Heavy rainfall analysis over Teesta catchment and adjoining areas of Sub-Himalayan West Bengal and Sikkim

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ABSTRACT. Heavy rainfall (HRF) forecasting in hilly region is always a challenge to the operational forecasters. Synoptic Analogue Model (SAM) is considered as one of the useful tools for HRF forecasting in topographically influenced hilly regions. In every monsoon season, the Teesta river catchment and its adjoining areas in Sub-Himalayan West Bengal and Sikkim (SHWB-S) generally receive several events of HRF. With the primary objective to find the method to issue HRF warning over Teesta river catchment and adjoining areas in SHWB-S, a SAM has been developed by analyzing 18 years (1998-2015) data comprising prevailing synoptic situations affecting the area and daily rainfall data of subsequent day of HRF. In addition, impact of different synoptic systems on the distribution of HRF has also been studied. The results revealed that there exists a good agreement between daily HRF warnings issued with the corresponding HRF event observed over this region on the next day.

Key words – Synoptic analog model, Teesta basin, Heavy rainfall warning.

1. Introduction

Teesta River Catchment and its adjoining areas in Sub-Himalayan West Bengal and Sikkim (SHWB-S) is one such area where Heavy rainfall (HRF) is a very common phenomenon during south-west monsoon season (JJAS). These HRF activities often results water induced hazards like flash floods and landslides causing significant loss of lives and damage to the properties. Therefore, accurate forecasting of HRF in SHWB-S is of vital importance in general and of great challenge to the operational forecasters, in particular. The challenge of timely and location specific forecasting of HRF in the area increases due to its high elevated mountains. Topography itself has a profound effect on spatial patterns of precipitation both globally and regionally (Smith, 1979). The interaction of atmosphere with topography is well documented by Durran, 1986; Simpson, 1987. Houze, 1993 showed that the vertical profiles of temperature and moisture content and the velocity of the incoming air, which vary from storm to storm, as well as characteristics of the topography, including the length, width and height of the mountain range, determine how the atmosphere interacts with the mountains.

Many studies by several authors (Abbi et al., 1970; Rao et al., 1970; Abbi et al., 1979; Lal et al., 1983; Daoud et al., 2011) suggested that synoptic analog model (SAM) to estimate the quantitative precipitation over the river catchments. Obled et al. (2002), Gibergans-Baguena and Llasat (2007), Bliefernicht and Bardossy (2007) have also shown the usefulness of the analog models in forecasting the precipitation. Gao et al. (2014) have presented an analogue method to detect the occurrence of heavy
precipitation events without relying on modeled precipitation and showed that the method captured the HRF events very well. The rainfall characteristics of the Teesta river catchment and adjoining areas in SHWB-S has been studied by Bhattacharya and Bhattacharya, 1980; Dhar et al. (1996); Biswas and Bhadram, 1984. Lahiri (1981) have discussed the method of forecasting of rain and floods in the Teesta River. Rao et al. (1997) have shown that statistical analog procedure gives a good idea for predicting average areal precipitation semi-quantitatively for Teesta basin.

In this present study, daily rainfall data and synoptic situations prevailed on the previous day over SHWB-S during south-west monsoon season (1st June to 30th September) for the period 1998 to 2015 have been considered to find out the existence of correlation between them, if any, so that HRF warning over this region can be issued with more accuracy. In addition, impact of different synoptic systems in the distribution of HRF (65 mm and above) during this season over Teesta basin & adjoining areas in SHWB-S has also been studied.

2. The study area

The River Teesta originates in the glacial mountains of the state of Sikkim. It is flowing through the districts of Darjeeling and Jalpaiguri and then enters the Rangpur Division of Bangladesh. The Teesta is a perennial, rain and snow fed river. The Teesta is classified as a high-altitude basin in the state of Sikkim, with nearly one fourth of the basin area at an elevation of 4,000 to 5,000 meters and more than 59 per cent of the catchment area above 3,000 meters. The Teesta is joined by a number of tributaries such as the Leesh, the Geesh, the Chel, the Neora and the Karala in the Sub-Himalayan plains before entering Bangladesh. The transboundary basin of the Teesta River encompasses 12,159 square kilometers, of which 83% are in India and remaining 17% are in Bangladesh. About, 66% of the river basin lies in hilly parts of Sikkim (86%) and West Bengal (14%). The upper catchment of the Teesta Basin in Sikkim is prone to sudden variations in rainfall and temperature due to the high altitude and mountainous topography. Middle and lower catchment are open to the moist southerly/ south westerly monsoon current. Frequency of the HRF is highest along Middle and lower catchment which lies in the foot hills (wind-ward side) of Himalayas. The rain gauge stations over the Teesta catchment and adjoining areas of SHWB-S are shown in Fig. 1.

3. Data and methodology

The synoptic situations along with the HRF realized on the next day over the Teesta catchment and adjoining areas of SHWB-S during south-west monsoon season of 1998-2015 have been utilized for the present study. The synoptic situations recorded in the mid-day inferences issued by Area Cyclone Warning Centre (ACWC), Regional Meteorological Centre, Kolkata have been utilized. Based on the closeness to the catchment and intensity of the systems which have most significant impacts on the rainfall activity over the catchment and adjoining areas have been taken into consideration. To find the impact of different synoptic situations on the frequency of HRF (more than 64.4 mm) event over different locations, the study area has been divided into three portions viz., Upper Portion, Middle Portion and Lower Portion. Accordingly, all the rain gauge stations (9) of Sikkim in the Upper Portion; Middle Portion consists of 14 rain gauge stations whereas 12 rain gauges in the Lower Portion are considered for of the purpose.

4. Results and analysis

4.1. Salient features of rainfall distribution over Teesta basin and adjoining areas of SHWB-S

HRF event over this area is frequent during the monsoon season and induces many weather and terrain related hazards. Most of the parts of state Sikkim and Darjeeling district falls in mountainous region where as Jalpaiguri, Alipooduar and Coochbehar districts are at the foot hills of Himalayas. On an average, 250-400 cm rainfall occurred during the months of south-west monsoon season (June to September) over various rain gauge stations of this region. Frequencies of heavy to very heavy rain falls over these stations are also considerably high, about 10-20 days during the south-west monsoon season.

Primarily, due to prolonged thunderstorm activity, this area receives good amount of rainfall during the late night & early morning of a day. On the other hand, the typical orographic features in combination with the moisture incursion from Bay of Bengal due to southerly/south-easterly flow in the lower levels are the deciding factors for causing HRF activity on daily scale over this region. Even in absence of any synoptic situations invariably after a gap of two / three days of dry spell, strong instability in the atmosphere along with southerly moisture flow from Bay of Bengal and its interaction with the orography causes significant rainfall activity over this region.

Some salient features of rainfall activity over Teesta catchment and adjoining areas of SHWB-S during south-west monsoon season (1998-2015) are summarized in the Table 1. Table 1 reveals that
during the study period, on an average Gangtok and Rongo experience the highest number of rainy days (99) whereas Neora rainfall observatory recorded highest one day rainfall (53 cm on 18th June, 1998) during the months of south-west monsoon season. On the other hand, it is seen that the station Rongo receives highest amount of average rainfall (427 cm) whereas the mean frequencies of HRF is maximum over Buxaduar (21) during the months of south-west monsoon season. Buxaduar also experienced highest number (total 33) of days with extremely HRF during the period of study 1998-2015.

4.2. Distribution of HRF events over Teesta basin and adjoining areas of SHWB-S

The Analysis of HRF distribution over Teesta catchment and adjoining areas using SAM method for the period 1998 to 2015 are summarized in the Table 2. From this table, following points may be inferred:

(a) Total seventy one (71) types of synoptic situations have been identified and shown in Table 8. Out of 2196 days during 1998 to 2015 of monsoon months (June to September), it has been
found that the study area received HRF events at (i) Isolated places in 1165 days (53%), (ii) A few places in 203 days (9%) and (iii) Many places in only 15 days (1%).

(b) During the study period, location wise occurrences of HRF events are stated below:

**Upper Portions:** (i) At Isolated places in 171 days (8%), (ii) At a few places in 102 days (5%) and (iii) At many places only in 4 days (0%).

**Middle Portions:** (i) At Isolated places in 718 days (33%), (ii) At a few places in 302 days (14%) and (iii) At many places only in 43 days (2%).

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**TABLE 1**  
Various features of rainfall distribution during southwest monsoon season (1998-2015) over Teesta basin and adjoining areas in SHWB & Sikkim

| Area                  | Station   | Lat. (N) | Long. (E) | Altitude (m) | Average seasonal rainfall (mm) | Mean frequency of rainy days | Average no. of days with rainfall 65 mm & above | Highest rainfall recorded (mm) | No. of days of extreme HRF |
|-----------------------|-----------|----------|-----------|--------------|-------------------------------|----------------------------|-----------------------------------------------|-------------------------------|--------------------------|
|                       |           |          |           |              |                                |                            |                                                |                                |                         |
|                       | Gangtok   | 27° 20’  | 88° 36’  | 1765        | 2333                          | 99                         | 4                                             | 188                           | 0                        |
|                       | Tamang    | 27° 19’  | 88° 36’  | 1322        | 1996                          | 91                         | 3                                             | 213                           | 1                        |
|                       | Chungthang| 27° 36’  | 88° 39’  | 1131        | 1284                          | 91                         | 1                                             | 101                           | 0                        |
|                       | Mangan    | 27° 30’  | 88° 32’  | 1166        | 2105                          | 90                         | 4                                             | 197                           | 0                        |
|                       | Damthung  | 27° 14’  | 88° 23’  | 1981        | 2017                          | 86                         | 5                                             | 156                           | 0                        |
|                       | Namthung  | 27° 10’  | 88° 30’  | 1350        | 1382                          | 65                         | 3                                             | 240                           | 3                        |
|                       | Mazitar   | 27° 11’  | 88° 30’  | 340          | 1261                          | 62                         | 3                                             | 159                           | 0                        |
|                       | Khanitpur | 27° 11’  | 88° 30’  | 302          | 1341                          | 65                         | 3                                             | 181                           | 0                        |
|                       | Lava      | 27° 04’  | 88° 40’  | 2621        | 2670                          | 88                         | 10                                            | 271                           | 3                        |
|                       | Singlabazar| 27° 07’ | 88° 14’  | 240          | 1270                          | 61                         | 3                                             | 178                           | 0                        |
|                       | Sevoke    | 26° 53’  | 88° 28’  | 152          | 3388                          | 85                         | 17                                            | 332                           | 15                       |
|                       | Rongo     | 27° 10’  | 88° 32’  | 1189        | 4265                          | 99                         | 20                                            | 322                           | 13                       |
|                       | Neora     | 26° 52’  | 88° 46’  | 164          | 3037                          | 83                         | 13                                            | 532                           | 11                       |
|                       | Nagrakata | 26° 54’  | 88° 55’  | 229          | 3012                          | 84                         | 14                                            | 324                           | 13                       |
|                       | Murti     | 26° 51’  | 88° 50’  | 143          | 2898                          | 80                         | 13                                            | 294                           | 11                       |
|                       | Bagrakot  | 26° 56’  | 88° 32’  | 205          | 3330                          | 85                         | 15                                            | 310                           | 10                       |
|                       | Diana     | 26° 56’  | 89° 00’  | 200          | 3050                          | 83                         | 13                                            | 404                           | 20                       |
|                       | Champasari| 26° 43’  | 88° 25’  | 123          | 2805                          | 76                         | 14                                            | 241                           | 1                        |
|                       | Bagdora   | 26° 38’  | 89° 19’  | 131          | 2677                          | 74                         | 13                                            | 254                           | 6                        |
|                       | Darjeeling| 27° 03’  | 88° 16’  | 2127         | 1772                          | 70                         | 6                                             | 220                           | 1                        |
|                       | Kalimpong | 27° 04’  | 88° 28’  | 1209         | 1598                          | 64                         | 5                                             | 189                           | 0                        |
|                       | Gazoldoba | 26° 45’  | 88° 40’  | 110          | 2961                          | 72                         | 15                                            | 396                           | 8                        |
|                       | Jalapiguri| 26° 32’  | 88° 43’  | 83           | 2708                          | 71                         | 13                                            | 474                           | 16                       |
|                       | Domohoni  | 26° 33’  | 88° 45’  | 85           | 2550                          | 71                         | 12                                            | 347                           | 12                       |
|                       | NH-31     | 26° 35’  | 88° 56’  | 82           | 2208                          | 67                         | 10                                            | 423                           | 6                        |
|                       | Falakata  | 26° 31’  | 89° 12’  | 63           | 2159                          | 55                         | 11                                            | 312                           | 11                       |
|                       | Mathabhanga| 26° 20’ | 89° 14’  | 50           | 2127                          | 64                         | 9                                             | 326                           | 10                       |
|                       | Chepan    | 27° 19’  | 89° 39’  | 55           | 2693                          | 65                         | 13                                            | 467                           | 21                       |
|                       | Alipurdaar| 27° 29’  | 89° 31’  | 46           | 2503                          | 63                         | 12                                            | 351                           | 17                       |
|                       | Kamaragram| 27° 37’  | 89° 48’  | 76           | 2998                          | 64                         | 15                                            | 370                           | 27                       |
|                       | Buxaduar  | 27° 54’  | 89° 35’  | 814          | 3029                          | 62                         | 15                                            | 401                           | 33                       |
|                       | Barobhisha| 27° 31’  | 89° 48’  | 57           | 2556                          | 65                         | 12                                            | 375                           | 18                       |
|                       | Hasimara  | 27° 40’  | 89° 20’  | 119          | 3045                          | 76                         | 15                                            | 390                           | 19                       |
|                       | Cooch Behar| 26° 20’ | 89° 28’  | 43           | 2388                          | 70                         | 10                                            | 346                           | 14                       |
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TABLE 2
Summary of heavy/very heavy/extremely rainfall events during the period 1998 to 2015

| Distribution       | Frequency of event [ % of event] |
|--------------------|----------------------------------|
|                    | Total Study Area | Upper Portion | Middle Portion | Lower Portion |
|                    |                   |               |               |              |
| HRF (more than 64.4 mm) |
| Isolated Places    | 1165[53]          | 171[8]        | 718[33]       | 474[22]      |
| A Few Places       | 203[9]            | 102[5]        | 302[14]       | 295[13]      |
| Many Places        | 15[1]             | 4[0]          | 43[2]         | 52[2]        |
| Very HRF (more than 115.5 mm) |
| Isolated Places    | 648[30]           | 25[1]         | 343[16]       | 288[13]      |
| A Few Places       | 39[2]             | 13[1]         | 94[4]         | 109[5]       |
| Many Places        | 0[0]              | 0[0]          | 3[0]          | 17[1]        |
| Extremely HRF (more than 204.4 mm) |
| Isolated Places    | 202[9]            | 3[0]          | 77[4]         | 108[5]       |
| A Few Places       | 1[0]              | 0[0]          | 3[0]          | 22[1]        |
| Many Places        | 0[0]              | 0[0]          | 0[0]          | 1[0]         |

Lower Portions: (i) At Isolated places in 474 days (22%), (ii) At a few places in 295 days (13%) and (iii) At many places only in 52 days (2%).

(c) Table 2 reveals that during the study period, frequency of Very HRF (more than 115.5 mm) event at many places over Teesta catchment and adjoining areas in Sub-Himalayan West Bengal was nil. However, it has been found that the Very HRF occurred at (i) Isolated places in 648 days (30%) and (ii) At a few places in 39 days (2%).

(d) Location wise occurrence of Very HRF events which were observed during the study period are:

Upper Portions: (i) At Isolated places in 25 days (1%) and (ii) At a few places only in 13 days (1%).

Middle Portions: (i) At Isolated places in 343 days (33%), (ii) At a few places in 94 days (4%) and (iii) At many places only in 3 days.

Lower Portions: (i) At Isolated places in 288 days (13%), (ii) At a few places in 109 days (5%) and (iii) At many places only in 17 days (1%).

(e) It is also seen that that out of 2196 days during monsoon months (JJAS) of 1998 to 2015, the entire study area received extremely HRF (more than 204.4 mm) event at isolated places in 202 days (9%) in which Higher portions received only in 3-days, Middle Portions in 77 days (4%) and Lower portions in 108 days (5%).

4.3. Most Favourable systems for occurrence of HRF events over Teesta basin and adjoining areas of SHWB-S

The most favourable synoptic systems producing HRF events over Teesta basin & adjoining areas in SHWB-S for the period 1998 to 2015 are summarized in the Table 3. From this table, following points may be inferred:

(a) Total 12-numbers of most favorable synoptic systems (with frequencies more than 1% of total study period) have been identified for the occurrence HRF (at least over isolated places) over the entire area of study period. These are denoted as S1: Trough over SHWB & Sikkim - 89% (270 out of 302) occasions; S2: Upper air cyclonic circulation along with trough passing through SHWB & Sikkim - 90% (28 out of 31) occasions; S3: Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 94% (48 days out of 51 days) occasions; S4: Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 91% (21 days out of 23 days) occasions; S5: Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 74% (32 out of 43) occasions; S6: Upper air cyclonic circulation over Bihar - 75% (66 out of 88) occasions; S7: Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar - 70% (21 out of 30) occasions; S8: Trough over Gangetic West Bengal - 67% (103 out of 153) occasions; S9: Upper air cyclonic circulation over SHWB and Sikkim - 65% (24 out of 37) occasions; S10: Low over
TABLE 3
Most favourable systems producing at least HRF event during the period 1998 to 2015

| System | Total Study Area | Upper Portion | Middle Portion | Lower Portion |
|--------|-----------------|---------------|---------------|--------------|
|        | Percentage      | System        | Percentage    | System        | Percentage |
|        | (No. of events) | [No. of events] | (No. of events) | [No. of events] | [No. of events] |
| S3     | 94[51(48)]     | S4            | 26[23(6)]     | S3            | 75[51(38)] |
| S4     | 91[23(21)]     | S11           | 25[63(16)]    | S1            | 74[302(224)] |
| S2     | 90[31(28)]     | S1            | 20[302(60)]   | S4            | 70[23(16)] |
| S1     | 89[302(270)]   | S9            | 19[317]       | S2            | 61[31(19)] |
| S6     | 75[88(66)]     | S7            | 17[29(5)]     | S9            | 54[37(20)] |
| S5     | 74[43(32)]     | S8            | 17[153(26)]   | S5            | 51[43(22)] |
| S7     | 72[29(21)]     | S3            | 16[51(8)]     | S11           | 51[63(32)] |
| S11    | 70[63(44)]     | S2            | 16[31(5)]     | S5            | 51[43(22)] |
| S8     | 67[153(103)]   | S10           | 13[54(7)]     | S12           | 43[35(15)] |
| S9     | 65[37(24)]     | -             | -             | -             | -           |
| S10    | 63[54(34)]     | -             | -             | -             | -           |
| S12    | 53[34(18)]     | -             | -             | -             | -           |

TABLE 4
Impact of different synoptic systems on the distribution of HRF over Teesta basin and adjoining areas in SHWB & Sikkim during the period 1998 to 2015

| Synoptic system | Impact of the system to HRF | Impact of the system to Very HRF | Impact of the system to Extremely HRF |
|-----------------|-----------------------------|----------------------------------|-------------------------------------|
|                 | (Total cases when HRF realized) | (Total cases when very HRF realized) | (Total cases when extremely HRF realized) |
|                 | Isolated | Few | Many | Isolated | Few | Many | Isolated | Few | Many |
| S1              | 184(61)  | 80(26) | 6(2) | 161(53)  | 19(6) | 0(0)  | 76(25)   | 1(0) | 0(0)  |
| S2              | 23(74)   | 3(10)  | 2(6)  | 16(52)   | 2(6)  | 0(0)  | 6(19)    | 0(0) | 0(0)  |
| S3              | 38(75)   | 9(18)  | 1(2)  | 29(57)   | 1(2)  | 0(0)  | 5(10)    | 0(0) | 0(0)  |
| S4              | 16(70)   | 4(17)  | 1(4)  | 10(43)   | 1(4)  | 0(0)  | 2(9)     | 0(0) | 0(0)  |
| S5              | 29(67)   | 3(7)   | 0(0)  | 13(30)   | 2(5)  | 0(0)  | 6(14)    | 0(0) | 0(0)  |
| S6              | 64(74)   | 2(2)   | 0(0)  | 30(35)   | 0(0)  | 0(0)  | 6(7)     | 0(0) | 0(0)  |
| S7              | 16(55)   | 5(17)  | 0(0)  | 8(28)    | 0(0)  | 0(0)  | 1(3)     | 0(0) | 0(0)  |
| S8              | 89(58)   | 14(9)  | 0(0)  | 56(37)   | 3(2)  | 0(0)  | 15(10)   | 0(0) | 0(0)  |
| S9              | 23(64)   | 1(3)   | 0(0)  | 10(28)   | 0(0)  | 0(0)  | 2(6)     | 0(0) | 0(0)  |
| S10             | 32(59)   | 2(4)   | 0(0)  | 11(20)   | 1(2)  | 0(0)  | 4(7)     | 0(0) | 0(0)  |
| S11             | 38(60)   | 5(8)   | 1(2)  | 20(32)   | 1(2)  | 0(0)  | 5(8)     | 0(0) | 0(0)  |
| S12             | 18(53)   | 0(0)   | 0(0)  | 1(3)     | 0(0)  | 0(0)  | 0(0)     | 0(0) | 0(0)  |

Jharkhand - 63% (34 out of 54) occasions; S11: North-South trough of low/trough in monsoon westerlies - 70% (44 out of 63) occasions; and S12: Low over Gangetic West Bengal - 53% (18 out of 34) occasions.

(b) Most favourable synoptic systems (with frequencies more than 5) for the occurrence HRF (at least over isolated places) over different locations in study area were:
TABLE 5
Impact of different synoptic systems on the distribution of HRF over the upper portion of the study area during the period 1998 to 2015

| Synoptic system | Impact of the system to HRF | Impact of the system to Very HRF | Impact of the system to Extremely HRF |
|-----------------|-----------------------------|----------------------------------|--------------------------------------|
|                 | Total cases (% of cases when HRF realized) | Total cases (% of cases when very HRF realized) | Total cases (% of cases when extremely HRF realized) |
|                 | Isolated | Few | Many | Isolated | Few | Many | Isolated | Few | Many | Isolated | Few | Many |
| S1              | 34(11)   | 23(8) | 3(1)  | 6(2)    | 5(2) | 0(0)  | 1(0)     | 0(0) | 0(0) |
| S2              | 1(3)     | 4(13) | 0(0)  | 0(0)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S3              | 5(10)    | 3(6)  | 0(0)  | 1(2)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S4              | 3(13)    | 3(13) | 0(0)  | 1(4)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S5              | 2(5)     | 0(0)  | 0(0)  | 1(2)    | 0(0) | 0(0)  | 1(2)     | 0(0) | 0(0) |
| S6              | 6(7)     | 0(0)  | 0(0)  | 0(0)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S7              | 3(10)    | 2(7)  | 0(0)  | 0(0)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S8              | 18(12)   | 8(5)  | 0(0)  | 2(1)    | 1(1) | 0(0)  | 1(1)     | 0(0) | 0(0) |
| S9              | 6(17)    | 1(3)  | 0(0)  | 0(0)    | 1(3) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S10             | 5(9)     | 2(4)  | 0(0)  | 1(2)    | 1(2) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S11             | 8(13)    | 8(13) | 0(0)  | 4(6)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S12             | 1(3)     | 1(3)  | 0(0)  | 0(0)    | 0(0) | 0(0)  | 0(0)     | 0(0) | 0(0) |

TABLE 6
Impact of different synoptic systems on the distribution of HRF over the middle portion of the study area during the period 1998 to 2015

| Synoptic system | Impact of the system to HRF | Impact of the system to Very HRF | Impact of the system to Extremely HRF |
|-----------------|-----------------------------|----------------------------------|--------------------------------------|
|                 | Total cases (% of cases when HRF realized) | Total cases (% of cases when very HRF realized) | Total cases (% of cases when extremely HRF realized) |
|                 | Isolated | Few | Many | Isolated | Few | Many | Isolated | Few | Many | Isolated | Few | Many |
| S1              | 12(42)   | 78(26) | 20(7)  | 93(31)   | 37(12) | 2(1)  | 35(12)   | 2(1) | 0(0) |
| S2              | 11(35)   | 7(23)  | 1(3)   | 9(29)    | 3(10)  | 0(0)  | 4(13)    | 0(0) | 0(0) |
| S3              | 19(37)   | 16(31) | 3(6)   | 16(31)   | 2(4)   | 0(0)  | 2(4)     | 0(0) | 0(0) |
| S4              | 8(35)    | 7(30)  | 1(4)   | 7(30)    | 0(0)   | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S5              | 16(37)   | 5(12)  | 1(2)   | 8(19)    | 2(5)   | 0(0)  | 2(5)     | 0(0) | 0(0) |
| S6              | 32(37)   | 14(16) | 0(0)   | 17(20)   | 1(1)   | 0(0)  | 4(5)     | 0(0) | 0(0) |
| S7              | 6(21)    | 6(21)  | 0(0)   | 4(14)    | 0(0)   | 0(0)  | 1(3)     | 0(0) | 0(0) |
| S8              | 52(34)   | 20(13) | 1(1)   | 32(21)   | 4(3)   | 0(0)  | 4(3)     | 0(0) | 0(0) |
| S9              | 17(47)   | 3(8)   | 0(0)   | 8(22)    | 0(0)   | 0(0)  | 2(6)     | 0(0) | 0(0) |
| S10             | 18(33)   | 8(15)  | 0(0)   | 7(13)    | 2(4)   | 0(0)  | 2(4)     | 0(0) | 0(0) |
| S11             | 26(41)   | 6(10)  | 0(0)   | 8(13)    | 3(5)   | 0(0)  | 0(0)     | 0(0) | 0(0) |
| S12             | 15(44)   | 2(6)   | 0(0)   | 1(3)     | 0(0)   | 0(0)  | 0(0)     | 0(0) | 0(0) |

Upper Portions: (i) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 26% (6 out of 23) occasions; (ii) North-South trough of low/trough in monsoon westerlies - 25% (16 out of 63) occasions; (iii) Trough over SHWB-S - 20% (60 out of 302) occasions; (iv) Upper air cyclonic circulation over SHWB-S - 19% (7 out of 37) occasions; (v) Upper air cyclonic circulation over East...
Uttar Pradesh & adjoining Bihar - 17% (5 out of 29) occasions; (vi) Trough over Gangetic West Bengal - 17% (26 out of 153) occasions; (vii) Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 16% (8 out of 51) occasions; (viii) Upper air cyclonic circulation along with trough passing through SHWB & Sikkim - 16% (5 out of 31) occasions and (ix) Low over Jharkhand - 13% (7 out of 54) occasions.

Middle Portions: (i) Upper air cyclonic circulation over Bihar along with trough passing through SHWB & Sikkim - 75% (38 out of 51) occasions; (ii) Trough over SHWB-S - 74% (224 out of 302) occasions; (iii) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 70% (16 out of 23) occasions; (iv) Upper air cyclonic circulation along with trough passing through SHWB-S - 61% (19 out of 31) occasions; (v) Upper air cyclonic circulation over SHWB-S - 54% (20 out of 37) occasions; (vi) Upper air cyclonic circulation over Bihar - 52% (46 out of 88) occasions; (vii) North-South trough of low/trough in monsoon westerlies - 51% (32 out of 63) occasions; (viii) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 51% (22 out of 43) occasions and (ix) Low over Gangetic West Bengal - 50% (17 out of 34) occasions.

Lower Portions: (i) Upper air cyclonic circulation along with trough passing through SHWB-S - 71% (22 out of 31) occasions; (ii) Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S - 65% (33 out of 51) occasions; (iii) Trough over SHWB & Sikkim - 59% (179 out of 302) occasions; (iv) Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal - 57% (13 out of 23) occasions; (v) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - 51% (22 out of 43) occasions; (vi) Trough over Gangetic West Bengal - 48% (73 out of 153) occasions; (vii) Upper air cyclonic circulation over West central Bay, Andhra Pradesh and Telengana - 43% (15 out of 35) occasions and (ix) Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar - 41% (12 out of 29) occasions.

### 4.4. Impact of important synoptic systems for occurrence of HRF events over Teesta basin and adjoining areas of SHWB-S

(a) The impact of various important synoptic systems on the HRF activities over Teesta basin & adjoining areas in SHWB-S for the period 1998 to 2015 are summarized in the Table 4. From this table, following points may be inferred:

(i) Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S responsible for

| Synoptic System | Impact of the system to HRF | Impact of the system to Very HRF | Impact of the system to Extremely HRF |
|-----------------|-------------------------------|---------------------------------|------------------------------------|
|                 | Total cases                  |                                 | Total cases                        |
|                 | Isolated Few Many            | Isolated Few Many               | Isolated Few Many                  |
| S1              | 82(27) 81(27) 16(5)          | 67(22) 36(12) 11(4)             | 30(10) 14(5) 0(0)                  |
| S2              | 13(42) 7(23) 2(6)            | 8(26) 2(6) 1(3)                 | 2(6) 0(0) 0(0)                     |
| S3              | 17(33) 14(27) 2(4)           | 14(27) 7(14) 0(0)               | 3(6) 0(0) 0(0)                     |
| S4              | 8(35) 4(17) 1(4)             | 6(26) 1(4) 1(4)                 | 2(9) 0(0) 0(0)                     |
| S5              | 12(28) 9(21) 1(2)            | 8(19) 2(5) 0(0)                 | 3(7) 0(0) 1(2)                     |
| S6              | 31(36) 6(7) 2(2)             | 12(14) 2(2) 0(0)                | 2(2) 0(0) 0(0)                     |
| S7              | 8(28) 2(7) 2(7)              | 3(10) 3(10) 0(0)                | 1(3) 0(0) 0(0)                     |
| S8              | 41(27) 26(17) 6(4)           | 26(17) 9(6) 1(1)                | 8(5) 3(2) 0(0)                     |
| S9              | 9(25) 2(6) 1(3)              | 1(3) 1(3) 0(0)                  | 0(0) 0(0) 0(0)                     |
| S10             | 9(17) 5(9) 1(2)              | 4(7) 0(0) 1(2)                  | 1(2) 1(2) 0(0)                     |
| S11             | 11(17) 13(21) 0(0)           | 8(13) 3(5) 2(3)                 | 5(8) 0(0) 0(0)                     |
| S12             | 2(6) 0(0) 0(0)               | 0(0) 0(0) 0(0)                  | 0(0) 0(0) 0(0)                     |
## TABLE 8

Various synoptic systems identified over SHWB & Sikkim during 1998 to 2015

| S. No. | Synoptic System | S. No. | Synoptic System |
|--------|-----------------|--------|-----------------|
| 1.     | Low over SHWB & Sikkim | 29.    | Low over Jharkhand and trough passing through SHWB & Sikkim |
| 2.     | Low over Bihar    | 30.    | Low over Chhattisgarh & East Madhya Pradesh and trough passing through SHWB & Sikkim |
| 3.     | Low over Jharkhand | 31.    | Low over East Uttar Pradesh & adjoining Bihar and trough passing through SHWB & Sikkim |
| 4.     | Low over Gangetic West Bengal | 32.    | Low over Uttar Pradesh and trough passing through SHWB & Sikkim |
| 5.     | Low over Bangladesh | 33.    | Low over Northwest Madhya Pradesh and trough passing through SHWB & Sikkim |
| 6.     | Low over Assam & Meghalaya | 34.    | Low over West central Bay Andhra Pradesh and Telengana and trough passing through SHWB & Sikkim |
| 7.     | Low over North Bay of Bengal | 35.    | Upper Air Cyclonic Circulation over SHWB & Sikkim and trough passing through Gangetic West Bengal |
| 8.     | Low over Orissa   | 36.    | Upper Air Cyclonic Circulation over Bihar and trough passing through Gangetic West Bengal |
| 9.     | Low over Chhattisgarh & East Madhya Pradesh | 37.    | Low over West central Bay, Andhra Pradesh and Telengana |
| 10.    | Low over East Uttar Pradesh & adjoining Bihar | 38.    | Depression over Bihar |
| 11.    | Low over Uttar Pradesh | 39.    | Depression over Jharkhand |
| 12.    | Low over Northwest Madhya Pradesh | 40.    | Depression over Gangetic West Bengal |
| 13.    | Upper Air Cyclonic Circulation over Bihar | 41.    | Depression over Bangladesh |
| 14.    | Upper Air Cyclonic Circulation over Jharkhand | 42.    | Depression over North Bay of Bengal |
| 15.    | Upper Air Cyclonic Circulation over Gangetic West Bengal | 43.    | Depression over Orissa |
| 16.    | Upper Air Cyclonic Circulation over Bangladesh | 44.    | Depression over Chhattisgarh & East Madhya Pradesh |
| 17.    | Upper Air Cyclonic Circulation over Assam & Meghalaya | 45.    | Depression over Uttar Pradesh |
| 18.    | Upper Air Cyclonic Circulation over North Bay of Bengal | 46.    | Depression over Northwest Madhya Pradesh |
| 19.    | Upper Air Cyclonic Circulation over Orissa | 47.    | Depression over West central Bay, Andhra Pradesh and Telengana |
| 20.    | Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh | 48.    | Upper Air Cyclonic Circulation over SHWB & Sikkim |
| 21.    | Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar | 49.    | Trough passing through SHWB & Sikkim |
| 22.    | Upper Air Cyclonic Circulation over Uttar Pradesh | 50.    | Trough passing through Gangetic West Bengal |
| 23.    | Upper Air Cyclonic Circulation over Northwest Madhya Pradesh | 51.    | Trough passing through Assam & Meghalaya |
| 24.    | Upper Air Cyclonic Circulation over West central Bay, Andhra Pradesh and Telengana | 52.    | Trough passing through Orissa |
| 25.    | Upper Air Cyclonic Circulation over West central Bay Andhra Pradesh and Telengana and trough passing through SHWB & Sikkim | 53.    | Upper Air Cyclonic Circulation over SHWB & Sikkim and trough passing through SHWB & Sikkim |
| 26.    | North-South trough of low / trough in monsoon westerlies | 54.    | Upper Air Cyclonic Circulation over Bihar and trough passing through SHWB & Sikkim |
| 27.    | Low over SHWB & Sikkim and trough passing through SHWB & Sikkim | 55.    | Upper Air Cyclonic Circulation over Jharkhand and trough passing through SHWB & Sikkim |
| 28.    | Low over Bihar and trough passing through SHWB & Sikkim | 56.    | Upper Air Cyclonic Circulation over Bangladesh and trough passing through SHWB & Sikkim |
occurrence of HRF at isolated, at a few and at many places respectively in 28 (75%), 9 (18%) and 1 (2%) days; for very HRF at isolated and at a few places respectively in 29 (57%) and 1 (2%) day whereas for extremely HRF at isolated in 5 (10%) days, (ii) Upper air cyclonic circulation along with trough passing through SHWB-S - contributes HRF at isolated, at a few and at many places respectively in 23 (74%), 3 (10%) and 2 (6%) days; very HRF at isolated and at a few places respectively in 16 (52%) and 2 (6%) where as extremely HRF at isolated places in 6 (19%) days, (iii) Upper air cyclonic circulation over Bihar- contributes HRF at isolated and at a few places in 64 (74%) and 2 (2%) days; very HRF at isolated places in 30 (35%) where as extremely HRF at isolated places in 6 (7%) days, (iv) Upper air cyclonic circulation over Bihar along with trough passing through Gangetic West Bengal - contributes HRF at isolated, at a few and at many places respectively in 16 (70%), 4 (17%) and 1 (4%) days; very HRF at isolated and at a few places respectively in 10 (43%) and 1 (4%) days where as extremely HRF at isolated places in 2 (9%) days, (v) Upper air cyclonic circulation over Chhattisgarh and East Madhya Pradesh - responsible for occurrence of HRF at isolated at a few places in 28 (67%) and 7 (18%) days; very HRF at isolated and at a few places in 13 (30%) and 2 (5%) day whereas for extremely HRF at isolated in 6 (14%) days, (vi) Upper air cyclonic circulation over SHWB-S- responsible for occurrence of HRF at isolated and at a few places in 23 (64%) and 1 (3%) days; very HRF at isolated places in 10 (28%) days where as extremely HRF at isolated places in 2 (6%) days, (vii) The monsoon trough or trough of low- responsible for occurrence of HRF at isolated, at a few and at many places respectively in 184 (61%), 80 (26%) and 6 (2%) days; for very HRF at isolated and at a few places respectively in 161 (53%) and 19 (6%) days where as for extremely HRF at isolated and at a few places in 76 (25%) and only 1 (0%) day, (viii) North-South trough of low/ trough in monsoon westerlies - responsible for occurrence of HRF at isolated, at a few and at many places respectively in 38 (60%), 5 (8%) and 1 (2%) days; for very HRF at isolated and at a few places respectively in 20 (32%) and 1 (2%) days where as for extremely HRF at isolated places in 5 (8%) days, (ix) Low over Jharkhand- contributes HRF at isolated, at a few and at many places in 32 (59%) and 2 (4%) days; very HRF at isolated and at a few places respectively in 11 (20%) and 1 (2%) days where as extremely HRF at isolated places in 4 (7%) days, (x) Trough over Gangetic West Bengal - contributes HRF at isolated, at a few and at many places in 89 (58%) and 14 (9%) days; very HRF at isolated and at a few places respectively in 56 (37%) and 3 (2%) days where as extremely HRF at isolated places in 15 (10%) days, (xi) Upper air cyclonic circulation over East Uttar Pradesh and adjoining Bihar - responsible for occurrence of HRF at isolated and at a few places in 16 (55%) and 5 (17%) days; very HRF at isolated places in 8 (28%) days where as extremely HRF at isolated places in 1 (3%) day and (xii) Low over Gangetic West Bengal - contributes HRF at isolated places in 18 (53%) days; very HRFs at isolated places in 1 (3%) day.

TABLE 8 (Contd.)

| S. No. | Synoptic System | S. No. | Synoptic System |
|--------|-----------------|--------|-----------------|
| 57.    | Upper Air Cyclonic Circulation over Orissa and trough passing through SHWB & Sikkim | 65.    | Upper Air Cyclonic Circulation over North Bay of Bengal and trough passing through Gangetic West Bengal |
| 58.    | Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh and trough passing through SHWB & Sikkim | 66.    | Upper Air Cyclonic Circulation over Orissa and trough passing through Gangetic West Bengal |
| 59.    | Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar and trough passing through SHWB & Sikkim | 67.    | Upper Air Cyclonic Circulation over Chhattisgarh & East Madhya Pradesh and trough passing through Gangetic West Bengal |
| 60.    | Upper Air Cyclonic Circulation over Northwest Madhya Pradesh and trough passing through SHWB & Sikkim | 68.    | Upper Air Cyclonic Circulation over East Uttar Pradesh & adjoining Bihar and trough passing through Gangetic West Bengal |
| 61.    | Upper Air Cyclonic Circulation over Jharkhand and trough passing through Gangetic West Bengal | 69.    | Upper Air Cyclonic Circulation over Uttar Pradesh and trough passing through Gangetic West Bengal |
| 62.    | Upper Air Cyclonic Circulation over Gangetic West Bengal and trough passing through Gangetic West Bengal | 70.    | Upper Air Cyclonic Circulation over Northwest Madhya Pradesh and trough passing through Gangetic West Bengal |
| 63.    | Upper Air Cyclonic Circulation over Bangladesh and trough passing through Gangetic West Bengal. | 71.    | Upper Air Cyclonic Circulation over West central Bay Andhra Pradesh and Telangana and trough passing through Gangetic West Bengal |
| 64.    | Upper Air Cyclonic Circulation over Assam & Meghalaya and trough passing through Gangetic West Bengal |
(b) Location wise, impact of most important synoptic systems (with frequencies more than 5) for the occurrence HRF (at least over isolated places) are shown in Tables 5-7.

5. Conclusions

The distribution of HRF Analysis over Teesta catchment and adjoining areas using synoptic analog method for the period 1998 to 2015 are summarized here:

(a) Total seventy one (71) types of synoptic situations have been identified during 1998 to 2015;
(b) Out of 2196 days during 1998 to 2015 of monsoon months (June to September), it has been found that over the entire study area, HRF occurred at least at isolated places in 53% cases; at a few places in 9% cases and at many places in 1% cases; (c) In Upper portion of the study area, HRF occurred at least at isolated places in 8% cases and at a few places in 5% cases; (d) In Middle portion, at least at isolated places in 33% cases; at a few places in 14% cases and at many places in 2% cases; (e) In Lower portion, at least at isolated places in 22% cases; at a few places in 13% cases and at many places in 2% cases; (f) Frequency of HRF event is higher over the Middle and Lower Portion as compared to the Upper Portion of the study area. This is due to the fact that most parts of the Middle and Lower Portions are falling in the foothills and windward side of the Himalayas; (g) Frequency of extremely high HRF event is highest over the Lower Portion whereas lowest over the Upper Portion of the study area; (h) Most favorable systems for producing HRF events over study are: Upper air cyclonic circulation over Bihar along with trough passing through SHWB-S (94%); Upper air cyclonic circulation over Bihar along with trough passing through over Gangetic West Bengal (91%), Upper air cyclonic circulation along with trough passing through SHWB-S (90%), Trough over SHWB-S (89%), Upper air cycloonic circulation over Chhattisgarh and East Madhya Pradesh (74%), Upper air cyclonic circulation over Bihar (73%), North-South trough of low/ trough in monsoon westerlies (70%), Upper air cyclonic circulation over East Uttar Pradesh & adjoining Bihar (70%), Trough over Gangetic West Bengal (67%), Upper air cyclonic circulation over SHWB-S (65%) and Low over Jharkhand (63%); (i) The synoptic situation viz., Upper air cyclonic circulation over SHWB-S has the highest impact in producing HRF activities over Upper and Middle Portion where as Upper air cyclonic circulation along with trough passing through SHWB-S has the most significant impact over the Lower Portion of the study area. Presence of these synoptic systems may warrant for issuing HRF warning at a few places in the area and (j) The occurrence of HRFS at a few or many or most places over this area are mainly due to the presence of (i) Upper air cyclonic circulation along with trough passing through SHWB-S (ii) monsoon trough or trough of low on sea level chart passing through SHWB-S and (iii) Upper air cyclonic system over Bihar with trough passing through SHWB-S and. Persistence of these conditions for two or more days may cause disastrous flood situation in this area. On the other hand, the synoptic situations other than trough passing through SHWB & Sikkim may be responsible for occurrence of HRF only at the isolated places for one or two days but may not create flood like situation over this region generally.

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