Kenneth Walton

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CONTENTS

FIGURES

I

THE NATURE AND CAUSES OF ARIDITY

Fundamental to the creation of the characteristics of the arid environment is the climate. This conditions the way in which landforms, vegetation, animals, soils and modes of life differ in degree and kind from those of the humid areas of the earth's surface. From the interior deserts of Central Asia and the Sahara to the foggy but arid coastlands of Peru or South-west Africa scarcity of water in the upper layers of the rocks and the surface deposits is a limiting factor in land use and development. Since water shortage is often caused by low rainfall linked with high evaporation rates, it is logical to examine the extent and causes of the low precipitation of the dry lands which cover about one-third of the earth's surface. Unfortunately through the nature of the environment population densities are normally low and accurate analyses of the climate can be based only on recently established scientific stations and meteorological observatories such as those established by the French in the Sahara and by the Chinese and Russians in Central Asia. More climatic statistics are available for the Algerian Sahara and the American deserts than for the Libyan desert, but records rarely extend for fifty years and stations are often very far apart. Where they have existed for a long period they have not always recorded the information which the climatologist and biogeographer require. Climatic maps suffer from the lack of these statistics since they tend to be constructed from the data of a few widely spaced stations with interpolated values for the intervening areas. It is apparent that the simple curves of desert isohyets (lines showing equal amounts of rainfall) are broad generalisations which will be modified in years to come.

Arid and semi-arid lands: definitions of aridity

This lack of adequate climatological information is, in part, responsible for the numerous and often unsatisfactory attempts to delimit the margins of the arid zone by climatic data, and to divide the arid area into its more and less humid components. Since aridity is primarily a function of rainfall, temperature and evaporation, it is wrong to define it in terms of one parameter alone, although average annual rainfall totals have been frequently used as a simple index of aridity. Some workers have taken the humid boundary as the 254 mm (10 in) isohyet and the margin of the inner arid zone as the 127 mm (5 in) isohyet. The southern margin of the Sahara was drawn where the annual rainfall is 250 mm (9·8 in) and the equatorial margin of the semi-arid savanna at the 400 mm (15·7 in) isohyet. These are, however, oversimplifications which ignore the influence of temperature on the efficiency of precipitation but may be of value if the isohyet chosen is related to a change in the character of the vegetation, land-use or way of life. In this respect the 400 mm (15·7 in) isohyet, said to define the southern limit of the North African arid zone, is of significance. To the north of this isohyet agriculture cannot take place without irrigation, the need for which is frequently used to define the arid lands.

For geomorphological processes, vegetation and agriculture, other climatic phenomena such as the season, duration and intensity of rainfall are as important as the total amount while temperature, which in part controls the rate of evaporation, is also of great significance. That evaporation exceeded precipitation in the arid zone was recognised by Penck in 1910 when he delimited the boundary of the dry lands at the places where evaporation and precipitation are equal in amount. There is clearly an important link between temperature, precipitation and evaporation but unfortunately while temperature and precipitation are easy to measure and have been recorded at stations in the arid lands for many years, the measurement of evaporation is more difficult and records are both of shorter duration and much less plentiful. This lack of data on evaporation prevented Penck's concept from being developed on a large scale and many indices of aridity and related classifications of climate have been attempted using the criteria of rainfall and temperature alone.

Recognising the limitations of rainfall statistics, Köppen in 1918 linked temperature with rainfall to define the boundaries of the desert and steppe lands. In his scheme of climate classification the humid boundary of the deserts, in areas with rainfall well distributed throughout the year, is linked with the 200 mm (7·9 in) isohyet when the mean annual temperature is 5–10°C (41–50°F), but it follows the 320 mm (12·6 in) isohyet in areas with a mean annual temperature of 25°C (77°F). The corresponding figures for the humid margin of the steppe are 400 mm (15·7 in) at 5–10°C and 640 mm (25·2 in) at 25°C.

An elaboration of this scheme recognised that the efficiency of the rainfall varies according to the season of incidence; cold-season rainfall is more effective in areas with sufficiently high temperatures for plant growth since less is lost by direct evaporation than in the hot-season rainfall regimes. This is shown by the difference in agricultural potential of areas with the same rainfall on the Mediterranean and Sudanese margins of the Sahara. As an example, the margin of the humid steppe occurs at the 750 mm (29·5 in) isohyet in a summer rainfall regime with a mean annual temperature of 25°C (77°F). For an area with winter rainfall and the same mean annual temperature it corresponds to the 530 mm (21 in) isohyet. Köppen's amended climatic classification (the first was based on vegetation zones) is linked with these seasonal characteristics of temperature and rainfall. The steppe climate (BS) and the desert climate (BW) are further differentiated as 'h' (heiss) with mean annual temperatures of over 18°C (64·4°F) and 'k' (kalt) where the mean annual temperature is less than 18°C and the warmest month about 18°C, i.e. with a cold winter. Coastal deserts are distinguished by the suffix 'n' (nebelig) indicating frequent mist and fog.

Other indices of aridity used to prepare maps of humidity provinces derive from the work of Lang and de Martonne. They have been used to demarcate the dry lands of the USA and Australia. Lang produced the 'Rain Factor Index' obtained by dividing the mean annual precipitation in millimetres by the mean annual temperature in °C—the $\frac{P}{T}$ ratio $\left(\frac{P\,mm}{C^\circ}\right)$. Regions with a $\frac{P}{T}$ ratio of under 40 were defined as arid. Yuma in Arizona has a

$\frac{P}{T}$ ratio as low as 3·5 while Gadames in Tripolitania has a value of only 0·7. Places with insignificant rainfall, such as Insalah in the Sahara, Assuan in Egypt and Walvis Bay in South-west Africa, have $\frac{P}{T}$ ratios of zero.

De Martonne slightly modified Lang's $\frac{P}{T}$ ratio to produce, in 1928, an index which also uses temperature and rainfall data—the Index of Aridity—$\left(\frac{P}{T+10}\right)$ where P represents mean annual precipitation expressed in millimetres and T=Temperature in degrees Centigrade. If this formula is applied, Yuma in Arizona has an index of 2·4 and Lima one of 2, so that both are within the limit of the true desert which de Martonne defined by an aridity index of 5. The dry steppe boundary, or the limit of cultivation without irrigation, was drawn where the aridity index had a value of 10 (cf. Teheran's index of 9½). In 1942 de Martonne amended the formula by including a representation of the total average rainfall (p in mm) and the average temperature (t in °C) of the driest month. The formula thus became $\frac{\frac{P}{T+10}+\frac{12p}{t+10}}{2}$ which gives values of less than 5 for the Sahara and Death Valley in California. Denver, Colorado, on the other hand, has an index of 18 and would thus not be considered to lie within the arid zone.

The formulae of Lang and de Martonne are both open to the criticism that they make evaporation appear to be a function of temperature alone although it is related to many factors including the amount of moisture in the soil, the soil type and texture, wind velocity, atmospheric pressure, relative humidity, plant cover and land-use. Nevertheless the definition of the arid lands provided by Lang and de Martonne is a reasonable approximation using only the means of the climatic parameters of temperature and rainfall. As with all the formulae based on averages, however, the assessment is confused by the high variability of rainfall from year to year which is a reality of the arid lands. Compare, for instance, de Martonne's index of aridity calculated for Yuma in 1899 with that for 1905; in 1899 Yuma received 25 mm (1 in) but in 1905 more than 280 mm (11 in). Rainfall variability of such magnitude discourages unthinking reliance on even the more refined formulae devised to differentiate the arid from the humid lands and degrees of aridity within the arid lands.

An attempt was made by Meyer in 1928 to overcome the problem of the lack of information on actual rates of evaporation. He regarded evaporation as a function of the saturation deficit which can be determined if the figures for temperature, rainfall and relative humidity are available, i.e. by using the moisture characteristics of the atmosphere at the recording station. Using the absolute saturation deficit of the air obtained by subtracting, for the prevailing air temperature, the actual from the maximum vapour pressure possible at that temperature (the latter is available from dew-point tables), he produced the Precipitation–Saturation deficit ratio (or the $\frac{P}{SD}$ ratio where P is expressed in millimetres of precipitation and SD in millimetres of mercury). On this basis the boundary of the semi-arid lands would have a value of about 89 and that of the arid zone less than 44. Although the $\frac{P}{SD}$ ratio does not take into account all the factors controlling evaporation it is a more reliable index than those which use only temperature and precipitation; unfortunately although relative humidity values are more frequent than those for evaporation they are still not readily available enough to provide a practical solution to the problem. Nevertheless the most accurate delimitations of the arid zone using climatic parameters must use measured values of evaporation, a task which Thornthwaite in 1931 attempted with the formulation of the $\frac{P}{E}$ ratio or Precipitation-Effectiveness Index.

The $\frac{P}{E}$ ratio is essentially an index of the efficiency of precipitation and attains its maximum value when the rate of evaporation from a free water surface is known. The index is obtained by determining the sum of the $\frac{P}{E}$ ratios for each month of the year and multiplying by 10 to eliminate fractions. ($\frac{P}{E} = \sum^{12} \times 10$ where P = precipitation and E evaporation, both expressed in inches.) For stations where evaporation data are not available, Thornthwaite provided a formula based on mean monthly precipitation and temperature $\left(\frac{P}{E} = \sum^{12} 115\left(\frac{P}{T-10}\right)^{\frac{9}{10}}\right.$ where T is the mean monthly temperature value in °F). Compared with Meyer's values of 89 and 44 for the semi-arid and arid margins, the Thornthwaite values are 31 and 16 respectively.

In the former French Sahara there are about thirty meteorological stations which measure evaporation and Capot-Rey defined the margin of the Sahara using data from these records. The average of the ratios, annual rainfall/annual evaporation and rainfall/evaporation for the wettest month, $I = \dfrac{100\frac{P}{E} + 12\frac{p}{e}}{2}$, provides by this method an index of rainfall efficiency. For stations with the same annual rainfall amount the lowest index is obtained when the rainfall is in the warmer months. Values of between 4 and 5 indicate the desert limit. The success of this method depends on the frequency of stations which measure evaporation and, in consequence, the northern limit of the Sahara was more accurately defined than the southern.

If the amount of evaporation in arid areas is difficult to obtain, it is clear that the amount of transpiration by plants, an important means of water loss, will be even less readily available. Yet it has been shown by Thornthwaite that the potential evapo-transpiration values are a most accurate guide to the climatic differentiation of the arid lands. Potential evapo-transpiration is the amount of water which will return to the atmosphere from ground completely covered with vegetation where there is sufficient soil moisture for the use of vegetation at all times. That such conditions do not, by definition, obtain in the arid zone does not detract from the value of the method since it represents the water need of plants and cultivated crops and gives a useful guide to agricultural potential and to the amount of rainfall or irrigation required for a particular crop under the given climatic conditions. It does not, of course, take into account the problems imposed by the socio-economic systems of the farmers themselves. By this index, derived by Thornthwaite in 1948, the potential evapo-transpiration value for the semi-arid margin is 20 and for the arid margin 40.

Few stations have so far recorded evapo-transpiration values so Thornthwaite provided a formula using data from latitude and temperature alone.[1] Using this technique, Peveril Meigs in 1952 constructed for UNESCO (fig. 1) a map of the world's arid lands divided into semi-arid, arid and extremely-arid categories (the extremely-arid is defined as that which may have at least twelve consecutive months without recorded rainfall and where the rainfall lacks a seasonal rhythm). The table below indicates the area of the dry lands which fall into the three categories.

	Square miles
Semi-arid	8,202,000
Arid	8,418,000
Extremely-arid	2,244,000
Total	18,864,000

This represents about 36 per cent of the total land area of 52 million square miles. Maps on larger scales are now being constructed which will represent in more detail areas where drought conditions are characteristic.

It has been shown that there are many difficulties inherent in formulating climatic indices of aridity and some workers would prefer to use vegetation as an index. Provided there had been no interference by animals or man, which is doubtful, the vegetation would indicate the climatic values under similar edaphic (soil-forming) conditions. The vegetation of the arid zone is either tolerant to drought or drought avoiding or drought evading (see Chapter 4). It is often *xerophytic*, i.e. living in a comparatively dry habitat, and is frequently sparse and widely spaced with areas of bare soil between the patches of plant cover. Field surveys of vegetation in the arid zone are scarce although it is hoped that they will increase, while air photographs may speed up the work despite the difficulties imposed by the highly mobile character of steppe and desert boundaries. In Tunisia, for instance, in the four-year low rainfall period, 1944–7, the desert margin stood 270 km farther north than in the moister four-year period from 1931 to

[1] Khosla produced, in 1949, a simple formula for evapo-transpiration

$$Lm = \frac{Tm - 32}{9 \cdot 5}$$

where Lm is the monthly water loss or evapo-transpiration in inches, Tm is the mean monthly temperature in °F. When the Tm is less than 40°F Lm is as follows:

Tm 40°F	30°F	20°F	10°F	0°F
Lm 0·84″	0·70″	0·60″	0·50″	0·40″

Values obtained by this method are almost identical with those obtained from the more elaborate Thornthwaite computation.

1934. In 1947 even the olive trees at Sfax near the Mediterranean coast lost their leaves and the effect on the distribution of less deeply rooted vegetation was very marked. It is clear that such wide variations in the arid and semi-arid margins are to be expected in these zones of high rainfall variability; the boundaries are zones of transition rather than lines clearly demarcated by abrupt changes in species or associations. When the vegetation of the arid zones is defined by the rigid criterion of its mechanisms to combat drought, the area of the dry lands has been measured as follows:

	Square miles	
Semi-arid		
Sclerophyll brushland	1,180,000	
Thorn forest	340,000	
Short grass	1,200,000	
		2,720,000
Arid		
Desert grass savanna	2,300,000	
Desert grass, desert shrub	10,600,000	
		12,900,000
Extremely arid		
Desert	2,430,000	
		2,430,000
Total		18,050,000

This represents 35 per cent of the land area of the globe and is only 1 per cent less than the estimate of the arid lands measured on a climatic basis. There are, however, large variations in the areas assigned to the various categories which underline the problems of classification.

The relationship between the arid areas and the regions where the drainage of the rivers does not reach the sea has often been noted. De Martonne used the term *endoreism* to describe areas of interior drainage, a phenomenon employed by Richthofen to differentiate the arid regions of Central Asia from the more humid periphery through which flow the major rivers of southern and eastern Asia. According to de Martonne (fig. 1), the *areic* regions, whose drainage does not reach the sea, cover approximately 33 per cent of the land surface, a proportion which agrees well with the figures already given using climatic and vegetation indices. The

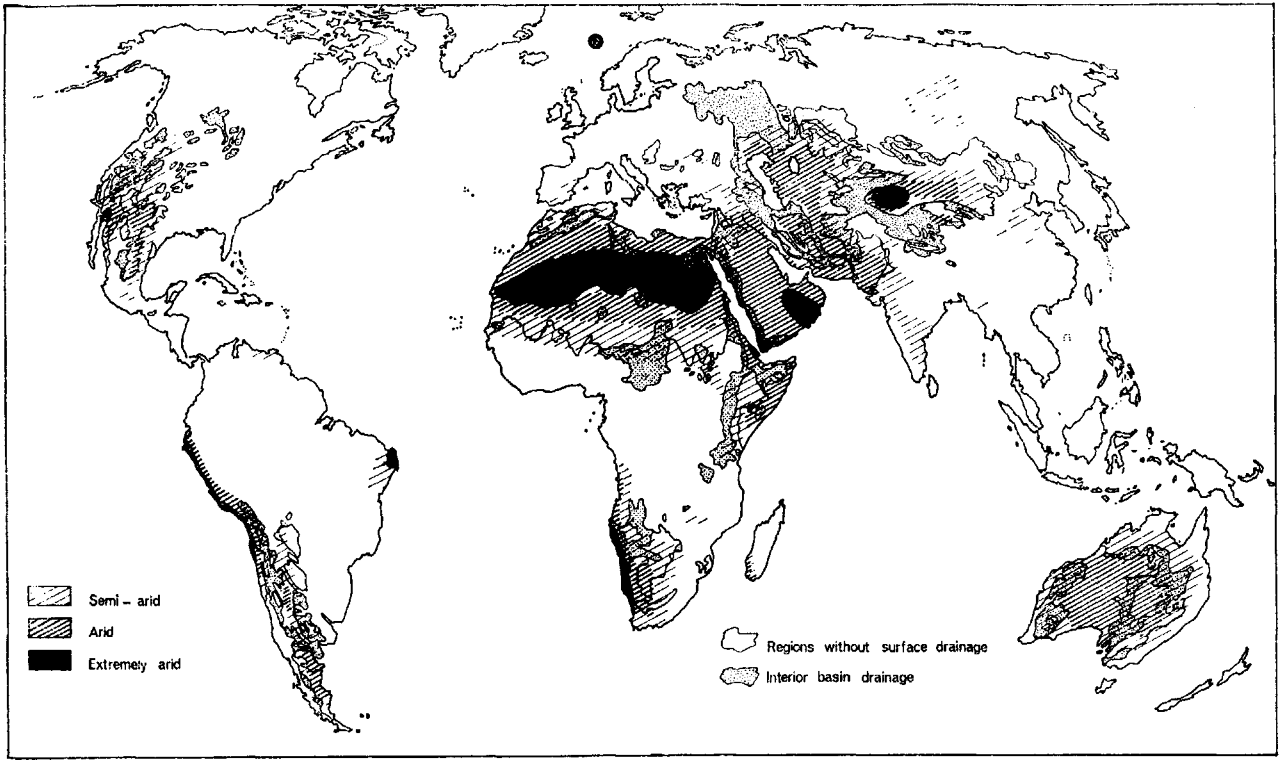

Fig. 1. Distribution of grades of aridity, basins of interior drainage and areas without regular surface run-off. (After Meigs, by courtesy of UNESCO, and de Martonne)

boundaries of the basins of interior drainage conform broadly with climate and vegetation boundaries and it might be possible to differentiate the arid from the semi-arid by an analysis of the frequency with which the watercourses actually carry water, if seasonally regular flows, as from snow melt in the basins of Central Asia, and sub-surface flows in the alluvium of river beds are excluded. Yet whatever the subtle variations in the vitality of the hydrological network, it is important to remember that for one-third of the earth's surface the rivers do not reach the oceans; such rivers are not linked to the general base level provided by the sea and this has important consequences for the evolution of the land forms of the arid zone.

The soils of the dry land regions possess distinguishing characteristics which permit a demarcation of the arid area although complications arise from the climatic variations which have occurred in the past. Arid zone soils are usually shallow, calcareous and only slightly weathered. These *pedocals* (p. 73) are found wherever evaporation exceeds precipitation in both middle and low latitudes. The climatic processes result in the deposition of the soluble carbonates at the base of the moist layer, whose depth below the surface varies with the degree of aridity and with the degree of slope. It is near the surface in the very arid areas but may be as much as three feet down on the more humid margins where the *chernozems* (p. 74) show some slight calcification as they change to the arid chestnut-brown soils where the grassland becomes degraded with the lowering of $\frac{P}{E}$ values. There are, however, certain dangers in equating the *pedocals* with the arid areas since it is also possible to find deeply weathered and leached soils in desert and steppe lands. Such soils as those of the Alice Springs area of Central Australia have been inherited from past climatic and weathering cycles when the effective precipitation was higher. If the pedocals are taken as characteristic of the arid zone, such soils cover about 43 per cent of the land surface, which is nearly 10 per cent higher than estimates obtained by other methods. To what extent this discrepancy is due to lack of precise information on the areal distribution of the pedocals is unknown.

Enough has been said to indicate the problems and difficulties of delimiting the arid and semi-arid areas. The fact remains that for at least one-third of the land area of the globe lack of moisture is the limiting factor for vegetation, animal life and land-use. Plants, animals and human beings must adapt themselves to an existence where they are constantly faced with the problem of water shortage, often under extremely high temperature regimes. In so doing, a complex physical/biological relationship is established, a dynamic relationship which betrays a constant adjustment to changes in precipitation and evaporation and makes the arid environment of vital interest. Most people think that they can recognise aridity when they see it but the history of human occupation of the arid lands indicates that a survey of indices of aridity is not of academic interest alone. They are essential for a true appreciation of variations in the arid environment.

The causes of aridity

Lack of precipitation in relation to the prevailing temperature and evapo-transpiration values is one of the principal factors in the creation of desert and semi-desert areas. Areas of low rainfall are often distant from the sea in the interior of continents, and the aridity is enhanced when high ground checks the entry of onshore winds. The arid lands frequently coincide with areas of permanently high atmospheric pressure although seasonally low-pressure zones may also lack precipitation under certain conditions. Some extremely arid areas are found, paradoxically, adjacent to the prime source of atmospheric moisture, the oceans. It is noteworthy also that the humid western margins of Eurasia give place to transitional arid types as where the Continental and Mediterranean climates of the Old World degenerate eastwards towards the heart of the continent.

Continentality and aridity are often coincident. Many regions of Central Asia have less than 254 mm (10 in) of rainfall which is quite ineffective when concentrated principally in the summer months when mean July temperatures often exceed 20–25°C (68–77°F). In winter the wind systems associated with the East Siberian anticyclone approach the dry lands of Central Asia from the north having crossed hundreds of miles of land. By the time they reach the dry interior they are low in humidity and high in evaporative power due to their passage from higher to lower latitudes, from colder to warmer areas. Only the Dzungarian desert, to the east of Lake Balkhash, receives some cyclonic rain from moist air transported from the Atlantic. When the East Siberian anticyclone disappears in summer, a low-pressure area is formed over the intensely heated interior of the continent while, to the west, an extension of the Azores High Pressure system develops across southern Europe and dry north-westerly winds prevail over