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Rainfall distribution in Yamuna catchment and quantitative estimation of heavy rainfall in related synoptic situations

Y. M. DUGGAL, H. S. SAGAR and A. K. MITTAL
Flood Meteorological Office, New Delhi
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सार — 1 जून से 15 अक्टूबर तक बाढ़ परिचालन अवधि के लिए जलग्रहण क्षेत्र पर विभिन्न शृंखलाओं में वर्षा के सही वितरण को समझने का प्रयास करने के लिए 1976 से 1990 तक की अवधि के लिए अपने मूल उद्गम से दिल्ली तक यमुना जलग्रहण पर वर्षा का अध्ययन किया गया। सिनॉप्टिक संरचना के लिए जल ग्रहण क्षेत्र में भारी वर्षा की गतिविधि के लिए सम्बद्ध सिनॉप्टिक स्थितियों का अध्ययन किया गया। आर्द्रता वहन के आकलन से जलग्रहण क्षेत्र में औसत समवर्षण वर्षा के आकलन के लिए सिनॉप्टिक आनुभविक आरेखों को व्यक्त किया गया है।

ABSTRACT. A study of rainfall over Yamuna catchment from its origin upto Delhi for the period from 1976 to 1990 is made with an attempt to understand the fine distribution of rainfall in different ranges over the catchment for the flood operational period from 1 June to 15 October. The study of associated synoptic situations for heavy rainfall activity in the catchment is made for synoptic typing. Synoptic empirical diagrams have been developed for estimation of average isohyetal rainfall over the catchment from estimation of moisture transport.

Key words — Synoptic empirical diagrams, Semi quantitative precipitation forecast

1. Introduction

The knowledge of seasonal and monthwise distribution of rainfall in different ranges is considered useful in understanding the basin hydrometeorology of river catchments. This helps in issuing and improving the routine semi-quantitative precipitation forecasts for different segments of the catchment and also acts as a climatological tool for issue of quantitative precipitation forecast if the intensity of rainfall distribution is related to the synoptic situation. With the above in view an attempt has been made to study the rainfall distribution over Yamuna catchment from its origin up to Delhi during the monsoon period June to October (1 June to 15 October) for the last fifteen years, *i.e.*, from 1976 to 1990 under different synoptic situations. The results of the study are presented in this paper.

The *Yamuna* from its origin (Yamnotri) to Delhi can be divided into two segments, *i.e.*, upper catchment consisting of hills of Himachal Pradesh and west Uttar Pradesh up to Kalanaur and the lower catchment from Kalanaur to Delhi railway bridge consisting of plains of west Uttar Pradesh and Haryana. The catchment is fan-shaped being wider in the upper cachment and narrow in the lower catchment. The hills of upper catchment rise up to 20,000 ft and the area of the upper catchment (12,672 sq km) is almost double the area of the lower catchment (6,963 sq km) (Johri and Veeraraghavan 1976). The orientation of the upper catchment is NE-SW whereas the orientation of the lower catchment is N-S. The orography, the shape of the catchment area and the orientation of upper and lower catchments are seen to have profound affect on rainfall distribution within the catchment when the relative position/orientation of monsoon axis and position and depth of low pressure system are considered in relation to the river catchments.

2. Data

The daily rainfall data received at the Flood Meteorological Office, Safdarjung during the 15 years period from 1976 to 1990 from 1 June to 15 October each year from the raingauge stations in the upper and lower catchments of *Yamuna* river is utilised for this study. On days of generally widespread and heavy precipitation over two catchments, synoptic charts are studied and the synoptic situations responsible for this precipitation noted down. The arithmatic or isohyetal averages are worked out for each rainfall distribution up to 2.5 cm of rainfall whereas only isohyetal averages are used for rainfall distribution greater than 2.5 cm for upper as well as for lower catchments. For 03 GMT rainfall report of the day, the synoptic situation of the previous day is taken into consideration.

3. Analysis

3.1. *Seasonal rainfall frequencies*

Rainfall distribution of each day for the available rainfall data from the State raingauge stations in the upper and lower catchments during the flood operational period is plotted and the arithmatic and isohyetal averages worked out for each catchment separately. The

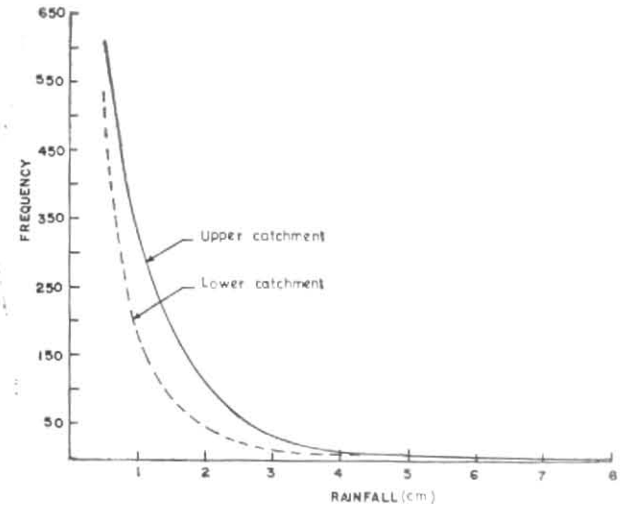
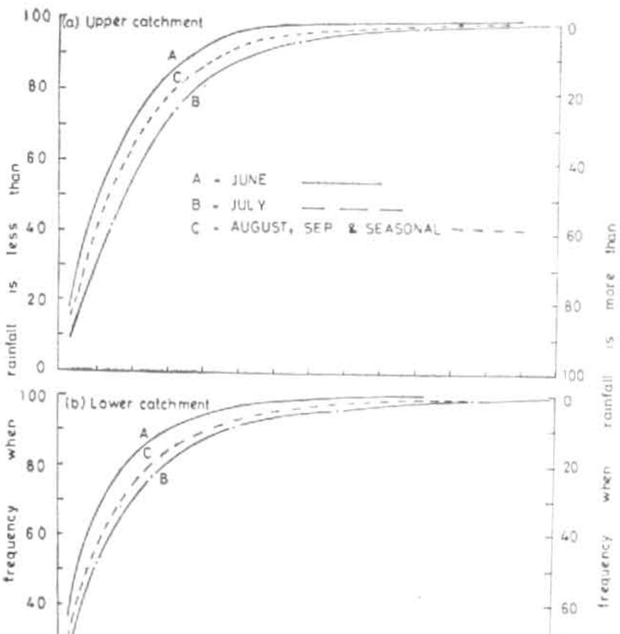


Fig. 1. Seasonal frequency variation *vs* rainfall amount



Figs. 2(a&b). Cumulative frequency (ogive) diagrams of seasonal & monthly rainfall over (a) upper & (b) lower Yamuna catchment

frequencies of worked out averages are grouped in four ranges, *i.e.*, from (*i*) 0.1 to 1.0 cm, (*ii*) 1.1-2.5 cm, (*iii*) 2.6-5.0 cm and (*iv*) greater than 5.0 cm for each catchment since the quantitative precipitation forecast is issued in the above ranges as per the prevalent hydrometeorologcial practice for Yamuna catchment. Data for rainfall less than 0.1 cm is not taken into consideration. The frequency of various ranges of

TABLE 1

Frequency of various ranges of precipitation (cm) in upper Yamuna catchment (UC) and lower Yamuna catchment (LC) (1976-90)

Year	0.1 to 1.0		1.1 to 2.5		2.6 to 5.0		>5.0		Total	
	UC	LC	UC	LC	UC	LC	UC	LC	UC	LC
1976	50	42	27	14	1	6	3	1	81	63
1977	59	54	28	18	14	3	1	1	102	76
1978	55	65	31	12	12	6	6	3	104	86
1979	46	36	25	11	—	—	—	1	71	48
1980	53	42	28	13	3	9	2	1	86	65
1981	56	33	22	11	2	3	—	—	80	47
1082	50	37	18	12	3	3	—	—	71	52
1983	66	45	28	17	3	4	1	1	98	67
1984	81	67	17	8	1	2	—	—	99	77
1985	72	62	31	16	2	1	1	—	106	79
1986	72	45	15	12	4	1	—	—	91	58
1987	50	27	14	1	—	2	—	—	64	30
1988	41	41	36	16	13	9	2	3	92	69
1989	70	45	15	7	4	1	3	—	92	53
1990	71	66	31	9	4	3	—	1	106	79
%	66.4	74.5	27.3	18.7	4.9	5.6	1.4	1.2	100	100

precipitation (cm) in upper catchment and lower catchment 1976 to 1990 is shown in Table 1.

3.2. *Monthly rainfall frequencies*

Rainfall distributions frequencies for different months of the season for different quantitative precipitation forecast ranges is later worked out separately for upper and lower catchment and the results are tabulated in Table 2.

3.3. *Seasonal fine spectrum of frequencies*

An attempt is also made to study the seasonal fine spectrum distribution of rainfall at an interval of 0.5 cm range and the results are presented in Fig. 1.

3.4. *Cumulative frequency diagrams*

Ogives are constructed for the upper catchment and lower catchment and are presented diagramatically in Figs. 2 (a & b) respectively.

3.5. *Synoptic features*

Since heavy generally widespread rainfall cases are of great importance for flood forecasting, an attempt is made in the first instance to isolate cases of heavy rainfall distribution for which isohyetal average of greater than 5.0 cm is realised for upper as well as lower catchment separately. These cases are studied with respect to the prevailing synoptic parameter of the previous day in order to find out the factors which could be correlated for generally heavy widespread precipitation in the catchments. The results are presented in succeeding paragraphs.

3.6. *Moisture transport*

Though physical processes involved in the phenomena of rainfall are complex, the moisture transport and the vertical fields in the system are the fundamental parametres for estimation of rainfall. A given value of moisture influx may give rise to realisation of different rainfall amounts under different values of convergence/vorticity field and may also depend upon the location/distance of maximum convergence zone from the catchment area. An attempt is made to calculate and correlate the magnitude of resultant average moisture transport over Delhi associated with the synoptic systems of different depths with the cases of heavy rainfall in the Yamuna catchment. The moisture is computed for unit length per unit thickness up to 700 mb (hPa) by considering two slabs, *i.e.,* from surface to 850 (hPa) and from 850 (hPa) to 700 (hPa) level as per Ghosh *et al.* (1978, 1985). The moisture transport so calculated is related to the realised average isohyetal rainfall amount graphically for different depths of the systems. These graphs are drawn for Yamuna catchment as a whole, for upper and lower Yamuna catchment.

4. Discussion

4.1.1. *Statistical analysis*

From the statistical scrutiny of the data, it is observed that of the total seasonal rainfall events in the Yamuna catchment, 70% events are experienced in the rainfall range from 0.1 to 1.0 cm, 24% in the range from 1.1 to 2.5 cm, 5% in the range from 2.6 to 5.0 cm and 1% only in the rainfall range greater than 5.0 cm.

Catchmentwise, the seasonal rainfall events in the upper catchment (59%) are slightly higher than those in the lower catchment (41%) indicating that the orography of the upper catchment plays an important role in the rainfall activity of the catchment. Lower catchment frequency is 71% of the upper catchment.

4.1.2. Rangewise difference in upper and lower catchments are observed only up to 2.5 cm range. Upper catchment gets 66%, 28%, 5% and 1% in the range from 0.1 to 1.0 cm, 1.1 to 2.5 cm, 2 6 to 5.0 cm and greater than 5.0 cm respectively whereas lower catchment gets 74%, 19%, 6% and 1% of the rainfall events respectively.

4.1.3. Monthly spectrum of distribution of rainfall events from June to October give percentage frequencies as 13, 32, 20 and 3 respectively for the upper catchment whereas for the lower catchment it is 12, 35, 33, 17 and 3 per cent respectively indicating that July and August are the rainiest months.

4.1.4. Monthwise and rangewise study of rainfall events also show that in general lower catchment gets less rainfall events as compared to upper catchment up to average rainfall of 2.5 cm. The difference is considerably reduced for higher rainfall amounts.

4.1.5. Highest frequencies are observed for low rainfall amounts. The curves drawn for the seasonal frequencies/monthly frequencies of rainfall against rainfall amounts show exponential decrease of rainfall events with increasing rainfall amounts.

Monthly rainfall frequencies from highest to lowest are in the order for the months of July, August, September, June and October. Further frequencies for July and August are very close to each other as well as of June and September. For lower catchment the frequencies are in general lower than for upper catchment, but are comparable for amounts greater than 5.0 cm.

4.1.6. In order to find out rainfall frequencies above or below certain average rainfall amount, seasonal and monthly cumulative frequency diagrams are constructed. They show that the mean seasonal frequencies for August and September coincide whereas for June and July are farthest apart. These diagrams are useful for determining the rainfall events above/below a given rainfall value for lower rainfall amounts. For higher amounts they merge with each other as the frequencies are very small.

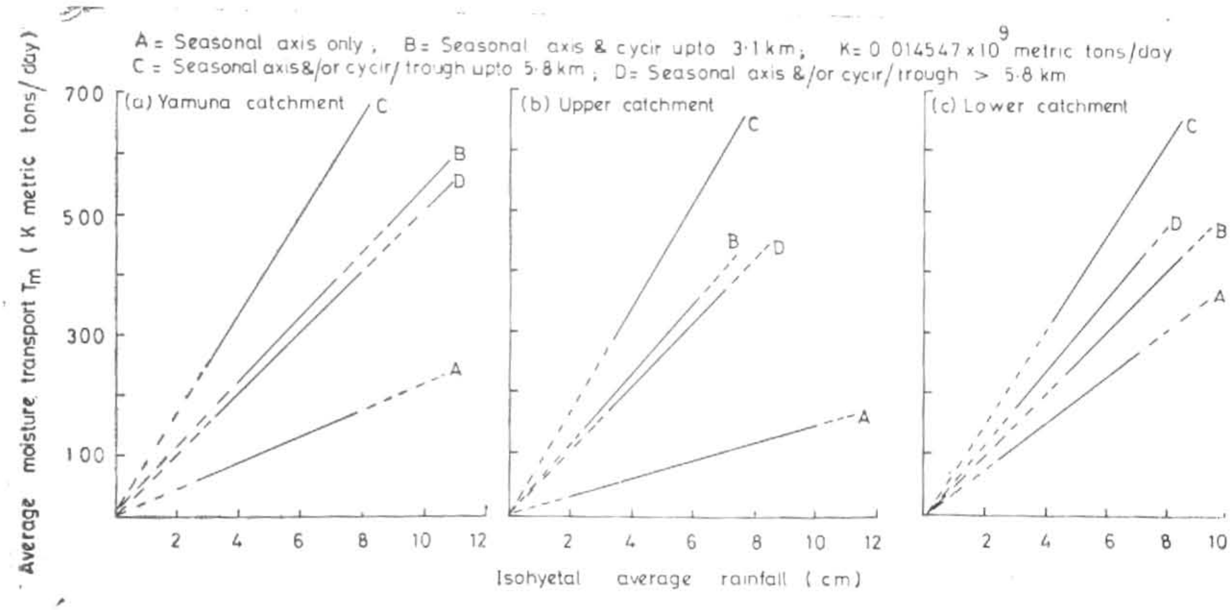
4.2.1. *Synoptic analysis*

The identification and generalisation of synoptic features responsible for widespread and heavy rainfall in the catchment is a complex process. It is observed that the same type of systems give different rainfall intensity distribution in the catchment depending upon their location, depth and moisture feed. Rainfall distribution also differs with the month of the season. The synoptic features responsible for generally heavy widespread precipitation are identified and are broadly classified into four groups, *i.e.,* (a) seasonal monsoon axis, (b) low pressure systems with upper air cyclonic circulation (CYCIR) and/or trough, (c) troughs in the westerlies, and (d) any combination of above synoptic features, *i.e.,* a, b and c.

Taking above synoptic situations into consideration, the heavy rainfall cases which give fairly widespread distribution of greater than 5.0 cm isohyetal average were isolated from the data for the period 1976 to 1990. There are total of 25 such cases and their synopsis is given in Table 3. Monthwise 10 cases were detected in July, 8 in August, 6 in September and 1 in October.

4.2.2. *Monsoon axis*

It is observed that the position/orientation of the monsoon axis plays an important role for generalisation of synoptic situations responsible for heavy widespread rainfall in the catchment. The position of axis, *i.e.,* north of Delhi, over Delhi, south of Delhi or west of Delhi can be categorised alongwith the steepness of its orientation or the degree of tilt in the north-south direction to determine the intensity of precipitation over the catchment. Steep north-south orientation, *i.e.,* the higher degree of tilt in the north-south direction brings the monsoon axis in greater alignment to the catchment axis which is geographically oriented north-south and thus brings larger areas of convergence zone over the catchment. In the absence of any other low pressure system/CYCIR etc., when there is a well marked seasonal low with active and steep monsoon axis like the one running from Jammu to Delhi, the lower catchment becomes parallel to it giving rise to fairly widespread heavy rainfall activity in the lower catchment. When the position of monsoon axis crossing the catchment is midway north of Delhi with a well marked seasonal low and/or upper air trough running from north Pakistan to Rajasthan, it gives heavy rainfall



Figs. 3(a-c). Moisture transport over Delhi & areal rainfall depth over Yamuna catchments in different synoptic situations

TABLE 2

Monthly distribution of various ranges of rainfall
(Upper and lower Yamuna catchment)
(1976-1990)

Ranges	Jun		Jul		Aug		Sep		Oct		Total	
	UC	LC	UC	LC	UC	LC	UC	LC	UC	LC	UC	LC
0.1-1.0 cm	130	96	236	241	274	224	213	127	39	19	892	707
1.1-2.5 cm	39	15	152	69	122	68	48	21	5	4	366	177
2.6-5.0 cm	4	3	30	21	25	20	7	9	—	—	66	53
⩾5.0 cm	—	—	7	5	6	3	5	4	1	—	19	12
%	12.9	12.0	31.6	35.4	31.2	33.2	20.3	17.0	3.4	2.4	100	100

UC — Upper catchment, LC — Lower catchment.

TABLE 3

Synopsis of heavy rainfall cases of amount greater than 5.0 cm isohyetal average
(1976-1990)

Position of monsoon axis	Orientation of monsoon axis	Prominent synoptic features	No. of cases	
			Upper catchment	Lower catchment
Over Delhi	Steep and active	LOPAR, CYCIR near catchment	5	2
	Do.	Well marked seasonal low	—	2
South of Delhi	Flat	LOPAR with deep CYCIR south of Delhi within 100-150 km	3	4
	Do.	LOPAR with CYCIR over north-east west Rajasthan, Haryana or west Uttar Pradesh	4	—
North of Delhi	Flat but active	Axis crossing mid way catchment north of Delhi with LOPAR CYCIR over north Rajasthan	3	—
	Steep and active	No proiminent system near catchment	—	2
West of Delhi	Steep and active	Deep north-south trough in low level westerlies from Gujarat to Punjab. Also trough in mid-tropospheric westerlies along70°E, north of 25° N	4	2

TABLE 4

Observed and estimated rainfall depths — Isohyetal average from nomograms (cm)

Depth (System)	AV moisture transport (*k* metric tons/day)	Upper catchment			Lower catchment			Whole catchment		
		Obs	Est	Res	Obs	Est	Res	Obs	Est	Res
Shallow near	70	5.8	4.7	—1.1	1.1	1.7	+0.6	4.1	3.3	—0.8
Surface	77	5.2	5.1	—0.1	2.0	1.0	—1.9	3.4	3.5	+0.1
Seasonal axis	125	7.0	8.5	+1.5	4.1	3.3	—0.8	6.0	6.1	+0.1
	131	8.6	8.7	+0.1	1.5	3.4	+1.9	6.1	6.0	—0.1
CYCIR up to 3.1 km	177	2.7	3.3	+0.6	5.2	2.9	—2.3	3.6	3.2	—0.4
a.s.l.	255	4.7	4.4	—0.3	5.1	5.1	0.0	4.9	4.8	—0.1
	304	4.9	5.8	+0.9	5.9	5.1	—0.8	5.3	6.1	+0.8
CYCIR up to 5.8 km	522	6.2	6.0	—0.2	5.5	6.6	+1.1	6.0	6.4	+0.4
a.s.l.	689	7.0	8.0	+1.0	11.0	9.0	—2.0	8.4	8.6	+0.2
CYCIR >5.8 km	257	5.8	5.0	—0.8	3.6	4.3	+0.7	4.7	5.2	+0.5
a.s.l.	291	6.1	5.4	—0.7	5.0	4.9	—0.1	5.7	5.8	+0.1
	352	5.1	6.6	+1.5	7.3	5.8	—1.5	6.2	7.0	+0.8

$k = 0.014547 \times 10^9$ metric tons/day, Obs — Observed, Est — Estimated, Res — Residual.

in the upper catchment. Upper catchment or the lower catchment gets more rainfall depending upon which segment is nearer and parallel to the monsoon axis or trough. The upper catchment because of its orographic features normally gets more rainfall when southerly winds strike the hills.

4.2.3. *Low pressure systems*

In July and August, the low pressure systems generally move in westnorthwesterly direction from north Madhya Pradesh to south Rajasthan. In late August, September they move initially in a northwesterly direction and later have a tendency to recurve north or northwest and break up over the western Himalayas. On a few occasions depression also form in the Arabian sea which initially move northwards and then northwestwards and breakup over Himachal Pradesh. Such depressions have been associated by Dhar (1962) for heavy rainfall in the catchment.

It is observed that the low pressure systems moving northwards from south of Delhi first give heavy precipitation in the lower catchment which extends to upper catchment. Low pressure systems centred around Delhi within about 160 km with/or CYCIR over north Rajasthan, Punjab, Haryana or north Pakistan close to the catchment moving northward give heavy rainfall activity in the upper catchment.

4.2.4. *Trough in the westerlies*

Due to the passage of troughs in the zonal westerlies, the western end of the axis of the seasonal monsoon trough becomes more active over northwest India and its orientation becomes more north-south as compared to its normal position. This results in appreciable increase in the rainfall activity over the catchment. Under the influence of the trough in westerlies, the existing low pressure systems over northwest India are intensified or new ones induced. This results in their recurvature north or northeastwards in the months of August-September and finally break over the Western Himalayas.

Low level troughs in north-south direction running from Punjab, Haryana to Gujarat and/or mid-tropospheric troughs in the westerlies along 25°N, 70°E have been found to give very heavy rainfall activity in the catchment.

4.2.5. *Combined systems*

In general, it is observed that the above synoptic systems are experienced in combination with others. The monsoon axis is always there during the season. In addition to the monsoon axis when there is/are other systems like low pressure/CYCIR/trough etc. the effect of different systems in combination with other depends upon their mutual position/movement/interaction and the moisture feed. In any given situation the intensity and pattern of heavy rainfall activity depends upon their combined activity in which any one system may dominate over the other.

4.3. *Moisture transport*

Computation of moisture transport over Delhi is considered useful for determining the rainfall activity over the Yamuna catchment. Heavy rainfall cases are grouped after categorising the synoptic systems with respect to their depth in order to roughly gauge the degree of lifting mechanism affecting the catchment area. This is done by considering the synoptic systems at the surface like,(*i*)seasonal monsoon axis/seasonal low,(*ii*)low pressure systems with CYCIR/trough up to 3.1 km a.s.l., (*iii*) up to 5.8 km a.s.l and(*iv*)greater than 5.8 km a.s.l.The resultant average moisture transport-average isohyetal rainfall nomograms drawn as per Figs. 3(a & b) represent the value for their most probable mean position. These nomograms when tested with the available moisture transport data for heavy rainfall cases show satisfactory results as per Table 4. These may be used as general tool for guiding the forecaster for semi-quantitative prediction of isohyetal average rainfall in the catchment. However, the success depends upon careful selection of (a) the nomogram and (b) catchment/segment of catchment.

5. Conclusions

(*i*) The study of the rainfall spectrum over the Yamuna catchment up to Delhi from 1976-90 during the flood operational period from 1 June to 15 October show characteristic variation in frequency and amount of rainfall as discussed in para 4. The cumulative frequency diagrams are useful for determining the frequency of rainfall events pertaining to a given rainfall amount.

(*ii*) The generalisation of synoptic situations for heavy rainfall activity greater than 5.0 cm isohyetal average show that the position/orientation of monsoon axis alongwith, (a) position/movement of low pressure system/cyclonic circulation/trough and (b) position/orientation of troughs in the westerlies are important synoptic features responsible for heavy rainfall activity in the catchment when they are within about 160 km of catchment.

(*iii*) The resultant average moisture transport average isohyetal rainfall nomograms developed in the above study can serve as a useful guide for the forecaster for assessment of semi-quantitative precipitation forecast range for the Yamuna catchment/segment of Yamuna catchment if the depth/intensity/distance of the synoptic system is properly gauged.

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