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17. Dry warm flatlands

Occurrence and general characteristics

Definition. An idealized flatland could be represented by a horizontal area without any runoff. If it is impervious, the rainfall remains on the surface until it evaporates. If it is sufficiently pervious, all the water infiltrates, and in the arid and semi-arid zone is evaporated later, as the potential evaporation exceeds the annual rainfall. In favorable circumstances, part of the infiltrated water may recharge an aquifer.

The real world is not so simple, but the hydrological characteristics described above may occur at a macro scale from land areas which slope locally. More generally, flatlands are characterized by a macro-scale response which is far from the conventional one in a sloping catchment, and is evidenced by a degeneration of the surface drainage network (Rodier 1964, 1985).

In warm arid areas, stream flow is infrequent and sediment concentrations are very high, for endogenous streams influenced only by the local climate. In these conditions, small watercourses with a slope between 1 and $3m\ km^{-1}$ usually disappear after a few kilometers.

For exogenous rivers entering arid plains from humid areas, the degeneration of the drainage network begins at slopes of the order of magnitude of $0.1m\ km^{-1}$. These two sets of limits, with intermediate situations, define an upper slope limit for flatlands in dry warm areas.

Occurrence. While the dry warm areas in general are shown in Fig.11.1, a separate presentation of dry warm flatlands on a world map is infeasible, because of the countless small plains more or less randomly distributed in the lower part of many watercourses in the hyper-arid, arid and semi-arid zones. To show these areas would require a scale of 1:200 000. The problem is similar to that of exclusion from the warm zone of mountainous areas with an annual potential evaporation below 1000*mm.*

The larger areas covered by this chapter are as follows:

Asia: The Dead sea (Israel, Jordan), the Tigris-Euphrates plain (Iraq), marshes and lakes of the Sistan area (Iran, Afghanistan), lower valley of Indus (Pakistan), great and little Rann of Kutch (India).

Africa: Lower valley of Nile (Egypt), Sudd marshes on upper Nile (Sudan), Lake Turkana (Rudolph) and its catchment (Kenya, Ethiopia), Lake Chad and its catchment (Chad, Cameroon, Nigeria, Niger), internal delta of Niger (Mali), lower valley of Senegal river (Senegal, Mauretania), Kalahari desert (Botswana).

North America: Central valley (California), Great Salt Lake (Utah).

South America: Marshes near Bermeja and Pilcomayo rivers, Gran Chao (Argentina, Paraguay).

Australia: Lake Eyre and its basin, the Simpson desert, the Great Sandy desert, the Nullarbor plain, the West Australian plateau, and several other large plains (see map in Australian Water Resources Council 1972).

The above areas, though having a diversity of hydrological characteristics, do not include chotts, which are not so large but may be significant in relation to water resources. In Africa the most important chotts are chott Dierid (Tunisia), and chott Melrhir and chott ech Chergui (Algeria).

Morphological and hydrological characteristics. As noted above, the spatial scale of topography is important in the hydrological definition of flatlands. Most flatlands have micro depressions at areal scales of some cm^2 or dm^2. At the meso scale, very shallow depressions may cover $500 m^2$ up to $1 km^2$. At the macro scale, in playas, salt lakes and some plainlands, the depressions may cover many km^2. Several desert formations may be classified as flatlands at the macro or meso scale: the plains of regs with an impervious surface of mixed gravel and clay; the ergs; sand dunes, generally very pervious; and the hamada, a plain of blocks.

The general characteristics of plant distribution and growth in dry warm flatlands are similar to those described in Chapter 11 for areas with catchment response, but the dominant species differ, and perennial grasses in particular are more likely to occur on the flatlands.

For permeable soils, rainfall enters the plant root zone and is later transpired by the vegetation or evaporated from the soil surface. It remains in the plant root zone for a period related to the depth of the rainfall event, the aridity of the climate, and the season. A small part of a high rainfall may penetrate beyond the plant root zone and continue to move slowly downwards until it reaches the water-table. This is a feature of sand dunes, where the soil at the bottom of the dunes is observed to be damp for several weeks after a high rainfall. Groundwater recharge is typically of the order of $1 mm\ y^{-1}$, and the time taken for water to reach the water-table is very long, often of the order of hundreds or thousands of years (Allison et al 1985).

In the case of impermeable soils, most of the rainfall is stored in micro depressions. If the rainfall is sufficient, these small depressions overflow and water moves slowly towards the larger depressions. At the meso scale there is no overland flow to streams or lakes, but a small increase in the slope may induce overland flow and streamflow in the poorly organized channel network.

Impermeable soils are relatively frequent in tropical areas. The kinetic energy of the rainfall creates an impervious film (surface crust) at the soil surface, even in some sandy soils. This film inhibits further infiltration and allows water to pond on soils for which laboratory studies indicate a significant permeability. The surface of the soil dries very quickly after rainfall, and the small amount of water which has penetrated the surface film is also evaporated.

The hydrological characteristics of flatlands with exogenous inputs will be described later.

Water balance components

Precipitation. With the exception of orographic effects, dry warm flatlands have the precipitation characteristics described in Chapter 11 for areas with catchment response.

Evaporation. In arid areas, the long term actual evaporation E is far below the potential evaporation E_o, because of the lack of available water for most of the year. It is close to the potential evaporation for periods during which water is lying on the soil surface or the surface is close to saturation. These periods are generally short (hours to days), but may be much longer or even permanent when there are exogenous inputs, as in interior deltas and chotts.

In the arid and hyper-arid zones, the annual evaporation E is practically equal to the annual precipitation P_y. In high rainfalls, small amounts of recharge can occur, as reported by Colombani (1978) and Vachaud et al (1981) for areas in Africa with no permanent vegetation, and by Chapman (1961), Allison et al (1985) and others for areas in Australia with various soils and types of natural vegetation.

Fig. 11.3 shows the variation with latitude of both potential and actual evaporation in central Africa. The interannual variability of the potential evaporation is relatively low.

In sub-tropical areas, the seasonal variation of potential evaporation is characterized by a maximum monthly value in summer which may exceed 200*mm*. For tropical areas, the maximum is just before the rainy season. At the boundary between the tropical and subtropical zones, often in desert, the rainy season is very short, and the maximum potential evaporation occurs in summer, often reaching 300*mm* per month.

Owing to the spatial variability of rainfall, water may pond on the surface in relatively small areas at a particular time. In these circumstances, the rate of evaporation may be considerably higher than the potential evaporation, due to advection (the "oasis effect").

Infiltration. Except in the sub-humid zone, infiltration into impermeable soils is 15-50% of a heavy rainfall (say 50-80 *mm*). Part of the water accumulated in micro depressions infiltrates, and part evaporates, at rates of several $mm\ d^{-1}$. The water consumption of plants increases with each input of infiltration, and the roots of trees and other deep-rooted plants may exploit the water to depths of 10 *m*.

Impermeable soils cover large areas because of the formation of an impermeable film (Valentin 1981), which transforms soils, which in other climates would be relatively permeable, into soils which have low infiltration rates. This occurs mainly in areas with sparse vegetation and where there are some fine grain sizes in the composition of the upper soil layers. Even ploughed soils become impervious after several rains. The phenomenon does not occur in sub-humid areas where plant cover impedes the formation of a surface crust.

Except again in the sub-humid zone, there is more infiltration into pervious soils, but virtually all the water at the micro and meso scales is removed by evapotranspiration. The main opportunity for direct groundwater recharge is where there are fissured rocks (which occurs only in sloping areas) and in some subtropical soils where the rainfall occurs in the cold season. Opportunities for recharge are greatly enhanced where there is endogenous input from sloping land in the same climate, which concentrates the runoff before it reaches the flatlands, or where there is exogenous input from humid zones. In desert areas, this only occurs in exceptionally wet years.

A striking example of an endogenous input is the Korama basin in the semi-arid area of Niger. Here a perennial river is fed by an aquifer recharged by percolation from the pervious soils in the flatlands and the surrounding sloping areas. This is a transitional case of an endogenous interaction.

The situation is different in sub-humid areas, as the soil is often pervious and the higher rainfall increases the probability of groundwater recharge in favorable geological conditions, in spite of higher water consumption by the more dense plant cover.

In considering infiltration at the macro scale, it should be noted that, for most of the large flatland areas listed above, the morphology of the plains and surrounding areas corresponds to wetter conditions than have existed for the last 2000 - 3000 years (the Chad basin for instance was partly an internal sea). This accounts for the negligible slopes, large areas of clay soils, and the frequent presence of high concentrations of salt in the soil.

Surface storage. For relatively pervious soils there can be significant storage of water on the surface during periods of high intensity rainfall, and for a short period after. For less pervious soils, the scale of the depressions is significant, as described earlier.

After rainfall, the micro depressions dry up very quickly. At the meso scale, depressions with water depths of 50-200*mm* dry less quickly but nevertheless rapidly. In tropical areas the water is warm, and as the proportion of the land surface covered by water is small, the advective effect is important. Evaporation rates are higher than from large deep reservoirs, and may reach $10 mm\ d^{-1}$.

In subtropical areas the water remains on the surface for a relatively long time in winter. This occurs frequently in semi-arid areas, and also in arid and even hyper-arid areas during exceptionally wet periods. As desert trails often follow the flat clayey land, travelling in these areas is very difficult at such times.

At the macro scale the depressions are larger and deeper, and the daily evaporation rate is lower. There may be some surface drainage during periods of exceptional rainfall, through depressions which are covered by vegetation.

However, as a general rule runoff in dry warm flatlands occurs only under endogenous or exogenous influences.

Groundwater. Groundwater is a very important component of the water resources of dry warm areas (Jacobson and Lau 1983). There is no space here for a review of all the main aquifers of this very large region, but the characteristics of the main types will be described, with some examples.. Unesco/UNEP/FAO (1979) gives a short review which covers most of this area.

Some parts of what follows applies also to some areas with catchment response, as the same aquifer may underlie alternating sloping lands and flatlands. Except in the sub-humid zone, direct groundwater recharge from rainfall is infrequent, but important inputs to aquifers come from the intermittent rivers of areas with catchment response and exogenous rivers originating in the humid zone. Such inputs may also be significant to the equilibrium of fossil aquifers, which can be very extensive.

The five categories of aquifers described below follow the Unesco/UNEP/FAO (1979) classification, with slight modifications towards a classification developed by Margat (in press) for groundwater in Africa.

Shallow aquifers. Alluvial aquifers may be important when a watercourse overlies a recharge zone thick and permeable enough to constitute a groundwater reservoir Particularly favorable conditions may occur in the distributary zones (deltas) frequent in the lower reaches of watercourses. Although these watercourses are dry most of the time, the aquifers may be recharged by one or two floods, particularly in exceptionally wet years. The smaller aquifers of this kind may be exhausted before the arrival of the next recharge event; in such cases, enhancement of the recharge by low surface dams and/or reduction of groundwater outflow by subsurface barriers may provide a perennial water resource.

Crystalline rock and Precambrian areas. Although these formations cover a considerable part of the arid zone, their water resources are poor because, under normal conditions, they are compact and devoid of porosity. Aquifers can be found only in the overlying weathered formations, in networks of fissures, and in faults and dikes. Sometimes, for example in India, there are horizontal zones of fractures which form significant aquifers. Generally however the yield is poor, as indicated in Table 17.1.

Primary areas. Considerable well production can be acheived from aquifers of interbedded limestone with a network of fissures, or dolomite or porous sandstone. In the Northern Territory of Australia, some wells supply up to $90 m^3 h^{-1}$. The water quality is often acceptable .

Volcanic and karstic areas and generally folded or dislocated chains. These very different formations may contain groundwater, principally under sloping land. Some volcanic rocks may contain considerable quantities of water in their vesicular cavities.

Karstic areas are relatively frequent in the subtropical zone. They sometimes feed springs, but there is typically a considerable diminution of flow in drought years. In most cases the aquifers are small and the recharge irregular in arid and hyper-arid areas. A particularly large system underlies much of the Nullarbor plain in Australia; the groundwater is discharged at the coast of the Great Australian Bight.

Large sedimentary basins. These underlie wide areas in western Africa and in Australia they contain continuous and often important aquifers.
The most extensive sedimentary basin in Africa is the interbedded continental aquifer of the Cretaceous period. It is continuous from Tasudeni to the Sudan, and extends across tropical and subtropical arid and hyper-arid zones. It is unconfined at some of the margins, but the central part is confined. Its clay sandstones have quite high permeability, and flow from wells is high. Although there is variable mineralization, the quality of the water is generally good. The main body of water is

mineralization, the quality of the water is generally good. The main body of water is fossil, but wadis on the margins occasionally recharge the aquifer to a small extent. While this resource is permanent and independent of droughts, overuse will of course reduce the head.

Another very substantial aquifer is the Maestrichtian sand, which extends over more than 100 000 km^2, and is several hundred meters thick in Senegal. Flows of 50-120m^3h^{-1} of good quality water can be obtained from wells. Similar aquifers are used in northern Nigeria (see Table 17.1) and in Chad.

Table 17.1

GROUNDWATER RESOURCES IN NORTHERN NIGERIA

Aquifer	Lithology	Thickness (m)	Area of outcrop (km^2)	Average SWL# (m)	Range in yield ($l s^{-1}$)
Chad formation (Pliocene)	Clays, silts, fine sand with beds of sand and gravel.	100-200	9 200	36	1.7-5.0
Sokoto group (Paleocene)	Clays and shales with a fissured limestone formation.	90	n.d.*	n.d.	n.d.
Rima group (Maestrichtian)	Sandstones and siltstones with interbedded shales.	250	6 800	6	2.2-4.4
Gundumi formation (Maestrichtian)	Coarse sands and gravels. Some clays.	n.d.	8 200	14	1.6-3.3
Basement complex	Weathered basement mantle or jointed and fractured crystalline rocks.	100	12 200	13	0.0-0.3

#SWL - Static water level (below surface) * not determined

In Australia the most important sedimentary basins are the Great Artesian basin, the Canning basin and the Carnarvon basin (Hahn and Fisher 1963).

The Great Artesian basin is a sandstone aquifer from the Triassic to the Cretaceous period, with a thickness up to 2100*m*. It covers 1 700 000km^2, principally in the tropical and subtropical parts of Queensland. It is recharged from streams along the eastern and northern margins, where the annual rainfall is much higher than in the center of the basin. Its hydrology and use have been described by Habermehl (1987).

The Canning basin is less important; it consists of a thick sequence of formations in Western Australia, and is principally exploited near the coast. The Carnarvon basin, also in Western Australia, extends further south along the coast.

There are also large sedimentary basins in India, California and Peru, but not as extensive as the largest ones in Africa and Australia.

Endogenous interactions

This section will consider the influence of adjacent sloping areas on the hydrology of flatlands in the dry warm regions. On flatlands not subject to external influences, the accumulation of sufficient water will cause flow between surface depressions, first at the micro scale, then at the meso and macro scales if the water supply is sufficient. The flow paths between depressions may take the form of shallow unstable channels, or it may occur as sheet flow. This surface movement of water, which can be thought of as the beginning of runoff, is very sensitive to influences such as the spatial pattern of storm rainfall, wind direction, plant growth, the processes of erosion and sedimentation, and human influences.

When watercourses on sloping land, with a well defined channel network, flow on to flatlands with these characteristics, an intermediate situation develops between a fully organized drainage network and the flatland situation described above. This phenomenon has been termed "hydrographic degeneration" by Rodier (1964, 1985).

Hydrodraphic degeneration. The characteristic feature is that the continuity of runoff is no longer obvious, nor the continuity of the channel itself, and losses of water from the main channel are very important.

A simple case is that of a watercourse which, before it reaches the flatland, has distinct banks with often a narrow flood plain with thorn trees. On reaching a lower slope the stream bed becomes unstable, producing a lowering of the banks and increasing the width of the flood plain, often with one or more depressions detached from the main stream bed. The runoff generally ends in a clay based depression which receives the water and sediments carried by the watercourse; sometimes a short delta is formed.

Before reaching this stage, the channel may join a major depression with very low slope, which collects the input of several such streams. With sufficient input the flows of these tributaries may travel in both directions along this main depression, filling a series of pools. After sufficient storm events to fill these pools, runoff from the whole area continues in a downstream direction.

If the slope of the main depression is low but significant, it may carry continuous runoff from the beginning of the rainy season and have a relatively large flood plain, several discontinuous channels and many small pools. The flow finally terminates at the point where it cannot be sustained by the total input from the tributaries. At the limit of the arid and semi-arid zones these conditions may permit the formation of a river which is fed successively from different parts of a large catchment with an area of the order of 50 000km^2. The Ba Tha river in the Chad basin is an example; for two to three months each year it flows into a small lake (Lake Fitri), and it dries up for the remainder of the year.

In the hyper-arid and arid zones, where there is a fossil channel network resulting from the earlier wetter period mentioned above, the situation is more complex; the river may use part of an old bed for one flood, and another one for the following flood.

Hydrographic degeneration is characteristic of low slopes in hyper-arid, arid and semi-arid areas, but is less common in sub-humid areas. It results from the following factors:

(i) A long period without rainfall when the vegetation disappears and the soil on the slopes becomes bare, without any protection against erosion. The water reaching the flat lands has a high sediment concentration.

(ii) Flows for a very short duration which may not be long enough for the maintenance of a continuous channel, particularly in flatlands where the potential energy is very low and the runoff has a large sediment load.

(iii) Often a fossil drainage network in very flat areas where flow becomes more and more difficult.

Consequences of hydrographic degeneration. When a stream from sloping land enters a flatland, it develops a channel which results in some runoff from the flatland as well as the runoff from the sloping land. The resulting runoff however has little relation to catchment area, and values of specific discharge, measured in $m^3 s^{-1} km^{-2}$, are meaningless.

In addition, when the potential evaporation is high, the runoff becomes very low soon after leaving the sloping areas, even in favorable circumstances (for example in tropical areas where the rainfall is concentrated into a wet season). A general study of annual runoff in the tropical Sahel (Rodier 1975) gives an average annual runoff of 15 *mm* for an area of 2000km^2 with an annual rainfall of 500*mm*. In the very favorable conditions of the Ba Tha river the annual runoff is 10*mm* from a catchment area of 4500km^2 and the same annual rainfall. As in sloping areas, the distribution of values of annual runoff is generally skewed.

Often the flow stops completely after a distance related to the magnitude of the discharge reaching the flatland area, and does not reach a drainage terminus in a lake or the sea. This is typical of the arid and particularly the hyper-arid zones.

The duration of surface storage on the flatlands remains short, though longer than it would be without the input from the sloping land. There is an increase in the depth of infiltration, which may result in groundwater recharge in arid and even some hyper-arid areas.

As a result of the input from the sloping land, the evaporation from the flatlands may be higher than the local precipitation.

Exogenous interactions

This section discusses the exernal inputs from rivers rising in wetter regions, such as the tropical humid zone, or from mountainous areas in the same general climate which have much higher rainfall due to the orographic effect. Most of the world's large flatlands listed earlier benefit from this external influence.

General hydrographic features. Because of their large mean discharges, most of the large rivers from humid areas are able to cross arid areas (Fig.17.1) and reach the sea. However in their passage through the drier areas they are affected by a different form of hydrographic degeneration, which results in very large flood plains and many channels which leave the main branch. These distributary channels often do not join the main branch again, and the water is evaporated from ponds, lakes and swamps. There are several different hydrographic patterns:

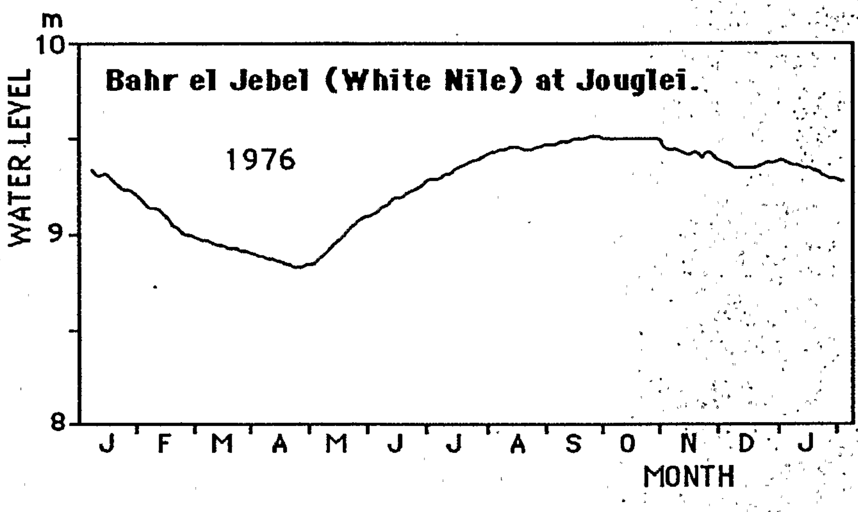

Fig.17.1 Water level of the Bahr el Jebel at Jouglei in a typical year, showing the regulating effect of Lake Victoria on low flows.

The rivers flow in a wide flood plain with secondary branches and lakes (e.g. Senegal river, Indus and lower Nile);

The common flood plain of two or more rivers becomes very large, with widths reaching 200-400*km*. Many large channels are relatively stable, and there may be large lakes which fill or empty with long wet periods or droughts. Examples are the Tigris and Euphrates, the Chari and Logone in the Chad basin, and the internal delta of the Niger. The water of the Chari flows into an internal depression whose southern but not deepest part is Lake Chad. The lake area ranges from less than 2000 to 26000km^2. In very wet years the water overflows eastwards towards a depression 400*km* away, but is stopped after 50*km* by evaporation and transmission (infiltration) losses.

Chotts are flat depressions in the arid area of North Africa, which receive an important supply from groundwater. These chotts (e.g. Chott ech Chergui, Chott Tharsa, Chott el Hodna, Chott el Djerid) are very shallow and swampy, and contain high salt concentrations because of the geological conditions.

The rivers flowing towards Lake Eyre in Australia exhibit a wide variety of drainage patterns (Kotwicki 1986), from single main channels to the complexity of the Channel Country, a large area of innumerable small watercourses which create a mosaic of small islands.

Influence on water balance components. The water balance varies widely in space. There is a large difference between areas influenced by large permanent rivers with a flood for several months each year, and the margins of flatlands which receive only a small supplement of external water for two or three weeks once every five years or so. The annual evaporation from Lake Chad is about 2200*mm*, but it would be only 350*mm* for a flat area in the same climatological zone without external water input. For given geological conditions, the disparity for groundwater recharge is even greater.

The actual annual evaporation is generally higher in areas with exogenous inputs than for flatlands with only endogenous inputs. This is due to the longer duration of floods and generally shallow water-tables. The evaporation may approach the potential evaporation over large areas, and because of advective effects may exceed it over open water bodies.

The locally produced runoff may be increased in areas with exogenous inputs, as the rain falls on water or wet soil, particularly when the local rainfall occurs at about the same time as the flood in the large river. At the macro scale this effect is not significant compared with the external water supply. Losses by evaporation remain very high if we consider only the runoff measured upstream of the large basin. For instance, the Niger river loses about 48% of its runoff by evaporation while crossing its internal delta (Rodier 1985). While the volume of runoff recharging the aquifers is considerable, it is very small compared with the evaporation. The Bahr el Jebel (White Nile) loses 50% of its mean annual discharge of $840 m^3 s^{-1}$ while crossing the swamps of the Sudd (Sutcliffe 1974). The mean discharge of the Tigris in Iraq decreases from $1236 m^3 s^{-1}$ at Baghdad to $218 m^3 s^{-1}$ not far from the delta (Guilcher 1979).

These losses smooth the peaks of the annual hydrograph into a uniform curve (as for the Chari river in Chad), except in a very dry year. A flat maximum to the hydrograph is observed in some cases, e.g. the Logone, a tributary of the Niger (see Fig.17.2). Owing to the extreme width of the flood plain, an unusually high peak flow results in a very small change in water level in the main channel; the flood frequency curve for the Logone at Logone Birne has almost an asymptote at $950 m^3 s^{-1}$. This explains the negative skew of many flood frequency curves in such areas. This is not as characteristic in distribution curves for annual runoff, because during wet years when the maximum discharge is not much different from the mean, the flat part of the hydrograph lasts for a longer time.

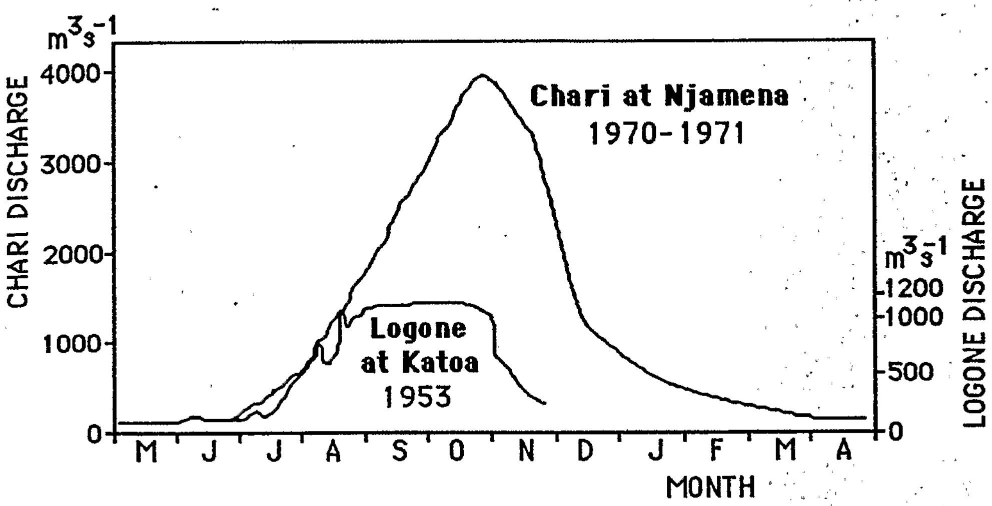

Fig.17.2 Discharges of the Chari in a typical year and of the Logone in 1953.

In discussing frequency distribution curves it should be recognized that, while the channels of exogenous rivers are more stable than those of endogenous streams, there can be modifications of the pattern of channels or the longitudinal profile of the bed (Sutcliffe 1974), resulting in the distribution being shifted while retaining the same general character.

The runoff of exogenous rivers usually joins the sea by a delta, or in very arid zones a sebkha (a flat plain more or less connected with the sea, which is flooded only during the wet period).

Exogenous runoff brings with it much sediment, often very advantageous for agriculture. Under natural conditions, a large part of this sediment is trapped by the natural vegetation in swamps. Without any other external input, water often leaves flatland areas with little sediment but some organic matter; the resulting output is sometimes called the "black flood".

Exogenous runoff from humid tropical areas often originates in very old geological formations and therefore carries few solutes; this is the reason why the water in Lake Chad is relatively fresh. However, this is not true everywhere, particularly in subtropical areas, and the flatlands themselves may be a source of salt. Many flatland areas have salt problems. Because the external water supply increases interactions with groundwater, the phenomenon of salt rising towards the upper soil layers may be more frequent than in areas under endogenous influences only.

Other things being equal, the greater duration of depression storage and the lar inundated area should provide excellent conditions for infiltration in areas wi exogenous inputs. However, the deposition of fine-grained sediments may crea impervious layers which impede downward water movement. On averag infiltration is higher than in areas only under endogenous influences, but for a giv area it depends on the geological and morphological conditions.

All these aspects are very sensitive to human influence, as will be shown later.

Current pattern of land and water use

General considerations. Before discussing particular forms of land and wate use, it will be useful to consider the hydrological characteristics which determine th situation relating to the two main problems of water use:

- lack of water (low flow or dry season period)
- excess of water (disastrous floods, waterlogging)

These problems will be considered mainly in relation to areas with external inflows, which are frequent in flatland areas and allow much more economic development.

The relevant hydrological characteristics are:

- the annual precipitation, its interannual variability (which determines the drought hazard), its seasonal distribution in relation to crop cultivation, and maximum daily values in relation to erosion flood hazards, particularly in areas subject to tropical hurricanes;
- the annual volume of runoff produced locally in sloping areas or externally in humid areas. The first is less important and has a very irregular time distribution, with a series of floods on occasions and also the possibility of no runoff for some years. The second is much more important; all the flat areas may be flooded for a duration which has a statistical distribution with negative skew. The distribution of flood magnitudes also has a negative skew and almost an upper limit. The water-level regime is also ver important for irrigation, as are the characteristics of the minimum flow.

In order to manage the water resources in flatland areas it is essential to understand the operation of the complex hydrological system of rivers, channels with or without flow, lakes, reservoirs and swamps; the fluxes between components of this system under various conditions; and possible evolution of the system and its flows. In addition, consideration must be given to the possibilities of water supply from aquifers, taking account of aquifer depth, recharge rates and groundwater quality. Good knowledge of water quality, particularly salinity and chemical composition, is essential for water resource project management and operation. The nature and volume of sediments may also have a strong influence on the development of land and water use.

There is a wide range in the physical conditions in flatlands. In areas such as the lower Nile, the Tigris-Euphrates and the Indus, conditions were found to be extremely favorable for agriculture several thousand years ago, with flat fertile soils, ample water and the possibility of controlling it, easy water transport, and the possibility of establishing cities protected by water bodies and swamps. At the other end of the scale of land use are areas such as the lowest part of the Chad, a flat depression with brackish water near the surface, in which a few wisps of grass at intervals of $50m$ constitute a good pasture for camels.

Socio-economic conditions vary as widely as the physical conditions. The over-populated lower Nile valley with its agricultural traditions and transport facilities is very far from the Chari-Logonne system with a population density of $1\text{-}3p\ km^{-2}$, where the inhabitants generally do not practise agriculture and there are serious difficulties in the export of goods.

There are also great differences in the methods of water use, from maintaining natural hydrological conditions to flow modification by primitive structures and to the sophisticated methods of large projects. Each method may correspond to an optimal adjustment to the prevailing physical and socio-economic conditions. There are also large differences in the stage of development and operation of water systems; some have been used for so many years that most of the land is useless for cultivation, while in others the impact of man has been negligible up to this time.

In view of this diversity, only some examples of land and water use will be given. As the availability of water is more tied to the existence of external inputs than to geographical zones, water problems will be considered in relation to the different types of water use.

Stock grazing. Extensive stock grazing generally uses the driest areas of the dry warm flatlands, with the exception of the hyper-arid. It is also common in semi-arid areas, but is prevented by some diseases in parts of the sub-humid zone.

Stock need both food and water, and cannot graze beyond a certain range from watering points. If water is available at too few points, over-grazing and trampling in these areas makes them unproductive. Effective management therefore requires increasing the number of watering points, by diverting local runoff into surface ponds or cisterns and/or by constructing wells or bores. As evaporation losses from surface storages are considerable, increasing the water depth in at least part of the pond (as has been done in the Hafir area of Sudan) can be effective. Various ways are used to raise groundwater to the surface, from primitive methods using donkeys or oxen as a power source to windmills and electric pumps. Maintenance of mechanical and electrical equipment may be a problem in some areas.

The water requirement for stock grazing is less than that for agriculture, but during drought periods there is a tendency for stock to be moved towards more humid areas near permanent rivers or an internal delta.

Agriculture. With the exception of dryland farming, which is not possible everywhere in the dry warm areas, agriculture in this region is determined by the need for water. In some depresssions in flood plains it may be possible to cultivate crops without modifying the water system, but irrigation of crops is the general rule. In some areas, water from mountainous areas may be used with simple techniques, as in the Mzab area in Algeria, but generally a more or less complex system of channels is necessary, and regulation of river flow upstream of the flatlands is also often required. In some areas, such as the Central Valley in California, water may be transported by artificial channels from more humid areas.

Water availability in irrigation areas may be a problem of water-level as well as one of volume of supply. For instance, in the recent drought in the Sahel the irrigation of rice failed because water levels were too low; although there was adequate river flow, no pumping plant was available.

Useful water supplies in irrigation areas can be improved by:

(i) increasing the water supply by methods such as construction of storage reservoirs, diversion of water from other catchments, and using ground-water conjunctively with surface water, possibly with the provision of artificial recharge;

(ii) reduction of wasteful use of water by good maintenance and the use of water- economizing irrigation techniques such as drip irrigation.

Navigation. Where large rivers cross dry flatlands, there are often excellent opportunities for economic transport of goods, including agricultural products and stock.

Mining and tourist trade. These have been briefly discussed in Chapter 11.

Urban water supplies. Urbanization in flat areas presents two water-related problems: water supply and protection against floods. During the drought in the Sahel, the city of Niamey in Niger used half of the flow of the Niger river for a few days in 1974, and the river flow stopped completely for a short period in 1985. Water supply systems have to be constructed that can cope with such situations, and this may involve diversion of water over long distances. The system should also be designed to provide for the needs of industry in urban areas.

For flood protection, many villages in swamp areas have been built on hills, while others have constructed dikes. Fortunately the difference between water levels in average and extreme floods is not very high in flatland areas, but protection may be required against floods which inundate plains that remain dry for several years at a time.

Hydrological impacts of human activities

Past effects. Human activities may influence the natural hydrology of an area in three ways: construction of large structures (dams, large channels, roads etc), agricultural and grazing practices (including some small structures), and urbanization. This influence may have a major impact on the natural system particularly when it continues for centuries on a large part of a flatland area.

Many flatland areas which some centuries ago were swamps of low economic value are now areas with a high agricultural yield, after development and proper management of a good network of drainage channels. Some also make use of old irrigation schemes based on surface or groundwater resources.

Unfortunately, if the principles of soil and water conservation are not respected, the influence of these human activities may be disastrous. Particularly in warm areas, many flatlands which were good pastures have been over-grazed, resulting in a change in the floristic composition towards less palatable and often less nutritious plants. In more arid areas this has resulted in the onset of desertification, with changes in the hydrology at the micro scale, usually involving less infiltration, more surface runoff and, in sloping areas, more erosion.

Flatlands may suffer two serious consequences of irrigation, salinization of the soil and land subsidence. In the first case, evapotranspiration causes a capillary rise of groundwater through the unsaturated zone, leading to accumulation of salt at and near the surface and sevare constraints on plant growth and survival. The soil surface may become less pervious, reducing infiltration. The effect can be prevented by a well managed network of drainage channels, but these should be established a priori, as salinization effects are difficult to reverse. As a result of salinization, some parts of Mesopotania and the Indus valley can no longer be cultivated, and agricultural yields have decreased in many flatland areas that have been used for centuries.

In irrigation areas, extraction of groundwater at a higher rate than it can be recharged causes a lowering of the water-table. In fine-grained soils this leads to land subsidence, which may change the complex natural drainage system of flatland areas.

It is seldom that roads and railways, and particularly bridges over waterways, are constructed without having some effect on the complex hydrological system of flatlands, specially during floods. Although the effect may be beneficial, frequently there is an increase in the area affected by floods, and there may be a reduction in groundwater recharge.

The effect of urbanization is to increase the area of impermeable or less permeable land, and so reduce infiltration overall. This increases the volume of surface water which must be removed by drainage under conditions where there is little gravitational head to cause flow. These conditions also make it difficult to dispose of sewage, and frequently the groundwater in urban areas becomes polluted as a result.

Potential for future effects. In recent years the characteristic feature of flatlands, specially in warm areas, has been the increasing need for food resulting from an increasing population density. While this situation has been catastrophic for many areas in the subtropical zone, it has had less impact in tropical flatlands in Africa and Central and South America, with lower densities of population. Even in these areas, populations are increasing and it will be necessary to develop agriculture for more intensive production.

This section will cover five types of human activity which can have a serious impact on the hydrology of a flatland area: desertification, salinization, lowering of water-tables, pollution, and the effect of structures. Erosion has already been discussed in relation to sloping areas (see Chapter 11). Increased sediment, which is its consequence in flatlands, is not always a benefit, as in the case of a large flood from an eroding area leaving a meter or more of infertile sand and gravel on an irrigation area. Such problems are however more restricted in their areal impact than the five categories listed above.

Desertification is a consequence of over-grazing, often by goats, which is greatly accelerated by severe droughts. As the plant cover is reduced, the top soil is eroded and sorted by wind action, and the end result may be the development of sand dunes or clay plains which are often saline.

The process of salinization has been explained above and in Chapter 5. In warm dry flatlands the risk of salinization is high if one or more of the following factors is present: significant salinity in the irrigation water, a shallow saline aquifer, saline bedrock below the flatland sediments, or an inadequate drainage network. It is essential that there should be continuous monitoring of the salinity of both the irrigation water and the drainage water. In arid areas there is seldom the opportunity to remove soil salinity by application of large volumes of fresh water, as occurs in rice fields. The crops and cultural practices should suit the chemical composition of the soil water and the soil structure. The process of salt accumulation is a major risk for irrigation development in the future.

Increased use of groundwater for irrigation is developing rapidly, and there is an increasing danger of excessive lowering of water-tables. Some lowering of the water-table may be beneficial, as it may increase the natural recharge, but in general there will be a need for artificial recharge of groundwater which is being over-exploited.

In flatland urban areas, the problem of wastewater disposal, and the avoidance of pollution of groundwater and even surface water, is probably more critical than the problem of disposal of flood water. Increased individual water use and increases in industrial use of water can cause serious impacts even when the population density is not increasing. Treatment of wastewater to the point where it can be re-used, either locally or downstream after a period of natural purification, should be considered as an alternative to importing more fresh water into the urban area.

The possible effects of road and railway structures have already been mentioned. Hydraulic structures (dams, canals, irrigation systems etc) may have both immediate and subtle impacts on the hydrological system. Changes in the amount and nature of the sediment downstream from such structures can have long-term effects on the morphology of the channel system, and it may be many years before a new stable water and materials balance is achieved. Such long-term effects on the ecosystem are often difficult to predict, but an attempt should be made to identify possible consequences; if they cannot be ameliorated by changing the hydraulic design, monitoring systems should be established to give early warning of trends and their magnitude. Unfortunately, as a result of other conflicting interests, the best technical solution is not always adapted.

Implications for hydrological data collection

For rainfall and groundwater data, the main difference from sloping areas is the difficulty of access in flatland areas during wet periods. In arid areas, groundwater studies should place emphasis on water quality and the process of groundwater recharge.

Due to advective effects, the evaporation from pans will depend on the wetness of the surrounding area, so that information on local conditions is essential for analysis of pan data.

The main impact of flatlands on hydrological data collection however relates to measurements on surface water, which are completely different from those used in sloping areas with catchment response.

With no external inputs, the first surface water characteristic to be studied is the area which is flooded, the depth at selected points, and if possible the direction of flow under different conditions. More detailed flow measurements should be made at one or more characteristic depressions at the meso scale. Where flows occur at the macro scale in extreme events, measurements should attempt to identify the direction and magnitude of the flow.

With a significant external input, there will be a reasonably well defined channel crossing the flatland area, and due to its importance for water management the following observations should be made: downstream discharge in the main channel and floodplains, lateral flow (and its direction) between the channel and the floodplain, water-levels in depressions and lakes, slope of the water surface, changes in channel and floodplain morphology, and the influence of drought and vegetation on the hydrological regime. A long-term hydrometric station is required to monitor seasonal changes and long-term trends.

The surface water system should be sufficiently observed in low, normal and flood conditions, to enable the development and calibration of a hydraulic or mathematical model, possibly including sediment transport and water quality. The operation of such a network by traditional methods is difficult; there are problems of access, of having competent observers at the right location, of maintaining recorders, and of measuring channel losses. In an ORSTOM study on the Logone river, one set of loss measurements extended over a width of 30*km*. In spite of the low slope, the bed at even main hydrometric stations may be unstable, as in the upper Nile and the Logone. In these circumstances even slight movements due to tectonic activity can modify the natural water system.

Many of these problems are resolved by remote sensing and remote data transmission. The relative absence of clouds in dry warm areas provides favorable conditions for remote sensing, but the requirements for efficient maintenance may inhibit the use of remote data transmission.

Effective use of remote sensing for hydrological purposes in dry warm flatlands requires a spatial resolution not exceeding 50*m*, repetition of coverage at frequent intervals (preferably less than 15 days), and a suitable observation network for ground truth. The last is particularly important in flatland areas, because of the diversity of surface conditions. For example, on Lake Chad the following elements must be unambiguously identified: free water, fixed islands of papyrus, mobile islands of papyrus, water areas more or less covered by reeds, grass plains with saturated soil, etc.

Although the value of remote sensing and remote data transmission has been demonstrated in dry warm flatlands, few of the large areas listed earlier make operational use of remote sensing. There is some use of remote data transmission.

Management of land and water resources

In the drier areas or where the soil is too poor for agriculture, economic activity in dry warm flatlands is confined to stock grazing (and sometimes mining or tourism).

However these flatlands are often contiguous with sloping areas which pour their runoff on to the flatlands. In these circumstances, conditions are favorable for agriculture, with low soil erosion and a topography suitable for irrigation, provided there is sufficient water, good soil, and people who are prepared to undertake agriculture rather than be pastoralists.

A major difficulty is the variability from year to year of the runoff from sloping arid lands, and particularly the phenomenon of persistence of both wet and dry years. This can be ameliorated by the construction of dams where sites can be found in sloping areas, but this is not always possible or fully effective. To combat drought efficiently, it is necessary to have an integrated approach covering food supplies, land and agricultural management, and social and political issues (Tixeront 1979).

The situation is better in flatlands receiving runoff from more humid areas. The statistical distribution of the runoff is less skewed, and the consequences of droughts and extreme floods are not so serious. The difficulty is often to obtain sufficient understanding of the complex water system in flatland areas.

In managing land and water resources in dry warm flatlands, the hydrology is only one component, but it is an essential component. Disasters will occur in the future, as they have in the past, if this is ignored.

Comparative hydrology

An ecological approach to land and water resources

Edited by Malin Falkenmark
and Tom Chapman

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