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# FLOOD PRODUCING RAINSTORMS OVER THE MARKANDA CATCHMENT OF NORTH-WEST INDIA: A HYDROLOGICAL STUDY

**Dinesh Kumar**
**Omvir Singh**

## Abstract

*Flooding in downstream areas of Markanda catchment of north-west India occurs due to heavy rainstorm events in the Siwalik Hills. This study, therefore, aims to analyse the extreme rainstorm events and resulting peak floods during the rainy season (June-September) for the period 1996-2013. The study is based on daily rainfall data of eight rain gauge stations and stream flow measurements collected from various Government departments of Himachal Pradesh and Haryana. The results of the study reveal that rain in the catchment falls at a greater intensity during the month of July, due to onset of south-west monsoon winds, whereas highest contribution of annual rainfall in the catchment was observed during the month of August. The mean annual rainfall of the catchment is 95.7 cm and it varies from about 153 cm at Nahan (rainiest) in upper reaches to about 53 cm (driest) at Gulha in the downstream reaches. However, majority of flood producing rainstorms affecting the Markanda catchment has been of 7-day duration. The study may be useful for policy interventions for mitigation and management of floods in the catchment.*

## Introduction

Amongst the hydrological hazards, floods referring to extreme rainstorm events are the most destructive due to their suddenness and unpredictability (Barredo, 2007). Extreme rainstorm events and resulting floods have a significant impact on agriculture, infrastructure (industry, roads, bridges, buildings, communication system etc.), food and water supplies, health, ecosystems and human lives, causing a serious concern in the society (Devereux, 2007; Middleton and Sternberg, 2013; Singh and Kumar, 2013, Das and Deka, 2017). Of late, frequent extreme rainstorm events and increased flood risks have become the focus of the society as the intensity and frequency of floods and the vulnerability of society and economy are all increasing quickly in recent times (Krausmann and Mushtaq, 2008; Hirabayashi et al., 2013; Zhou et al., 2017). Flood risks due to extreme rainstorm events are not likely to reduce in the future since the onset of climate change, and the intensity and formation of floods threaten many regions of the world (Jonkman and Dawson, 2012; Korah and Lopez, 2015). Deadly floods will be more widespread in future with increasing extreme rainstorm events (Mazzorana et al. 2009). Indeed, several tropical and sub-tropical countries are vulnerable to shifts in rainstorm patterns and resultant floods (Anderson et al., 2015, Chadwick et al., 2015). Further, the links between rainstorms and floods are diverse in intensity and locations, because localized extreme rainstorm events occur with the context of changes in large-scale atmospheric processes. The intensity and duration of the resulting flood depends on the intensity, duration and movement of the rainstorm which, in turn, depends on the location and movement of its corresponding synoptic system with respect to the catchment.

Global warming and climate change are being alleged to be accentuating floods and flood risks, because warming climate has the potential to accelerate the hydrological cycle at global and continental scales (Alan et al., 2003; Allan and Soden, 2008; Zhang et al., 2013). Occurrence of extreme rainstorm events for a short duration and resultant floods has been poorly understood; therefore leave a devastating effect (Borga et al. 2014). Hence, description and analysis of every flood event resulting from extreme rainstorm event in a catchment is extremely important for water resource managers and policy makers in order to reduce flood damages (Tariq, 2013). Determination of frequencies and magnitudes of these events would enhance the effective utilization of water resources in an area. Such information can also be used for flood plain management and planning and designing of drains, dams, reservoirs, flood control works, and soil and water conservation measures (Biniyam and Kemal, 2017).

Recently, floods with regard to extreme rainstorm events have severely impacted India as well as the Markanda catchment. However, most of flood research in the country is focused on mapping of flood affected areas, vulnerability analysis and effects of floods on agricultural productivity and peoples' livelihoods. A little work has been done on rainstorm induced floods especially in the river catchments originating from Siwalik Hills. This study therefore, has been taken up to assess the rainstorm induced flood vulnerability in the flood prone Markanda catchment of north-west India.

## Objectives

Major objectives of the present study are:

- to compute the percentage departure from normal rainfall to understand the flood situation over Markanda catchment.
- to demonstrate the distribution of rainstorms over the catchment during the occurrence of major flood years.
- to estimate the design rainstorm depths for different durations based on depth-duration curves and depth-area-duration analysis.

## Study Area

Markanda catchment is located in the Doab region of the Ghaggar and Yamuna rivers. The catchment extends between 30° 01' to 30° 43' north latitudes and 76° 24' to 77° 24' east longitudes and exhibits a dendritic to sub-dendritic drainage pattern (Fig. 1). It is a left bank tributary of river Ghaggar and attains seventh order (Strahler's scheme) before its merger with the river. The catchment covers an area of about 2696 $km^2$ and commences from the southern slopes of Siwalik Hills in Himalayas in Sirmour district of Himachal Pradesh (333 $km^2$). Furthermore, the river flows towards south-west direction in alluvial plains of Haryana (2189 $km^2$) and Punjab (174 $km^2$) till its merger with Ghaggar river. Neither the trunk streams nor any of its tributaries originate from snow covered areas of the Himalayas. The lowest and highest elevations in the catchment have been noticed between 240 m (Bhagal village) and 1530 m (Dadu peak) above mean sea level (amsl). Topography of the catchment hinders the movement of

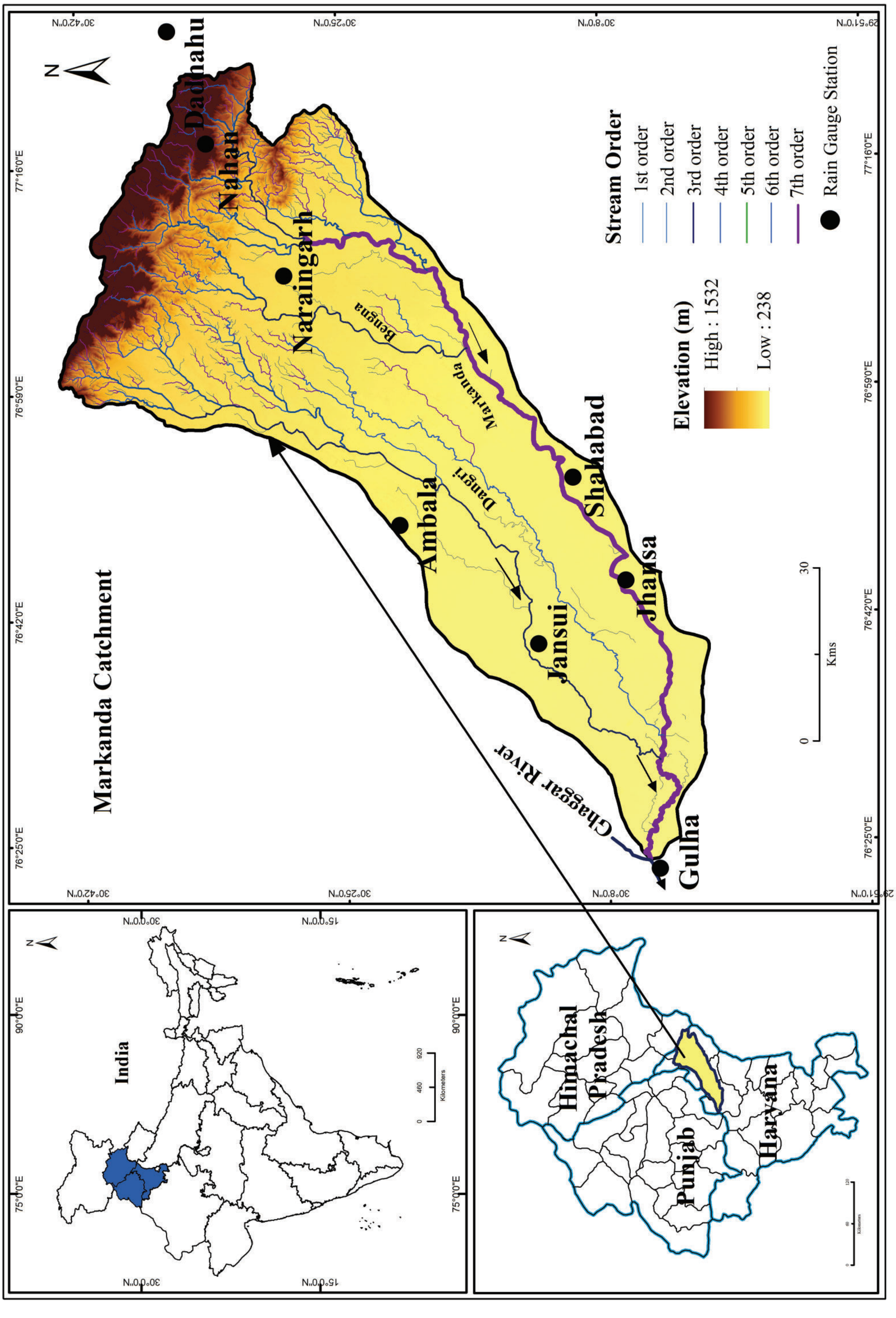
Markanda Catchment
N
Dadhahu
Nahan
Naraingarh
Bengna
Markanda
Shahabad
Ambala
Dangri
Jhansa
Jansui
Gulha
Ghaggar River
Elevation (m)
High : 1532
Low : 238
Stream Order
1st order
2nd order
3rd order
4th order
5th order
6th order
7th order
Rain Gauge Station
0
30
Kms
30°42'0"N
30°25'0"N
30°8'0"N
29°51'0"N
76°25'0"E
76°42'0"E
76°59'0"E
77°16'0"E
India
75°0'0"E
90°0'0"E
30°0'0"N
15°0'0"N
Kilometers
Himachal Pradesh
Punjab
Haryana

Fig. 1

surface runoff, which is characterized by low relief (plains) in downstream areas, while a variety of erosional landforms such as dissected hills, ridges, rills, gullies and scarps in upstream section comprising of with unconsolidated formations. Geological formations in the catchment comprise of Tertiary and Quaternary sediment deposits. Rocks pertaining to Tertiary age cover the northern parts, while alluvial deposits of Quaternary age capture the southern parts of the catchment. The soils are generally deep with loamy to sandy loam in texture, which supports the growth of several crops such as rice, wheat, sugarcane, maize and potato.

The catchment experiences sub-humid and semi-arid climatic regimes. The sub-humid climate prevails over the hills and piedmont, while the semi-arid climatic conditions exist in the alluvial plains. Annually, the catchment receives about 1100 mm of rainfall, which varies from 550 mm in southern alluvial plain to 1560 mm in hills. The monthly rainfall on an average basis fluctuates from 3.1 mm in the month of November to 240 mm in the month of July. More than 80 per cent of the annual rainfall is received during June-September months.

## Materials and Methods

### Acquisition of Data

This study is primarily based on the secondary sources of data procured for the period 1996-2013. Daily rainfall data for eight rain gauge stations located at Dadhahu and Nahan in Himachal Pradesh and Naraingarh, Ambala, Shahabad, Jansui, Jhansa and Gulha in Haryana along with annual peak discharge data of the catchment were procured from Department of Land Records, Government of Himachal Pradesh, Shimla and Department of Irrigation, Government of Haryana, Panchkula. The area of the catchment represented by each rain gauge station is about 350 km$^2$. This network of rain gauges is fairly satisfactory when compared with the neighbouring catchments of Chenab, Ravi, Sutlej, Beas and Yamuna and that of in United States of America (Dhar and Narayanan, 1965). However, there are gaps in rain gauge network in Markanda catchment especially in north-west and central parts, where the distribution of rain gauges is not uniform. The Dadhahu and Nahan rain gauge stations are located in Siwalik ranges of Himalayas, while others are located in alluvial plains of the catchment. Additionally, Ambala and Jansui rain gauge stations fall in Dangri sub-catchment, whereas Naraingarh, Shahabad and Jhansa fall in Markanda catchment and Gulha rain gauge station is just at the outlet point. The location and geographic characteristics of each rain gauge and flow measurement stations have been shown in Fig. 1 and Table 1. Generally, annual peak discharge measurements observed at the outlet of a catchment are used as an indicator of floods. In this study, peak discharge occurring during rainy season (June-September) was considered. Further, in the absence of discharge measurements at the outlet of catchment, a sum of annual peak discharge measurements available at Jansui gauging station for Dangri river and at Jhansa gauging station for Markanda river were taken together to compute the annual peak discharge at the outlet of the catchment during the study period (Table 2).

### Computation of Per cent Departure from Normal Rainfall

Per cent departure from normal rainfall is an excellent tool to understand the flood situation in a catchment. Therefore, in this study, per cent departure from normal rainfall was computed as the percentage deviation from

**Table 1**
**Markanda Catchment: Geographic Positioning of Rainfall and Stream Flow Measurement Stations**

| Stations | Type of Data | Period of Data | Latitude ($^o$) | Longitude ($^o$) | Elevation (m) |
|---|---|---|---|---|---|
| Dadhahu | Rainfall | 1996-2013 | 30$^o$ 36' N | 77$^o$ 26' E | 652 |
| Nahan | Rainfall | 1996-2013 | 30$^o$ 33' N | 77$^o$ 17' E | 909 |
| Naraingarh | Rainfall | 1996-2013 | 30$^o$ 28' N | 77$^o$ 07' E | 335 |
| Ambala | Rainfall | 1996-2013 | 30$^o$ 24' N | 76$^o$ 43' E | 271 |
| Shahabad | Rainfall | 1996-2013 | 30° 30' N | 77$^o$ 12' E | 263 |
| Jhansa | Rainfall and Stream Flow | 1996-2013 | 30° 07' N | 76$^o$ 44' E | 259 |
| Jansui | Rainfall and Stream Flow | 1996-2013 | 29° 35' N | 76$^o$ 32' E | 257 |
| Gulha | Rainfall | 1996-2013 | 30° 03' N | 76$^o$ 19' E | 245 |

**Source**: Compiled by Authors

**Table 2**
**Markanda Catchment: Year-wise Peak Discharges at the Outlet of Catchment (1996-2013)**

| Date | Peak Discharge ( $m^3$/s) |
|---|---|
| September 09, 1996 | 870.2 |
| August 03, 1997 | 4009.8 |
| July 13, 1998 | 2402.3 |
| August 31, 1999 | 1494.3 |
| September 09, 2000 | 3021.0 |
| August 15, 2001 | 2646.9 |
| August 14, 2002 | 1314.0 |
| September 09, 2003 | 1258.0 |
| August 17, 2004 | 1390.3 |
| July 07, 2005 | 2752.0 |
| July 27, 2006 | 2144.0 |
| August 15, 2007 | 233.8 |
| September 22, 2008 | 2225.8 |
| September 13, 2009 | 2631.9 |
| August 22, 2010 | 3243.9 |
| July 11, 2011 | 1205.0 |
| July 31, 2012 | 2134.0 |
| July 16, 2013 | 254.3 |

**Source:** Department of Irrigation, Government of Haryana, Panchkula the normal rainfall from its long term mean instead of standard deviation. Mathematically, it can be expressed as:

$$\text{Per cent departure from normal rainfall} = \left(\frac{Po - \text{long term mean of } P}{\text{Long term mean of } P}\right) \times 100$$

where, Po is the maximum/minimum observed rainfall in the catchment during a particular month/season/year and P is the long-term mean annual rainfall in the catchment during a particular month/season/year.

## Categorization of Rainfall Events

Based on India Meteorological Department (IMD) classification, rainfall events in the catchment were classified in different categories from very light rainfall to extremely heavy rainfall, depending on the amount of rainfall in a day. Daily rainfall 0.01 to 0.24 cm/day was considered as very light rain, 0.25 to 0.75 cm/day as light rain, 0.76 to 3.55 cm/day as moderate rain, 3.56 to 6.44 cm/day as rather heavy rainfall, 6.45 to 12.44 cm/day as heavy rain, 12.45 to 24.44 cm/day as very heavy rainfall and more than 24.44 cm/day as extremely heavy rainfall in the catchment.

## Estimation of Design Rainstorm Depth for Different Durations

From the daily rainfall recorded in the catchment, a design rainstorm depth for different durations was calculated by depth-duration method and depth-area-duration analysis. From the daily depths of storm rainfall, maximum depths of rainfall over the catchment for durations of, say, one-day, two-day, three-day etc. were derived for each storm. Maximum values of rainfall, thus obtained, were then plotted against different durations and for each storm a depth-duration curve was drawn. Subsequently, an envelope curve was drawn to obtain the maximum depths of rainfall for different durations such as one day, two day, three day etc. For depth-area-duration analysis, isohyets were drawn for rainstorms leading to major floods by interpolation between the rain gauge stations.

## Preparation of Maps Showing Rainstorms Distribution during Major floods

Geographical Information System (GIS) has been considered as an essential tool to analyse and estimate the character and distribution of rainfall during major flood events. Therefore, the point location of 8 rain gauge stations was geo-referenced in the GIS environment (ArcGIS 9.3) (Fig. 1). Subsequently, the raster map of rainfall distribution over the catchment during major floods was developed by inverse distance weighing (IDW) method, which is considered as a deterministic method for multivariate interpolations with a known scattered set of points. In this method, the assigned values to unknown points can be calculated with a weighted average of the values available at the known points. Apart from this, the method is based on the assumption that the nearby values contribute more to the interpolated values than distant observations. Another advantage of this method is that it is intuitive and efficient. Therefore, this method has been widely preferred and recognized as standard approach for surface interpolations based on scalar measurements at different points for studying the spatial and temporal distribution of rainfall.

## Results and Discussion

## Mean Monthly and Annual Rainfall

Table 3 demonstrates the mean monthly and annual values of rainfall for each rain gauge station in the Markanda catchment during 1996-2013. The major amounts of rainfall at all rain gauge stations in the catchment were experienced during the period of south-west monsoons (June to September). The highest

**Table 3**

**Markanda Catchment: Rain Gauge Station-wise, Mean Monthly and Annual Rainfall (cm), (1996-2013)**

| Months | Dadhahu | Nahan | Naraingarh | Ambala | Shahabad | Jhansa | Jansui | Gulha | Whole Catchment |
|---|---|---|---|---|---|---|---|---|---|
| January | 4.6 (3.6) | 3.9 (2.5) | 3.6 (2.6) | 2.1 (2.7) | 1.7 (2.7) | 1.5 (1.9) | 2.2 (2.9) | 1.4 (2.6) | 2.6 (2.7) |
| February | 6.0 (4.7) | 5.2 (3.4) | 4.8 (3.4) | 3.0 (3.9) | 2.8 (4.4) | 2.8 (3.7) | 3.3 (4.3) | 1.6 (3.1) | 3.7 (3.8) |
| March | 3.5 (2.8) | 4.0 (2.6) | 3.8(2.7) | 2.3(2.3) | 2.1 (3.3) | 2.0 (2.7) | 1.9 (2.4) | 1.4 (2.7) | 2.6 (2.7) |
| April | 2.8 (2.2) | 2.1 (1.4) | 1.6 (1.2) | 1.3 (1.6) | 1.2 (1.9) | 1.2 (1.6) | 1.4 (1.8) | 1.3 (2.4) | 1.6 (1.7) |
| May | 6.0 (4.7 | 4.1 (2.7) | 3.0 (2.2) | 2.8 (3.6) | 2.6 (4.1) | 3.1 (4.1) | 2.5 (3.2) | 2.3 (4.3) | 3.3 (3.4) |
| June | 18.2 (14.2) | 22.7 (14.8) | 18.6 (13.4) | 10.1 (13.2) | 7.9 (12.5) | 9.9 (13.1) | 9.9 (12.7) | 8.6 (16.3) | 13.2 (13.8) |
| July | 33.1 (25.8) | 41.8 (27.4) | 38.8 (27.8) | 22.1 (29.0) | 17.0 (26.9) | 18.1 (24.0) | 18.9 (24.2) | 10.2 (19.3) | 25.0 (26.1) |
| August | 33.3 (26.0) | 43.4 (28.4) | 38.7 (27.8) | 19.9 (26.1) | 16.2 (25.6) | 21.7 (28.7) | 22.6 (29.1) | 14.1 (26.6) | 26.2 (27.4) |
| September | 16.2 (12.7) | 19.1 (12.5) | 22.6 (16.2) | 10.3 (13.5) | 9.9 (15.6) | 11.6 (15.3) | 12.4 (15.9) | 9.9 (18.7) | 14.0 (14.6) |
| October | 2.1 (1.7) | 5.3 (3.5) | 2.3 (1.7) | 1.4 (1.8) | 1.1 (1.8) | 2.4 (3.2) | 1.4 (1.8) | 1.4 (2.7) | 2.2 (2.3) |
| November | 0.9 (0.7) | 0.4 (0.3) | 0.3 (0.2) | 0.2 (0.2) | 0.2 (0.2) | 0.4 (0.5) | 0.3 (0.4) | 0.1 (0.2) | 0.3 (0.4) |
| December | 1.2 (1.0) | 0.9 (0.6) | 1.2 (0.8) | 1.0 (1.3) | 0.6 (0.9) | 0.9 (1.2) | 1.0 (1.3) | 0.5 (1.0) | 0.9 (1.0) |
| Annual | 128.1 (100) | 152.8 (100) | 139.2 (100) | 76.2 (100) | 63.1 (100) | 75.5 (100) | 77.8 (100) | 52.9 (100) | 95.7 (100) |
| Annual CV (%) | 33.8 | 20.5 | 25.9 | 25.6 | 40.7 | 38.9 | 41.1 | 47.6 | 19.5 |
| June-September | 100.8 (78.7) | 126.9 (83.1) | 118.6 (85.2) | 62.3 (81.7) | 50.9 (80.7) | 61.2 (81.1) | 63.7 (81.9) | 42.8 (81.0) | 78.4 (81.9) |
| Highest Rainfall | 230.2 (2010) | 203.8 (2011) | 215.2 (2013) | 115.7 (1998) | 147.4 (1998) | 154.6 (2010) | 179.4 (2010) | 110.4 (1997) | 139.1 (2010) |
| Lowest Rainfall | 41.5 (2001) | 107.3 (2000) | 93.7 (2012) | 42.3 (2012) | 25.8 (2013) | 39.3 (2006) | 43.3 (2006) | 17.3 (2012) | 67.5 (2009) |

Figures in the parentheses in rows 1-13 and 15 indicate per cent rainfall and in last two rows the year.

**Source:** Compiled by Authors

amount of annual rainfall in the catchment was recorded during the month of August (27.4 per cent) followed by July (26.1 per cent), September (14.6 per cent) and June (13.8 per cent) months, contributing about 82 per cent of the total mean annual rainfall. The highest and lowest values of catchment rainfall for the four flood months of June to September along with their per cent departure from mean monthly rainfall have been given in Table 4.

The mean annual rainfall of the catchment is 95.7 cm (Fig. 2), which varies from about 153 cm at Nahan (rainiest) in upper reaches to about 53 cm (driest) at Gulha in the downstream reaches. The coefficient of variation (CV) of the annual rainfall is 19.5 per cent and it varies from 20.5 per cent (Nahan) to 47.6 per cent (Gulha) (Table 3). Similarly, inter-annual variability of annual rainfall totals is high among the rain gauge stations (Fig. 3). This high variability in annual rainfall totals may be due to local spatial variability of the convective storms. Amongst the rain gauge stations, Dadhahu recorded the highest annual rainfall of 230.2 cm in 2010, while Gulha had the lowest annual rainfall of 17.3 cm during the year 2012 (Table 3). The cumulative rainfall curves for each year's mean annual rainfall of the catchment from January to December months have been shown in Fig. 4. The study reveals that during the study period, 2010 was the year of maximum rainfall (139 cm), while 2009 was the year of minimum rainfall (67.5 cm) for Markanda catchment (Fig. 4). Besides, cumulative rainfall curves move upward rapidly after June due to onset of south-west monsoon winds over the catchment till the month of September and afterwards become constant representing the occurrence of minimum rainfall on account of retreating of south-west monsoon winds over the catchment. Apart from this, annual rainfall departure from mean for highest catchment rainfall occurring during the study period was observed to be about plus 45 per cent, while this departure from mean for lowest catchment rainfall was witnessed to be about minus 30 per cent (Table 4).

## Frequencies of Rainstorm events

South-west monsoons set in over the Markanda catchment in the last week of June and normally withdraw by the middle of September. Therefore, the frequencies of different range of rainstorms occurred during the months of June to September at different rain gauge stations in the catchment were examined for the study period and have been presented in Table 5. The analysis revealed that Naraingarh rain gauge station located in the foot of Siwalik Hills has the highest frequencies of heavy to extremely heavy rainstorms during

**Table 4**
**Markanda Catchment: Highest and Lowest Amount of Rainfall during June to September (1996-2013)**

| Month | Highest Catchment Rainfall (cm) | Departure from Mean Monthly/Annual Rainfall (per cent) | Lowest Catchment Rainfall (cm) | Departure from Mean Monthly/Annual Rainfall (per cent) |
|---|---|---|---|---|
| June | 28.5 (2011) | +115.9 | 1.2 (2012) | -90.9 |
| July | 49.9 (2010) | +99.6 | 5.7 (2004) | -77.2 |
| August | 49.9 (2004) | +90.5 | 12.2 (2000) | -53.4 |
| September | 27.3 (2010) | +95.0 | 1.1 (2001) | -92.1 |
| Annual | 139.1 (2010) | +45.4 | 67.5 (2009) | -29.5 |

**Source:** Compiled by Authors

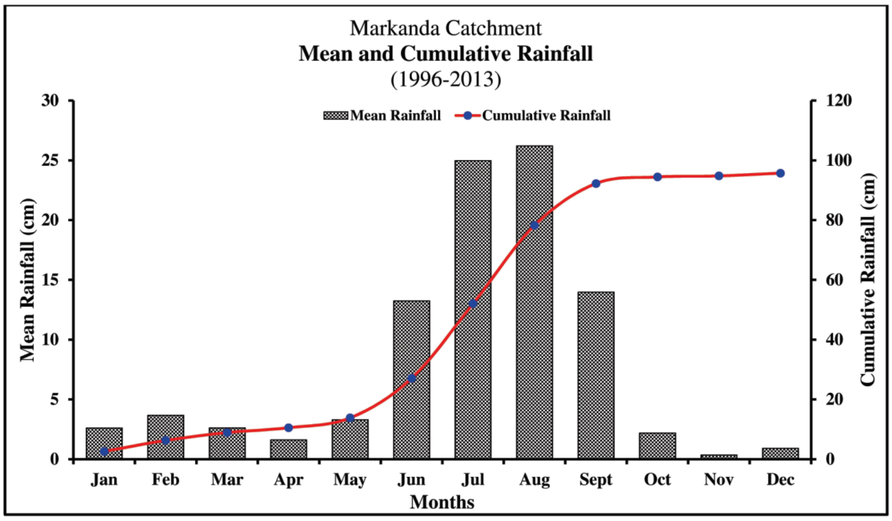

Fig. 2

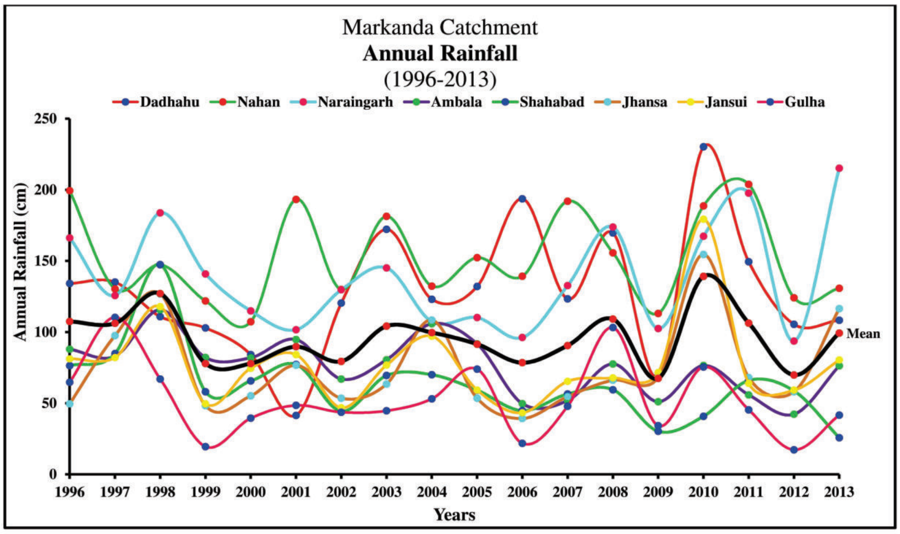

Fig. 3

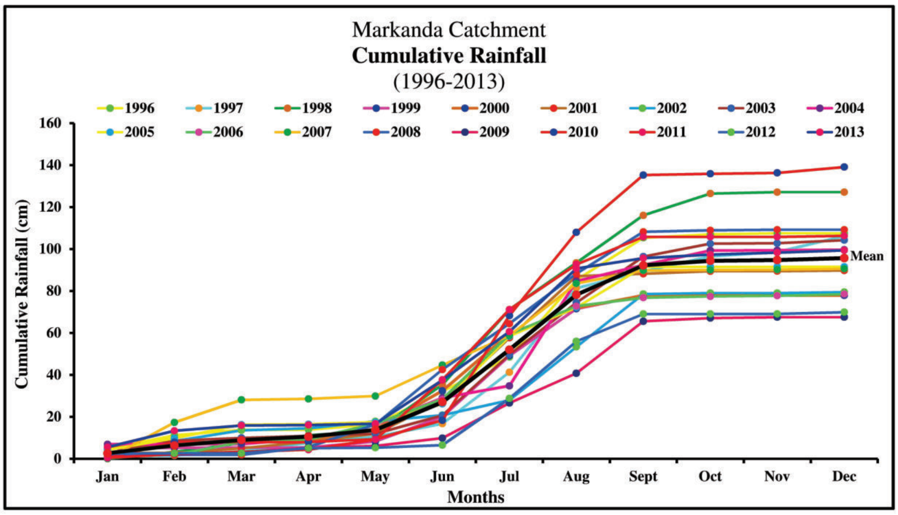

Fig. 4

the months of June, July, August and September. Among the remaining rain gauge stations, Nahan and Dadhahu have recorded the next higher frequencies pertaining to heavy, very heavy and extremely heavy rainstorms. Higher frequencies of heavy to extremely heavy rainstorms at Naraingarh, Nahan and Dadhahu can be attributed to abrupt lifting of moist monsoon winds of Arabian Sea branch over the Siwalik Hills. Table 5 also shows that the rain gauge stations such as Ambala, Shahabad, Jhansa, Jansui and Gulha located in south-western half of the catchment have witnessed lower frequencies of heavy to extremely heavy rainstorms as these stations are located in plains. However, it has been noticed that Jhansa and Jansui rain gauge stations in this half of the catchment received extremely heavy rains (>24.45 cm) only once in the year, in the month of July during the study period.

## Highest 24-hour Rainstorm Values

The highest 24-hour rainstorm recorded at each rain gauge station, inside the catchment, during the flood months of June to September, was picked up and has been given in Table 6. During the study period, the highest rainfall of 37.0 cm, occurred in 24 hours, in the Markanda catchment was recoded at Jansui rain gauge station on July 7, 2010. Similarly, the second highest rainfall (35.5 cm) was recorded on July 7, 2010 at Jhansa rain gauge station. These results reveal that rain in the catchment falls at a greater intensity during the month of July due to onset of south-west monsoon winds. The number of occasions of heavy rainfall of more than 5, 10 and 15 cm, in 24-hours, at each rain gauge station, for the study period, has been given in Table 6. Amongst the rain gauge stations, high intensities of rainfall of more than 5 cm and above in 24-hours are experienced at Naraingarh rain gauge station on 152 occasions in a period of less than 20 years followed by Nahan rain gauge station (129 occasions). High rainfall intensities at Naraingarh, inside the catchment, can be attributed to its location in the foot of Siwalik Hills (Fig.1).

## Flood Producing Rainstorms

Data referring to peak discharges at the outlet of the catchment, for the period 1996-2013, were computed and examined for further analysis. In this study, peak discharges exceeding 2000 $m^3/s$ were selected for analysis in relation to daily depth of storm rainfall. Table 7 highlights major peak floods in the catchment along with their dates of occurrence and the corresponding rainfall amounts received during rainstorms over the catchment. Similarly, Table 8 shows the total rainfall amount recorded at different rain gauge stations inside the catchment during these rainstorm periods. An examination of peak discharge data reveal that major floods in Markanda River generally occur in July, August and September months. It has been observed that major floods exceeding 2000 $m^3/s$ occurred four times in the month of July followed by thrice in August and twice in the month of September during the period 1996-2013. Peak floods were not noticed in the month of June, which is one of the principal rainy months of catchment after July, August and September months (Table 3).

## Rainstorms Causing Major Floods

Corresponding to each major flood occurrence during study period, daily rainfall data of all rain gauge stations in the catchment were examined to fix the length of rainstorms and subsequently, some typical total rainstorm isohyetal maps were prepared for depth-duration analysis (Fig. 5). The analysis reveals that maximum depth of rainfall over the

Table 5

**Markanda Catchment: Frequencies of Rainfall under Different Categories (*) during June to September (1996-2013)**

| Stations | Very Light Rain (0.01 - 0.24) (cm) | Light Rain (0.25 - 0.75) (cm) | Moderate Rain (0.76 - 3.55) (cm) | Rather Heavy (3.56 - 6.44) (cm) | Heavy Rain (6.45 - 12.44) (cm) | Very Heavy Rain (12.45 - 24.44) (cm) | Extremely Heavy Rain (>24.45) (cm) |
|---|---|---|---|---|---|---|---|
| **June** | | | | | | | |
| Dadhahu | 28 | 21 | 95 | 19 | 5 | 2 | 0 |
| Nahan | 35 | 38 | 90 | 16 | 11 | 3 | 0 |
| Naraingarh | 2 | 26 | 40 | 15 | 18 | 1 | 0 |
| Ambala | 17 | 34 | 59 | 10 | 1 | 0 | 0 |
| Shahabad | 8 | 30 | 53 | 2 | 2 | 0 | 0 |
| Jhansa | 16 | 35 | 43 | 11 | 4 | 0 | 0 |
| Jansui | 16 | 22 | 41 | 15 | 3 | 0 | 0 |
| Gulha | 5 | 9 | 34 | 7 | 5 | 1 | 0 |
| **Total** | **127** | **215** | **455** | **95** | **49** | **7** | **0** |
| **July** | | | | | | | |
| Dadhahu | 22 | 37 | 116 | 30 | 22 | 1 | 0 |
| Nahan | 63 | 59 | 135 | 42 | 23 | 4 | 0 |
| Naraingarh | 25 | 46 | 79 | 27 | 31 | 7 | 0 |
| Ambala | 29 | 42 | 76 | 26 | 12 | 1 | 0 |
| Shahabad | 15 | 39 | 58 | 13 | 9 | 3 | 0 |
| Jhansa | 22 | 40 | 70 | 11 | 6 | 2 | 1 |
| Jansui | 16 | 34 | 66 | 16 | 6 | 2 | 1 |
| Gulha | 9 | 23 | 42 | 17 | 1 | 0 | 0 |
| **Total** | **201** | **320** | **642** | **182** | **110** | **20** | **2** |
| **August** | | | | | | | |
| Dadhahu | 25 | 42 | 119 | 28 | 25 | 2 | 0 |
| Nahan | 68 | 66 | 157 | 34 | 21 | 4 | 1 |
| Naraingarh | 19 | 49 | 104 | 28 | 27 | 7 | 0 |
| Ambala | 24 | 55 | 78 | 18 | 7 | 2 | 0 |
| Shahabad | 28 | 51 | 70 | 11 | 9 | 0 | 0 |
| Jhansa | 34 | 37 | 84 | 20 | 10 | 2 | 0 |
| Jansui | 20 | 41 | 84 | 11 | 12 | 4 | 0 |
| Gulha | 10 | 20 | 50 | 16 | 4 | 3 | 0 |
| **Total** | **228** | **361** | **746** | **166** | **115** | **24** | **1** |
| **September** | | | | | | | |
| Dadhahu | 8 | 20 | 58 | 13 | 10 | 2 | 0 |
| Nahan | 40 | 38 | 61 | 19 | 12 | 1 | 0 |
| Naraingarh | 14 | 25 | 51 | 17 | 13 | 7 | 0 |
| Ambala | 28 | 23 | 45 | 8 | 7 | 0 | 0 |
| Shahabad | 11 | 25 | 42 | 8 | 5 | 0 | 0 |
| Jhansa | 12 | 26 | 36 | 16 | 5 | 1 | 0 |
| Jansui | 10 | 24 | 37 | 13 | 6 | 2 | 0 |
| Gulha | 10 | 18 | 26 | 9 | 6 | 2 | 0 |
| **Total** | **133** | **199** | **356** | **103** | **64** | **15** | **0** |

*Categories of rainfall frequency are based on IMD Classification

**Source:** Compiled by Authors

**Table 6**

**Markanda Catchment: Rain Gauge Station-wise Highest 24-Hour Rainfall Recorded during June to September (1996-2013)**

| Stations | June | | July | | August | | September | | Annual | | Rainfall Frequency | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Highest Rainfall (cm) | Date | Highest Rainfall (cm) | Date | Highest Rainfall (cm) | Date | Highest Rainfall (cm) | Date | Highest Rainfall (cm) | Date | 5 cm and above | 10 cm and above | 15 cm and above |
| Dadhahu | 17.0 | 12.06.2008 | 13.7 | 30.07.2008 | 15.4 | 13.08.2002 | 14.7 | 04.09.2010 | 17.0 | 12.06.2008 | 101 | 14 | 02 |
| Nahan | **21.0** | **29.06.2011** | 17.8 | 17.07.2010 | **25.8** | **09.08.2001** | 20.4 | 03.09.2003 | 25.8 | 09.08.2001 | 102 | 19 | 08 |
| Naraingarh | 17.3 | 29.06.1998 | 17.4 | 24.07.2011 | 16.0 | 01.08.2003 | 19.5 | 12.09.2012 | 19.5 | 12.09.2012 | 107 | 31 | 14 |
| Ambala | 8.3 | 08.06.2000 | 20.7 | 16.07.2001 | 23.9 | 04.08.2004 | 8.1 | 22.09.1998 | 23.9 | 04.08.2004 | 43 | 04 | 02 |
| Shahabad | 8.8 | 29.06.1998 | 15.7 | 10.07.1998 | 12.0 | 03.08.2004 | 10.6 | 16.09.2002 | 15.7 | 10.07.1998 | 30 | 08 | 02 |
| Jhansa | 8.3 | 30.06.1998 | 35.5 | 07.07.2010 | 16.2 | 03.08.1997 | 12.6 | 20.09.2008 | 35.5 | 07.07.2010 | 46 | 06 | 04 |
| Jansui | 11.4 | 29.06.1998 | **37.0** | **07.07.2010** | 21.2 | 04.08.2004 | 16.0 | 20.09.2008 | 37.0 | 07.07.2010 | 39 | 13 | 05 |
| Gulha | 17.0 | 08.06.2000 | 8.1 | 24.07.2010 | 16.4 | 27.08.1997 | 16.6 | 20.09.2008 | 17.0 | 08.06.2000 | 31 | 03 | 03 |

**Source:** Compiled by Authors

## Table 7

## Markanda Catchment: Peak Discharge and Daily Rainfall Depth during Storm Spells (1996-2013)

| Storm Spells | Peak Discharge ($m^3$/s) | Date | Daily Rainfall Depth during Storm Spells (cm) | | | | | | | | Total Storm Spell Rainfall (cm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1st Day | 2nd Day | 3rd Day | 4th Day | 5th Day | 6th Day | 7th Day | 8th Day | |
| July 28-August 3, 1997 | 4009.81 | August 03 | 1.5 | 0.5 | 1.5 | 3.9 | 4.1 | 6.0 | 9.1 | - | 26.6 |
| July 6-13, 1998 | 2402.25 | July 13 | 2.5 | 3.2 | 1.9 | 3.9 | 4.9 | 4.0 | 1.0 | 0.1 | 21.5 |
| August 9-15, 2001 | 2646.86 | August 15 | 7.0 | 1.4 | 1.3 | 0.6 | 2.0 | 8.5 | 3.8 | - | 24.6 |
| July 4-7, 2005 | 2751.99 | July 07 | 1.7 | 6.2 | 4.6 | 1.8 | - | - | - | - | 14.4 |
| July 22-27, 2006 | 2143.95 | July 27 | 1.1 | 1.2 | 0.4 | 2.1 | 5.4 | 3.3 | - | - | 13.6 |
| September 18-22, 2008 | 2225.83 | September 22 | 0.8 | 3.1 | 10.2 | 3.8 | 0.4 | - | - | - | 18.4 |
| September 9-13, 2009 | 2631.88 | September 13 | 2.4 | 4.5 | 7.8 | 5.1 | 0.4 | - | - | - | 20.2 |
| August 16 -22, 2010 | 3243.92 | August 22 | 5.3 | 3.7 | 4.7 | 4.6 | 1.5 | 3.6 | 1.2 | - | 24.6 |
| July 25-31, 2012 | 2133.97 | July 31 | 2.2 | 1.9 | 1.1 | 3.6 | 0.0 | 2.8 | 0.6 | - | 12.3 |

**Source**: Compiled by Authors

### Table 8
### Markanda Catchment: Amount of Rainfall Received at Rain Gauge Stations during Peak Discharges (1996-2013)

| Peak Flood Date at the outlet of the Markanda Catchment | Storm Spells | Total Rainfall Recorded at Rain Gauge Stations inside the Markanda Catchment during the Storm Spells (cm) |
|---|---|---|
| August 3, 1997 | July 28 to 3 August | Dadhahu (36.6), Nahan (22.0), Naraingarh (21.66), Ambala (22.7), Shahabad (19.4), Jhansa (22.3), Jansui (27.5), Gulha (30.2) |
| July 13, 1998 | 6 to 13 July | Dadhahu (19.5), Nahan (20.3), Naraingarh (22.5), Ambala (23.6), Shahabad (32.3), Jhansa (27.0), Jansui (25.5), Gulha (1.6) |
| August 15, 2001 | 9 to 15 August | Dadhahu (5.6), Nahan (54.7), Naraingarh (24.9), Ambala (17.3), Shahabad (23.3), Jhansa (22.6), Jansui (34.6), Gulha (13.9) |
| July 7, 2005 | 4 to 7 July | Dadhahu (15.1), Nahan (23.7), Naraingarh (17.7), Ambala (16.6), Shahabad (8.8), Jhansa (6.3), Jansui (15.5), Gulha (14.4) |
| July 27, 2006 | 22 to 27 July | Dadhahu (12.0), Nahan (8.0), Naraingarh (20.3), Ambala (11.6), Shahabad (12.0), Jhansa (14.6), Jansui (14.7), Gulha (6.1) |
| September 22, 2008 | 17 to 22 September | Dadhahu (22.0), Nahan (15.6), Naraingarh (21.8), Ambala (11.4), Shahabad (13.1), Jhansa (17.5), Jansui (19.1), Gulha (26.3) |
| September 13, 2009 | 8 to 13 September | Dadhahu (24.8), Nahan (25.9), Naraingarh (39.6), Ambala (16.8), Shahabad (8.6), Jhansa (19.3), Jansui (21.5), Gulha (5.4) |
| August 22, 2010 | 16 to 22 August | Dadhahu (41.5), Nahan (35.4), Naraingarh (35.4), Ambala (7.1), Shahabad (7.9), Jhansa (28.4), Jansui (30.4), Gulha (10.5) |
| July 31, 2012 | 25 to 31 July | Dadhahu (21.4), Nahan (26.4), Naraingarh (16.8), Ambala (7.7), Shahabad (8.5), Jhansa (6.2), Jansui (13.7), Gulha (6.4) |

Source: Compiled by Authors

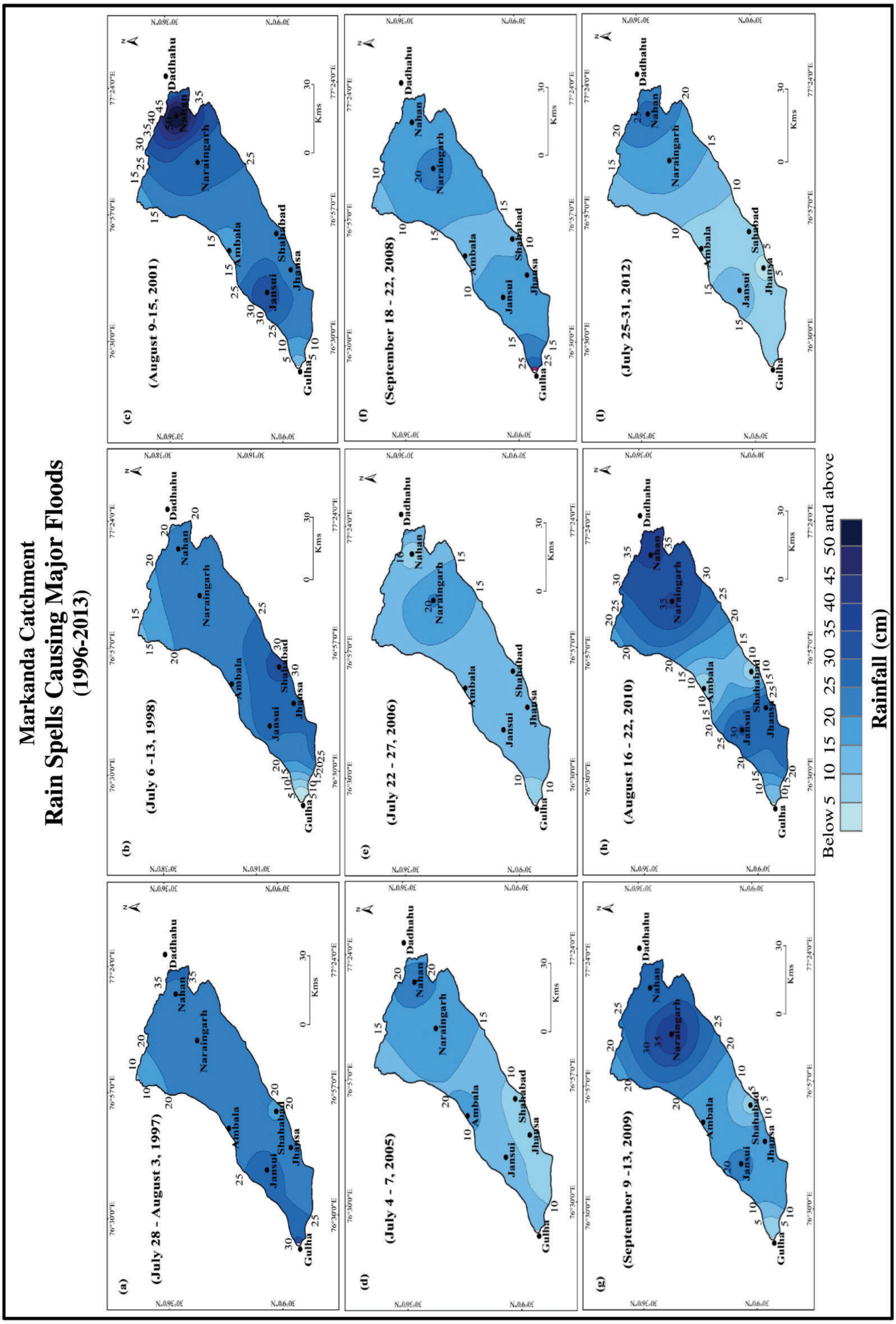
Markanda Catchment
Rain Spells Causing Major Floods
(1996-2013)
(a) (July 28 - August 3, 1997)
(b) (July 6 -13, 1998)
(c) (August 9-15, 2001)
(d) (July 4 - 7, 2005)
(e) (July 22 - 27, 2006)
(f) (September 18 - 22, 2008)
(g) (September 9 -13, 2009)
(h) (August 16 - 22, 2010)
(i) (July 25-31, 2012)
Dadhahu
Nahan
Naraingarh
Ambala
Shahabad
Jansui
Jhansa
Gulha
N
0 30 Kms
76°30'0"E
76°57'0"E
77°24'0"E
30°9'0"N
30°36'0"N
Rainfall (cm)
Below 5 10 15 20 25 30 35 40 45 50 and above

Fig. 5

catchment recorded during the rainstorm occurred in month of July-August 1997 when the catchment received about 26.6 cm of rain during a period of seven days. This rainstorm produced a record peak discharge in the catchment amounting to about 4000 $m^3/s$ at the outlet. In other words, during the seven days rainstorm period, the catchment received a total rainfall amount more than the amount of mean monthly rainfall for both July and August months, respectively. In this storm, the heaviest concentration of rainfall was witnessed on seventh, sixth, fifth and fourth day of the storm. Rainstorms of August 2001, 2010, July 1998 and September 2009 are also worth mentioning as the catchment received high concentrated rainfall during these rainstorms (Table 7). The high concentration of rainfall during August 2001 was witnessed on sixth, fifth and seventh day, thereby generating a peak discharge of about 2650 $m^3/s$ on seventh day of the storm. Similarly, the heavy concentration of rainfall during August 2010 occurred on first, third, second, fourth and sixth day, thereby producing a peak discharge of 3240 $m^3/s$ on seventh day. Apart from this, it has been observed that majority of the flood producing rainstorms affecting the catchment has been of 7-day duration.

## Depth-Duration Curves based Design Rainstorm Depths

On the basis of analysis of major rainstorms, an attempt has also been made to find out the design rainstorm depths for different durations by depth-duration method. From the daily depths of storm rainfall highlighted in Table 7, maximum depths of rainfall over the catchment for durations of one day, two day etc. were derived for each rainstorm. Maximum values of rainfall, thus obtained, were plotted against different durations and for each rainstorm depth-duration curves were drawn (Fig. 6). It is evident from the analysis that 1997 depth-duration curve shows the maximum depth of rainfall for different durations. Further, an envelope curve was drawn above all the other depth-duration curves. Subsequently, the maximum depths of rainfall for different durations such as one day, two day, three day etc. have been obtained from the drawn envelope curve for Markanda catchment as one-day (7.0 cm), two-day (12.0 cm), three-day

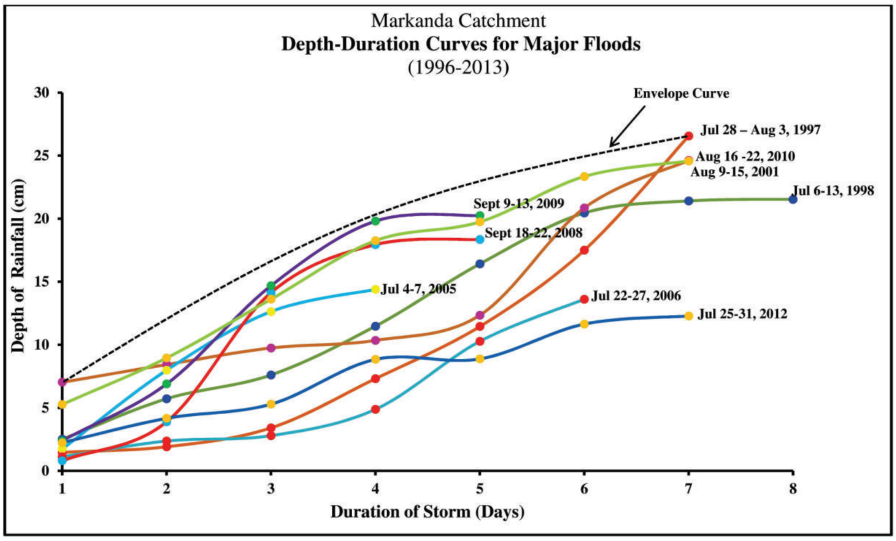

Fig. 6

(16.5 cm), four-day (20.5 cm), five-day (23.0 cm), six-day (25.5 cm) and seven-day (26.6 cm). These rainstorm values give the design depths of rainfall for the catchment up to the outlet. These values of design depths for the catchment are based on the analysis of rainstorms corresponding to peak discharges data exceeding 2000 $m^3/s$ for the period 1996-2013. It is most likely that higher design depths may be obtained for the catchment if rainstorms of earlier years are also examined.

## Depth-Area-Duration Analysis based Design Rainstorm Depths

In this study, depth-area-duration analysis of a rainstorm in the catchment has been carried out to quantify rainfall depth falling under a specified duration such as one-day, two-day, three-day, and so on. Taking the storm occurred on 28 July to 3 August, 1997 into account, depth-area-duration analysis was carried out and following design rainstorm depths for the catchment were obtained, say, one-day 3.0 cm, two-day 0.5 cm, three-day 1.4 cm, four-day 3.6 cm, five-day 3.7 cm, six-day 7.0 cm and seven-day 6.7 cm. While comparing these depths of rainfall with the actual rainfall depth received over the catchment for 28 July-3 August, 1997 storm, it has been found that rainfall depth obtained by the depth-area-duration method give very similar values of rainfall, which are perhaps very likely to occur, over the catchment. It appears from the analysis that application of depth-area-duration analysis can be applied to Markanda catchment, as this method gives judicious design depths of rainfall, as most of the rain gauge stations are located in plain area. Therefore, for depth design purposes, one can adopt the design rainstorm depths obtained by depth-area-duration analysis.

## Conclusions

From the forgoing analysis, following conclusions can be drawn:

- Mean annual rainfall of whole Markanda catchment is about 95.7 cm. Monsoon (June to September) rainfall of the catchment is about 82 per cent of the annual rainfall. The percentage departure of the maximum and minimum value from the mean annual are of the order of plus 45 and minus 30 per cent, respectively.
- South-western parts of the catchment receive comparatively less rainfall than the north-eastern parts located in the Siwalik Hills.
- The major flood producing month in the catchment is July, followed by August and September. Peak floods have never been noticed in the month of June. Thus, floods in this catchment are caused by monsoonal depressions prevailing over north-western parts of India.
- Rainfall analysis of major flood producing rainstorms, during the years 1996-2013, has shown that rainstorm occurred on 28 July-3August, 1997 caused maximum depths of the rainfall over the catchment. These depths, after drawing envelope curves and depth-area-duration analysis, may be taken as design depths of rainfall for estimation of design floods. However, high design depths should be obtained for the catchment by analysing rainfall data for a longer period e.g., 35 years or more.
- Finally, the upper part of the catchment is a hilly region, therefore, depth-area-duration analysis and transposition (envelope curve) method may not give correct design storm depths of rainfall for various durations in the catchment.

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**Dinesh Kumar**, Research Scholar,

**Dr. Omvir Singh**, Professor,
Email: ovshome@gmail.com
(Author for Correspondence)
Department of Geography,
Kurukshetra University,
Kurukshetra, Haryana.

# punjab geographer