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Arid zone of India and Pakistan : A study in its water balance and delimitation

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ABSTRACT. In this paper, a study of the water balance cf the arid zone of India and Pakistan has been made and on that basis the arid zone itself has been delimited. The limits obtained have been compared with the limits suggested by different authors.

1. Introduction

We, in India and Pakistan, are vitally concerned with the arid zone problem but so far no attempt appears to have been made to study scientifically the extent of the arid zone, its water balance and the magnitude of water deficiency in it. One of the factors responsible for the creation of arid zone is, of course, low rainfall and many authors have, during the past years, laid emphasis on this factor alone. It is no doubt true that mostly areas with low rainfall are found to be arid and this fact has resulted in the association of aridity with low rainfall and of arid zones with areas of low rainfall.

But aridity is not the result of low rainfall alone. Aridity signifies a deficiency of moisture and is caused when the rainfall of any region is unable to meet the requirements of evaporation from the soil and transpiration from the plants. The phenomena of evaporation and transpiration are absolutely independent of rainfall in so far as the factors responsible for them are concerned. The evaporation and transpiration, together called evapotranspiration, represent a process reverse to that of rainfall in the hydrologic cycle. Rainfall brings the water from the atmosphere to the surface of the earth while evaporation is responsible for carrying the water from the earth's surface back to the atmosphere. Therefore, by considering rainfall alone, we cannot know whether a place is arid or not. In any attempt to determine aridity, the phenomena of evapotranspiration must be considered along with rainfall.

The water requirement of evapotranspiration differs very much from the distribution of rainfall through the year and itself varies from season to season ; being high in summer and very low in winter. The rainfall too, varies from month to month. If the rainfall is more than the water requirement of evapotranspiration in any month, the surplus water runs off through and over the ground. If the rainfall is less than the water required for evaporation and transpiration, there is no surplus and no run-off. The vegetation uses less water than it would have used if more water were available and likewise less water evaporates from the soil. There is a deficiency of water and the evapotranspiration is limited to the amount of water available from rainfall. If, month after month, there is a deficiency of water, arid conditions may prevail. How arid a place would be depends upon the magnitude of water deficiency in relation to the water requirement of evapotranspiration.

2. The Technique

The water requirement of evapotranspiration mentioned above has been called potential evapotranspiration by Thornthwaite (1948). It expresses the amount of water that would evaporate and transpire if it were available. The measurement of potential evapotranspiration is a difficult task as it involves water that would evaporate and transpire rather than that which actually evaporates and transpires. Thornthwaite has, however, evolved a method for the determination of potential evapotranspiration from temperature, for which abundant data are available. The values of potential evapotranspiration obtained by this method are taken for water need and compared with the corresponding values of rainfall for each month. Water budgets for all stations, for which data are available, are prepared to determine water deficiency and water surplus for each month of the year. In the estimation of water surplus, Thornthwaite allows ten centimetres for storage in the soil and this is used before any deficiency appears. For example, when the rainfall of a month exceeds water need by 4 centimetres, it would be retained by the soil in storage and there would be no surplus water. In the succeeding months, the shortage of rainfall over water need upto an extent of 4 cm would be met from storage in soil before any deficiency occurs.

The annual water deficiency and water surplus obtained in the water budget are expressed as percentage of the annual water need to obtain the index of aridity and the index of humidity respectively. In the overall moisture index, both the indices are taken; the index of humidity affecting positively and the index of aridity affecting negatively, though the index of aridity is underweighted by multiplying it with 6/10. The moisture index thus obtained clearly expresses the relation between water need, rainfall, water surplus and water deficiency. On this basis, regions with a moisture index of less than —40 have been defined by Thornthwaite as 'arid' and areas with moisture index between —20 and —40 as 'semi-arid'. On the basis of the above given method, water budgets for stations noted in Appendix A have been prepared and the characteristics of each of these elements are discussed.

3. Water need in the arid zone of India and Pakistan

The annual water need throughout the arid and semi-arid regions of India and Pakistan varies from 135 to 160 cm over the plains though it considerably decreases with increase of elevations. All along the coast of West Pakistan, the annual water need varies from 140 to 150 cm while along the Saurashtra coast it is still higher. It is 152 cm at Jacobabad, 154 cm at Bikaner, 143 cm at Hissar, 141 cm at Khushab, 156 cm at Badin and 160 cm at Deesa. At Kalat (6616 ft), it is 72 cm while at Quetta (5490 ft) it is 82 cm. Along the coast, it is 148 cm at Karachi, 153 cm at Dwarka and 151 cm at Veraval.

In this region, the temperatures are the lowest during January and February. Consequently water need is low during these months. For instance, the water need in January at Jocobabad is only 0·98 cm; at Bikaner 1·31 cm; at Hissar 1·16 cm; at Khushab 0·89 cm; and 2·02 cm at Badin. In coastal areas, where the temperatures during winter do not fall very low, the water need in January is comparatively higher than the inland stations, *e.g.*, the January water need at Karachi is 4·16 cm, at Dwarka 5·02 cm and at Veraval it is 6·46 cm.

In the month of March, the temperatures shoot up and continue to rise in April and May. For instance, at Jacobabad, the temperature for February is 17·7°C and it rises to 24°C in March, to 29·6°C in April and to 35·1°C in the month of May. The water need too rises in the same way. Throughout this region, the temperatures reach a maximum in May or June and the highest water need occurs about the month of June. Maximum water need for a summer month varies from 20 to 22 cm over the Punjab plains, west Rajasthan and Sind. Along the coast, the maximum water need varies around 18 cm, *e.g.*, at Khushab it is 21·68 cm, at Bikaner 21·32 cm and at Hyderabad 20·58 cm in the month of June, while at Karachi it is 18·62 cm and at Dwarka 18·40 cm.

The water need for the three summer months in general varies from 36 to 45 per cent of the annual water need over the plains and near the coast. The percentage, however, increases with increase in elevations.

After the hot weather season, the water need falls though it is still considerable. For instance, at Jacobabad the water need is 20·3 cm in August and 17·7 cm in September. The corresponding figures for Bikaner are 19·3 and 17·2 cm. At Lyallpur, water need for August and September is 19·6 cm and 16·8 cm respectively. There is a steep fall in water need in the month of November when the water need falls by 5 to 10 cm from the October water need. For instance, at Jacobabad the water need falls from 14·2 cm in October to 4·9 cm in November; at Barmer it falls from 15·1 cm in October to 8·3 cm in November and at Hissar from 12·7 cm to 4·2 cm. Along the coast of West Pakistan, the fall in water need from October to November is only 4 to 5 cm, *e.g.*, at Karachi, the fall is 4·2 cm. Along the Saurashtra coast, the fall is only 2 to 3 cm, *e.g.*, at Veraval the fall from October to November is 2·5 cm.

Water need data for some stations in the arid zone of India and along its borders are given in Table 1.

4. Rainfall in the arid zone of India and Pakistan

The rainfall in the arid zone is obviously low and in general, it decreases westwards and inland within the region under consideration. Not only is the annual rainfall small, it is unevenly distributed through the year, apart from being erratic and highly variable. The rainfall in this region is received in two distinct seasons when the rainfall is definitely more than in any other period during the year. These two seasons are (*i*) monsoon season and (*ii*) the winter season, when western disturbances provide a small amount of rainfall which is extremely valuable, as at that time the water need is quite low.

In general, the rainfall in the monsoon season constitutes more than 50 per cent of the annual and at most places it makes up 60 to 75 per cent of the year's total. In the heart of the desert, at Jacobabad, the annual rainfall is 9·1 cm (3·6 inches) and of this 4·64 cm (about 51 per cent) falls in the months of July and August. At Karachi, out of an annual total of 19·5 cm, the rainfall in July and August contributes 12·08 cm (about 62 per cent). The winter rainfall derived from western disturbances forms only a small percentage over most of the region though in the extreme west, particularly in the elevated parts, winter rainfall is very significant. For instance, at Dera Ismail Khan, the rainfall of January and February totals to 2·84 cm (about 12 per cent of the year's total) but this is enough to meet the water need for January and February which is only 2·44 cm. At Quetta (5490 ft) the winter rainfall forms the bulk of the annual rainfall. At Kalat (6616 ft) the rainfall for January and February is only 6·85 cm but this is enough to ward off any deficiency during the two succeeding months. Table 2 gives the annual, winter and monsoon rainfall for some selected stations.

Here it may be mentioned that the variability of rainfall in the arid zone is very great but in the present paper, it has not been taken into account because the corresponding values for water need have not been calculated. Unless the two can be compared, any mention of variability of rainfall would be out of place in a study like this.

A comparison of the march of rainfall and water need through the year in the area under consideration is shown in Fig. 1.

5. Water deficiency in the arid zone of India and Pakistan

The rainfall is far short of the water need in all or most months in the year throughout the arid zone. Nowhere in the arid zone is there a water deficiency of less than 95 cm in a year except in the elevated regions. Over the plains and in the central parts of the arid zone, the annual deficiency of water is above 130 cm though over a small region, it exceeds 140 cm. Over most parts there is w ter deficiency in all the twelve months of the year but in some parts, particularly in the

TABLE 1

Water need (in cm) at selected stations

Station	Annual water need	Summer water need (3 months)		Maximum monthly need	Minimum monthly need
		Actual	% of annual		
Agra	137.80	61.00	44.3	20.80	0.90
Ahmedabad	172.57	59.81	34.6	20.72	5.44
Ajmer	140.59	59.24	42.1	20.42	1.98
Aligarh	143.09	60.94	42.5	20.76	1.53
Ambala	138.81	61.33	44.1	20.90	1.39
Badin	155.95	60.24	38.6	20.33	2.02
Bahawalpur	143.65	63.46	44.1	21.51	0.91
Bareilly	140.92	59.41	42.1	20.28	1.88
Barmer	156.23	60.82	38.9	20.76	2.18
Baroda	155.66	56.35	36.2	19.95	4.32
Bhavnagar	163.41	57.71	35.3	20.07	4.65
Bhuj	156.15	57.34	36.7	19.69	3.39
Bikaner	153.88	63.48	41.2	21.32	1.31
Brijnagar	143.17	58.81	41.0	20.86	2.67
Dehra Dun	117.55	52.20	44.3	17.99	1.94
Dera Ismail Khan	140.26	63.93	45.5	21.80	0.93
Dwarka	153.50	54.26	35.3	18.40	5.02
Hissar	143.62	62.43	43.4	21.06	1.16
Hyderabad	158.22	61.68	38.9	20.65	2.11
Jacobabad	152.67	64.41	42.1	21.71	0.98
Jaipur	143.05	60.18	42.0	20.52	2.00
Jaisalmer	150.52	62.36	41.4	21.17	1.96
Jamnagar	152.46	56.60	37.1	19.21	3.60
Jodhpur	150.61	61.21	40.6	20.69	2.25
Karachi	148.10	54.74	36.9	18.62	4.16
Khanpur	148.13	63.61	42.2	21.47	0.91
Khushab	141.88	64.03	45.1	21.68	0.89
Kotah	156.49	61.31	39.1	21.15	2.44
Lahore	132.73	61.80	46.5	21.16	1.11
Ludhiana	139.87	62.18	44.4	21.12	1.16
Lyallpur	138.57	63.49	45.8	22.18	0.91
Mainpuri	146.32	61.48	42.0	20.87	1.74
Multan	144.33	64.06	44.3	21.78	0.90
Neemuch	139.82	56.15	40.1	20.10	3.02
Ormara	146.28	56.42	38.5	18.96	3.53
Pasni	141.91	54.86	38.6	18.51	3.53
Rajkot	155.52	56.18	36.1	19.65	4.18
Rawalpindi	122.36	59.16	48.3	20.77	0.97
Sialkot	135.36	62.14	45.9	21.34	1.17
Sikar	142.15	62.19	43.7	21.12	1.67
Veraval	150.01	50.43	33.4	17.16	6.46

TABLE 2

Rainfall (in cm) in the arid zone

Station	Elevation (ft)	Annual rainfall	Monsoon rainfall Jul-Aug	Winter rainfall Jan-Feb	Maximum monthly rainfall (with month)
Barmer	10	29·99	21·63	1·16	13·38 (Aug)
Bikaner	734	29·07	17·62	1·36	9·14 (Aug)
Bhuj	343	34·59	23·52	0·63	16·08 (Jul)
Hissar	725	42·57	23·24	2·64	12·37 (Aug)
Jacobabad	186	9·09	4·64	1·41	2·41 (Jul)
Karachi	13	19·50	12·08	2·27	8·12 (Jul)
Khushab	612	38·52	18·81	4·08	9·90 (Jul)
Lahore	702	48·74	26·92	5·10	13·84 (Jul)
Las Bela	292	21·27	9·37	2·89	6·68 (Jul)
Pasni	10	15·61	1·62	8·53	4·95 (Jan)
Quetta	5490	23·92	1·99	9·94	5·02 (Feb)

elevated regions, there is no deficiency during one or two winter months. For instance, at Jacobabad and Bikaner, the annual water deficiency is 143 and 124 cm respectively and there is deficiency in all months though varying in magnitude. At Khushab and Sibi there is an annual deficiency of 103 and 140 cm respectively but there is no deficiency in the months of January and February.

A study of the march of water deficiency through the year shows that throughout the arid zone, peak of deficiency is reached in the month of May or June preceding the monsoon. This would be so because the hot weather season in India lasts from March to June. The monsoon begins at the end of the hot season and this generally results in slight fall in temperatures but the temperatures are still quite high in the rainy season. Therefore, the water deficiency remains high from April upto the month of October, though during the rainy season, it may fall.

The march of water deficiency at Jacobabad, in the heart of the arid zone, and at Hissar and Khushab on the borders is given in Table 3. For comparison, the data for Delhi and Aligarh, which lie outside the arid zone, is also given. In Table 4 some interesting data on the characteristics of water deficiency at selected stations is given. The march of water deficiency through the year is shown in Fig. 2.

The index of aridity which expresses annual water deficiency as a percentage of annual water need, gives a fair picture of the magnitude of aridity. The index of aridity in the arid zone is, by definition, more than 66·6 and obviously along the borders, it is nearer this value while towards the interior of the arid zone, the index of aridity increases. In the extreme case where the annual water deficiency equals annual water need, the index of aridity equals 100. In the arid zone of India and Pakistan, the magnitude of aridity becomes clear when we note the aridity index for Jacobabad and Sukkur. The aridity index is 94 for Jacobabad and 93·9 for Sukkur. These places represent the extreme cases within the arid zone and the area around Jacobabad and Sukkur is undoubtedly the heart of the Great Indian Desert. In fact, in the entire area of central and southwestern parts of West Pakistan and along the Indo-Pakistan border in western Rajasthan, the index of aridity is more than 80. The indices of aridity for a number of stations in and around the arid zone are given in Table 5.

6. Delimitation of the arid zone of India and Pakistan

Different authors have suggested varying limits of the arid zones in general and it would be of interest to discuss them briefly and compare them with the limit obtained by the present writer on the basis of Thornthwaite's concepts. Several authors who consider rainfall alone, have suggested the isohyet of 10 inches (25 cm) as the boundary for arid regions. Miller (1944) suggests that "rainfall is the most significant single element in the climate and deserts may be expected wherever the rainfall is less than 15 inches and generally presumed where it

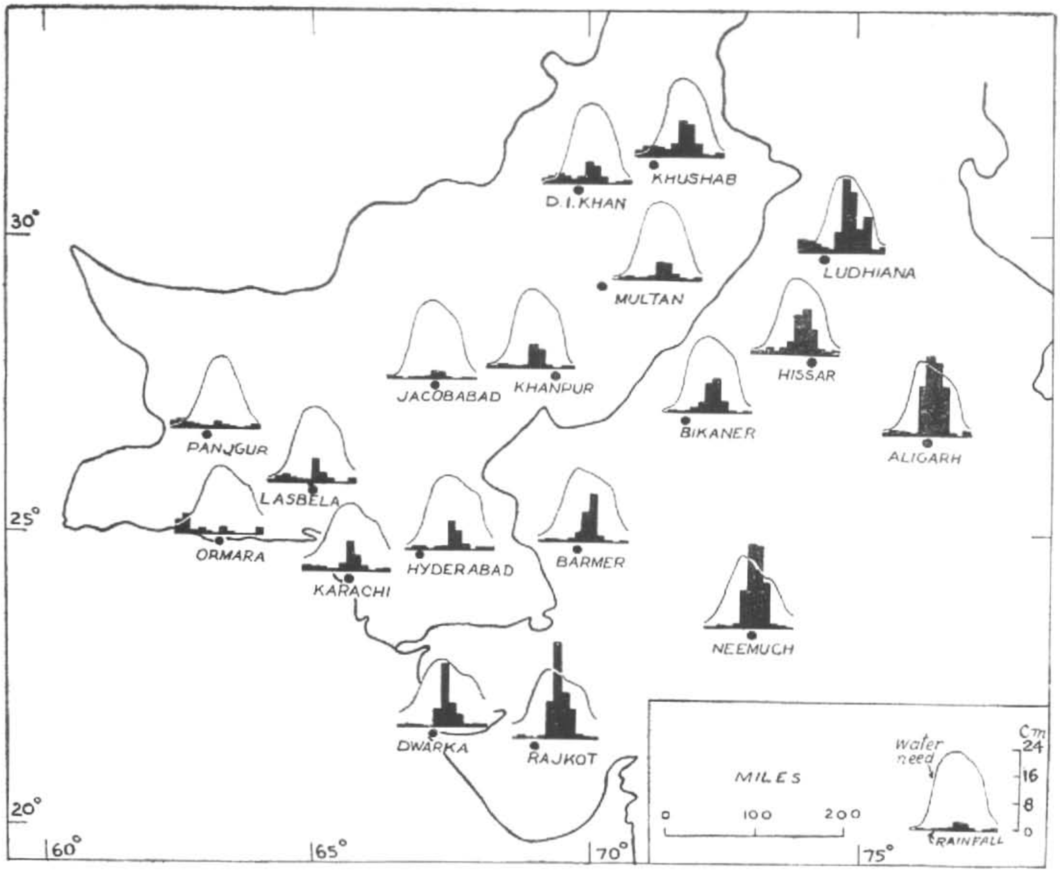

Fig. 1. Rainfall and water need

TABLE 3

March of water deficiency (in cm) at typical stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jacobabad	0·4	1·3	8·9	16·6	20·9	20·8	19·3	18·1	17·3	14·1	4·8	0·9
Hissar	..	0·8	6·3	15·1	19·2	17·8	9·9	6·5	9·4	11·2	4·0	0·6
Khushab	..	..	1·7	12·4	18·7	18·1	11·7	11·2	13·6	11·9	3·7	0·1
Delhi	..	..	5·7	16·3	18.8	13·4	0·1	..	3·5	10·1	3·2	0·2
Aligarh	0·4	0·8	6·6	14·5	19·7	6·9	..	..	..	9·7	5·2	0·9

TABLE 4

Water deficiency (in cm) in the arid zone

Station	Elevation (ft)	Annual water deficit	No. of months with deficiency	Max. monthly deficiency	Month with max. deficiency
Agra	553	70·10	7	19·70	May
Ahmedabad	163	103·97	9	19·73	,,
Ajmer	1593	87·85	11	18·79	,,
Aligarh	615	64·73	9	19·72	,,
Ambala	892	55·11	6	18·62	,,
Bahawalpur	384	129·36	12	20·60	Jun
Bareilly	586	52·09	6	18·55	May
Barmer	10	126·24	12	19·88	,,
Baroda	115	72·36	9	19·45	,,
Bhavnagar	55	107·31	12	19·03	,,
Bhuj	343	121·56	12	19·03	,,
Bikaner	734	124·81	12	19·64	,,
Brijnagar	1053	67·19	9	19·97	,,
Dehra Dun	2239	18·70	2	14·03	,,
Dera Ismail Khan	570	117·22	10	20·16	Jun
Dwarka	37	118·16	12	17·90	May
Hissar	725	101·05	11	19·20	,,
Hyderabad	96	140·26	12	20·17	,,
Jacobabad	186	143·58	12	20·89	,,
Jaipur	1431	82·00	10	19·03	,,
Jodhpur	736	114·51	12	19·58	,,
Karachi	13	128·60	12	17·54	,,
Khanpur	297	131·68	12	20·68	Jun
Khushab	612	103·36	10	18·76	May
Kotah	843	85·29	9	19·96	,,
Lahore	702	83·99	10	18·33	,,
Ludhiana	812	63·40	8	19·18	,,
Lyallpur	605	108.00	11	19·09	Jun
Mainpuri	516	75.27	10	19·58	May
Montgomery	558	118·61	11	19·90	,,
Multan	413	126·43	11	20·08	Jun
Neemuch	1626	69·49	9	18·60	May
Ormara	15	131·06	10	18·89	Jun
Panjgur	3177	107·86	9	19·39	,,
Pasni	10	126·30	10	17·85	May
Peshawar	1164	94·16	8	20·40	Jun
Rajkot	432	92·54	10	18·38	May
Rawalpindi	1674	34·37	4	14·91	Jun
Sialkot	830	54·46	6	17·60	May
Sukkur	221	143·39	12	20·80	Jun
Veraval	26	100·60	11	15·99	May

falls below 10 inches". Pramanik and others (1952) have also suggested the isohyet of 10 inches (25 cm) as the boundary for the arid zone of India and Pakistan.

Köppen was the first to distinguish desert climates (BW) on the basis of both rainfall and temperature. According to Köppen, BW type of climate prevails where the annual rainfall is equal to or less than $0{\cdot}44\,t - 8{\cdot}5/2$ where t is the mean temperature in °F for the year and rainfall is taken in inches. For regions where the rainfall maximum occurs in summer, Köppen's formula is modified to allow for excess of evaporation and it becomes $0{\cdot}44\,t - 3/2$. On the basis of general formula, BW type will prevail with less than 11·1 inches of annual rainfall when mean annual temperature is 70°F, 13·3 inches with 80°F, 15·5 inches with 90°F and 17·7 inches with 100°F.

De'Martonne (1926) employed an index of aridity to delimit the arid zone.

$$\text{Index of aridity} = P/(T + 10)$$

where P is mean annual rainfall (mm) and T is the mean annual temperature in degrees Centigrade. According to him, indices of less than 5 characterise deserts, while indices around 10 delimit the dry steppe types. Indices increase with increase of rainfall.

According to Thornthwaite, a moisture index of less than —40 defines the arid zone and this limit corresponds to his aridity index of more than 66·6. This has been taken as the basis of the present study and moisture indices for the area under consideration have been calculated. The isopleth of the moisture index of —40 has been drawn to delimit the arid zone of India and Pakistan. The boundary of the arid zone of India roughly runs from northwest of Veraval to Jamnagar, passes east of Rann of Cutch to just west of Ajmer and Sambhar, a little east of Sikar and Hissar, onwards to south of Lahore, east of Khushab and northwestwards to Peshawar.

We may now compare the arid zone delimited by the present writer with the limits of different authors noted above.

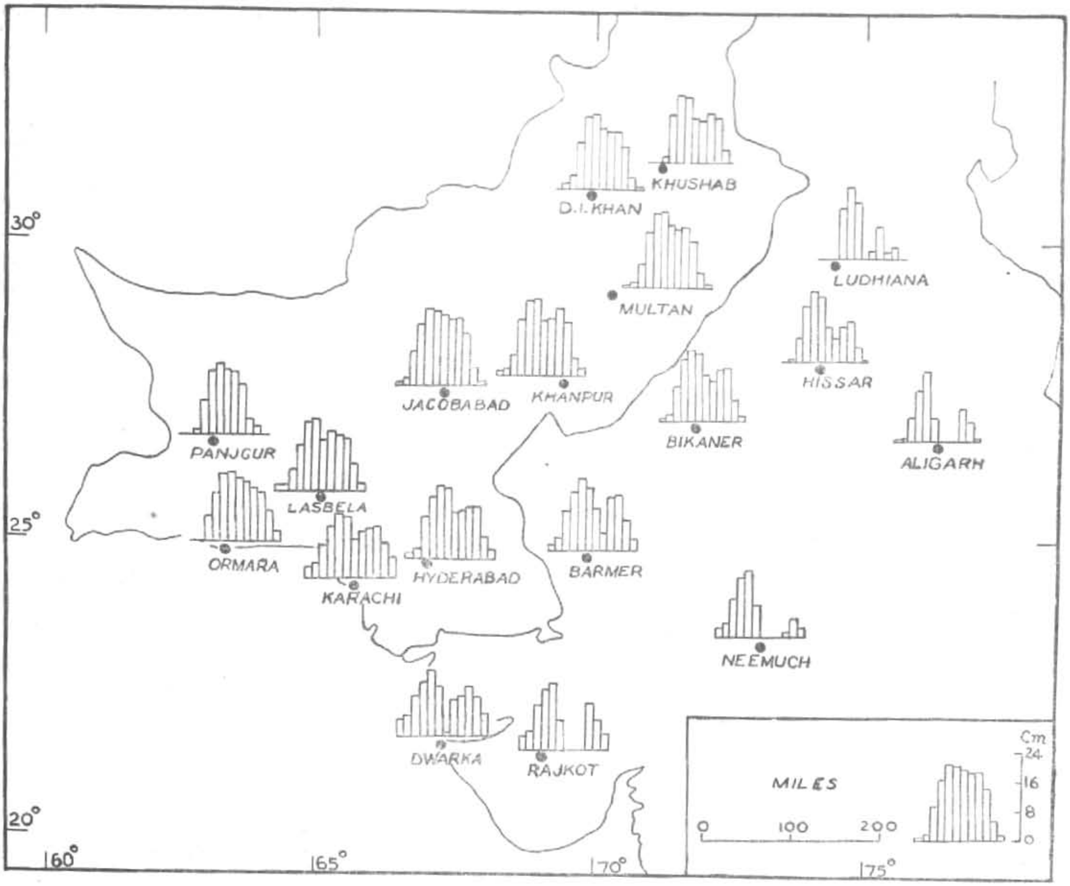

Fig. 2. March of water deficiency

Isohyet of 10 inches (25 cm), Thornthwaite's limits, the arid zone as suggested by Köppen's climatic types and De'Martonne indices are shown in Fig. 3.

Firstly, taking the isohyet of 10 inches (25 cm) as suggested by many authors, particularly by Pramanik and others (1952), we find that the arid zone delimited by 10 inch isohyet leaves out a large part of west Rajasthan and the Punjab which decidedly form part of the arid zone. For instance, the annual water deficiency at Barmer, Bikaner and Lyallpur each with a rainfall of about 30 cm (12 inches) is 126, 125 and 108 cm respectively. The deficiency at these stations comes to 80·8., 81·1, and 77·8 per cent of the annual water need respectively. Barmer and Bikaner have water deficiency in all the twelve months while Lyallpur is deficient for eleven months in a year. It is, therefore, not possible to accept the isohyet of 10 inches as the boundary of the arid zone of India.

In a similar way, De'Martonne's aridity index of 5 for true deserts fails to delimit the real arid zone of India. His aridity index of 10 for dry steppe comes closer but the aridity index of about 13 provides an excellent fit for the arid zone of India delimited according to Thornthwaite's concepts. De'Martonne's aridity indices for a number of stations within and just outside the arid zone of India are given in Table 6.

Köppen's climatic types have been calculated for a large number of stations in the

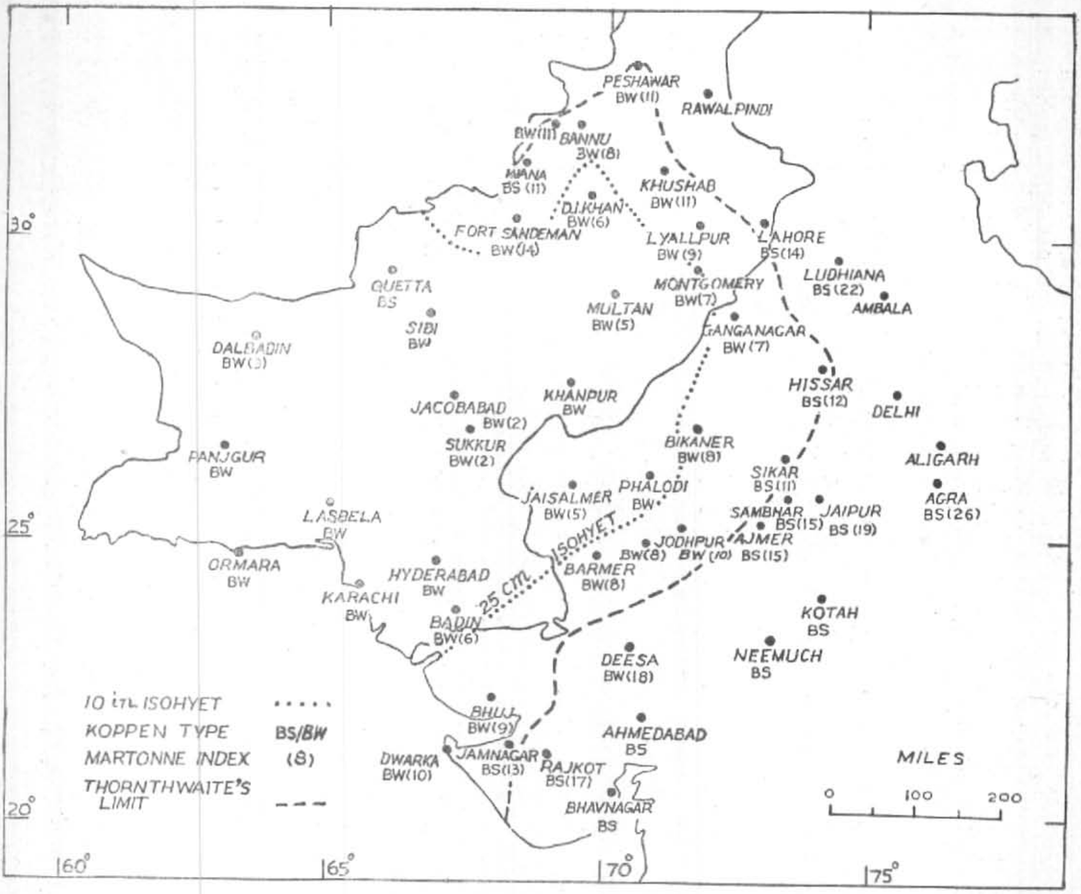

Fig. 3. Delimitation of the zone

area under consideration. It is found that Köppen's desert type (BW) prevails over most of the arid zone demarcated according to Thornthwaite's moisture index of minus 40. The boundary between Köppen's BW/BS has an irregular fit with Thornthwaite's boundary. Some stations which lie on the borders of one also happen to be on the border of the other. An excellent illustration of this fact is given by a study of the data for five stations, *viz.*, Hissar, Sikar, Khushab, Peshawar and Jamnagar.

Sikar has an annual rainfall of 16·9 inches and according to Köppen's formula it falls in BS type but with a rainfall of 16·5 inches it would be classed in BW type and obviously it lies on the border. According to Thornthwaite's method, Sikar has a moisture index of —41·8 and in this case too, it lies on the border of the arid zone.

According to Köppen's formula, Khushab which gets 15·2 inches of rainfall in a year falls in BW type. But with a rainfall of 15·3 inches, it would fall in BS type. According to Thornthwaite's method, Khushab has a moisture index of —43·6. Evidently the station lies on the border of the arid zone.

The annual rainfall at Peshawar is 13·6 inches and it falls in BW type according to Köppen's formula; but with a rainfall of 14·4 inches, it would be classed in BS type. The moisture index for Peshawar is —43·9. The station positively lies on the border of the arid zone.

TABLE 5

Thornthwaite's aridity and moisture indices for selected stations

Station	Annual need (cm)	Annual deficiency (cm)	Annual surplus (cm)	Aridity index	Humidity index	Moisture index	Arid or semi-arid
Agra	137·80	70·10	0	50·1	0	—30	Semi-arid
Ahmedabad	172·57	103·97	5·61	60·2	3·2	—33	Do.
Ajmer	140·59	87·85	0	62·4	0	—38	Do.
Aligarh	143·09	64·73	0	45·2	0	—27	Do.
Ambala	138·81	55·11	0	39·7	0	—24	Do.
Badin	155·95	132·90	0	85·2	0	—51	Arid
Bahawalpur	143·65	129·36	0	90·0	0	—54	Do.
Barmer	156·23	126·24	0	80·8	0	—48	Do.
Baroda	155·66	72·36	9·77	46·4	6·2	—22	Semi-arid
Bhavnagar	163·41	107·31	0	65·6	0	—39	Do.
Bhuj	156·15	121·56	0	77·8	0	—46	Arid
Bikaner	153·88	124·89	0	81·1	0	—48	Do.
Deesa	159·91	96·75	3·22	60·5	2·0	—34	Semi-arid
Dera Ismail Khan	140·26	117·22	0	83·5	0	—50	Arid
Dwarka	153·50	118·16	0	76·9	0	—46	Do.
Hissar	143·62	101·05	0	70·3	0	—42	Do.
Hyderabad	158·22	140·26	0	88·6	0	—53	Do.
Jacobabad	152·67	143·58	0	94·0	0	—56	Do.
Jaipur	143·05	82·00	0	57·3	0	—34	Semi-arid
Jaisalmer	150·52	132·61	0	88·1	0	—53	Arid
Jamnagar	152·46	105·33	0	69·0	0	—41	Do.
Jodhpur	150·61	114·51	0	76·0	0	—46	Do.
Karachi	148·10	128·60	0	86·8	0	—52	Do.
Khanpur	148·13	131·68	0	88·8	0	—53	Do.
Kotah	156·49	85·29	3·82	54·5	2·4	—30	Semi-arid
Khushab	141·88	103·36	0	72·8	0	—43	Arid
Lahore	132·73	83·99	0	63·2	0	—38	Semi-arid
Ludhiana	139·87	63·40	0	45·3	0	—27	Do.
Lyallpur	138·57	108·00	0	77.8	0	—47	Arid
Mainpuri	146·32	75·27	0	51·4	0	—31	Semi-arid
Montgomery	144·05	118·61	0	82·3	0	—49	Arid
Multan	144·34	126·43	0	87·5	0	—52	Do.
Neemuch	139·82	69·49	6·12	42·5	4·3	—21	Semi-arid
Ormara	146·28	131·06	0	89·5	0	—54	Arid
Pasni	141·91	126·30	0	89·0	0	—53	Semi-arid
Rajkot	155·52	92·54	0	59·5	0	—36	Do.
Sialkot	135·26	54·46	0	40·2	0	—24	Do.
Sikar	142·15	99·10	0	69·7	0	—42	Arid

Likewise Jamnagar with an annual rainfall of 18·6 inches falls in BS type according to Köppen's formula. With a rainfall of 15·8 it would fall in BW. The moisture index for Jamnagar is —41·4. The station definitely lies near the border.

A comparison of Thornthwaite's moisture index, De'Martonne's aridity index, Köppen's climatic types and rainfall for some typical stations is shown in Table 6.

7. Conclusion

From the above discussion, it may be inferred that the arid zone delimited according to Thornthwaite's method gives a realistic idea of the arid zone of India and Pakistan. In addition, a study of the water balance of the region gives an insight to the magnitude of aridity and deficiency of moisture at different periods of the year. An estimate of water deficiency in the arid zone is a key to the problem of planning for the reclamation of the desert.

More work is needed to determine the variability of water deficiency in the arid zone of India and Pakistan. Such an analysis would bring out the deterioration of the arid conditions, if any, within this area during the past sixty to seventy years for which records of temperature and rainfall are available. There is a definite need to set up many more stations for recording temperature, rainfall and particularly evaporation within the arid zone. This would not only lead to a better understanding of the problems of the arid zone of India and Pakistan but it may also help in the refinement of the method itself.

TABLE 6

Comparison of moisture indices with Köppen's types, De'Martonne's indices and rainfall

Station	Thornthwaite's moisture index	Köppen's type	De'Martonne's aridity index	Annual rainfall (in)	Annual rainfall (cm)
Aligarh	—27	BS	22.3	30.8	78.4
Bhuj	—46	BW	9.5	13.6	34.6
Bikaner	—48	BW	7.9	11.4	29.0
Deesa	—34	BS	17.9	26.1	66.4
Dwarka	—46	BW	9.8	13.9	35.3
Hissar	—42	BS	12.1	16.7	42.6
Jacobabad	—56	BW	2.0	3.6	9.1
Jamnagar	—41	BS	13.1	18.5	47.1
Jodhpur	—45	BW	10.0	14.2	36.1
Khushab	—43	BW	11.1	15.2	38.5
Lahore	—38	BS	14.3	19.2	48.8
Lyallpur	—46	BW	8.9	12.1	30.6
Multan	—52	BW	5.0	7.0	17.9
Pachpadra	—48	BW	7.8	11.2	28.5
Peshawar	—44	BW	10.5	13.5	34.4
Rajkot	—35	BS	17.3	24.8	62.9
Sambhar	—39	BS	14.5	19.8	50.3
Sikar	—42	BS	11.3	16.9	43.0
Sriganganagar	—49	BW	7.5	10.2	25.9
Sukkur	—56	BW	2.5	3.7	9.4

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Appendix A

Stations used in the present study

Station	Lat. (N)	Long. (E)	Elevation (ft)	Period	Station	Lat. (N)	Long. (E)	Elevation (ft)	Period
Agra	27° 10′	78° 02′	553	1881-1940	Khanpur	28° 39′	70° 41′	297	1926-1940
Ahmedabad	23 02	72 35	163	1896-1940	Khushab	32 18	72 22	612	1891-1940
Ajmer	26 27	74 37	1593	1881-1940	Kotah	25 11	75 51	843	1901-1940
Aligarh	27 53	78 04	615	1932-1940	Lahore	31 35	74 20	702	1881-1940
Ambala	30 23	76 46	892	1896-1940	Las Bela	26 14	66 19	292	1931-1940
Badin	24 38	68 54	31	1931-1940	Ludhiana	30 56	75 52	812	1881-1940
Bahawalpur	29 24	71 47	384	1926-1940	Lyallpur	31 26	73 06	605	1916-1940
Bannu	30 00	70 36	1264	1921-1940	Mainpuri	27 14	79 03	516	1896-1940
Barmer	25 45	71 23	10	1931-1940	Miranshah	33 57	70 07	3026	1932-1940
Baroda	22 18	73 15	115	1933-1940	Montgomery	30 39	73 08	558	1891-1940
Bhavnagar	21 45	72 12	55	1891-1940	Multan	30 12	71 31	413	1881-1940
Bhuj	23 15	69 48	343	1881-1940	Murree	33 55	72 23	7113	1881-1940
Bikaner	28 00	73 18	734	1881-1940	Neemuch	24 28	74 54	1626	1881-1940
Brijnagar	24 32	76 10	1953	1931-1940	Ormara	25 15	64 39	15	1931-1940
Chaman	30 55	66 28	4311	1891-1940	Pachpadra	25 55	72 21		*
Cherat	33 50	71 54	4272	1896-1940	Panjgur	26 58	64 06	3177	1911-1940
Dalbandin	28 54	64 26	2785	1911-1940	Parachinar	33 52	70 94	5673	1901-1940
Deesa	24 14	72 12	466	1881-1940	Pasni	25 16	63 28	10	1911-1940
D.I. Khan	31 49	70 55	570	1881-1940	Peshawar	34 01	71 35	1164	1881-1940
Dohad	22 50	74 16	9310	1931-1940	Phalodi	27 09	72 24		*
Dwarka	22 22	69 05	37	1901-1940	Quetta	30 10	67 01	5490	1881-1940
Ft. Sandeman	31 21	69 27	4614	1916-1940	Rajkot	22 18	70 50	432	1881-1940
Hissar	29 10	75 44	725	1916-1940	Rawalpindi	33 36	73 07	1674	1881-1940
Hyderabad	25 23	68 25	96	1881-1940	Sambhar	26 54	75 13		*
Jacobabad	28 17	68 29	186	1881-1940	Sialkot	32 30	74 32	830	1881-1940
Jaipur	26 55	75 50	1431	1881-1940	Sibi	29 33	67 53	441	1926-1940
Jaisalmer	26 55	70 57		*	Sikar	27 36	75 15		*
Jamnagar	22 29	70 04	60	1901-1940	Sriganganagar	29 55	73 53	580	1934-1940
Jodhpur	26 18	73 01	736	1891-1940	Sukkur	27 42	68 54	221	1926-1940
Kalat	29 02	66 35	6616	1896-1940	Veraval	20 55	70 22	26	1891-1940
Karachi	24 48	66 59	13	1881-1940	Wana	32 18	69 44	4456	1931-1940

*Short period