

Central Board of Irrigation
Publication No 36

THE ROLE OF GLACIERS AND SNOW ON HYDROLOGY OF PUNJAB RIVERS

BY

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PUBLISHED BY ORDER OF THE BOARD

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SIMLA

24th April 1946

CORRIGENDUM

- Page 2, Line 2 from top *read* 'recrystallized' for 'recrystalized'
- Page 16 and 11 Table VIII under year 1945 *read* 'Jan' for 'Jun'
- item 2 column May 1944, *read* '956' for '946'
- item 8 column Jan 1945 *insert* '10'
- item 8 column April 1945 *insert* '12'
- item 8 column May 1945 *read* '26' for '2'
- Page 14 Table XI against February Minimum, column 9 *read* '2 459' for '2 59'
- Page 18, Line 10 from bottom *read* 'from' for 'rom'
- Last line from bottom *read* 'melt' for 'ment'
- Page 19 Line 10 *read* 'Snowfed' for 'Snowed'
- Page 20 Line 22, *read* 'D o' for 'D'
- Page 28 Line 2 *read* 'Della' for 'Delle'
- Line 3 from bottom *read* 'Horton RE' for 'Horton RR'
- Page 29 against (18) Wilson WT should read 'Saur SR'

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FOREWORD

The Role of Glaciers and Snow on Hydrology of the Punjab Rivers was presented as a paper at the Annual Research Committee Meeting of the Central Board of Irrigation held in August 1945, by Sri Bahadur Kanwar Sam O B E I S E. The Research Committee considered that the subject required wide publicity and recommended* that the paper be published as a Central Board of Irrigation Publication.

The Board at its 16th Annual Meeting held in November 1945 accepted† the recommendation of the Research Committee and ordered that the paper be published as a C B I Publication after it had been examined by Mr A P Watal Chief Engineer P W D Irrigation Branch United Provinces and Dr S K Bannerji Director General, Meteorological Department Government of India. Both of these officers have since reported that it would be useful to publish the paper.

The author has shown in this publication that snow and glaciers form natural storage reservoirs for the Punjab Canals and he stresses the necessity of keeping a proper account of these resources. It should be possible to forecast river supplies from March to June from snow surveys. Such forecasts will be of great help to irrigation engineers for the distribution of available water supplies and the operation of irrigation works particularly the proposed storage reservoirs. Although the study made by the author relates to the Punjab only it is considered that the principles dealt with in this publication will have a wide application.

The Board hopes that this publication will help in focussing attention on the subject and will lead to further studies being carried out throughout India.

N D GULHATI,

Secretary

Central Board of Irrigation

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Dated 24th April, 1946

Central Board of Irrigation Annual Report (Technical) 1945, Page 125
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The Role of Glaciers and Snow On Hydrology of Punjab Rivers

INTRODUCTORY

11 Studies made in connection with the supplies likely to be available for storage at Kishau on the Tons a tributary of the Jumna, and for diversion from the Chenab (Chanda Bhaga) at Marhu into the Ravi through a five mile tunnel under the Pangri Range showed that the usual method of determination of runoff by applying a certain percentage to rainfall gave results that were materially out in the case of these streams. This method does not take into account the contribution made by water from melted snow and glaciers. This source of discrepancy was first suspected in connection with the investigations for the proposed Larji Dam on the Beas River by Rai Bahadur A N Khosla⁽¹²⁾.

12 Practically all the Punjab rivers are snow fed. A rough idea of the extent of glaciers in the catchment area of these rivers will be gathered from Table I taken from Khosla's paper referred to above.

TABLE I
Glacier area on the Punjab Rivers

| Name of river | Glacier area in the catchment (from 1 = 16 miles Relief G T S Map of the Punjab) (square miles) | Percentage of glacier area to total catchment area | Mean elevation of Glacier area above mean sea level (feet) |
|---------------|---|--|--|
| Indus | 14 415 | 12 | 20 500 |
| Jhelum | 142 | 1 | 18 000 |
| Chenab | 1 475 | 13 | 19 000 |
| Ravi | 100 | 3 | 17 000 |
| Beas | 277 | 5 | 19 000 |
| Sutlej | 2 468 | 11 | 20 000 |
| Jumna | 131 | 3 | 18 000 |

The areas given in the above table do not give a complete picture as the area covered by seasonal snows are not included therein.

So enormous is the aggregate volume of water locked up in the crystalline state in the glaciers and ice caps on the Himalayas that if it were all released by melting and flowed down the Punjab rivers, most of the Punjab and Sind plains would be submerged.

13 The process of estimating the amount of snow accumulated at high altitudes and the utilization of this knowledge to forecast the supplies in the rivers fed by these natural storage reservoirs comprise the present-day science of snow surveying.

GLACIERS—GENERAL CHARACTERISTICS AND SECULAR VARIATION

2.1 The general term glacier is applied to all bodies of land ice that consist of recrystallized snow accumulated on the surface of the Earth. Glaciers are formed in those localities where more snow accumulates annually than wastes away by melting, evaporation and other dissipating processes. The continued addition of annual layers of snow however does not cause the thickness of the glacier to increase indefinitely for when the mass attains a certain minimum thickness its own weight suffices to overcome its rigidity as well as the frictional resistance of its base to initiate a sluggish flow like motion. Thus the glacier will gravitate to lower and warmer zones where the ice is finally converted into runoff⁽¹⁾.

The lower end of a glacier is known as its "snout" and at its snout there is an "ice cave" from which water issues. The ancient Hindus gave the name of *Gau Mukh* (the Cow's mouth) to the ice cave near Gangotri from its resemblance to former⁽²⁾.

Regions where the climatic conditions permit continual accumulation of snow in excess of wastage are commonly referred to as 'regions of perpetual snow' and their lower limit of altitude is known as the 'snow line'. The snow line of the Assam Himalayas is at an altitude of R L 14 500 feet. In the North it varies between R L 17 000 and R L 19 000. The glaciers of the Kashmir Himalayas descend to a much lower limit of R L 8 000.

2.2 The size of a glacier varies with the amount of the annual effective accumulation of snow. The variation in the size is made evident by the oscillation of the snout of the glacier. This oscillation is termed the 'recession' or 'advance' of the glacier.

The glaciers in general all over the world are at present in a state of recession. This commenced after the great advance of 1850 A.D. has since 1920 proceeded at an accelerated rate⁽³⁾. This is merely the latest episode in this 'little ice age'. It may however merely mark the beginning of a brief interlude of moderate glacier shrinkage that will be followed ere long—possibly within a few decades from now—by another period favourable to glacier growth. That this "little ice age" of the last 4 000 years has been interrupted frequently by such interludes of glacier shrinkage is evident from the disposition of modern moraines at the fronts of many reborn glaciers in closely spaced concentric series.

Should however the present period of glacier recession continue indefinitely it would surely result in widespread deglaciation and in increasing aridity over the Punjab and Sind. Conditions such as prevailed during mid Post Pleistocene time might then return and the irrigation engineers in the Punjab and Sind might face an era of water scarcity to which present conditions in the two provinces might find it difficult to adjust.

23 The first step towards the determination of the secular variations of the Himalayan Glaciers was taken by the Geological Survey of India in 1906. The positions of the snouts of the glaciers were marked by pillars, cairns and rock cuts.

In 1930 the Geological Survey published a paper by Major K. Mason⁽²⁾ in which a history was given of the observations of thirty four glaciers in the Karakoram Mountains. The notes of every explorer who had visited these glaciers during the last hundred years were summarised in this paper. The period during which these observations had been accumulated was however found to be too short to justify any definite conclusions.

In recent years, the Survey of India Department seemed to indicate that they regarded glaciological surveys beyond the scope of their financial resources.

The glaciological surveys made so far in India have not contributed anything to the solution of the problems of run off from snow fall. The observations have revealed that the variations of the snouts of glaciers have been erratic, neither seasonal nor secular variation has been discovered.

HYDROLOGICAL CHARACTERISTICS OF GLACIER STREAMS

31 The author is not aware of any detailed study having been made of rainfall run off of glacier streams in India. The number of rain gauge stations at the higher altitudes in the catchment areas of the Punjab rivers is very few and not fully representative of the area. In the catchment of the Sutlej and the Indus the average area represented by one rain gauge station comes to 2,340 and 7,400 square miles respectively. On the Jhelum, Ravi and Beas which have more rain gauge stations the percentage of glacier area is comparatively small.

32 On the Chenab there are 12 rain gauge stations for a catchment area of over 11,000 square miles. A very detailed study for this river for 20 years from 1923 to 1942 has been made in connection with the investigations regarding the Dhanganah Storage and the Marhla Tunnel Diversion Schemes. Lines of equal rainfall for each month of each year were drawn for the catchment area above Marhla Headworks and weighted rainfall for the entire catchment calculated from these charts. One such typical chart is enclosed as Plate I. This chart shows the recorded rain gauge stations in the catchment.

The actual discharges of the river are measured daily at Marhla. From this have been calculated the figures of actual runoff for each month of each of the 20 years.

33 Table II shows certain characteristics of this catchment for each month based on the average of 20 years.

TABLE II
Some Hydrologic Characteristics of the Chenab River at Marala
 (Average of 20 years 1913 to 1941)

Total catchment = 11 110 sq miles Glacier Area = 1 sq miles

| Months | Weighted precipitation | Total precipitation over catchment during the month | Actual measured run off at Marala | Coefficient of run off to precipitation $\frac{\text{col 4}}{\text{col 2}}$ |
|--------------|------------------------|---|-----------------------------------|---|
| 1 | 2 | 3 | 4 | 5 |
| | (Inches) | (Acre feet) | (Acre feet) | |
| January | 3.81 | 2 767 399 | 451 531 | 0.199 |
| February | 4.59 | 2 723 117 | 585 716 | 0.215 |
| March | 4.09 | 2 422 905 | 907 180 | 0.395 |
| April | 2.99 | 1 775 115 | 1 197 571 | 0.675 |
| May | 2.23 | 1 320 332 | 2 155 861 | 1.633 |
| June | 2.01 | 1 194 062 | 3 376 442 | 2.828 |
| July | 6.17 | 3 656 652 | 5 297 949 | 1.449 |
| August | 6.15 | 3 643 857 | 5 115 279 | 1.404 |
| September | 2.24 | 1 326 904 | 2 419 347 | 1.823 |
| October | 1.17 | 699 877 | 786 771 | 1.124 |
| November | 0.69 | 408 515 | 433 628 | 1.061 |
| December | 2.17 | 1 285 828 | 408 847 | 0.318 |
| Annual Total | 38.31 | 22 724 563 | 23 186 122 | 1.020 |

It will be seen that run off during May to October is appreciably greater than total precipitation. Even the average annual run off is slightly greater than total precipitation. Realizing that there must be some losses by absorption and evaporation the obvious conclusions is that glaciers are responsible for a material contribution to the run off. A so considerable part of the precipitation falling in the form of snow during winter months does not add to the run off in those months. It appears as run off in later months when higher temperatures melt this seasonal snow. The above conclusions would hold even if the precipitation data over the catchment is considered to be inadequate.

34 Table III for the same catchment clearly indicates that contributions from snow and glaciers are not constant from year to year particularly for the summer months.

35 Some valuable work of a pioneer nature has been done by Secondo Alfieri⁽¹⁾ in the Italian Alps and Appennines. He selected five basins three of which had snow and glacier one snow and one mostly rain. His observations cover a period of seven years 1931-1937.

TABLE III

Statement showing variation in the ratio of Run off to precipitation on the Chenab Basin above Marala for each month in 20 years from 1923 to 1942

Total catchment = 11 110 square mile

Glacier Area = 1 475 square miles

| Years | January | February | March | April | May | June | July | August | September | October | November | December | Annual |
|------------------|---------|----------|-------|-------|-------|------|------|--------|-----------|---------|----------|----------|--------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 1923 | 0 15 | 0 30 | 0 60 | 1 40 | 0 76 | 6 60 | 1 00 | 1 09 | 73 | 0 53 | 1 65 | 0 28 | 0 85 |
| 1924 | 0 22 | 0 17 | 0 44 | 0 85 | 0 53 | 6 71 | 2 09 | 0 91 | 1 09 | 2 59 | 1 19 | 0 26 | 0 85 |
| 1925 | 0 29 | 0 33 | 0 56 | 1 26 | 0 93 | 11 | 1 04 | 0 97 | 2 47 | 1 00 | 0 37 | | 1 07 |
| 1926 | 0 41 | 0 30 | 0 24 | 0 32 | 0 92 | 2 78 | 0 99 | 1 21 | 1 44 | 5 67 | 1 68 | | 0 80 |
| 1927 | 0 19 | 0 17 | 0 39 | 0 67 | 0 87 | 4 55 | 1 03 | 1 36 | 3 85 | 1 49 | 1 57 | 0 67 | 0 99 |
| 1928 | 0 09 | 0 29 | 0 36 | 0 48 | 6 05 | 4 70 | 1 80 | 1 06 | 1 11 | | 0 29 | 0 20 | 0 85 |
| 1929 | 0 26 | 0 34 | 0 55 | 0 65 | 2 09 | 2 01 | 1 18 | 1 03 | 6 57 | 0 55 | 3 76 | 0 18 | 0 91 |
| 1930 | 0 21 | 0 32 | 0 55 | 0 47 | 3 06 | 3 89 | 1 87 | 2 53 | 4 00 | 1 24 | | 0 97 | 1 18 |
| 1931 | 0 16 | 0 10 | 0 12 | 0 73 | 0 73 | 7 01 | 1 38 | 1 13 | 2 31 | 1 02 | 0 91 | 2 47 | 0 97 |
| 1932 | 0 18 | 0 22 | 0 31 | 1 51 | 0 64 | 2 98 | 1 17 | 1 97 | 3 0 | 0 95 | | 0 19 | 1 06 |
| 1933 | 0 18 | 0 16 | 0 23 | 0 42 | 2 77 | 3 19 | 1 37 | 1 97 | 7 16 | 4 40 | 2 79 | 1 8 | 1 07 |
| 1934 | 0 2 | 0 61 | 0 34 | 0 37 | 1 54 | 2 78 | 1 73 | 1 37 | 7 16 | 4 40 | 1 74 | 0 18 | 1 22 |
| 1935 | 0 12 | 0 29 | 0 35 | 0 65 | 5 19 | 1 60 | 1 94 | 1 94 | 3 38 | 1 23 | 0 43 | 0 21 | 1 04 |
| 1936 | 0 25 | 0 14 | 0 33 | 1 00 | 5 25 | 1 83 | 1 40 | 1 42 | 2 09 | 2 07 | 1 27 | 0 18 | 1 04 |
| 1937 | 0 24 | 0 16 | 0 41 | 0 70 | 4 01 | 3 67 | 1 60 | 2 70 | 1 35 | 0 32 | 1 18 | 0 15 | 1 03 |
| 1938 | 0 29 | 0 23 | 0 57 | 1 33 | 14 29 | 2 11 | 2 30 | 2 28 | 4 33 | 2 17 | 0 0 | 0 60 | 1 43 |
| 1939 | 0 18 | 0 14 | 0 41 | 0 60 | 4 27 | 2 51 | 1 46 | 2 74 | 1 92 | 0 43 | | | 1 06 |
| 1940 | 0 16 | 0 34 | 0 24 | 0 50 | 1 34 | 3 09 | 1 53 | 1 51 | 1 19 | 3 68 | 2 34 | 0 83 | 1 06 |
| 1941 | 0 19 | 0 21 | 0 20 | 0 63 | 1 25 | 4 52 | 1 90 | 1 55 | 0 89 | 3 05 | 1 55 | 0 28 | 1 06 |
| 1942 | 0 26 | 0 22 | 1 07 | 0 81 | 0 85 | 3 82 | 1 27 | 1 21 | 1 16 | 1 57 | 3 34 | 0 36 | 1 06 |
| 20 years average | 0 20 | 0 2 | 0 40 | 0 68 | 1 63 | 2 83 | 1 45 | 1 49 | 1 82 | 1 12 | 1 06 | 0 32 | 1 02 |

The essential characteristics of these five basins⁽¹⁾ are shown in Table IV

TABLE IV
Hydrologic Characteristics of Alpine Basins

| Stream and Gauging Station | Glacier Area (Square Kilo meters) | Proportion of glacier to total catchment | Coefficient of annual run off to precipitation (Average of 1931-1937) |
|--|---|--|---|
| <i>Glacier</i> | | | |
| Lys a D Ejola | 14.4 | 47 | 1.39 |
| Frodolfo al Forni | 22.8 | 47 | 2.04 |
| Rutor a Promise | 13.8 | 28 | 1.31 |
| <i>Snow</i> | | | |
| Corsaglia Alla Pressa Centrale Molline | Generally snow at higher altitudes remains on ground for several months | | 0.82 |
| <i>Rain</i> | | | |
| Reno a Praocchia | Limited amount of Winter snow but melts quickly | | 0.70 |

The heavy melting of the glaciers that have been in regression naturally increases the coefficient of run off to annual precipitation. But Alfieri's reference to non glacier basins in which on certain years the run off equalled or exceeded the precipitation indicates lack of sufficient precipitation data.

Even if the coefficient of run off on account of above factors is somewhat exaggerated, it still represents the relative effect of ice snow and rain on run off.

36 The monthly and seasonal phases of precipitation and run off in above catchments⁽²⁾ are clearly shown as percentages of the annual in Table V.

From Table V it will be seen that precipitation is quite evenly distributed throughout the year with slight excess in the summer months. This however has little effect on the flow of the streams. The latter phase is chiefly affected by temperature acting upon the accumulation and snow.

37 The Alpine glacier streams have their major run off during June-September. This is due to the low temperatures at their high altitudes in other months. The lower snow fed basin (eg Corsaglia) has its major run off in March-June which ends in the exhaustion of the seasonal storage of snow. The excess of 20 per cent in the major run off of the former three over the latter indicates the present wastage of ice reserve. If annual replacement were equal to ablation the major run off should be more comparable with that of the snow basin except that the run-off will last longer.

TABLE V
Mean Precipitation and Run off of Alpine Basins (Monthly Percentage of Annual)

| Annual | Jan uary | Feb ruary | March | April | May | June | July | August | Sep tember | Octo ber | Nov ember | Dec ember | |
|------------------------|---|--------------|-------|-------|------|------|------|--------|---------------|-------------|--------------|--------------|--|
| | <i>Glacier—Lys a D Ejola (Sq km 30 4 ice 47 / mean altitude 3 112 meters)</i> | | | | | | | | | | | | |
| Precipitation 1260 mm | 4 3 | 5 5 | 8 5 | 8 5 | 18 5 | 8 8 | 6 7 | 7 6 | 10 6 | 8 2 | 10 6 | 8 3 | |
| Runoff 55 5 | 0 6 | 0 5 | 0 5 | 1 9 | 9 0 | 19 0 | 23 5 | 23 3 | 13 7 | 5 6 | 1 6 | 0 8 | Major runoff 79 5% (June to Sept) |
| | <i>Glacier—Frodolfo as Forn (Sq km 48 5 ice 47% mean altitude 2 800 metes)</i> | | | | | | | | | | | | |
| Precipitation 894 mm | 5 1 | 4 7 | 6 3 | 6 9 | 1 0 | 10 6 | 1 5 | 11 7 | 10 6 | 10 3 | 6 5 | 4 7 | |
| Runoff 57 9 | 0 8 | 0 6 | 0 5 | 0 7 | 4 0 | 18 2 | 28 4 | 23 4 | 15 0 | 5 6 | 1 7 | 1 0 | Major runoff 85 0% (June to Sept) |
| | <i>Glacier—Rutor Promet (Sq km 49 8 ice 28 / mean altitude 2 616 meters)</i> | | | | | | | | | | | | |
| Precipitation 1 484 mm | 7 6 | 6 0 | 10 2 | 7 5 | 8 0 | 7 7 | 8 2 | 9 9 | 11 5 | 6 9 | 7 5 | 9 0 | |
| Runoff 61 8* | 1 0 | 0 8 | 0 8 | 1 9 | 9 7 | 21 8 | 25 2 | 19 4 | 11 8 | 4 4 | 1 9 | 1 3 | Major runoff 78 2% (June to Sept (5 mos 87 2%)) |
| | <i>Snow—Coraschia alla Pesca della Centrale M Huns (Sq km 88 5 mean altitude 1 530 metres)</i> | | | | | | | | | | | | |
| Precipitation 1 536 mm | 6 0 | 4 3 | 12 2 | 8 3 | 11 8 | 6 8 | 5 5 | 6 4 | 7 4 | 8 9 | 14 6 | 7 8 | |
| Runoff 40 1* | 3 3 | 3 6 | 7 3 | 15 2 | 5 4 | 13 1 | 6 4 | 3 1 | 3 8 | 6 7 | 7 1 | 4 8 | Major runoff 61 0% (March to June) |
| | <i>Rain mostly—Reno a praccchia (Sq km 40 9 mean altitude 890 metres)</i> | | | | | | | | | | | | |
| Precipitation 2 189 mm | 7 9 | 7 9 | 11 9 | 8 2 | 8 5 | 8 5 | 2 4 | 3 2 | 4 9 | 15 0 | 13 7 | 10 0 | |
| Runoff 51 9 | 9 9 | 9 7 | 17 6 | 8 6 | 7 9 | 5 6 | 1 7 | 0 8 | 1 0 | 9 8 | 15 5 | 12 1 | Major runoff 3 mos 2 5% (July to Sept) |

*Liters per second per square kilometer

Run off from the rain basin more or less corresponds to the rainfall with some lag

38 There is a prevalent belief that snow cover is an important factor in flood causation. This is proved to be fallacious. On the contrary snow cover has a moderating influence.

There are two principal ways in which snow cover may act as a flood deterrent. The first may be called the sponge effect, the second the surface detention effect.

Snow cover is capable of absorbing rain and melt-water from the surface and hold it as a sponge holds water up to its capillary capacity. Surface detention depends on the fact (which is generally true for run off in all forms whether from a snow layer or bare ground) that surface run off can occur when and only when there is a layer of surface detention on the ground in the form of sheet flow of a depth adequate to discharge water into the stream or channel at the given run off rate. Because of the low ratio of run off intensity to detention depth with snow cover the run off intensity would be only a fraction of that or the same rain on bare ground.⁽¹⁰⁾ The result is that the deeper the snow the less the chance of a heavy flood.

CONTRIBUTION FROM SNOW AND GLACIERS ON SOME OF THE PUNJAB RIVERS

41 For the investigation of discharges available for storage daily discharge observations were started on the Giri tributary of the Jumna from the 1st July 1942 and on the Tons tributary from the 1st July 1943. On the Giri there is no glacier area. Assuming that discharge due to springs and seepage on the Tons and Jumna catchment is the same in magnitude as that of the Giri catchment per square mile of the non glacier area the glacier contribution has been worked out both for the Jumna above Tajewala as a whole as well as the Tons above Kishau. The results are shown in Table VI.

TABLE VI
Glacier Contribution in Jumna Catchment
(Cusecs per square mile of glacier area)

| | In Jumna system as a whole | | | In the Tons catchment | | |
|-----------|---|------|------|-----------------------|------|------|
| | 1943 | 1944 | 1945 | 1943 | 1944 | 1945 |
| January | | 11 | 10 | | 11 | 6 |
| February | | 18 | 6 | Discharges | 9 | 5 |
| March | 12 | 10 | 9 | not | 12 | 10 |
| April | 16 | 17 | 12 | observed | 27 | 22 |
| May | 26 | 34 | 26 | | 39 | 34 |
| June | 36 | 37 | 33 | | 37 | 37 |
| July | Results in these months are vitiated by rainfall May assume same as for June | | | | | |
| August | | | | | | |
| September | | | | | | |
| October | 23 | 22 | | 20 | 17 | |
| November | 18 | 11 | | 10 | 10 | |
| December | 13 | 10 | | 11 | 8 | |

In working out the figures average of such days only was taken when the discharges were fairly steady thus omitting fluctuations due

TABLE VII
Glacier Contribution in the Tons Catchment
(Discharge in Cusecs)

| No | Particulars | Year 1943 | | | Year 1944 | | | | | | | | Year 1945 | | | | | | |
|----|--|-----------|-------|-------|-----------|-------|-------|-------|-------|-------|-------|-------|-----------|-------|-------|-------|-------|-------|-------|
| | | Oct | Nov | Dec | Jan | Feb | March | April | May | June | Oct | Nov | Dec | Jan | Feb | March | April | May | June |
| 1 | Average daily discharge of Giri at Chudini excluding abnormal discharge | 1 192 | 657 | 537 | 483 | 491 | 488 | 903 | 411 | 292 | 660 | 510 | 438 | 555 | 588 | 614 | 530 | 343 | 226 |
| 2 | Discharge per square mile of Giri Catchment (Catchment area = 956) | 1 25 | 0 69 | 0 56 | 0 50 | 0 51 | 0 51 | 0 94 | 0 43 | 0 30 | 0 68 | 0 54 | 0 46 | 0 55 | 0 6 | 0 64 | 0 55 | 0 36 | 0 24 |
| 3 | Average daily discharge of Tons at Kishau excluding abnormal discharges | 4 294 | 2,329 | 2 163 | 024 | 1 883 | 2,160 | 4 493 | 4 771 | 4 288 | 2 987 | 2 015 | 1 667 | 1 592 | 1 685 | 2 137 | 3 199 | 4 104 | 4 155 |
| 4 | Catchment area of tons excluding its Glacier area (1927 102) above Kishau (square miles) | 1,825 | 1 825 | 1,825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 | 1 825 |
| 5 | Seepage discharge of Tons (S No 4-S No 2) | 2 281 | 1 259 | 1,022 | 913 | 931 | 931 | 1,715 | 785 | 548 | 1,241 | 985 | 840 | 1 004 | 1 132 | 1 168 | 1,004 | 657 | 438 |
| 6 | Glacier discharge of Tons catchment (S No 3-S No 5) | 2,013 | 1,070 | 1 141 | 1 111 | 952 | 1 229 | 2 778 | 3 986 | 3 740 | 1 746 | 1 030 | 827 | 588 | 553 | 969 | 2 195 | 3 447 | 3 717 |
| 7 | Discharge per square mile of glacier area (Glacier area = 102 square mile) | 20 | 10 | 11 | 11 | 9 | 12 | 27 | 39 | 37 | 17 | 10 | 8 | 6 | 5 | 10 | 22 | 34 | 37 |

TABLE
Glacier Contribution on the
(Discharge)

| S N | Particulars | Year 1943 | | | | | | | | |
|--------|--|-----------|-------|-------|-------|-------|-------|-------|-------|-------|
| | | March | April | May | June | Oct | Nov | Dec | Jan | Feb |
| 1 | Average daily discharge of Giri at Chandni for days of steady supplies (Excluding abnormal discharges) | 433 | 407 | 302 | 239 | 1192 | 657 | 537 | 483 | 491 |
| 2 | Catchment area of Giri above Chandni in square miles | 956 | 956 | 956 | 956 | 956 | 956 | 956 | 956 | 956 |
| 3 | Discharge in cusecs per square mile of Giri catchment which is purely seepage spring water | 0 45 | 0 43 | 0 32 | 0 25 | 1 25 | 0 69 | 0 56 | 0 50 | 0 51 |
| 4 | Catchment area of Jumna above Tajewala in square mile (excluding glacier area (4386—133)) | 4 253 | 4 253 | 4 253 | 4 253 | 4 253 | 4 253 | 4 253 | 4 253 | 4 253 |
| 5 | Seepage discharge of Jumna above Tajewala taking discharge per square mile as worked out in S No 3 & 4 (No 4 x No 3) | 1 914 | 1 829 | 1 361 | 1 063 | 5 316 | 2 934 | 2 382 | 2 127 | 2 169 |
| 6 | Actual average daily discharge above Tajewala per day of steady supplies | 3 531 | 3 824 | 4 774 | 5 884 | 8 427 | 5 272 | 4 133 | 3 617 | 3 224 |
| 7 | Glacier contribution of Tons and Jumna from a total glacier area of 102+31=133 square miles (S No 6—5) | 1 617 | 1 995 | 3 413 | 4 821 | 3 111 | 2 338 | 1 751 | 1 480 | 1 055 |
| 8 | Discharge per square mile of Glacier area on Tons and Jumna (Total area=133 square miles) | 12 | 15 | 26 | 35 | 28 | 18 | 13 | 11 | 8 |

VIII

Jumna System as a whole
in cusecs)

| Year 1944 | | | | | | | Year 1945 | | | | | |
|-----------|-------|-------|-------|-------|-------|-------|-----------|-------|-------|-------|-------|-------|
| March | April | May | June | Oct | Nov | Dec | Jan | Feb | March | April | May | June |
| 488 | 903 | 411 | 292 | 650 | 512 | 438 | 525 | 588 | 614 | 530 | 343 | 226 |
| 956 | 956 | 945 | 956 | 956 | 956 | 956 | 956 | 956 | 956 | 956 | 956 | 956 |
| 0 51 | 0 94 | 0 43 | 0 30 | 0 68 | 0 54 | 0 46 | 0 55 | 0 62 | 0 64 | 0 55 | 0 36 | 0 24 |
| 4 253 | 4 253 | 4 253 | 4 253 | 4,253 | 4,253 | 4 253 | 4 253 | 4 253 | 4,253 | 4,253 | 4 253 | 4 253 |
| 2 169 | 3 998 | 1 828 | 1 276 | 2 892 | 2 297 | 1 956 | 2 339 | 2 637 | 2 722 | 2 339 | 1 531 | 1 027 |
| 3 490 | 6 308 | 6 305 | 6 098 | 5 780 | 3 813 | 3 286 | 3 631 | 3 465 | 3 906 | 4 949 | 4 975 | 5 228 |
| 1 321 | 2 310 | 4 477 | 4 822 | 2 892 | 1 516 | 1 330 | 1 292 | 828 | 1 184 | 1 610 | 3 444 | 4 201 |
| 10 | 17 | 34 | 37 | 22 | 11 | 10 | | 6 | 9 | | 2 | 33 |

to rainfall. For this very reason the months of July August and September had to be omitted for this analysis. Details of the method followed in working out the results are shown in Tables VII and VIII.

42 In August and September 1944 some observations were made on the Kolahai glacier near Pahlgam in the Kashmir State. The glacier area as measured from 1 inch to a mile survey of India sheets comes to 12.65 square miles. Discharge observations were made immediately downstream of the glacier area thus eliminating errors due to additions from seepage and springs. The results are given in Table IX.

TABLE IX

Run off from Kolahai Glacier (area=12.65 square miles)

| Date (year 1944) | Rainfall at Kolahai (Inches) | Air temperature (F) | | Discharge (Gusecs) | | Run off per square mile (Gusecs) | |
|---------------------|---------------------------------------|------------------------|-----|-----------------------|---------|--|---------|
| | | Max | Min | Evening | Morning | Evening | Morning |
| 27 8 | 44 | 80 | 46 | 556 | | 44 | |
| 28 8 | 03 | 84 | 48 | 498 | 414 | 39 | 33 |
| 29 8 | | 76 | 45 | 493 | 308 | 39 | 28 |
| 30 8 | | 86 | 48 | 526 | 337 | 42 | 27 |
| 31 8 | | 86 | 51 | 446 | 334 | 30 | 27 |
| 1 9 | 88 | 88 | 50 | 379 | 303 | 30 | 24 |
| 2 9 | 57 | 72 | 48 | 387 | 303 | 29 | 24 |
| 3 9 | 1 67 | 70 | 45 | 280 | 276 | 22 | 22 |
| 4 9 | 40 | 62 | 38 | 276 | 250 | 22 | 20 |
| 5 9 | 12 | 58 | 38 | 203 | 196 | 16 | 16 |
| 6 9 | 10 | 70 | 40 | 204 | 177 | 16 | 14 |
| 7 9 | 06 | 70 | 42 | 203 | 176 | 16 | 14 |
| 8 9 | | 70 | 41 | 195 | 150 | 10 | 12 |
| 9 9 | 02 | 68 | 45 | 190 | 149 | 15 | 12 |
| 10 9 | 30 | 70 | 44 | 141 | 122 | 11 | 10 |
| 11 9 | | 65 | 40 | 139 | 122 | 11 | 10 |
| 12 9 | | 65 | 40 | 139 | 116 | 11 | 9 |

43 Discharge observations were also set up in summer 1944 on the Chandra Bhaga (The Chenab River) near Tindi. Two over-seers were left across the Pangl Range for observations during winter months. For about 6 months they were entirely cut off. It has just* been possible to get the results of their observations. The results have still to be analysed after obtaining precipitation figures for the rain gauge stations upstream of this discharge site. Excluding the discharges on such days as appear to have been affected by rain the glacier and snow contribut on per square mile of glacier area at Tindi is shown in Table X

TABLE X

| Year | Month | Glacier area | Average air temperature | Average Discharge in cusecs | Discharge in cusecs per sq mile of glacier area |
|------|-------|------------------|-------------------------|-----------------------------|---|
| 1944 | Sept | 725 square miles | 62 | 6 050 | 8.4 |
| | Oct | | 52 | 2 386 | 3.3 |
| | Nov | | 40 | 1 330 | 1.9 |
| | Dec | | 34 | 1 100 | 1.5 |
| 1945 | Jan | | 27 | 995 | 1.4 |
| | Feb | | 29 | 880 | 1.2 |
| | March | | 37 | 1 183 | 1.6 |
| | April | 44 | 1 653 | 2.3 | |
| | May | 54 | 4 899 | 6.9 | |
| | June | 59 | 19 218 | 26.5 | |

IMPORTANCE AND POSSIBILITIES OF FORECASTING RIVER DISCHARGES

51 Discharges of Punjab rivers for the same months vary very widely from year to year. Table XI gives the mean monthly maximum minimum and average discharges of the Punjab rivers for the years 1923-1942.

Mean Monthly Discharge of these Rivers for Summer and Winter Months for twenty years are shown on Plates 2 to 15.

* November 1944.

TABLE XI
Discharges of Punjab Rivers
(Mean monthly in cusecs)

| Months | Partic- ulars | Indus at Kala bagh | Jhelum at Mangla above | Chenab at Marala above | Ravi at Madho pur above | Beas at Mandi Plain | Sutley at Rupar above (Patial) | Jumna at Taje wala above |
|-----------|------------------|-----------------------------|---------------------------------|---------------------------------|-------------------------------------|------------------------------|--|--------------------------------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| January | Maximum | 34 004 | 12 581 | 17 756 | 4 813 | 8 4 1 | 5 596 | 7 460 |
| | Minimum | 22 931 | 5 450 | 4 343 | 1 332 | 3 266 | 3 464 | 2 718 |
| | Average | 26 584 | 7 926 | 6 830 | 2 403 | 4 641 | 4 325 | 4 242 |
| February | Maximum | 45 810 | 23 725 | 19 286 | 9 861 | 12 257 | 7 140 | 9 455 |
| | Minimum | 22 046 | 6 145 | 5 161 | 1 593 | 3 097 | 3 109 | 2 59 |
| | Average | 29 128 | 12 818 | 10 375 | 3 808 | 5 604 | 4 677 | 5 494 |
| March | Maximum | 70 088 | 46 857 | 27 224 | 11 541 | 10 364 | 6 193 | 9 637 |
| | Minimum | 26 335 | 11 101 | 8 427 | 2 484 | 3 333 | 3 406 | 2 575 |
| | Average | 41 707 | 25 539 | 15 440 | 5 857 | 6 350 | 4 665 | 5 375 |
| April | Maximum | 112 380 | 63 778 | 34 840 | 18 964 | 12 373 | 10 238 | 9 454 |
| | Minimum | 47 786 | 26 063 | 12 197 | 4 108 | 3 499 | 3 837 | 2 682 |
| | Average | 70 040 | 42 960 | 19 98 | 8 078 | 7 598 | 6 340 | 5 410 |
| May | Maximum | 239 416 | 80 409 | 73 357 | 26 893 | 16 706 | 36 917 | 8 871 |
| | Minimum | 59 501 | 28 632 | 18 459 | 5 399 | 4 027 | 5 511 | 3 192 |
| | Average | 139 536 | 59 744 | 34 760 | 11 185 | 9 863 | 15 041 | 6 222 |
| June | Maximum | 338 060 | 90 021 | 86 008 | 22 059 | 27 310 | 59 987 | 12 996 |
| | Minimum | 149 777 | 41 492 | 29 415 | 8 381 | 9 209 | 16 141 | 5 404 |
| | Average | 253 115 | 64 852 | 57 706 | 13 550 | 15 055 | 31 966 | 8 0 0 |
| July | Maximum | 559 812 | 91 877 | 110 376 | 28 728 | 69 010 | 90 841 | 45 471 |
| | Minimum | 227 923 | 38 324 | 59 624 | 13 090 | 13 314 | 34 877 | 9 460 |
| | Average | 337 077 | 61 420 | 85 735 | 20 947 | 40 516 | 54 863 | 21 305 |
| August | Maximum | 432 843 | 72 534 | 113 601 | 34 741 | 129 574 | 75 432 | 80 327 |
| | Minimum | 200 442 | 24 960 | 59 916 | 14 653 | 17 724 | 34 550 | 14 194 |
| | Average | 297 023 | 48 033 | 82 640 | 22 072 | 61 07 | 5 352 | 38 025 |
| September | Maximum | 188 692 | 59 204 | 7 250 | 17 686 | 65 456 | 42 899 | 51 534 |
| | Minimum | 96 529 | 15 957 | 28 510 | 6 375 | 16 169 | 14 856 | 9 589 |
| | Average | 137 287 | 27 490 | 40 328 | 9 880 | 30 081 | 25 190 | 22 278 |
| October | Maximum | 79 162 | 25 333 | 19 060 | 5 788 | 31 029 | 20 542 | 37 138 |
| | Minimum | 41 278 | 8 039 | 9 269 | 2 764 | 0 819 | 6 441 | 4 862 |
| | Average | 52 169 | 12 663 | 12 538 | 3 713 | 10 337 | 9 135 | 9 619 |
| November | Maximum | 44 641 | 15 275 | 9 782 | 3 271 | 7 622 | 8 605 | 12 3 5 |
| | Minimum | 27 280 | 5 728 | 5 879 | 1 888 | 311 | 4 450 | 3 311 |
| | Average | 33 690 | 8 369 | 7 223 | 2 323 | 5 348 | 5 798 | 5 84 |
| December | Maximum | 34 026 | 11 602 | 11 630 | 4 078 | 6 933 | 6 624 | 8 396 |
| | Minimum | 24 380 | 5 265 | 4 482 | 1 476 | 3 851 | 3 708 | 2 98 |
| | Average | 28 169 | 7 246 | 6 611 | 2 086 | 4 839 | 4 719 | 4 344 |

52 The percentage variations above and below average of the 20 years have been shown in Table XII

TABLE XII

*Variation in the Discharges of Punjab Rivers
(Percentage above and below 20 years average 1923-1942)*

| Month | Indus at Kalabag | Jhelum at Mangla above | Chenab at Marala above | Ravi at Madhopur above | Beas at Mandi Plain | Sutlej at Ruvor above (Patial) | Junna at Tajwala above |
|-----------|------------------|------------------------|------------------------|------------------------|---------------------|--------------------------------|------------------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| January | +28 | +59 | +87 | +100 | +82 | +29 | +76 |
| | -14 | -31 | -36 | -45 | -30 | -20 | -36 |
| February | +58 | +85 | +86 | +109 | +115 | +53 | +72 |
| | -24 | -52 | -30 | -58 | -46 | -34 | -55 |
| March | +68 | +83 | +76 | +97 | +63 | +33 | +79 |
| | -37 | -57 | -45 | -58 | -48 | -27 | -52 |
| April | +60 | +48 | +74 | +135 | +64 | +61 | +75 |
| | -32 | -39 | -39 | -49 | -54 | -40 | -50 |
| May | +72 | +35 | +111 | +140 | +73 | +145 | +43 |
| | -57 | -2 | -47 | -52 | -58 | -63 | -49 |
| June | +34 | +39 | +50 | +63 | +81 | +88 | +59 |
| | -41 | -36 | -49 | -38 | -39 | -50 | -33 |
| July | +66 | +50 | +29 | +37 | +70 | +65 | +113 |
| | -32 | -38 | -30 | -37 | -67 | -37 | -56 |
| August | +46 | +31 | +37 | +57 | +111 | +36 | +111 |
| | -33 | -48 | -28 | -34 | -71 | -38 | -63 |
| September | +39 | +115 | +42 | +79 | +118 | +71 | +131 |
| | -29 | -42 | -29 | -35 | -46 | -41 | -57 |
| October | +38 | +100 | +52 | +56 | +200 | +105 | +290 |
| | -21 | -37 | -26 | -26 | -34 | -29 | -49 |
| November | +33 | +82 | +35 | +41 | +37 | +50 | +156 |
| | -19 | -32 | -19 | -18 | -22 | -22 | -39 |
| December | +21 | +60 | +80 | +95 | +47 | +40 | +93 |
| | -13 | -27 | -32 | -29 | -20 | -21 | -31 |

53 These heavy variations in discharges are most disconcerting to the irrigation engineer particularly in the critical months of April, May and June and again in September, October and November. If it were possible to predict these variations beforehand, it would go a long way in helping the irrigation engineer in the regulation and distribution of available supplies. It would also guide the cultivators in planning their crops and would permit efficient operation of irrigation works.

54 In the near future it is proposed to construct large reservoirs on the Punjab rivers. These reservoirs would be used to store water for irrigation and power purposes. They can be used to good effect as flood control works if the discharges of these streams could be predicted even approximately a few months ahead. The forecast would be very valuable where water is to be used for both irrigation and generation of electric power. For instance at Bhakra Dam on the Sutlej river the economy of generating as much firm power as possible on a continuous basis and at the same time retaining enough water for irrigation would make it necessary to know in advance how much water the river would yield from month to month.

55 During July, August and September the discharges are affected by heavy monsoon rains. The October, November and December discharges are to a large extent a function of the preceding monsoons.

The Indian Meteorological Department⁽¹⁸⁾ made their first attempts at monsoon forecasting in the eighties mainly in connection with agricultural operations. These forecasts were based on empirical relations observed between certain pre-monsoon weather conditions over India (and later on over certain regions outside India such as South America and Alaska) and the subsequent monsoon rainfall. However they depended largely upon what may be termed as meteorological intuition developed chiefly by the experience of the forecaster. It was Sir Gilbert T. Walker who first eliminated this personal equation completely. He did this by applying to the problem the methods of modern statistics.

His first formula for forecasting was worked out in 1908. From the data for the years 1919 to 1924 different formulae were adopted for different regions of India.

Rainfall is forecast for N.W. India for the following seasons⁽⁹⁾ —

Winter—January-March

Monsoons—June-September

Monsoons—August-September

These forecasts refer to large areas of the country and are issued for periods of not less than two months with 80 per cent chance of correctness.

Considerable further improvement in the methods of forecasting monsoon and winter rainfall should be possible from a detailed statistical analysis of meteorological data in other regions of the earth such as Australia, America, Africa, Antarctica and the Upper air.

56 From April to June, however, the main source of run off is snow For more than 30 years forecasts have been made on certain rivers in the United States of America particularly for April to July run off from the data obtained by making measurements of the water content of the snow that accumulates during the winter

Upto 1935 forecasts based on snow surveys had been successfully made for most of the principal water sheds in Nevada Utah and California and some forecasting had been done in Oregon Idaho Wyoming and Washington Since July 1935 there has been under way a programme authorised by the Federal Government to extend and unify the activity throughout the eleven Western States

Accuracy within 10 per cent on the forecast has been usually possible In 63 forecasts covering 19 years, 41 or practically two thirds were within 10 per cent of accuracy and all were within 31 per cent Twenty seven or nearly one half were within 5 per cent (6)

A CHANGE IN THE METHOD OF MEASURING SNOW IN INDIA IS INDICATED

61 At present, in India precipitation in the form of snow is measured in two ways At stations provided with raingauges the snow collected in the gauge is usually melted by adding a known volume of very warm water and then measured as water At other places 10 inches of snow is taken as equivalent to 1 inch of rain (6)

62 The snow that falls does not flow to the stream like rain water It forms a natural storage reservoir and goes on accumulating at high elevations till it is melted by the heat received from the sun The amount of run off from a drainage basin cannot therefore be predicted from the present meteorological measurements of the snow that falls

Because the water from melting snow is far more effective in creating perennial water resources the first need is that precipitation should be classified into rain and snow separately rather than collectively as annual precipitation, as is the present practice

63 Snow is an elusive substance when falling, and is elastic and liable to erosion after it has come to rest Only in sheltered places will the precipitation gauges give readings comparable to the water content of the actual snow fall and even if the snow field is stable the snow stake will furnish a reliable index of the relative depth only after a sufficient interval has elapsed to permit the newly fallen snow to approach the density of that beneath (4)

Shielded gauges and devices for neutralizing air currents at the orifice of the precipitation are now being developed The results obtained by these methods are comparable to those of snow survey One such is the Fergusson recording rain and snow gauge fitted with an Alter Screen now being widely used on snow surveys in the Western States (U S A) The amount of precipitation is determined by weight (6)

64 Measurement of snow by means of the "snow sampler" is a very accurate method of estimating the water content of a snow field. The snow is reduced to the inelastic standard of water and the distortion in measurements due to wind can be avoided.

Vertical cores are cut from the snow along definite 'snow courses' at regular intervals and the water content is determined by weighing. The uncertain factor of the varying snow density is thus eliminated.

The snow sampler consists of—

- (a) A tube for holding the sample while being weighed
- (b) A cutter for bounding the area of the sample and
- (c) A spring balance for indicating directly the water equivalent of the snow cover.

For details of the snow sampler and other equipment reference is invited to items 6, 11 and 14 of the Bibliography.

FACTORS AFFECTING RUN OFF FROM SNOW COVER

71 The factors affecting run-off from a snow cover vary not only with geographical regions but also with seasons in the same area.

The rate and quantity of run off from melting snow are determined primarily by the water equivalent of the snow cover, ground conditions affecting infiltration losses, evaporation and the rate of release by melting.

Water contents of snow cover

72 The volume of run off from a snow cover is limited by the amount of water contained in the form of snow and ice plus the water stored in the snow structure. Water equivalent of a snow cover may substantially exceed the moisture equivalent of precipitation that occurs in the form of snow by reason of the retention of rainfall in the voids of the snow structure.

Under average conditions the density of freshly fallen snow is 10 per cent and 10 inches of snow are equivalent to 1 inch of water. As the snow remains on the ground the density increases by reason of packing and by an alternate thawing and freezing process. The density of snow may be as high as 50 to 60 per cent. The most common densities range from 20 to 30 per cent.

An appreciable amount of moisture may be retained in a snow cover in a free or unfrozen state. A fairly comprehensive series of field studies have indicated that under average conditions a column of snow is capable of retaining free water equal to 20 to 25 per cent of the dry weight of snow.

Ground conditions

73 The infiltration capacity of the soil beneath a snow blanket has a very important influence on the quantity of run off from snow melt. If the ground is frozen, the infiltration loss may be very small.

Inasmuch as snow is a poor conductor of heat very little additional freezing of moisture in the soil may be expected after a moderate depth of snow has been accumulated. The optimum ground conditions for high percentage of run off from snow melt result when a severe freeze occurs prior to the occurrence of deep snow and the capillary field moisture is high at the time of the freeze⁽⁸⁾

Evaporation

74 Monthly evaporation of snow on a watershed may vary from .04 inch to 1.4 inches or even more. Author has not been able to get any figures for evaporation in the snowed catchments of Punjab rivers. On the basis of the extremes for any single month as shown by measurements of evaporation in the open at an elevation of 6000 feet in the Sierra Nevada the maximum monthly variation in evaporation expected from the variation in the weather was about 6 per cent of the normal snow cover at that elevation. Since the increase in evaporation with elevation will be offset by the increase in depth of snow cover the percentage may well be taken as representative of other elevations.

Rate of release by melting

75 Heat of the Sun is the ultimate cause of melting. The immediate factors in the probable order of effectiveness, are

(a) radiation from sun and sky

(b) convection and conduction from the air

(c) warmth of rain

(d) penetration of snow by the energy of the sun and its radiation from beneath and the residual warmth of the earth from the previous season.

A detailed discussion of these factors would be outside the scope of this paper. Only general results are stated for the information of readers.

(a) Radiation from Sun and Sky

Under ordinary conditions there is an appreciable exchange of heat by means of radiation between a snow cover and space. The snow absorbs solar radiation and at the same time radiates heat back into space.

The net loss or gain of heat to the snow mantle by radiation has not been quantitatively determined.

Owing to direct insolation the surface of snow near midday in sunlight may melt although the air temperature is 18°F below freezing. This effect is however, greatly limited by the reflectivity of the snow surface.

(b) Convection and conduction from the air

Heat from the air to the snow mantle is transferred in two ways (i) by direct heat exchange due to the temperature difference between the air and snow and (ii) by the release of heat through condensation of moisture on the snow surface. This transfer of heat results in

conversion of the solid portion of the snow into liquid form at the rate of 1 g per 80 cal, the heat of fusion of ice. Inasmuch as the heat of fusion of ice is only 80 cal and the heat of vaporisation of water is 600 cal per g the moisture condensed on the snow surface melts 7.5 times its own weight in snow⁽¹⁷⁾

Wind may drift the snow into sheltered portions or it may increase the rate of evaporation or accelerate melting. The maximum variation in the annual drifting of snow during deposition period cannot be large and its chief effect may be retardation of melting.

Contrary to the usual belief, temperature changes within normal limits merely accelerate or retard the rate of run off without noticeably changing the total amount. This is because dripping from the snow fields once started in the spring does not cease sufficiently to allow the soil to dry out and require a second priming. In other words melting snow has the effect of continuous rain. Furthermore the snow descends into the soil in the form of what may be called 'restrained rain' rather than a 'deluge'. This is especially true at the higher elevations where the depth of the snow gives it additional capillarity. The extent of the influence of these factors on the melting of snow is indicated by the following formulae presented by Wilson⁽¹⁸⁾ —

$$D_m = K_1 V (e - 6.11)$$

$$D = K_2 V (T - 32^\circ)$$

Where D_m is the water equivalent of snow melted in 6 hours in inches depth by moisture condensation

(D_c is the depth melted in 6 hours by direct heat exchange from the air by convection and conduction

V is the wind velocity in miles per hour

T is the dry bulb temperature in F°

e is the vapor pressure in millibars

K_1 is a co-efficient involving the latent heat of ice exposure of instruments and conversion units

K_2 is a co-efficient involving the factors mentioned for K_1 and air density and turbulence

K_1 is approximately 3 to 4 times the values of K_2

For the most common arrangement of instrument installation and stations less than a few thousand feet in elevation above sea level the total water equivalent of snow melted in 6 hours by the processes referred to above (say = D_a) is given by the following approximate relationship —

$$D_a = V(0.002 T + 0.006 e - 0.100)$$

The above may be modified by multiplying with a constant representing any particular basin characteristics

(c) *Warmth of rain*

The latent heat of melting of ice is so great that the amount of melt water produced by rain is ordinarily trivial. The relation of melt-water produced in inches depth to depth of rain in inches is given by Horton(4) as

Melt water = $0.006954 (\theta - 32)p$ where θ is the temperature of the rain in deg F and p = rainfall in inches

Even with rain at as high a temperature as 52° F or 20° above freezing 1 inch of rain would produce only 1/7 inch of melt water

(d) *Residual warmth of earth*

The effect of the residual warmth of the earth from the previous season may be considered as almost negligible in the light of dry cores of snow formed throughout the winter and the relatively tiny winter run off of the streams. The exact effect of this factor in the case of Punjab rivers has yet to be evaluated

DEGREE DAY METHOD OF ESTIMATING RUN OFF FROM SNOW COVER

81 Observations of the necessary data affecting run off from snow cover are rarely available. Several investigators have tried to obtain correlations between 'degree days' of temperatures above 32° F and the run off from snow melt expressed in inches depth from the snow cover

82 Experimental data by Horton(10) and Clyde indicate that 1° F of temperature excess above 32° will produce 0.04 to 0.06 inch of melt water per 24 hours from clean snow under laboratory conditions in diffused light

83 Meagre data of snow melting rate under natural conditions by Folse Clyde and by Dr J E Church and Leach Cook and Horton(12) indicate that under natural conditions the melting constant is either of the same order of magnitude or somewhat greater. In exceptional cases the runoff from snow melt has exceeded 0.22 inch per degree day for at least 24 hours(12)

84 Observations at the foot of the Kolahai glacier (Kashmir State, India) carried out in August and September 1944 and reproduced in Table IX give a variation of 0.015 to 0.053 inches per degree day above 32° F, the average being 0.031

85 On the Chandra Bhaga (The Chenab River of the Punjab) temperatures are available for Tindi only which lies at a height of 8000 feet while the glaciers are at heights varying from 16000 to 20000 feet above mean sea level. The depth of snow melt in inches calculated on the basis of discharges and temperatures at Tindi for the various months are given in Table XIII

TABLE XIII
Depth of snow melt at Tindi
(In ins per degree day)

| Month | Depth of Snow melt in inches per degree day |
|----------------|--|
| September 1944 | 0 007 to 0 098 |
| October 1944 | 0 004 to 0 010 |
| November 1944 | 0 006 to 0 013 |
| December 1944 | 0 005 to 0 030 |
| January 1945 | 0 019 (Temperatures below 32°F but about 1 000 cusecs discharge still existed) |
| February 1945 | 0 015 to 0 044 (Temperatures below 32 F but the stream carried a discharge of about 800 cusecs) |
| March 1945 | 0 005 to 0 046 |
| April 1945 | 0 004 to 0 011 |
| May 1945 | 0 006 to 0 017 |
| June 1945 | 0 017 to 0 067 |

86 Although the range in values given above is very large it is perhaps no greater than what might be expected in consideration of the variables discussed in para 7

87 Actual melting takes place at a rate dependent on the heat balance The temperature of the air near the ground is only an indirect indicator of melting rate The intensity of solar radiation received at the snow surface appears certainly to be the principal controlling variable⁽¹⁰⁾ Measurements of solar radiation are at present meagre Neither are they likely to become sufficiently numerous compared with air temperature record to permit their general use in predicting snow melting phenomena It seems possible by researches to correlate the direct variables with air temperature in such a way as to provide a basis for selection of a melting constant for given conditions to be applied in conjunction with air temperature excess much as an engineer selects a roughness factor for use in conjunction with the Kutter or the Manning formula⁽¹⁰⁾ Such researches are greatly to be desired

HOW STREAM FLOW CAN BE FORECAST FROM SNOW SURVEYS

91 Dependable estimates of the run off of the snow fed streams of the Punjab particularly from April to June can be made from the measurement of the snow pack after the accumulation of snow has reached its maximum

Two methods of forecasting based upon snow surveying have been developed in America. The difference between the two methods is fundamental. The earlier is known as 'the method of areas' and the more recent one as 'the percentage method'.

The method of Areas

92 Snow surveying had first taken the form of measurement of the cubic contents or acre feet of water in the snow for entire basins with estimates of losses suffered *en route* to the discharging streams. This was accomplished by the use of numerous measurements at random or in fixed locations as the surveyors might elect. It was known as 'The method of areas'. It differed in no way from the precipitation gauge except that it covered the area in greater detail. This method suffers from two difficulties —

(1) the large variation of the snow cover (even of individual basins) with elevation and distance from the crest of its watershed

(2) the difficulty of determining the normal seepage and evaporation losses of the region

The above two difficulties cause a wide divergence between the snow cover and the run off.

The percentage method

93 A more recent method developed at Nevada, U.S.A. and known as 'the percentage method' discards entirely the 'method of areas' — It merely seeks to determine the percentage the snow field at any fixed point bears to the average snow field in the basin. To do this it is necessary only to maintain a series of measurements carefully taken in the same spot each year. These measurements laid out at definite intervals from one fixed point to another were named 'snow courses'. To avoid the effects of drifting long courses with twenty-five to fifty samplings are sometimes employed and the average taken as indicating the snow cover.

The 'percentage method' is based upon the fact that the big storms which furnish the bulk of the winter snow are comparatively uniform in intensity over a considerable area thus differing from the spotted character of rainfall.

According to this method the only thing required is to maintain 4 to 6 snow survey courses distributed over characteristic parts of a basin and by averaging these individual seasonal percentages to obtain a close seasonal percentage for the basins as a whole. If averaged for a fair number of years the course would give a 'normal' or 'mean' water content by which to estimate the percentage relationship of coming seasons. This would be obtained by dividing the new snow cover by the mean snow cover. Variations of snow cover are known to range from 30 per cent to 160 per cent of the normal and even more on occasions.

94 This percentage relationship is found to correspond closely with a similar percentage relationship of run off in the streams fed by the snow fields. Thus a 75 per cent snow cover of April assumed an approximately 75 per cent runoff during the months of April to June inclusive. After this streams will be affected by heavy monsoon rain.

The graph reproduced below as Figure 1 shows the harmony that exists between snow cover and runoff of the Truckee River Basin (California Nevada) (from item No 6 of Bibliography)

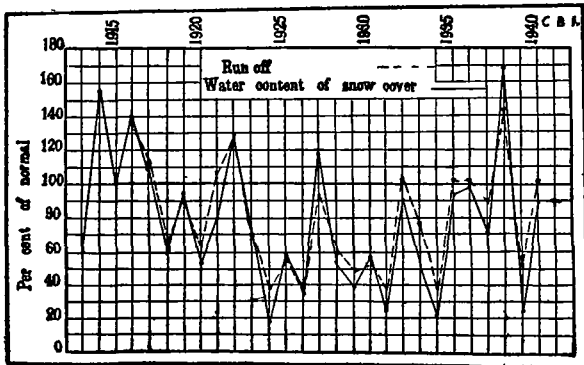


Figure 1

The percentage method avoids practically all the objections to the rainfall or area method and permits unified treatment of all basins irrespective of their size elevation physical character forestation and the nature of the catchment drainage.

The water content is determined by means of the ' Snow sampler ' described in paragraph 64.

95 The water supply forecasts based on snow surveys are made on the assumption that there is a simple relationship between the water content of the snow cover on a drainage area and the run off from that area⁽¹⁴⁾

Observations are maintained for a number of years for the measurement of average depth of water in snow cover at suitably selected points and net run off in acre feet. The results are plotted as shown in Figure 2 (Boise River Basin Idaho) and a correlation between the two quantities obtained.

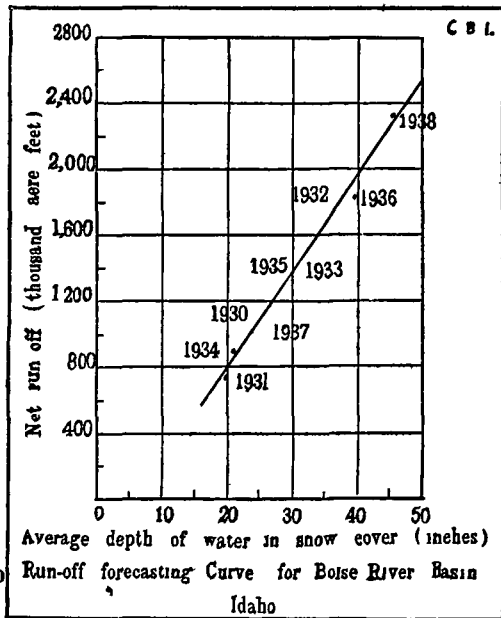


Figure 2

The average depth of water in snow cover is the arithmetic mean of the means of the water content measurements for the three courses on the Boise River Basin. The net run off is the sum of the stored water accumulating in Deer Flert and Arrowrock Reservoirs.

In the case cited a first degree function was fitted the equation representing the straight line being⁽¹⁴⁾

$$R = 57.9 P - 369.4$$

Such a function can be used very effectively for forecasting the supplies available during the coming hot weather if P , the water content is determined by systematic observations of suitable points on a few selected snow courses.

96 The factors affecting the forecast by the percentage method are few. The basic preliminary requirement is the maintenance of fixed snow courses with fixed points of measurements. Courses should be fairly long say about 40 measurements 50 to 100 feet apart. Also courses should be located at sufficient altitudes to prevent distortion of the measurements by winter melting.

Accuracy of stream measurements is equally important Unless based on a long period the normals for snow cover and stream flow should represent the same series of years

The chief distorting factor is the possible divergence from the normal of the precipitation during the period If precipitation is entirely lacking the runoff will fall below the forecast to an amount dependent upon the rate of the water content of the normal snow cover to the normal precipitation during the period

On the Punjab rivers this factor during April May and June is comparatively less significant Thus a high degree of accuracy in forecasting for these months should be possible

SNOW SURVEYING—A FIT SUBJECT FOR THE CENTRAL WATERWAYS IRRIGATION AND NAVIGATION COMMISSION

101 The snow fields and glaciers which feed the Punjab rivers are mostly situated outside the provincial boundaries of the Punjab While the Punjab will undoubtedly gain from any snow surveys that are undertaken the subject is of interest to many others not connected with the Punjab The subject appears therefore to be worthy of the attention of the newly constituted Commission of Waterways Irrigation and Navigation at the Centre

102 In the United States too prior to the winter of 1935-36 snow surveying by the percentage method was in progress in California and parts of Nevada and Utah with local measurements in two or three other western states From July 1 1935 the Federal Congress authorised the Division of Irrigation of the United States Department of Agriculture to coordinate and extend snow surveying and the forecasting of irrigation water supplies to all western states Co operation has been effected with the western Canadian Provinces as well Exchange of data between the States and with Canada has been most effective The equipment has been standardized so as to give comparable results

103 Under the Federal Government progress has been very rapid In 1943 there were 829 dependable snow courses The number of measurements on each course averaged at least 15 There were 177 active operators The snow courses are measured three times each year in some States four times in others and five times in still others complete measurements being made on February 1 and April 1

Releases of snow survey and water supply information were made from two to five times in each state There were 153 radio broadcasts giving information on water supply and snow conditions In addition information is furnished to the local press and for release in Washington There were 966 individuals who took part in snow surveying on February 1 and again on April 1 1943 The snow surveyors have at their disposal 266 shelter cabins and of these 77 are owned by the Government Many of the snow courses are so located that they are readily accessible to roads that are kept open during the winter or near habitations where food and shelter are obtainable

104 It is further suggested that the co operation of the Meteorological Department of India should be enlisted in improving the

methods of forecasting rainfall more accurately with a view to utilizing the information along with the results of snow surveys for the purpose of forecasting the discharges of rivers

SUMMARY AND CONCLUSIONS

11 The author has shown that snow and glaciers have very important effect on the discharges of Punjab rivers. There are appreciable contributions to the run off from glaciers. The question naturally arises that if the glaciers from which the Punjab rivers are fed are receding how are the discharges of these rivers in the distant future likely to be effected.

Snow and glaciers form very valuable natural storage reservoirs for the Punjab canals. It is therefore highly desirable that a proper account of such resources is kept. Snow fields and glaciers feeding the Punjab rivers are however mostly situated outside the boundaries of the province. Snow surveying will also be of interest to others besides the Punjab. It is therefore suggested that Snow Surveying is a fit subject to be taken up by the newly constituted Commission of Water ways Irrigation and Navigation just as it is being done by the Federal Government of the United States of America.

The present methods of measuring snow in India are inadequate. It is therefore necessary to introduce more modern methods such as have been developed in the United States in recent years.

It has been shown that it is possible to forecast river discharges from March to June from snow surveys and that such forecasts will be of great help to irrigation engineers for the distribution of available water supplies and in the operation of irrigation works including proposed storage reservoirs.

A case has been made out for effecting improvements in forecast of rainfall by the Meteorological Department with a view to utilizing the information in conjunction with results of snow surveys for forecasting discharges of rivers.

ACKNOWLEDGMENTS

12 Analysis of Chenab catchment was done by Mr G S Lamba and of Jumna catchment by S B Raghbir Singh both Executive Engineers Irrigation Department Punjab under general directions of the Author.

Dr J E Church Meteorologist of the International Commission of Snow and Glaciers United States of America has very kindly supplied a complete set of literature on the work done in this connection in the States. The Author has drawn freely on this literature. A complete list of authors referred to is given in the bibliography.

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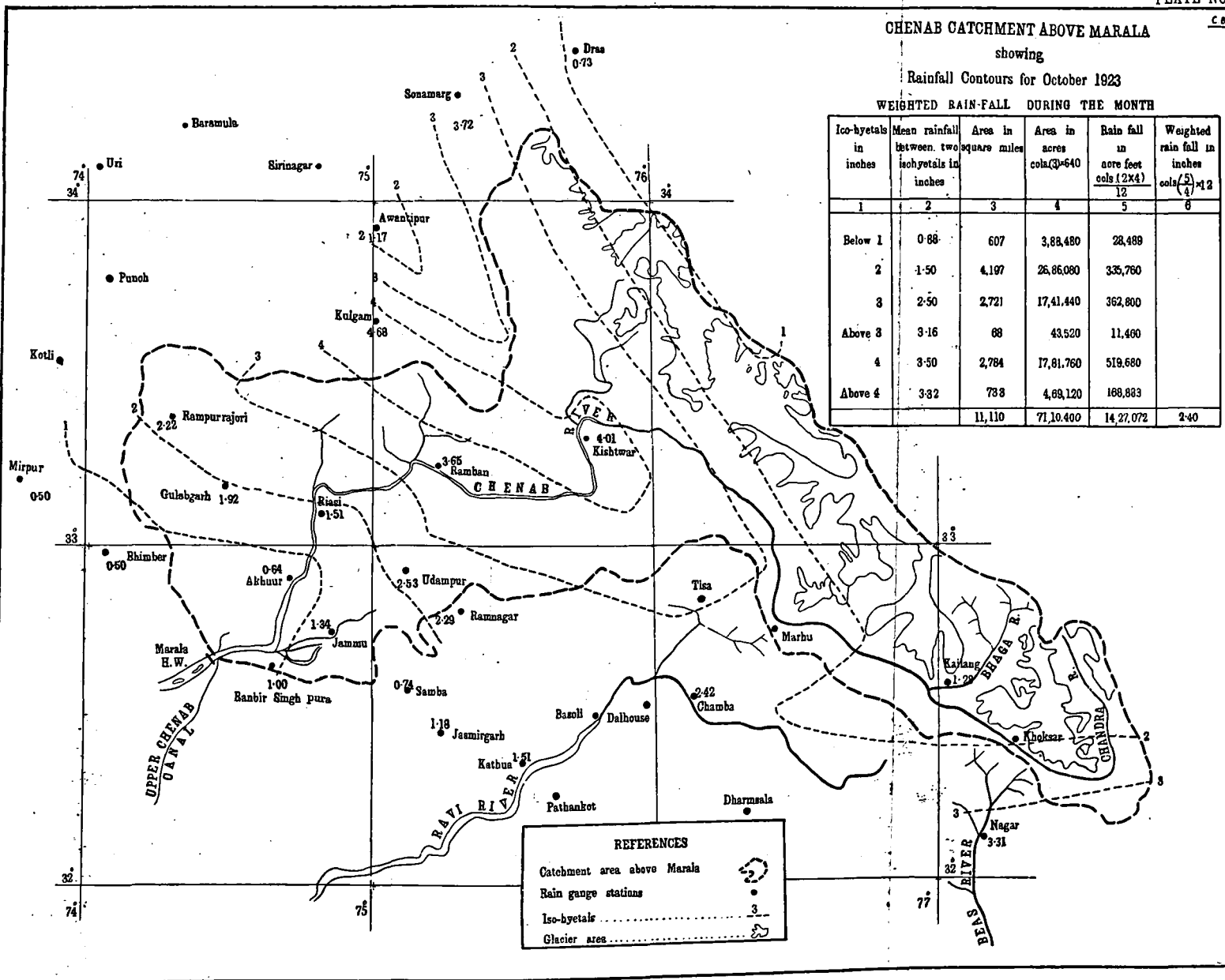
CHENAB CATCHMENT ABOVE MARALA

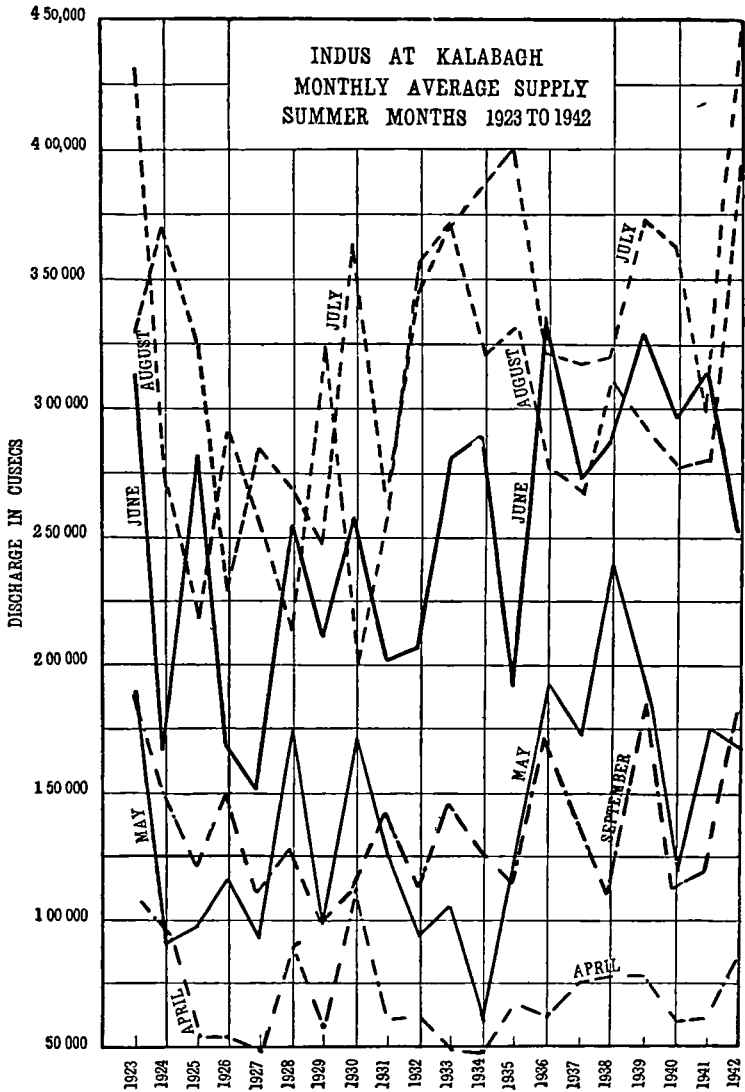
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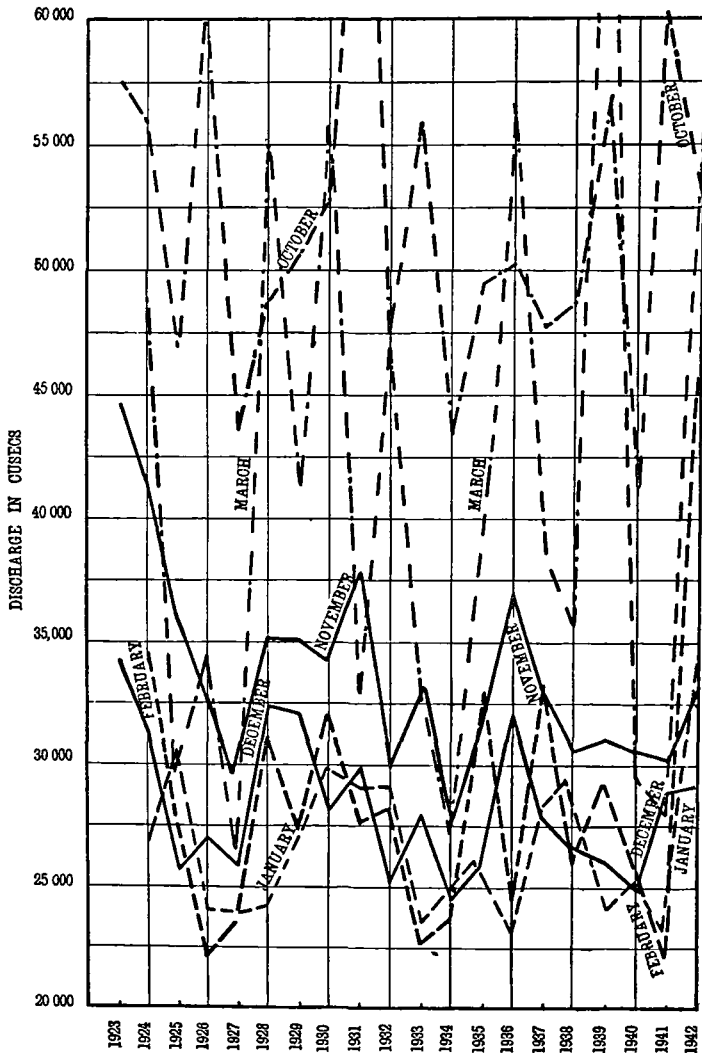
Rainfall Contours for October 1923

WEIGHTED RAIN-FALL DURING THE MONTH

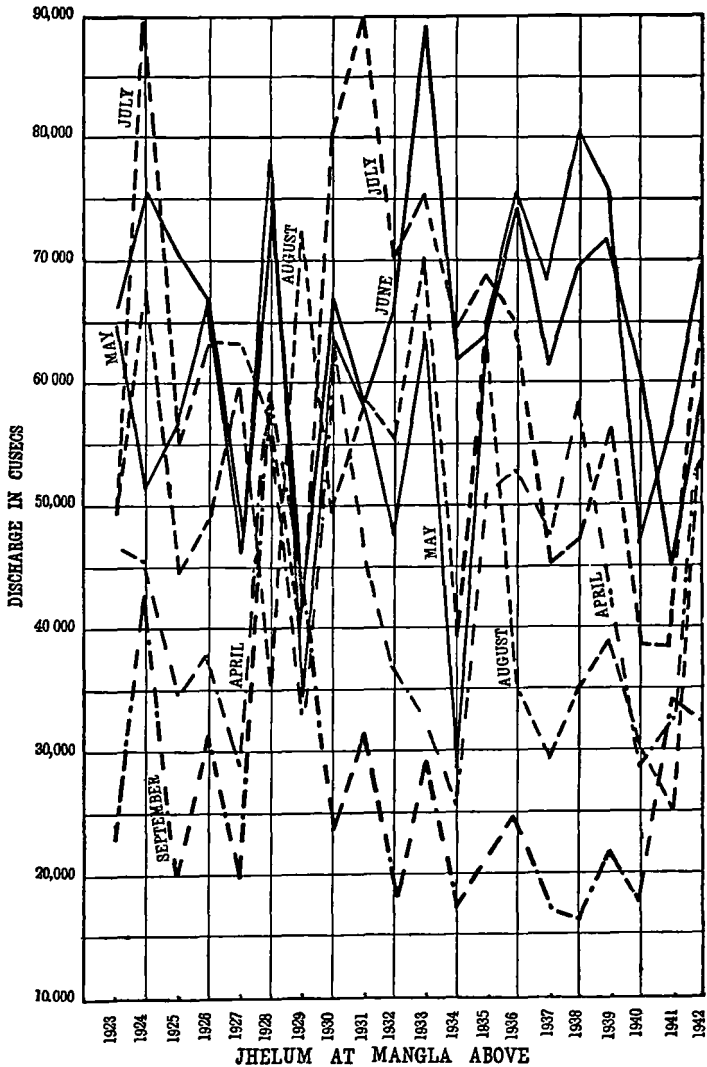
| Iso-hyetsals in inches | Mean rainfall between two isohyetsals in inches | Area in square miles | Area in acres cols (3) x 640 | Rain fall in acre feet cols (2) x 4 / 12 | Weighted rain fall in inches cols (2) / 4 x 12 |
|------------------------|---|----------------------|------------------------------|--|--|
| 1 | 2 | 3 | 4 | 5 | 6 |
| Below 1 | 0.88 | 607 | 3,88,480 | 28,488 | |
| 2 | 1.50 | 4,197 | 26,86,080 | 335,760 | |
| 3 | 2.50 | 2,721 | 17,41,440 | 362,800 | |
| Above 3 | 3.16 | 88 | 43,520 | 11,460 | |
| 4 | 3.50 | 2,784 | 17,81,760 | 519,680 | |
| Above 4 | 3.32 | 733 | 4,69,120 | 168,883 | |
| | | 11,110 | 71,10,400 | 14,27,072 | 2.40 |



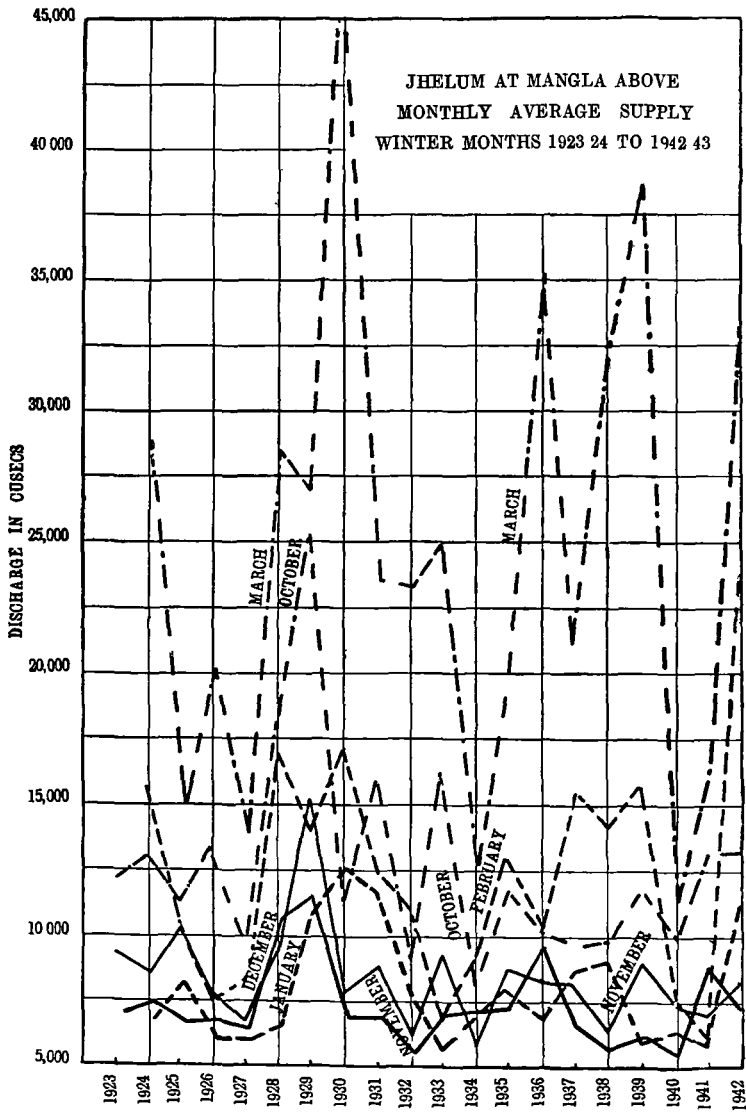


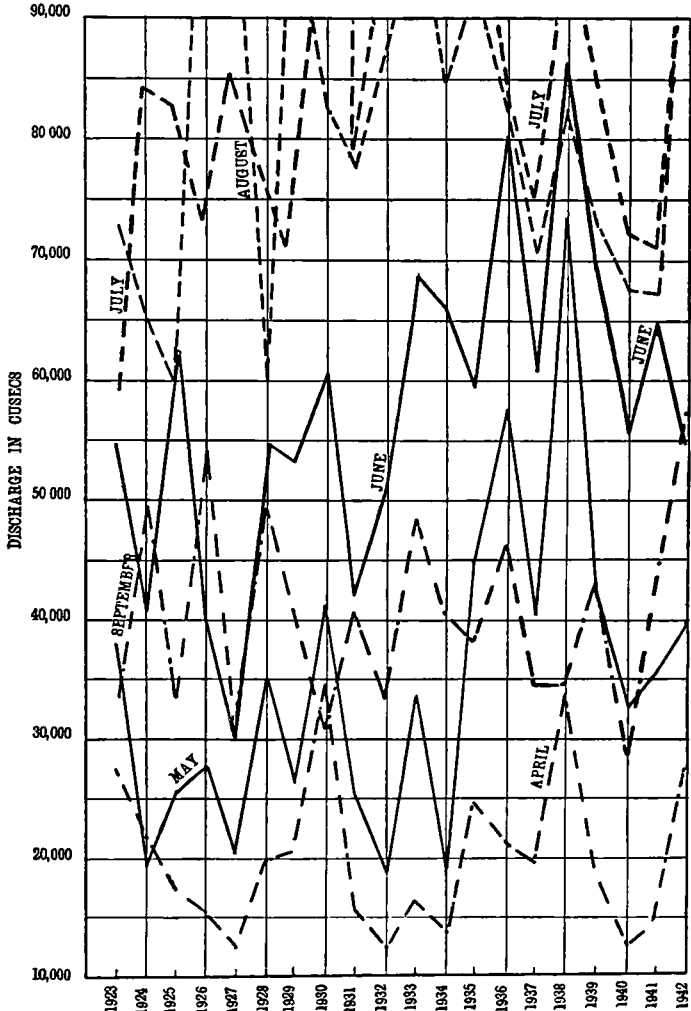


INDUS AT KALABAGH
MONTHLY AVERAGE SUPPLY-WINTER MONTHS 1923 24 TO 1942 43

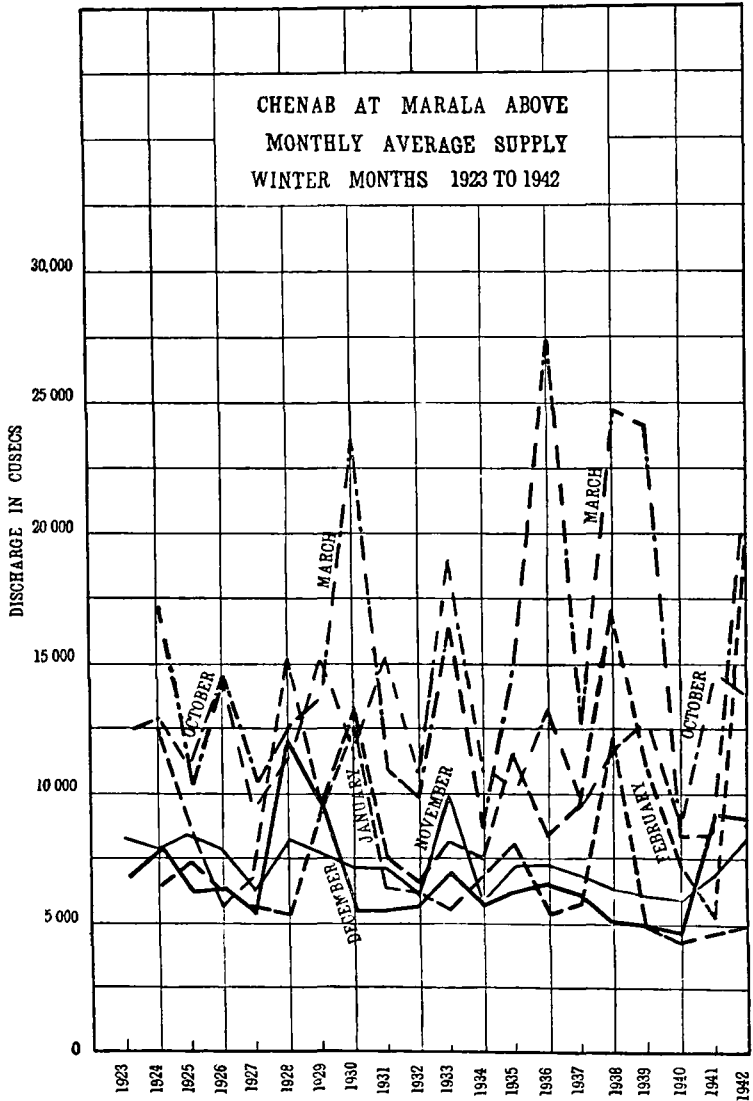


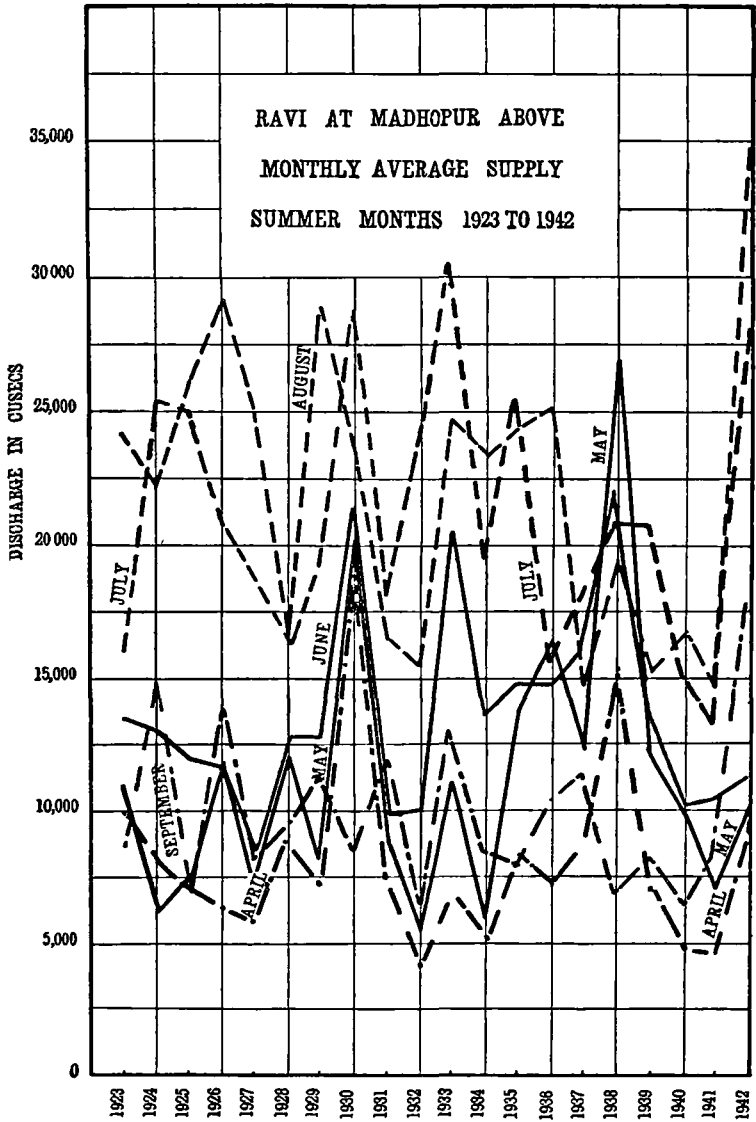
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MONTHLY AVERAGE SUPPLY—SUMMER MONTHS 1923 TO 1942

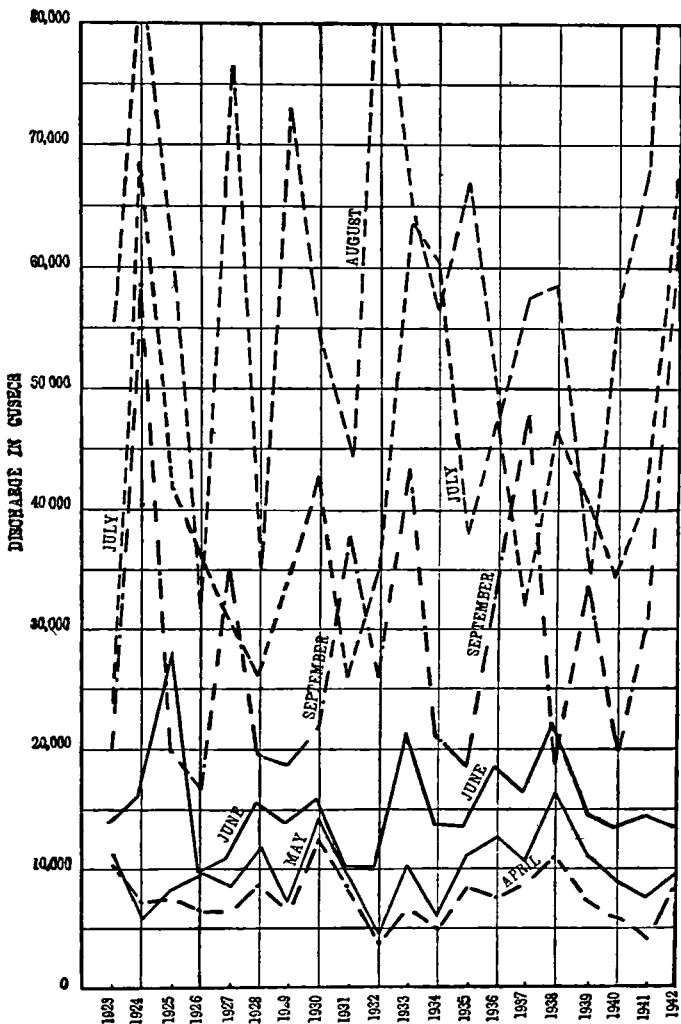




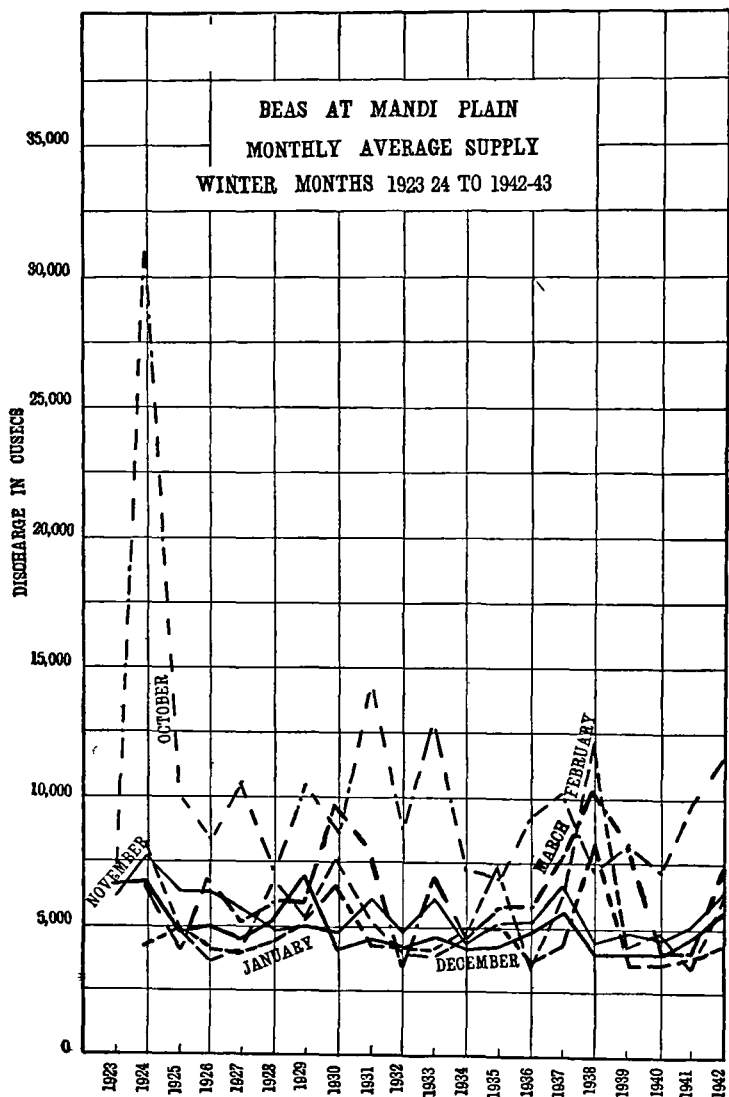
CHENAB AT MARALA ABOVE
MONTHLY AVERAGE SUPPLY SUMMER MONTHS 1923 TO 1942

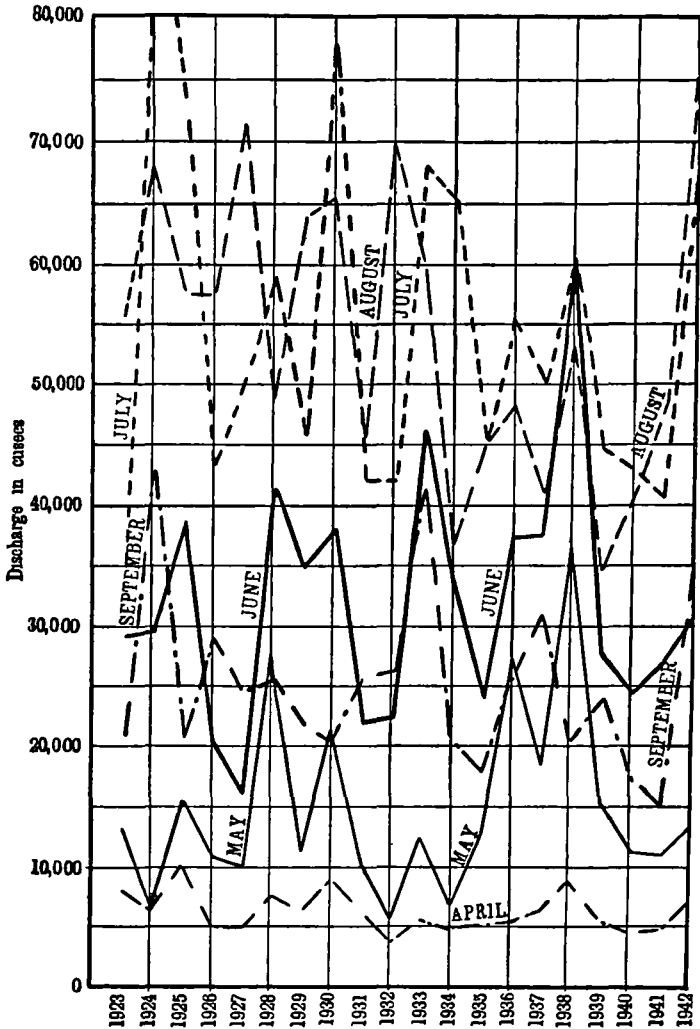




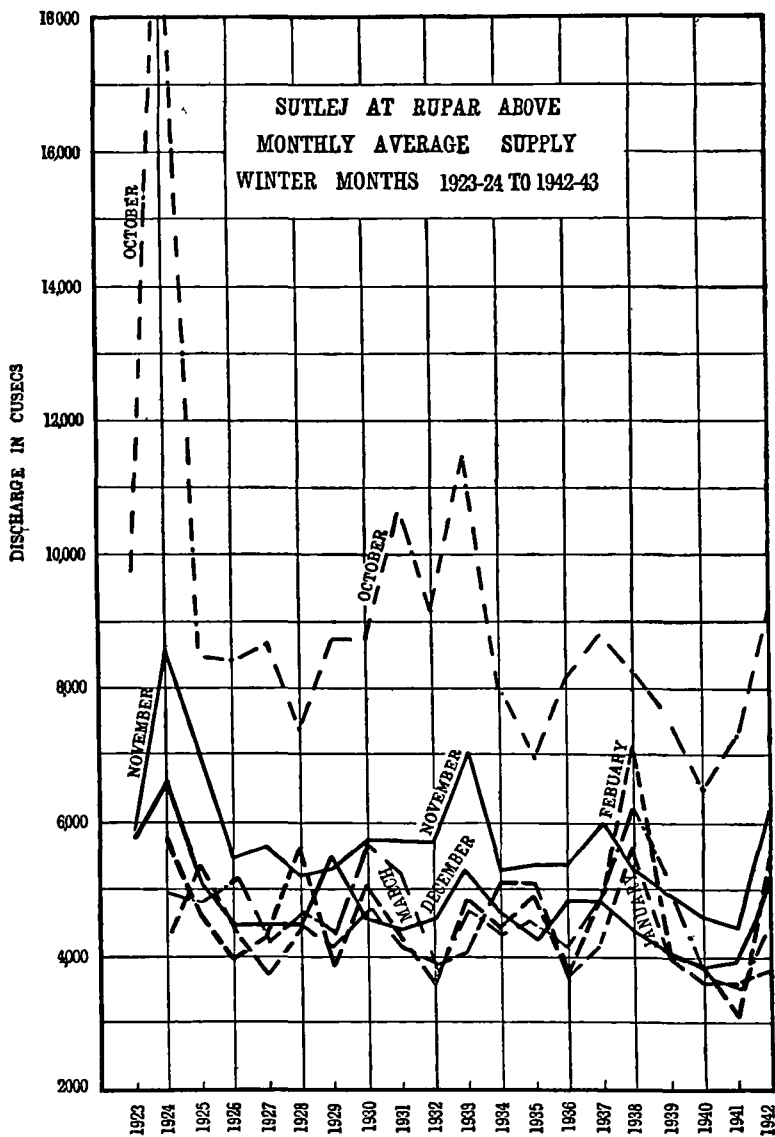


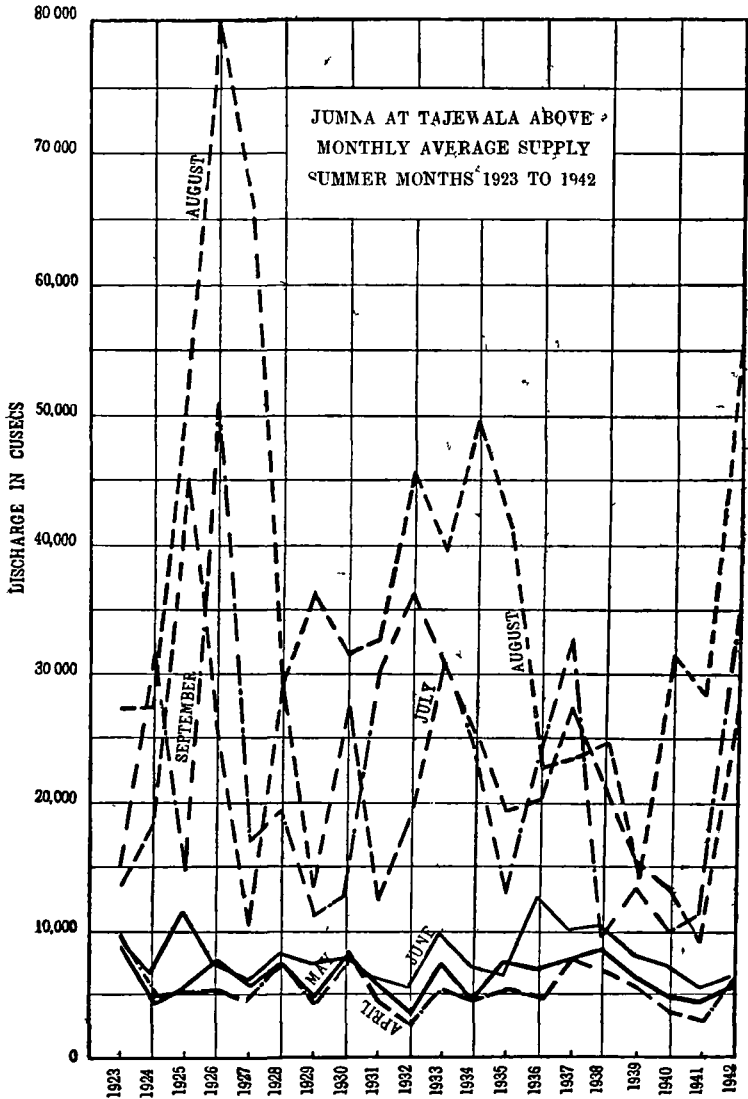
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MONTHLY AVERAGE SUPPLY—SUMMER MONTHS 1923 TO 1942

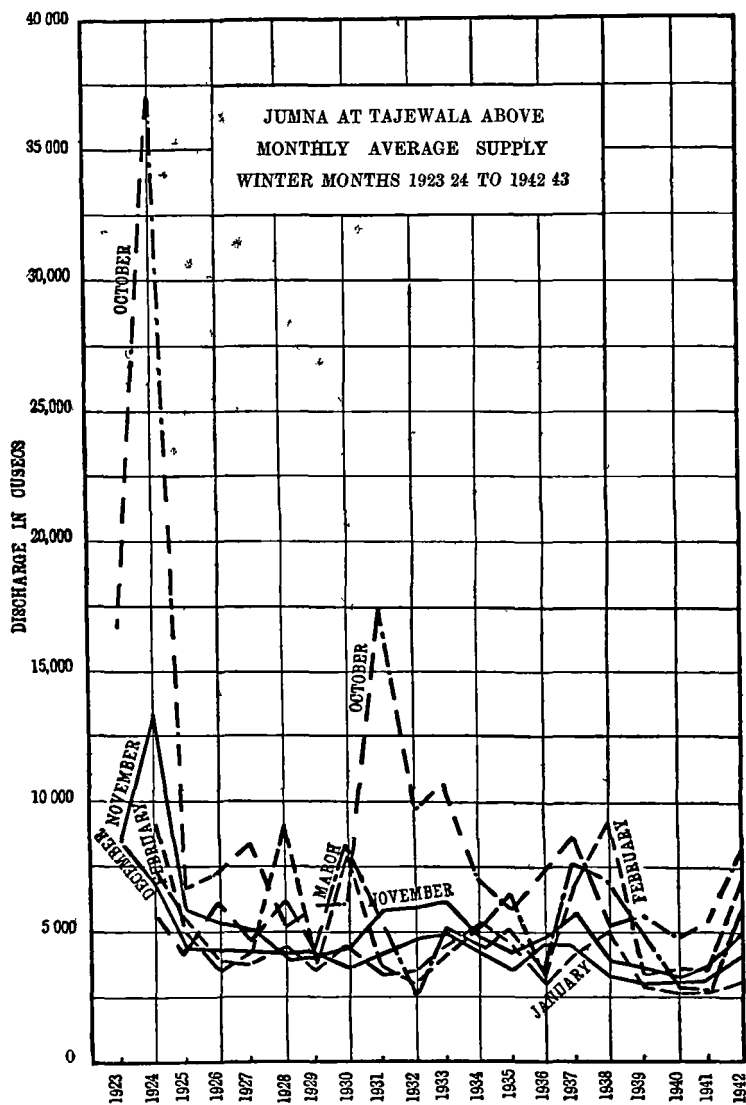




SUTLEJ AT RUPAR ABOVE
MONTHLY AVERAGE SUPPLY FOR SUMMER MONTHS
1923 TO 1942







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- i Waterlogging & Reclamation
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 - iii Design of works on sand foundations
 - iv Fluming of canal works
 - v Regulation at canal headworks
 - vi Design of canal falls
- 2 Digest of Technical Notes 1932
 A summary of views of Chief Engineers on the following Subjects —
- i Waterlogging
 - ii Design of works on sand foundations
 - iii Design of canal falls
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- 11 Annual Report (Technical) of the work of the Central Board of Irrigation India 1934 35
- 12 Design of Weirs on Permeable Foundations by R B A J J Nath Khosla Dr Nolini Kanto Bose and Dr E McKenzie Taylor
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