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Development of synoptic analogue model for quantitative precipitation forecast in the sub-basins of river Krishna

M. RAJAVEL*

Meteorological Centre, India Meteorological Department, Ministry of Earth Sciences, Bengaluru, India

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***Corresponding author's email: rajavel2018@rediffmail.com**

सार – कृष्णा नदी बेसिन के 10 उप-बेसिनों में दक्षिण-पश्चिम मानसून ऋतु (2012 से 2022) के दौरान औसत क्षेत्रीय वर्षा (AAP) के आंकड़ों की गणना की गई और इन उप-बेसिनों में वर्षा उत्पन्न करने वाली समस्थानिक प्रणालियों का डेटा एकत्र किया गया। अध्ययन में पांच समस्थानिक प्रणालियों को शामिल किया गया है - निम्न दबाव क्षेत्र/गहरा निम्न दबाव क्षेत्र, निम्न दबाव क्षेत्र/स्पष्ट रूप से चिह्नित निम्न दबाव क्षेत्र (WML), ऊपरी वायु चक्रवाती परिसंचरण (UAC), अपतटीय गर्त (OST)/अंतर्निहित चक्रवाती परिसंचरण वाला OST और पूर्व-पश्चिम अपरूपण क्षेत्र। इन प्रणालियों के कारण 11-25 मिमी, 26-50 मिमी, 51-100 मिमी और > 100 मिमी की वर्षा (AAP) को शामिल किया गया है। सभी उप-बेसिनों में वर्षा की उच्चतम आवृत्ति OST/अंतर्निहित चक्रवाती परिसंचरण वाले OST के कारण होती है। नदी बेसिनों में भारी वर्षा (26-50 मिमी) के कारण बाढ़ आना मुख्यतः नदी बेसिन के विभिन्न स्थानों पर अंतर्निहित चक्रवाती परिसंचरण के साथ अपतटीय गर्त/पूर्व-तटीय गर्त के कारण होता है। विभिन्न उप-बेसिनों में 26-50 मिमी की आवृत्ति 51-100 मिमी की तुलना में अधिक है। अपरूपण क्षेत्र और ऊपरी वायु चक्रवाती परिसंचरण भी भारी वर्षा में महत्वपूर्ण योगदान देते हैं। अपतटीय गर्त, ऊपरी वायु चक्रवाती परिसंचरण और पूर्व-पश्चिम अपरूपण क्षेत्र के कारण घाटप्रभा, बन्नेहल्ला, ऊपरी कृष्णा, ऊपरी तुंगभद्रा और निचली भीमा नदियों में 51-100 मिमी से अधिक वर्षा हुई। अपतटीय गर्त के कारण ऊपरी कृष्णा और ऊपरी तुंगभद्रा नदियों में 100 मिमी से अधिक वर्षा हुई। ऊपरी वायु चक्रवाती परिसंचरणों के कारण ऊपरी तुंगभद्रा उप-बेसिन में 100 मिमी से अधिक वर्षा हुई। गुजरात से केरल और कर्नाटक तक फैले अपतटीय गर्त के कारण अधिकांश अवसरों पर 100 मिमी से अधिक भारी वर्षा हुई। प्रत्येक श्रेणी के अंतर्गत इन परिदृश्य प्रणालियों द्वारा वर्षा में योगदान देने वाले दिनों की संख्या की गणना की गई। किसी विशेष प्रणाली के लिए उच्चतम आवृत्ति वाली वर्षा श्रेणी को परिदृश्य अनुरूप मॉडल माना गया। परिदृश्य अनुरूप मॉडल का सत्यापन विभिन्न उप-बेसिनों में मॉडल के बेहतर प्रदर्शन को दर्शाता है और इसका उपयोग बाढ़ पूर्वानुमान के लिए जारी किए गए परिचालन मात्रात्मक वर्षा पूर्वानुमान (क्यूपीएफ) की सटीकता में सुधार के लिए किया जा सकता है।

ABSTRACT. Average areal precipitation (aap) data during south west monsoon season (2012 to 2022) in 10 sub-basins of Krishna river basin were computed and synoptic systems inducing rainfall in the sub-basins were collected. Five synoptic systems-depression/deep depression, low/well marked low (WML) pressure area, Upper air cyclonic circulations (UAC), off-shore trough (OST)/OST with embedded cyclonic circulations, east-west shear zone are considered in the study. Rainfall (AAP) occurrence in the range of 11-25 mm, 26-50 mm, 51-100 mm and > 100 mm due to these systems are considered. OST/OST with embedded cyclonic circulation leads to highest frequency of rainfall in all the sub-basins. Occurrence heavy rainfall (AAP from 26-50 mm) culminating flood in the river basins is mainly due to Off-shore trough/OST with embedded cyclonic circulation at different locations around the river basin. Frequency of 26-50 mm range is more than 51-100 mm in different sub-basins. Shear zone and upper air cyclonic circulations are also contributed significantly to heavy rainfall. Off-shore troughs, upper air cyclonic circulations and East-West shear zone resulted >51-100 mm rainfall in Ghataprabha, Bannehalla, Upper Krishna, Upper Tungabadra and Lower Bhima. Off-shore trough resulted >100mm rainfall in Upper Krishna and Upper Tungabhadra. Upper air cyclonic circulations resulted >100 mm rainfall in Upper Tungabhadra sub-basin. Heavy rainfall >100 mm in maximum number of occasions are due to off-shore trough from Gujarat to Kerala and Karnataka. Number of days for which these synoptic systems contributed rainfall under each range was computed. The rainfall range with highest frequency for the particular system is considered as synoptic analogue model. Validation of synoptic analogue model indicates better performance of the models in different sub-basins and it can be used to improve the accuracy of operational Quantitative precipitation forecast (QPF) issued for flood forecasting.

Key words – Average areal precipitation, QPF, Krishna river basin, Synoptic analogue model.

1. Introduction

River basin is regarded as the basic hydrological unit for planning and development of water resources and Krishna basin is one of 12 major river basins of India with catchment area more than 10 lakh km^2. Krishna basin is the second largest and eastward draining interstate river basin in Indian peninsular region. The basin is situated between longitudes 73° 21’ to 81° 09’ E and latitudes 13° 07’ to 19° 25’ N in the Deccan Plateau covering large areas in the States of Maharashtra, Karnataka and Andhra Pradesh. Krishna Basin is bounded on the north by the ridge separating it from the Godavari basin, on the south and east by the Eastern Ghats and on the west by the Western Ghats. Krishna basin is roughly triangular in shape with its base along the Western Ghats, the apex at Vijayawada and the Krishna itself forming the median. All the major tributaries of the river draining the base of the triangle lies in the Krishna River in the upper two-thirds of its length. Drainage area of Krishna basin is 2,58,948 km^2 which is nearly 8% of the total geographical area of India. Mean annual rainfall in the Krishna basin is 784 mm. South West Monsoon sets in by middle of June and withdraws by the middle of October and nearly 90% of annual rainfall is received during Monsoon months. More than 70% of rainfall occurs during July, August and September.

In tropical regions like India, weather forecasting by using statistical and numerical methods is quite useful for operational purpose. In view of this, quantitative precipitation forecast (QPF) might be done by adopting conventional synoptic analysis method since it can serve as a potential tool for operational flood forecasting purposes. A study by Dhar and Nandergi (1993) indicates how the synoptic weather situations are responsible for the occurrence of flood while analysing the spatial distribution of severe rainstorms over India and their associated areal rain depth.

The challenge is that the rainfall products by most of NWP models have considerable forecast errors leading to limitations in issue of accurate forecast of the rainfall intensity (Novak *et al*., 2014). QPF from Advection of the radar reflectivity field (ADV), Identification, tracking and forecasting of convective structures (CST) and numerical weather prediction (NWP) models using observational data assimilation (radar, satellite etc.) are combined to obtain a single and optimized QPF at each lead time (Atencia *et al*., 2010) is studied in Spain. The Japan Meteorological Agency (JMA) developed QPE and QPF products as well as QPE/QPF-induced products using radar data, rain gauge data and numerical weather prediction (NWP) output (Nagata, 2011). Liu *et al*. (2021) attempted Quantitative Precipitation Forecasting Using an improved probability-matching method and applied it to a Typhoon event in China. Chul-Min Ko *et al*. (2020) developed Quantitative Precipitation Forecast correction technique based on Machine Learning for Hydrological applications.

Miller and Keshavamurthy (1968) have noticed that most of the west coast rainfall during monsoon season is associated with the OST and mid-tropospheric circulations (MTC). George (1956) has pointed out the presence of cyclonic vorticity along the west coast in OST, and Rao (1976) observed shear vorticity above 1 km in OST. Most of the time during the summer monsoon, these synoptic systems cause rainfall over the Konkan and Karnataka coasts (Francis and Gadgil, 2006; Das *et al*., 2007). In general, they form over the coastal Karnataka and moves northward to 2 degrees per day. During the OST, rains occur in the off or onshore of the southwest coast of India. IMD classifies offshore trough into active and feeble categories, based on the strength of meridional gradient of mean sea level pressure. Besides, the onset of the Indian summer monsoon is manifested by an offshore trough at the west coast of India extending from north Kerala coast to south Gujarat coast. Offshore trough helps low-level Somali jet to converge along the convergence line and flow over the Indian landmass. A strong offshore trough guides the progress of monsoon into Kerala and further north after the onset. Frequent development and persistence of low pressure systems in West central Bay of Bengal and its subsequent westward movement across North Coastal Andhra Pradesh are favourable for higher seasonal rainfall in Monsoon over the Peninsular region excluding west coast.

Abbi *et al.* (1979) identified movement of cyclonic storms/depressions affecting Bhagirathi catchment & prepared analogue maps depicting the associated rainfall distribution. Analogue methods try to address the problem of making forecasts in the presence of complex temporal dependence without a model parameterization of any geophysical dynamics. In their simplest form, analogue methods match the current climate state to observed climate states from a library of historical observations in order to forecast some future quantity (*e.g*., precipitation tomorrow) with the observed successor of the historical match (*e.g*., precipitation on the day following the historical match). While the atmosphere is known to be a chaotic dynamical system that is unstable under slight perturbations of initial conditions (Lorenz, 1969), analogue approaches are justified by the tendency of that system to regularly revisit subsets of the phase space over time.

Synoptic analogue model is based on the concept of analogy applied to rainfall forecasting and exploits the reliable representation of synoptic scale weather systems to quantify the rainfall in the river basins. Synoptic analogue is based on the principle that weather behaves in

Fig. 1. Location of the basin

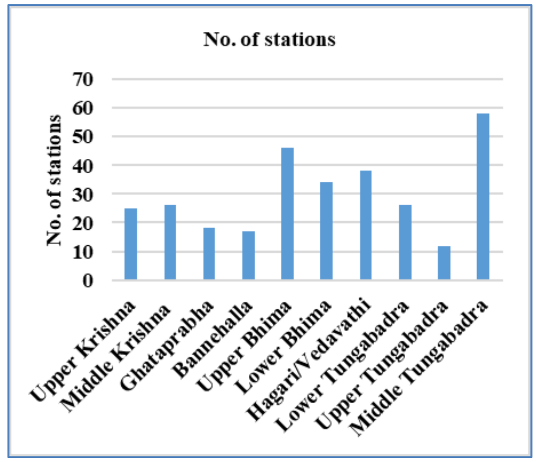


Fig. 2. Sub-basin wise number stations

such way that if the present initial conditions, if it is similar to a past situation, will evolve in a similar fashion and it is possible to find good analogues over a small area even with limited data set (Roebber and Bosart, 1998). Different types of synoptic situations, its correlation with the resulting rainstorms over Gomti river catchment area during 1976–1980 is studied by Lal *et al.* (1989) and synoptic analogue for forecast range for areal rainfall is prepared. Procedure for developing synoptic analogue model is prepared by IMD (Manual of Hydrometeorology, 2010). Synoptic analogue model for different river basins in India was also developed (Singh *et al.*, 1995; Ray and Sahu, 1998; Ram and Kaur, 2004; Raha *et al.*, 2009; Ray and Patel, 2000; Ali *et al*. (2011); Chakraborty and Sen (2012); Ray *et al.*, 2014; Chattopadhyay and Senguptha, 2021). Sravani *et al.* (2023) developed synoptic analogue for Godavari basin and the model has observed a 62% correct forecast for the monsoon season 2020 and it gives a 90% correct forecast for 50-100 mm and >100 mm AAP events. This model is generally accurate for the generation of QPF before the 24hr provided the synoptic conditions over the region which will be very helpful to facilitate the 48hrs forecast to the flood forecasters and end-users like the central Water commission and Disaster management authorities in Godavari basin. The synoptic analogue model can be simply implemented and is capable of quickly generating objective forecasts; furthermore it does not rely upon complex and subtle reasoning inherent in physical/statistical methods (Radinovic, 1975; Bergen and Harnack, 1982; Toth, 1989) yielding a real solution to a difficult problem and not introducing any simplification over the physics of the atmosphere. Gao *et al.* (2014) and Gao and Schlosser (2019) used analogue methods to couple GCM forecasts of predictive atmospheric variables with the historical precipitation so as to understand the changes in the distributions of extreme precipitation under different climate forcing scenarios. Recently Bopp *et al.* (2020) used Bayesian Analogue Model to predict flood inducing precipitation.

India Meteorological Department (IMD) is the nodal agency for issuing QPF for river basins/ sub-basins and QPF is the main input in the Flood Forecasting models for issuing flood forecast. Forecasters in Flood Meteorological Office (FMO) are issuing the bulletin by utilizing the various tools *viz*., synoptic charts, satellite/radar imageries & products, synoptic analogue, sub-basin wise NWP model information and their vast field experiences for final operational forecast. IMD issue QPF for 156 sub-basins in India and synoptic analogue models developed for few river basins only. Accurate synoptic analogue model requires comprehensive study of the rainfall (Average Areal Precipitation) and associated synoptic systems in the river basin. Development synoptic analogue models for Krishna river basin is not attempted in the past and therefore this study intended to prepare such model for sub-basins of Krishna river basin for issuing QPF.

2. Data and methodology

Daily rainfall data from rain guage stations in each sub-basins of Krishna river basin from 1st June to 30th September for 2012 to 2022(except 2017) was collected. Average Areal Precipitation was computed from daily rainfall data. QGIS software is currently used to compute AAP. Location of the river basin is provided in Fig. 1. Sub-basin wise number stations considered in the study is provided in the Fig. 2.

Synoptic systems associated with rainfall as inferred from analysed surface (03 UTC), upper air charts (00 UTC) and inference issued from Meteorological Centre, Bengaluru were considered to choose predominant

TABLE 1

Synoptic Systems and their notation

Notation	Synoptic Systems	Notation	Location of the system
S1	Depression/Deep Depression	1	Coastal Andhra Pradesh
S2	Low/Well Marked Low	2	Telangana
S3	Upper Air Cyclonic Circulation (UAC)	3	Rayalaseema
		4	South Interior Karnataka
		5	North Interior Karnataka
		6	Coastal Karnataka
		7	Madhya Maharashtra
		8	Marathwada
		9	West Central Bay of Bengal off Coastal Andhra Pradesh
S4	Off-shore Trough/OST with embedded cyclonic circulation	1	Gujarat to Lakshadweep/Konkan & Goa/Maharashtra
	East-West Shear Zone	2	Konkan-Goa/Maharashtra to Lakshadweep
		3	Karnataka to Lakshadweep
		4	Gujarat to Kerala and Karnataka
		5	Konkan-Goa/Maharashtra to Kerala
		6	Konkan- Goa/Maharashtra to Karnataka
S5		1	Latitude from 12-21ºN

Combination of synoptic systems and their location

Notation	Description	Notation	Description
S1,1	Depression/Deep Depression over Coastal Andhra Pradesh	S3,1	Upper Air Cyclonic Circulation (UAC) over Coastal Andhra Pradesh
S1,2	Depression/Deep Depression over Telangana	S3,2	Upper Air Cyclonic Circulation (UAC) over Telangana
S1,3	Depression/Deep Depression over Rayalaseema	S3,3	Upper Air Cyclonic Circulation (UAC) over Rayalaseema
S1,4	Depression/Deep Depression over South Interior Karnataka	S3,4	Upper Air Cyclonic Circulation (UAC) over South Interior Karnataka
S1,5	Depression/Deep Depression over North Interior Karnataka	S3,5	Upper Air Cyclonic Circulation (UAC) over North Interior Karnataka
S1,6	Depression/Deep Depression over Coastal Karnataka	S3,6	Upper Air Cyclonic Circulation (UAC) over Coastal Karnataka
S1,7	Depression/Deep Depression over Madhya Maharashtra	S3,7	Upper Air Cyclonic Circulation (UAC) over Madhya Maharashtra
S1,8	Depression/Deep Depression over Marathwada	S3,8	Upper Air Cyclonic Circulation (UAC) over Marathwada
S1,9	Depression/Deep Depression over West Central Bay of Bengal off Coastal Andhra Pradesh	S3,9	Upper Air Cyclonic Circulation (UAC) over off Coastal Andhra Pradesh
S2,1	Low/Well Marked Low over Coastal Andhra Pradesh	S4,1	Off-shore Trough/OST with embedded cyclonic circulation from Gujarat to Lakshadweep/Konkan & Goa/Maharashtra
S2,2	Low/Well Marked Low over Telangana	S4,2	Off-shore Trough/OST with embedded cyclonic circulation from Konkan-Goa/Maharashtra to Lakshadweep
S2,3	Low/Well Marked Low over Rayalaseema	S4,3	Off-shore Trough/OST with embedded cyclonic circulation from Karnataka to Lakshadweep
S2,4	Low/Well Marked Low over South Interior Karnataka	S4,4	Off-shore Trough/OST with embedded cyclonic circulation from Gujarat to Kerala and Karnataka
S2,5	Low/Well Marked Low over North Interior Karnataka	S4,5	Off-shore Trough/OST with embedded cyclonic circulation from Konkan-Goa/Maharashtra to Kerala
S2,6	Low/Well Marked Low over Coastal Karnataka	S4,6	Off-shore Trough/OST with embedded cyclonic circulation from Konkan Goa/Maharashtra to Karnataka
S2,7	Low/Well Marked Low over Madhya Maharashtra	S5,1	East-West Shear Zone over Latitude from 12-21ºN
S2,8	Low/Well Marked Low over Marathwada		
S2,9	Low/Well Marked Low over West Central Bay of Bengal off Coastal Andhra Pradesh		

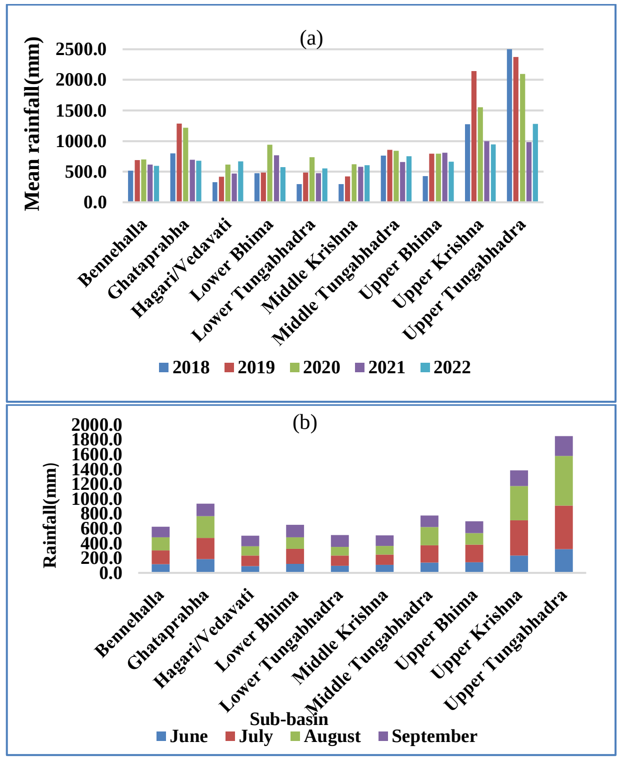
systems for rainfall. Most influential synoptic systems based on rainfall during South West Monsoon season over the river basins are Depression/Deep Depression, Low/ Well Marked Low, Upper Air Cyclonic Circulation (UAC), Off-shore Trough/OST with embedded cyclonic circulation, East-West Shear Zone, and their locations are Gujarat to Lakshadweep/Konkan & Goa/Maharashtra, Konkan-Goa/ Maharashtra to Lakshadweep, Karnataka to Lakshadweep, Gujarat to Kerala and Karnataka, Konkan-Goa/Maharashtra to Kerala, OST from Konkan-Goa/ Maharashtra to Karnataka, Coastal Andhra Pradesh, Telangana, Rayalaseema, South Interior Karnataka, North Interior Karnataka, Coastal Karnataka, Madhya Maharashtra, Marathwada, West Central Bay of Bengal off Coastal Andhra Pradesh and Latitude from 12-21° N. These important systems are considered for development of synoptic analogue model. Synoptic systems considered in the study are denoted as synoptic system (S1 to S5) followed by its geographical location (Table 1). Rainfall (AAP) under the influence of these systems considered are 11-25 mm, 26-50 mm, 51-100 mm and > 100 mm as per Standard Operational Procedures of IMD. To prepare synoptic analogue model, monthly tables of synoptic systems and AAP (day wise) are prepared. Based on this, frequency of different ranges of rainfall for each system and location is prepared. All the months frequencies are summed up to prepare seasonal frequencies and total frequencies from 2012 to 2021. Number of days for which these systems cause rainfall under each range was considered to develop synoptic analogue model. The rainfall range with highest frequency for the particular system and its location is considered as Synoptic Analogue Model. In case of rainfall for a particular day is caused by more than one systems simultaneously, the dominant system which is giving more frequent rainfall is considered. Rainfall range with highest frequency of rainfall is considered as QPF.

To issue operational QPF to Central Water Commission, QPF from synoptic analogue model and NWP model forecasts are used. Using the model developed from data from 2012 to 2021, operational forecasts are issued and it is validated for 2022. Operational QPF is issued sub-basin-wise as an average areal precipitation forecast in 11-25 mm, 26-50 mm, 51-100 mm and > 100 mm categories. The sub-basin-wise QPF are verified with the observed sub-basin-wise AAP during the south west monsoon 2022. In this procedure, forecasted AAP as QPF and observed AAP is compared in excel based package and errors are computed. Performance of forecast is assessed by per cent correct, usable and incorrect forecast for each sub-basin. Correct forecasts are percentage of days in the season where forecast rainfall range is equal to observed rainfall range. Usable forecast is percentage of days in the season where forecast rainfall range is one range below/above to observed rainfall range. Incorrect forecast is percent days where forecast rainfall range is two range below/above observed rainfall range.

3. Results and discussion

3.1. *Seasonal rainfall and frequency of rainfall associated with synoptic systems*

Seasonal rainfall during south west monsoon of recent years (2018-2022) in sub-basins is depicted in Fig. 3a. Upper Krishna and Upper Tungabhadra received higher rainfall (>1000 mm) in the season



Figs. 3(a&b). (a) Mean-monsoon rainfall (AAP) and (b) Seasonal and Monthly rainfall in sub-basins

compared to other sub-basins & Hagari/Vedavathi received 500.7 mm. Average rainfall of Krishna basin was 705.9 to 1011 mm Highest rainfall occurred in 2020 (1011 mm) and lowest rainfall occurred in 2021 (705.9 mm). Highest rainfall occurred in July (262.2 mm) followed by August (253.1 mm), September (171.3 mm) months in the river basin. Lowest rainfall occurred in June (156 mm). Average rainfall of the Krishna basin during recent years was 842.6 mm (Fig. 3b).

Analysis of rainfall (AAP) in Krishna basin indicated that rainfall >10 mm received in 1341 days due to formation of five synoptic systems around the river basin (Fig.4a-j). Upper Tungabhadra received rainfall in highest frequency (318 days) and Middle Krishna received rainfall in lowest frequency (70 days). Ghataprabha, Upper Krishna, Upper Bhima, Lower Bhima and Middle Tungabhadra also received rainfall in more than 100 days.

Maximum days of rainfall (612 days) are due to formation of off-shore trough in Krishna river basin (Table 2). Off-shore trough from Konkan-Goa/ Maharashtra to Kerala resulted in highest frequency (280 days). Off-shore trough from Gujarat to Kerala and Karnataka resulted rainfall in 241 days. Off-shore trough from Konkan & Goa/Maharashtra to Karnataka could cause rainfall in 42 days and off - shore trough from Gujarat to Lakshadweep/

Figs. 4(a-j). Frequency of occurrence of AAP more than 10mm due to different systems (summary)

TABLE 2

Frequency of occurrence of AAP more than 10mm

Symbol	Upper Krishna					Middle Krishna					Ghataprabha					Bannehalla				
	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total
S1,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,2	1	0	0	0	1	2	0	0	0	2	1	0	0	0	1	0	0	0	0	0
S2,3	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
S2,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,9	12	0	0	0	12	6	0	0	0	6	6	0	0	0	6	3	0	0	0	3
Total	14	0	0	0	14	8	1	0	0	9	7	0	0	0	7	3	0	0	0	3
S3,1	2	0	1	0	3	1	0	0	0	1	1	0	1	0	2	2	0	0	0	2
S3,2	4	0	0	0	4	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0
S3,3	2	1	0	0	3	2	0	0	0	2	1	0	0	0	1	1	1	0	0	2
S3,4	0	2	0	0	2	4	0	0	0	4	1	0	0	0	1	1	0	0	0	1
S3,5	2	1	0	0	3	2	0	0	0	2	4	0	0	0	4	2	0	0	0	2
S3,6	2	0	0	0	2	1	0	0	0	1	2	0	0	0	2	2	0	0	0	2
S3,7	1	0	0	0	1	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0
S3,8	1	2	0	0	3	1	0	0	0	1	2	0	0	0	2	2	0	0	0	2
S3,9	20	0	0	0	20	9	1	0	0	10	6	0	0	0	6	6	0	0	0	6
Total	34	6	1	0	41	21	1	0	0	22	20	0	1	0	21	16	1	0	0	17
S4,1	4	2	0	0	6	0	0	0	0	0	2	0	1	0	3	2	0	0	0	2
S4,2	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
S4,3	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S4,4	27	12	2	1	42	3	0	0	0	3	22	3	1	0	26	15	2	0	0	17
S4,5	33	11	5	0	49	11	1	0	0	12	16	5	4	0	25	12	3	2	0	17
S4,6	5	0	0	0	5	4	0	0	0	4	4	0	0	0	4	3	0	0	0	3
Total	71	25	7	1	104	19	1	0	0	20	44	8	6	0	58	32	5	2	0	39
S5,1	39	9	1	0	49	15	3	0	0	18	32	5	1	0	38	18	3	0	0	21
GT	158	40	9	1	208	63	6	0	0	69	103	13	8	0	124	69	9	2	0	80

Table 2 continued

Symbol	Upper Bhima					Lower Bhima					Hagari/Vedavathi					Lower Tungabhadra				
	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total
S1,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,1	2	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,2	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
S2,4	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
S2,5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,9	7	0	0	0	0	5	2	0	0	3	0	0	0	0	0	0	6	0	0	0
Total	10	0	0	0	7	8	3	0	0	3	0	0	0	0	3	6	7	0	0	0
S3,1	2	0	0	0	2	2	2	0	0	4	2	1	0	0	3	0	1	0	0	1
S3,2	4	0	0	0	4	3	2	0	0	5	0	0	0	0	0	1	0	0	0	1
S3,3	3	0	0	0	3	2	0	0	0	2	1	0	0	0	1	2	0	0	0	2
S3,4	0	1	0	0	1	1	1	0	0	2	1	0	0	0	1	0	2	0	0	2
S3,5	1	1	0	0	2	1	1	0	0	2	4	0	0	0	4	2	2	0	0	4
S3,6	1	0	0	0	1	1	0	0	0	1	1	0	0	0	1	2	0	0	0	2
S3,7	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
S3,8	3	0	0	0	3	3	0	0	0	3	2	0	0	0	2	1	0	0	0	1
S3,9	12	0	0	0	12	20	3	0	0	23	11	1	0	0	12	12	2	0	0	14
Total	26	2	0	0	28	34	9	0	0	43	22	2	0	0	24	20	7	0	0	27
S4,1	3	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S4,2	1	0	0	0	1	0	1	0	0	1	2	0	0	0	2	1	0	0	0	1
S4,3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
S4,4	23	2	0	0	25	9	1	0	0	10	11	0	0	0	11	4	0	0	0	4
S4,5	22	1	0	0	23	12	2	2	0	16	13	1	0	0	14	14	1	0	0	15
S4,6	3	0	0	0	3	4	1	0	0	5	2	1	0	0	3	2	0	0	0	2
Total	52	3	0	0	55	25	5	2	0	32	28	2	0	0	30	22	1	0	0	23
S5,1	32	1	0	0	33	37	7	1	0	45	22	3	0	0	25	23	4	0	0	27
GT	120	6	0	0	126	104	24	3	0	131	75	7	0	0	82	72	12	0	0	84

Symbol	Upper Tungabhadra					Middle Tungabhadra					GT
	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	
S1,1	0	0	0	0	0	0	0	0	0	0	0
S1,2	0	0	0	0	0	0	0	0	0	0	0
S1,3	0	0	0	0	0	0	0	0	0	0	0
S1,4	0	0	0	0	0	0	0	0	0	0	0

Table 2 continued….

S1,5	0	0	0	0	0	0	0	0	0	0	0
S1,6	0	0	0	0	0	0	0	0	0	0	0
S1,7	0	0	0	0	0	0	0	0	0	0	0
S1,8	0	0	0	0	0	0	0	0	0	0	0
S1,9	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0
S2,1	1	0	0	0	1	0	0	0	0	0	6
S2,2	1	0	0	0	1	0	0	0	0	0	7
S2,3	0	0	0	0	0	0	0	0	0	0	3
S2,4	0	0	0	0	0	0	0	0	0	0	0
S2,5	0	0	0	0	0	0	0	0	0	0	0
S2,6	0	0	0	0	0	0	0	0	0	0	0
S2,7	0	0	0	0	0	0	0	0	0	0	0
S2,8	0	0	0	0	0	0	0	0	0	0	0
S2,9	8	0	0	0	8	7	0	0	0	7	65
Total	10	0	0	0	10	7	0	0	0	7	81

	Upper Tungabhadra					Middle Tungabhadra					
	11-25	26-50	51-100	>100	Total	11-25	26-50	51-100	>100	Total	GT
S3,1	5	0	0	1	6	0	0	0	0	0	24
S3,2	4	0	0	0	4	1	0	0	0	1	21
S3,3	0	0	0	1	1	1	1	0	0	2	19
S3,4	5	0	0	0	5	0	0	0	0	0	19
S4,5	8	1	0	0	9	2	0	0	0	2	34
S3,6	1	0	1	0	2	1	0	0	0	1	15
S3,7	3	1	0	0	4	2	0	0	0	2	10
S3,8	3	0	0	0	3	0	0	0	0	0	20
S3,9	20	4	0	0	24	11	1	0	0	12	139
Total	49	6	1	2	58	18	2	0	0	20	301
S4,1	7	4	0	1	12	4	1	0	0	5	31
S4,2	3	0	0	0	3	1	0	0	0	1	11
S4,3	0	2	1	1	4	1	0	0	0	1	7
S4,4	45	27	16	4	92	7	4	0	0	11	241
S4,5	54	20	4	0	78	28	3	0	0	31	280
S4,6	7	0	0	0	7	6	0	0	0	6	42
Total	116	53	21	6	196	47	8	0	0	55	612
S5,1	31	15	7	0	53	38	0	0	0	38	347
GT	206	74	29	8	317	110	10	0	0	120	1341

Konkan & Goa /Maharashtra resulted rainfall in 31 days. Rainfall in more than 50 days is due to Off-shore trough in Upper Bhima, Upper Tungabhadra, Middle Tungabhadra, Upper Krishna and Ghataprabha sub-basins. Most of the time during the summer monsoon, OST and its position, mid-tropospheric circulations (MTC) and the presence of cyclonic vorticity along the west coast, and shear vorticity cause rainfall over the South India (Francis and Gadgil, 2006; Das *et al*., 2007, Konduru and Mrudula (2021). Due to formation of east-west shear zone in 12-21° N, rainfall recorded in 347 days. Cyclonic circulations over different areas in sea and land contributed rainfall for 301 days. Cyclonic circulations over West Central Bay of Bengal off Coastal Andhra Pradesh contributed rainfall for 139 days in the sub-basins and cyclonic circulations over North Interior Karnataka resulted in 34 days of rainfall. Low pressure area/well marked low pressure area resulted rainfall in 81 days and those formed over West Central Bay of Bengal off Coastal Andhra Pradesh resulted rainfall for 65 days. There was no depressions/deep depressions formed during the study years. Frequency of rainfall received in Krishna sub-basins is in descending order due to formation of off-shore trough, east-west shear zone, upper air cyclonic circulations, low pressure/well marked low pressure area.

Instance of heavy rainfall (AAP from 26-50 mm) triggering flood in the river basins is mainly due to Off-shore trough/OST with embedded cyclonic circulation at different locations. More occurrence in 26-50 mm range is observed as compared to 51-100 mm in different sub-basins. Shear zone and upper air cyclonic circulations are also contributed significantly to heavy rainfall. Heavy rainfall in the range of 26-50 mm due to low pressure systems are observed in less frequency. Off-shore troughs, upper air cyclonic circulations and East-West shear zone resulted in >51-100 mm rainfall in Ghataprabha, Bannehalla, Upper Krishna, Upper Tungabhadra and Lower Bhima. Off-shore trough c ause >100 mm rainfall in Upper Krishna and Upper Tungabhadra. Upper air cyclonic circulations caused >100 mm rainfall in Upper Tungabhadra sub-basin. Heavy rainfall >100 mm in maximum number of occasions are due to off-shore trough from Gujarat to Kerala and Karnataka. Heavy rainfall >100 mm occurred in 8 days in Upper Tungabhadra and for one day in Upper Krishna.

3.2. *Development of synoptic analogue model*

Based on the data, synoptic analogue model for issuing quantitative precipitation forecast is prepared and presented in Table 3. Rainfall in the range of 11-25mm is expected due to Off-shore troughs in all sub-basins. Rainfall in 26-50mm range is expected due to OST from Karnataka to Lakshadweep in upper Krishna and OST from Konkan-Goa/Maharashtra to Lakshadweep in Lower Bhima. Amount of rainfall is depends on the extent of off-shore trough in most of the cases. If East-West shear zone is formed, it will result in 11-25mm rainfall in all sub-basins. Upper air cyclonic circulations will result in 11-25 mm rainfall in all sub-basins. Heavy rainfall from 26-50 mm is possible due to cyclonic circulations over South Interior Karnataka and Marathwada in Upper Krishna sub-basin, cyclonic circulations over Coastal Andhra Pradesh in Ghataprabha sub-basin, cyclonic circulations over Rayalaseema in Bannehalla sub-basin, cyclonic circulations over Interior Karnataka in Upper Bhima and Lower Bhima sub-basins, cyclonic circulations over Coastal Andhra Pradesh and Interior Karnataka in Lower Tungabhadra sub-basin, cyclonic circulations over Coastal Karnataka in Upper Tungabhadra sub-basin and cyclonic circulations over Rayalaseema in middle Tungabhadra sub-basin. Formation of low pressure area/well marked low pressure area will result in heavy rainfall (26-50 mm) in middle Krishna and lower Bhima

3.3. *Validation of the model*

Synoptic analogue models developed for the different sub-basins was validated during south west monsoon season 2022. QPF issued was verified with the AAP realized for the sub-basins in the study (Table 4) and it was found that QPF was 66-77% correct in Day 1Bannehalla, Ghataprabha, Middle Krishna and Lower Tungabhadra registered >70% correct forecasts. Correct forecast is exact QPF forecast is realized. Usable forecasts are Correct and out by ± 1 stage. Incorrect forecasts are out by 2-4 stages.

Usable forecasts are >95% in all sub-basins. Model suggested AAP in all sub-basins except Ghataprabha is 100% usable (Correct and out by ± 1 stage). Model predictions in Ghataprabha is 95% usable and 5% incorrect (out by 2-4 stages). In Upper Krishna sub-basin, QPF forecast from synoptic analogue model(11-25 mm) is usable in 12 instances and none is incorrect. Similar models in Sabarmati basin in Gujarat also indicated usable forecasts to the extent of 93-95%. Therefore, it is evident that synoptic analogue model is useful to improve operational QPF forecasts.

Qualitative verification results are presented in Fig. 5. Critical Success Index (CSI) is >0.6 for QPF range 0.1-10 mm and around 0.2 for QPF range 11-25 mm in Day 1. CSI is around 0.2 for QPF range 26-50 mm. False Alarm Rate (FAR) is <0.2 for QPF range 0.1-10 mm and it increases for higher QPF ranges (>0.6). Probability of Detection (POD) is around 0.8 for QPF range 0.1-10 mm and it decreases with increasing QPF ranges. POD is around 0.5 for QPF range 11-25 mm and it is around 0.4 for QPF range 26-50 mm in Day 1.

TABLE 3

Synoptic analogue model

Zone	Upper Krishna					Middle Krishna					Ghataprabha				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1	Nil	11-25	11-25	11-25	11-25	Nil	Nil	11-25	Nil	11-25	Nil	Nil	51-100	11-25	11-25
2	Nil	11-25	11-25	11-25		Nil	Nil	11-25	11-25		Nil	11-25	11-25	Nil	
3	Nil	Nil	11-25	26-50		Nil	11-25	11-25	Nil		Nil	11-25	11-25	Nil	
4	Nil	Nil	26-50	11-25		Nil	26-37	11-25	11-25		Nil	Nil	11-25	11-25	
5	Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25	
6	Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25	
7	Nil	Nil	11-25			Nil	Nil	Nil			Nil	Nil	11-25		
8	Nil	Nil	26-50			Nil	Nil	11-25			Nil	Nil	11-25		
9	Nil	11-25	11-25			Nil	Nil	11-25			Nil	11-25	11-25		

	Bannehalla					Upper Bhima					Lower Bhima				
Zone	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1	Nil	Nil	11-25	11-25	11-25	Nil	11-25	11-25	11-25	11-25	Nil	26-50	11-25	Nil	11-25
2	Nil	Nil	Nil	Nil		Nil	Nil	11-25	11-25		Nil	11-25	11-25	26-50	
3	Nil	Nil	26-50	Nil		Nil	11-25	11-25	Nil		Nil	Nil	11-25	Nil	
4	Nil	Nil	11-25	11-25		Nil	Nil	26-50	11-25		Nil	Nil	26-50	11-25	
5	Nil	Nil	11-25	11-25		Nil	Nil	26-50	11-25		Nil	Nil	26-50	11-25	
6	Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25	
7	Nil	Nil	Nil			Nil	Nil	Nil			Nil	Nil	11-25		
8	Nil	Nil	11-25			Nil	Nil	11-25			Nil	Nil	11-25		
9	Nil	11-25	11-25			Nil	11-25	11-25			Nil	11-25	11-25		

	Hagari/Vedavathi					Lower Tungabhadra					Upper Tungabhadra				
Zone	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
1	Nil	Nil	11-25	Nil	11-25	Nil	Nil	26-50	Nil	11-25	Nil	11-25	11-25	11-25	11-25
2	Nil	Nil	Nil	11-25		Nil	Nil	11-25	11-25		Nil	11-25	11-25	11-25	
3	Nil	Nil	11-25	Nil		Nil	11-25	11-25	11-25		Nil	11-25	Nil	Nil	
4	Nil	Nil	Nil	11-25		Nil	Nil	26-50	11-25		Nil	Nil	11-25	11-25	
5	Nil	Nil	Nil	11-25		Nil	Nil	26-50	11-25		Nil	Nil	11-25	11-25	
6	Nil	Nil	11-25	11-25		Nil	Nil	11-25	11-25		Nil	Nil	51-100	11-25	
7	Nil	Nil	Nil			Nil	Nil	Nil			Nil	Nil	11-25		
8	Nil	Nil	11-25			Nil	Nil	11-25			Nil	Nil	11-25		
9	Nil	11-25	11-25			Nil	11-25	11-25			Nil	11-25	11-25		

	Middle Tungabhadra				
Zone	S1	S2	S3	S4	S5
1	Nil	Nil	Nil	11-25	11-25
2	Nil	Nil	11-25	11-25	
3	Nil	Nil	26-50	11-25	
4	Nil	Nil	Nil	11-25	
5	Nil	Nil	11-25	11-25	
6	Nil	Nil	11-25	11-25	
7	Nil	Nil	11-25		
8	Nil	Nil	Nil		
9	Nil	11-25	11-25		

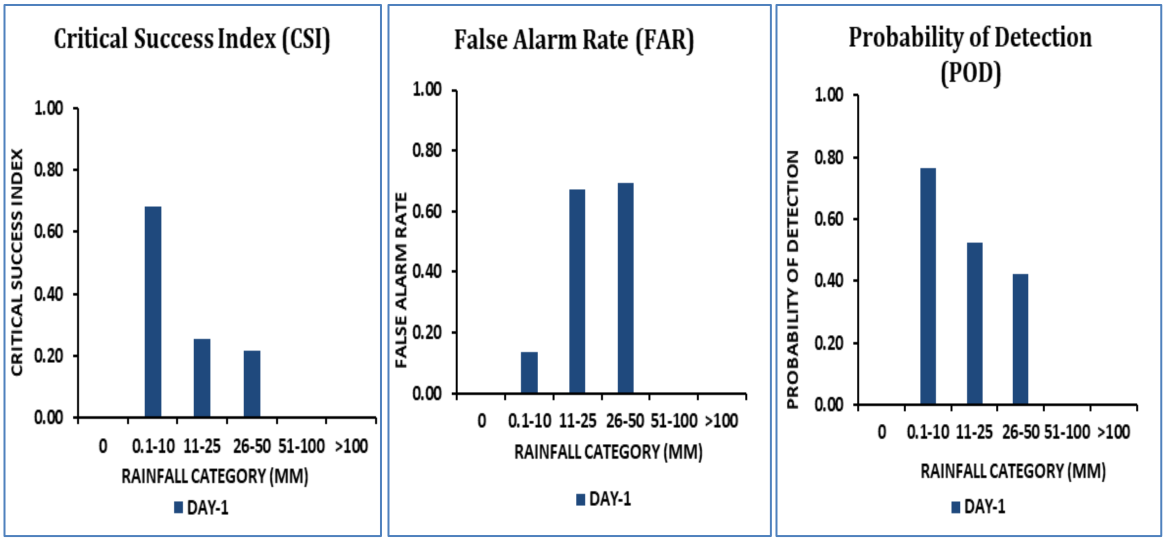


Fig. 5. CSI, FAR and POD in 2022

TABLE 4

Verification of QPF with AAP during 2022

Sub-basin	Day 1	
	Correct	Usable
Bannehalla	73	100
Ghataprabha	77	100
Hagari/Vedavathi	68	97
Lower Bhima	68	97
Lower Tungabhadra	77	98
Middle Krishna	74	100
Middle Tungabhadra	66	97
Upper Bhima	66	100
Upper Krishna	66	100
Upper Tungabhadra	68	97
Mean	72	98

4. Conclusions

Occurrence heavy rainfall (AAP from 26-50 mm) in Krishna basin which leads to flood is mainly due to off-shore trough/OST with embedded cyclonic circulation at different locations. Shear zone and upper air cyclonic circulations are also contributed significantly to heavy rainfall. Synoptic analogue model developed for different sub-basins indicate that rainfall in the range of 11-25 mm is expected due to off-shore troughs in all sub-basins. Rainfall in 26-50 mm range is expected due to OST from Karnataka to Lakshadweep in upper Krishna sub-basin and OST from Konkan-Goa/Maharashtra to Lakshadweep in Lower Bhima sub-basin. Formation of East-West shear zone will result in 11-25 mm rainfall in all sub-basins. Formation of upper air cyclonic circulations will result in 11-25 mm rainfall. Heavy rainfall from 26-50 mm is also possible due to cyclonic circulations over South Interior Karnataka and Marathwada in Upper Krishna sub-basin, cyclonic circulations over Coastal Andhra Pradesh in Ghataprabha sub-basin, cyclonic circulations over Rayalaseema in Bannehalla sub-basin, cyclonic circulations over Interior Karnataka in Upper Bhima sub-basin and Lower Bhima sub-basin, cyclonic circulations over Coastal Andhra Pradesh and Interior Karnataka in Lower Tungabhadra sub-basin, cyclonic circulations over Coastal Karnataka in Upper Tungabhadra sub-basin and cyclonic circulations over Rayalaseema in middle Tungabhadra sub-basin. Low pressure area/well marked low pressure area will results heavy rainfall (26-50 mm) in middle Krishna and lower Bhima.

Validation of Synoptic analogue model indicates better performance of the models in different sub-basins. However, development of synoptic analogue model in this study is based on data for limited number of years and needs to be updated with 15-20 years data to generate more accurate models and improvement in accuracy of quantitative precipitation forecast due to synoptic analogue model may be included in validation study and its comparison with NWP model forecasts. Also, the extend of Low/Depression/Deep Depression/cyclonic circulation etc. to the upper atmospheric level may be considered for development of the model in further studies.

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Data availability

All relevant data are available in the paper.

Authors' contributions

M. Rajavel: Collected the data, analysed and prepared the manuscript. *(email:rajavel2018@rediffmail.com).*

Disclaimer: The contents and views presented in this research article/paper are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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