



# Spatio-temporal analysis and estimation of rainfall variability in and around upper Godavari River basin, India

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## Abstract

Spatio-temporal analysis and estimation of rainfall variability is an important factor to characterize the hydrological manifestation for precise water management. Fifteen years' daily rainfall data (2000–2014) of 39 rain gauge stations (RGS), situated in and around upper Godavari basin (UGB), was analyzed using statistical computations. Mean annual rainfall (MAR) and mean half-decadal rainfall, along with standard deviation (SD), coefficient of variation (CV), standardized anomaly (SA), mean absolute deviation (MAD), and spatial distribution of rainfall (SDR), were computed to delineate the orographic effect, if any, over rainfall. Box and whisker diagrams display rainfall distribution. The analyzed data was incorporated in Geographical Information System (GIS) software, and spatial estimation of half-decadal rainfall, SA, and SDR carried out using inverse distance weighting (IDW) interpolation method. RGS mean rainfall of 2000–2004, 2005–2009, and 2010–2014 were correlated with satellite-derived Tropical Rainfall Measuring Mission (TRMM) data using Pearson correlation coefficient ( $R$ ) to confirm the accuracy and validity of both the data. Statistical results and spatial estimation of rainfall indicate high spatio-temporal variability during 2010–2014 and lower during 2005–2009. Monsoon intensity revealed increasing trend from 2000 to 2006, which was seen to be decreasing later, with rise and fall from 2006 to 2014. The rainfall was seen to increase towards west due to an obstruction posed by the Western Ghat to the east flowing monsoon wind. Strong positive correlation was found between TRMM and 3 half-decade rainfall data. The approach adopted in this paper identified the micro level rainfall variability which will be greatly advantageous for sustainable water resource management.

**Keywords** Rainfall variability · GIS · Spatio-temporal estimation · Water management

## Introduction

Rainfall and other potable resources are unevenly distributed over the globe. Asia has 35% of freshwater resources and is inhabited by about 60% of the world's population,

whereas the Amazon River basin has 13% of water reserves with a population of only 0.5% (Boddu et al. 2011). The Indian subcontinent has tropical and subtropical climate zones which experience strong seasonality from warm humid to arid and cold arid conditions within its geographical expanse (Adams et al. 1999). The picture of average precipitation of peninsular India is seen to cover the anomalies in many small pockets that may have an important bearing on the rainfall pattern of those areas. Out of 22 Indian river basins, 15 basins exhibited a decreasing trend in annual rainfall and rainy days (Kumar and Jain 2011). This decrease in annual rainfall (Khan et al. 2000; Mirza 2002; Min et al. 2003; Goswami et al. 2006; Dash et al. 2007) suggests South Asia is vulnerable to climate change (Caesar and Janes 2018). Dash et al. (2007) have refrained from assigning any reasons for monsoonal decrease. However, they seem to implicate global effect of GHGs, but caution to look more closely at regional features that can modulate the warming effects.

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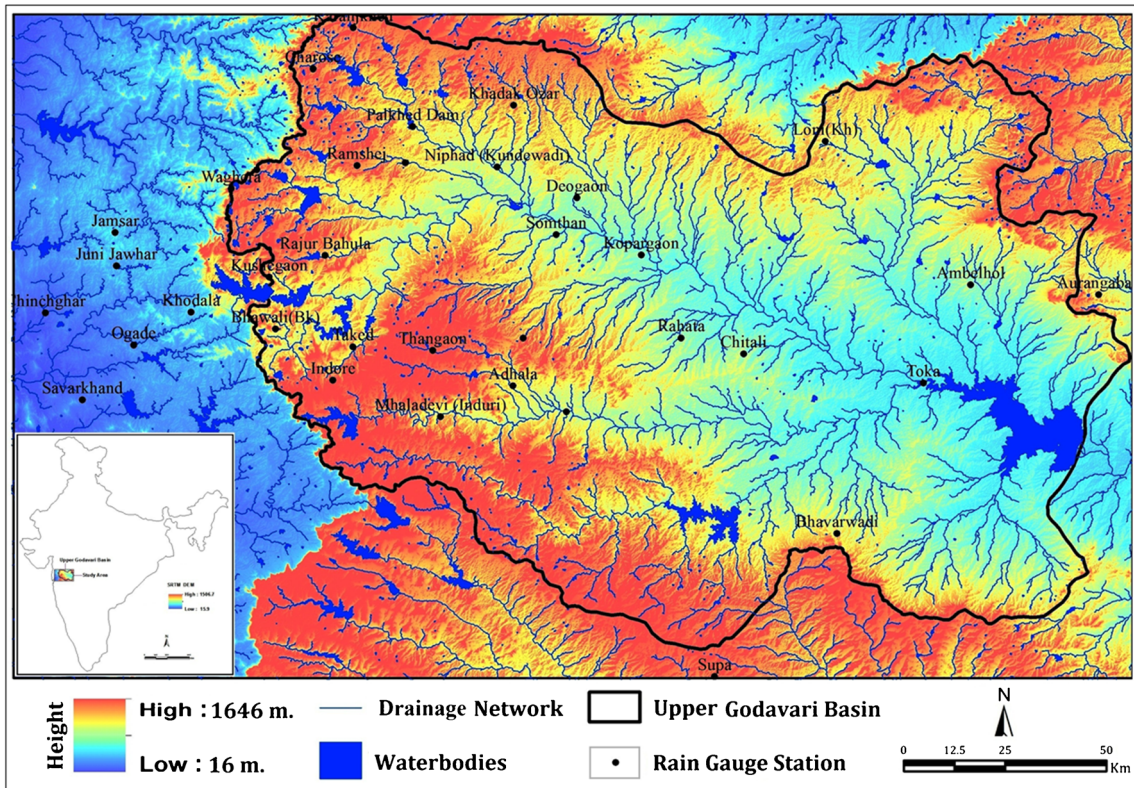
Morphologically, the subcontinent has many physiographic divisions (Wadia 1976; Sen 2002) that greatly influence the variability of monsoon. Singh and Mal (2014) found a decline in annual rainfall in high altitudes and an increase in low altitudes suggesting the impact of physiographic changes in a locality. Local physiography accounts for complex rainfall patterns, spatial differences in rainfall events, trends, and variability in hilly areas due to large elevation differences (Mal 2012; Palazzi et al. 2013). The Himalayas in the north and Western Ghats in the west control the precipitation pattern due to their strong and major orographic relief (Basistha et al. 2009). These features create conditions for uneven distribution of precipitation; hence, a comprehensive understanding of macro as well as micro level spatio-temporal variations in rainfall becomes an area of critical necessity. The study of monsoonal variability is significant from hydrological, ecological, and socioeconomic point of view (Sawant et al. 2015), since it impacts the water availability. Quantification of such spatio-temporal variability is extremely important to carry out hydrological and meteorological modeling. Rainfall analysis, only from rain gauge station (RGS) data, is often not reliable in deciphering precise spatio-temporal variability studies on a regional scale (Hunink et al. 2014), since it suffers from insufficient data (Keblouti et al. 2012). Also, ground-based measurements are costly and time consuming (Deshmukh and Aher 2016). Rainfall is extremely erratic in the hilly tracts (Buytaert et al. 2006) and difficult to record its precise gradients (Celleri et al. 2007; Ward et al. 2011).

Understanding rainfall variability in semi-arid hilly areas is a key challenge due to the undulating nature of the terrain. This lacuna can be overcome by carrying out spatial estimation of RGS-based rainfall data using interpolation techniques in GIS software. This methodology can be postulated to be more precise to predict the rainfall variability. Satellite-derived TRMM rainfall data can be combined, or compared with, RGS rainfall data, to understand the climate dynamics in a more integrated and broad manner. The RGS- and satellite-derived rainfall data, in isolation, seem to be a limiting and unattractive proposition for effective water resources management and other auxiliary tasks. Hence, different authors have therefore developed the interpolation and aggregation algorithms that allow them to combine satellite-derived data with ground data (Dinku et al. 2008; Immerzeel et al. 2009; Scheel et al. 2011; Yatagai et al. 2012; Li et al. 2014). Chen and Liu (2012) and Noori et al. (2014) used the IDW method to estimate rainfall distribution in central Taiwan and Duhok Governorate. Chen and Liu et al. (2012) derived high correlation coefficient values to confirm IDW is a suitable method to predict the probable rainfall intensity. IDW is a geostatistical interpolation method which is based on the assumption that the attribute value of an unsampled point is the weighted average of known values within the neighborhood (Lu and Wong 2008; Deshmukh and Aher 2016).

The regional studies on monsoonal changes within the Indian subcontinent (Parthasarathy and Yang 1995; Yihui and Chan 2005; Aher et al. 2017a, 2017b; Jin and Stan 2019) revealed trends that were pan-Indian in nature. But, deciphering the micro and local level changes, which may or may not be in tandem with the overall trend, is also very important. Such “local” studies are very few. Rao (1999) has studied monsoon variability of the entire Godavari basin. Hence, the present attempt is aimed at finding out the local spatio-temporal rainfall variability and its spatial estimation by concentrating on the upper Godavari basin (UGB) terrain. The area selected comprises of UGB and its adjoining area (Fig. 1), bounded by some spectacular hills of the Western Ghat and deep valleys. The present study is the first attempt to assess the micro scale spatio-temporal rainfall variability in and around UGB by using MAR and mean half-decadal rainfall along with SD, CV, SA, MAD, and SDR. In addition, IDW spatial estimation technique is used to find spatio-temporal variation on different time scales, especially for the half-decadal SA and SDR. Attempt is also made to find if any dominant trend lies hidden within the 15 year (2000–2014) rainfall data. These types of short-term and micro level understanding of rainfall variability is expected to help improve long range predictability for water resource management.

## The study area

Godavari River has its origin in the Western Ghat near Trimbakeshwar, which lies almost 80 km east of the Arabian Sea. This place is situated in Maharashtra states' Nashik district, and the river traverses nearly 1465 km through Maharashtra and Andhra Pradesh to debouch into the Bay of Bengal near Rajahmundry. The area chosen for study, UGB and contiguous area towards its west, lies between 19° 02' to 20° 44' N latitude and 73° 47' to 75° 48' E longitude, situated solely in the western and central part of Maharashtra (Fig. 1). UGB covers 33,130 km<sup>2</sup> area spread across Nashik, Ahmednagar, and Aurangabad districts of Maharashtra state of India. It is bordered, on the NSW, by the Western Ghat range of varying elevation, tablelands, and stretches of plains. Except for the hills, forming the watershed around the basin, the whole drainage basin comprises of undulating terrain, a series of ridges, and valleys that are interspersed with low hill ranges (Sakti 2015). At the western boundary of UGB can be found a very steep slope, characterized by high rainfall, geological breaking, lineaments (Aher et al. 2014), lateritic rocks and non-soil Ghat sections covered by dense evergreen and deciduous vegetation (CWC 2014). The topography of this region is undulating and hilly, comprising 1000–1200 m average height from mean sea level (MSL) containing a few pinnacles like Kalsubai (1646 m), Harichandragarh (1422 m), Ghanchakar Donger (1497 m), and Salher



**Fig. 1** Location map of the study area depicting elevation, drainage network, water bodies (reservoirs), and RGS. The upper Godavari basin is marked by a thick black line

(1567 m) peaks. It forms an almost unbroken rampart on the fringe of western peninsula parallel to the west coast and is often hardly 70–90 km away from the Arabian Sea (Aher and Shinde 2016). The topographic morphology greatly influences the rainfall distribution and the weather pattern prevalent in the study area.

## Material and methods

### Rainfall data and statistical computation

For the present study, 15 years’ daily rainfall data from 39 RGS, located in and around UGB (Fig. 1), was obtained from hydrological data user group (HDUG), Nashik for the time period from 2000 to 2014. Daily recorded RGS rainfall data were used to calculate the 15 years’ mean rainfall and MAR of all RGS (Table 1). Mean rainfall of 15 years was grouped in 3 half-decades (2000–2004, 2005–2009, and 2010–2014) to decipher small-scale spatio-temporal variations that may have been masked within the dominant large-scale trend. In any case, 15 years’ mean has also been calculated in the present effort. SD of grouped 3 half-decade mean rainfall data for the 39 RGS was calculated using Eq. 1 and presented in Table 2.

$$SD = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \tag{1}$$

where  $x$  is the half-decade mean rainfall and  $n$  is the number of RGS.

In order to know the 3 half-decade variability of the rainfall at selected 39 RGS, CV was calculated based on SD values (Table 2), which fined the ratio of SD to mean. The main purpose of finding CV was to ascertain quality of data by measuring dispersion of the 15 years’ rainfall data of the selected stations. CV is important to measure the annual relative variability in mean rainfall data on a ratio scale of multiple RGS. CV from 3 half-decades’ SD data were calculated using Eq. 2.

$$CV = (\text{standard deviation } (\sigma) / \text{mean } (\mu)) \tag{2}$$

SA for each RGS from 15 years’ mean rainfall was calculated to test the variations within the rainfall data. It frequently helps to express the data in terms of normalized anomalies. SA provides extra information about the magnitude of rainfall anomalies. SA was calculated using Eq. 3 and is presented in Table 2.

**Table 1** Mean annual rainfall (mm) and 15 years' mean rainfall data

ID	RGS	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	Mean (15 years)
1	Karanjkhed	400	1184	1389	1393	1634	2094	2554	1521	1437	943	995	1205	1007	1392	1147	1353
2	Charose	971	985	1410	1651	1782	1549	2375	1071	1405	1040	1373	1595	1665	2213	1742	1522
3	Dongarpada	1230	1990	2313	2771	2277	1209	1919	1533	2150	734	1563	2797	2519	2663	1505	1945
4	Waghera	1512	1430	1409	1682	2377	1316	3620	1145	1292	552	850	907	961	1041	1265	1424
5	Ramshej	877	867	788	906	1330	1581	713	1005	1185	593	911	702	879	836	824	933
6	Ambedindori	515	520	369	490	789	811	820	714	823	318	271	226	226	301	484	531
7	Khadak Ozar	358	542	672	553	547	205	1038	481	544	324	306	204	309	538	539	477
8	Rajur Bahula	736	874	904	850	790	480	1290	934	1116	497	1152	912	579	1056	1074	883
9	Jamsar	1755	2190	2622	2688	2940	3621	3911	2951	3263	1703	2563	2994	2203	2971	2315	2713
10	Juni Jawhar	2196	2947	2698	3291	3334	4204	3205	2346	3391	1705	2935	2158	1840	3262	3115	2842
11	Chinchghar	2158	2353	2346	2795	2623	3412	3103	2906	3190	2215	3138	3494	1821	2743	2475	2718
12	Khodala	2108	2198	2072	2647	3251	3977	4224	2822	3444	2843	3027	3209	2401	3308	2936	2964
13	Ogade	2025	2493	2080	2812	3434	3406	3450	2679	2625	1761	2865	2993	1902	3327	2707	2704
14	Savarkhand	2446	2332	2243	2802	2769	3473	3372	2634	3017	1705	2682	3032	1892	3122	2588	2674
15	Pundas	2243	2179	2324	2399	2797	3208	2466	1613	3649	1772	3341	3227	2043	2456	2738	2564
16	Pimpnas(kl)	1916	3099	2848	2445	2512	3456	2279	1495	2473	8263	3108	2742	1508	2179	2129	2830
17	Shendrun	2225	2757	2159	2481	2431	3824	3510	1741	2220	1694	2959	2721	1723	2862	2593	2527
18	Kushgaon	1437	1088	1028	1964	2364	3281	3971	1828	2770	1422	1908	2242	1819	2525	2125	2118
19	Bhawali(Bk)	584	1361	1409	2498	1811	1476	3801	1638	2778	1522	2467	2599	1998	2476	2223	2043
20	Indore	931	1260	845	2696	1186	1377	2044	1352	1110	1139	1530	1539	1320	1638	1574	1436
21	Thangao	346	603	361	670	639	639	1061	925	758	388	580	500	427	464	443	587
22	Nandur Shingote	344	445	243	388	465	422	740	297	439	269	385	219	397	541	323	394
23	Rahata	550	473	384	267	489	561	739	526	383	332	522	396	556	634	304	474
24	Somthan	404	484	242	329	585	553	716	464	632	315	765	235	329	470	414	462
25	Deogaon	587	315	425	339	506	609	950	732	737	302	626	274	351	669	380	520
26	Loni(Kh)	609	438	393	230	330	252	899	590	855	559	1024	636	496	497	397	547
27	Ambelhol	509	430	607	407	618	492	1034	664	816	626	963	694	435	774	496	638
28	Toka	815	373	713	397	785	240	1111	684	640	1098	1118	1011	652	733	476	723
29	Bhavarvadi	413	493	414	170	281	454	602	393	513	482	680	370	345	483	309	427
30	Supa	469	387	349	212	405	366	744	715	524	743	669	361	196	623	427	479
31	Sangammer	370	417	457	387	456	481	738	609	484	373	508	289	519	390	437	461
32	Adhala	401	411	337	323	570	581	737	451	615	251	495	305	533	448	447	460
33	Kopangaon	486	428	387	398	425	725	556	762	481	328	681	400	403	414	269	476
34	Mhaladevi	628	708	439	752	784	784	1070	836	676	382	678	533	574	519	505	658
35	Aurangabad	552	612	673	644	674	1014	1307	629	891	622	924	875	558	745	377	740
36	Chitali	274	18	150	282	466	442	730	552	530	328	586	635	362	572	237	411
37	Palkhed Dam	1354	1274	1195	1115	1036	956	1127	672	863	319	551	338	387	400	372	797
38	Taked	2469	2347	2224	2102	2034	2324	2095	1438	933	991	1096	825	989	1260	1073	1613
39	Niphad	482	488	425	451	844	689	990	878	657	442	603	369	616	549	481	598
MAR		1094	1225	1188	1376.4	1471	1604	1888	1262	1495	1125	1427	1354	1071	1439	1238	

Note: Sangammer: Sangammer (Waghapur), Mhaladevi: Mhaladevi (Induri), Niphad: Niphad (Kundewadi)

**Table 2** Spatial height of RGS, half-decade mean (mm), TRMM rainfall, and standardized anomaly

RGS	RGS height (MSL)	2000–2004	2005–2009	2010–2014	TRMM (mm)	SA
Karanjkhed	790	1200	1710	1149	849	−0.02
Charose	690	1360	1488	1718	646	0.16
Dongarpada	722	2116	1509	2210	1131	1.04
Waghera	947	1682	1585	1005	1642	0.54
Ramshej	723	953	1015	831	576	−0.31
Ambedindori	614	536	697	360	491	−0.79
Khadak Ozar	653	534	518	379	742	−0.79
Rajur Bahula	652	831	863	955	778	−0.45
Jamsar	455	2439	3090	2609	2323	1.41
Juni Jawhar	273	2893	2970	2662	2063	1.94
Chinchghar	24	2455	2965	2734	2612	1.43
Khodala	386	2455	3462	2976	2752	1.43
Ogade	112	2569	2784	2759	1921	1.56
Savarkhand	93	2518	2840	2663	2196	1.50
Pundas	29	2388	2542	2761	1727	1.35
Pimplas(kl)	17	2564	3593	2333	2046	1.56
Shendrun	98	2411	2598	2572	2194	1.38
Kushegaon	785	1576	2654	2124	1267	0.41
Bhawali(Bk)	618	1533	2243	2353	1529	0.36
Indore	779	1384	1404	1520	2212	0.19
Thangaon	839	524	754	483	656	−0.81
Nandur Shingote	650	377	433	373	753	−0.98
Rahata	517	433	508	482	350	−0.91
Somthan	527	409	536	443	565	−0.94
Deogaon	532	434	666	460	667	−0.91
Loni(Kh)	582	400	631	610	692	−0.95
Ambelhol	528	514	726	672	669	−0.82
Toka	467	617	755	798	871	−0.70
Bhavarwadi	581	354	489	437	501	−1.00
Supa	718	364	618	455	511	−0.99
Sangamner	546	417	537	428	574	−0.93
Adhala	610	408	527	445	583	−0.94
Kopargaon	507	425	570	433	742	−0.92
Mhaladevi	599	662	750	562	650	−0.65
Aurangabad	557	631	893	696	539	−0.68
Chitali	525	238	516	478	548	−1.14
Palkhed Dam	581	1195	787	410	478	−0.03
Taked	615	2235	1556	1049	867	1.18
Niphad	554	538	731	524	701	−0.79
SD	–	862.91	993.84	929.29	702.26	–
CV (%)	–	70.74	69.82	74.09	62.79	–
MAD	–	772.37	862.27	842.88	613.26	–
		$R = (2000–2004) 0.8647$				–
			$R = (2005–2009) 0.9015$			–
				$R = (2010–2014) 0.893$		–

$$SA = \frac{(x - \bar{x})}{SD} \quad (3)$$

where  $x$  is the sum of annual rainfall,  $\bar{x}$  is the mean of the entire rainfall series, and SD is the standard deviation of half-decade rainfall.

MAD is a measure of dispersion. It measures how much the values in the rainfall data set are likely to differ from their mean (Alcula 2017). Thus, to know the temporal variations, MAD was calculated using Eq. 4 and is presented in Table 2.

$$MAD = \frac{1}{n} \sum_{i=1}^n |x_i - \bar{x}| \quad (4)$$

where  $n$  is the number of RGS,  $\bar{x}$  is the mean of the half-decade rainfall, and  $x_i$  are the individual values of RGS half-decade mean.

SDR helps to accurately delineate higher and lower rainfall regimes in a given area. Thus, 15 years' mean rainfall was grouped in 5 classes, i.e., >2000 mm (very high), 1500–2000 mm (high), 1000–1500 mm (moderate), 500–1000 mm (low), and <500 mm (very low) for dissemination of SDR in and around the study area.

A comparison of longitudinal rainfall changes from the Toka, Rahata, Taked, and Ogade RGS was carried out to know the orographic effect on rainfall. Similarly, half-decades' mean rainfall and TRMM rainfall data for 39 RGS were also plotted with box and whisker diagram. This will reveal where most values lie and also those values that greatly differ from the normal rainfall. It is a diagram that gives a graphic representation of the distribution of the outliers.

### Spatial estimation of rainfall variability

The RGS map produced by HDUG was georeferenced in Global mapper software with WGS 1984, UTM 43 N zone. The 39 RGS points were then extracted from georeferenced map by a point mode digitization method. A Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM), downloaded from <http://srtm.csi.cgiar.org>, was used to extract the spatial height of RGS and to discern the topographical effects on rainfall. The SRTM DEM, produced originally by NASA, is a major breakthrough in digital mapping and provides accessibility to high-quality elevation data for large portions of the tropics. The SRTM data are available at 90-m resolution/3 arc sec (Sun et al. 2003; Aher et al. 2017a, b). Thirty-nine RGS points were superimposed over SRTM DEM, and spatial heights were linked to the same points in Global Mapper software (Table 2).

The statistical outcomes of rainfall data were imported into ArcGIS software and were linked to digitized RGS points. The spatial interpolation of a half-decade mean rainfall: (1)

2000–2004, (2) 2005–2009, and (3) 2010–2014, along with SA and SDR for 39 RGS points, was carried out using the IDW method for the purpose of spatio-temporal estimation of the entire study areas' rainfall variability. The IDW method is a multivariate interpolation technique which estimates the values of an attribute at unsampled points using a linear combination of values of sampled points weighted by the inverse function of distance from the point of interest to the sampled points (Deshmukh and Aher 2016). According to Keblouti et al. (2012), weights can be expressed using Eq. 5.

$$\lambda_j = (1/d^p_i) / \left( \sum_{j=1}^n 1/d^p_i \right) \quad (5)$$

where  $\lambda$  is the weight,  $d_i$  is the distance between  $x_0$  and  $x_i$ ,  $p$  is a power of the parameter, and  $n$  is the number of sampled points used for the estimation.

The main factor affecting the accuracy of IDW is the value of the power parameter. Weights diminish as the distance increases, especially when the value of the power parameter increases, so nearby samples have a heavier weight and have more influence on the estimation and the resultant spatial interpolation is local (Isaaks and Srivastava 1989; Keblouti et al. 2012; Deshmukh and Aher 2016).

Spatial interpolated maps of half-decades' mean rainfall (1) 2000–2004, (2) 2005–2009, and (3) 2010–2014 were prepared in ArcGIS software where mean rainfall estimated variability was divided into 10 zones with an equal apportioning of 400 mm for every zone. This was done to understand if there were any major and minor changes occurring in the precipitation pattern in the study area. Moreover, SA map and SDR maps were also prepared to know the spatio-temporal variability within 15 years and 39 RGS.

### TRMM rainfall data

Satellite-derived TRMM data, available on a global scale, were downloaded from <http://www.geog.ucsb.edu/~bodo/TRMM/> portal. The rainfall measuring instruments on the TRMM satellite includes precipitation radar (PR), electronic scanning radar operating at 13.8 GHz, TRMM microwave image (TMI), nine-channel passive microwave radiometer, visible and infrared scanner (VIRS), and five-channel visible/infrared radiometer (Liu et al. 2012; Duan and Bastriaanssen 2013). Bookhagen (2016) processed TRMM data for the periods 1998 to 2009 from product 2B31, a combined PR/TRMM TMI rain-rate product with path-integrated attenuation at 4 km horizontal and 250 m vertical resolution. TRMM freely disseminates high- and medium-resolution precipitation data from tropical regions (Hunink et al. 2014) providing a unique opportunity to improve rainfall estimates in remote and hilly areas. TRMM rainfall is currently compared with RGS in various parts of the world (Immerzeel et al. 2009; Javanmard et al. 2010; Liu et al. 2012; Gao and Liu 2013;

Duan and Bastriaanssen 2013). Rahman and Sengupta (2007) carried out such an assessment over India using a spatial resolution of  $1^\circ \times 1^\circ$ . However, the suitability of TRMM data for hydrological modeling is yet to be studied for most river basins of India (Kneis et al. 2014), even though it offers uniformity in estimating spatio-temporal precipitation variability. These TRMM rainfall data (mean of 1998–2009) are processed and linked to 39 RGS after superimposing the vector shape points on orthorectified TRMM grid in Global Mapper software. Obtained TRMM data in specific RGS areas are shown in Table 2.

Pearson correlation coefficient ( $R$ ) measures the strength of the linear association between two variables, where the value  $r = 1$  means a perfect positive correlation and the value  $r = -1$  means a perfect negative correlation (SSS 2018). In this study, it was used to validate whether RGS rainfall and TRMM rainfall are correlated to confirm the spatio-temporal variability.  $R$  values were calculated for 3 half-decades using Eq. 6 and are presented in Table 2.

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} \sqrt{\sum_i (y_i - \bar{y})^2}} \tag{6}$$

## Results and discussion

### Spatio-temporal variation in rainfall

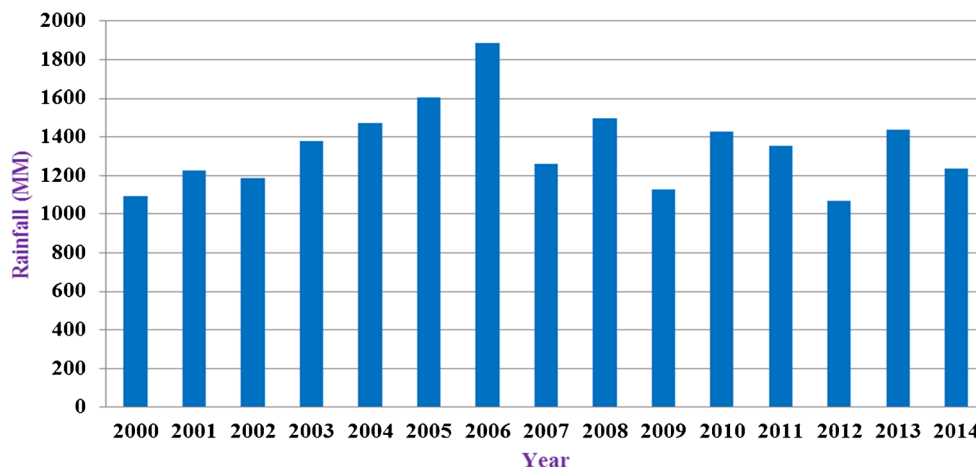
In the study area, the highest MAR, i.e., 1888 mm, was recorded in the year 2006 and the minimum, i.e., 1071 mm, in 2012 (Fig. 2). The relative difference (rainfall anomaly) between high and low annual rainfalls was 817 mm between 2000 and 2014. There is a continuous rise in annual rainfall from 2000 to 2006, except at 2002, where it is seen to record a

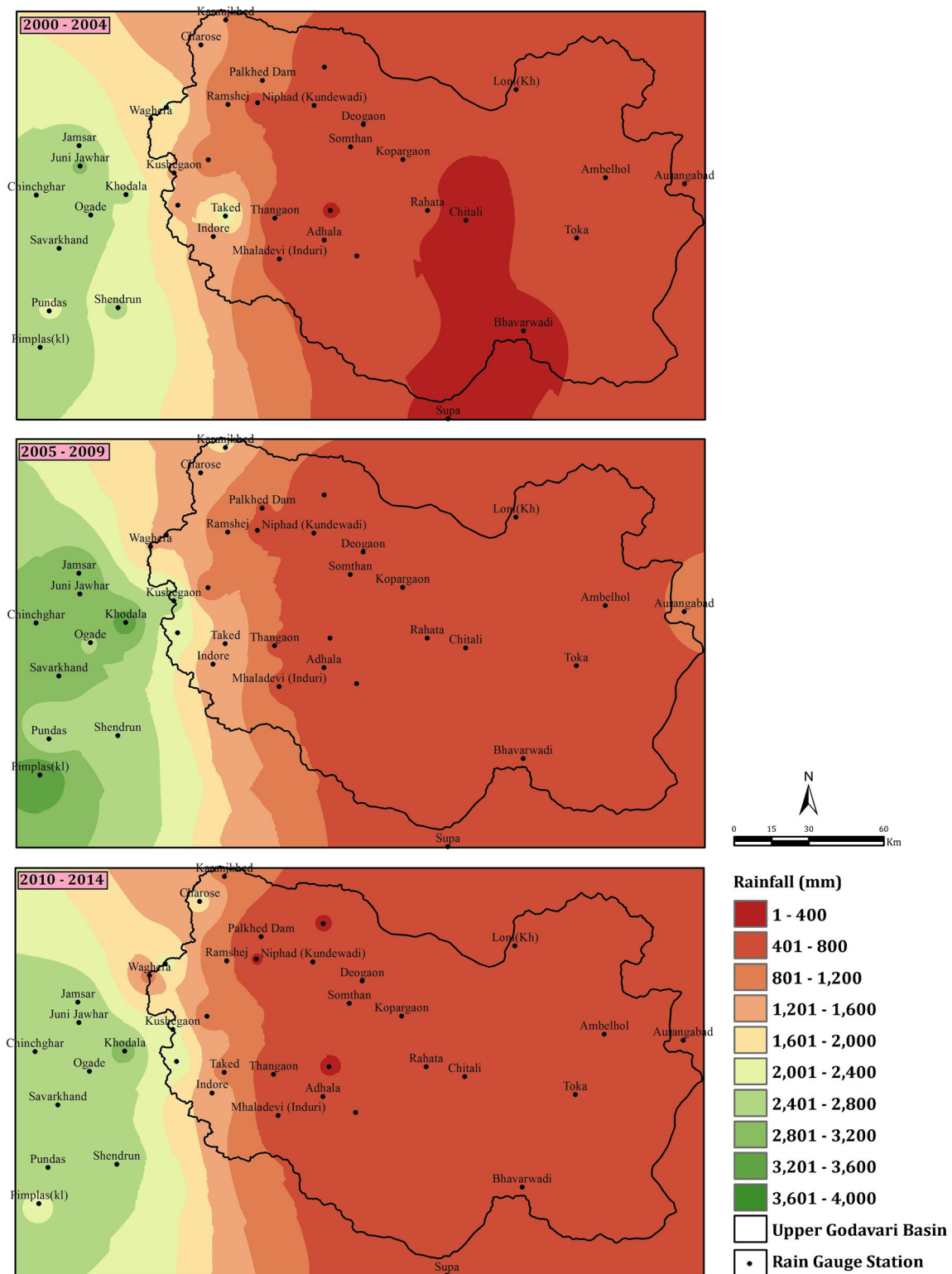
slight decrease from the previous years' precipitation. There is a sharp decline in 2007, from the 2006 annual precipitation, and an alternate rise and decline till 2014, except at 2011 and 2012 (Table 1). These two years depict the declining trend (Fig. 2) with respect to 2010.

The data for the 5-year period from 2000 to 2004 (half-decade) reveals maximum precipitation occurred in the western part of the UGB (Fig. 3; top panel), which is seen to gradually decrease towards the east. High precipitation (3601–4000 mm) is seen to occur at Jamsar, Juni Jawhar, Chinchghar, Khodala, Ogade, Savarkhand, and Pimplas. Within this high rainfall zone can be seen Pundas which receive comparatively less rain (2001–2400 mm). However, towards the east of Pundas, Shendrun receives the highest rainfall, which is seen to lie in the zone depicting 2001–2400 mm rainfall. In the time period 2005 to 2009, the highest rainfall (3601–4000 mm) is concentrated more towards the west (Fig. 3; middle panel), around Jamsar, Juni Jawhar, Chinchghar, Khodala, Savarkhand, and Pimplas. Ogade, Pundas, and Shendrun are seen to receive 2401–2800 mm rainfall. These RGS are located beyond the UGB domain. The zone depicting 2001–2400 mm rainfall that was wider between the years 2000 to 2004 (Fig. 3; top panel) is seen to constrict in the years 2005 to 2009 (Fig. 3; middle panel) and 2010 to 2014 (Fig. 3; bottom panel). In the half-decade of 2010–2014, the rainfall has fallen down appreciably in the western region (Fig. 3; bottom panel), where the RGS had received maximum rainfall in the first half-decade of 2000 to 2004. At the same time, it can be discerned that with a good monsoon the reach can be as far as Kusbegaon, which was breached in 2005–2009 (Fig. 3; bottom panel).

The zones encompassing 2001–2400 mm till 1201–1600 mm rainfall are seen to wax and wane during the three half-decadal periods (Fig. 3). Some of the notable features relate to changes in precipitation rates at Charose, Waghera, and Taked RGS during the 15-year duration. The 801–1200 mm rainfall zone is almost unchanged during all the

**Fig. 2** Mean annual rainfall (temporal variation) from 2000 to 2014 which are seen to have caused by many local and regional monsoonal features. The trend is of increasing type from 2000 till 2006 from where it changes to alternate rise and fall till 2014 with a few exceptions at 2008 and 2009





**Fig. 3** Top panel: Spatial estimation of rainfall for the years from 2000 to 2004 reveal high precipitation in the western and low in the eastern part of the study area. This clearly reveals orographic effect on the precipitation. Middle panel: Spatial estimation of rainfall for the half-decadal timeframe from 2005 to 2009 showed almost the same precipitation, except in areas

nearby Aurangabad where some enhancement in precipitation can be seen. Bottom panel: Spatial estimation of rainfall for timeframe from 2010 to 2014 reveals rainfall intensity lowered from the past decadal activity in the western part of the study area, though a small increase is seen around Aurangabad and Toka region



three half-decades, as also the 401–800 mm rainfall zone. The lowest rainfall zone is found to exist in a region encompassing Chitali, Bhavarwadi, and Supa, and around Adhala between the years 2000 and 2004. A low is seen at Palked dam and Adhala in the half-decadal period of 2010–2014. Precipitation is seen to have marginally increased around Aurangabad during 2005–2009 (Fig. 3). The orographic effect is clearly discernible in the UGB, where the maximum precipitation is seen to exist on the western side (the Western Ghats, Fig. 1) during all the years that the data is gathered from. The physiographic high of the Western Ghat forces the moisture laden air to rise up. This leads to cooling and condensation ultimately leading to precipitation. The leeward side is parched due to loss of moisture.

The spatio-temporal variability deciphered in the selected 33,130-km<sup>2</sup> area of UGB for the half-decadal time frames of 2000–2004, 2005–2009, and 2010–2014 revealed quite a few characteristics. The topographic arrangement of the Western Ghats stretch has been influencing the spatial distribution of rainfall pattern. It consists of undulating topography and variations in the climatic conditions, especially the annual monsoon behavior. In general, the western part of study area receives around 4000 mm rainfall, while the eastern part records only about 400 mm rainfall. High annual rainfall was recorded at Khodala (2964 mm), Juni Jawhar (2842 mm), and Pimplaskl (2830 mm) which are located in the western part, whereas Chitali (411 mm), Nandur Singote (394 mm), and Sangamner-Waghapur (461 mm) received low rainfall and are situated in the eastern part depicting intra-regional precipitation variations (Fig. 3).

Thus, it can be seen that Adhala, Ambedindori, Ambelhol, Chitali, Aurangabad, Bhavardi, Deogaon, Khadak, Kopargaon, Loni, Nandur Shingote, Rahata, Palkhed, Somthan, Supa, and Taked experience average annual rainfall between 0 and 500 mm (Table 1). Charose, Indore, Karanjkhed, Rajur Bahula, Ramshej, Mahaladevi, Niphad, Thangaon, Toka, and Waghera get an annual average precipitation between 501 and 1500 mm (Table 1). Bhawali, Chinchghar, Dongarpada, Jamsar, Juni Jawhar, Khodala, Kusbegaon, Ogade, Pimplas, Pundas, Sawarkhand, and Shendrun are the places that receive maximum annual average rainfall between 1501 and 3000 mm (Table 1). During dry months (October to May), precipitation is almost negligible and is comparatively more at Deogaon, Khodala, Pimplas, Supa, and Toka. Changes in rainfall, higher or lower, or changes in its spatial and seasonal distribution can influence runoff, soil moisture, and groundwater reserves in the UGB.

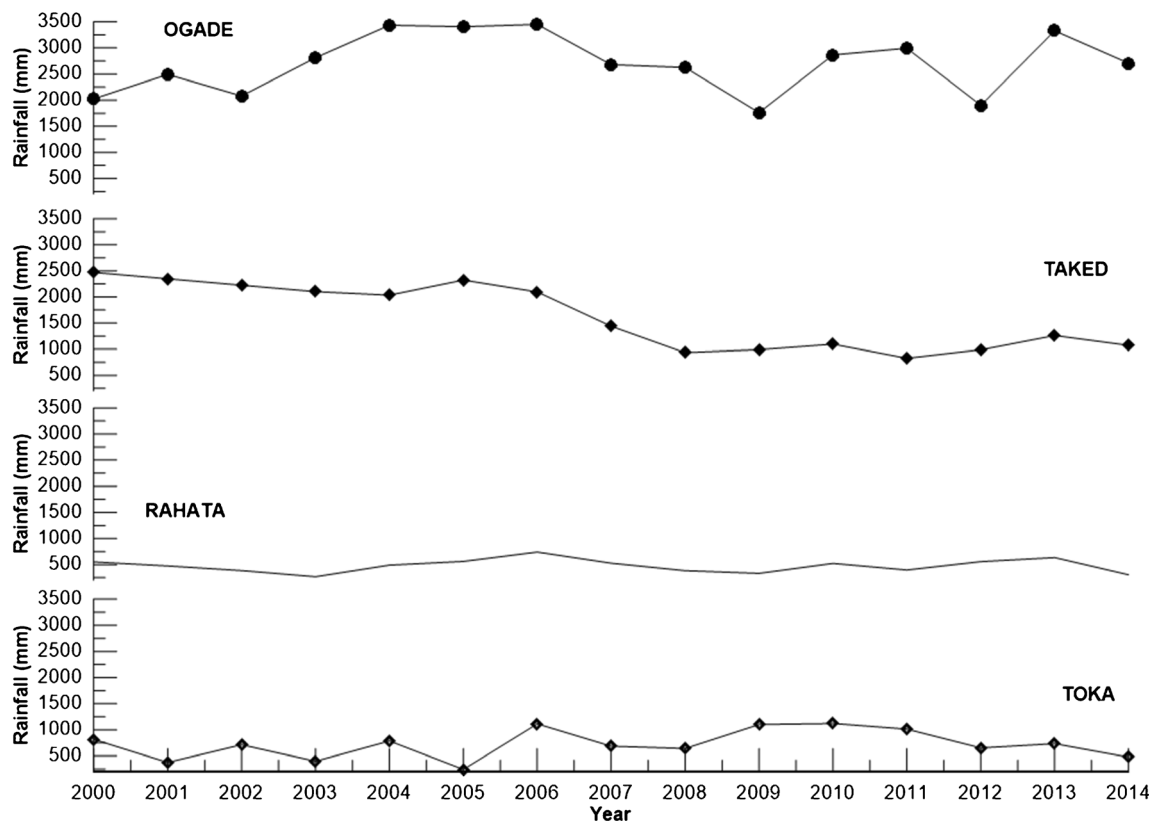
To know how spatio-temporal variation pans out in the study area, four RGS were selected comprising Toka, Rahata, Taked, and Ogade which span from east to west of the study area, almost on the same horizontal line (Fig. 4). Toka is located in the mid-eastern portion of the study area which receives ~723 mm rainfall, on an average, every year.

The bulk of this precipitation is received during the monsoon months from June to September, wherein 2006 witnessed maximum rainfall, followed closely by 2009 and 2011 (Fig. 4). The precipitation was less during 2001, 2003, and 2014 and moderate in the rest of the years, which witnessed erratic and fluctuating rainfall. Rahata lies to the west of Toka RGS. The rainfall at Rahata is low (~474 mm per year average) compared to Toka, and the maximum precipitation was recorded here in 2006, followed by 2013, 2012, and 2010 (Fig. 4). The precipitation shows an increasing trend till 2006 and is seen to marginally increase and decrease throughout the 15-year period. At Taked, the precipitation is more (~1613 mm per year average) than that at Toka and Rahata. The average maximum precipitation can be seen in 2000, followed closely in decreasing order by 2001, 2005, and 2002 (Fig. 4). A decreasing trend in average precipitation is seen from 2006 till 2012, with an exception in 2010. 2011 onwards, this RGS is on an increasing trail. Ogade RGS is situated on the extreme west of the study area and is seen to receive the maximum rainfall (~2704 mm per year average) with wide fluctuations throughout the 15-year period. Thus, it can be seen that there is an alternation between erratic and even precipitation between the four stations. The orographic effect is more pronounced at Toka. It receives low precipitation due to its geographical location in a rain shadow zone.

It must be noted that the four stations are situated on topographic highs and lows that seem to have an influence on the degree of intensity and amount of precipitation received. Toka and Rahata are the easternmost stations. However, Rahata receives less rainfall than Toka. Both are located in a basin, which are shielded from, at least the three sides, by the elevated ranges (Fig. 1). Taked and Ogade are on either side of an elevated divide (Fig. 1), and the proportion of rainfall they receive is more than their eastern counterparts. The rainfall is high and erratic at Ogade and moderately low and uniform at Taked. Thus, it can be surmised that the monsoonal clouds are hampered by the presence of elevated ridges at Ogade which facilitate the maximum downpour, on an average, over Ogade and Taked, though they are separated by a ridge-like structure. Toka is on the far eastern side of the study area; even then, it receives more average rainfall than Rahata. Toka and Rahata are basinal stations, and the quantum of precipitation is comparatively quite low than the mountainous stations. The orographic effect is more at Toka because of the cloud movement that is broken by the elevated topography that lies beyond it (Fig. 1). The monsoonal advance that starts from the west, and proceeds towards the east, is blocked at places by the topographic elevations of these four stations (Fig. 4).

### Statistical parameters

The intra-annual variability can be expressed by calculating the CV, which gives an indication of the relative differences



**Fig. 4** Comparison of longitudinal precipitation changes between Toka, Rahata, Taked, and Ogade which spread from east to west of the study area. They all lie almost on the same horizontal line. The precipitation and orographic effect is seen to amplify from west to east

between wet and dry seasons (Hunink et al. 2014). SD in the study area was higher (994) for the half-decade period 2005–2009 and mildly lower (863) for 2000–2004 half-decade (Table 2). CV was 70% during 2005–2009, 71% during 2000–2004, and 74% between 2010 and 2014 (Table 2). This indicates in 2000–2004 and 2010–2014 the rainfall variability was high compared to that in 2005–2009.

SA ranged between  $-0.02$  and  $1.94$  (Table 2) and is higher ( $> 1$ ) in the western part. RGS at Jamsar, Juni Jawhar, Ogade, Pundas, Savarkhand, and Shendrum show higher SA. It was observed from spatial estimation, the eastern part of the study area reveals low SA ( $< 1$ ). In this area are located Loni, Ambelhol, Rahata, Sangamner, Toka, Supa, and Adhala RGS (Fig. 5). The western part of the study area exhibited positive SA ( $1.2$ – $1.9$ ) and the eastern part negative ( $-1.1$ – $0.58$ ). This indicates low rainfall variability exists in the western and high in the eastern portion of the study area (Fig. 5).

Higher MAD was observed during 2005 to 2009 half-decade, i.e.,  $862.27$  mm, while lower in the 2000 to 2004 half-decade, i.e.,  $772.37$  mm (Table 2). The MAD of TRMM data was observed to be lesser than three half-decades, i.e.,  $613.26$  mm (Table 2).

SDR revealed the western margin of the study area experienced high rainfall ( $> 2000$  mm) while the eastern part experienced low ( $> 500$  mm). Out of the total 39 RGS, 11 are

associated with very high rainfall (kindly refer to Table 1 for RG stations, ID 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19), 3 with high rainfall (2, 3, and 38), 3 with moderate rainfall (1, 4 and 20), 12 with low rainfall (5, 6, 8, 21, 25, 26, 27, 28, 34, 35, 37, and 39), and the remaining 10 are associated with very low rainfall (7, 22, 23, 24, 29, 30, 31, 32, 33, and 36). The SE margin of the study area revealed the very low SDR while the WS margin exhibited very high SDR. The RGS like Supa, Bhavarwadi, Kopargaon, Chitali, Sangamner, and Adhala were consisted with low SDR while Jamsar, Ogade, Chinchghar, Pundus, Pimplas, Saverkhand, etc. have very high SDR in the study area (Fig. 6).

Annual mean, half-decade mean, SD, CV, SA, and SDR revealed the highest rainfall occurred in the year 2006 (1888 mm), followed by in the year 2004 (1471 mm) and 2005 (1604 mm, Table 1). The lowest rainfall was observed in the year 2012 (1071 mm), followed by the year 2000 (1094 mm) and 2009 (1125 mm). Heavier rainfall was observed along the western margin along the wind-ward slope of Western Ghat at places like Shendrun, Savarkhand, Pundas, Chinchghar, and Pimplas located in the low elevation regions and wind-ward direction of the Western Ghat. The highest mean rainfall was recorded in 2005–2009 and the lowest in 2000–2004.

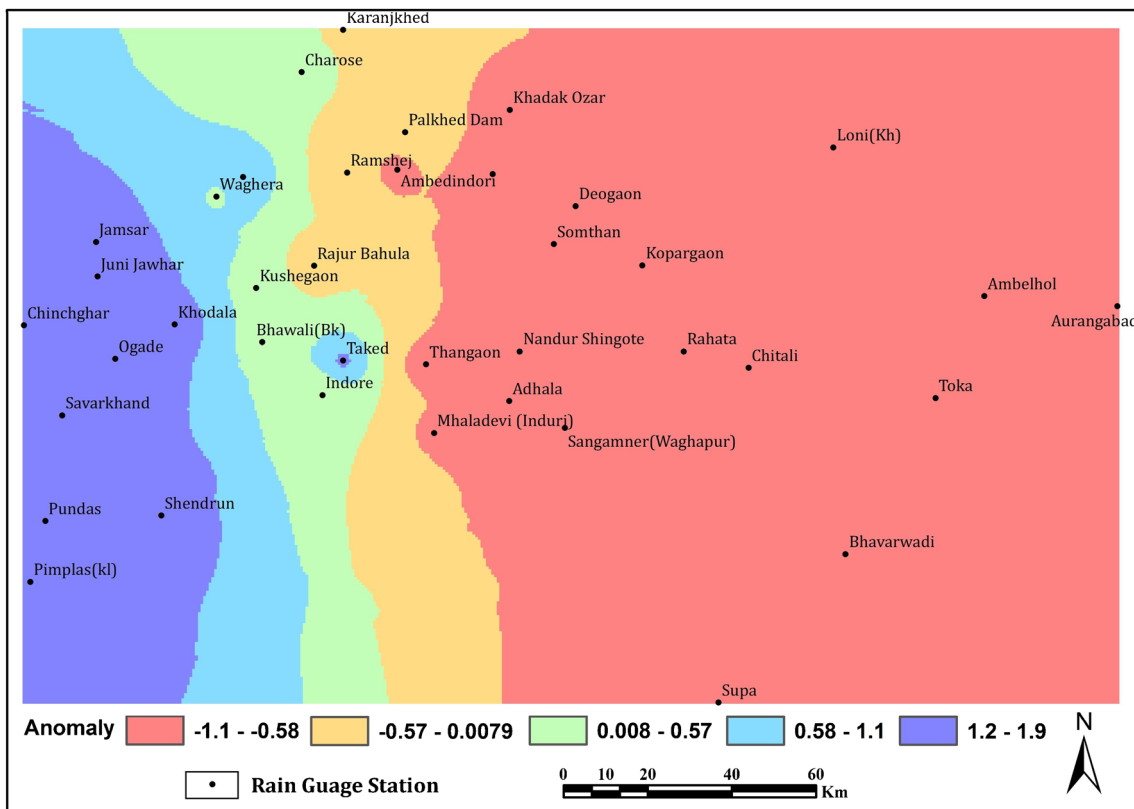


Fig. 5 Estimation of standardized anomaly in the study area

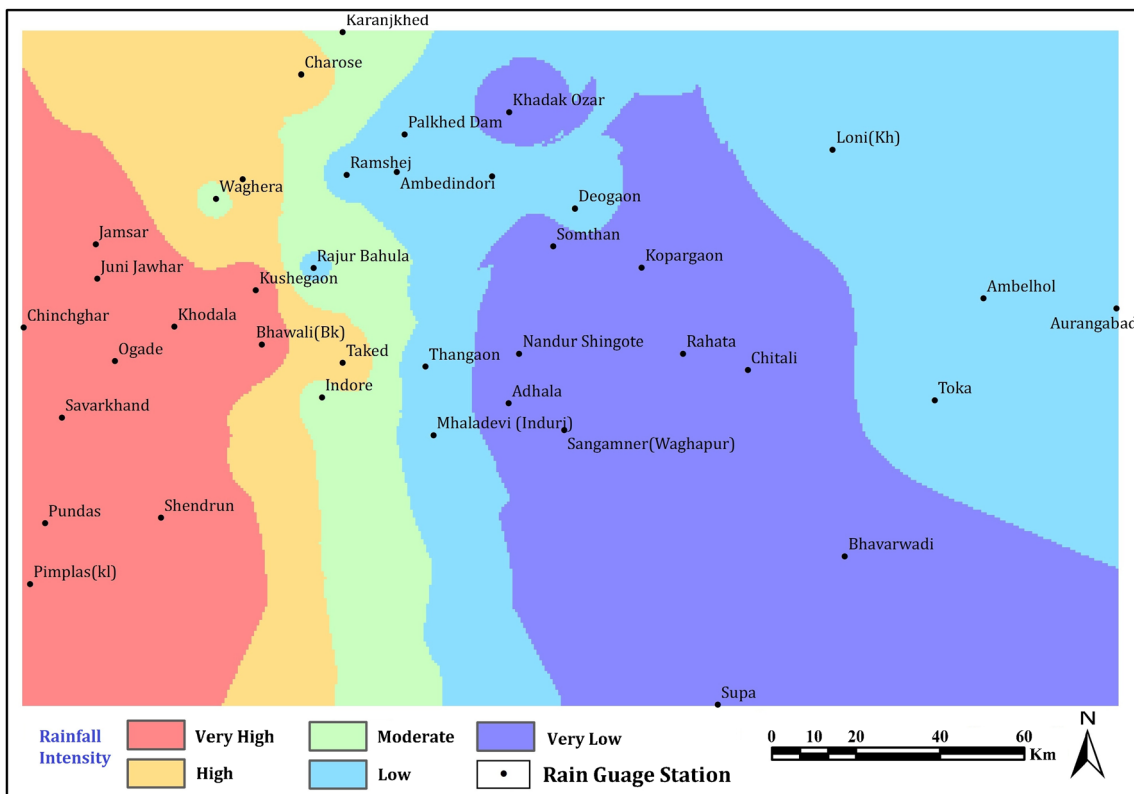
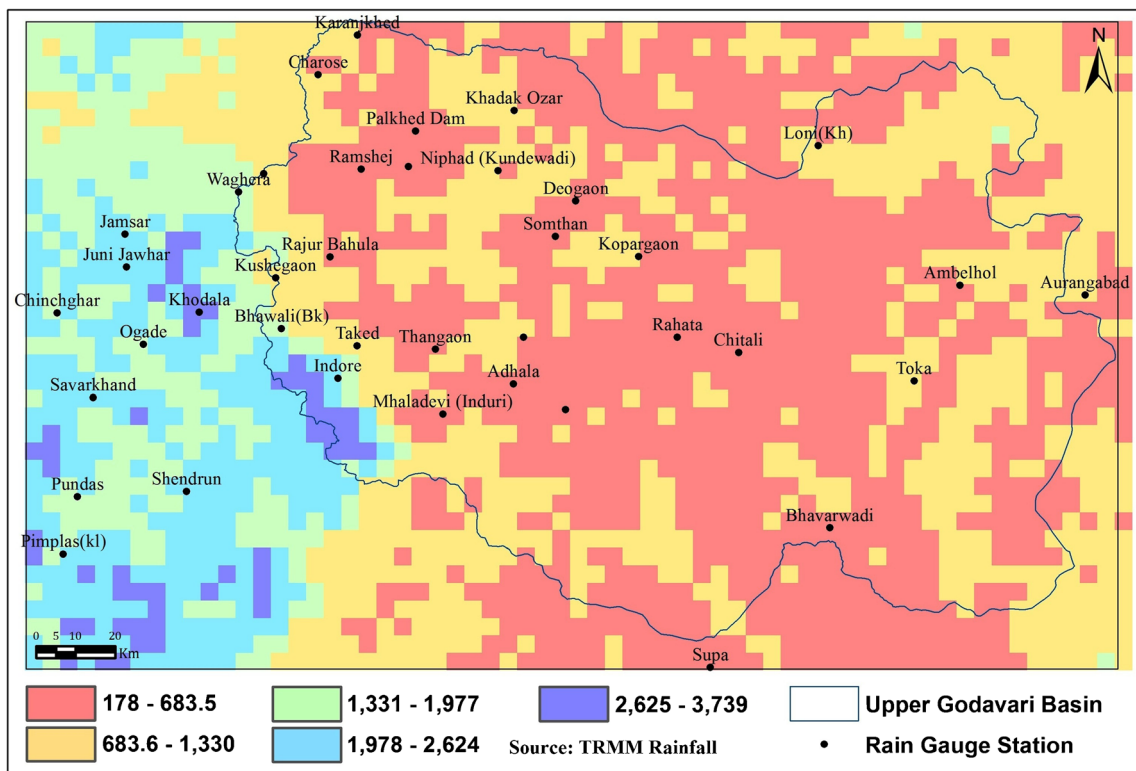
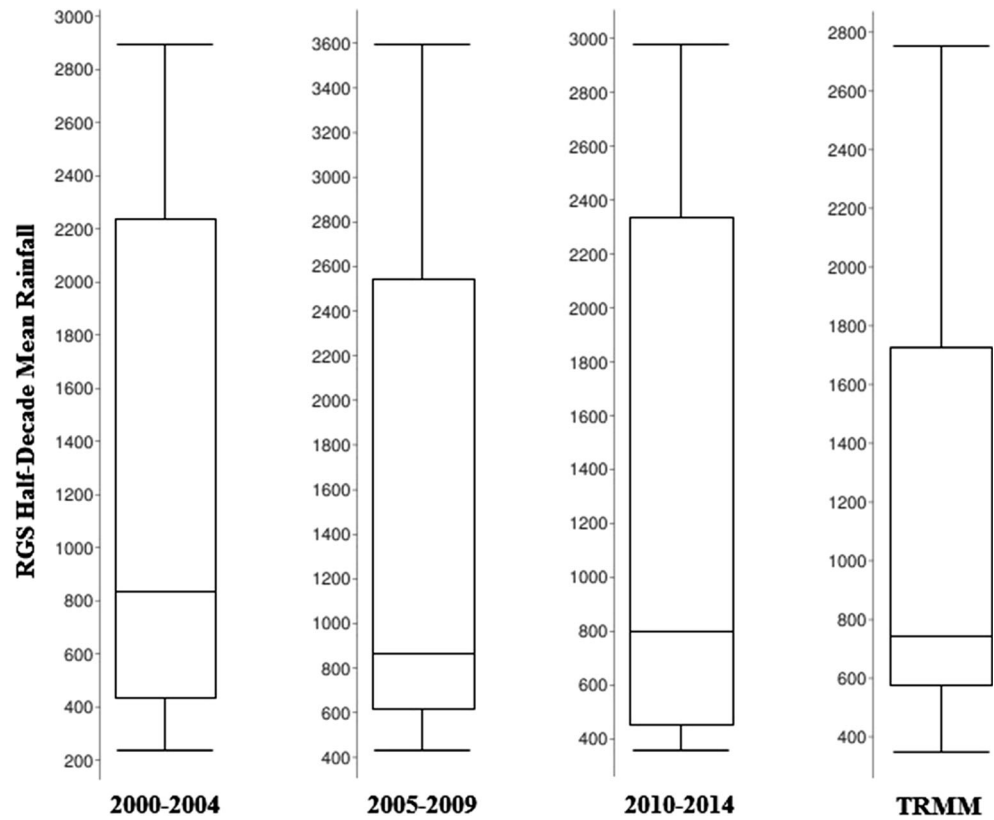


Fig. 6 Estimation of SDR in the study area

**Fig. 7** Box and whisker plot of a half-decade mean rainfall and TRMM data for 39 RGS



**Fig. 8** TRMM-based rainfall (mm) variations found in the study area for the period 1998 to 2009. The zonation is arbitrarily done based on the average of 11 years' TRMM data

It was observed in the box and whisker diagram that the outliers' rainfall value limits were more than 2300 mm in 2005 to 2009 and 2010 to 2014 half-decades, while it was more than 2200 mm in 2000 to 2004 half-decade. In TRMM data, it was more than 1700 mm (Fig. 7).

### Spatial variations in TRMM rainfall

The rainfall distribution pattern based on TRMM data is depicted (Fig. 8). The zonation is arbitrarily done based on the average of 11 years' TRMM data. As expected, the highest TRMM spatial rainfall distribution (2625–3739 mm) can be seen in the western part, while a minimum spatial distribution (178–683 mm) is seen to occur in the eastern part of the study area. Very few areas in the western part are seen to cross 2625 mm rainfall limit, whereas the rest of the study area receives comparatively less rainfall (178–683 mm). The NW part of the study area received 1331–1977 mm TRMM rainfall, while in the SE part it was around 683–1330 mm rainfall. The fluctuations in spatial RGS rainfall data are observed in a TRMM rainfall pattern as well (Fig. 8).

An interesting pattern can be discerned between the RGS and TRMM data depicted in Fig. 9. Though the overall pattern of the average variation in rainfall is similar in both RGS and TRMM data, there are some conspicuous differences between the two data sets as well. Close examination of Fig. 9 will reveal abnormalities between stations 10 to 20. These RGS, from the westernmost part of the study area, receive the maximum rainfall. The orographic effect is clearly discernible. However, the TRMM data, possibly cannot distinguish gentle orographic effects. Hence, there has crept some discrepancy in

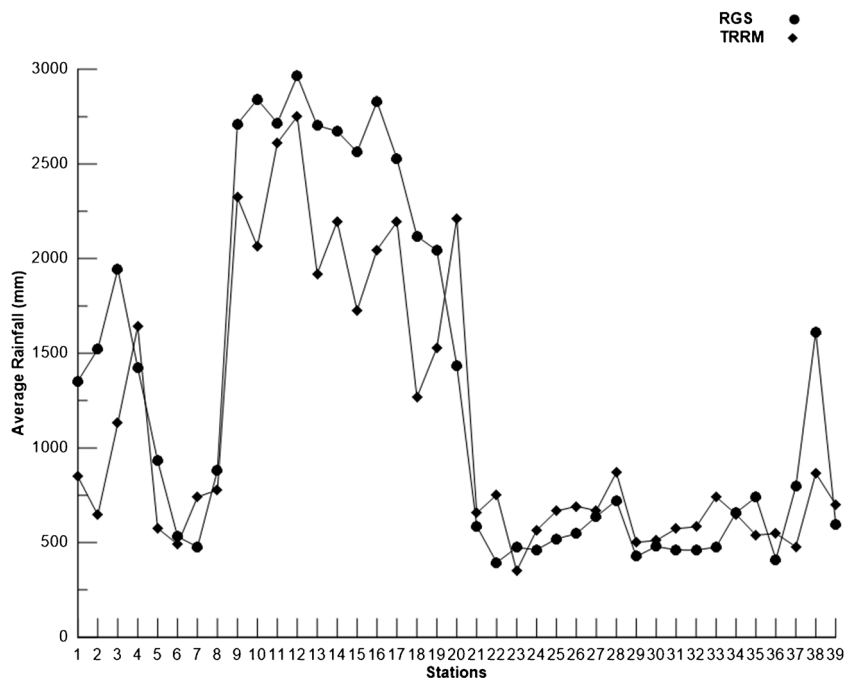
the rainfall pattern compared to RGS stations. However, the variation is not drastic and TRMM data can be used to understand the regional pattern of rainfall. The local pattern will need to be derived with a lot of caution.

The *R* value of 2000 to 2004 half-decade was 0.86, 2005–2009 was 0.90, and 2010 to 2014 was 0.89 (Table 2). A strong positive correlation was observed between TRMM and 3 half-decade rainfall data, which confirms the validity of both types of rainfall data (Fig. 10). Thus, the positive correlation between RGS and TRMM increases the confidence in using the combined data to understand the spatio-temporal variability of a given area.

Rainfall variability recorded at all the RGS from the study area, for the three half-decades, are depicted in Fig. 11 which reveals high correspondence between the height of the RGS and the intensity of rainfall.

The Indian monsoon is a complex feature and is caused by seasonal reversal of winds over the Indian subcontinent. The Indian monsoon is a macro scale feature which is aided and abetted by causes of regional and global nature, and impacts the socioeconomic fabric of the subcontinental inhabitants. The antiquity of the Indian monsoon is placed at about 8–10 Ma ago and has evolved by complex interaction between Indian Ocean and Himalaya-Tibetan plateau (Webster et al. 1998; Clemens et al. 1991). Of all the tropical or subtropical features, the monsoon has the largest annual amplitude (Pant 2003). According to Charney (1969) and Gadgil (2003), monsoon reflects the movement of intertropical convergence zone (ITCZ), which is seasonal in nature. Riehl 1979 considers monsoon to be an equatorial trough, formed due to variable latitude of maximum insolation. Kumar et al. (1999) deduce

**Fig. 9** There is an interesting pattern between the RGS and TRMM data, wherein some conspicuous dissimilarity can be seen at stations between 10 and 20. These RGS stations form the westernmost part of the study area, which lie in the neighborhood of topographic highs, which receive the maximum rainfall



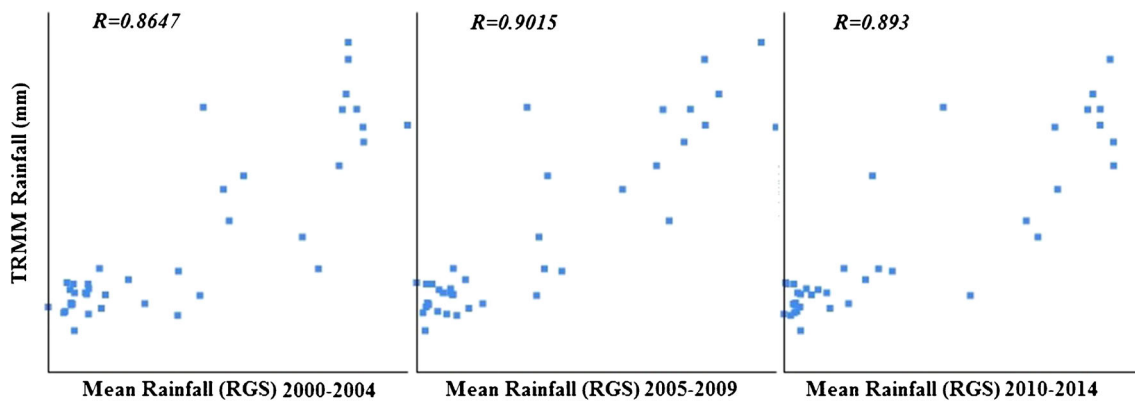


Fig. 10 Observed positive correlation between three half-decades and TRMM rainfall

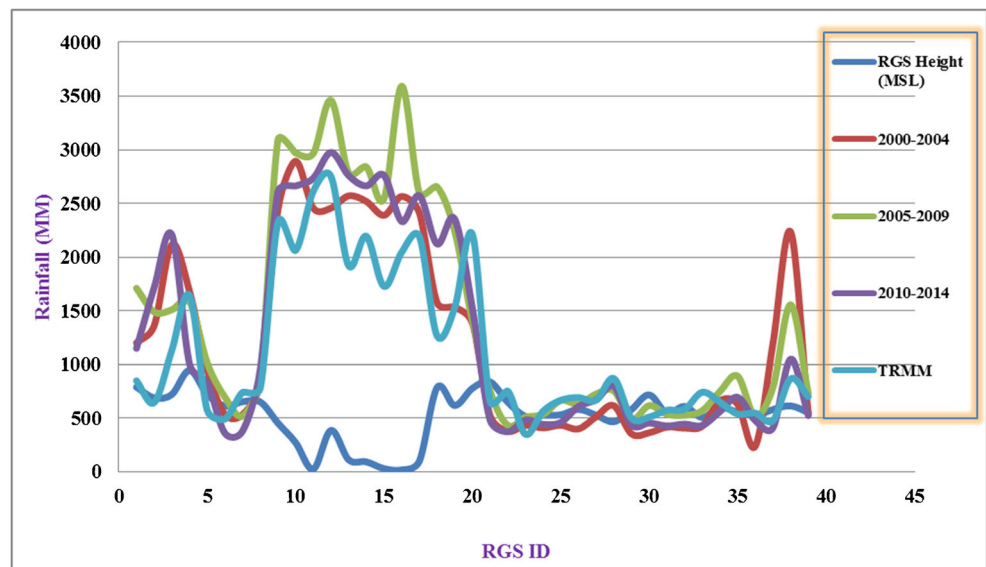
continuous increase in Eurasian surficial temperatures, during winter, leads to greater thermal ranges between continent and ocean, giving rise to enhanced monsoons. It should be enlightening to investigate if any correlation exists between the mean precipitation in wet and rain shadow zone with ENSO, El Nino or La Nina.

### Conclusions

The western part of UGB experiences higher rainfall than the eastern region. The rainfall in the study area is largely influenced by topographic configuration. It experienced rainfall variability from 2000 to 2014, wherein precipitation is seen to gradually increase from 2000 to 2006, which then decreased with continuous rise and fall in annual rainfall from 2006 to 2014. The highest rainfall was recorded in 2006 (1888 mm). CV indicated high rainfall variability during 2010–2014 (74%) and minimum during the 2005–2009 (70%). Statistical parameters calculated confirm low annual

rainfall in the eastern part and high in the western part of the UGB. Some mismatch was seen to occur between the RGS and TRMM data within the vicinity of mountainous terrain. However, the validity of RGS and TRMM rainfall data was confirmed from calculated  $R$  values between half-decade rainfall (2000–2004, 2005–2009, 2010–2014) and TRMM data. The changes in rainfall are significant in monsoon months (June to September) as compared to the dry seasons (October to May). The estimated rainfall highlights some major and minor changes occurring in the precipitation pattern. It revealed an alternation between even and erratic precipitation. All these variations in UGB and its contiguous regions could be because this area is bordered on the north by hills and elevated tablelands; on the south by large stretches of plains, interspersed along hill ranges; on the west Western Ghat (Sahyadri ranges) stand tall; and on the east Jayakwadi Dam forms its eastern boundary. Eastern regional interiors tend to be dry because of their distance from the moisture source, the Arabian Sea. Clouds lose their moisture before they reach the eastern margin of the study area. The inside of the basin is a

Fig. 11 Spatial variability during 2000–2004, 2005–2009, 2010–2014, and TRMM, indicating close correspondence between the height at which the RGS is situated and the intensity of rainfall



plateau divided into a series of valleys sloping normally towards east direction. Thus, the monsoon movement from west to east direction and local influence of the Western Ghat section are seen to cause the spatio-temporal variability, which is seen to be higher in the western and low in the eastern part of the area. Future climate change could affect regional rainfall patterns considerably in the present area. The integration of ground- and space-based rainfall data can improve the accuracy of results obtained in the mountainous terrain. The present result can aid in the decision-making process for precise water resources management in UGB and its surrounding region. The proposed advance approach of spatial estimation of entire area rainfall for short terms and micro level understanding of rainfall variability will ultimately help to improve predictability for better water resource management.

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### Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest.

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