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Extreme rainfall events and urban floods in the growing cities of India

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सार – भारत में पिछले कुछ वर्षों से शहरों में आने वाली बाढ़ संबंधी आपदाओं की बढ़ती हुई प्रवृत्ति पाई गई है। इस अध्ययन में, 1969 से 2010 की अवधि में भारत के शहरों में भारी वर्षा की घटनाओं (≥ 65 मि. मी.) और बहुत भारी वर्षा की घटनाओं (≥ 125 मि. मी.) के कारण शहरों में आने वाली बाढ़ की जाँच की गई है। साथ ही, अनुकूल सिनॉप्टिक परिस्थितियों के साथ भारी वर्षा की घटनाओं के प्रवृत्ति विश्लेषण पर चर्चा की गई है। भोपाल और जयपुर में भारी मौसमी वर्षा की घटनाओं में कमी की प्रवृत्ति देखी गई है। यह प्रवृत्ति भोपाल के संबंध में महत्वपूर्ण है। अहमदाबाद, हैदराबाद, पुणे और बंगलुरू में मौसमी वर्षा की वृद्धि की प्रवृत्ति देखी गई है जबकि भारी वर्षा की घटनाओं में ऐसा नहीं देखा गया है। भारी वर्षा की घटनाओं की मासिक प्रवृत्ति में लखनऊ में जून, भोपाल में अगस्त और हैदराबाद में सितम्बर के महीने में महत्वपूर्ण नकारात्मक (कमी) प्रवृत्ति का पता चला है। बंगलुरू और पटना में जून, हैदराबाद में अगस्त और भुवनेश्वर में सितम्बर के महीने में भारी वर्षा की घटनाओं (≥ 65 मि.मी.) की मासिक प्रवृत्ति महत्वपूर्ण सकारात्मक (वृद्धि) प्रवृत्ति का पता चला है। शेष मामलों में मासिक प्रवृत्तियों में विविधता पाई गई है। समग्र रूप से भारी वर्षा की घटनाओं में कोई व्यवस्थित प्रवृत्ति नहीं देखी गई है।

ABSTRACT. There has been an increasing trend of urban flood disasters in India over the past several years. An attempt has been made in the present study, to examine urban flood caused by heavy rainfall events (≥ 65 mm) and very heavy rainfall events (≥ 125 mm) for the growing cities in India for the period from 1969 to 2010. Also, the trend analysis of occurrences of heavy rainfall along with favourable synoptic situations has been discussed. Bhopal and Jaipur have shown decreasing trend in seasonal heavy rainfall events. Trend is significant for Bhopal only. Ahmedabad, Hyderabad, Pune and Bangalore show increasing trend in seasonal rainfall though not significant in heavy rainfall events. Monthly trend for heavy rainfall events (≥65 mm) show significant negative (decreasing) trend for the month of June for Lucknow, August for Bhopal and September for Hyderabad. Monthly trends in heavy rainfall events (≥65 mm) show significant positive (increasing) trend for the month of June for Bangalore and Patna, August for Hyderabad and September for Bhubaneswar. In rest of the cases monthly trends are in different. Overall there is no systematic trend in the heavy rainfall events.

Key words – ISMR, Extreme rainfall, Flooding, Urban development.

1. Introduction

Southwest monsoon also known as the Indian Summer Monsoon (ISM) season is the main rainy season in India during which the country receives over 80 to 85 per cent of its annual rainfall. The Indian Summer Monsoon Rainfall (ISMR), defined here as the cumulative rainfall over continental India during June-July-August-September (JJAS), has important implications on the socio-economic growth of the subcontinent. ISMR averaged over the whole of India is found to be stable over past hundred or more years with no noticeable significant long term trend, but several locations across India show an increasing trend in heavy rainfall occurrence (≥65 mm/day) during the summer monsoon season (Sinha Ray and Srivastava, 2000). De *et al*., (2005) presented a factual and brief review of extreme weather events that occurred in India during last 100 years (1901-2004), discussed specially the major rainstorms causing severe flood situations. The increase in extreme rainfall (≥100 mm/day) events during ISM has been particularly strong in the last 50 years (Goswami *et al*., 2006). There have been specific cases of urban flood disasters in India over the past several years where by major cities in India have been severely affected. The most notable amongst these are the floods in Hyderabad and Ahmedabad in 2000, Delhi in 2002, 2003, 2009 and 2010, Chennai in 2004 and 2005, Mumbai in 2005, Surat in 2006, Kolkata in 2007, Jamshedpur in 2008, and Guwahati in 2010.

Flooding is a natural hazard giving rise to a third of all losses due to natural events. On 16 June 2013,

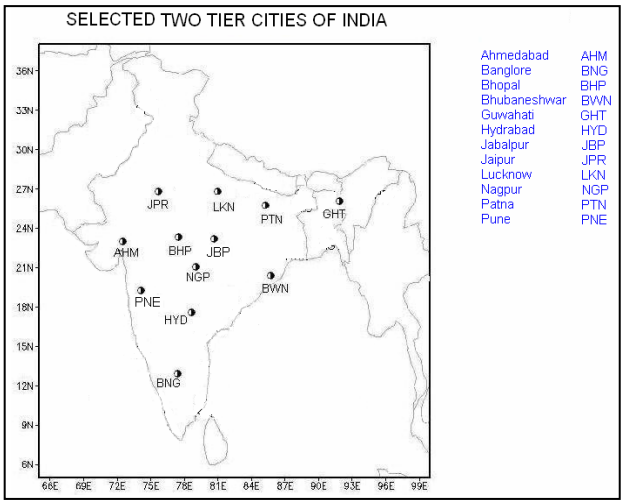


Fig. A. Location of 12 two-tier cities over India used in this study. Cities are also being listed for easy geographical reference

Uttrakhand received heavy rainfall without breaks, (about 200 mm rain within an hour) causing severe landslides and flash floods in Kedarnath valley. There is no clear estimate so far, of the number of villages wiped out, property destroyed, roads washed away and hydropower projects damaged in the mountain state of Uttarakhand. Floods are a major disaster in India in term of occurrences (41% of total disasters) as well as casualties (De *et al*. 2002). Floods can occur anywhere after heavy rains. They can be triggered by severe thunderstorms, tornadoes, tropical cyclones, monsoons, cloudburst etc. Floods threaten human life and property and it is estimated that about 1.5 billion people were affected in the world during last decade of the twentieth century [Khole and De (2001); De and Dandekar (2001); De *et al*. (2004); (De *et al*., 2013)]. Continued urbanization of natural flood plain has caused significant loss of life and damage to property and the trend could be alarming if not checked through improved flood management practices. Extreme weather events over the last decades have shown that flooding is becoming more extreme, more frequent and more widespread [Guhathakurta *et al*. (2011); Tongdi Jamir *et al*. (2008)]. Whether these extreme events are due to anthropogenic global warming or otherwise are a matter of current scientific debate.

Urban flooding is significantly different from rural flooding. Urban areas are densely populated and people living in vulnerable areas suffer due to flooding, sometimes resulting in loss of life. It is not only the event of flooding but the secondary effect such as exposure to infection that adds to human suffering, loss of livelihood and, in extreme cases, loss of life (De and Sinha Ray (2000). Major cities in India have witnessed loss of life and property, disruption in transport and power and incidence of epidemics due to floods. Increasing trend of urban flooding is a universal phenomenon and poses a great challenge to urban planners over the world. Problems associated with urban floods ranges from relatively localized incidents to major incidents, resulting in cities being inundated from hours to several days.

2. Data and methodology

The study is in relation to selected 12 growing urban cities of India except mega cities (Fig. A), namely Ahmedabad (AHM) (23.03° N, 72.58° E), Bangalore (BNG) (12.58° N, 77.34° E), Bhopal (BHP) (23.15° N, 77.25° E), Bhubaneswar (BBN) (20.27° N, 85.84° E), Guwahati (GHT) (26.11° N, 91.44° E), Hyderabad (HYD) (17.34° N, 78.48° E), Jabalpur (JBP) (12.10° N, 79.56° E), Jaipur (JPR) (26.93° N, 75.82° E), Lucknow (LKN) (26.85° N, 80.95° E), Nagpur (NGP) (21.15° N, 79.09° E), Patna (PTN) (25.61° N, 85.14° E), Pune (PNE) (18.31° N, 73.51° E).

Criteria for choosing the cities are:

(*i*) Where the population is fast growing and is in excess of 4 million.

(*ii*) Cities are well distributed over the country.

(*iii*) These cities have long record of climatological data (> 40 years).

Daily rainfall data for the period 1969-2010 for the selected cities for the monsoon months (June-September) available from the India Meteorological Department (IMD) have been utilized to study heavy rainfall (≥65 mm) and very heavy rainfall (≥125 mm) epochs and their trends. The daily rainfall for the period 1969-2010 of above cities has been analysed for 1-Day, 2-Day, 3-day, 4-Day and 5-Day highest rainfall occurrences (Table 1).

3. Aim of the study

In this paper authors aim at finding the urban flooding in 12 cities of the country. It also discusses the synoptic scale circulation situation for heavy to very heavy rainfall during last decades. The types of flooding criteria are briefly discussed.

(*i*) *Single event floods* : This is the most common type of flooding, in which widespread heavy rains lasting several hours to a few days over a drainage basin results in severe floods. Typically, these heavy rains are associated with thunder storm activity, cloud burst, cyclonic

TABLE 1

Highest rainfall (mm) for 1-Day, 2-Day, 3-Day, 4-Day and 5-Day duration (1969-2010)

Station	Height (m)	1-Day	2-Day	3-Day	4-Day	5-Day	Duration for 5-day
Ahmedabad	53	325.9	390.6	553.6	591.8	618.2	(24-28) Jun, 1997
Bangalore	900	177.6	186.9	312.8	314.0	358.9	(8-12) Sep, 1988
Bhopal	500	291.6	489.6	506.4	534.1	545.8	(19-23) Aug, 1974
Bhubaneswar	45	282.8	363.8	387.0	398.1	-	(27-30) Jul, 1969*
Guwahati	55	179.6	206.0	221.6	246.4	284.2	(6-10) Jul, 1990
Hyderabad	542	241.5	314.4	316.1	324.0	327.8	(23-27) Aug, 2000
Jabalpur	411	255.9	358.3	432.5	482.3	556.4	(10-14) Jul, 1994
Jaipur	431	326.0	488.5	623.3	638.0	709.9	(16-20) Jul, 1981
Lucknow	23	250.0	352.4	360.4	386.5	439.8	(13-17) Sep, 1970
Nagpur	310	304.0	293.8	426.6	449.2	474.1	(9-13) Jul, 1994
Patna	53	250.8	341.1	380.8	467.4	496.1	(10-14) Jul, 1997
Pune	560	141.7	228.2	298.0	357.5	385.5	(6-10) Jun, 1991

* Duration of 4 days.

disturbances, mid-latitude depressions and storms, with well mark synoptic scale systems.

(*ii*) *Multiple event floods* : These result from heavy rainfall associated with successive synoptic scale weather disturbances following each other, these include for example floods in the Indo-Gangetic plains and central Indian regions often caused by the passage of series of low pressure areas or depressions from the Bay of Bengal, more or less along the same path.

(*iii*) *Seasonal floods* : These are floods that occur with general regularity as a result of major seasonal rainfall activity. The areas of the world which have a monsoonal type of climate are the areas most affected. Here, critical situation arises when "normal" flooding is replaced by extended or high run-off floods.

4. Results and discussions

Floods in India occur mostly during southwest monsoon season due to very heavy rains caused by synoptic scale monsoon disturbances. Most of such cases have been noticed during July and August. Embedded in monsoon system, there are other synoptic systems such as vortices (lower/mid-tropospheric cyclonic circulations, off-shore vortices along the west coast, low pressure areas, depressions and cyclones), troughs (monsoon trough, off-shore trough along the west coast, north-south troughs over peninsular India during break monsoon conditions) and east-west wind shear zone in the lower troposphere that largely enhance the monsoon rainfall activity.

A depression may originate over the sea or land and may cause significant rainfall along its path. Sometime depressions originating over the ocean may develop into tropical cyclones where wind speed in the circulation can be 33 knots or more can intensify and move towards land providing heavy to very heavy rainfall on the coast. After crossing the coast, they weaken into depressions and move across the land along its path causing heavy rainfall over the land it covers. Thunderstorms are much localized short duration transient weather phenomena observed in some parts of India. These weather systems during the monsoon season greatly enhance the quantity of rainfall locally and are the major source of short duration heavy rainfall leading to flash floods/ flooding. Cloud burst in India

TABLE 2

Chief amount of one day rainfall events (mm) with dates for two-tier cities from 1969-2010

S. No.	City	June	July	August	September
1.	Ahmedabad	249.3 (27/6/1997) 222.1 (11/6/1988)	325.9 (14/7/2000) 236.0 (1/7/2005)	250.0 (30/8/1976) 242.4 (24/8/1990)	195.8 (19/9/1975) 184.8 (8/9/1994)
2.	Bangalore	89.6 (11/6/2009) 84.5 (1/6/2009)	123.5 (18/7/1998) 100.7 (6/7/1988)	92.0 (4/8/1998) 91.6 (2/8/2000)	177.6 (12/9/1988) 136.0 (13/9/1979)
3.	Bhopal	155.0 (22/6/1986) 107.0 (26/6/1977)	275.5 (22/7/1973) 223.4 (6/7/1978)	291.6 (14/8/2006) 284.0 (30/8/1973)	214.5 (1/9/2006) 166.3 (15/9/1999)
4.	Bhubaneswar	277.8 (22/6/1971) 248.7 (4/6/1982)	282.8 (30/7/1969) 172.3(30/7/1997)	254.2 (20/8/1997) 186.5 (6/8/2007)	137.0 (9/9/2005) 120.2 (5/9/2006)
5.	Guwahati	128.7 (21/6/1974) 126.9 (16/6/1993)	179.6 (10/7/1985) 139.0 (2/7/1979)	113.2 (7/8/1991) 107.2 (27/8/1995)	130.3 (2/9/2010) 109.8 (18/9/1995)
6.	Hyderabad	114.6 (12/6/2001) 97.2 (16/6/1981)	140.5 (24/7/1989) 110.0 (1/7/1980)	241.5 (24/8/2000) 190.6 (3/8/2006)	148.9 (9/9/1975) 122.2 (25/9/1971)
7.	Jabalpur	168.2 (8/6/1971) 158.2 (27/6/1977)	222.5 (28/7/1999) 196.8 (11/7/1994)	255.9 (30/8/1972) 234.0 (15/8/1972)	208.3 (9/9/2009) 147.8 (15/9/2005)
8.	Jaipur	172.9 (29/6/1971) 92.2 (29/6/1977)	326.0 (19/7/1981) 162.5 (18/7/1981)	160.5 (27/8/1989) 140.8 (23/8/1974)	99.8 (28/9/1975) 74.2 (3/9/1996)
9.	Lucknow	182.4 (26/6/1971) 161.4 (30/6/1975)	140.7 (9/7/2006) 124.9 (29/7/1990)	330.0 (28/8/1991) 250.0 (30/8/2000)	292.0 (4/9/1991) 177.1 (14/9/1985)
10.	Nagpur	170.7 (14/6/2001) 117.2 (25/6/2002)	304.0 (12/7/1994) 183.0 (30/7/1991)	215.4 (4/8/1979) 147.8 (9/8/1999)	143.8 (3/9/1976) 142.7 (14/9/2005)
11.	Patna	205.4 (30/6/1997) 152.6 (8/6/2006)	157.0 (13/7/2006) 156.0 (11/7/1997)	166.7 (14/8/2007) 166.0 (15/8/1988)	181.1 (27/9/1975) 168.8 (15/9/1997)
12.	Pune	123.3 (8/6/1991) 104.9 (7/6/1991)	95.2 (3/7/2007) 65.2 (2/7/1969)	141.7 (17/8/1987) 101.5 (1/8/1976)	115.3 (26/9/1971) 110.7 (19/9/1983)

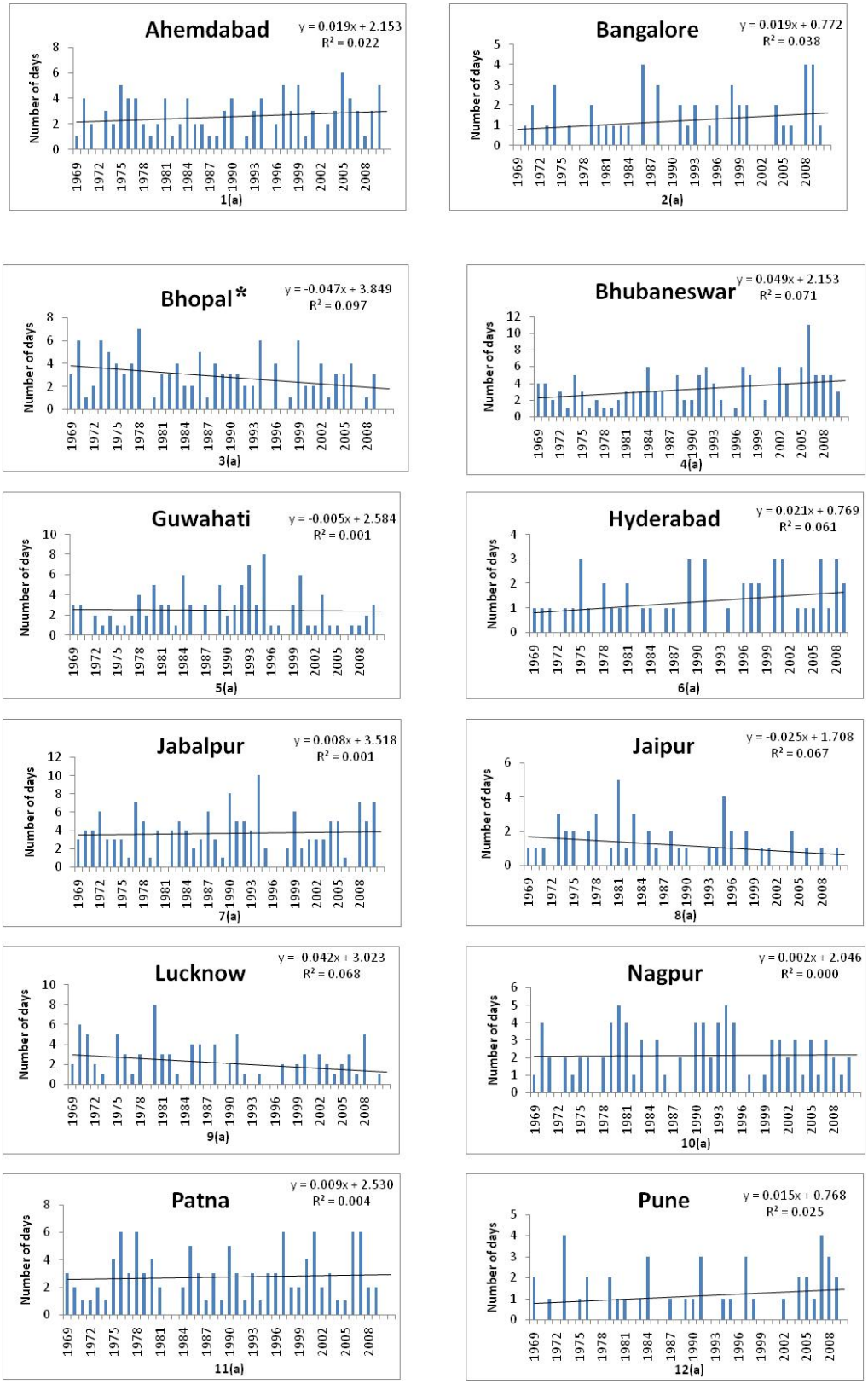
occurs during the monsoon season over the orographically dominant regions like Himalayan region, north-eastern states and Western Ghats and in other areas as well recently in Uttrakhand. The rate of rainfall may be of the order of 100 mm/hr causing floods and landslides. Dhar and Nandargi (1995) have shown that during the last 110 years, the Indian region recorded 231 severe rainstorms. Of these, 27 were of 2-day duration and the rest (204) were of 3-day duration. Within a rainstorm, maximum rain fell on the 2nd day on 63% of occasions. Rakecha and Pisharoty (1996) have also examined daily rainfall of 5000 stations in India during monsoon periods of several decades (1875-1982) for occurrences of heavy rainfall for 1, 2 and 3 day durations and also Depth-Area-Duration values of extreme rainstorm on India.

4.1. *City wise discussions of the floods/extreme rainfall events*

Some of the extreme one day rainfall events for selected cities from 1969-2010 are given in Table 2 and month-wise analysis of heavy rainfall events (HRF) and very heavy rainfall events (VHRF) for the 12 cities. A detailed city wise discussion of the floods/extreme rainfall events is given below.

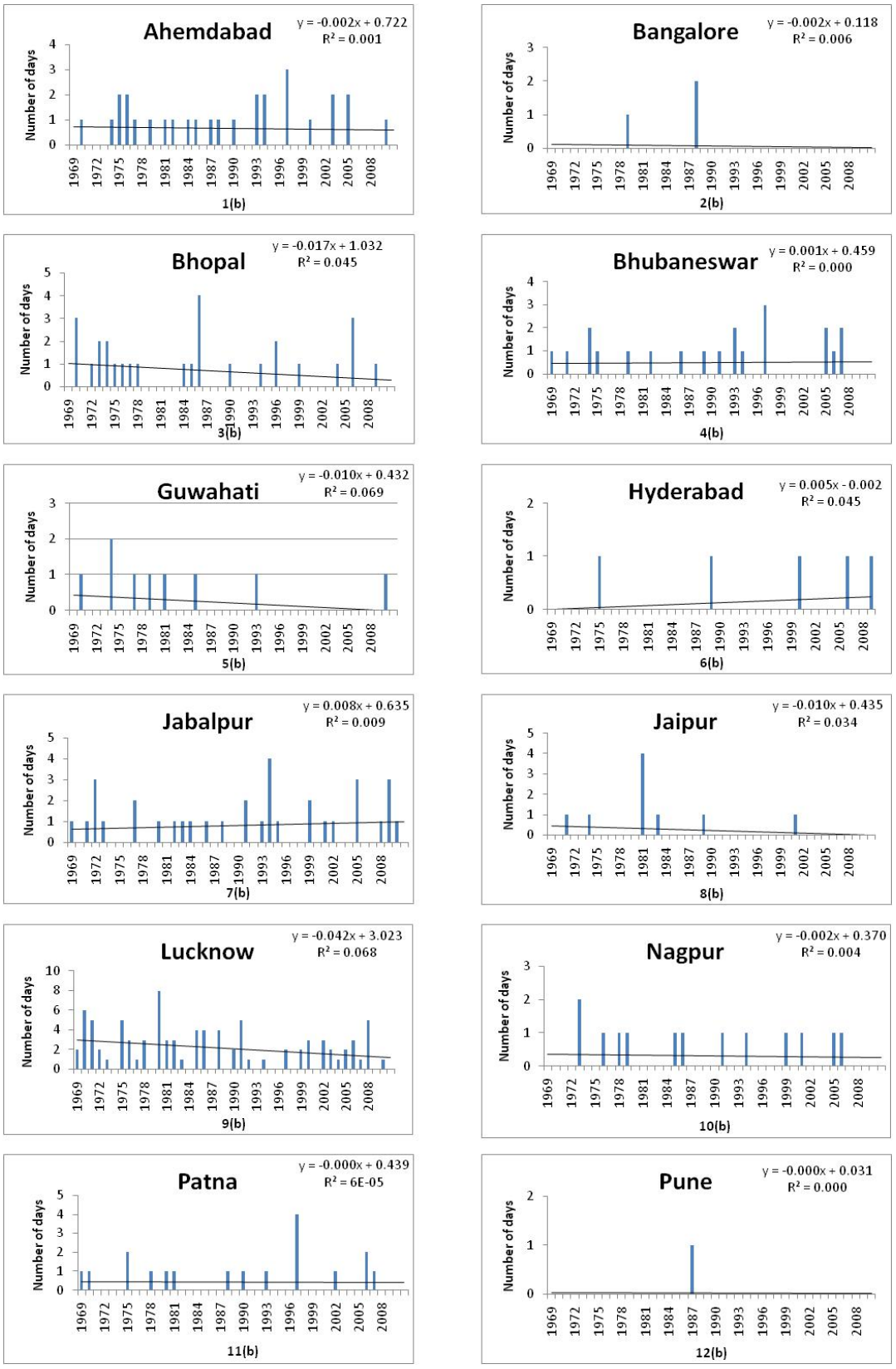
4.1.1. *Ahmedabad*

In Ahmedabad, there is an increasing trend in Heavy rainfall events (HRF) – Fig. 1 (1a), with increasing trend in the months of July and August, Fig. 4 (1d) & Fig. 5 (1e)

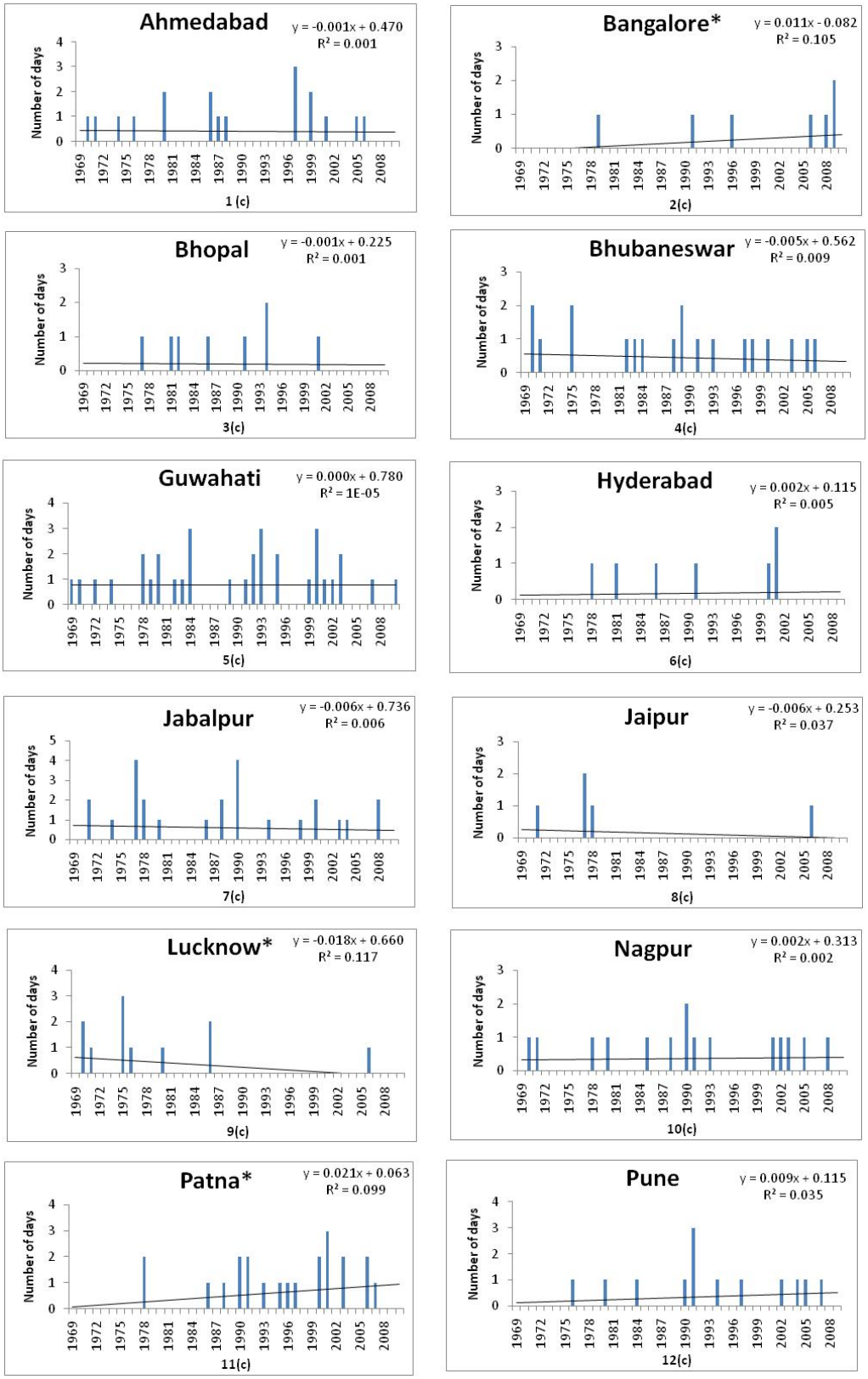


* indicate trend significant at 95% confidence level

Figs. 1 (1a-12a). Inter-annual distribution of heavy rainfall (≥65 mm) days during SW monsoon

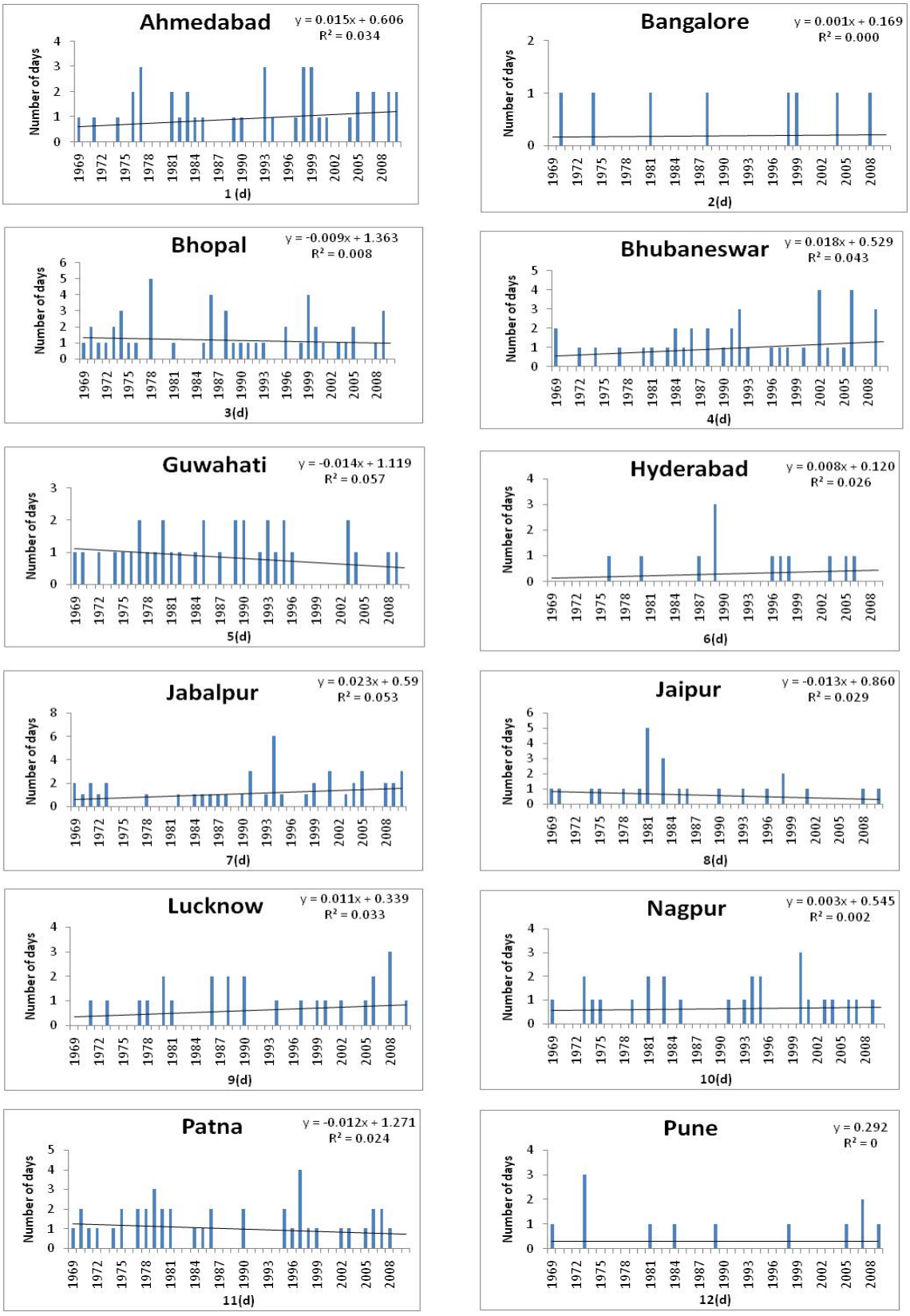


Figs. 2 (1b-12b). Inter-annual distribution of very heavy rainfall (≥125 mm) days during SW monsoon

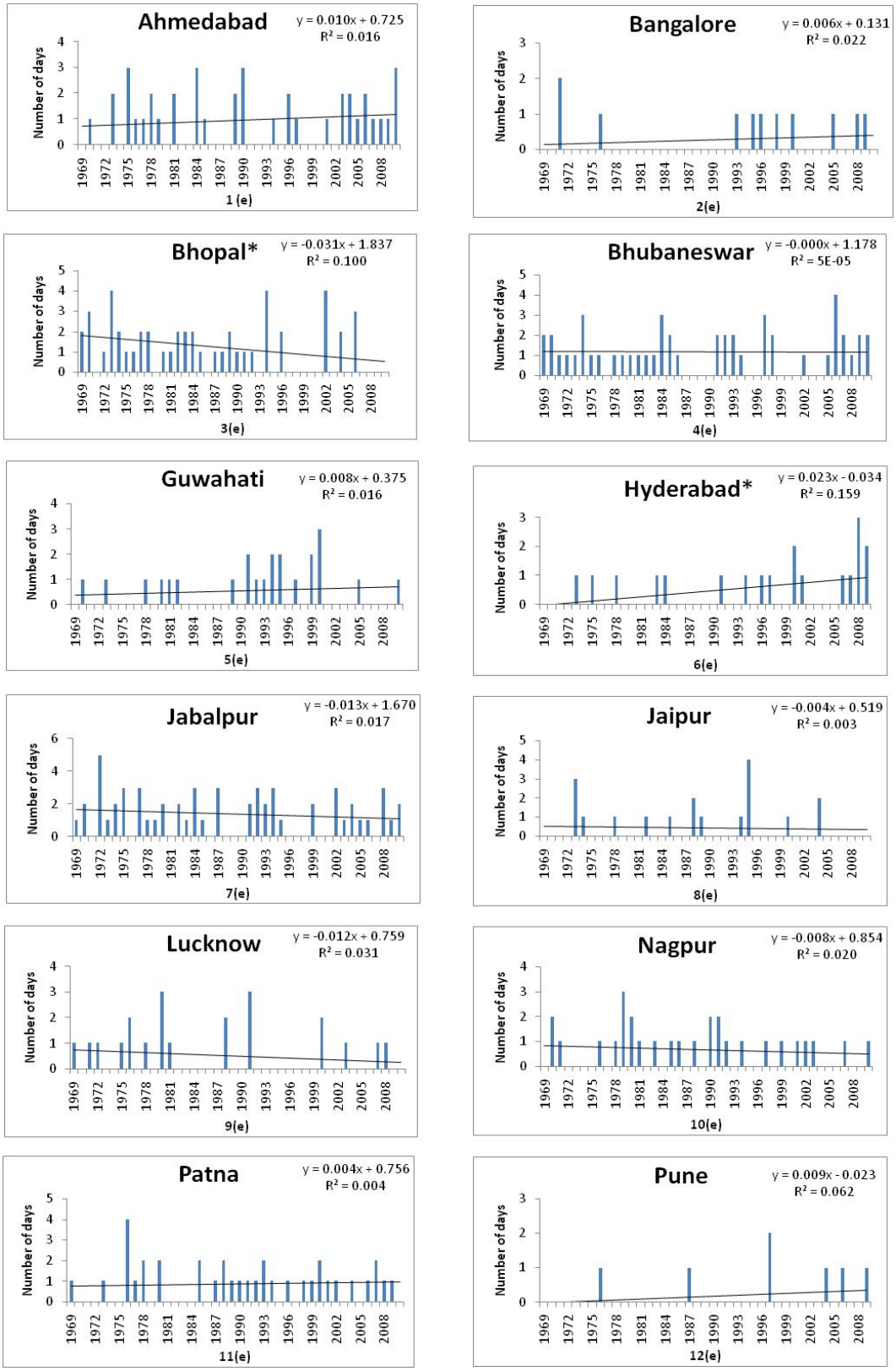


* indicate trend significant at 95% confidence level

Figs. 3 (1c-12c). Number of days of heavy rainfall (≥65 mm) for the month of June



Figs. 4 (1d-12d). Number of days of heavy rainfall (≥65 mm) for the month of July



* indicate trend significant at 95% confidence level

Figs. 5 (1e-12e). Number of days of heavy rainfall (≥65 mm) for the month of August

and decreasing trend for June and September, Fig. 3 (1c) & Fig. 6 (1f). Very heavy rainfall events (VHRF) have highest number of days (11) in the month of August. There is decreasing trend for VHRF - Fig. 2 (1b).

Some cases of extremely heavy rainfall

Single event flood : On 14th July, 2000 when Ahmedabad city received 32.6 cm rainfall in four hours, 98% of people were affected due to power cuts. The power supply was restored after 96 hours.

Synoptic situation : A cyclonic circulation extending up to mid-tropospheric level over northwest Bay and neighbourhood on 10th July moving in north-westerly direction reached western parts of Rajasthan on 12th July.

Single event flood : On 8th August, 2010, heavy rains during 12 hours adversely affected life in several parts of Ahmedabad causing flooding in residential areas. Four persons were killed in a house collapse in Dudheshwar area of western part. The city recorded an unprecedented rainfall of 237.4 cm throwing life out of gear.

Synoptic situation : On 8th August, 2010, there was a well marked low pressure area over west Madhya Pradesh and adjoining south Rajasthan and north Gujarat region along with a very active off-shore trough during 8-9 August extending from south Gujarat to Kerala coast.

Seasonal flood : During the last week of June 1997, it was reported that due to heavy rains and floods in Gujarat state, 172 people lost their lives and damage to properties worth cores of rupees occurred.

Synoptic situation : A cyclonic circulation which was situated over Gulf of Cambay and adjoining south Gujarat region concentrated into low pressure area over northeast Arabian Sea off Gujarat coast on 21th June moved in north-easterly direction and dissipating over north Gujarat region and adjoining parts of Rajasthan.

4.1.2. *Bangalore*

In Bangalore, there is an increasing trend in HRF Fig. 1 (2a), with increasing trend in the months of June, July and August in which for the month of June trend is significant at 95% significance level, Figs. 3-5 (2c), (2d) & (2e) and no trend for September. Maximum number of days of VHRF events (3) observed in the month of September.

Single event flood : A torrent of rain engulfed the city in the evening of 24th September, 2010 for about one hour, as the city was pounded by record rainfall of 114.1 mm caused due to thundershower. The city had to face the severe after effects of water logging, flooding while trees fell onto streets. Several areas were hit by power cuts and low lying colonies were inundated.

Synoptic situation : A Cyclonic circulation in lower and middle tropospheric levels during 11 to 13 September over South Interior Karnataka and neighbourhood was quasi-stationary causing heavy rainfall over coastal Karnataka and neighbourhood.

4.1.3. *Bhopal*

In Bhopal, there is a significant deceasing trend in HRF – Fig. 1 (3a), with deceasing trend in the all months, Figs. 3-6 (3c-3f) in which for the month of August trend is significant. There is also a deceasing trend in VHRF- Fig. 2 (3b). Maximum number of days of events in both HRF and VHRF is in the months of July and August (49 and 12 each) respectively.

Single event flood : On August 14, 2006, Bhopal received over 29 cm of rain during the span of five hours, which was the heaviest rainfall in past 70 years. This incessant rains in Madhya Pradesh capital caused havoc with 22 people feared dead, several areas submerged and major trains halted outside the city as water flowed through the streets causing floods in at least 15 low lying areas with water as high as two feet in some parts.

Synoptic situation : Under the influence of an upper air cyclonic circulation over the North Bay of Bengal, a low pressure area concentrated into depression on 11th August, 2006 crossed Orissa coast on 12th, and reached east Madhya Pradesh and neighbourhood on 14th as a well-marked low.

Seasonal flood : During 21-25 July, 1986, widespread heavy rainfall was reported over northwest part of Madhya Pradesh.

Synoptic situation : A depression formed over North Bay of Bengal on 13th July, intensified into cyclonic storm on 14th near Sagar Island, crossed West Bengal on 15th, moved westnorthwest across Madhya Pradesh remained as deep depression during 22-25 and dissipated over northwest Madhya Pradesh and neighbourhood.

4.1.4. *Bhubaneswar*

In Bhubaneswar, there is an increasing trend in HRF- Fig. 1 (4a), with deceasing trend in the months June and

August, Fig. 3 (4c) & Fig. 5 (4e) and an increasing trend for July and September, Fig. 4 (4d) & Fig. 6 (4f) in which for the month of September trend is significant. Maximum number of days of VHRF events (10) observed in the month of September. There is also an increasing trend in VHRF - Fig. 2 (4b).

Single event flood **:** During 5-6 August, 2007, Bhubaneswar city received 139.2 and 186.5mm rainfall on two consecutive days.

Synoptic situation : Under the influence of upper air cyclonic circulation, a low pressure area formed over northwest Bay of Bengal off Orissa coast on 4thAugust which concentrated into a deep depression on 5thAugust, moving westwards crossed Orissa coast near Paradip and was centred close to Cuttack on 6thAugust.

4.1.5. *Guwahati*

In Guwahati, there is a deceasing trend in HRF Fig. 1 (5a), with deceasing trend in the month of July, Fig. 4 (5d) and increasing trend for August, Fig. 5 (5e). There is also a deceasing trend in VHRF – Fig. 2 (5b). Maximum number of days of VHRF events (6) observed in the month of July.

Single event flood : On 19 August, 2005, at least five persons, four children and a woman were killed in a landslide at three different places of Guwahati due to heavy rainfall.

Synoptic situation : An upper air cyclonic circulation upto mid-tropospheric level during 17 to 24 August lay over northeast and adjoining east central Bay moved initially northwest and then oscillating finally moved over Bihar.

4.1.6. *Hyderabad*

In Hyderabad, there is an increasing trend in HRF – Fig. 1 (6a), with increasing trend in the months of June, July and August, Figs. 3-5 (6c), (6d) & (6e) in which for the month of August trend is significant. There is significant decreasing trend in September, Fig. 6 (6f). There is also an increasing trend in VHRF - Fig. 2 (6b). Maximum number of days of VHRF events (3) observed in the month of August.

Single event flood : On 18th August, 2009, sudden rain and thundershowers lashed the city on Monday evening, brought the traffic to a standstill with the water logged areas such as busy Dilsukhnagar, Moazamjahi Market area, Kotibankstreet, Malakpet, Chapel Road and at some parts of city.

Synoptic situation : An upper air cyclonic circulation extending upto lower tropospheric level over southwest Bay off south Andhra to north Tamil Nadu coasts was quasi-stationary during 17-18 August.

Seasonal flood : Between 22 and 24 August, 2000, the twin cities of Hyderabad and Secunderabad experienced the wettest spell in 92 years due to heavy downpour. The 24 cm rainfall was measured on a single day on 24th August, 2000. Many of the low-lying areas in Hyderabad which are known to be flood-prone were inundated.

Synoptic situation : A low pressure area over west central Bay off Orissa - north Andhra coast on 21 and 22 August concentrated into a depression on 23rd about south of Vishakhapatnam. It crossed north Andhra coast near Kakinada as depression. It further weakened into well marked low pressure area over Telangana and neighbourhood on 24 August, 2000.

4.1.7. *Jabalpur*

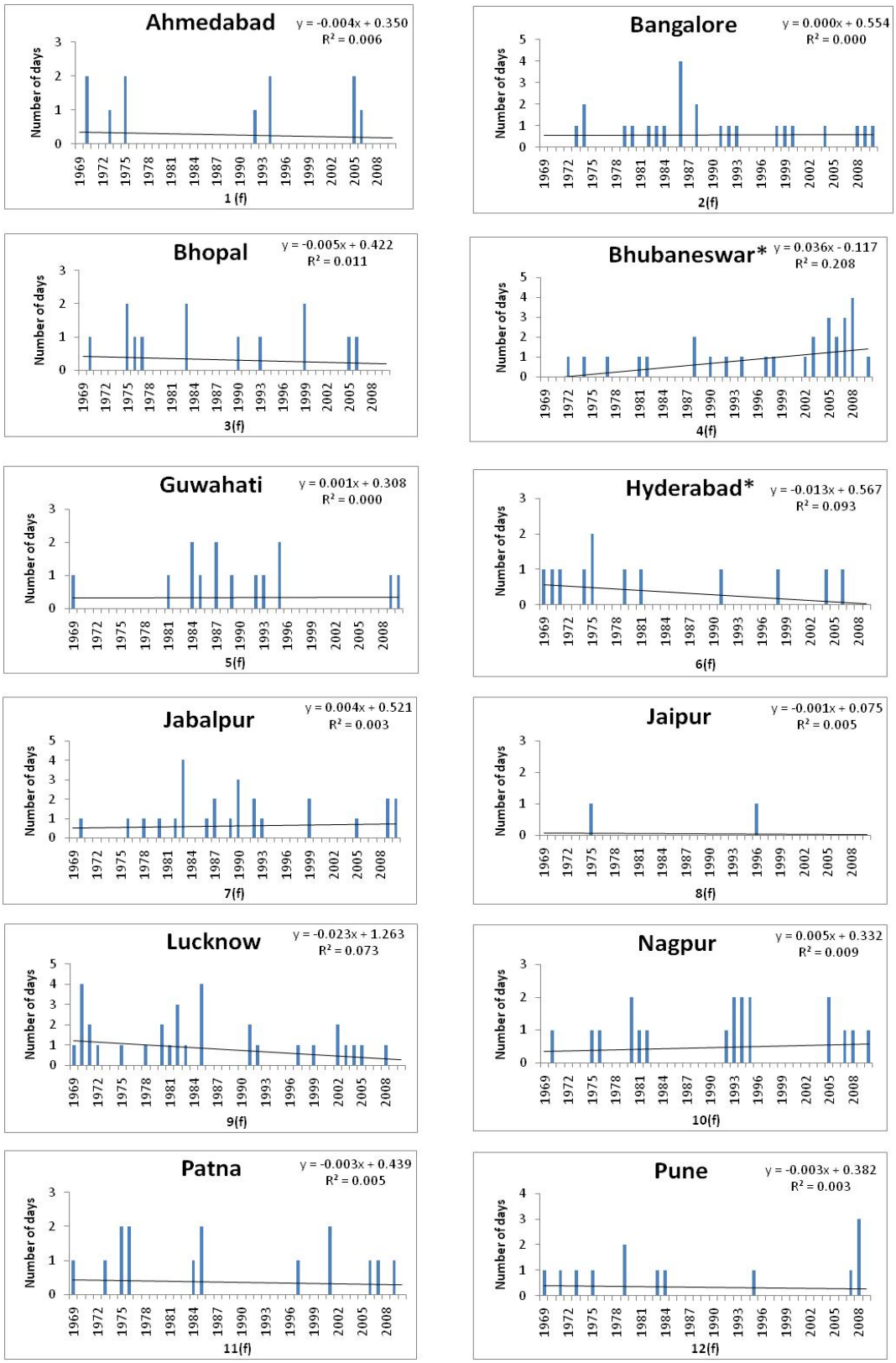
In Jabalpur, there is an increasing trend in HRF Fig. 1 (7a), with increasing trend in the months of July and September, Fig. 4 (7d) & Fig. 6 (7f) and decreasing trend for June and August, Fig. 3 (7c) & Fig. 5 (7e). There is also an increasing trend in VHRF – Fig. 2 (7b). Maximum number of days of events (16) in VHRF is in the month of August.

Single event flood : On 9th September, 2009, Jabalpur city received 208.3 mm rainfall in 24 hours resulting in flooding of streets and power cuts in the city.

Synoptic situation : A deep depression over the northwest Bay moved northwards and crossed West Bengal coast on 5th September, further moved towards northeast Madhya Pradesh and neighbourhood. It weakened into a well-marked low pressure area on 8th and lay over central parts of Madhya Pradesh on 9th September.

Seasonal flood : During 16-20 August, 2002, widespread heavy rainfall was reported over central part of Madhya Pradesh.

Synoptic situation : A low pressure area lay over north Madhya Pradesh and adjoining south Uttar Pradesh with associated cyclonic circulation extending upto mid-tropospheric levels during 16-20 August.



* indicate trend significant at 95% confidence level

Figs. 6 (1f-12f). Number of days of heavy rainfall (≥65 mm) for the month of September

4.1.8. *Jaipur*

In Jaipur, there is a deceasing trend in HRF- Fig. 1 (8a), with deceasing trend in all the months, Figs. 3-6 (8c-8f). There is also a deceasing trend in VHRF - Fig. 2 (8b). Maximum number of days of events (6) in VHRF is in the month of July.

Single event flood : On 19 July, 1981 the Pink City had witnessed 32.6 cm rainfall in a single day which was the heaviest downpour in more than three decades. Heavy rains flooded large parts of the capital of Rajasthan leaving about 100 people feared drowned and about one lakh people rendered homeless and forcing the administration to shut down schools. Another 85 people died in a village nearby which was washed away by floods.

Synoptic situation: Under the influence of the cyclonic circulation over northeast Rajasthan, adjoining Haryana and plains of west Uttar Pradesh, a low pressure area formed over the same area with associated cyclonic circulation extending upto mid-tropospheric levels. Axis of the monsoon trough at 0.9 km a.s.l. passed through Bikaner, Agra, Lucknow, Patna and Imphal.

Seasonal flood : During 25-29 July, 1983, wide-spread heavy rainfall was reported over north Rajasthan.

Synoptic situation : A cyclonic circulation developed in the lower troposphere over north Pakistan and adjoining Punjab on 24th July, under the influence of a trough in mid and upper tropospheric westerlies. It moved eastwards and lay over North West Rajasthan and adjoining Haryana and Punjab on 27th July.

4.1.9. *Lucknow*

In Lucknow, there is a deceasing trend in HRF- Fig. 1 (9a), with deceasing trend in the month of June, August and September, Figs. 3, 5, 6 (9c), (9e) & (9f) in which for the month of June trend is significant and increasing trend for July, Fig. 4 (9d). There is also a deceasing trend in VHRF - Fig. 2 (9b). Maximum number of days of events (10) in VHRF is in the month of September.

Single event flood : On 30thAugust, 2000 Lucknow city received 250.0 mm rainfall in 24 hours causing flooding of streets and power cuts in the city.

Synoptic situation : A cyclonic circulation in mid-tropospheric level observed over East Uttar Pradesh and neighbourhood on 19th August. It remained stationary and merged with monsoon trough.

4.1.10. *Nagpur*

In Nagpur, there is a no trend in HRF Fig. 1 (10a), with deceasing trend in the month of August, Fig. 5 (10e) and increasing trend for September, Fig. 6 (10f). There is also no trend in VHRF Fig. 2 (10b). Maximum number of days of events (6) in VHRF is in the month of July.

Single event flood : On 18 July, 2006, Nagpur city received 173.9 mm rainfall in 24 hours and caused flooding streets and power cuts in the city.

Synoptic situation : A low pressure area which formed over North Bay and adjoining Gangetic West Bengal on 15th July moved westnorthwest, lay over Chhattisgarh and adjoining Jharkhand on 17th July. It became less marked on 18th with associated upper air cyclonic circulation over the area.

Seasonal flood : During 9-13 July, 1994, widespread heavy rainfall was reported in Vidarbha region.

Synoptic situation : A well-marked low pressure area formed over North West Bay on 8th July and moved north-westward and merged with the monsoon trough.

4.1.11. *Patna*

In Patna, there is an increasing trend in HRF- Fig. 1 (11a), with increasing trend in the months of June and August, Fig. 3 (11c) & Fig. 5 (11e) in which for the month of June trend is significant and decreasing trend for July and September, Fig. 4 (11d) & Fig. 6 (11f). There is decreasing trend in VHRF - Fig. 2 (11b). Maximum number of days of events (9) in VHRF is in the month of July.

Single event flood : On 28th July, 1987, Patna city received 250.8 mm rainfall in 24 hours which inundated low lying areas and causing flooding of main streets and power cuts in the city.

Synoptic situation : A cyclonic circulation in the lower tropospheric levels over Bangladesh and

neighbourhood on 16th July concentrated to low pressure area during 17 to 24. It moved in westnorthwestly direction and dissipated over Bihar.

Seasonal flood : During 26 to 30 June, 1997, widespread heavy rainfall was reported over central part of Bihar.

Synoptic situation : A cyclonic circulation in the lower tropospheric levels over northern parts of Gangetic West Bengal and neighbourhood on 21st June becomes low pressure area on 23rd over north Bay and further became well-marked over northwest Bay off Gangetic West Bengal. It concentrated into depression over the same area on 26th. Further moving in a northwesterly direction, it intensified into deep depression moving in northerly direction. It crossed coast and weakened into low pressure area on 29th over northern parts of Bihar plains and adjoining east Uttar Pradesh.

4.1.12. *Pune*

In Pune, there is an increasing trend in HRF - Fig. 1 (12a), with increasing trend in the months of June and August, Fig. 3 (12c) & Fig. 5 (12e) and decreasing trend for September, Fig. 6 (12f). There is also no trend in VHRF–Fig. 2 (12b). Maximum number of days of events (1) in VHRF is in the month of August.

Single event flood : On 17 August, 1987, Pune city received 141.7 mm rainfall in 24 hours and led to flooding streets and power cuts in the city.

Synoptic situation : A cyclonic circulation in the mid-tropospheric levels over west central Bay and adjoining Andhra Pradesh moved northwest and lay over Marthawada on 17th August.

Seasonal flood : During 6-10 June, 1991, widespread heavy rainfall was reported over central part of Maharashtra.

Synoptic situation : A well marked low pressure area formed over southwest Bay off Tamil nadu coast on 4th June moved northwest and further in northerly direction and lay over central Maharashtra during the period 6-10 June.

Long term trends of Indian monsoon rainfall for the country as a whole as well as for smaller regions have been studied by several researchers. Most of the studies are based on the either rainfall series constructed on considering point rainfall data over India or gridded data. Sen Roy and Balling (2004) analysed the trends in the patterns of extreme precipitation events from 1910 to 2000 and showed an increasing trend over most of western India including Deccan Plateau. Guhathakurta and Rajeevan (2006) has found that August rainfall has increased significantly (at 95% significance level) for the subdivisions Konkan & Goa, Marathwada, Madhya Maharashtra, Vidarbha, West M. P., Telangana and west U.P. Contribution of July rainfall is decreasing in central and west peninsular India (significantly in South interior Karnataka (95%), East M. P. (90%) Vidarbha (90%), Madhya Maharashtra (90%), Marathwada (90%), Konkan & Goa (90%), and North interior Karnataka (90%). Therefore, we see a major shift in rainfall pattern spatially and temperally during the recent years. The synoptic systems as Low pressure Area generated over Bay of Bengal are seen forming at southern lower latitude in the recent years and their movements are mostly over peninsular India showing positive trend in monthly rainfall events (≥65 mm) in August for Hyderabad.

Joshi and Rajeevan (2006) found that significant positive trends are observed mainly along the west coast and some parts of central India and over Bihar. Onset and delayed advancement of monsoon over the Northern parts of India and also delayed withdrawal phase of monsoon in recent decade has shown some positive trends at monthly rainfall events in June for Bangalore and Patna and in September for Bhubaneswar and negative trend in June for Lucknow. The synoptic systems as Low pressure Area generated over Bay of Bengal are seen forming at southern lower latitude in the recent years and their movements are mostly over peninsular India showing positive trend in monthly rainfall events (≥65 mm) in August for Hyderabad.

5. Conclusions

Urban flooding results mainly from two causes in India, firstly because of prolonged heavy rainfall. Urban areas face threat of flash flooding of streets and property in low lying areas. Often such flooding is due to drainage obstructions caused by debris blocking drainage outlets and encroachment of the flood plains. Secondly, urban areas which are situated close to the flood plain of rivers (such as, Lucknow, Guwahati) can be inundated by these rivers due to wide spread rains in their catchment areas.

(*i*) Bhopal and Jaipur have shown decreasing trend for seasonal rainfall in heavy rainfall events. Trend is significant for Bhopal only. Ahmedabad, Hyderabad, Pune and Bangalore show increasing trend for seasonal rainfall in heavy rainfall events though these are not significant. These are the most populated cities after four megacities of India. Land-use changes due to urbanization may be responsible for greater damage due to floods.

(*ii*) Guwahati, Patna and Lucknow show decreasing trend for seasonal rainfall in very heavy rainfall events (≥125 mm) though not significant still they are very prone to the seasonal flooding as and when monsoon becomes vigorous over large area causing widespread rains in the river catchments close to these cities.

(*iii*) Trend for heavy rainfall in monthly rainfall events (≥65 mm) show significant positive (increasing) trend in June for Bangalore and Patna, in July for none of the cities, in August for Hyderabad and in September for Bhubaneswar. Monthly heavy rainfall events (≥65 mm) show significant negative (decreasing) trend in June for Lucknow, in July for none of the cities, in August for Bhopal and in September for Hyderabad.

(*iv*) Monthly heavy rainfall events (≥65 mm) show positive (increasing) trend in June for Hyderabad and Pune, in July for Ahmedabad, Bangalore, Bhubaneswar, Hyderabad, Jabalpur and Lucknow, in August for Ahmedabad, Bangalore, Guwahati and Patna, in September for Jabalpur and Nagpur though none of the trends are significant. Monthly heavy rainfall events (≥65 mm) show negative (decreasing) trend in June for Ahmedabad, Bhopal, Bhubaneswar, Jabalpur and Jaipur, in July for Bhopal, Guwahati, Jaipur and Patna, in August for Bhubaneswar, Jabalpur, Jaipur, Lucknow and Nagpur, in September for Ahmedabad, Bangalore, Bhopal, Jaipur, Lucknow, Patna and Pune though none of the trends are significant.

(*v*) Jabalpur and Bhubaneswar, the cities in the monsoon zone show increasing trend in heavy rainfall though not significant, because of active monsoon systems travelling close to these cities more often as compared to Bhopal and Jaipur which show decreasing trends in heavy and very heavy rainfall events where trend is significant for Bhopal. There is no trend for Nagpur City in both the categories.

(*vi*) By and large though there is no significant increasing or decreasing trends. Location specific heavy or very heavy rainfalls are matter of concern for sustainable urban growth.

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