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11. Dry warm sloping land

Introduction

For the purpose of this book, dry warm areas have been defined as areas with an annual potential evaporation over 1000*mm*, lying within the hyper-arid, arid, semi-arid and sub-humid classifications of the MAB map "World distribution of arid areas" (Unesco 1979). This encomposses a very large part of the earth's surface (Fig.11.1), including more than half of Africa, a large part of the Middle East, important parts of India and Pakistan, most of Australia, large regions in North and South America including the coastal zones of Peru and northern Chile, and parts of the Mediterranean coast of Europe.

On a global map it is impossible to exclude all the relatively small areas of higher land where potential evaporation is less than 1000$mm\ y^{-1}$. It should also be noted that local aridity is influenced by geology and soils. When these conditions are very favorable, some areas in the sub-humid and even semi-arid zones may have hydrological features not too unlike those of humid areas. On the other hand, if conditions are unfavorable, arid features may be found in regions where the precipitation is above the upper limit of the sub-humid zone.

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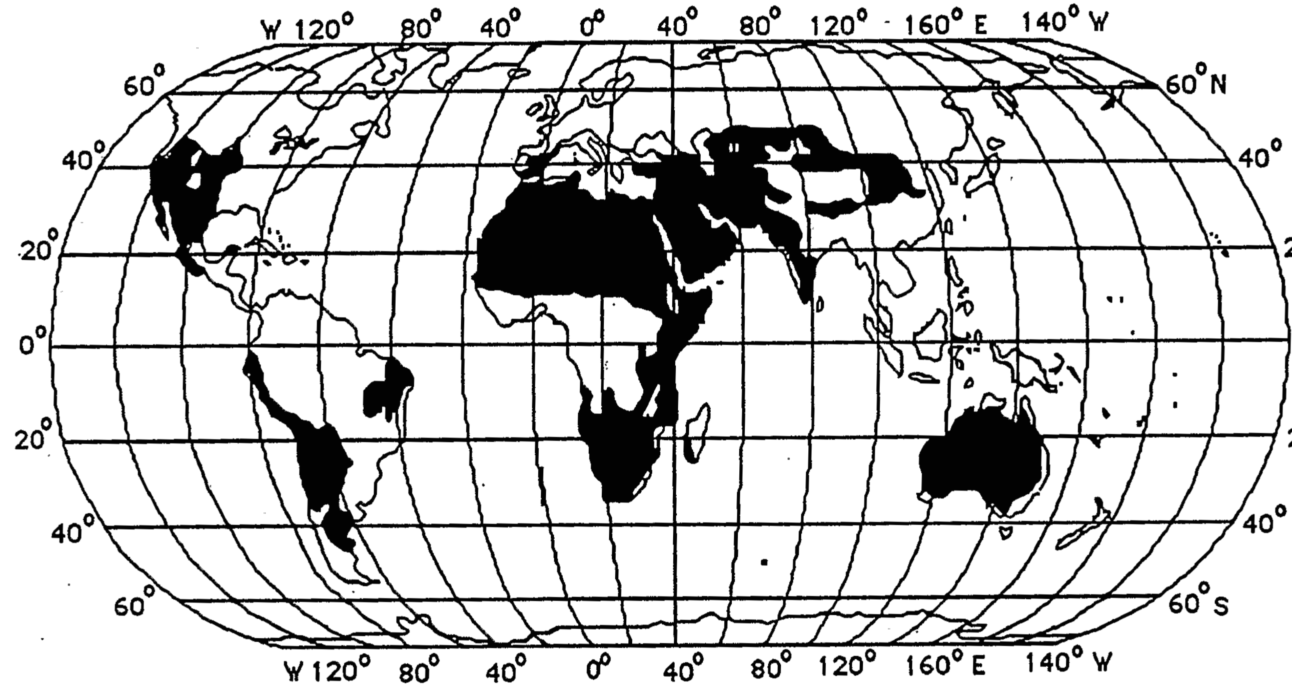

Fig.11.1 Generalized map of the warm dry region

Large parts of the dry warm area are occupied by flatlands, and there are also numerous small areas of flatlands more or less randomly distributed in the region. For this reason it is not practicable to show a small scale world map which delineates flatlands from areas with catchment response, which have a more or less well organized natural stream network. In this zone, areas with catchment response correspond to basins with a slope exceeding $0.1\,m\,km^{-1}$ for large rivers and 0.5-1.0 or even up to $3m\,km^{-1}$ for small watercourses, taking into account aridity and soil types.

In view of the size and global distribution of this hydrological region, it is only possible to indicate the main hydrological features and the main problems relating to water use and management.

A general characteristic is that trees and shrubs are sparsely or very sparsely distributed, and the hydrological effects of canopy and litter are negligible, with the exception of some sub-humid areas with shrub savanna in tropical areas and scrub (maquis) in sub-tropical areas. In the hyper-arid, arid and some semi-arid zones the plant cover is negligible, and before the first rains there is almost no plant- water interaction. Germination and growth of plants, soon after the first rain, change the situation: a slight interception by plants begins, and the evaporation of the soil-plant complex increases, the roots extending deeply into the soil. The depth of the plant root zone is more important than in temperate and humid areas, particularly for the few trees.

Where the soils are permeable, part of the rainfall enters the unsaturated plant root zone and infrequently penetrates to groundwater. The remainder becomes overland flow which is concentrated into the network of stream channels. Depression storage is negligible. Part of the soil water may also enter the drainage network, but most is transpired by plants or evaporated from the soil surface. Where the water-table is sufficiently shallow, there may also be a contribution from groundwater to stream flow.

For impermeable soils an important part of the precipitation becomes overland flow and joins the drainage network. There is little that infiltrates into the soil, with the exception of fractures or karstic zones through which water can reach the groundwater system. Some water returns to the atmosphere by evapotranspiration. There is some depression storage. Again there may be a contribution from groundwater to stream flow when the water-table is shallow, or the groundwater may be recharged from stream flow when the water-table is deeper.

The hydrologic characteristics, particularly near rivers, may be strongly influenced by exogenous inputs from regions with higher precipitation. There may also be endogenous inputs from up-catchment flatlands, which affect the surface and possibly the subsurface hydrology of downstream sloping areas.

Water balance components

Precipitation. By the definition of the region, the mean annual precipitation is less than the annual potential evaporation, and is generally low with, in most cases, a completely dry period of at least 2-3 months. Table 11.1 shows the range of annual precipitation for the four sub-classifications of aridity. The values given in the Table correspond to the data provided by meteorological services. It must be noted that, depending on the type of rain gage used, they can be lower than the actual rain depth at the soil level (Sevruk and Hamon 1984; Chevallier and Lapetite 1986). The overlapping of the limits results from variations of the potential evaporation, the lower limit being in relation to the chosen limit of 1000*mm*.

Table 11.1

ANNUAL PRECIPITATION (*mm*) IN DRY REGIONS

Classification	Lower limit	Upper limit
hyper-arid	10	75-100
arid	40	400-500
semi-arid	200	800
sub-humid	500	1100

The interannual variability of the annual precipitation is high or very high, with a statistical distribution evidencing positive skew. This characteristic is particularly important in subtropical areas and in the Sahel in Africa. For example, in Gabes (Tunisia) the lowest yearly precipitation is 36*mm* and the highest is 534*mm* with a median value of 158*mm*. At the same place the highest daily precipitation recorded is 124*mm* and it could probably be over 200*mm*. Fig.11.2 shows the percentage difference between the 10-year or 100-year rainfall and the mean annual rainfall P_y, over a range of 100-1100*mm* for P_y, obtained from 21 rain gages in the Lake Chad catchment area. The difference is more important for humid years than for dry years, corresponding to the positive skew of the statistical distribution. Such a pattern is not necessarily general for the warm arid zone, but it is observed over large areas.

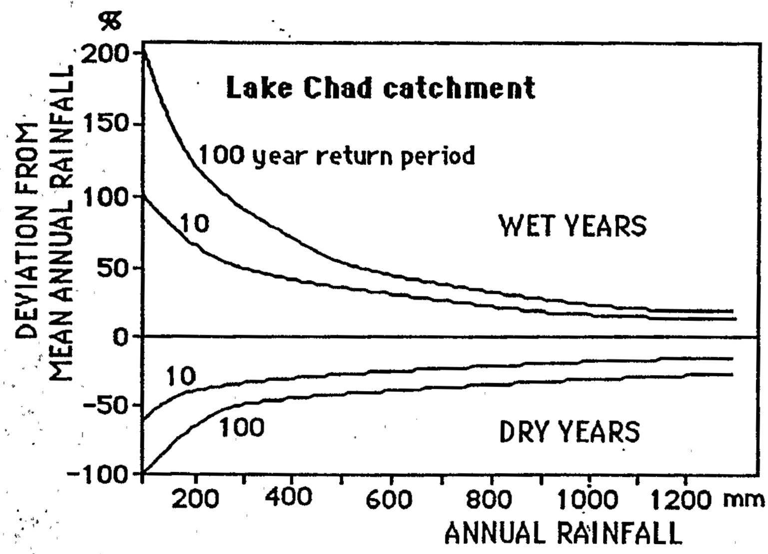

Fig.11.2 Difference between extreme and mean annual rainfall for the Lake Chad catchment (from Colombani 1979).

Orographic influences on the mean annual precipitation are generally important, with precipitation increasing with altitude. As a result, some high areas may be outside the general limits set for the warm arid region, but it is difficult to map them because of their small areal extent. Another orographic influence, the aspect of land slope relative to wind direction, also has some influence on the depth of precipitation.

The seasonal distribution of precipitation may vary widely from one place to another, even over a relatively short distance. The main patterns observed are as follows:

(a) A well defined rainy season in summer, with the second half of the dry season very hot. Most of the tropical areas, from the hyper-arid to the sub-humid zone, are in this class. The following situations may be observed: occurrence of one or several storms over a period of about six weeks (hyper-arid), or a rainy season over two to three months (arid), over t hree to four months (semi-arid), or over four to six months (sub-humid). For example, in the Lake Chad catchment area the July-September rainfall increases from 63 to 90% of the annual precipitation with a change in latitude from 8 to 14 °N (Fig.11.3). A variant of this category in very low latitudes (e.g. Somalia, Kenya and Ethiopia) has two rainy seasons.

(b) Rainfall concentrated near the end of autumn and the beginning of spring, with a warm or hot summer, or most rainfall concentrated in the winter. Most of the subtropical areas, from sub-humid to hyper-arid zones, have this pattern.

(c) Rainfall occurring at any time of the year, generally in arid or hyper-arid regions (western coast of South America, the coast of Namibia and parts of the Sahara in Africa, and most of the Australian arid zone).

Some areas have transitional patterns between (b) and (c). All types of daily precipitation occur: low intensity rainfalls, high intensity convective storms in tropical areas, cyclonic storms (hurricanes principally in tropical areas) or continuous precipitation. High intensity storms occur in most of the areas under study. The maximum values of daily precipitation are lower than the world maximum records of the humid tropics, but not by a large margin.

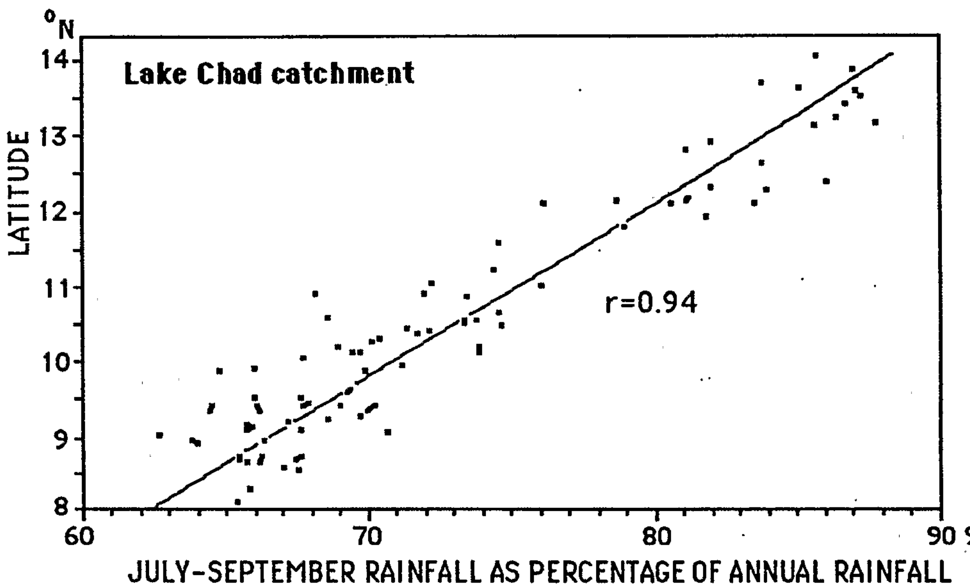

Fig.11.3 Relation between wet season rainfall and latitude in the Lake Chad catchment (from Colombani 1979).

Another important characteristic of the rainfall is the spatial distribution in a storm. Very often in arid zones the area covered by a storm is small, with a rapid decrease of rain depth around the point where the maximum is observed. A storm commonly covers an area from a few square kilometres to 100 - 200km^2, with more frequent values of 30 to 60km^2 in Africa. In mountainous zones the area covered by a storm is often smaller than elsewhere. There are also some regional differences: for example, in northeast Brazil a storm covers a smaller area than in west Central Africa.

This aspect of spatial distribution is important for studies on floods, erosion and sediment transport. It is rare for the area covered by a storm to be as large as the 1000km^2 observed in Boulsa (Burkina Faso) in 1962, though where typhoons occur the area covered (a strip centered on the axis of the cyclone track) may be very large, producing major floods. In some areas, particularly countries bordering the Mediterranean, frontal type rainfall on large areas can produce very large floods if it falls on saturated soils (Rodier 1985).

Rainfall intensity is also very important for generation of overland flow and floods, and for erosion. In tropical arid zones, rainfall ocurs generally as a convective storm of short duration, between 15 minutes and 2 or 3 hours. After some minutes of low intensity, high intensity rainfall occurs for the main part of the storm, which ends with a long low intensity tail. Depending on the area concerned, the intensity may be high (100 to 150$mm\ h^{-1}$ in five minutes). With cyclonic rains the intensity may be lower (15 to 50$mm\ h^{-1}$ in five minutes), as in the Mediterranean climate where however very high intensities can also be observed, as at Haffouz (Tunisia) in 1969, where the maximum intensity over five minutes was 212$mm\ h^{-1}$ (Colombani et al 1972).

Evapotranspiration. The theoretical maximum evaporation is given by the potential evaporation E_0. However in arid countries the actual evapotranspiration E is far below E_0 because of the lack of water availability during most of the year, and relatively low depression storage on sloping land. When a major storm occurs, an important part of the water runs along the slopes and joins the first order streams, another part is infiltrated, and a very small part is stored in depression storage which can evaporate before infiltration occurs.

As conditions of potential evaporation do not exist, the estimation of E is quite difficult, as it depends on many factors, including soil permeability, slopes, type of precipitation, and plant cover when it develops towards the end of the rainy season. Most of the evaporation comes from bare soils of various types and evapotranspiration of a soil-plant complex under a water stress not far from the wilting point.

In subtropical areas where the potential evaporation is a maximum during the summer, the actual evaporation at the same time is almost zero because there is almost no summer rainfall. In such a region, the aridity for a given rainfall depth is less severe than in tropical regions where there are higher temperatures during the rainy season.

The actual evaporation can be estimated from the water balance if groundwater recharge can be estimated, either from measurements of variations in water-table depth or soil water profiles, or by use of tracers in the soil water zone.

Potential evaporation can be estimated from Penman's equation (see Eqn.2.3, p.50). For warm arid countries it ranges from 1000 to over 3000 $mm\ y^{-1}$. Fig.11.4 shows the variation of potential and actual evaporation with latitude in central Africa.

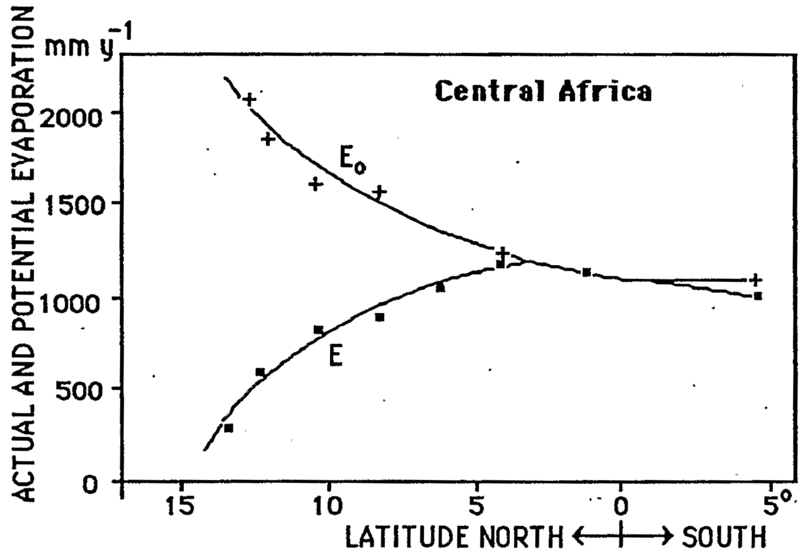

Fig.11.4 Variation of potential evaporation E_0 and actual evapotranspiration E with latitude, for longitudes between 15° and 22° (from Riou 1975).

Infiltration. In this zone, infiltration generally does not penetrate very deep into the soil. For hydrological purposes, it can be described by two significant parameters:

(a) The "initial loss", which is the depth of rainfall required before runoff begins from a small plot of very low slope; it includes microscale depression storage

(b) The "long-term loss rate", which is the rate of infiltration on a plot when the runoff becomes constant during a period of continuing rainfall of uniform intensity. It corresponds to the infiltration rate as $t \rightarrow \infty$ in the Horton and Philip infiltration equations.

Table 11.2 is based on studies (Casenave 1982; Collinet 1980; Chevallier 1985) in the Sahel region of North Africa, from the hyper-arid to the sub-humid zone, using data from artificial rainfall on plots, from representative basins, and from neutron probe measurements of soil water content.

Table 11.2

TYPICAL VALUES OF INITIAL LOSS AND LONG-TERM LOSS RATE

Soil type	Initial loss (*mm*)	Long-term loss rate (*mm* h^{-1})
very impermeable	3	2
impermeable	4 - 8	2.5 -16
permeable	12 - 25	20 - 50
very permeable with some vegetation	> 50	-

The figures in Table 11.2 are for conditions at the end of a long dry period. After several rains, both parameters decrease considerably, e.g. for impermeable soils the initial loss may be 2*mm*, while the long-term loss rate is 0-2*mm* h^{-1}.

The formation of a surface seal (Valentin 1981), due to the impact of rain drops on the soil surface, can make large areas impermeable, but this effect decreases and eventually disappears with increasing land slope. As a result, where the only variable is slope, there can be higher infiltration on sloping land than on flat land.

Except in the sub-humid zone, infiltration is generally low, particularly in impermeable soils, where it may be 10-40% of a heavy rainfall. Most of the infiltration is returned to the atmosphere by evapotranspiration, and any groundwater recharge from the soil water zone occurs only from extreme events, except possibly in karst or fissured rocks.

In the sub-humid zone, infiltration is likely to be higher, because of biological activity in the soils that makes them more permeable, and because there is a greater depth of precipitation. Groundwater recharge is then possible if permitted by the geological substratum, even with a higher consumption of soil water by the more dense plant cover. In texture contrast (duplex) soils, infiltrated water may move downslope through the relatively permeable surface soil, forming a temporary saturated zone over the impermeable subsoil. When this water-table meets the surface, the water runs overland to the first order streams. This occurs for example in the catchment of Oued Sidi ben Naceuv in the north of Tunisia.

Overland flow. Overland flow is a very important component of the water balance in warm dry areas with catchment response, both for water production and for erosion. Microscale depression storage can retain a significant part of small rainfall occurrences, but in larger storms a great part of the rainfall excess joins overland flow. The proportion of the precipitation which becomes overland flow varies widely, from 90% or more on impervious catchments with high slopes, to 5% or less on pervious catchments with low slopes.

Overland flow has been studied more by runoff measurements at the outlet of small catchments than by direct measurements on the slope. In Burkina Faso a comparison has been made (Albergel 1987) between low-slope plot runoff, using artificial rainfall, and catchment runoff. The plot rainfall excess L_i was measured for each soil type i, and the catchment rainfall excess L_{calc} calculated from

$$L_{calc} = \sum_{i=1}^{n} L_i \frac{A_i}{A} \qquad (11.1)$$

where A_i is the area of soil type i, and A is the area of the whole catchment. The ratio $K = L_{calc} / L_{obs}$ of this value to the rainfall excess measured at the outlet was 0.66 for Gagara east ($25 km^2$) and 0.80 for Gagara west ($35 km^2$), which can be considered an impermeable basin. The implication is that overland flow measured on a plot is partially infiltrated while running overland to the catchment outlet. An important part of this infiltration corresponds to transmission loss in the stream channel network, comprising storage in stream beds and banks and possibly recharge to groundwater. Depression storage may also be significant. On steeper basins the effect may be reversed, with values of K greater than 1, because the artificial rainfall measurements were made on plots which are almost horizontal.

Runoff. As a result of the characteristics of precipitation described above, violent floods are typical in the warm dry zone. Slope also has an important effect on peak flood discharges, as shown by Fig.11.5 for a storm in the Sahel representing a 10 year flood in a region with a mean annual rainfall of 250*mm*.

The temporal pattern of runoff depends mainly on the precipitation pattern, evapotranspiration and slope. Intermittent flows are most frequent, though permanent flows may occur in subtropical and sub-humid areas or as a result of exogenous inputs from more humid zones. Three general patterns of runoff distribution can be distinguished:

(a) Climates with a well defined rainy season in the summer. This includes most of the tropical areas from hyper-arid to sub-humid zones. For small basins, the runoff pattern is similar to the rainfall pattern, with some differences resulting from varying soil permeabilities and from plant cover growing after the first rains. On steep catchments with impervious soils, the runoff pattern is similar to the rainfall pattern, but with more pervious soils the first storms may give little or no runoff

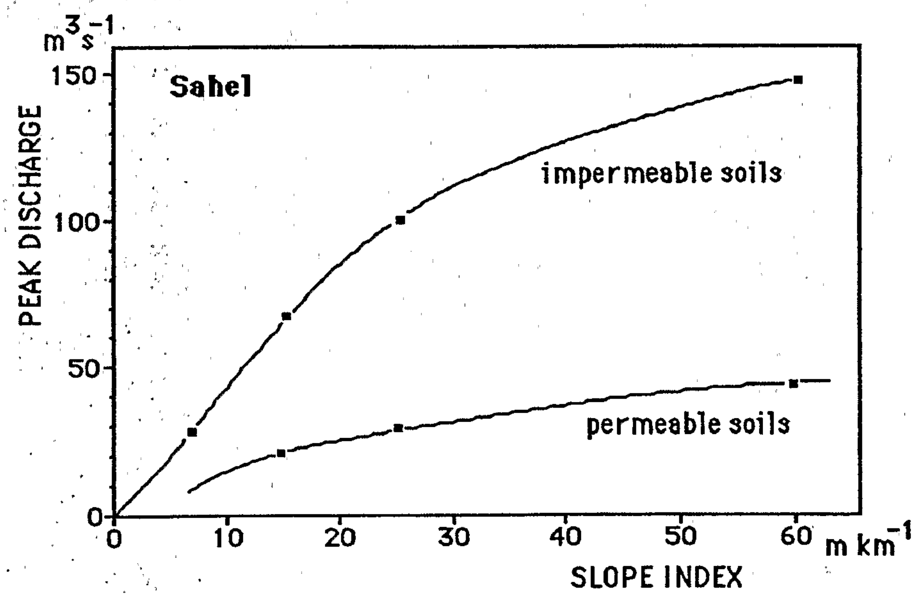

Fig.11.5 Relations between peak discharge and catchment slope for a 70*mm* convective storm on a 10km^2 catchment in the Sahel (from Rodier 1986).

compared with floods observed later in the season (Rodier1964). Between storm events, the runoff from small catchments usually stops, except in the sub-humid zone when the soils are permeable enough to store some water, or even in the arid or hyper-arid zones in an occasional year of very high precipitation. When the plant cover grows sufficiently during the rainy season, peak flood discharges at the end of the season are lower, even if they have a larger volume for the same precipitation.

With larger catchment areas, the flood hydrographs depend less on individual storms, but become more complex due to the various origins of runoff on the catchment. The drainage network causes important transformations of the runoff pattern. In the sub-humid zone, permanent flow becomes more frequent, but in arid and hyper-arid tropical zones it becomes less frequent as the catchment size increases. Even where there are springs, permanent flow does not extend far downstream.

(b) Climates with winter rainfall or with two rainy periods. This occurs mainly in the subtropical zone, with aridity ranging fron hyper-arid to sub-humid. Again the pattern of flood hydrographs on small catchments is similar to rainfall patterns, but in larger catchments is strongly influenced by the drainage network. Continuing flow between flood events is more frequent, because evapotranspiration is relatively less important when the rain falls during the cold or temperate season. In the sub-humid zone, permanent flow can be observed frequently even during the dry season.

In this zone the interannual variability of rainfall is higher than in zone (a), and the statistical distribution of maximum discharges has a strong positive skew, higher than for rainfall, particularly in the arid and semi-arid zones. For example, on Oued Zeroud in Tunisia the maximum discharge in 1969 on a 8500km^2 catchment area was 2$m^3 s^{-1} km^{-2}$ or 1700$m^3 s^{-1}$ (Rodier et al 1970; Colombani et al 1972). The return period of this discharge is diffficult to evaluate, but the total discharge for the year was 2.5 x $10^9 m^3$, compared with a median of 75 x $10^6 m^3$ and a mean of 110 x $10^6 m^3$.

(c) Climates with rain falling at any time of the year. This occurs in the arid and hyper-arid zones where floods are infrequent, and flow generally stops between two floods. There may be no flow for periods of a year or more.

To summarize, the annual hydrograph is closely related to the temporal distribution of the precipitation, and varies according to aridity as follows:

- Hyper-arid zone. One or a few short floods, with no runoff in some years and almost continuous floods for two or three weeks in exceptionally wet years.
- Arid zone. One or two series of floods each year, with floods normally separated by dry spells; but with pervious soils and/or close spacing between floods, there may be continuous flow for at least part of the rainy season.
- Semi-arid zone. A longer series of floods, with generally continuous flow in the rainy season.
- Sub-humid zone. Hydrographs generally similar to those in the neighbouring humid zone, with a succession of peaks and recession curves, but the period of low flow is more accentuated, and the river can be dry for a variable length of time.

The length of period without runoff is an important parameter, and varies from more than one year in the hyper-arid zone to zero in the sub-humid zone.

The volume of runoff varies considerably with slope, soil type, rainfall pattern and catchment size. As an example, for a tropical dry area with a median annual rainfall of $400mm$, the annual runoff on a $25km^2$ catchment ranged from $1.6mm$ for sandy permeable soils to $140mm$ for colluvium, clay and marls (Rodier 1975). For slopes greater than $3m\ km^{-1}$, slope did not have a great influence. The runoff decreased with increasing catchment size , so that the corresponding runoff figures for a $1000km^2$ catchment were 0 and $80mm$.

In the semi-arid and sub-humid zone, direct recharge of aquifers is more frequent and more important, but losses by evaporation along the river beds decrease sharply.

The interannual variability of runoff depth is very high. The value of the coefficient of variation is high and the skew coefficient is positive (McMahon 1979; Rodier 1985). Both increase with increasing aridity, with some exceptions (Nordeste Brazil for instance). Cyclonic precipitation (hurricanes) may sometimes affect the distribution by occurrence of very large runoffs (and peak floods), which increases the irregularity of the runoff distribution. It is more suitable to use median values to describe distributions than mean values, which are too much influenced by the high extreme values.

In subtropical areas the irregularity of the rainfall pattern can produce a great irregularity of runoff. For instance on the Oued Zita basin, a small $3.2 km^2$ catchment area in south Tunisia, comparable annual rainfalls have given very different annual runoffs: with $P_y = 378 mm$ in 1973-74, the runoff was $234 mm$, and with $P_y = 320 mm$ in 1975-76, the runoff was only $34 mm$. The reason for this difference is that in 1973-74 a single rainfall in 17 hours represented almost $300 mm$ of the yearly total of $378 mm$ (the median yearly precipitation is about $170 mm$ (Camus and Bourges 1983).

It is important to consider also that when there is a multi-annual drought as has been observed recently in the African Sahel, the consequences for runoff are very severe. When the yearly precipitation is far below the median value for several years in succession, runoff becomes very low.

The distribution of the main yearly flood is similar to that of the annual runoff, but flood peak discharges are increased by high slopes, and this influence is even greater than that of the climate. However for the same basin area, the same yearly precipitation and the same slope, floods in the tropical zone, although also violent, are not as large as those in the subtropical zone and in regions affected by tropical cyclones (hurricanes).

Groundwater. In catchment response areas, groundwater has not the same importance in the water balance as in flatlands, because infiltration towards deep groundwater is much more limited, unless there are many fissures or karstic formations. As has been said above, water can infiltrate into the upper part of the soil when it is pervious enough and may reappear further downstream. Shallow aquifers may permit a permanent flow, specially in sub-humid zones. Generally recharge and discharge of such aquifers is rather rapid. Most of the infiltration takes place along the river beds, and some in overland flow. The water thus infiltrated generally returns quickly to the rivers in the sub-humid zone.

Erosion and sediment transport

Erosion and sediment transport are very important in catchment response areas of the warm dry zone because of the sparse plant cover, and the high velocity of the overland and stream flow, combined with the effect of the slope. Erosion can be observed as sheet erosion in which the whole surface of the soil is lowered, or linear erosion in which soils are cut by rills and deep gullies, or bank and bed erosion in the channel network. The solids transported can be divided into fine suspended matter (with a sedimentation diameter less than $60 \mu m$), coarse suspended matter (sedimentation diameter more than 60 μm) and bed load. Data are not very numerous, and not accurate because study of these processes is expensive and time consuming.

Sheet erosion has been studied by means of measurements on plots. Studies on such small areas (generally between 20 and 200m^2) give information for field erosion which is useful for agronomic purposes. Statistical studies have led to formulas such as that of Wischmeier and Smith (1982), established with 10 000 plot-years of data and known as Universal Soil Loss Equation. Unhappily it is not universal, but it can give useful results after local adjustment with new measurements, but only for sheet erosion. As soon as rills and gullies appear, the Wischmeier formula cannot be used, and it is therefore inapplicable for most of the catchment response areas in the warm arid zone. Many authors have found relations between sediment delivery at the outlet of a catchment area, and different parameters such as slope, catchment area, precipitation etc. Generally the results are not very good, and extrapolation to other regions is not possible. Some facts seem to be reliable: the amount of fine suspended matter carried in a river is not determined by the hydraulic conditions in the stream flow, but by the amount which can be supplied from the catchment upstream. In many cases it seems possible to determine an upper limit of concentration of suspended solids for a flood on a given basin, when the flood volume exceeds a critical value. This limit on the concentration seems to be a characteristic of the basin (Demmark 1980; Rodier et al 1981).

Bed load transport is not well known because measurement is difficult, except for indirect measurements in natural or artificial lakes. For more than one hundred years many formulas have been developed to calculate bed load transport, but the results are not at all coherent. The bed load transport at a given time in a given place on a river depends not only on the hydraulic characteristics of the river but also on the past chronology of river discharges. Numerical modeling may be the only possibility for calculation, and this requires much further study (Abdalla Sharfi 1986).

Langbein and Schumm (1958) published a graph illustrating the variation of erosion with precipitation. Maximum erosion is observed for 250 to 350 *mm* of annual precipitation when there is enough rain to produce significant runoff, but not enough to permit the growth of plant cover to protect the soil.

The concentrations of suspended solids vary greatly in dry warm areas, from less than $1g\,l^{-1}$ to more than $500g\,l^{-1}$. The highest values are observed in the arid and semi-arid zones of the subtropical region.

The annual sediment delivery expressed as specific erosion also varies greatly, from 50*t km*$^{-2}$ to 50 000*t km*$^{-2}$ as on Zeroud (Tunisia) in 1969 (Colombani et al 1984). Sometimes it has been possible to evaluate the part of the sediment due to sheet erosion and the part due to bed and bank erosion. During a single flood in 1973-74 on Oued Zita in south Tunisia, it was estimated that sheet erosion was 2*mm* and bed erosion 5*mm*, very high values of erosion typical of these regions, while the mean concentration of suspended matter was at least 45*g l*$^{-1}$ and the maximum concentration at least 84*g l*$^{-1}$ (it probably exceeded 100*g l*$^{-1}$) (Camus and Bourges 1983; Colombani et al 1984).

On the Kountkouzout basins in the sahelian zone in Niger, with a semi-arid climate and a mean annual precipitation of 400*mm*, concentrations of suspended matter varied from 1*g l*$^{-1}$ to 20*g l*$^{-1}$ for catchment areas varying from 2.6 to 10.6*km*^{2}. The annual specific erosion varied from 65 to 215*t km*$^{-2}$ on cultivated slopes of 1% and from 1450 to 1950*t km*$^{-2}$ on cultivated slopes of 12% (Dubreuil and Vuillaume 1970).

In the Cameroons, with a sub-humid climate (P_y=1000*mm*), the yearly specific erosion on a 6.6*ha* catchment area on Mayo Kereng was 640*t km*$^{-2}$ and the concentration of suspended matter varied between 0.12 and 2.8*g l*$^{-1}$. A large part (about 60%) of the solid transport is bed load in this case. Plant cover is a good protection against sheet erosion in this region (Pelleray 1957).

In conclusion, erosion and sediment transport are generally more important in the arid and semi-arid zones than in the hyper-arid and sub-humid zones, and in the subtropical rather than in the tropical zone. However, erosion in the sub-humid zone may become important because of agricultural practices; when the natural plant cover disappears, overland flow and runoff are able to carry a high sediment load.

Water and land use

In this region the two main problems affecting water use are the lack of water for a significant time each year, and water excesses involving floods and erosion.

The possibility of water supply from aquifers, the depth of those aquifers, the possibilities of recharge, and the quality of the groundwater are also important, though aquifers have not the same importance as in flatlands.

Salinity and water quality are very important for management and operation. The nature and the volume of sediments may have a strong influence. All these characteristics are closely tied to the origin and development of water and land use.

Agriculture. Most human activities need a continuous water supply. Agriculture is a main exception, since many crops need water only for a limited number of months. The seasonal patterns of precipitation and runoff often do not fit the timing of these water needs. In subtropical areas the water supply stops in summer and autumn, which causes stress on trees and shrubs. In tropical regions the lack of water is an impediment to dry season agriculture.

Human activities must be adapted to the difficulties related to the hydrological regime, or possibly the water resources may be controlled in order to cope with human needs. A combination of both attitudes is often required. There are good examples of appropriate solutions that have been found in the past, which have tried to fit the agricultural techniques to the natural water regime. For example, in the Nabatean terraces in the Negev desert (Israel) and in south Tunisia, the slopes of the upper parts of small catchments are cleaned up to facilitate surface runoff which is concentrated into first order streams, sometimes by construction of small channels. The sediment from the catchment area is stopped by very small dams (made of stone blocks without mortar) and very low earth dikes. Consequently, series of terraces of silt and sand are created in the stream beds. Water accumulated in this deep soil in winter and spring allows crops of vegetables and cereals upstream and fruit downstream. In the Matmata hills in Tunisia, small rock dams with little spillways are built along the valleys. Deep terraces called "gessours" accumulate behind the dams, permitting valuable production of various crops. In the tropical Sahel the runoff downstream of small watercourses stops in ponds where sediment is deposited. When the ponds dry up, the peasants plant out the sorghum that has been previously seeded on small plots. Enough water remains in the sediments for the complete growth of the sorghum crop. In many developing countries of the dry warm areas, the main agricultural resources are produced by rain-fed agriculture.

Another possibility is the large scale management of water resources, but it must be stressed that management of water resources is expensive and must be supported by valuable crops. This is not possible in many areas like the African Sahel, where the soils are often too poor to support rich crops. In such situations the only possibility for management is the modification of the cultivated areas by the farmers themselves, using cheap processes mainly supported by manual work. When the crops are sufficiently valuable, more expensive techniques may be used, such as storage of water by dams, or the use of groundwater (if any) or of water coming from more humid regions upstream (exogenous inputs). There are however many obstacles to these techniques due to the hydrological characteristics described above. It is not easy to transform the soil surface by terracing or other methods without increasing peak floods and erosion during exceptional rainfall (Heusch 1985). During the last century in Maghreb (in the subtropical zone of north Africa) the erosion due to human activities has probably been multiplied by five as a result of the destruction caused by roads and other forms of damage (Heusch 1985).

Drip irrigation can be used, but it requires some technology and it may be too expensive in most places.

Another technique is research to find new crop varieties which fit the rainfall pattern. For instance some varieties of millet can develop a crop in three months, while others need five, six or eight months. Some plants can grow even with high water salinity, which permits the use of very poor quality water such as occurs in oases in the arid and hyper-arid zones.

In many cases it is very difficult to find an acceptable solution to the drought problem in dry warm areas.

Stock grazing. Extensive stock grazing generally uses the driest land areas (except in the hyper-arid zone). The stock need food and water, if possible in the same place. Nomads know where the rain falls and drive their herds accordingly. However, too many oxen around a single water pond or well during a drought has dangerous consequences upon soils and plant cover, and it is necessary to increase the number of ponds, small dams, wells and bores. Possibly a better solution is to reduce the number of oxen. Goats, which are numerous in subtropical regions, may be a calamity for the scarce plant cover, and are an important factor leading to desertification.

Fuel wood. People need wood for cooking and also sometimes, in the subtropical zone, for warming themselves during cold days in winter. This is also a problem for desertification, with no evident solution unless a cheap fuel to replace wood can be found.

Urbanization. The main problems in urban areas are water supply, sewage disposal, and protection against floods. Water supply can be maintained by water storage either behind dams, or in large cisterns with management of their catchment area, or from groundwater if there is any. It is always a difficult problem in this region, except when there is an input of exogenous water coming from a humid zone upstream.

Sewage must be treated before it is returned to the river, where discharge may be zero or very low during the dry season. After treatment, it can be used to recharge the groundwater by infiltration from shallow ponding basins, or sometimes by means of injection wells.

Particularly on higher slopes, floods may be very dangerous due to the high velocity of the water. If sediment transport is important this is a supplementary danger. Dikes may be necessary to protect urban areas, or dams may be built upstream in order to reduce peak discharges.

Mining and tourist trade. These two activities use relatively little water (unless it is used for site processing of mine ores) and may support a relatively high cost for it, unlike irrigation water. The use of deep aquifers, if any, is possible or water may be piped over a long distance; even carriage by trains or trucks is possible in special cases. However there may sometimes be a conflict between the needs of agriculture and tourism in sea-side resorts like the coastal area of Tunisia or even in the south of Spain, where there was a severe drought for some years before 1986.

Human impacts

Past hydrological impacts of human activities. Human activities have had an increasing effect on natural hydrological regimes because of the exponential increase in human population, due largely to technical advancement and medical progress. The areas with catchment response in dry warm regions have difficulties in supporting this increase. The natural hydrological pattern may be transformed in three ways: by construction of large structures such as dams, large channels and so on, by agricultural and grazing practices (including small structures) and by urbanization. This influence may be very important when it has lasted for centuries on very large parts of the region. It is specially evident in the subtropical zone where there has been a high population for many centuries, as around the Mediterranean. It is principally the influence of agricultural and grazing practices which have modified the natural pattern. In the sub-humid zone the clearing of natural plant cover in order to obtain crops and grazing land have caused higher erosion, with the best part of the soils being removed, and another consequence has been an increase in flood peaks. Over-grazing in warm areas has often modified the floristic composition of these pastures, the interesting plants for stock being progressively replaced by shrubs of lower palatability, and in the more arid areas a desertification process has taken place, resulting in different hydrological processes at the microscale, typically more runoff and less infiltration.

More recently, large structures have greatly modified the hydrological regime in many places. Peak floods may be limited by special dams; for instance floods of $17000 m^3 s^{-1}$ occurred on the Oued Zeroud in Tunisia before the construction of the Sidi Saad dam which is expecteded to reduce peak floods downstream to a maximum of 10 000m^3s^{-1}.

Building of roads and railways may cause new gully erosion during the construction period. Mining activities also can increase erosion by a factor of 50-100 , or even more with open-cut operations.

Urbanization causes very specific problems, with the decrease in surface permeability producing increased overland and stream flow, and the need for disposal of a large volume of sewage which is too often returned to the local river, even if its natural discharge is low or zero. Pollution may spread far downstream in the river, with many consequences for fish, aquatic plants and the people who live there and use this polluted water for their own supply of drinking water.

Potential for future human impacts. As noted above, the exponential increase of the population, specially during the last century, has produced a need for food which has very important consequences. In the subtropical zone in particular, such high population densities result in a catastrophic situation, because of the necessary development of agriculture to produce enough food. Too often agricultural practices are at variance with the climatic conditions. This is true also in the tropical zone, for instance in Africa and in South America, where the population density is less critical but is increasing rapidly and where also the effects of droughts seem to be more intense. Almost everywhere in dry warm areas where agriculture is the main activity, countries may pass beyond the limits of sound management of water and soils, even involuntarily, because it is not easy to know the appropriate long term limits. Effects that will be significant only after ten, twenty or fifty years may be neglected by governments that have so many urgent problems to solve.

The main dangers that may be mentioned here are desertification, erosion and sediment transport, water pollution, lowering of water-tables, and modifications of the drainage network causing unknown effects on the hydrological regime. Desertification is a well known problem as a result of its recent increase. Many people think that the main factor in desertification is a change of the climate, with the occurrence of severe droughts for several years when the annual precipitation is far below the median value; but the main factor is the growth of the population, and the climatic hazards only reveal the dramatic effects of this growth. The first and the main action to consider is to persuade these communities that they must drastically control this increase. All the other technical practices are also necessary, but of no use if birth control is not efficient.

Desertification may lead to a diminution of infiltration into the soil and consequently to a higher overland flow and higher peak floods. Desertification induces also a change in the plant cover, mainly in sub-humid areas. Fifty years ago in Africa the soil remained without cultivation for several consecutive years, and the plant cover was woodland with many small trees and shrubs. This cover is now changing rapidly, with the trees being cleared either for fuel wood or in order to obtain more land for crops. The new plant cover, if any, consists of cultivated plants or a poor new natural cover. Soils are no longer well protected, and erosion produced by a higher overland flow is more important, contributing to the degradation of the landscape. Another consequence is the loss of storage capacity in the dams which receive and trap a larger volume of sediment. For instance, in Algeria each year $20x10^6 m^3$ of dam capacity is currently being lost. All these phenomena have been observed for centuries in the subtropical zone, and now they can also be seen in the tropical zone and will extend greatly in the future.

Comparative hydrology

An ecological approach to land and water resources

Edited by Malin Falkenmark
and Tom Chapman

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