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ON VARIABILITY OF HYDROLOGICAL WET SEASON, SEASONAL RAINFALL AND RAINWATER POTENTIAL OF THE RIVER BASINS OF INDIA (1813-2006)

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ABSTRACT *In tropical monsoonal climate rainfall is subject to strong seasonality. Further, attributes of rainy season (starting date, ending date and duration) exhibit large spatial and temporal variations. Numerous notions of rainy season exist in the real world and the literature, e.g. green season, growing season, wet season, monsoonal rainy season and wet period. For Indian region, a hydrological wet season (HWS) is defined as 'continuous period with each of the monthly rainfall greater than 50mm'. Climatological and fluctuation features of important parameters of the HWS (starting and ending dates and duration, seasonal rainfall/rainwater and surplus rainfall/rainwater potential) are described for the 11 major and 36 minor river basins as well as the West Coast Drainage System (WCDS) and the whole country using highly quality-controlled monthly rainfall from well-spread network of 316 raingauge stations from earliest available year (sometimes going back to 1813) up to 2006. The average period of the HWS is in close agreement with the (southwest) monsoonal rainy season (MRS) over the basins in the core monsoon rainfall regime (CMRR- basins between parallels of 16°N and 32°N and west of meridian 88°E). In the mixed monsoon rainfall regime (MMRR- south peninsula, northeast and extreme north), the HWS is of longer duration compared to the MRS due to extra-monsoonal rainfall over there. For the whole country, the mean starting date of the HWS is 30 May, ending 11 October and duration 135 days. Fluctuations of the HWS parameters do not show significant long term trend anywhere. However, nature of recent tendency according to a subjective deduction from a set of time series displays (actual and 9-point Gaussian low-pass filtered values and the Cramer's t_k-statistic for 31-term running means) is reported. Sixteen basins across the country experienced multiple wet seasons in some years, important characteristics of these wet seasons are discussed. The average HWS rainwater (and hydrological rainwater potential, HRWP) of the major basins (in billion cubic meters or bcm) is as: Indus 147.392 (34.884), Ganga 740.507 (316.383), Brahmaputra 430.168 (285.992), Godavari 282.584 (122.865), Krishna 180.95 (18.922), Sabarmati 19.06 (6.912), Mahi 28.537 (12.777), Narmada 87.532 (49.110), Tapi 45.646 (16.366), Mahanadi 173.181 (98.141), Cauvery 97.478 (27.046) and the WCDS 270.825 (179.399). For the whole country, the mean wet season rainwater is 2911.064 bcm, of which 1856.947 bcm evaporates and the remaining as surplus rainwater (or HRWP) 1054.117 bcm goes through different surface hydrological processes (soil moisture recharge, deep percolation, surface storage and streamflow/riverflow). Declining tendency is seen in the HWS rainfall/rainwater and surplus rainfall/HRWP over most of the minor basins in the CMRR in recent years/decades. Over the country, the HWS rainfall during 1965-2006 was less by 4.15% compared to the period 1912-1964, and the surplus rainfall/HRWP during 1978-2006 less by 11.93% compared to 1915-1977.*

Key words: River basins of India; longest instrumental rainfall series; variability of hydrological wet season; variability of hydrological rainwater potential.

INTRODUCTION

Given global climate warming background and projected climate change scenarios, it is a curiosity to know the nature of variability of rainy season across the country. Rainfall is characterized by seasonality and parameters of the rainy season (starting and ending dates and duration) exhibit large variation from place to place and over the same place from one year to another. Numerous notions of rainy season can be seen in the real world and the literature: green season (ecology), growing season (agriculture), wet season (hydrology and water resources), monsoonal rainy season (meteorology and atmospheric sciences) and wet period (general). Seasonality refers to when something becomes peculiarly available abundantly during some part of the year. For scientific studies abundantly needs to be objectively/quantitatively defined. Limited or no attempt has been made to study variability of the rainy season of the country though some studies attempted to demarcate climatological period of the rainy season. In the present study, climatological and fluctuation characteristics of the important features of hydrological wet season (HWS) over major and minor river basins, the West Coast Drainage system (WCDS) and the whole country are reported. The HWS is defined as 'continuous period of reliable rainfall activities irrespective of weather systems those brought the rainfalls' (Singh, 1986).

With three large watersheds, the Himalayas, the Vindhyas and the Western Ghats, the country is drained by 11 major and 43 minor rivers and numerous rivulets. Besides this, in the West Coast Drainage System (WCDS) there are 25 small rivers that originate in the Sahayadri Range (Western Ghats) and discharge into the Arabian Sea (NATMO, 1996; Rao, 1975). Due to large variation in intensity and frequency of rain-producing weather systems (western disturbances, thunderstorms, monsoon/cyclonic storms/depressions, monsoon troughs etc.) and summer (or southwest) monsoon and post-monsoon circulations over different parts of the country rainfall occurrences are characterized by large spatial and temporal variability. Hence areal representation of the area-averaged rainfall series for the whole country is limited (Singh et al., 1991). The value of the IAR (Index of areal representativeness), which is defined as the ratio of variance of all India series and mean variance of different series averaged and expressed in percent, is only about ~14% for monsoon rainfall (Singh, 1994). The National Atlas & Thematic Mapping Organization (NATMO, 1996) has published a map of India 'Drainage' on 'Conical Equal Area Projection with two Standard Parallels' projection system and 1:6M scale showing boundary of major and other basins. For the present study classification of the country's river systems into major and minor basins by K L Rao (1975) is adopted. Longest possible monthly rainfall series have been developed for 11 major basins, 36 minor basins and the West Coast Drainage System (WCDS) as well as the whole country using instrumental observations from earliest available year up to 2006. Twenty seven of the 36 minor basins are sub-basins of five major basins- the Indus 3 (Chenab, Beas and Satluz), the Ganga 13 (Yamuna, Ramganga, Gomati, Ghaghara, Gandak, Kosi, Mahananda, Chambal, Sind, Betwa, Ken, Tons and Son), the Brahmaputra 3 (Tista, Brahmaputra minor and Dhansiri), the

Godavari 5 (Wainganga, Wardha, Penganga, Godavari minor and Indravati) and the Krishna 3 (Bhima, Krishna minor and Tungabhadra). The other 9 minor basins are Luni, Surma, Kasai, Damodar, Suvarnarekha, Brahmani, Penner, Palar & Ponnaiyar and Vaigai. The Sabarmati, the Mahi, the Narmada, the Tapi, the Mahanadi and the Cauvery are the major basins without any distinct minor basin on the 1:6M scale map of India. In the present study Sikkim State (7,096 km^2), Arunachal Pradesh State (83,743 km^2), Andaman & Nicobar Islands (8,249 km^2) and Lakshadweep Islands (32 km^2) are not considered owing to non-availability of long period rainfall data. Thus the geographical area of the country considered in the present study is 3,188,111 km^2.

In tropical monsoonal climate understanding basin-scale variability of wet (or rainy) season is as important as the variability of rainfall, very little attempt has been made to study the former compared to later. Identification of wet season in the annual weather cycle on yearly basis is the crucial issue of the problem. Earlier attempts have been made to depict the climatological summer monsoon (or rainy season) onset across the Asian monsoon region (IMD, 1943; Tao and Chen, 1987; Tanaka, 1992; Lau and Yang, 1997; Wang, 1994; Wang and LinHo, 2002 and many others). Ananthakrishnan and Soman (1988), however, identified yearwise (1901-1980) onset date of southwest monsoon over Kerala (India) by applying an objective criterion to raingauge observations and studied variation and distribution characteristics of the onset date. It is not known whether this criterion can be applied in reverse order to obtain the withdrawal date. Further, this information is limited to Kerala. Singh (1986) has applied an objective criterion ‘continuous period with monthly rainfall greater than 50mm’ to obtain climatological start and cessation dates of (hydrological) rainy season at 466 locations across the country. The specific objective of the this study is to apply the criterion to area-averaged monthly rainfall to determine yearly start and end of the HWS in order to understand climatological and fluctuation characteristics of the parameters of wet season (starting date, ending date and duration) over major and minor river basins, the WCDS and the whole country during the period of instrumental records. Important characteristics of the HWS rainfall (and rainwater) and surplus rainfall (and hydrological rainwater potential or HRWP) have also been discussed keeping in view wide spread apprehension caused by the global climate warming background and climate change scenario projections.

In recent years, a new perspective has been added to hydrological investigations of the country with the launch of the most ambitious Master Plan 'Interbasin Water Transfer –Interlinking of Rivers of India'. The plan is intended to utilize the country's water resources to the fullest extent viable by transferring water from the surplus basin to deficit areas. One of the important issues to be addressed amicably in the planning process of the program is the impact of global changes, particularly global warming, on the rainfall fluctuation over different basins across the country. Basin-scale characteristics of the wet season and rainfall based on longest available instrumental records are expected to provide vital information to this plan.

RAINFALL DATA USED

Instrumental monthly rainfall from a ubiquitous network of 316 raingauge stations from earliest available year up to 2006 is used in the study. For all the 316 raingauges the data is available for the period 1901-2006. Prior to 1901, number of available stations from this network decreases back in time- 314 raingauges go back to 1900, 312 back to 1871, 196 to 1870, 101 to 1861, 80 to 1860, 70 to 1851, 60 to 1846, 57 to 1844, 13 to 1842, 6 to 1829, 4 (Chennai, Mumbai, Pune and Nagpur) to 1826, 2 (Chennai and Mumbai) to 1817 and sole station Chennai to 1813. Missing observations in the continuous data sequence have been filled by the ratio method (Rainbird, 1967) using nearest available observation as reference value. Number of filled values is less than 2% of the total number of monthly rainfall records. Data up to 1900 is obtained from the India Meteorological Department (IMD) publication '*Monthly and Annual Rainfall of 457 Stations in India to the End of 1900*' (Elliot, 1902), and for period 1901-2006 from the National Data Center and Hydrology Section of the IMD, Pune. A detailed account of this dataset is given by Mooley and Parthasarathy (1984).

Blanford (1886) checked the reliability of data then available, and concluded that selected data were 'free from any serious error'. In his attempt to compile and publish rainfall data for all the gauges over British India up to 1900 AD, Eliot (1902) also checked them thoroughly. Regarding reliability of rainfall data of the Indian region, Walker (1910) had stated that 'long established observatories like Madras (Chennai), Bombay (Mumbai) and Calcutta (Kolkata) which have rainfall records available for earlier periods in the nineteenth century are trustworthy'.

BRIEF PHYSICAL AND CLIMATOLOGICAL DESCRIPTION OF THE RIVER BASINS

For description of some physical features and the rainfall data availability, the basins are arranged from north to northwest to northeast to south. The Indus, the Ganga, the Brahmaputra, the Godavari and the Krishna are described first in order along with their minor basins. The remaining major basins are given afterwards followed by independent minor basins. The WCDS is given thereafter. In the end, the description for the whole country longest rainfall series is given as general information. Table 1 lists important information about the basins, the WCDS and the whole country: (i) geographical/drainage area; (ii) length of the river; (iii) number of raingauge stations since 1901; (iv) mean annual rainfall; (v) number of rainy days; (vi) number of meteorological stations used in the potential evapotranspiration (PE) estimation; and (vii) mean annual PE. Number of rainy days (days with rainfall equal to or greater than 2.5mm) is extracted from the IMD publication '*Monthly and Annual Normals of Rainfall and of Rainy Days*' (IMD, 1961).

Table 1 Some physical properties of the river basins (and the country), number of available raingauges since 1901, mean annual rainfall, mean rainy days, number of meteorological stations used for PE estimation and the normal annual PE.

Major river basins/ Minor river basins	Drainage area (km^2)	Length of the river (km)	No. of rain-guages since 1901	Mean annual rainfall (mm)	Rainy days	No. of PE stations used	Mean annual PE (mm)
1. Indus major	291,749	--	19	860.3	41.6	8	1390.4
i. Chenab	54,501	330	3	1084.4	57.9	1	874.0
ii. Beas	18,866	460	3	1379.4	61.4	2	1445.9
iii. Satluz	79,331	120	12	631.3	31.3	5	1471.5
2. Ganga major	860,884	2525	131	1083.5	52.2	53	1455.1
i. Yamuna	112,695	1376	28	754.1	38.1	11	1375.1
ii. Ramganga	31,572	596	5	1333.2	56.1	2	1278.5
iii. Gomati	77,152	940	11	984.5	48.1	4	1440.6
iv. Ghaghara	50,431	1080	9	1128.2	53.1	3	1427.6
v. Gandak	28,001	300	4	12045.0	56.1	2	1347.8
vi. Kosi	13,364	320	1	1384.7	59.5	1	1362.3
vii. Mahananda	11,530	--	5	2117.1	83.0	6	1151.3
viii. Chambal	156,054	965	21	817.2	39.6	8	1588.3
ix. Sind	28,634	415	7	874.5	41.2	4	1507.7
x. Betwa	44,479	590	7	1039.2	49.2	3	1528.4
xi. Ken	30,100	360	5	1142.5	53.4	2	1499.9
xii. Tons	39,425	264	5	1060.0	53.6	4	1531.1
xiii. Son	111,300	784	9	1211.0	61.5	7	1475.4
3. Brahmaputra major	186,773	720	11	2478.3	112.4	9	1147.4
i. Tista	10,444	309	1	3279.9	110.5	5	1085.0
ii. Brahmaputra	37,344	--	6	2238.7	105.4	3	1149.1
iii. Dhansiri	17,256	--	1	1843.6	123.0	1	939.8
4. Godavari major	330,628	1465	22	1068.3	57.1	15	1609.7
i. Wainganga	658,999	--	6	1271.2	64.9	5	1488.9
ii. Wardha	22,766	--	4	1050.2	56.3	2	1771.3
iii. Penganga	24,282	--	1	1076.5	55.6	1	1773.3
iv. Godavari	143,213	--	10	871.2	50.7	6	1719.0
v. Indravati	46,605	--	2	1481.7	79.7	2	1422.3
5. Krishna major	295,650	1400	25	825.7	50.9	27	1669.8
i. Krishna	141,466	--	15	893.7	54.9	15	1661.9
ii. Bhima	76,772	--	6	703.7	42.5	7	1700.9
iii. Tungabhadra	77,412	--	7	745.4	49.5	5	1650.2
6. Sabarmati major	36,688	300	4	742.8	34.5	1	1676.8
7. Mahi major	41,179	533	8	836.1	40.1	2	1653.4
8. Narmada major	94,562	1312	8	1107.3	54.1	6	1466.7
9. Tapi major	65,041	724	7	894.4	48.6	4	1665.3
10. Mahanadi major	145,040	587	11	1410.4	70.2	8	1519.4
11. Cauvery major	91,691	800	13	1265.5	64.3	10	1499.1
12. Independent minor basins							
i. Luni	79,456	--	8	487.7	24.4	5	1685.2
ii. Surma	47,216	--	3	2519.5	120.2	3	1012.5
iii. Kasai	21,625	--	3	1442.6	76.2	3	1480.7
iv. Damodar	64,753	541	11	1473.4	78.8	9	1428.7
v. Suvarnarekha	32,647	395	4	1509.4	79.1	5	1416.8
vi. Brahmani	50,581	800	3	1434.3	76.3	1	1539.9
vii. Penner	96,538	597	6	870.2	45.6	6	1807.3
viii. Palar & Ponnaiyar	48,084	--	3	1194.4	56.1	3	1590.8
ix. Vaigai	39,522	--	5	904.2	53.0	9	1793.5
13. The WCDS	117,962	--	21	2528.5	102.2	19	1564.3
14. All India	3,188,111	--	316	1165.9	57.4	234	1519.4

THE METHODS- DEVELOPMENT OF LONGEST RAINFALL SEQUENCE

Longest instrumental area-averaged monthly rainfall sequence of the basins has been developed in two parts: (i) simple arithmetic mean for the period with all available observations from the selected network (1901-2006), and (ii) construction by applying established objective method for the period with lesser available observations (prior to 1901). Details of empirical procedure to construct the representative rainfall series backward are given in Sontakke and Singh (1996) and Sontakke et al. (2008a), simulation in Singh (1994) and theory in Wigley *et al.* (1984).

For pre-1901 period, the constructed value is retained if correlation coefficient (CC) between all the gauges mean series and limited available gauges mean series based on the period 1901-2000 is found significant (at 5% level and above), otherwise rejected. For most of the constructed rainfall amounts the CC was in the range 0.55 to 0.99 (number of observations = 100). However, sometimes constructions with low CC (0.2 to 0.5, significant at 10% level) have also been accepted if ignoring few data points was creating break in the long continuous series. In the absence of any data the constructed rainfall amounts based on instrumental observations might provide vital information. The longest period for which the monthly rainfall sequence could be developed of the individual basins is given in Table 2.

Table 2 Longest monthly rainfall series developed, and the mean (and the SD) of the HWS starting date, ending date, duration, total rainfall and surplus rainfall for the major and minor basins, the WCDS and the whole country.

Major river basins/ Minor river basins	Longest period of rainfall data	Starting date (SD in days)	Ending date (SD in days)	Duration (SD) in days	Rainfall (SD) in mm	Surplus rainfall (SD) in mm
1. Indus major	1844-2006	25 Jun (12)	9 Sept (13)	77 (17)	505.2 (167.8)	119.6 (110.4)
i. Chenab	1891-2006	29 May (65)	11 Sept (25)	106 (70)	593.8 (323.1)	224.7 (186.4)
ii. Beas	1853-1854; 1857-2006	7 Jun (34)	19 Sept (16)	105 (42)	950.9 (309.5)	412.2 (261.7)
iii. Satluz	1844-2006	30 Jun (15)	5 Sept (17)	68 (21)	370.1 (165.2)	49.5 (80.4)
2. Ganga major	1829-2006	9 Jun (9)	28 Sept (11)	112 (15)	860.2 (136.4)	367.5 (106.8
i. Yamuna	1844-2006	25 Jun (12)	14 Sept (16)	82 (19)	526.9 (157.3)	178.1 (105.9)
ii. Ramganga	1844-2006	8 Jun (13)	24 Sept (15)	109 (19)	1076.6 (322.9)	657.8 (283.8)
iii. Gomati	1844-1855; 1860-2006	19 Jun (13)	27 Sept (15)	101 (19)	760.1 (229.5)	320.72 (188)
iv. Ghaghara	1844-2006	10 Jun (12)	30 Sept (14)	113 (19)	933.0 (237.4)	474.3 (199.3)
v. Gandak	1848-1854;1859-2006	31 May (15)	1 Oct (15)	124 (23)	995.5 (259.7)	477.8 (213.6)
vi. Kosi	1870-2006	20 May(19)	4 Oct (17)	138 (27)	1183.9(326.4)	591.7(272.9)
vii. Mahananda	1837;1848-1853; 1860-2006	24 Apr (18)	11 Oct (13)	171 (23)	1945.9 (314.5)	1320.1 (295.6)
viii. Chambal	1844-2006	20 Jun (11)	14 Sept (15)	87 (18)	636.8 (181.2)	246.8 (135.4)
ix. Sind	1860-2006	22 Jun (12)	16 Sept (15)	87 (18)	691.8 (213.2)	317.8 (175.7)
x. Betwa	1844-1855;1860-2006	17 Jun (10)	22 Sept (13)	98 (16)	857.3 (199.3)	435.4 (168.9)
xi. Ken	1844-1855;1860-2006	17 Jun (11)	25 Sept (17)	101 (19)	947.0 (237.3)	531.2 (207.4)
xii. Tons	1844-1855;1860-2006	18 Jun (12)	28 Sept (16)	103 (20)	876.6 (217.2)	445.1 (174)
xiii. Son	1842- 2006	8 Jun (10)	2 Oct (12)	117 (17)	1003.7 (176.1)	516.9 (147.8)

3. Brahmaputra major	1848-2006	26 Mar (13)	20 Oct (12)	209 (17)	2303.2 (256.2)	1531.2 (236.8)
i. Tista	1869-2006	14 Apr (18)	15 Oct (13)	185 (24)	3092.7 (574.0)	2447.6 (567.7)
ii. Brahmaputra minor	1848-2006	27 Mar (14)	18 Oct (13)	206 (19)	2072.9 (285.6)	1314.8 (264.7)
iii. Dhansiri	1871-2006	4 Apr (25)	18 Oct (16)	198 (30)	1677.7 (283.9)	1098.1 (267.1)
4. Godavari major	1826-1831;1844-1849; 1854-2006	9 Jun (7)	4 Oct (16)	118 (19)	854.7 (177.7)	371.6 (142.9)
i. Wainganga	1844-1849;1861-2006	9 Jun (8)	2 Oct (15)	116 (17)	1051.1 (214.2)	602.3 (183.5)
ii. Wardha	1826 1831;1854 2006	9 Jun (8)	28 Sept (18)	113 (20)	840.1 (218.3)	338.8 (177.1)
iii. Penganga	1865-2006	10 Jun (10)	28 Sept (18)	111 (21)	872.6 (256.1)	382.5 (219.6)
iv. Godavari minor	1844-1847;1861-2006	11 Jun (9)	3 Oct (15)	115 (18)	682.3 (195.4)	176.4 (145.4)
v. Indravati	1871- 2006	29 May (20)	12 Oct (18)	137 (28)	1270.9 (273.7)	792.4 (237.7)
5. Krishna major	1826-1830;1836-2006	5 Jun (14)	19 Oct (17)	137 (24)	612.0 (137.7)	64 .0(82.9)
i. Krishna minor	1836;1841-2006	6 Jun (14)	21 Oct (17)	138 (24)	688.1 (150.1)	125.2 (110.7)
ii. Bhima	1826-1830;1842; 1844-1849;1853-2006	9 Jun (16)	28 Sept (33)	112 (36)	503.8 (207.0)	48.5 (87.9)
iii. Tungabhadra	1837- 2006	31 May(21)	18 Oct (19)	141 (31)	534.0 (146.4)	14.3 (32.7)
6. Sabarmati major	1861-2006	22 Jun (14)	7 Sept (18)	78 (23)	519.5 (229.6)	188.4 (182.8)
7. Mahi major	1857-2006	18 Jun (12)	15 Sept (17)	90 (21)	693.0 (229.3)	310.3 (172.4)
8. Narmada major	1844-2006	12 Jun (8)	25 Sept (15)	106 (17)	925.7 (201.8)	519.3 (172.4)
9. Tapi major	1845-1849;1851-1854; 1859-2006	11 Jun (7)	24 Sept (18)	106 (20)	701.8 (193.5)	251.6 (153.1)
10. Mahanadi major	1848-2006	4 Jun (10)	10 Oct (15)	129 (18)	1194.0 (211.0)	676.6 (182.6)
11. Cauvery major	1830-1832;1837-2006	4 May (15)	11 Nov (18)	192 (20)	1063.1 (166.5)	294.9 (143.1)
12. Independent minor basins						
i. Luni	1856-2006	3 July (14)	31 Aug (19)	60 (24)	302.9 (164.4)	44.9 (75.3)
ii. Surma	1849-1854;1863-2006	17 Mar (18)	26 Oct (14)	224 (21)	2311.6 (317.2)	1599.1 (2921)
iii. Kasai	1831-1832;1848-1851; 1853-1854;1859-2006	12 May (22)	12 Oct (16)	154 (26)	1213.4 (243.4)	560.8 (195.1)
iv. Damodar	1829-2006	4 May (22)	14 Oct (14)	164 (26)	1272.9 (215.8)	590.2 (197.5)
v. Suvarnarekha	1848-1851;1859-2006	12 May (24)	16 Oct (15)	158 (28)	1276.6 (213.4)	641.7 (194.5)
vi. Brahmani	1871-2006	21 May (18)	11 Oct (16)	144 (25)	1208.7 (216.3)	611.9 (193.7)
vii. Penner	1813-2006	21 July (44)	24 Nov (21)	127 (47)	587.4 (225.0)	65.1 (95.3)
viii. Palar & Ponnaiyar	1853-1854;1863-2006	3 July (32)	12 Dec (21)	163 (39)	944.1 (305.4)	295.7 (233.4)
ix. Vaigai	1846-2006	14 Aug (49)	9 Dec (21)	118 (54	543.2 (202.3)	76.5 (103.2)
13. The WCDS	1838-2006	30 Apr (16)	11 Nov (15)	196 (20)	2295.8 (315.7)	1520.8 (293)
14. The Whole India	1813-2006	30 May (10)	11 Oct (14)	135 (19)	913.1 (121.3)	330.6 (92.6)

DEFINITION OF THE HYDROLOGICAL WET SEASON (HWS)

Annual weather cycle at stations over major parts of country can be broadly divided into two periods, dry and wet. The wet period is essentially due to occurrence of monsoon rainfall during boreal summer. It is also commonly known as monsoonal rainy season (MRS). Some areas of the country receive rainfall during other parts of the year also, winter (JF), pre-monsoon (MAM) and post-monsoon (OND). Extreme northern India receives ample winter precipitation from western disturbances. In the extreme northeast abundant pre-monsoon rainfall is received associated with thunderstorms. Kerala starts getting heavy rainfall starting from pre-monsoon thunderstorms, the large-scale monsoon circulation to post-monsoon tropical cyclone rainfall without any long dry spell. In Tamilnadu, the post-monsoon period (October to December) is the main rainy season, pre-monsoon thundershowers and monsoon rainfall over the area is relatively low and less reliable. The south peninsula and the northeast experience longer duration of wet season, much beyond the MRS, and the entire period is of great practical significance in these areas. While over arid areas of the northwest India, the rainy season is confined to the middle of the monsoon period (July-August) and is a major constraint for many agricultural and hydrological operations. Singh (1986) has determined climatological starting and ending dates of the (hydrological) rainy season at 466 individual stations across the country by applying the objective criterion ‘continuous period with each of the monthly rainfall greater than 50mm’. It is seen that if for any station (universal) the mean monthly rainfall is greater than 50mm, its coefficient of variation (CV) is generally found less than 100% and probability of occurrence of zero rainfall in that month negligible. Development of this objective criterion is based on the earlier studies attempted to demarcate the period of rainy season in the annual weather cycle (Ananthakrishnan et al., 1981; Davey et al., 1976; IMD, 1943; Mooley and Appa Rao, 1970; Ramamurthy, 1967; Stern et al., 1981; Wallén, 1968 and Walter, 1967). Over extreme southwestern and northeastern India the wet season starts around 28 March and over northwestern India around 28 July. Over most parts of the country the starting date progressively shifts between these two extremes. The wet season over the extreme southwest and northeast India starts much before the onset of the southwest monsoon due to heavy and reliable rainfall activities there associated with thunderstorms. The late start over northwestern part is because of lesser rainfall activities during onset phase of the southwest monsoon over the region. Due to rain-shadow effect for the southwest monsoon winds, the extreme southeast peninsula gets reliable rainfall only during post-monsoon (or northeast monsoon), and the date varies between 15 August and 10 October, from north to south. Being the area outside the monsoon regime, Jammu and Kashmir gets rainfall from extra-tropical systems like western disturbances and trough in the westerlies. The wet season over the region starts between 20 December and 7 January. The cessation date is especially more consistent, organized and progressively shifting from northwest to southeast. The extreme dates are 10 August for northwestern India and 10 January for southeastern peninsula. For Jammu and Kashmir, the cessation date is 10 May. Consequently there is large variation in the duration of the wet season over different parts of the country, about 20 days over northwestern India to exceeding 240 days over southwestern peninsula (Kerala State).

In the present study the criterion ‘continuous period with monthly rainfall greater than 50mm’ is applied to monthly rainfall of 11 major basins, 36 minor basins, the West Coast Drainage System (WCDS) and the whole country on yearly basis, and the period will be referred to as hydrological wet season (HWS) to avoid confusion with rainy season generally used for southwest monsoon period. In the first month of the continuous period with monthly rainfall greater than 50mm, the starting date of the HWS is determined by linear interpolation up to which, from the beginning of the month, 50mm rainfall is expected. And the ending date is determined in the last month of the period so that between linearly-interpolated date and end of the month 50mm rainfall is expected to occur. The margin of 50mm rainfall before the start and after the ending date is to exclude unreliable rainfall due to scattered random convection. For application of the criterion to yearly determination of the HWS, the interpretation would be that the continuous one month (30 days) period would not go dry (rainfall less than 50mm) during the season. In essence, the HWS delineates the period of reliable rainfall during which rainfall occurrences are associated with large-scale spatially organized convection. Time series plots of starting date, ending date and duration of the HWS for the longest possible period are shown in Figs. 1-13 for 11 major basins, the WCDS and the whole country respectively.

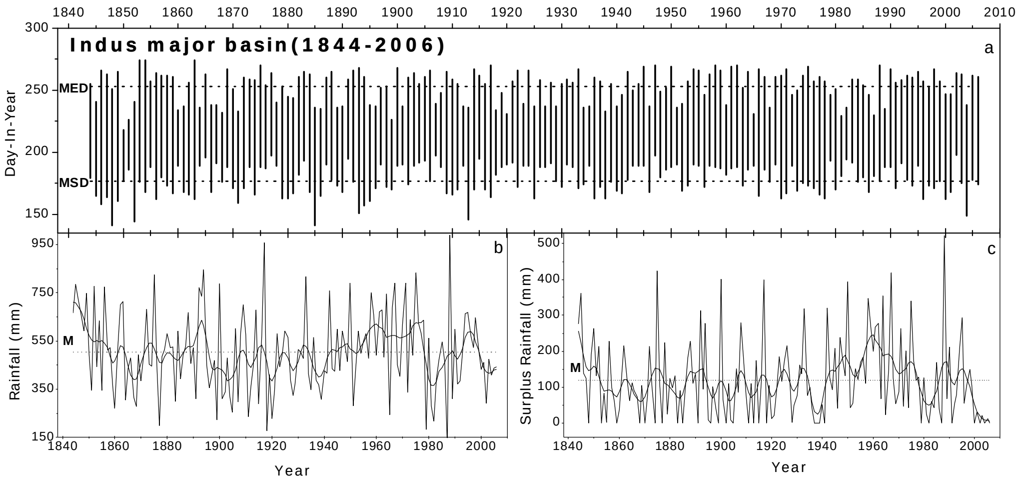

Fig. 1 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Indus major basin. ‘M’ indicates mean, ‘MSD’ mean starting date and ‘MED’ mean ending date.

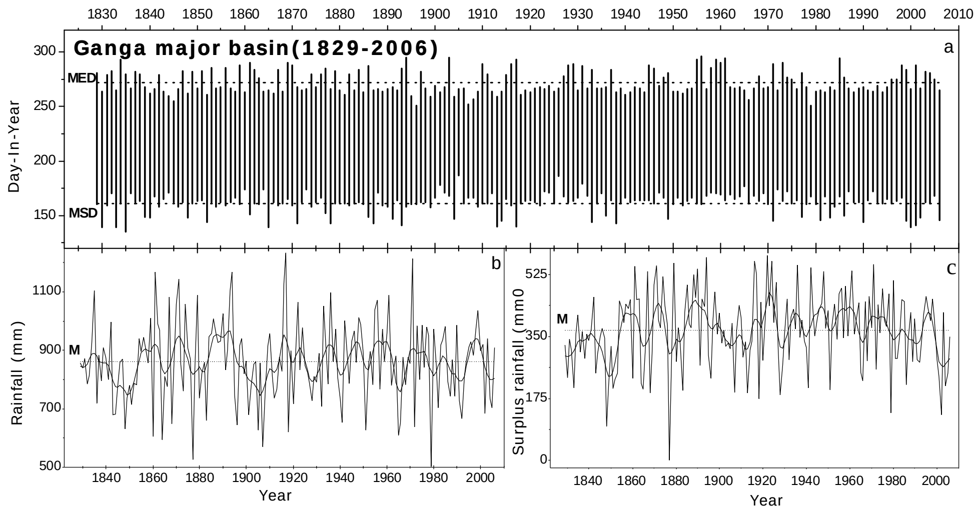

Fig. 2 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Ganga major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

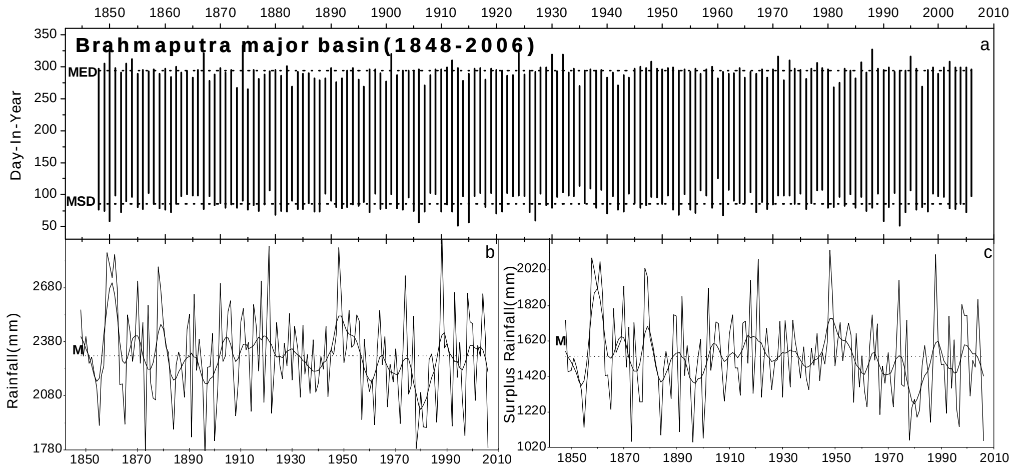

Fig. 3 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Brahmaputra major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

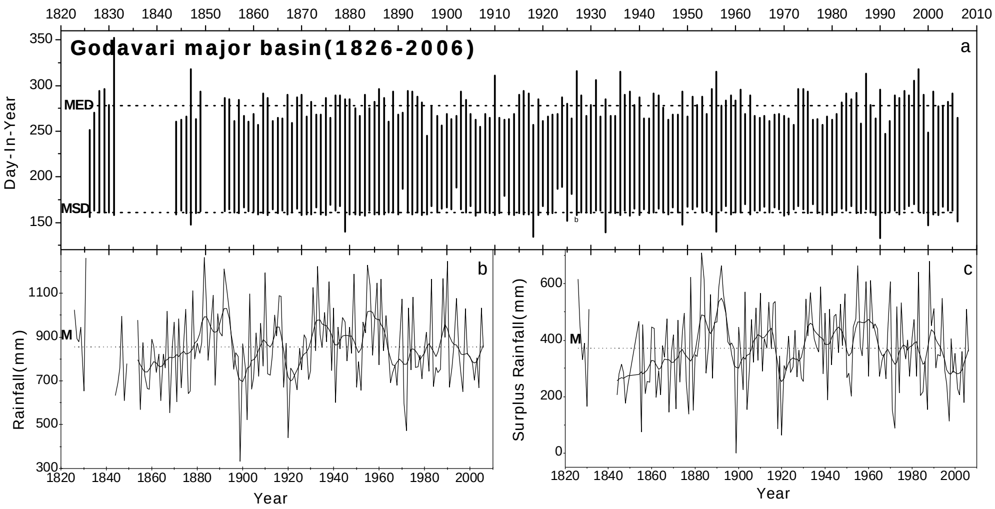

Fig. 4 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Godavari major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

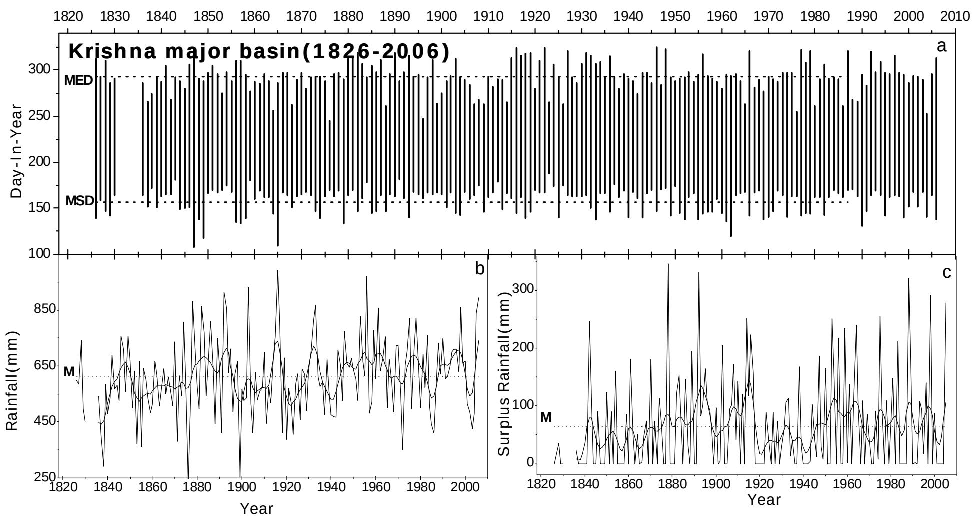

Fig. 5 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Krishna major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

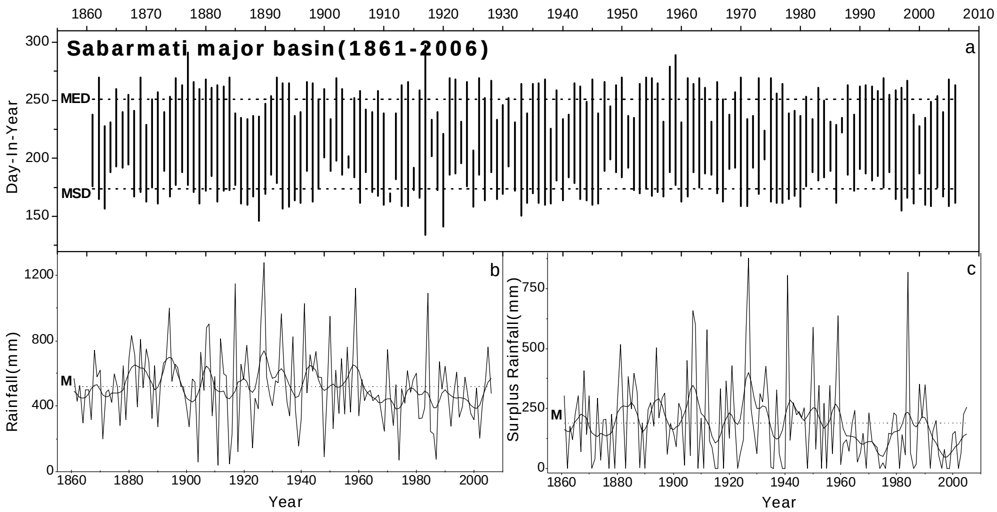

Fig. 6 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Sabarmati major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

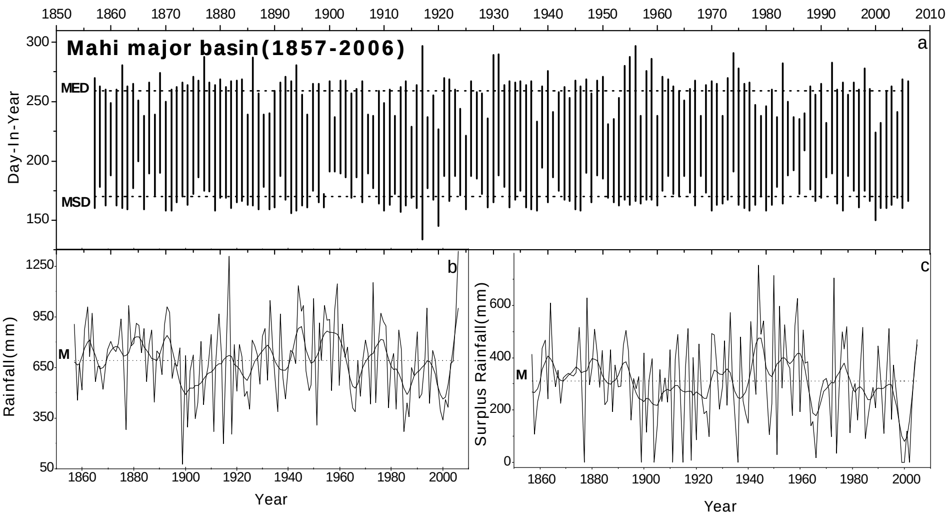

Fig. 7 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Mahi major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

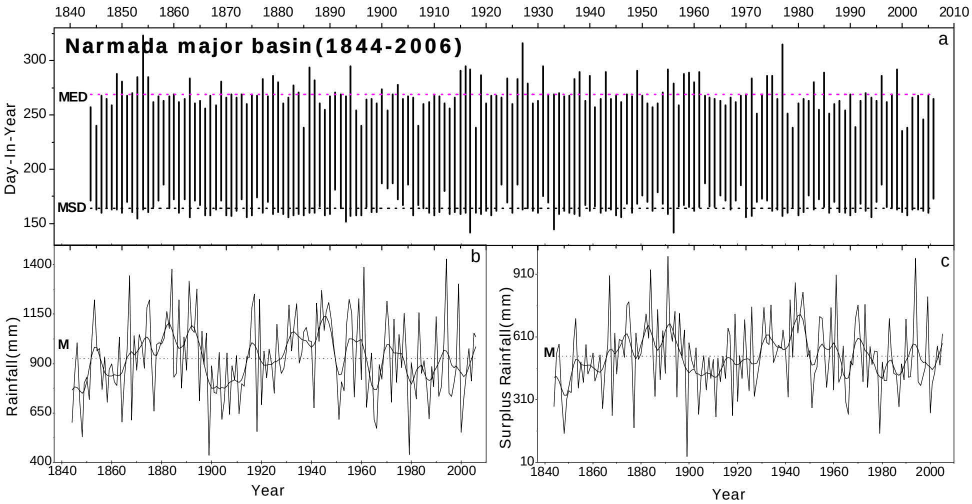

Fig. 8 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Narmada major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

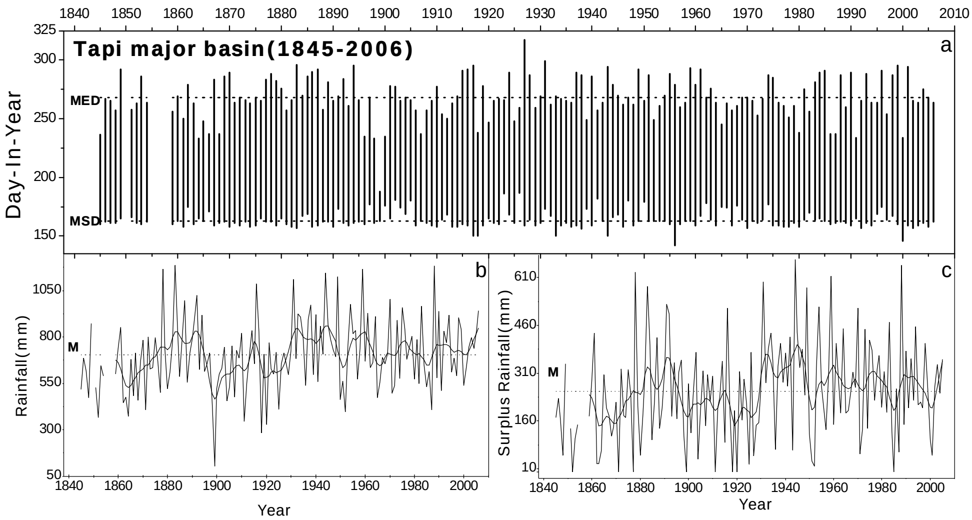

Fig. 9 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Tapi major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

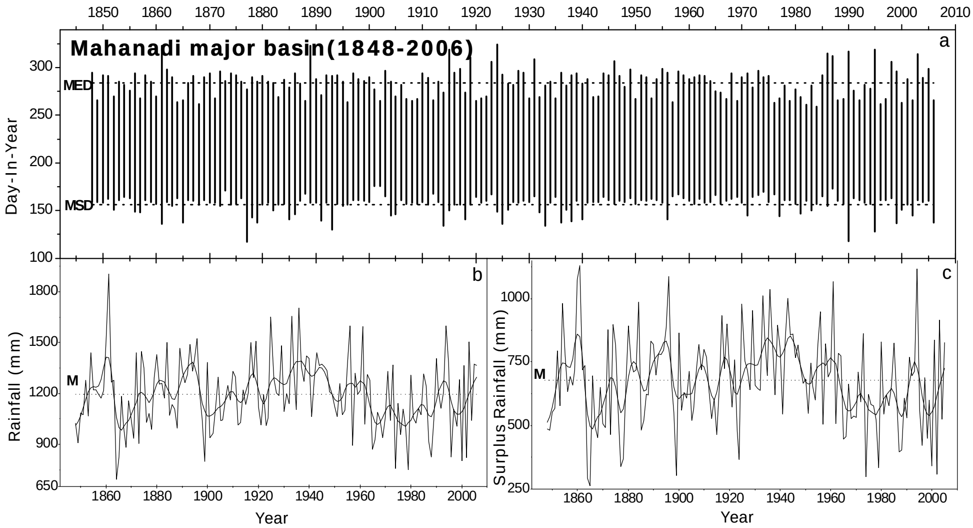

Fig. 10 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Mahanadi major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

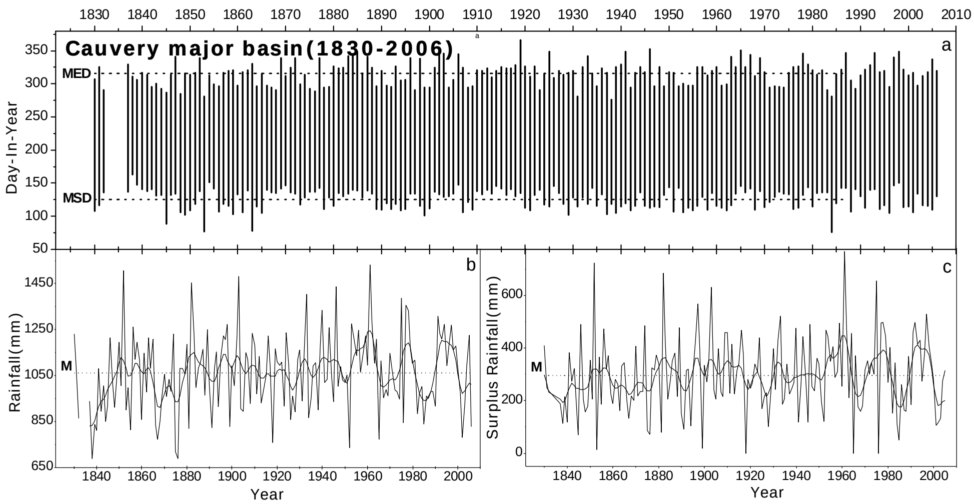

Fig. 11 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the Cauvery major basin. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

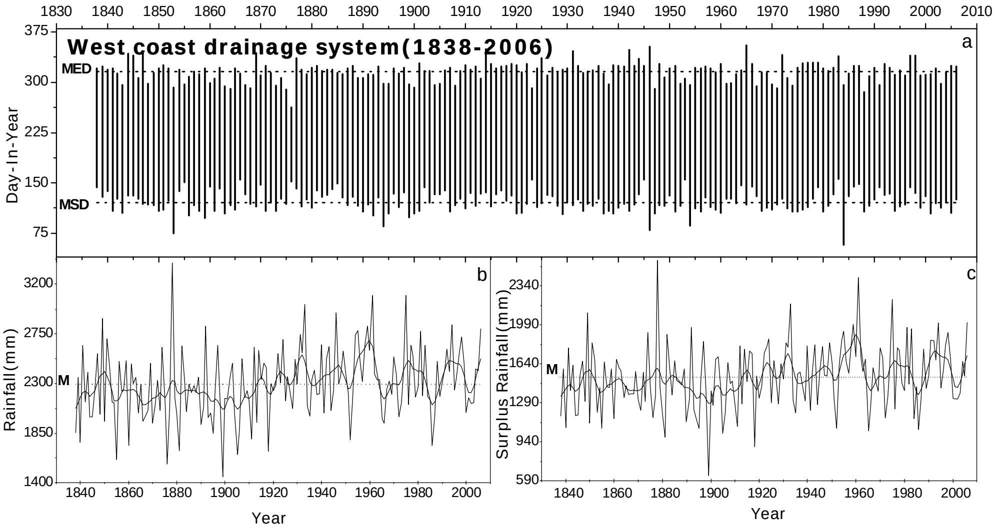

Fig. 12 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the West Coast Drainage System (WCDS). 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

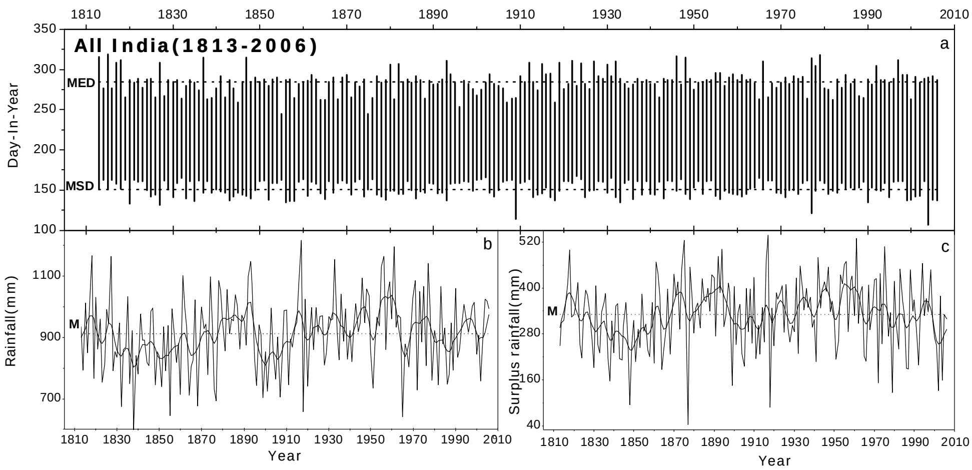

Fig. 13 Interannual variation of the starting date, ending date and duration of the HWS (a); time series plots of the actual and 9-point filtered values of the HWS total rainfall (b) and the surplus rainfall (c) over the whole country. 'M' indicates mean, 'MSD' mean starting date and 'MED' mean ending date.

Limitations of the criterion for determining the HWS should be borne in mind. It cannot be applied to individual stations, particularly in arid and semiarid regions in which case in large number of years monthly rainfall may not exceed 50mm. However, it is useful for any spatial unit of reasonable size (> 50,000 km^2) such as states, meteorological subdivisions, physiographic regions and hydrologic river basins.

RESULTS AND DISCUSSION

Climatological Features of the HWS Parameters

The mean and the standard deviation (SD) of the HWS parameters, starting date, ending date and duration calculated using longest instrumental data are given in Table 2 for different basins, the WCDS and the whole country. Following description of statistical characteristics includes nature of frequency distribution of the parameters. Fluctuation features of the three parameters are described thereafter.

Starting date

Normally, the HWS starts the earliest over the Surma basin (17 March) followed by the Brahmaputra minor basin (27 March). Over Dhansiri the season starts by 4 April, Tista 14 April and Mahananda 24 April. By 30 April the WCDS starts getting thunderstorm-associated rainfall due to strengthening of moist westerlies over the Arabian Sea and heating of the Indian subcontinent from enhanced seasonal solar insolation. As the season advances thunderstorm rainfall activities spread over larger spatial domain, both in the east and the south- the season starts simultaneously (4 May) over Damodar (central northeast) and Cauvery (south peninsula). Due to moist air incursion from Bay of Bengal over east India the spreading of rainfall activities continue over Kasai and Suvarnarekha (12 May), Kosi (20 May), Brahmaputra (21 May) and Gandak (31 May). The Tungabhadra in the central peninsula starts experiencing rainfall as the season advances over Gandak (Bihar State). Over these basins, the pre-monsoon rainfall is considerable and reliable and gives rise to early start and longer duration of the HWS in continuation with the monsoon rainfall. By 31May, the Chenab also starts getting considerable precipitation from western disturbances and the wet season over the basin starts before the arrival of the southwest monsoon currents.

The starting date of the HWS and the onset date of the southwest monsoon are almost the same over the core monsoon rainfall regime (CMRR) of the country, between parallels of 16°N and 32°N, and west of meridian 88°E. Over the CMRR, the date advances from south to north and from southeast to northwest between 1 June and 1 July. Areas of the country outside the CMRR can be referred to as mixed monsoon rainfall regime (MMRR). Over Palar & Ponnaiyar river systems the mean starting date is 3 July, Penner 21 July and Vaigai 14 August. Over these basins the wet season starts with the monsoon rainfall when the monsoon circulation over the

Indian region is relatively stable under the influence of positive net radiation balance over the northern extra-tropical latitudes with 14 to 16 hours of sunshine although during this period the sun starts withdrawing towards the equator (Trewartha and Horn, 1980).

The standard deviation (SD) of the starting date shows large spatial variation. It is lowest (7 days) over the Tapi basin in the CMRR (Satluz, Yamuna, Gomati, Ramganga, Ghaghara, Gandak, Luni, Sabarmati, Mahi, Chambal, Sind, Betwa, Ken, Tons, Son, Narmada, Tapi, Mahanadi, Wainganga, Wardha, Penganga, Godavari, Indravati, Sabarmati, Bhima, Krishna and Tungabhadra). In the east (Kosi, Mahananda, Damodar, Kasai, Suvarnarekha and Brahmani) the SD varies from 18 days to 24 days, in the extreme northeast (Surma, Dhansiri, Brahmaputra minor and Tista) 13 to 25 days, in northern Indus basin (Chenab and Beas minor basins) 34 to 65 days, in the western south peninsula (West Coast and Cauvery) 15 to 21 days and in the eastern south peninsula (Penner, Palar & Ponnaiyar and Vaigai) 32 to 49 days. The SD is higher where starting date of the HWS is much earlier than the arrival of the monsoon currents due to pre-monsoon rainfall. The pre-monsoon rainfall is less reliable than the monsoon rainfall. Therefore, sometimes the HWS starts over these regions with the arrival of the southwest monsoon.

The HWS can start as early as 27 November (1981) of the previous year over Chenab basin and 10 January of the same year over Beas basin. In the remaining parts of the country the earliest start can be over east/northeast India- Surma, Damodar and Suvarnarekha 28-31 January, Dhansiri, Tista, Brahmaputra minor, Mahananda, and Kasai the dates are 1-21 February, Kosi, Gandak, Brahmani, Indravati, Cauvery and Vaigai 15-31 March, Ramganga, Ghaghara, Son, Mahanadi, Krishna, Godavari, Bhima, Tungabhadra, Penner and Palar & Ponnaiyar 14-30 April and over central and Northwest India 5-29 May. The earliest start over the WCDS is 27 February.

Excluding south peninsula, the latest start could be 10 September over Satluz, 6-16 August over Yamuna, Sind, Luni and Sabarmati, 5-28 July over north and central India, 4-24 June over Dhansiri, Mahananda, Damodar, Kasai, Brahmani, Mahanadi, West Coast and Cauvery, 4-17 May over Tista and Brahmaputra minor and 24 April over Surma. The latest start over south peninsula is as: 10-16 September over Bhima, Tungabhadra and Palar & Ponnaiyar, 20 October over Vaigai and 13 November over Penner.

Frequency distribution of the wet season parameters has been studied by employing Fisher's g-statistic test (Rao, 1952). The distribution of the starting date is Gaussian (or normal) for 23 major and minor basins (Indus major, Satluz, Yamuna, Ramganga, Gomati, Gandak, Kosi, Mahananda, Chambal, Betwa, Ken, Son, Brahmaputra major and minor, Tista, Dhansiri, Krishna major, Tungabhadra, Sabarmati, Mahi, Cauvery, Surma, and Palar & Ponnaiyar) and for others significantly different from normal. The data sequence becomes easily manageable if its frequency distribution follows the Gaussian law.

Ending date

End of the wet season from the country is smoother and well organized compared to the starting date. Normally the process starts from northwest and ends in southeast. The season ends by 23 August from western Rajasthan and by 31 August from the Luni basin. It ends between 1 and 15 September from Chenab, Beas, Sutluz, Yamuna, Chambal, Sabarmati and Mahi; between 16 and 30 September from Gomati, Ramganga, Ghaghara, Sind, Betwa, Ken Tons, Narmada, Tapi, Wardha, Penganga and Bhima; between 1 and 31 October from Gandak, Kosi, Tista, Mahananda, Brahmaputra minor, Dhansiri, Surma, Damodar, Kasai, Suvarnarekha, Brahmani, Mahanadi, Wainganga, Indravati, Godavari minor, Krishna and Tungabhadra; between 1 November to 30 November from Penner, Cauvery and West Coast; and between 1 and 10 December from Palar & Ponnaiyar and Vaigai (Table 2). The spatial pattern of the mean ending date is in close agreement with normal withdrawal dates of the southwest monsoon.

The SD of the ending date is the lowest (12 days) over the Son basin. It increases for basins away from the Son- it is 15 days for Godavari and Mahanadi, 16 days for Kasai and Dhansiri, 17 days for Satluz, Krishna and Mahi, 18 days for Sabarmati, Indravati, Cauvery and Tapi, and 19 days for Luni and Tungabhadra basins. In general, variability is large over the basins with multiple wet seasons such as Chenab (25 days), Bhima (33 days), Penner (21 days), Palar & Ponnaiyar (21 days) and Vaigai (31 days).

The earliest end of the HWS from Bhima basin was 19 May (1918). The end could be 18-20 June from Mahi and Sabarmati, 1-21 July from Chenab, Satluz, Yamuna, Luni, Chambal and Tapi, 1-28 August from minor basins of the Ganga and Godavari, Narmada, Kasai, Tungabhadra, Penner and Palar & Ponnaiyar, 1-24 September from Dhansiri, Brahmaputra minor, Tista, Surma, Mahananda, Damodar, Suvarnarekha, Brahmani, Mahanadi, Krishna and the WCDS and 21 October from Cauvery and Vaigai. Latest end of the season can be by 20-27 October from Satluz, Yamuna, Ramganga, Ghaghara, Sind, Chambal, Luni, Sabarmati and Mahi, 3-23 November Gomati, Gandak, Kosi, Tista, Dhansiri, Mahananda, Betwa, Tons, Son, Damodar, Kasai, Suvarnarekha, Brahmani, Mahanadi, Indravati, Narmada, Tapi, Wainganga, Penganga, Godavari minor, Bhima, Krishna, Tungabhadra, 3-31 December from Chenab, Beas, Brahmaputra minor, Surma, Ken, Wardha, Cauvery and the WCDS, 1 January from Penner, 14 February from Palar & Ponnaiyar and 12 April from Vaigai.

Frequency distribution of the ending date is significantly different from normal for 16 major and minor basins (Indus major, Chenab, Beas, Ganga major, Gomati, Ken, Tons, Son, Brahmaputra major and minor, Godavari major, Wainganga, Bhima, Sabarmati, Palar & Ponnaiyar and Vaigai) and for others it’s Gaussian.

Duration

In the CMRR, the mean duration of the wet season varies from 60 days (Luni) to 117 days (Son), and the SD from 17 days (Son) to 24 days (Luni). The SD of 17 days for Son, Narmada and Wainganga basins is the lowest amongst all the river basins except the Ganga Major basin (15 days), and in general it increases for basins away from central India. The West Coast, the south peninsula and Indravati, Mahanadi, Brahmani, Suvarnarekha, Kasai, Damodar, Kosi, Gandak, Mahananda, Tista, Brahmaputra, Dhansiri and Surma basins experience longer duration of wet season due to considerable and reliable rainfall in the post-monsoon period (October-December). In the northeast, the mean duration varies from 185 days (Tista) to 224 days (Surma) and the SD from 19 days (Brahmaputra minor) to 30 days (Dhansiri). Over basins in central northeast, the mean duration varies from 124 days (Gandak) to 171 days (Mahananda) and the SD from 23 days (Gandak) to 28 days (Suvarnarekha); over Mahanadi, Indravati and Krishna basins the mean duration varies from 129 to 137 days and the SD 18-28 days; over Tungabhadra and Cauvery basins the mean duration varies from 141 to 192 days and the SD 20-31 days; over Penner, Palar & Ponnaiyar and Vaigai basins the mean duration varies from 118 days to 163 days and the SD 39-54 days; and over minor basins of the Indus system the mean duration varies from 68 days (Satluz) to 107 days (Chenab) and the SD from 21 days (Satluz) to 70 days (Chenab) (Table 2).

In extreme years, shortest duration could be 8-10 days over Chenab, Satluz, Yamuna and Luni. The duration steadily increases towards east/northeast to 175 days over Surma and toward southeast to 90 days over Mahanadi. The WCDS experiences wet season of 112 days and the Cauvery 149 days. In extreme years, the basins in the south peninsula experienced unusually short wet season; Bhima 7 days, Tungabhadra and Palar & Ponnaiyar 30 days, Penner 8 days and Vaigai 19 days. On the other extreme, the Vaigai basin experienced the longest wet season (331 days from May 1982 to April 1983) followed by the Beas 307 days and the Surma 301 days. From these three extremes, the longest observed duration rapidly decreases toward northwest to 127 days (1917) over the Satluz basin. It may be interesting to note that the Luni basin in arid zone experienced wet season of 153 days during extremely wet year 1917.

Frequency distribution of the HWS duration is significantly different from Gaussian for 20 major and minor basins (Chenab, Beas, Ganga major, Ghaghara, Ken, Tons, Dhansiri, Surma, Sabarmati, Luni, Kasai, Damodar, Brahmani, Mahanadi, Godavari major, Indravati, Bhima, Palar & Ponnaiyar, Vaigai and the WCDS), but for others it’s Gaussian.

Start, end and duration over the whole country

The mean (1 σ days) of the HWS parameters over the whole country is: starting date- 30 May (10), ending date- 11 October (14) and the duration- 135 days (19). The season started earliest on 16 April (2004) and latest on 15 June (1923), it ended earliest on 10 September (1896) and latest on 14 November (1815), and it had shortest duration of 83 days (1855) and longest 194 days (1977). Early start occurs when wide spread pre-monsoon rainfall is quickly followed by southwest monsoon rains and late end occurs when monsoon withdrawal is followed by post-monsoon rains. The duration is short when rainfall is confined to middle of the monsoon period (July-August) and it is long when wide spread pre-monsoon, large-scale monsoon and extensive post-monsoon rains occur in quick succession. Frequency distribution of the ending date and the duration is normal but the starting date suffers from significant negative skewness as suggested by the Fisher's g-statistic test.

Chief Fluctuation Features of the HWS Parameters

To know if there is any significant long-term trend in the variations of the HWS parameters (starting and ending dates and duration) two statistical tests, e.g. Swed-Eisenhart's run test for homogeneity (hereafter SE test) and Mann-Kendall Rank test for randomness against trend (hereafter MK test) (WMO, 1966) have been applied on the longest available time series of the parameters. The tests did not suggest significant long-term trend for any parameter of any of the basins, the WCDS and the whole country. Critical visual examination, however, suggested different types of tendencies in the HWS parameters. Therefore, subjective judgmental approach has been applied on the time series plots of the actual and 9-point Gaussian low-pass filtered values (not shown) to document the recent tendency of the fluctuations. A deduction of recent tendency in the parameters, the basins affected and the year of start is in order.

(a) Major Basins (*early start, late end and longer duration*)- Ganga and all-India starting from 1966, Tapi from 1975, Brahmaputra from 1980, Indus and Cauvery from 1984, and Mahandi from 1986; (*stationary start, late end and longer duration*) - Godavari from 1973; (*late start, early end and shorter duration*) - Narmada from 1962; (*early start, stationary end and longer duration*) - Sabarmati from 1966; (no trend)- Krishna, Mahi and the WCDS.

(b) Minor basins (*early start, late end and longer duration*)- Penner from 1925, Damodar from 1962, Ramganga and Satluz from 1966, Bhima from 1970, Gomati, Kasai, Kosi and Luni from 1971, Beas from 1977, Tista from 1990, Palar & Ponnaiyar from 1993 and Mahananda from 1998; (*early start, early end and stationary duration*) - Suvarnarekha from 1971 and Brahmani from 1990; (*stationary start, late end and longer duration*) - Godavari from 1990; (*late start, early end and shorter duration*) - Vaigai from 1985; and (*early start, stationary end and longer duration*) - Chenab from 1974. Fluctuation is stationary for other minor basins.

Correlation Matrix for the Parameters of the Wet Season over Different Basins

The Pearson's product-moment correlation coefficient (CC) between pair of parameters of the wet season (starting date, ending date, duration and seasonal rainfall) for different basins and the whole country is calculated to know if there is any relation between the parameters. In general, the starting date is highly correlated with the duration which is highly correlated with ending date and the rainfall amount. But the starting date is weakly correlated with the ending date. Early start of the wet season provides an indication that the season may be of longer duration and the rainfall activities during the season are likely to be good. It may be noted that results of application of this statistical relationship can be realized after trial of large number of years rather than on year to year basis. Generally, the correlation between the ending date and the duration is the highest and that between the starting date and the ending date the lowest.

Correlation between wet season parameters over the whole country and respective parameters of the individual basins

In general the HWS rainfall over the country is highly correlated with the rainfall of individual basins. Starting date, ending date and duration of the wet season over the country is significantly correlated with the respective parameter over Godavari major basin (and its minor basins), Krishna major basin (and its minor basins), Narmada, Tapi and Mahanadi major basins, and Kasai, Suvarnarekha and Brahmani minor basins. The wet season parameters over the Ganga major and the Indus major basins have shown significant correlation with the respective parameters of the whole country but their minor basins did not show spatially coherent significant correlation.

Regional Peculiarities of the Wet Season

Undefined wet season

Over Luni basin in the arid region of the northwest India, there were 7 years without wet season according to the present criterion although the area received monsoon rainfall, albeit much less than normal. Application of the criterion to individual years may not produce satisfactory results in dry regions. But the climatological wet season determined from mean monthly rainfall (3 July to 31 August) is the same as the normal period of the southwest monsoon over the basin. It may be interesting to note that only 2 years (1987 and 2002) of the 7 years without wet season occurred in the past 66 years (1941-2006), while 5 occurred in the earlier 70-year period (1871-1940). This may be regarded as an indicator of improving rainfall condition over this dry basin.

The wet season over the Satluz basin also could not be determined for the year 1987 as the consecutive months did not satisfy the threshold criterion of 50mm. This was essentially due to drastic failure of the summer monsoon rains and weak rainfall associated with thunderstorms. Consecutive failure of the two wet seasons in a particular year (1987) requires detailed investigation.

Multiple wet seasons

Besides summer monsoon, the extreme north gets precipitation from western disturbances, the east, the northeast and the central India from pre-monsoon thunderstorms and south peninsula from pre-monsoon thunderstorms as well as post-monsoon period northeast monsoon circulation. In some years, the precipitation by two or more circulation/weather systems can occur in quick succession giving rise to a wet season of longer duration while in some other years they may be separated by a long dry spell. A third likely scenario is that only one wet season is accounted in a particular year and others are not accounted due to weak rainfall activities. There are 17 major and minor basins which experienced multiple wet seasons. The basins which experience multiple wet seasons due to winter precipitation are Indus major, Chenab, Beas, Satluz, Ramganga, Wainganga and Penganga, those due to pre-monsoon thunderstorms Kosi, Mahananda, Tista, Damodar, Suvarnarekha, Brahmani and Palar & Ponnaiyar and those due to post monsoon rainfall Bhima, Penner and Vaigai.

Chief Features of the Wet Season Rainfall/Rainwater

Having determined the HWS, total rainfall of the season of the particular year is also obtained. By repeating the process year after year the HWS rainfall series has been prepared for each basin, the WCDS and the whole. Climatology and fluctuation features of the HWS rainfall are discussed here. Based on all available records the mean and SD of the seasonal rainfall are given in Table 2.

The mean and the SD of the HWS rainfall over the major and the minor basins follow the pattern of mean annual rainfall and it's SD across the country. The SD increases with the increase of mean rainfall which is in compliance with the station rainfall characteristics i.e. standard deviation of annual, seasonal and monthly rainfall at stations over India increases with the increase of respective period mean rainfall (Singh and Mulye, 1991). The yearly lowest HWS rainfall ranges from 12.8mm (Yamuna basin) to 1507.4mm (Surma Basin), while the yearly highest rainfall from 865.6mm (Yamuna) to 4706.8mm (Tista). The wet season rainfall sequence of different major/minor basins, including the WCDS and the all India, is normally distributed except Chenab, Beas, Satluz, Gomati, Kosi, Sind, Tons, Brahmaputra, Godavari, Sabarmati major, Luni, and Vaigai.

The actual and the 9-point Gaussian low-pass filtered values of the wet season rainfall are presented in Figs. 1-13 for the 11 major basins, the WCDS and the whole country respectively. The Cramer's t_k-statistic test has been applied to 31-term running means of the individual series and the display of the t_k-statistic prepared (not shown) in order to know short-term changes in the HWS rainfall fluctuations. By applying subjective judgmental approach on the time series plots of the actual values, the 9-point filtered values and the t_k-statistic, chief features of the rainfall fluctuations are deduced. In general, the seasonal rainfall fluctuations showed 2-to-3 tendencies in the combination of increase, decrease and stationary. The major basins which showed declining tendencies in recent years/decades are:

Indus, Brahmaputra, Godavari, Narmada, Mahanadi, Sabarmati and Mahi; and stationary conditions are: Krishna, Cauvery, Tapi and the WCDS. There is a mild decrease in rainfall over Ganga basin also- wet season rainfall over the basin during 1963-2006 was 3.9% below compared to the period 1914-1962. No major basin showed increasing tendency. In the category of minor basins 19 showed decrease, 10 increase and 5 stationary conditions. Decreasing tendency in seasonal rainfall is seen over 54% of the basin area, increasing over 21% and stationary condition over 25%. The net effect is large-scale decrease in the HWS rainfall over the country (Fig. 14). The results are consistent with the recent trends in annual and monsoon rainfall over physiographic regions of the country (Sontakke et al., 2008b), and further with decrescendo phase during 1925-1999 in annual rainfall over northern tropic (Zhang et al., 2007).

The preceding results are directly useful in water resources and hydrological applications if expressed in terms of rainwater (rainfall multiplied by area). The mean (and SD) of the HWS rainwater of the major basins (in bcm) is: Indus 147.392 (48.955), Ganga 740.507 (117.425), Brahmaputra 430.168 (47.851), Godavari 282.584 (58.753), Krishna 180.95 (40.711), Sabarmati 19.06 (8.424), Mahi 28.537 (9.442), Narmada 87.532 (19.083), Tapi 45.646 (12.585), Mahanadi 173.181 (30.603), Cauvery 97.479 (15.267) and the WCDS 270.825 (37.241). In the category of minor basins, the mean rainwater varies from 15.822 bcm (Kosi) to 111.716 bcm (Son).

Recent tendency of the HWS rainfall fluctuation shows decrease over most major/minor basins north of 16°N. The wet season rainfall (and rainwater) over the whole country has decreased by 4.15% during 1912-1964 (953.4mm or 3039.545 bcm) compared to the period 1965-2006 (913.8mm or 2913.295 bcm). Based on rainfall data of 316 rainguage stations, the mean wet season rainwater of the country is 2911.064 bcm which is close to the figure (3000 bcm) given by the Central Water Commission (India) (CWC, 2007). The present study provides additional information about important features of the rainwater like standard deviation, distribution and fluctuation characteristics which is a natural demand by the scientific community and the society alike in the era of global climate change and does not seem to exist. After reaching the land surface the rainwater is partitioned into the green water vapour flow supporting the terrestrial ecosystem and the blue water liquid flow supporting the aquatic ecosystems and accessible for human use. Features of the blue water are described in the following section.

A GROSS ESTIMATE OF HYDROLOGICAL RAINWATER POTENTIAL (HRWP)

Determination of the yearly HWS and creation of area-averaged wet season rainfall (P) sequence of the river basins and the country provided an opportunity to study variability of hydrological rainwater potential (HRWP) of the river basins as well as the whole country. Here HRWP we refer the portion of HWS rainwater (rainfall multiplied by area) available for surface hydrological processes, soil moisture recharge, deep percolation, surface storage and streamflow/riverflow after removing the evapotranspiration. Owing to non-availability of long period requisite meteorological data to estimate potential evapotranspiration (PE), the normal PE is used on yearly basis to compute the term P-PE. For 235 well spread stations over the country normal monthly and annual PE estimated using Penman's method (Penman, 1948) is reported in Rao et al. (1971). From simple arithmetic mean of stations in the particular basin area-averaged normal monthly PE of the basin has been obtained. For corresponding HWS of the particular year the total PE is calculated from 12 monthly PE values. For fractional part of the month the PE is obtained by linear interpolation. In other words, climatological area-averaged monthly PE is used each year against actual rainfall in computing surplus rainfall (S).

$$\text{If } P \geq PE, \quad S = P - PE, \tag{1}$$

$$\text{If } P < PE, \quad S = P - AE = 0 \text{ as } AE = P, \tag{2}$$

where, AE is the actual evapotranspiration.

$$HRWP = S * \text{area} \tag{3}$$

Detailed characteristics of the S series (in mm) are documented. However, the final results are expressed as the HRWP (in bcm). There is some error in using climatological (or normal) PE on yearly basis for evaluating S (or HRWP) but there does not seem any better alternate presently which allows the study of variability of rainwater potential of the river basins and the country over the longest period of instrumental records (1813-2006). However, attempt will be made to refine the gross estimate of P-PE for the past few decades using PE estimated from actual meteorological data. Further, attempts will also be made to understand distribution of P-PE into its components, soil moisture recharge, deep percolation, surface storage and streamflow/riverflow employing sophisticated hydrological models. The results will be published elsewhere.

The mean surplus rainfall is greater if the catchment area of the river is spread over the West Coast, central India, east/northeast India and Western Himalaya (Uttarakhand, Himachal Pradesh and Jammu & Kashmir States) and smaller if the area is in the dry regions of northwest India and central peninsula (Table 2). The SD of the surplus rainfall increases in general with the increase in mean surplus which is in agreement with the station rainfall characteristics; i.e. SD is a linear function of mean for annual, seasonal and monthly rainfall.

The yearly lowest surplus rainfall varies from nil to 1048.9 mm (Brahmaputra). It is important to note that probability of zero surpluses is considerable for large number of basins. For major basins the probability (in %) of zero surplus is as: Indus 17.8, Ganga, Brahmaputra and Godavari 0.6, Krishna 44.3, Sabarmati 19.2, Mahi 6.0, Tapi 5.1 and Cauvery 7.1; and for minor basins: Chenab 11.2, Beas 5.9, Satluz 51.0, Yamuna 5.5, Ramganga 1.8, Gomati 4.4, Ghaghara, Betwa, Ken, Son and Damodar 0.6, Kosi 0.7, Chambal 4.9, Sind 2.7, Wainganga 0.7, Wardha 1.9, Penganga 2.8, Godavari 11.3, Krishna 19.8, Bhima 54.6, Tungabhadra 74.7, Luni

52.3, Penner 49.5, Palar & Ponnaiyar 10.3 and Vaigai 45.3. The yearly highest surplus rainfall varies from 222.5mm (Tungabhadra) to 3918.6mm (Tista). Other than Sabarmati, the surplus rainfall sequence is normally distributed over the major basins. Except 12 minor basins (Chenab, Beas, Satluz, Gomati, Kosi, Sind, Tons, Brahmaputra minor, Godavari minor, Luni, Damodar and Vaigai) the surplus sequence of other minor basins is normally distributed.

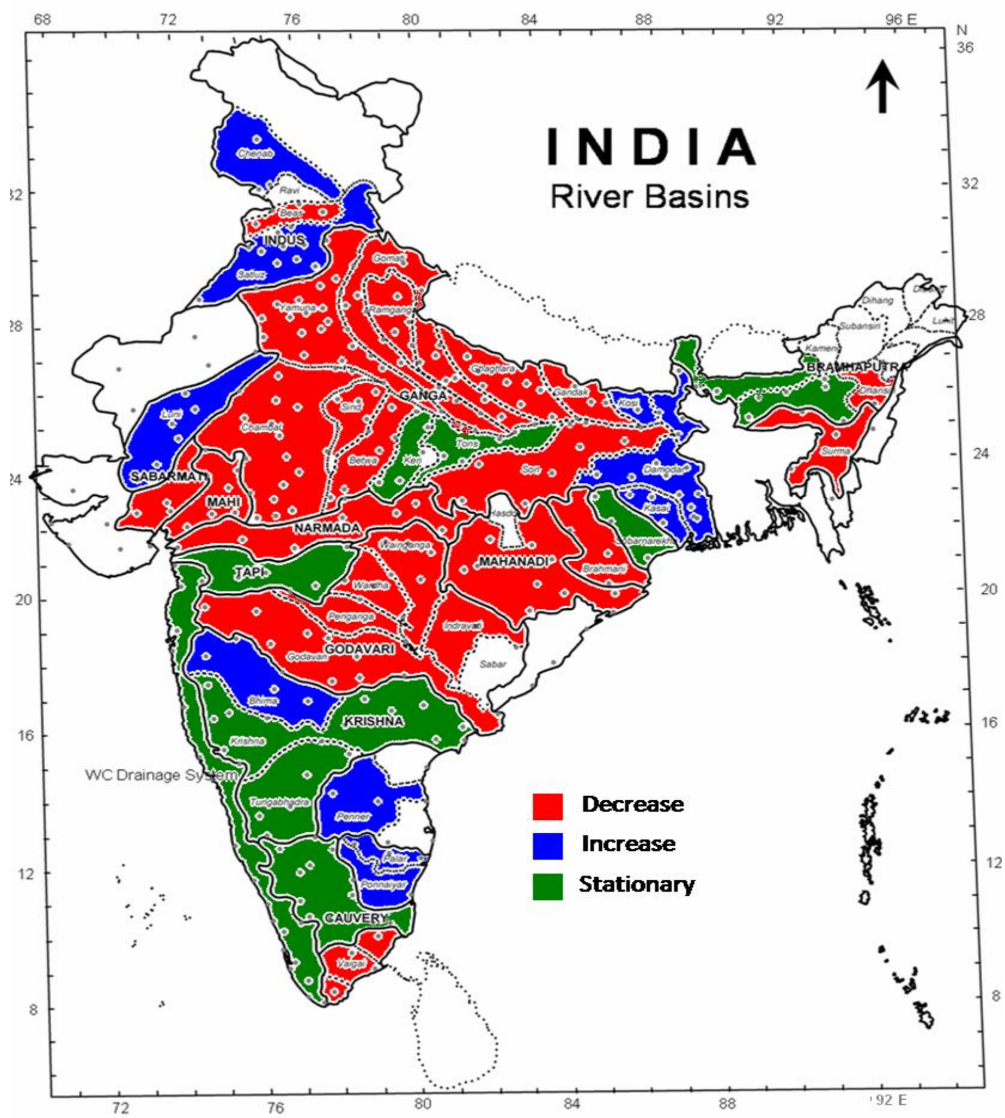

Fig. 14 Recent tendency of the HWS rainfall fluctuation over minor river basins of the country.

The actual and the 9-point Gaussian low-pass filtered values of the surplus rainfall are presented in Figs. 1-13 along side the HWS rainfall series of the respective basin, the WCDS and the whole country. Statistical tests (SE and MK tests) do not suggest significant long-term trend in surplus rainfall fluctuations over any of the basins, and also the WCDS and the whole country. A description of recent tendency in the surplus rainfall fluctuation as deduced from subjective judgment applied on time series plots of the actual and 9-point low-pass filtered values and the Cramer's t_k-statistic for 31-term running means (WMO, 1966) is given. Two to three tendencies (increase, decrease and stationary) in the surplus rainfall are seen over the period of instrumental records. The major basins over which decreasing tendency is seen in recent years/decades are: Indus from 1959, Ganga major from 1972, Brahmaputra major from 1949, Godavari major from 1956, Sabarmati from 1960, Mahi from 1960, Narmada from 1945, and Mahanadi from 1944; and over which no trend is seen are Krishna major, Tapi, Cauvery and the WCDS. In minor basins 21 showed decreasing tendency, 8 increasing tendency and 7 stationary conditions.

The mean (and SD) of HRWP for the major basins (in bcm) is: Indus 34.884 (32.092), Ganga 316.383 (91.253), Brahmaputra 285.992 (44.078), Godavari 122.864 (46.949), Krishna 18.922 (24.243), Sabarmati 6.912 (6.677), Mahi 12.777 (7.083), Narmada 49.11 (16.264), Tapi 16.366 (9.951), Mahanadi 98.141 (26.397), Cauvery 27.046 (13.111) and the WCDS 179.399 (34.562). Over minor basins the mean HRWP varies from 1.104 bcm (Tungabhadra) to 75.502 bcm (Surma). As indicated, recent tendency of surplus rainfall (or HRWP) fluctuations showed decrease over 8 major and 21 minor basins; increase over 8 minor basins; and stationary over 4 major and 7 minor basins. The net effect is large-scale decrease in surplus rainfall or the HRWP. For the whole country, the mean surplus rainfall (and the HRWP) of the period 1978-2006 is 311.6mm (993.415 bcm) which is 11.93% below the mean of 1915-1977, 353.8mm (1127.953 bcm). During normal wet season the country gets rainfall (rainwater) of 913.1mm (2911.064 bcm) of which 582.5mm (1856.947 bcm) evaporates and 330.6mm (1054.117 bcm) enters into chains of surface hydrological processes. The CWC fresh water estimate of 869 bcm (excluding 1000 bcm of snow-melt) (CWC, 2007) is slightly lower than our estimate of 1054 bcm. But it may be noted that our estimate (1054 bcm) includes soil-moisture also. If rainfall for soil moisture recharge is removed from 1054 bcm probably we will be quite close to CWC estimate. Under unstressed conditions, a water volume of 1000 m^3 per year per capita is required for domestic, agricultural and industrial uses. Therefore, the 1054 bcm of surplus water is marginally adequate for the country with the 1 billion plus population.

The decline in wet season rainfall/rainwater and surplus rainfall/HRWP is essentially due to decline in summer monsoon rainfall (SMR) over the country. Investigation has been carried out for this decline in the SMR. Gradient in the geopotential height of the upper tropospheric isobaric level, say 300 hPa, from northern subtropic (Indo-Pacific sector) to the southern subtropic (Indian Ocean-Australian sector) is a good indicator of intensity of Indian summer monsoon circulation. Though geopotential height of the 300 hPa level is increasing over both northern subtropic as well as southern subtropic due to global warming, it is rising at a faster rate over southern subtropic compared to northern subtropic, consequently geopotential height gradient from northern subtropic to southern subtropic is decreasing resulting into weaker Indian summer monsoon circulation (Sontakke *et al.*, 2008a).

SUMMARY AND CONCLUSION

A summary of climatology and variability of the starting date, the ending date and the duration of the hydrological wet season (HWS), the HWS total rainfall/rainwater and the HWS surplus rainfall (or hydrological rainwater potential, HRWP) across the river basins of the country is in order.

(1) Normally, the HWS starts by 17 March over Surma basin in the northeast. Thunderstorms associated rainfall activities spread westward and the HWS starts during 24 April-21 May over Kosi, Mahananda, Damodar, Kasai, Suvarnarekha and Brahmani basins. Around this time (30 April-31 May) the season starts over the WCDS, the Cauvery and the Tungabhadra basins in the peninsula. The rainfall occurrences spread further west/north/northwestwards only with the arrival of the monsoon currents. The mean date over Luni basin in the Thar Desert is 3 July. Over extreme north, the mean starting date varies from 29 May to 7 June, and over southeastern peninsula from 3 July to 14 August. The frequency distribution of the starting date is Gaussian (or normal) for 23 major and minor basins, and for other 26 basins significantly different from normal.

(2) The end of the HWS from the country is gradual and well organized. The process starts by 31 August from Luni and 19 September from Beas, 18-26 October from extreme northeast and 12 December from southeast peninsula. The frequency distribution of the ending date over 33 major and minor basins is normal and over 16 other basins significantly different from normal.

(3) The mean duration of the HWS is 60 days over Luni; it increases to 106 days over Chenab, 200 days over southeast peninsula and 224 days over Surma. The duration series of 28 major and minor basins is normal while that of 21 basins significantly different from normal. Thus, the ending date and the duration of the HWS over different river basins can be considered near-normal for detailed investigations.

(4) Fluctuations of the starting date, the ending date and the duration show significant long-term trend for none of the basins, including the WCDS and the whole country. However, a subjective deduction of recent tendency from the time series plots of the actual and 9-point filtered values and the Cramer's t_k-statistic for 31-term running means is as: (*early start, late end and longer duration*)- All-India, Ganga major, Tapi, Brahmaputra major, Indus, Cauvery, Mahanadi, Penner, Damodar, Ramganga, Satluz, Bhima, Gomati, Kasai, Kosi, Luni, Beas, Tista, Palar & Ponnaiyar and Mahananda; (*late start, early end and shorter duration*)- Narmada and Vaigai; (*early start, stationary end and longer*

duration)- Sabarmati and Chenab; (*stationary start, late end and longer duration*)- Godavari major and minor; (*early start, early end, stationary duration*)- Suvarnarekha and Brahmani; and (*no trend*)- the remaining major and minor basins.

(5) The Indus and 16 minor basins across the country experienced multiple wet seasons in some years, probability varied from 0.5% to 65%. Indus, Satluz and Ramganga experienced second wet season in winter. Chenab and Beas experienced 2 wet seasons in winter. Wainganga, Penganga, Damodar, Suvarnarekha, Brahmani, Kosi, Mahananda and Tista experienced second wet season in late winter and early summer. Bhima experienced second wet season in post-monsoon period. Penner experienced two additional wet seasons, one in early monsoon and another in post-monsoon. Palar and Ponnaiyar experienced second wet season in early summer. And Vaigai experienced additional three wet seasons, one in late summer, second in mid-monsoon and third in post-monsoon.

(6) In general, there is no significant long-term trend in the wet season rainfall fluctuations over different basins. However, according to a subjective deduction recent tendency of rainfall fluctuations is, decrease over 7 major and 19 minor basins, stationary over 5 major and 5 minor basins and increase over 10 minor basins. The mean HWS rainfall (and rainwater) over the country during wet epoch of 1912-1964 is 953.4mm (3039.545 bcm) and that during dry epoch of 1965-2006 913.8mm (2913.295 bcm) which suggests decline in seasonal rainfall/rainwater during recent dry epoch by 4.15%.

(7) Recent tendency of surplus rainfall (or HRWP) shows decrease over 8 major and 21 minor basins, increase over 8 minor basins and stationary over 4 major and 7 minor basins. The net effect is large-scale decrease in surplus rainfall. For the country, the mean surplus rainfall (and HRWP) of the period 1978-2006 is 311.6mm (993.415 bcm) which is 11.93% below the mean of 1915-1977 (353.8 mm or 1127.953 bcm).

(8) During a normal HWS the country gets rainfall (rainwater) of 913.1mm (2911.064 bcm), 63.8% of which evapotranspirates (green water flow) and 36.2% goes through different surface hydrological processes (blue water flow).

Results of the present basin-scale rainfall analysis based on longest instrumental observations are expected to provide informative resources to planners and managers in water-related sectors, including those working for '*interlinking of rivers*' program of the country. At catchment scale, partitioning of incoming rainfall into green water and blue water, understanding their interannual and long-term variability can provide valuable input to integrated water/land/ecosystem management within a socio-ecohydrological framework- that is taking into account different ethical and political dilemmas of the catchment.

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