75° E longitudes [Fig. 1(a)]. The catchment is delineated with respect to the outlet at Mula Dam located in Ahmednagar district, Maharashtra, which is the second largest dam (length = ~2.9km) in the upper Godavari basin. The dam was opened in 1972 and is currently managed by Maharashtra Government. The water from the left and right branch canal and Pathardi Branch canal of Mula dam is mainly used for irrigation purposes into the water-deficient central-eastern Ahmednagar district. The average annual rainfall of Mula catchment is <600 mm and it is not uniformly distributed over the monsoon period. The area is mostly dominated by clay loam type soil.

The Kangsabati reservoir is located in the Kangsabati river basin in West Bengal and lies between 25°-21° N latitudes to 85°-87.5° E longitudes. The dam was constructed in 1965, for many purposes like irrigation, water supply, and flood mitigation [Fig. 1(b)]. Kangsabati reservoir is formed by two dams one on the Kangsabati river and other on its tributary, Kumari near Mukutmonipur, Bankura, West Bengal. The Kangsabati reservoir catchment encloses an area of 3428 km^2. The average annual rainfall over the catchment is 1302 mm. Three types of soils, sandy loam, clay loam and loam, are found in the catchment area, though predominant soil is sandy loam. The reservoir supplies water to two main canal systems, namely, Right Bank Main Canal system and Left Bank Feeder Canal system.

2.2. *Observed hydro-climatic data*

Daily observed gridded rainfall data of Mula and Kangsabati reservoir catchment is obtained from India Meteorological Department (IMD), Pune (Pai *et al*., 2014). General characteristics curves (stage-area curve, stage-volume curve) and Mula and Kangsabati reservoirs' daily inflow data are collected from Mula irrigation department, Govt. of Maharashtra and Irrigation and Waterways Department, Bankura, Govt. of West Bengal, for the period of 28 years (1985-2013) and 26 years (1986-2011), respectively. The data requirement for SWAT model includes Digital Elevation Model (DEM), soil map and land use land cover map. Furthermore, Shuttle Radar Topography Mission (SRTM GL1) 30 m DEM is downloaded from https://earthexplorer.usgs.gov/ for both reservoirs catchment. Land use land cover classified maps are prepared using unsupervised classification of Landsat satellite images of the year 2005 and 2001 for Mula and Kangsabati catchment, respectively. Soil maps of Mula and Kangsabati catchments are obtained from http://www.fao.org/land-water/land/ and National Bureau of Soil Survey & Land Use Planning (NBSS & LUP), respectively.

2.3. *Reforecast data*

The daily meteorological variables like, rainfall, maximum and minimum temperatures, wind speed, from CFSv2 have been acquired for twenty-eight years (1985-2013) from Monsoon Mission Phase project, Indian Institute of Tropical Meteorology, Pune, India. Brief details of CFSv2 model are given below.

2.3.1. *Brief description of CFSv2 model*

The Climate Forecast System version 2 (CFSv2) (Saha *et al*., 2014) is a fully coupled atmosphere-land-ice-ocean model and Global Forecast System (GFS) (Moorthi *et al*., 2001) at a spectral triangular truncation of 382 waves (T382 Gaussian grid), with 64 sigma levels in the vertical represents the model's atmospheric component. In addition to these, the model utilizes a NOAH land surface model that consists of four layers (Ek *et al*., 2003), a sea-ice model (Winton, 2000), and Modular Ocean Model version 4p0d (Griffies *et al*., 2004). All these components are coupled in the Earth System Modeling Framework (ESMF). IMD uses this model for operational seasonal and extended range ISMR forecasting (Rao *et al*., 2019). In this study, 28 years re-forecasts datasets are used for the period of 1985-2013. The model is initialized every 5th day of February month (*i.e*., 5, 10, 15, 20 and 25 February of each year at 0000 and 1200 UTC), providing an ensemble of ten model integrations for each year (Saha *et al*., 2010). Once the model is initialized, it runs for a period of ~9 months (up to November). The ensemble mean from the lagged initial conditions is calculated for March to November, which is the arithmetic mean of the ten ensembles.

2.4. *Brief description of SWAT model*

Soil and Water Assessment Tool (SWAT) is a continuous-time step hydrological model which was developed by USDA-Agricultural Research Service (ARS) at river basin, or watershed scale (Arnold *et al.*, 1998). It is a physically-distributed and semi-distributed, for rainfall-runoff modeling (Neitsch *et al*., 2011). In this study, we used the SWAT model to perform the forecast experiments. The SWAT model can simulate the components of hydrological cycle such as precipitation, surface runoff, evapotranspiration, percolation, groundwater flow, interception, water yield *etc*. The water balance equation (1), in SWAT model (Neitsch *et al*., 2011) is represented as:

$$\mathrm{SW}_t = \mathrm{SW}_0 + \sum_{t=1}^{t}\left(R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_a - W_{\mathrm{seep}} - Q_{gw}\right) \quad (1)$$

where, SW_0 is initial soil water content (mm), R_{day} is the amount of rainfall (mm), Q_{surf} is amount of surface runoff (mm), E_a is amount of evapotranspiration (mm), W_{seep} is amount of water entering the vadose zone from soil profile (mm), Q_{gw} is amount of return flow (mm)and SW_t is final soil water content (mm).

In SWAT model, there are two methods for computing surface runoff, one employs a modified Soil Conservation Service (SCS) curve number approach (Mishra and Singh, 2003), and the other uses the Green and Ampt infiltration method (Green and Ampt, 1911). The curve number (CN) varies nonlinearly with the variations in soil moisture content. The curve number decreases when soil approaches the wilting point while increases to 100 as the soil approaches saturation. The CN method has been widely used for runoff simulation. Additionally, this method is selected to calculate the surface runoff is also based on the availability of rainfall data in the present study area. In this work, runoff is computed by using the modified SCS CN approach and Muskingum method is performed for river routing (Neitsch *et al*., 2011). The model employs the Hydrological Response Unit (HRU) in which vertical processes are performed. An HRU can be defined based on land use characteristics, soil type and topographic characteristics (*i.e*., slope).

2.5. *SWAT model setup*

During preprocessing, SRTM 30 m DEM of Mula and Kangsabati catchments areas are used for delineating sub-basins and extracted reach parameters. Land use classification map of 2005 and 2001, and soil maps are used for determining land use and soil type of each land cover of 21 and 17 sub-basins of Mula and Kangsabati reservoirs catchment, respectively. In the SWAT model setup, Manning's 'n' values are assigned according to the existing characteristics of the study area. This information is used as an input to SWAT model. The SWAT model has been run for the period 1985 to 2013 for Mula Basin and from 1986 to 2011 for Kangsabati Basin with three years warm-up period for reservoir inflow simulation using IMD climatic data at 0.25° gridded resolution and CFSv2 ensemble mean reforecast data. The February IC CFSv2 hindcast data is available from March to November for each year. Therefore, for continuous simulation of the watershed model (SWAT), observed IMD data for January, February and December is added to the February IC hindcast data of March to November of each year for 1985-2013 and 1986-2011 period for Mula and Kangsabati catchments, respectively. It is expected that this will not impact the simulation of reservoir inflow during monsoon season as the inflow is very less (close to zero) for this dry season.

2.6. *Calibration of SWAT model*

To predict reservoir inflow using SWAT-CUP, Sequential Uncertainty Fitting (SUFI)-2 algorithm, model needs to be calibrated to determine correct combination of 20 calibration parameters from various classes like ground water (groundwater recharge, re-evaporation, recharge to deep aquifer, base flow recession constant, threshold depth of water in the shallow aquifer), runoff (available soil water capacity, Manning's coefficient, curve number, soil and plant evaporation, and surface runoff *etc*.) Topographic characteristics (slope length for lateral subsurface flow and slope steepness), land cover characteristics (maximum canopy storage, manning's roughness coefficient for overland flow, travel time of lateral flow), Erosion (plant uptake and soil evaporation), Channel characteristics (manning's n for channel flow, effective hydraulic conductivity, base flow recession), Storm water (channel hydraulic conductivity, storm flow lag time *etc*.). The parameters are carefully chosen to take into account the hydrology of agricultural watershed and characteristics of both reservoir catchments (Table 1).

The selection and influence of the identified parameters on hydrological processes are well described in SWAT literature (Abbaspour *et al*., 2015; Qi*et al*., 2017; Sommerlot *et al*., 2016). The chosen set of 20 parameters is kept constant for both catchments in this study to achieve a trade-off between sensitivity analysis for each catchment to a given set of calibration parameters and obtaining reasonable performance for both

TABLE 1

Calibration Parameters for runoff prediction

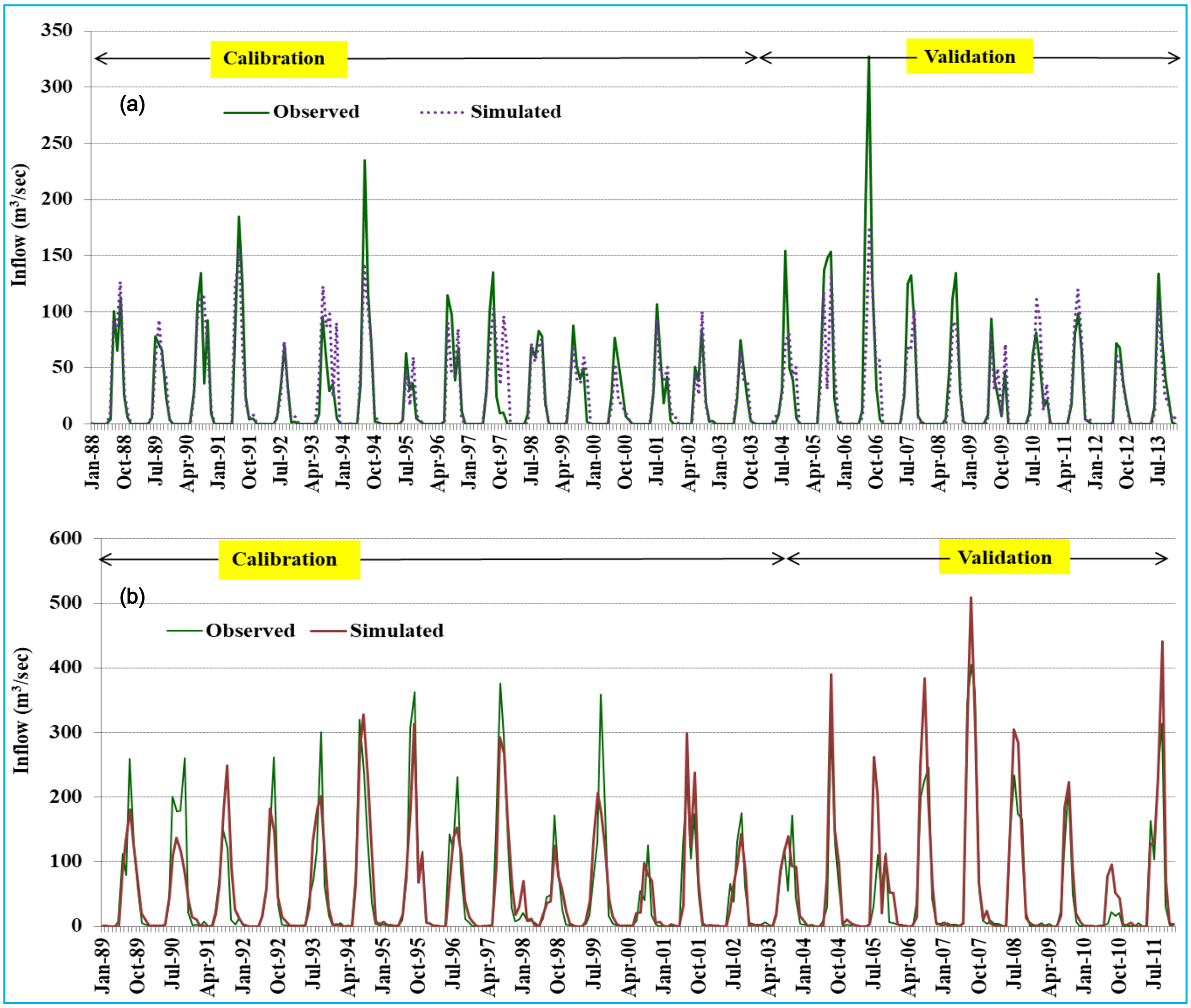
Flow calibration parameters	Method	Min value	Max value
Groundwater revap coefficient (GW_REVAP)	Replace	0	2
Soil evaporation compensation factor (ESCO)	Relative	-0.9	0.01
Available water capacity of the soil (SOL_AWC) (with respect to soil type)	Replace	0	1
Moist bulk density (SOL_BD) (with respect to soil type)	Relative	-0.3	0.3
Saturated hydraulic conductivity (SOIL_K)	Replace	0	2000
Base flow alpha factor for bank storage (ALPHA_BNK)	Replace	0	1
Threshold depth of water for revap to occur (REVAPMN)	Replace	0	500
Surface runoff lag time (SURLAG)	Replace	0	10
Average slope length (SLSUBBSN)	Replace	5	150
Baseflow alpha factor (ALPHA_BF)	Replace	0	1
Groundwater delay (days) (GW_DELAY)	Replace	30	450
Threshold depth of water (mm) (GWQMN)	Replace	0	5000
Manning's n value for main channel (CH_N2)	Replace	0.01	0.5
Effective hydraulic conductivity in main channel alluvium (CH_K2)	Replace	0.01	150
Manning's n value for overland flow (OV_N)	Replace	0	30
Groundwater recharge to deep aquifer (RCHRG_DP)	Replace	0	1
SCS runoff curve number (CN2) (with respect to LU/LC type)	Relative	-0.9	0.50
Constant of low flow upon when K_m is calculated for the reach (MSK_CO2)	Replace	0	10
Plant evaporation compensation factor (EPCO)	Relative	-0.7	0.10
Maximum Canopy index (CANMAX) (with respect to LU/LC type)	Relative	0	100
Lateral flow travel time (LAT_TTIME)	Replace	0	180
Sediment concentration in lateral and groundwater flow (LAT_SED)	Replace	0	5000
Slope length for lateral subsurface flow (SLSOIL)	Replace	0	150

catchments. The best combination of calibration parameters are chosen based on three performance indicators, namely, Nash Sutcliffe Efficiency (NSE), Percentage Bias (PBIAS), and Coefficient of determination (R^2). The NSE value can range from -infinity to +1, the higher NSE values (>0.75) consider as "very good" (Nash and Sutcliffe 1970; Moriasi *et al.*, 2007) and for a perfect model, values of NSE and R^2 should be 1.00.

After the completion of default runs, the SWAT-CUP is calibrated using SUFI-2 algorithm. The SWAT-CUP is calibrated for simulating monthly reservoir inflow from 1988-2004 and 1989-2003 for the Mula catchment and Kangsabati catchment, respectively. The calibration parameters in SWAT are varied according to the recommended limits. The calibration of the model setup was followed by validation of the inflow using calibrated parameters. And validated for the Mula catchment was taken from 2005-2013 and 2004-2011 for the Kangsabati catchment.

2.7. *Hydrologic simulations using CFSv2 coupled calibrated SWAT model*

The calibrated SWAT model is coupled with the drivers from CFSv2 from Jan 1985 to Dec 2013 for Mula catchment and from Jan 1986 to Dec 2011 for Kangsabati catchment with a warm-up period of 3 years. Combining the retrospective model simulations from IMD coupled SWAT models and the CFSv2 coupled SWAT models, seamless monthly simulation outputs are obtained from Jan 1988 to Dec 2013 and Jan 1989 to Dec 2011 for Mula and Kangsabati catchments, respectively. To assess the



Figs. 2(a&b). Time series of simulated versus observed (a) Mula and (b) Kangsabati reservoir inflow (calibration and validation years)

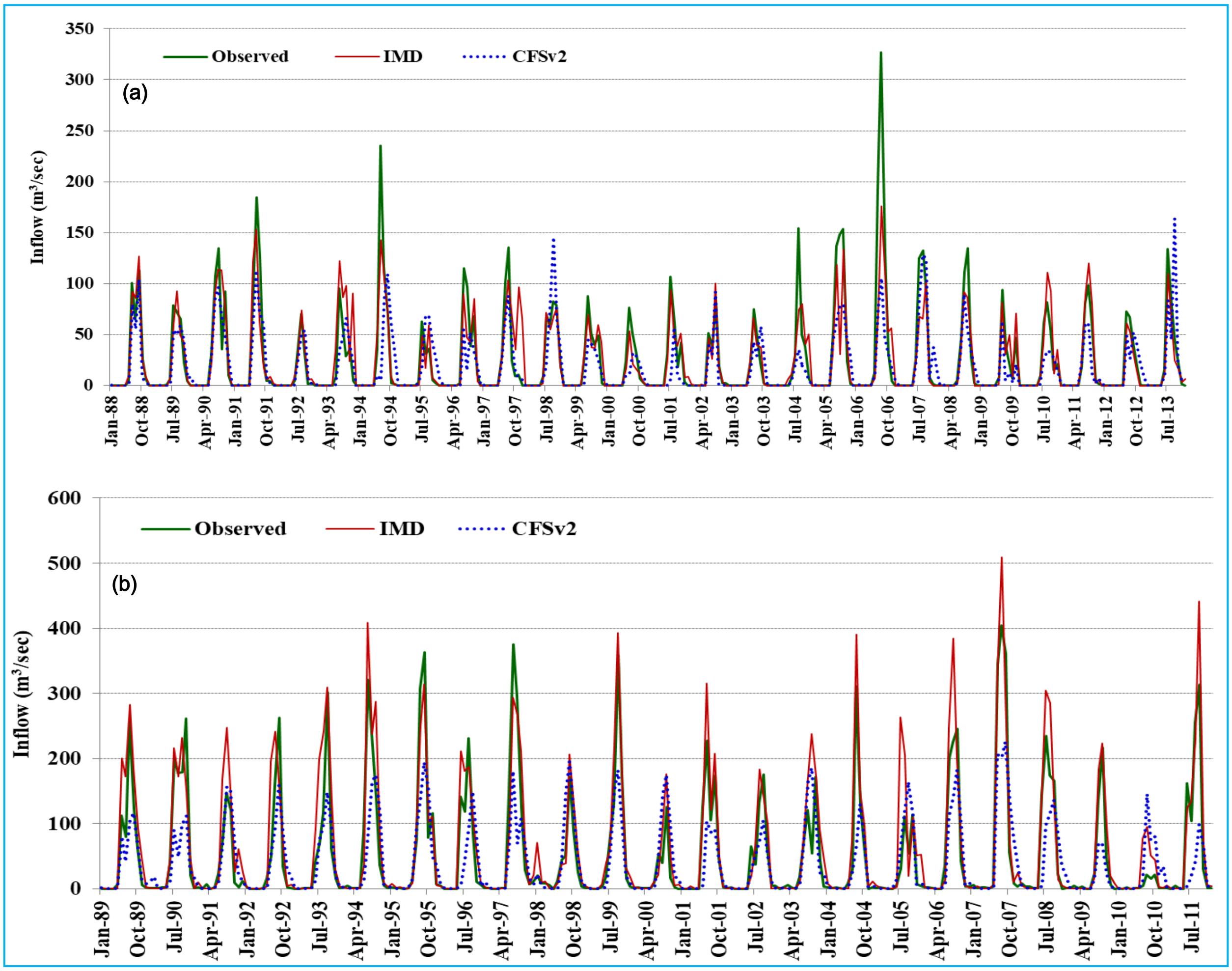
efficacy of SWAT-CFSv2 in monthly inflow forecasting, we compare SWAT-CFSv2 and SWAT-IMD simulated monthly inflow with observed monthly inflow for the monsoon season (JJAS).

3. Results and discussion

3.1. *Calibration and validation of SWAT model outputs*

In order to assess the robustness of the SWAT model outputs for Mula and Kangsabati reservoirs, the observed inflow data are used for calibration and validation for the period of 1985-2013 and 1986-2011, respectively. The calibrated parameters shown in Table 1 are accepted for testing the CFSv2 reforecast data for monthly inflow simulation over the Mula reservoir. The comparison between model simulated and observed inflow at monthly scale over the Mula reservoir catchment is presented in Fig. 2(a).

The comparison of observed and simulated monthly inflows over the Mula reservoir catchment is presented in Fig. 2(a). The SWAT-CUP is calibrated and validated for Mula catchment for 1985-2004 and 2005-2013 respectively. Time series of inflow demonstrates that the model produced a similar pattern to observations, but with smaller magnitude in some months. During the period of calibration, it is observed that the model underestimates inflow values in the years 1990, 1991, 1994, 1996, 1999, and 2000. The overestimation of monthly inflow estimates are somewhat large, especially during the year 1993 with IMD rainfall. This may be due to the uneven representation of the spatially distributed rainfall. The agreement between observed and simulated inflow in the study area is quantified by using NSE, PBIAS and R^2



Figs. 3(a&b). Time series of CFSv2 simulated versus observed (a) Mula and (b) Kangsabati reservoir inflow

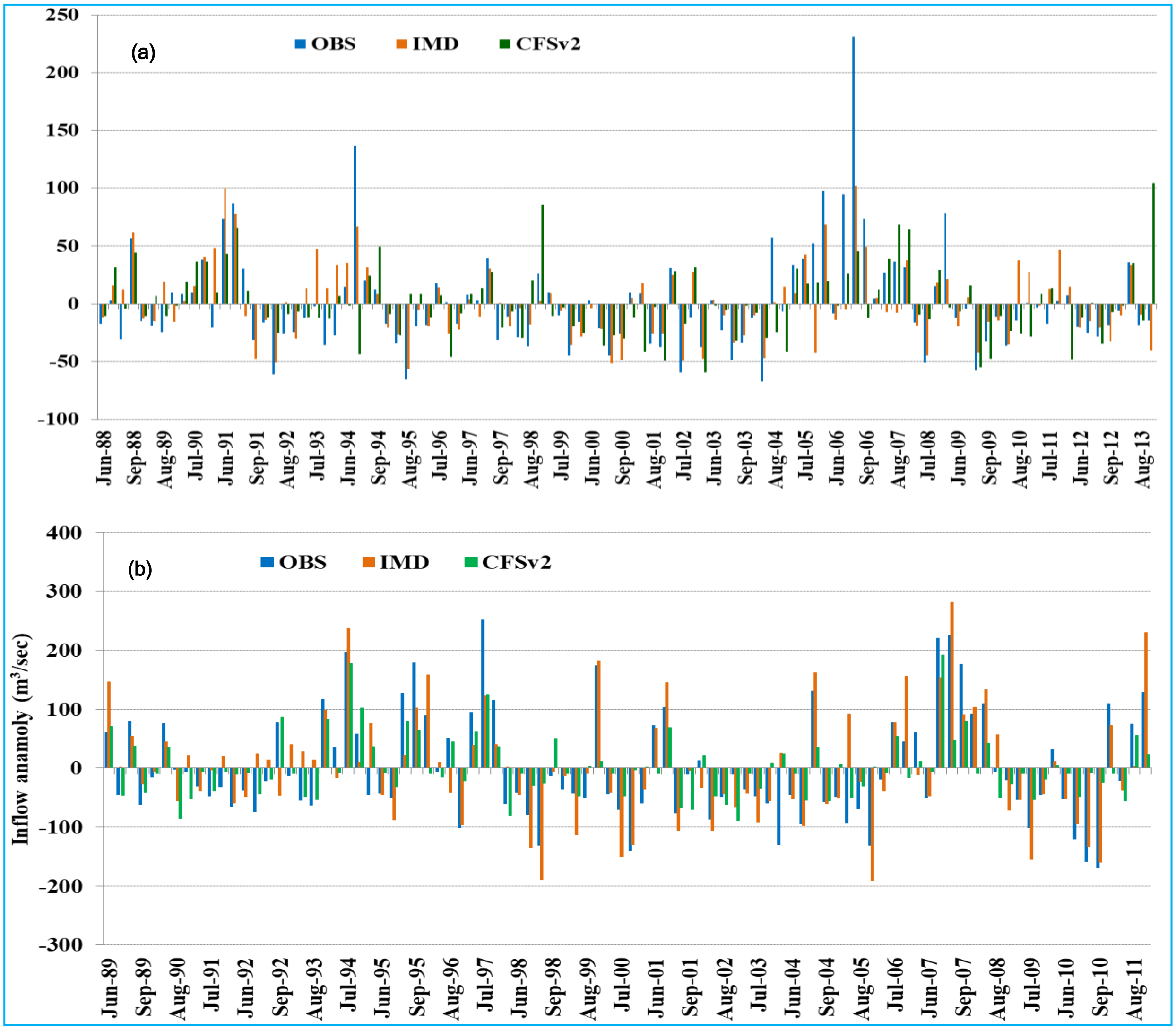
TABLE 2

SWAT performance for simulation of monthly inflow over the catchment of Mula reservoir and Kangsabati reservoir for the calibration and validation period

Statistical indices	Calibration period		Validation period	
	Mula (1988-2004)	Kangsabati (1989-2003)	Mula (2005-2013)	Kangsabati (2004-2011)
NSE	0.76	0.78	0.75	0.79
PBIAS	-0.03	0.008	0.16	-0.27
R^2	0.76	0.80	0.78	0.87

(Table 2) values. The comparison shows favourable agreement between observed and simulated inflow in Mula reservoir catchment during the calibration (NSE = 0.76, PBIAS = -3% and R^2 = 0.76) and validation period (NSE = 0.75, PBIAS = 16% and R^2 = 0.78) (scatter plots are not shown). The SWAT model's performance throughout the calibration and validation period is regarded as very good based on the criteria established by Moriasi *et al*., (2007).

Similarly, Fig. 2(b) depicts comparison of monthly observed and simulated inflow over the Kangsabati



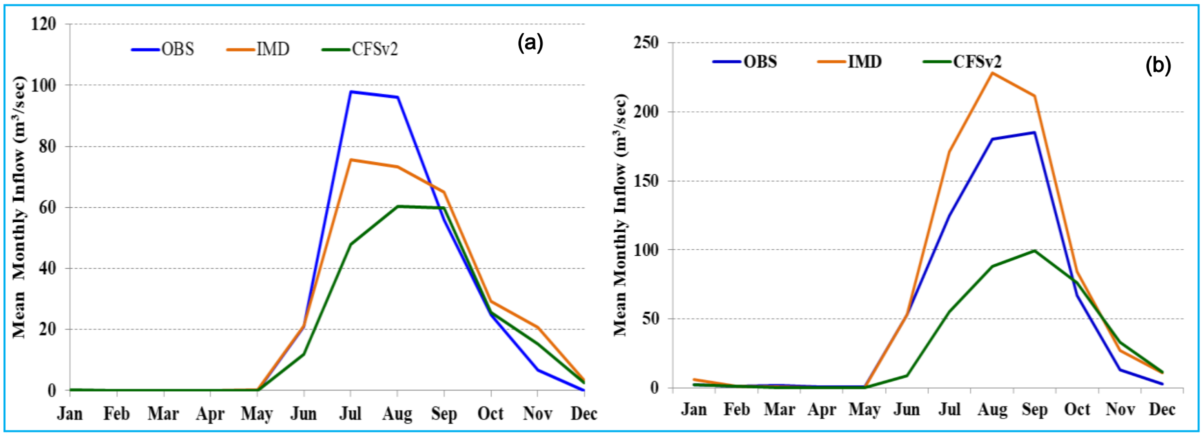
Figs. 4(a&b). Inflow anomaly of (a) Mula and (b) Kangsabati reservoirs using observed, IMD and CFSv2 reforecast data

TABLE 3

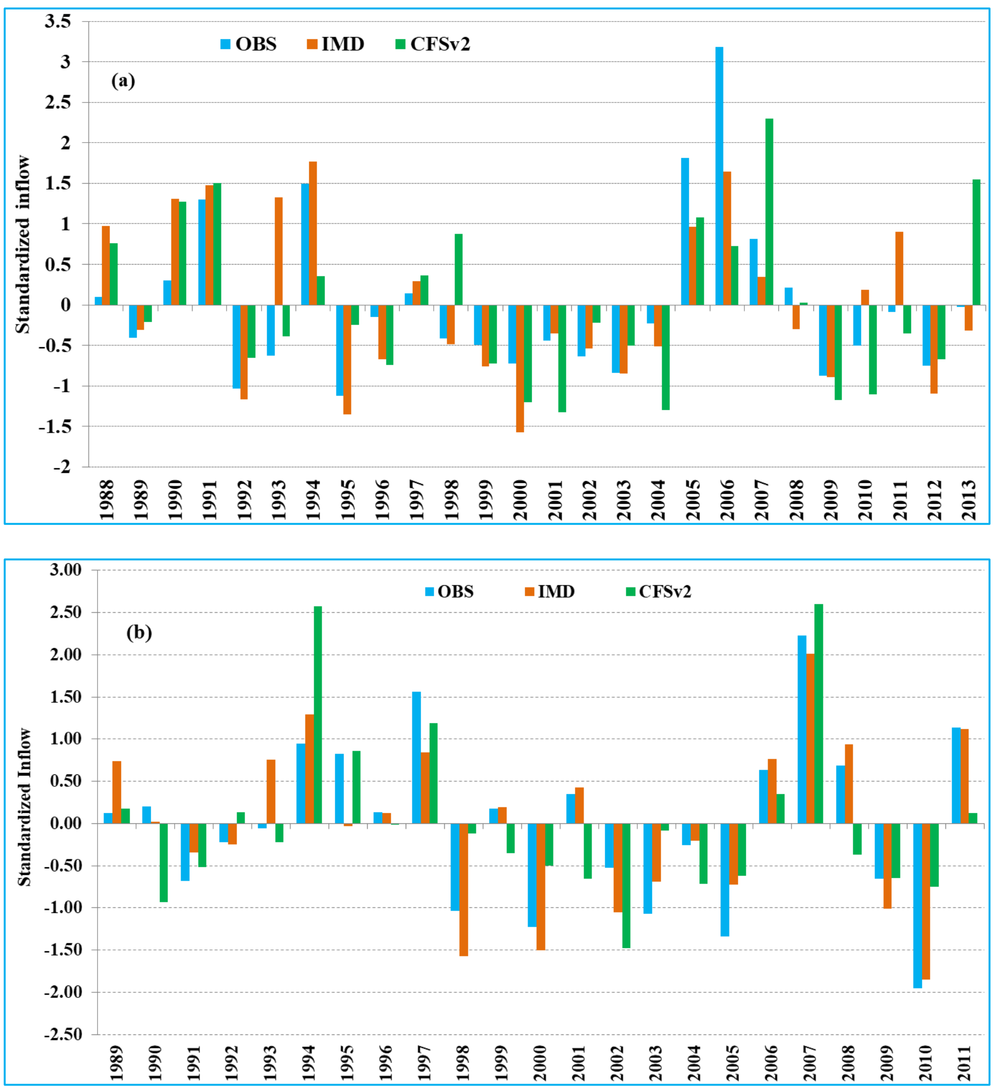
Statistical indices used for simulating inflow using SWAT over the catchment of Mula reservoir for the period of 1988-2013 and Kangsabati reservoir for the period of 1989-2011

Statistical indices	IMD		CFSv2	
	Mula	Kangsabati	Mula	Kangsabati
NSE	0.75	0.78	0.52	0.53
PBIAS	0.04	-0.25	0.26	0.40
R^2	0.76	0.85	0.56	0.65

reservoir catchment. Monthly rainfall and observed inflow data of 1989-2003 and 2004-2011 are used for calibration and validation, respectively. The same 20 parameters are utilized in SWAT-CUP calibration which are used for Mula catchment and the best possible calibration parameters for Kangsabati catchment. Results demonstrate that the simulated reservoir inflows are overestimated (underestimated) for most of the years during validation



Figs. 5(a&b). Monthly-climatology of inflow for (a) Mula and (b) Kangsabati reservoirs using observed, IMD and CFSv2 reforecast data over 1988-2013 and 1989-2011 periods, respectively



Figs. 6(a&b). Standardized plot of (a) Mula and (b) Kangsabati reservoirs using observed, IMD and CFSv2 reforecast data over 1988-2013 and 1989-2011 periods, respectively

TABLE 4

Correlation Coefficient (R) of IMD and CFSv2 simulated inflow with observed inflow for Mula and Kangsabati reservoirs

Correlation Coefficient	Mula catchment		Kangsabati catchment	
	IMD	CFSv2	IMD	CFSv2
R_{annual}	0.69	0.43	0.80	0.67
R_{JJAS}	0.79	0.55	0.81	0.71
$R_{monsoon}$	0.76	0.60	0.91	0.70

(calibration) period. It is observed that the model can capture peak inflow values for the years 1994, 1997, 2002, 2003 and 2009. During the calibration& validation period, the reasonable NSE = 0.78 & 0.79, PBIAS = 0.8% & -27% and R^2 = 0.80 & 0.87 (Table 2) values are obtained (scatter plots are not shown). The results indicate that the model can simulate the monthly inflow estimates by using the CFSv2 reforecast data over the Mula and Kangsabati reservoir catchments.

3.2. *Evaluation of CFSv2 reforecast data using well-calibrated SWAT model*

The monthly inflow simulations using SWAT-CUP with IMD and CFSv2-derived reforecast rainfall data for Mula and Kangsabati catchments are shown in Figs. 3 (a&b), respectively. The monthly reservoir inflow predictions are evaluated for Mula and Kangsabati catchments using CFSv2 reforecast datasets. The statistical indicators (NSE, PBIAS and R^2) are listed in Table 3 (scatter plots are not shown). Result shows model produces reasonably good results with CFSv2 reforecast data in the years 1988, 1990, 1992, 1995, 1997, 2002, 2007, 2008 and 2012 over the Mula catchment. Whereas in case of the Kangsabati reservoir catchment results are not very favourable for 1994, 2000, 2004, 2006 and 2010 with both CFSv2 and IMD-derived rainfall data. It is noted that with CFSv2 reforecast rainfall data, the SWAT model over estimates the inflow in 1998 and 2013 while during entire period inflow values are underestimated over the Kangsabati reservoir catchment. As shown in Table 3, NSE values (Mula = 0.52 and Kangsabati = 0.53) and R^2 values (Mula = 0.56 and Kangsabati = 0.65) indicates that model performance is satisfactory for simulating monthly inflow using CFSv2 reforecast data.

The under-prediction of the model inflow is a direct outcome of the dry bias simulated by the CFSv2 over the Indian continent (Saha *et al*., 2014; George *et al*., 2015; Ramu *et al*., 2016; Srivastava *et al*., 2017). Most of the current generation coupled models suffer from such a dry bias over India (Sabeerali *et al*., 2013), and concerted research efforts are being taken up in MM project to address this dry bias (Rao *et al*., 2019; Krishna *et al*., 2019). This dry bias may be corrected using statistical bias correction techniques. However, this will not be addressed in the current study. Amongst the two catchments, SWAT-CFSv2 model performed better for the Mula catchment than Kangsabati catchment based on NSE, PBIAS, and R^2 statistics. Furthermore, the monthly skill scores for the inflow anomalies over the Mula and Kangsabati reservoirs are observed to be reasonable, and at times, comparable to the JJAS skill scores (Fig. 4).

Illustrated in Figs. 5 (a&b) are monthly-climatology of inflow simulated by IMD and CFSv2 reforecast data of 26 years (1988-2013) and 23 years (1989-2011) for Mula and Kangsabati reservoirs, respectively. Result shows that CFSv2 reforecast inflow is underestimated with respect to observed inflow for both Mula and Kangsabati reservoirs due to dry bias. Amongst both the catchments, dry bias is more for Kangsabati catchment than the Mula catchment resulting in a larger bias in monthly inflows for lower Gangetic plains zone.

Furthermore, the simulated seasonal inflows have a high prediction skill for the monsoon season with 0.60 for Mula catchment and 0.70 for the Kangsabati catchment [Table 4 and Figs. 6(a&b)]. However, the inter-annual standard deviation is underestimated (Mula catchment = 19.90 m^3/sec and Kangsabati catchment = 30.87m^3/sec) in seasonal inflow prediction. It is interesting to note that SWAT model forecasts based on CFSv2 could capture the sign of inflow anomaly correctly for all years except 1998 and 2013 for Mula catchment; and 1990, 1999, 2001 and 2008 for Kangsabati catchment. Thus, it can be concluded that SWAT-CFSv2 model can capture the variability of inflow in Mula and Kangsabati reservoirs at monthly to seasonal time scales.

4. Conclusions

The primary objective of this study is to evaluate the effectiveness of CFSv2 re-forecasts for inflow forecasting using hydrological models. The SWAT model is forced with observed climatic data (IMD) as well as CFSv2 re-forecasts to simulate reservoir inflow of tropical reservoirs (Mula and Kangsabati) which belong to two different agro-climatic zones of India. SWAT-CUP is calibrated and validated using IMD-derived climatic data for Mula and Kangsabati reservoirs for 1988-2013 and 1989-2011 periods, respectively. Further, the robustness of CFSv2 reforecast is tested for inflow forecasting of both reservoirs for a predefined period. The value of NSE of SWAT-IMD model varies from 0.75-0.76 for Mula reservoir and 0.78-0.79 for Kangsabati reservoir during calibration and validation showed that the model is well calibrated for both catchments. It is observed that CFSv2 reforecast has reasonable skill (NSE = ~0.52) when the SWAT model is forced with CFSv2 re-forecasts for both catchments. The positive values of PBIAS (26%-40%) showed under-prediction of reservoir inflow for both catchments, which is an outcome of the dry bias in the CFSv2 over the Indian continent. The correlation coefficients (R) between CFSv2 simulated and observed annual inflows are 0.43 and 0.67 for Mula and Kangsabati catchments, respectively. In addition, the skill scores (correlation coefficients) for monthly mean and JJAS mean inflows are reasonable, indicating the model fidelity at monthly and seasonal time scales.

Therefore, it can be concluded that the CFSv2 re-forecasts are well suited for inflow simulations in both catchments with reasonable skill for estimating monthly averaged inflows. From the performance statistics of CFSv2 for simulation of reservoir inflow, it can be concluded that CFSv2 reforecast data have good potential for useful application to hydrological simulation at monthly and seasonal scales. These results hence provide new insights for coupled atmospheric-hydrologic forecasting in India. Reasonable skill scores have been obtained for monthly and seasonal mean simulations; however, considerable scope remains for further improving the inflow forecasts. One of the ways in which it can be done is by improving the base model, *i.e.*, the CFSv2 in terms of model physics and addressing the dry bias in the model. In future, to develop hydrological applications, statistical bias correction techniques can be employed to correct the systematic biases in CFSv2 model. Higher-resolution models may also be better suited to simulate the basin scale rainfall processes, and this will be taken up, once higher resolution model re-forecasts become available. Even though the current study addresses only two reservoirs, similar procedure may suitably be applied to other reservoirs as well, globally. The good skill scores stem from the good skill of the parent model (CFSv2) in simulating the inter-annual monsoon rainfall variability. The availability of global seasonal NWP model products makes this possible. This study demonstrates the translation of seasonal forecasts global NWP models for inflow forecasting and thus proving to be of great socio-economic importance. The operational forecasts from the MM model will subsequently be used for inflow forecasting in real-time, serving as a guideline for management of reservoir storage.

Data availability

The observed gridded rainfall data is freely available from the India Meteorological Department (IMD), Pune from their website (https://www.imdpune.gov.in/). General characteristics curves, Mula and Kangsabati reservoirs' daily inflow data are collected from Mula irrigation department, Govt. of Maharashtra and Irrigation and Waterways Department, Bankura, Govt. of West Bengal, for the period of 28 years (1985-2013) and 26 years (1986-2011), respectively. Shuttle Radar Topography Mission (SRTM GL1) 30 m DEM is downloaded from https://earthexplorer.usgs.gov/ for both reservoirs' catchment. Land use land cover classified maps are prepared using unsupervised classification of Landsat satellite images of the year 2005 and 2001 for Mula and Kangsabati catchment, respectively. Soil maps of Mula and Kangsabati catchments are obtained from http://www.fao.org/land-water/land/ and National Bureau of Soil Survey & Land Use Planning (NBSS & LUP), respectively. The daily meteorological variables like, rainfall, maximum and minimum temperatures, wind speed, from CFSv2 can be obtained by contacting the authors or by contacting the Monsoon Mission Directorate at the Indian Institute of Tropical Meteorology, Pune, India.

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Competing interests

The authors declare that there are no competing interests and there is no conflict of interest in this research.

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