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Development of synoptic analogue model for quantitative precipitation forecast over cauvery and east flowing river basin, India

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सार — **कावेरी और पूरब की ओर बहने वाली नदी घाटियों के उप-बेसिनों के संबंध में** 2012 **से** 2020 **के दौरान दक्षिण पश्चिम मॉनसूनऋतु के दैनिक औसत क्षेत्रीय वर्षा (एएपी) डेटा को उप-बेसिनों में वर्षा का कारण बनने वाले सिनोप्टिक सिस्टम के साथ एकत्र किया गया था। इस अध्ययन में पाँच सिनॉप्टिक प्रणालियों अर्थात् अवदाब/गहरा अवदाब, निम्न/सुनिश्चित निम्न दाब (डब्ल्यूएमएल) क्षेत्र, उपरितन वायु चक्रवाती परिसंचरण (यूएसी), अपतटीय गर्त (ओएसटी) / सन्निहित चक्रवाती परिसंचरण के साथ ओएसटी, पूर्व-पश्चिम अपरूपण क्षेत्र पर विचार किया जाता है। इन प्रणालियों के कारण होने वाली वर्षा (एएपी)** 11-25 **मिमी,** 26-50 **मिमी,** 51-100 **मिमी और** > 100 **मिमी मानी जाती है। यहाँ उन दिनों की संख्या की गणना की गई है जिनके लिए इन प्रणालियों ने सिनोप्टिक सिस्टम से जुड़ी प्रत्येक सीमा के तहत वर्षा की। किसी विशेष प्रणाली के लिए उच्चतम आवृत्ति वाली वर्षा सीमा को सिनॉप्टिक एनालॉग मॉडल के रूप में माना जाता है। सन्निहितचक्रवाती परिसंचरण के साथ ओएसटी/ओएसटी ने सभी उप-बेसिनों में वर्षा में महत्वपूर्ण योगदान दिया है। रायलसीमा, तमिलनाडु और पांडिचेरी, दक्षिण आंतरिक कर्नाटक या उत्तरी आंतरिक कर्नाटक पर अवदाब/गहरे अवदाब के कारण हरंगी बेसिन में** 50 **मिमी से अधिक वर्षा होती है। तेलंगाना में निम्न/सुनिश्चित निम्नदाब के कारण हेमवती बेसिन में** 50 **मिमी से अधिक वर्षा हुई। रायलसीमा के ऊपर उपरितन वायु चक्रवाती परिसंचरण (यूएसी) के कारण काबिनी बेसिन में** 50 **मिमी से अधिक वर्षा हुई है। रायलसीमा, दक्षिण पूर्व बंगाल की खाड़ी या तटीय आंध्र प्रदेश के पश्चिम मध्य बंगाल की खाड़ी पर यूएसी के कारण हरंगी में** 100 **मिमी से अधिक वर्षा होती है। तटीय कर्नाटक और उत्तरी आंतरिक कर्नाटक पर यूएसी या कोंकण गोवा/महाराष्ट्र से कर्नाटक तक ओएसटी के कारण ऊपरी वैगई में** 100 **मिमी से अधिक वर्षा होती है।**

ABSTRACT. Daily Average Areal Precipitation (AAP) data of South West Monsoon Season during 2012 to 2020 in respect of sub-basins of Cauvery and East flowing river basins were collected alongwith synoptic systems causing rainfall in the sub-basins. Five synoptic systems namely 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) caused by these systems considered are 11-25mm, 26-50mm, 51-100mm and > 100mm. Number of days for which these systems caused rainfall under each range associated with the synoptic systems was computed. The rainfall range with highest frequency for the particular system is considered as Synoptic Analogue Model. OST/OST with embedded cyclonic circulation has contributed significantly to rainfall in all the sub-basins. Depression/Deep Depression over Rayalaseema, Tamil Nadu and Pondicherry, South Interior Karnataka or North Interior Karnataka leads to > 50mm rainfall in Harangi basin. Depression/Deep Depression over Rayalaseema, Tamil Nadu and Pondicherry, South Interior Karnataka or North Interior Karnataka leads to > 50mm rainfall in Harangi basin. Low/Well Marked Low over Telangana causes > 50mm rainfall in Hemavathy basin. More than 50mm rainfall in Kabini basin is due to Upper Air Cyclonic circulation (UAC) over Rayalaseema. UAC over Rayalaseema, South East Bay of Bengal or West Central Bay of Bengal off Coastal Andhra Pradesh leads to >100 mm rain in Harangi. UAC over Coastal Karnataka and North Interior Karnataka or OST from Konkan Goa/Maharashtra to Karnataka leads to >100 mm rain in Upper Vaigai.

Key words – Aerial average precipitation, QPF, Cauvery river basin, Synoptic analogue model.

1. Introduction

Krishna and Cauvery river basins in the State of Karnataka covers 60% and 20% of the drainage area of the State. These river basins are interstate with 44 % of drainage area of Krishna basin and 42% of drainage area of Cauvery basins is in Karnataka. Cauvery basin is bounded by western ghats in the west and eastern ghats in the east and south and by the ridges separating it from Krishna basin and Pennar basin on the north. Physiographically the basin is divided into western ghats, pleateau of Mysuru and Delta. Cauvery river rises in Thalakaveri in the western ghats in Karnataka at an elevation of 1341 m and flows for about 800 km before it reaches Bay of Bengal. The important tributaries joining Cauvery are Harangi, Hemavathi, Kabini, Suvarnavati and Bhavani.

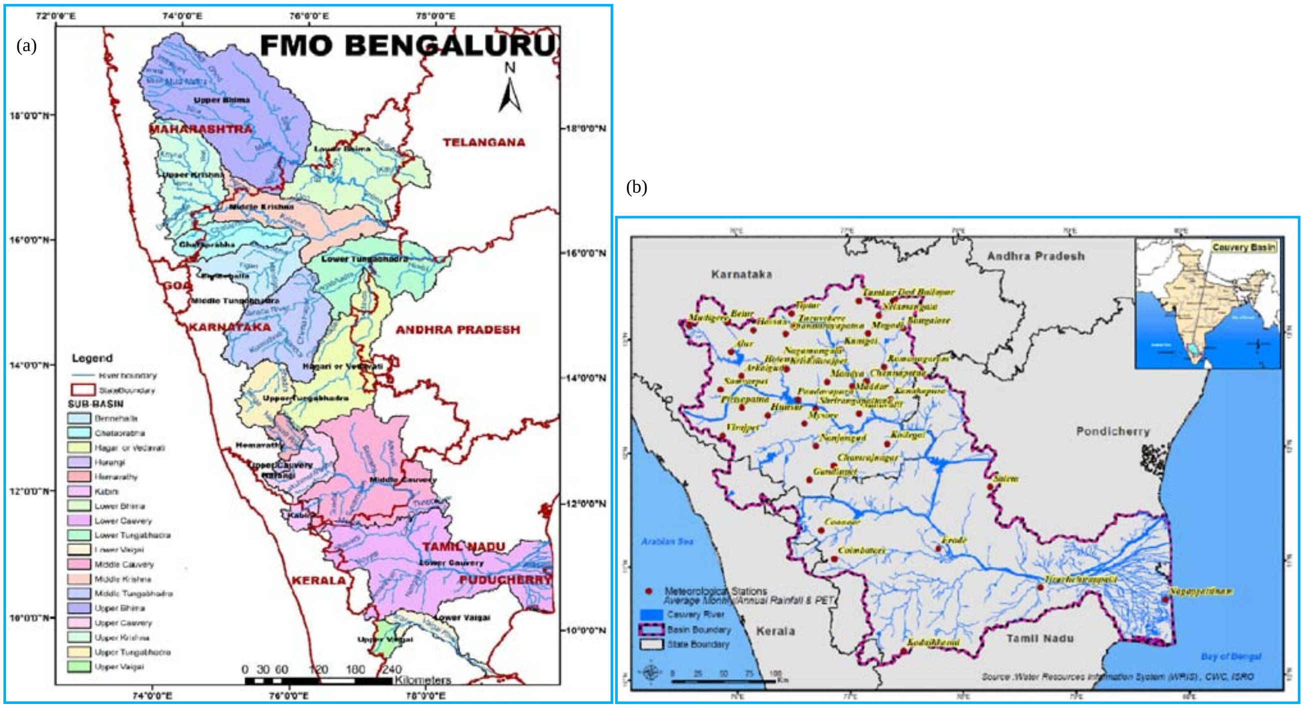
Water requirements and competition in agriculture, industry, rural, urban and environment sectors is high and in increasing trend for most of the river basins in the State. Weather systems formed in Bay of Bengal, Arabian Sea and land areas in the State and nearby States cause rainfall over the river basins in the State. Flood Meteorological Office (FMO) of IMD is issuing Quantitative Precipitation Forecast (QPF) for river basins in India. FMOs issue operational QPF by analysis of surface weather charts, upper air charts, NWP model analysis and forecast, satellite imageries and products, radar products and synoptic analogue models. High-resolution numerical weather prediction (NWP) models have been continuously improved with the rapid developments in information technology, and the models' forecast accuracy is steadily increased. However, weather forecasters may face some new challenges in operational applications. One crucial issue is that the precipitation products by almost all NWP models have considerable forecast errors and have limitations to accurately forecast the precipitation intensity (Novak *et al.*, 2014). Barali and Misra (2021) developed an approach for flood routing of the ungauged basin using rainfall-runoff and dynamic wave models. Barali and Misra (2021) predicted of flood hydrograph using the modified Cunge-Muskingum method in an ungauged basin (Kulsi river basin) in India.

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 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). Earlier, Lal *et al.*, (1983) developed synoptic analogue model for Gomti catchment in Ganga basin. Singh *et al.*, (1995) carried out a similar study for river Pun in Bihar. Ray and Sahu (1998) developed similar model for Sabarmathi river basin in Gujarat with four synoptic systems. Ram and Gaur (2004) studied QPF in Yamuna river basin by considering nine synoptic systems influencing the river basin. Raha *et al.*, *(*2009) developed synoptic analogue model for QPF and heavy rainfall warning in Teesta river basin and adjoining north Bengal and Sikkim. Ray and Patel (2000) developed semi QPF model for Narmada river basin in Gujarat. Ali *et al.*, (2011) developed synoptic model for QPF in lower Yamuna river basin. Chakraborty and Sen (2012) developed synoptic analogue model for QPF over Damodar catchment using 15 years data. Kamaljit Ray *et al.*,(2014) developed synoptic analogue model for Mahi river basin in Gujarat. Chattopadhyay and Senguptha (2018) developed synoptic analogue model for six catchments of Gangetic West Bengal and adjoining Jharkhand using 25 years data. To elevate the skill in forecasting heavy precipitation events (HPEs) in Yangtze-Huai river Valley with both long and short durations, the Key Influential Systems Based Analog Model (KISAM) was further improved and brought into operational application in 2020 by Zhou and Niu (2021). IMD issue QPF for 153 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 Aerial Precipitation) and associated synoptic systems in the river basin. Development Synoptic Analogue Models for Cauvery and East flowing Riverbasins is not attempted in the past and therefore this study intended to prepare such model for sub-basins of Cauvery and East flowing riverbasins to issue QPF.

2. Materials and methods

Daily rainfall data from 1st June to 30th September for 2012 to 2020 (except 2017) in respect of rainguage stations under each sub-basins of Cauvery and East flowing river basins were collected and Average Areal Precipitation was computed. Location of the river basins, sub-basins under FMO Bengaluru and indicative raingauge stations are provided in [Figs. 1(a&b)].Sub-basin wise number stations considered in the study is provided in the Table 1.

The associated synoptic systems have been inferred from analysed surface (0300 UTC), upper air charts (0000 UTC) and inference issued from Meteorological Centre, Bengaluru. Most influencial synoptic system based on rainfall and their location during South West Monsoon season over the river basins were considered and depicted here.



Figs. 1(a&b). (a) Location of the basin and sub-basins and (b). Location of raingauge stations

TABLE 1

Sub-basin wise number stations

S. No.	Sub-Basin	No. of stations
	Cauvery	
1	Harangi	2
2	Hemavathi	7
3	Kabini	6
4	Middle cauvery	65
5	Upper cauvery	22
6	Lower cauvery	106
	East flowing river	
7	Upper vaigai	4
8	Lower vaigai	14

Systems and their notation

S1	Depression/Deep Depression
S2	Low/Well Marked Low
S3	Upper Air Cyclonic Circulation(UAC)
S4	Off-shore Trough/OST with embedded cyclonic circulation
S5	East-West Shear Zone

Location of the system (zone)

1	OST from Gujarat to Lakshadweep
2	OST from Konkan-Goa/Maharashtra to Lakshadweep
3	OST from Karnataka to Lakshadweep
4	OST from Gujarat to Kerala and Karnataka
5	OST from Gujarat to Konkan-Goa/Maharashtra
6	OST from Konkan Goa/Maharashtra to Kerala
7	OST from Konkan Goa/Maharashtra to Karnataka
8	OST from Karnataka to Kerala
9	Coastal Andhra Pradesh
10	Telangana
11	Rayalaseema
12	Tamil Nadu & Pondicherry
13	South Interior Karnataka
14	North Interior Karnataka
15	Coastal Karnataka
16	South East Bay of Bengal
17	West Central Bay off Coastal Andhra Pradesh
18	East-West Shear Zone upto 12 Deg N
19	East-West Shear Zone upto 20 Deg N

Five synoptic systems are considered in the study and are denoted as synoptic system (S1 to S5) followed by its geographical location. Rainfall (AAP) caused by these

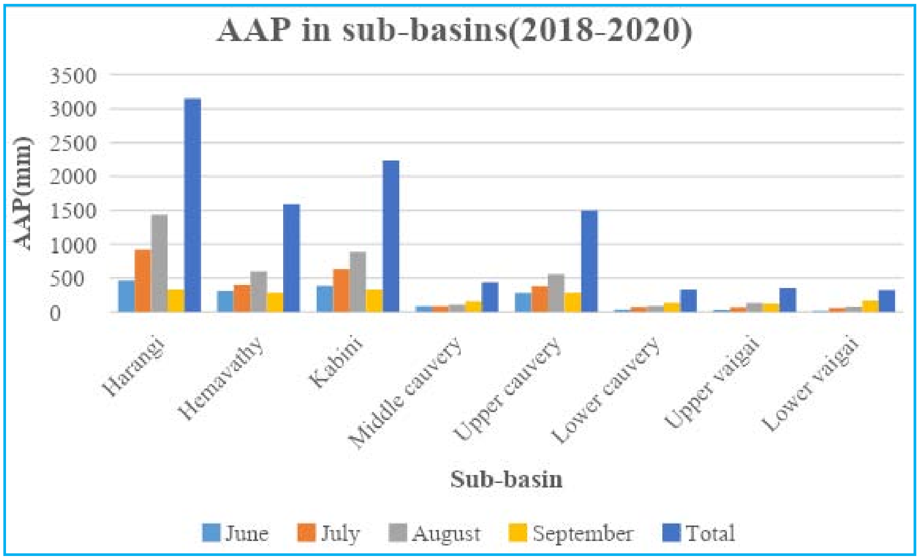


Fig. 2. Monthly mean rainfall of recent years (2018-2020) in sub-basins

systems considered are 11-25 mm, 26-50 mm, 51-100 mm and > 100 mm. Number of days for which these systems cause rainfall under each range was computed. The rainfall range with highest frequency for the particular system is considered as Synoptic Analogue Model.

3. Results and discussion

3.1. *Data analysis and synoptic model development*

Monthly mean rainfall of recent years (2018-2020) in sub-basins is depicted in Fig. 2. Harangi, Hemavathi, Kabini and upper Cauvery received higher rainfall in the season compared to other sub-basins. Higher rainfall is received in July and August months in the Cauvery and East flowing river basin.

It is observed that rainfall >10 mm received in 1085 days in Cauvery and East flowing river basins under the influence of synoptic systems selected in this study (Table 2). Maximum frequency of rainfall is due to formation of off-shore trough (645 days) in cauvery and East flowing river basins. Off-shore trough from Gujarat to Kerala and Karnataka resulted in highest frequency (248 days). Off-shore trough from Konkan-Goa/Maharashtra to Kerala could cause rainfall in 182 days and Off-shore trough from Karnataka to Kerala resulted rainfall in 122 days. Harangi, Hemavati, Kabini and Upper cauvery sub-basins received rainfall for more than 171 days due to Off-shore trough. Most of the time during the summer monsoon, OST, mid-tropospheric circulations (MTC) and the presence of cyclonic vorticity along the west coast in OST and shear vorticity cause rainfall over the Konkan and Karnataka coasts (Francis and Gadgil, 2006; Das *et al*., 2007). Konduru and Mrudula (2021) concluded from their study that south Indian rainfall mainly depends on the presence and position of offshore trough. Second maximum frequency of rainfall is due to upper air cyclonic circulations over different regions (242 days). Cyclonic circulations over west central Bay of Bengal off coastal Andhra Pradesh cause rainfall for 111 days. Cyclonic circulations over Tamil Nadu and Pondicherry causes rainfall for 55 days in the basins. East-west shear zone causes rainfall for 131 days. Low pressure area / well marked low pressure area contributes rainfall for 49 days and depressions/deep depressions cause rainfall for 20 days. In all sub-basins, frequency of rainfall received is highest due to off-shore trough followed by upper air cyclonic circulations, east-west shear zone, low pressure / well marked low pressure area and lowest due to depression/deep depression.

Heavy rainfall occurrence (AAP from 26-50mm) causing flood in the river basins is mainly due to Off-shore trough / OST with embedded cyclonic circulation at different location from Gujarat to Kerala (Table 2). Frequency of occurrence in 26-50 mm range is more as compared to 51-100 and >100 mm in different sub-basins. Depression / DD over Rayalaseema, Tamil Nadu and Pondicherry, South Interior Karnataka or North Interior Karnataka resulted 51-100 mm rainfall in Harangi sub-basin, Low/WML over Telangana cause 51-100 mm rainfall in Hemavathi sub-basin and UAC over Rayalaseema cause occurrence of 51-100 mm rainfall in Kabini sub-basin. Heavy rainfall more than 100 mm over Harangi, Hemavathi, Kabini, Upper Cauvery and Upper

TABLE 2

Frequency of occurrence of AAP more than 10mm

Symbol	Harangi					Hemavathi					Kabini					Middle cauvery				
	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
S1,9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
S1,10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,11	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	1	0	0	0	1
S1,12	0	0	1	0	1	1	1	0	0	2	2	1	0	0	3	4	0	0	0	4
S1,13	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
S1,14	0	0	1	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
S1,15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,16	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	1	4	0	5	1	1	0	0	2	2	4	0	0	6	6	0	0	0	**6**
S2,9	2	1	0	0	3	1	0	0	0	1	2	0	0	0	2	0	0	0	0	0
S2,10	1	3	0	0	4	1	0	1	0	2	1	1	0	0	2	0	0	0	0	0
S2,11	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
S2,12	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0
S2,13	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
S2,14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,17	5	6	0	0	11	7	1	0	0	8	8	3	0	0	11	0	0	0	0	0
Total	8	10	0	0	18	12	1	1	0	14	12	4	0	0	16	0	0	0	0	**0**
S3,9	2	0	0	0	2	2	0	0	0	2	4	0	0	0	4	0	0	0	0	0
S3,10	1	0	0	0	1	1	0	0	0	1	3	0	0	0	3	0	0	0	0	0
S3,11	0	1	0	1	2	0	1	0	0	1	1	0	1	0	2	2	0	0	0	2
S3,12	4	10	1	0	15	10	1	0	0	11	6	4	0	0	10	1	0	0	0	1
S3,13	4	1	0	0	5	3	1	0	0	4	2	0	0	0	2	2	0	0	0	2
S3,14	2	1	1	0	4	3	1	0	0	4	4	2	0	0	6	2	1	0	0	3
S3,15	2	0	0	0	2	3	0	0	0	3	1	0	0	0	1	0	0	0	0	0
S3,16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
S3,17	18	7	3	0	28	28	3	1	0	32	27	5	1	0	33	9	3	0	0	12
Total	33	20	5	1	59	50	7	1	0	58	48	11	2	0	61	17	4	0	0	**21**
S4,1	5	4	0	1	10	5	1	0	0	6	1	4	1	0	6	0	0	0	0	0
S4,2	3	1	0	0	4	3	0	0	0	3	1	3	0	0	4	0	0	0	0	0
S4,3	1	1	0	0	2	2	0	0	0	2	0	2	0	0	2	0	0	0	0	0
S4,4	30	24	20	4	78	47	27	2	0	76	41	30	16	1	88	0	0	0	0	0
S4,5	4	0	0	0	4	2	0	0	0	2	2	0	0	0	2	0	0	0	0	0
S4,6	28	16	8	4	56	31	11	3	1	46	40	21	10	3	74	8	1	0	0	9
S4,7	4	2	1	0	7	5	2	0	0	7	5	7	0	0	12	2	0	0	0	2
S4,8	20	15	8	3	46	22	7	1	0	30	24	10	9	0	43	5	1	0	0	6
Total	95	63	37	**12**	**207**	117	48	6	1	**172**	114	77	36	4	**231**	15	2	0	0	**17**
S5,18	4	2	2	0	8	12	0	0	0	12	8	1	0	0	9	2	1	0	0	3
S5,19	15	7	6	1	29	10	10	1	0	21	15	11	7	0	33	2	0	0	0	2
Total	19	9	8	1	37	22	10	1	0	33	24	12	7	0	43	4	1	0	0	5
G.Total	155	103	54	14	326	202	67	9	1	279	199	108	45	4	356	42	7	0	0	49

TABLE 2A

Frequency of occurrence of AAP more than 10mm

Symbol	Upper cauvery					Lower cauvery					Upper vaigai					Lower vaigai					
	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	G.Total
S1,9	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
S1,10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,11	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	4
S1,12	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9
S1,13	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
S1,14	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
S1,15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S1,16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
S1,17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	6	0	0	0	6	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	**20**
S2,9	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5
S2,10	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	8
S2,11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,12	1	0	0	0	1	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	5
S2,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
S2,14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
S2,17	7	0	0	0	7	2	0	0	0	2	1	0	0	0	1	1	0	0	0	1	30
Total	9	0	0	0	9	5	1	0	0	6	1	0	0	0	1	1	0	0	0	1	**49**
S3,9	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	8
S3,10	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3
S3,11	2	1	0	0	3	1	0	0	0	1	1	1	0	0	2	3	1	0	0	4	15
S3,12	7	2	0	0	9	4	1	0	0	5	6	1	0	0	7	6	1	0	0	7	55
S3,13	4	0	0	0	4	2	0	0	0	2	3	0	0	0	3	2	0	0	0	2	22
S3,14	4	0	0	0	4	2	0	0	0	2	1	0	0	1	2	1	0	0	0	1	20
S3,15	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	6
S3,16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	2
S3,17	20	2	0	0	22	3	0	0	0	3	4	4	1	0	9	5	0	0	0	5	111
Total	39	5	0	0	44	13	1	0	0	14	15	6	1	2	24	20	2	0	0	22	**242**
S4,1	6	1	0	0	7	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	24
S4,2	5	0	0	0	5	1	0	0	0	1	0	0	0	0	0	2	0	0	0	2	15
S4,3	2	0	0	0	2	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	7
S4,4	49	21	5	0	75	0	0	0	0	0	4	10	1	0	15	4	0	0	0	4	248
S4,5	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
S4,6	35	13	3	2	53	5	0	0	0	5	4	5	2	0	11	2	0	0	0	2	182
S4,7	7	0	0	0	7	0	0	0	0	0	1	0	0	1	2	1	0	0	0	1	26
S4,8	15	9	2	0	26	4	0	0	0	4	3	4	1	0	8	1	1	0	0	2	122
Total	120	44	10	2	**176**	23	1	0	0	**24**	14	19	4	1	**38**	10	1	0	0	**11**	**645**
S5,18	9	0	0	0	9	3	0	0	0	3	4	2	0	2	8	4	1	0	0	5	48
S5,19	13	8	3	0	24	3	0	0	0	3	3	0	0	0	3	0	0	0	0	0	82
Total	23	8	3	0	34	6	0	0	0	6	7	2	0	2	11	4	1	0	0	5	**131**
G.Total	198	57	13	2	268	47	4	0	0	51	37	27	5	5	74	35	4	0	0	39	1085

TABLE 3(a)

QPF model for Harangi

Zone/System	S1	S2	S3	S4	S5
1	Nil	Nil	-	11-25	-
2	Nil	Nil	-	11-25	-
3	Nil	Nil	-	26-50	-
4	Nil	Nil	-	11-25	-
5	Nil	Nil	-	11-25	-
6	Nil	Nil	-	11-25	Nil
7	Nil	Nil	-	11-25	-
8	Nil	Nil	-	11-25	-
9	Nil	11-25	11-25	-	-
10	Nil	26-50	11-25	-	-
11	51-100	Nil	>100	-	-
12	51-100	Nil	26-50	-	-
13	51-100	Nil	11-25	-	-
14	51-100	Nil	11-25	-	-
15	Nil	Nil	11-25	-	-
16	26-50	Nil	-	-	-
17	Nil	26-50	-	-	-
18	Nil	-	-	-	11-25
19	Nil	-	-	-	11-25

TABLE 3(b)

QPF model for Hemavathy

Zone/System	S1	S2	S3	S4	S5
1	-	Nil	-	11-25	-
2	-	Nil	-	11-25	-
3	-	Nil	-	11-25	-
4	-	Nil	-	11-25	-
5	-	Nil	-	11-25	-
6	-	Nil	-	11-25	Nil
7	-	Nil	-	11-25	-
8	-	Nil	-	11-25	-
9	Nil	11-25	11-25	-	-
10	Nil	51-100	11-25	-	-
11	Nil	Nil	26-50	-	-
12	26-50	11-25	11-25	-	-
13	Nil	26-50	11-25	-	-
14	Nil	Nil	11-25	-	-
15	Nil	Nil	11-25	-	-
16	Nil	Nil	Nil	-	-
17	-	11-25	11-25	-	-
18	-	-	-	-	11-25
19	-	-	Nil	-	26-50

TABLE 3(c)

QPF model for Kabini

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	26-50	-
2	-	-	-	26-50	-
3	-	-	-	26-50	-
4	-	-	-	11-25	-
5	-	-	-	11-25	-
6	-	-	-	11-25	Nil
7	-	-	-	26-50	-
8	-	-	-	11-25	-
9	Nil	11-25	11-25	-	-
10	Nil	26-50	11-25	-	-
11	26-50	11-25	51-100	-	-
12	11-25	Nil	11-25	-	-
13	26-50	Nil	11-25	-	-
14	26-50	Nil	11-25	-	-
15	Nil	Nil	11-25	-	-
16	Nil	Nil	Nil	-	-
17	Nil	11-25	11-25	-	-
18	-	-	Nil	-	11-25
19	-	-	Nil	-	11-25

TABLE 3(d)

QPF model for middle Cauvery

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	Nil	-
2	-	-	-	Nil	-
3	-	-	-	Nil	-
4	-	-	-	Nil	-
5	-	-	-	Nil	-
6	-	-	-	11-25	Nil
7	-	-	-	11-25	-
8	-	-	-	11-25	-
9	Nil	Nil	Nil	-	-
10	Nil	Nil	Nil	-	-
11	Nil	Nil	11-25	-	-
12	Nil	Nil	11-25	-	-
13	Nil	Nil	11-25	-	-
14	Nil	Nil	11-25	-	-
15	Nil	Nil	Nil	-	-
16	Nil	Nil	11-25	-	-
17	Nil	Nil	11-25	-	-
18	-	-	Nil	-	11-25
19	-	-	Nil	-	11-25

TABLE 3(e)

QPF model for upper Cauvery

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	11-25	-
2	-	-	-	11-25	-
3	-	-	-	11-25	-
4	-	-	-	11-25	-
5	-	-	-	11-25	-
6	-	-	-	11-25	-
7	-	-	-	11-25	-
8		-	-	11-25	-
9	11-25	Nil	11-25	-	-
10	Nil	11-25	Nil	-	-
11	11-25	Nil	11-25	-	-
12	11-25	11-25	11-25	-	-
13	11-25	Nil	11-25	-	-
14	11-25	Nil	11-25	-	-
15	Nil	Nil	Nil	-	-
16	Nil	Nil	Nil	-	-
17	Nil	11-25	11-25	-	-
18	-	Nil	-	-	11-25
19	-	-	-	-	11-25

TABLE 3(f)

QPF model for lower Cauvery

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	Nil	-
2	-	-	-	11-25	-
3	-	-	-	Nil	-
4	-	-	-	Nil	-
5	-	-	-	Nil	-
6	-	-	-	11-25	Nil
7	-	-	-	Nil	-
8	-	-	-	11-25	-
9	Nil	11-25	11-25	-	-
10	Nil	26-50	Nil	-	-
11	26-50	Nil	11-25	-	-
12	11-25	11-25	11-25	-	-
13	11-25	Nil	11-25	-	-
14	11-25	11-25	11-25	-	-
15	Nil	Nil	Nil	-	-
16	Nil	Nil	Nil	-	-
17	Nil	Nil	11-25	-	-
18	-	Nil	-	-	11-25
19	-	11-25	Nil	-	11-25

TABLE 3(g)

QPF model for upper vaigai

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	11-25	-
2	-	-	-	Nil	-
3	-	-	-	11-25	-
4	-	-	-	26-50	-
5	-	-	-	Nil	-
6	-	-	-	26-50	Nil
7	-	-	-	>100	-
8	-	-	-	26-50	-
9	Nil	Nil	11-25	-	-
10	Nil	Nil	11-25	-	-
11	Nil	Nil	11-25	-	-
12	Nil	Nil	11-25	-	-
13	Nil	Nil	11-25	-	-
14	Nil	Nil	>100	-	-
15	Nil	Nil	>100	-	-
16	Nil	Nil	Nil	-	-
17	Nil	11-25	26-50	-	-
18	-	Nil	-	-	11-25
19	-	11-25	Nil	-	11-25

TABLE 3(h)

QPF model for lower vaigai

Zone/System	S1	S2	S3	S4	S5
1	-	-	-	Nil	-
2	-	-	-	11-25	-
3	-	-	-	Nil	-
4	-	-	-	11-25	-
5	-	-	-	Nil	-
6	-	-	-	11-25	-
7	-	-	-	11-25	-
8	-	-	-	26-50	-
9	Nil	Nil	11-25	-	-
10	Nil	Nil	Nil	-	-
11	Nil	Nil	11-25	-	-
12	Nil	Nil	11-25	-	-
13	Nil	Nil	11-25	-	-
14	Nil	Nil	11-25	-	-
15	Nil	Nil	Nil	-	-
16	Nil	Nil	Nil	-	-
17	Nil	11-25	Nil	-	-
18	-	-	-	-	11-25
19	-	-	-	-	Nil

TABLE 4

Performance of synoptic analogue model during SWM 2021

Symbol	Harangi			Hemavathi			Kabini			Middle cauvery			Upper cauvery			Lower cauvery			Upper vaigai			Lower vaigai		
	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC	QPF as per model	U	IC
S1,9	Nil			Nil			Nil			Nil			11-25	0	0	Nil			Nil			Nil		
S1,10	Nil			Nil			Nil			Nil			Nil			Nil			Nil			Nil		
S1,11	51-100	0	0	Nil			26-50	0	0	Nil			11-25	0	0	26-50	0	0	Nil			Nil		
S1,12	51-100	0	0	26-50	0	0	11-25	0	0	Nil			11-25	0	0	11-25	0	0	Nil			Nil		
S1,13	51-100	0	0	Nil			26-50	0	0	Nil			11-25	0	0	11-25	0	0	Nil			Nil		
S1,14	51-100	0	0	Nil			26-50	0	0	Nil			11-25	0	0	11-25	0	0	Nil			Nil		
S1,15	Nil			Nil			Nil			Nil			Nil			Nil			Nil			Nil		
S1,16	26-50	0	0	Nil			Nil			Nil			Nil			Nil			Nil			Nil		
S1,17	Nil						Nil			Nil			Nil			Nil			Nil			Nil		
S2,9	11-25	1	0	11-25	1	0	11-25	1	0	Nil			Nil			11-25	1	0	Nil			Nil		
S2,10	26-50			51-100	0	0	26-50	0	0	Nil			11-25	0	0	26-50	0	0	Nil			Nil		
S2,11	Nil			Nil			11-25	0	0	Nil			Nil			Nil			Nil			Nil		
S2,12	Nil			11-25	0	0	Nil			Nil			11-25	0	0	11-25	0	0	Nil			Nil		
S2,13	Nil			26-50	0	0	Nil			Nil			Nil			Nil			Nil			Nil		
S2,14	Nil			Nil			Nil			Nil			Nil			11-25	0	0	Nil			Nil		
S2,15	Nil			Nil			Nil			Nil			Nil			Nil			Nil			Nil		
S2,16	Nil			Nil			Nil			Nil			Nil			Nil			Nil			Nil		
S2,17	26-50	2	0	11-25	2	0	11-25	0	0	Nil			11-25	2	0	Nil			11-25	2	0	11-25	3	0
S3,9	11-25	2	0	11-25	1	0	11-25	2	0	Nil			11-25	1	0	Nil			11-25	1	0	11-25	1	0
S3,10	11-25	4	0	11-25	3	0	11-25	3	0	Nil			Nil			11-25	3	0	11-25	3	0	Nil	3	0
S3,11	>100	0	0	26-50	0	0	51-100	0	0	11-25	0	0	11-25	0	0	11-25	0	0	11-25	0	0	11-25	0	0
S3,12	26-50	1	5	11-25	7	0	11-25	6	0	11-25	0	0	11-25	7	0	11-25	6	0	11-25	5	2	11-25	7	0
S3,15	11-25	0	0	11-25	0	0	11-25	0	0	Nil			Nil			Nil			>100	0	0	Nil		
S3,16	Nil			Nil			Nil			11-25	0	0	Nil			Nil			Nil			Nil		
S3,17	Nil			11-25	5	0	11-25	4	0	11-25	6	0	11-25	5	0	11-25	6	0	26-50	0	5	Nil		
S4,1	11-25	0	0	11-25	0	0	26-50	0	0	Nil			11-25	0	0	Nil			11-25	2	0	Nil		
S4,2	11-25	0	0	11-25	0	0	26-50	0	0	Nil			11-25	0	0	11-25	0	0	Nil			11-25	0	0
S4,3	11-25	0	0	11-25	0	0	26-50	0	0	Nil			11-25	0	0	Nil			11-25	0	0	Nil		
S4,4	11-25	3	0	11-25	2	0	11-25	2	0	Nil			11-25	0	0	Nil			26-50	2	0	11-25	2	0
S4,5	11-25	0	0	11-25	0	0	11-25	0	0	Nil			11-25	0	0	Nil			Nil	0	0	Nil		
S4,6	11-25	19	1	11-25	5	0	11-25	20	0	11-25	17	0	11-25	3	0	11-25	21	0	26-50	1	13	11-25	0	0
S4,7	11-25	3	0	11-25	2	1	26-50	3	0	11-25	3	0	11-25	3	0	Nil			>100	0	0	11-25	3	0
S4,8	11-25	11	1	11-25	10	0	11-25	12	0	11-25	11	0	11-25	11	0	11-25	12	0	26-50	4	7	26-50	0	11
S5,18	11-25	6	0	11-25	6	0	11-25	5	1	11-25	5	0	11-25	6	0	11-25	5	0	11-25	3	2	11-25	6	0
S5,19	11-25	13	2	26-50	6	1	11-25	16	0	11-25	17	0	11-25	16	0	11-25	15	0	11-25	16	0	Nil		
	Total	65	9		50	2		74	1		59	0		54	0		69	0		33	29		25	11
	%	88	12		96	4		99	1		100	0		100	0		100	0		53	47		69	31
	U-Usable,																							
	IC-Incorrect																							

TABLE 5

Verification of QPF with AAP during 2022

Day	Total No. of QPF	Correct forecast	Out by one stage	Out by two stage	Out by three stage	Out by four stage	Out by five stage	Correct (%)	Usable forecast Correct &± 1 stage(%)
Cauvery basin									
1	690	433	236	21	0	0	0	63	97
2	684	421	233	30	0	0	0	62	96
3	678	437	214	27	0	0	0	64	96
4	678	434	225	19	0	0	0	64	97
5	678	420	246	12	0	0	0	62	98
East flowing river basin									
1	230	177	48	5	0	0	0	77	98
2	228	171	51	6	0	0	0	75	97
3	226	173	49	4	0	0	0	77	98
4	226	176	46	4	0	0	0	78	98
5	226	172	50	4	0	0	0	76	98

Vaigai in maximum number of occasions are due to off-shore trough from Konkan-Goa/Maharashtra to Kerala. Heavy rainfall more than 100 mm occurred in 12 days in Harangi, one day in Hemavathy, 4 days in Kabini, 2 days in Upper Cauvery and one day in Upper Vaigai. OST from Gujarat to Kerala and Karnataka cause heavy rainfall more than 100 mm in 4 days, OST from Konkan-Goa/Maharashtra to Kerala cause heavy rainfall more than 100 mm in 4 days and OST from Karnataka to Kerala contributed to heavy rainfall more than 100 mm in 3 days. OST from Konkan-Goa/Maharashtra to Kerala cause heavy rainfall more than 100 mm in 3 days and OST from Gujarat to Kerala and Karnataka in one day in Kabini sub-basin. In Upper Cauvery, OST from Konkan-Goa/Maharashtra to Kerala contributed to rainfall more than 100 mm in 2 days. OST from Konkan-Goa/Maharashtra to Karnataka cause heavy rainfall more than 100 mm in one day in upper vaigai. Significant heavy rainfall instances are also observed due to East-west shear zone. Heavy rainfall due to low pressure systems are observed in less frequency.

Based on the data, synoptic analogue model for issuing quantitative precipitation forecast is prepared and presented in [Tables 3(a-h)]. Rainfall in the range of 11-25 mm is expected due to Off-shore troughs in most of the sub-basins except upper vaigai. Rainfall in 26-50 mm is expected in upper vaigai due to OST from Gujarat to Kerala and Karnataka, OST from Konkan-Goa/Maharashtra to Kerala and OST from Karnataka to Kerala. Heavy rainfall (26-50 mm) in Kabini sub-basin is due to OST from Gujarat to Lakshadweep, OST from Konkan-Goa / Maharashtra to Lakshadweep, OST from Karnataka to Lakshadweep and OST from Konkan-Goa / Maharashtra to Karnataka. Amount of rainfall is depends on the extent of off-shore trough in most of the cases. If depression / deep depression is formed over Rayalaseema / Tamilnadu & Pondicherry/Interior Karnataka, there is possibility of 51-100 mm rainfall in Harangi sub-basin. Upper Air Cyclonic circulation over Rayalaseema could cause >100 mm rain in Harangi. Low / WML over Telangana leads to 51-100 mm rainfall in Hemavathy and UAC over Rayalaseema resulted 51-100 mm of rainfall in Kabini. UAC over Coastal and North Interior Karnataka or off-shore trough from Konkan Goa/Maharashtra to Karnataka cause >100 mm rain in Upper Vaigai.

3.2. *Verification of the model*

Sensitivity of synoptic analogue models developed for the different sub-basins was tested during South West Monsoon season 2021 and the results are presented in Table 4. Model suggested AAP in Lower cauvery, middle cauvery and upper cauvery is 100% usable (Correct and out by ± 1 stage). Model predictions in Kabini, Harangi, Hemvavathy, lower vaigai and upper vaigai are 99%, 96%, 88%, 69% and 53% usable respectively and 1%, 4%, 12%, 31% and 47% incorrect (out by 2-4 stages).

QPF was issued daily for all sub-basins in the year 2022 based on above method and were verified with the AAP realized for the sub-basins in the study (Table 5) and it was found that QPF was correct for 433 cases (63%) in Day 1, 421 cases (62%) in Day 2, 437 cases (64%) in Day 3, 434 cases (64%) in Day 4 and 420 (62%) in Day 5 in Cauvery basin. QPF was usable (correct + out by one stage) in 97% cases in Day 1, 96 % cases Day 2 and Day 3, 97 % cases in Day 4 and 98 % cases in Day 5. Correct forecast is 77% in Day 1, 75% in Day 2, 77% in Day 3, 78% in Day 4 and 76% in Day 5 and usable forecast is 98% in Day 1, 97% in Day 2, 98 % in Day 3, day 4 and Day 5 in East flowing river basins.

4. Conclusions

Synoptic analogue models for prediction of Average Areal Precipitation based on selected influential synoptic systems and their locations responsible for rainfall and long term Average Areal Precipitation in different sub-basins of cauvery river basin were developed. Off-shore trough / OST with embedded cyclonic circulation has contributed significantly to rainfall in all the sub-basins. Off-shore trough from Gujarat to Kerala and Karnataka caused rainfall in 248 days. Off-shore trough from Konkan Goa / Maharashtra to Kerala caused rainfall in 182 days and Off-shore trough from Karnataka to Kerala resulted rainfall in 122 days. Second maximum frequency of rainfall is due to upper air cyclonic circulations over different regions (242 days). Upper Air Cyclonic circulations over west central Bay of Bengal off coastal Andhra Pradesh cause rainfall for 111 days.

Occurrence heavy rainfall (AAP from 26-50 mm) which leads to flood in the river basins is mainly due to Off-shore trough / OST with embedded cyclonic circulation at different location from Gujarat to Kerala. Frequency of occurrence in 26-50 mm range is more than 51-100 and >100 mm in different sub-basins. Synoptic analogue model developed for different sub-basins also indicate that (*i*) Upper air cyclonic circulations over Rayalaseema leads to >100 mm rain in Harangi (*ii*) Upper air cyclonic circulations over Coastal Karnataka or North Interior Karnataka or Off-shore trough from Konkan Goa/Maharashtra to Karnataka leads to >100 mm rain in Upper Vaigai (*iii*) Depression/Deep Depression over Rayalaseema, Tamil Nadu and Pondicherry, South Interior Karnataka or North Interior Karnataka causes > 50 mm rainfall in Harangi basin (*iv*) Low/Well Marked Low over Telangana leads to > 50 mm rainfall in Hemavathy basin (*v*) Upper air cyclonic circulations over Rayalaseema causes > 50 mm rainfall in Kabini basin.

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 more accuracy of the models and validation study can include improvement in accuracy of quantitative precipitation forecast due to synoptic analogue model.

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