CHAPTER 13

River Flow in Arid Regions

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13.1 INTRODUCTION

Often little is known about the surface hydrology of arid regions. Flow measurement presents a particular problem in such areas, and even when carefully made the irregular character of runoff in both time and space constitutes a serious obstacle in the determination of the parameters of the hydrological regime. These regions, however, can only be satisfactorily developed with exceptional effort to obtain the optimum utilization of existing resources as a whole, including surface water resources. A rational study of surface runoff in arid zones is often effected by means of a series of co-ordinated measurements, of which the measurement of flow constitutes an important part.

Some details concerning these measurements, however, can only be properly understood if they are placed in their general context, as defined by the natural conditions of the environment and the strategy to be implemented in making them.

13.2 GENERAL CHARACTERISTICS OF THE HYDROLOGICAL REGIME IN ARID ZONES

Despite the establishment of some quantitative indices suggested by Martonne, Koppens and Thornthwaite it will not be attempted here to offer an exact and quantitative definition of arid and semi-arid regions. It is not always a simple matter to classify all arid regions of the world since aridity, although related to low values of annual rainfall in relation to potential evaporation, depends on many other factors such as temperature, concentration of rainfall in time, seasonal rainfall, wind and geomorphological data.

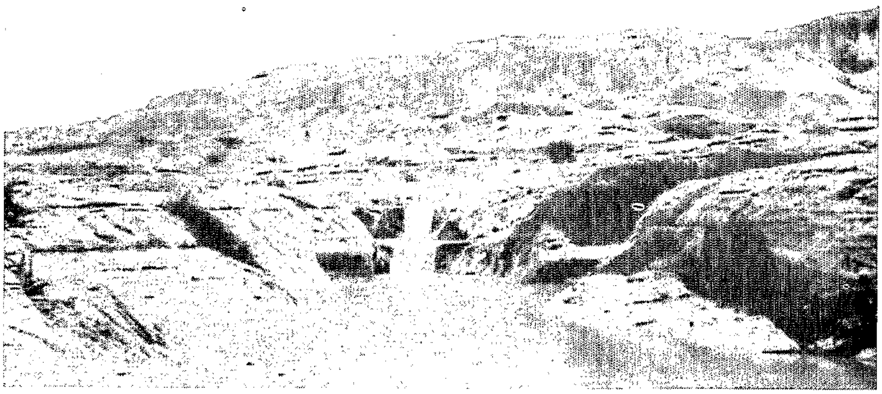
Generally, however, it may be stated that in countries with a mean annual temperature of more than 18°C, arid regions are those which have an annual rainfall below a vaguely defined limit of between 150 and 200 mm, and semi-arid regions are those with a rainfall limit of 500–600 mm. In countries with a mean annual temperature lower than 18°C, those zones which receive less than 100 mm of rainfall per year may be considered arid zones and those receiving less than 300 mm per year may be considered semi-arid zones.

The limits given above, however, may be appreciably modified in a certain number of special cases, notably when the water resources are concentrated in narrow valleys (palm groves and river oases).

13.3 CHARACTERISTICS OF SURFACE RUNOFF

In arid regions, runoff only occurs when the conditions are favourable, such as on soils of low permeability and on steep slopes, and on a few days per annum. Runoff is made up of one or more flood flows between which events the river bed is dry with the possible exception of instances of significant subterranean resources. Appreciable base flow may occur in some cases which may last all the year round. Flood flows, on the other hand, may occur over a short season, for example during two months in summer in some tropical arid zones, or in autumn or spring with low probability of occurrence in winter and summer, as in the north of the Sahara. Figure 13.1 shows three typical rivers in arid regions.

Irregularity of runoff is extreme from one year to the next, as in the case of the Enneri Bardague at Bardai (Tibesti massif, Saharra, mean annual rainfall



(a)

(b)

Figure 13.1 (a) Mountain torrent (Ennedi, Chad); (b) Wadi Guir (Morocco) from the air; (c) Rude Bahn (Baluchistan) from the air

(c)

15–20 mm), where maximum values for flood flows over a nine-year period were as follows:

1954	425 m^3 s^{-1}	1959	0 m^3 s^{-1}
1955	0	1960	$\geq$5
1956	0	1961	5
1957	0	1962	3 flood flows: 4 m^3 s,$^{-1}$, 9 m^3 s^{-1} and 32 m^3 s^{-1}
1958	$\geq$5		

Although the above example may illustrate an extreme case, nevertheless variations such as these are not uncommon.

Floods resulting from intense rainfall are often of short duration and torrential. The lack of vegetation may lead to considerable soil erosion, especially when the floods are the result of convective storms and the flows are sediment laden. In addition, hydrographic degeneration may occur, a phenomenon in arid regions which has considerable importance in the evaluation of flood flows.

13.4 HYDROGRAPHIC DEGENERATION

For a river in a normal river system the bed is well defined and each tributary contributes to the main river as far as the estuary or the delta. There is minimal loss of water if the river regime is not interfered with by man. However, when degradation is present the continuity of runoff is no longer obvious any more than the continuity of the bed itself. Minor floods sometimes produce no runoff and simply moisten the permeable sedimentary deposits of the bed downstream of the basin.

As soon as the slope reduces, the river overtops the banks and is then lost in the flood plains when only a small fraction returns to the river as runoff. Effluent arms leave the bed and are generally lost in marshy depressions. The river may reach inner delta zones from whence only slight runoff occurs towards the downstream area.

As a general rule, when there is significant slope at the head of the basin, and the soil is not too permeable, fine channels are formed with well-defined beds close to the watershed. These channels rapidly increase in size with distinct low banks as the flow becomes concentrated.

On reaching a zone with slight slope the bed is generally unstable, producing a lowering of the banks with one or more depressions becoming detached from the main bed. The runoff generally ends in a short delta which takes the remaining solid and liquid deposits into a clay-bottomed depression. Often, however, before reaching this stage the principal bed may join a major depression and, if the slope of the latter is steep enough, regular and possibly fairly low runoff may be observed, although possibly fairly small, especially if

Figure 13.2 Rapid hydrographic degeneration near the Piedmont, Archei pond (Ennedi, Chad)

the depression is covered with trees and bushes in their natural state. Runoff in the principal depressions is fed by successive tributaries and terminates at the point where their flows become inadequate.

If these tributaries are torrential they may direct their flows both upstream and downstream on reaching the main depression. As soon as all the swampy hollows in the depression have been filled, runoff occurs from the group as a whole towards the downstream area. In a desert regimen the greater the annual runoff the more its downstream limits enter the main depression. At the downstream end of this main collecting area, runoff sometimes occurs only every 50 or 100 years.

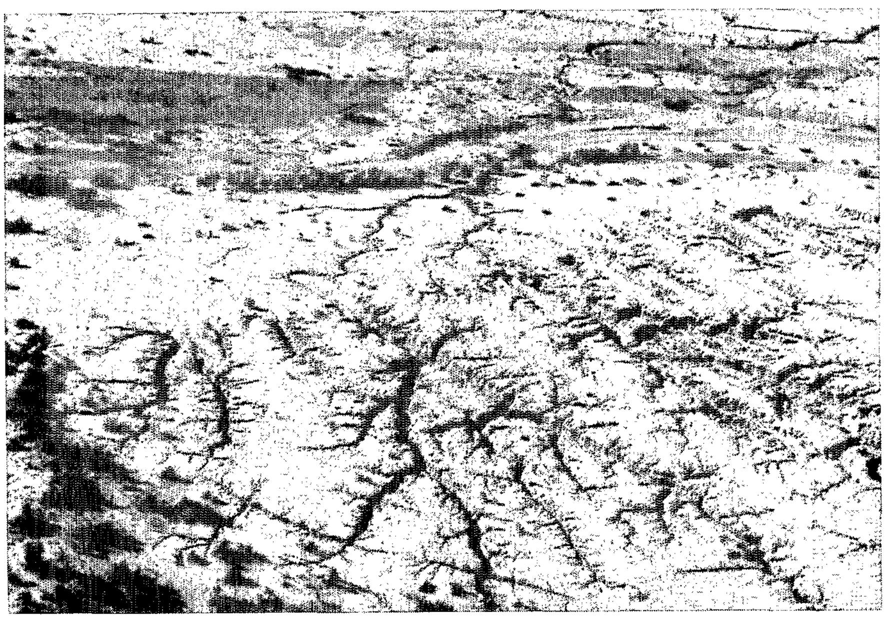


Figure 13.3 Hydrographic degeneration—Rude Bahn downstream of Bahn Kalat (Baluchistan) from the air

It is this phenomenon that is known as hydrographic degeneration. The common notion of a drainage basin becomes less marked, and discharge in $m^3\,s^{-1}$ per square kilometre no longer has much meaning. Careful account must be taken of these phenomena in setting up gauging stations and selecting sites for dams. An extreme case of hydrographic degeneration occurs when, during a flood, runoff occurs upstream at the beginning of the flood and downstream at the end of it. Figures 13.2 and 13.3 show typical examples of hydrographic degeneration.

13.5 LOGISTIC AND MATERIAL PROBLEMS PECULIAR TO ARID ZONES

Hydrological studies, especially flow measurement, are made particularly difficult in arid zones because of the sparseness of the population and because reliable observers are difficult to find.

The few who make up the permanent population are often nomadic and frequently their only interest in an instrument is shown in damaging it or making off with it. Even in developed arid countries it is sometimes necessary to set up apparatus which is bullet proof.

Access to gauging stations often poses serious problems, as very often there is no road available. Sand and sand-laden winds present problems outside mountain areas and in the latter it is even sometimes necessary to travel along the river bed when possible. However, clay zones which may be accessible whey dry become impassable when wet and the roads become dangerous for transportation.

Obviously the above problems may be substantially alleviated by spending a goodly sum of money but this is not usually available in arid countries other than in those which possess oil resources.

13.6 STRATEGIC PRINCIPLES FOR THE STUDY OF RUNOFF IN ARID REGIONS

It is not possible to install proper networks of gauging stations in arid zones, except in zones small in area and in rich countries. In semi-arid zones, however, adequate networks are possible but these of necessity are less dense than in humid regions.

In the arid and semi-arid zones the greater part of the basic data is obtained from temporary expeditions carried out over a period of two or three years. As a result of hydrographic degeneration the selection of gauging sites has to be studied with the greatest care, and it is necessary to carry out systematic measurements in order to follow the decrease in flows from upstream to downstream.

The scarcity of runoff data, even of a qualitative nature, has led hydrologists, in the course of expeditions, to try to locate traces of the latest floods or the most violent flows and to subsequently make use of these data for the calculation of discharge.

13.7 GENERAL ORGANIZATION FOR RUNOFF MEASUREMENTS IN ARID ZONES

It is possible to remedy the lack of hydrometric networks and the low raingauge density by means of a combination of the following operations:

(1) Extensive studies of the terrain of rainfall and flow over a period of two or, better still, three years.
(2) Studies on representative catchments on the structure of the rain and of the rainfall–runoff relation for the given geomorphological conditions.
(3) The installation of reference gauging stations.

13.7.1 Extensive studies of the terrain

These studies are carried out during the seasons when the probability of floods is greatest. Having set up a network of rain gauges, water level recorders and staff or ramp gauges the hydrologist proceeds around his base by the means of transport at his disposal. An example of transport by caravan is shown in Figure 13.4. He studies the geomorphological characteristics of the terrain (relief, geology, pedography, hydrogeology, the aspect of the hydrometric network) and the vegetation cover of the catchments including the river banks. During this reconnaissance the opportunity is taken to measure floods as they occur or, if the flood has recently passed, he is required to determine traces of the flood and its peak, with a view to computing the corresponding discharge from the slope area method (ISO 1070). He also gathers information on historical floods if at all possible.

Brief studies are also made on the variation in rainfall with altitude and exposure, and in very arid regions he is required to demarcate zones receiving no rain.

Figure 13.4 Caravan for extensive hydrological survey (Ennedi, Chad)

Rapid manoeuvrability is obviously essential if the best results of such a study are to be obtained. However, even if the necessary financial resources are available to utilize air transport (plane or helicopter), it is not always possible to employ this form of transport after major floods due to poor runway conditions, in the case of planes, or because helicopters are reserved for more urgent flood relief tasks. For the most part, therefore, cross-country vehicles are used for reconnaissance work. Figure 13.5 shows a typical organizational map for an extensive hydrological study in an arid zone.

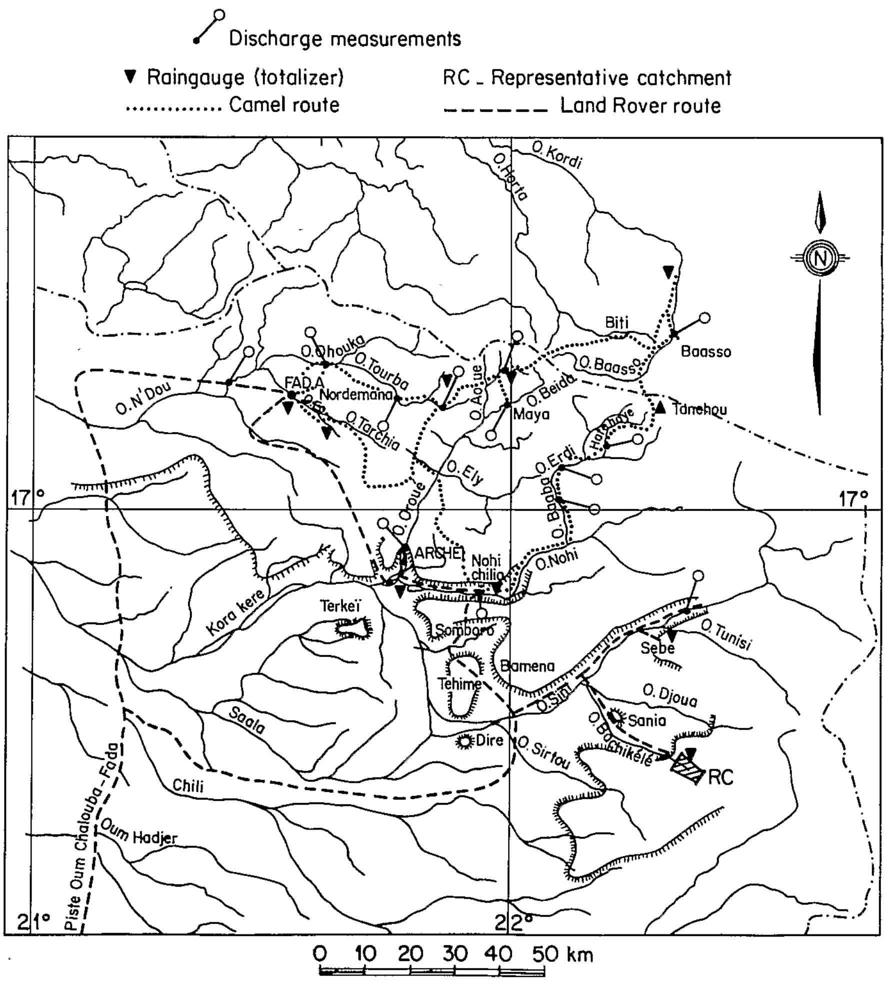


Figure 13.5 Example of field work organization for an extensive hydrological study in arid zone

13.7.2 Representative catchments

These catchments are set up to obtain rainfall–runoff relations, and generally within the framework of the main hydrometric studies. These catchments are usually small, rarely exceeding 10 km^2, and hydrographic degeneration is absent.

13.7.3 Reference stations

These stations are installed at locations where a permanent resident population exists and consist essentially of a rain gauge and a water level recorder and staff gauge. The objective of these stations is the provision of a statistical series of long-term data.

13.8 REFERENCE STATIONS IN ARID REGIONS

Because of the difficulties peculiar to arid regions, especially the problems of access, gauging stations of this type are costly to install and operate and are generally few in number.

The station should be installed on a river which is fully representative of the region. The catchment should not be too small and should extend to at least 200–300 km^2, an area of about 1000 km^2 being preferable. In so far as it is possible, runoff should not have been disturbed by hydrographic degeneration. These two conditions, which may seem contradictory, are aimed at facilitating correlation with other catchments. If the important resources are in the upper reaches of the catchments it may be necessary to modify the above rules and select smaller catchments.

In almost all cases it will be possible to acquire information of the effects of hydrographic degeneration if a secondary station is installed downstream of the reference station. The former will only be referred to from time to time so as to be familiar with degeneration effects in a wet year, an average year and a dry year.

Discharge measurements made at reference stations in arid zones are generally carried out by the velocity-area method, the techniques for which are described in Chapter 1. Natural controls are, however, rare although it should be pointed out that rocky sills are sometimes buried under deposits but exposed during major floods, as for example at Wadi Zeroud in Tunisia. Similar sills may be disclosed on aerial photographs and require to be verified by sounding, since at the time the station is being installed the sill is generally buried beneath the sand. Artificial controls are sometimes installed if funds are available.

In practically all cases the station requires to be designed to permit precise measurement in the range of zero flow to major flood flows. It is necessary to anticipate that flood flows may have velocities of the order of at least 5–6 $m\,s^{-1}$, and measurement by current meter is then impracticable. Discharge measurements then have to be made by floats (ISO 748) or by the slope-area method.

Peak flows of some 1000 $m^3 s^{-1}$ should be anticipated for a catchment of 1000 km^2 and up to 10 000 $m^3 s^{-1}$ in extreme cases (Texas).

13.9 REPRESENTATIVE BASIN STATIONS IN ARID REGIONS

The same methodology is used for discharge measurements at representative gauging stations as for reference stations, but with more rudimentary means. In all cases it is necessary to avoid bank overflow by some remedial works such as dikes or a curtain of stakes. Bed stabilization may be carried out by the installation of gabions but these are usually limited to about 1 m^3 (see Section 13.10). Portable cableways may be used with a 50 kg sounding weight and in many cases it is usually possible to install a catwalk, as shown in Figure 13.6. Generally, therefore, although representative stations demand a measure of improvization the quality of the calibration curves is usually high.

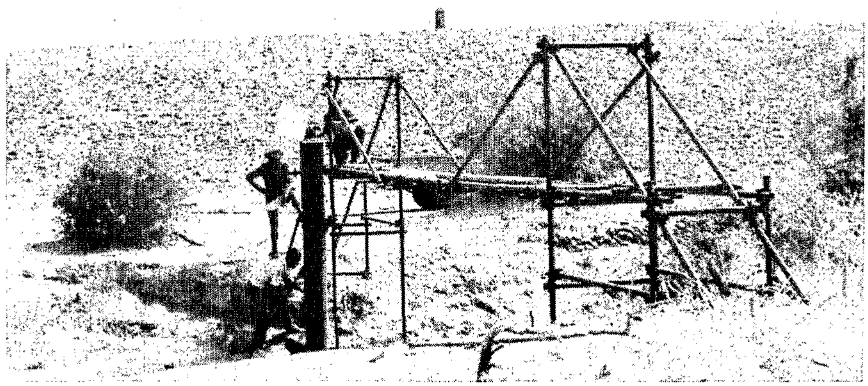


Figure 13.6 Footbridge and water level recorder at a representative basin station: kori Iberkoum (Air, Niger Republic)

Representative stations used for special studies, however, are installed on a more permanent basis and may include an artificial control or a measuring structure.

13.10 BED CONTROLS

It is an important condition, even in arid regions, that a velocity-area station should have a stable stage–discharge relation. This involves either a natural control or a section control (see Chapter 1). In arid zones, gabions are frequently used as bed controls. These consist of baskets of thick wire netting, each with a capacity of about 3 m^3 and filled with blocks and boulders, which are anchored in the alluvia by iron bars. The top of these bars should finish level with the bed. Solid mass constructions, such as continuous concrete, should be avoided in arid zones because they are too sensitive under pressure.

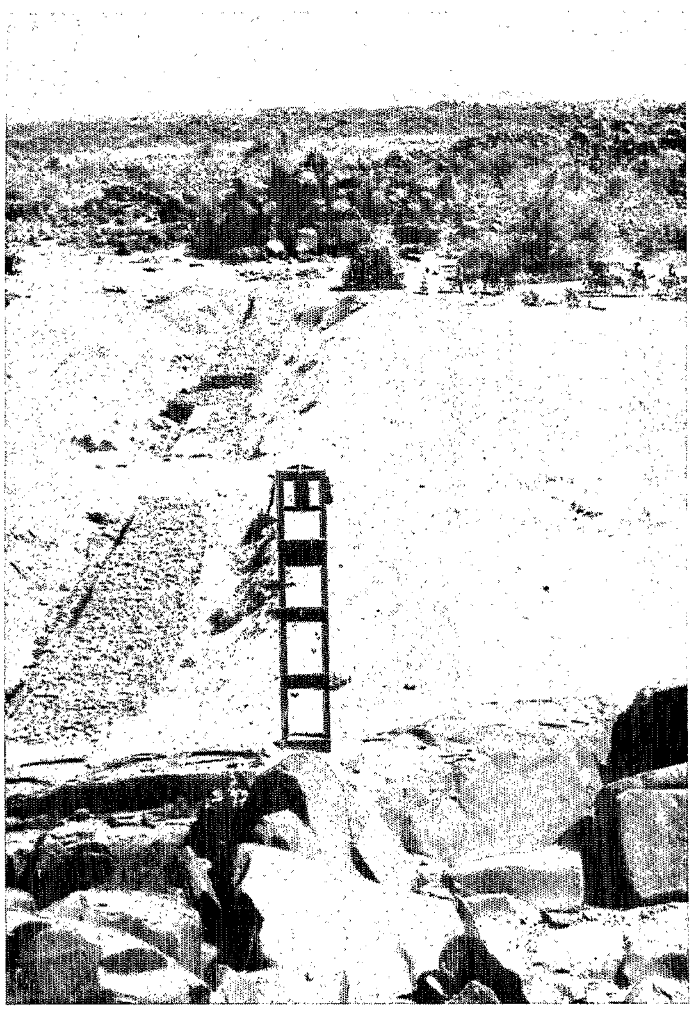


Figure 13.7 Reference station of the kori Teloua—carrying out a locking by 'gabions' (Air, Niger Republic)

Figure 13.7 shows the installation of a gabion bed control at a reference station on the kori Teloua.

13.11 WATER LEVEL RECORDER

An autographic recorder is virtually indispensable in arid regions. However, the river flow may sometimes contain more than 100 kg m^{-3} (10 000 mg l^{-1}) of sediment and intake pipes become frequently blocked even if made as large as 300 mm in diameter. Additional intakes are therefore desirable in order to

Figure 13.8 Water level recorder at Adoubdoub on Tamgak (representative basin), (Air, Niger Republic)

record higher water levels as the lower intake becomes blocked on a rising river. Measures require to be taken, therefore, to mitigate this situation and a porous filtering mass of sandy concrete (50 kg cement to 1 m^3 sand) is sometimes incorporated in the base of the stilling well to record low water levels.

The water level recorder requires to be set up so that it is protected from flood flows and trees carried down by the current. Pressure-actuated recorders, although sometimes used, are susceptible to silting up of the sensor and blockage of the conduit. Figure 13.8 shows a typical water level recorder installation in a representative catchment.

13.12 MEASUREMENT FROM BRIDGES

When a bridge is available it is sometimes convenient to use it to carry out discharge measurements. However it should be noted that:

(a) flow is usually irregular upstream of the bridge due to the high velocities;
(b) during flood flows in arid zones, bridges are especially vulnerable and it is then dangerous and sometimes prohibited to use them.

13.13 MEASUREMENT FROM CABLEWAYS

It is generally preferable to install cableways, since it is seldom practical to carry out measurements from boats in arid zones. Manoeuvrability is dangerous in velocities over 3.5 m s^{-1}, even for the expert.

Cableways used are similar to those described in Chapters 1 and 8. Due to the inexperienced local staff available, however, the remotely controlled type operated by a winch from the bank is generally preferred.

13.14 MEASUREMENT WITH FLOATS

At certain stations it is sometimes necessary to abandon measurements by current meter and to proceed to float measurements.

For float measurements a measuring reach should be selected where the flow is as uniform as possible and close to the cableway. Six reference points are chosen, three on each bank at the upstream end, downstream end, and at the centre of the reach (ISO:748). It is desirable for the length of the measuring reach to be about 3–5 times as long as the width of the river. A temporary telephone line or walkie-talkie set is useful for communication between the upstream and downstream reference points.

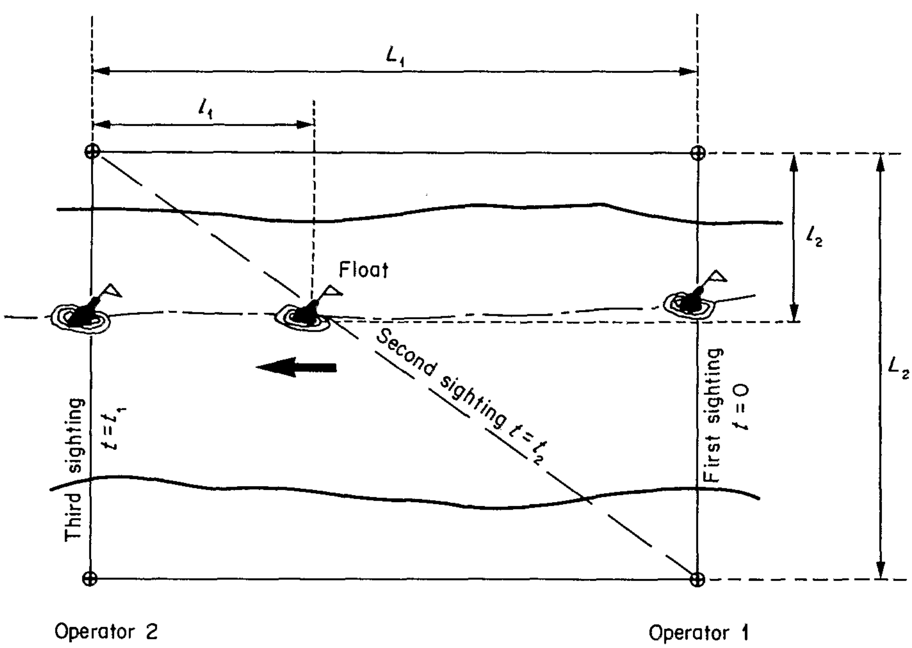
Various types of float are described in Chapters 2 and 8 but in arid zones it is sometimes convenient to use floating half-submerged trees descending with the current (on Wadi Zeround, 600 were counted on 27 September, 1969). This method is only appropriate, however, for deep rivers about 100 m wide.

Other floats include lemonade bottles and wood blocks. However, even in good conditions these floats are difficult to observe.

Float measurements are generally carried out in velocities of the order of 4–7 m s^{-1} and if carefully performed can yield acceptable results. If the float is adequately immersed and wind influence is negligible then the float speed is taken as the surface velocity of the water. For rivers with sandy beds and depths exceeding 3 m or 4 m on average, the coefficient to reduce surface velocity to average velocity is about 0.92 to 0.95. For greater reliability, however, the relation between mean velocity in the vertical and surface velocity is found from current meter gauging.

Floats are observed over periods of 10–15 min and during the measurement the corresponding stage is noted. A curve of surface velocities is established from which a mean surface velocity is deduced. The mean surface velocity is then multiplied by the reduction coefficient, corresponding to the appropriate stage, and by the cross-section area to provide discharge. The position of a float in the river may be found by employing two stopwatches. One measures the time taken for the float to pass from the upstream cross-section to the downstream cross-section (t_1) and the second measures the time taken (t_2) for the float to cross the diagonal between the upstream reference point on the left bank and the downstream reference on the right bank. If the upstream and downstream cross-sections are parallel then from Figure 13.9

$$l_1 = L_1 \frac{(t_1 - t_2)}{t_1}$$



13.9 Velocity measurement by floats (position fixing) and

$$l_2 = L_2 \frac{t_1 - t_2}{t_1}$$

Alternatively, and more conveniently, the position of the float may be found by using the cableway and lowering the sounding weight close to the water surface. The position of the float may then be estimated by sighting the float in relation to the sounding weight.

13.15 MEASUREMENT OF LOW FLOWS

In arid zones it is advisable to determine the reading of the water level recorder or staff gauge at zero flow. This will probably be one measurement in arid zones which may be determined with the greatest precision.

However, it should be noted that in beds of alluvium, runoff may cease at the measuring section and may reappear further downstream. This sort of resurgence occurs when the mass of alluvium no longer offers a sufficient depth for bed flow.

Measurement of very low flow (less than $0.2\,m^3\,s^{-1}$, for example) in a stream which yields more than $1000\,m^3\,s^{-1}$ in flood often demands special improvization. The usual gauging station is seldom sensitive enough, even if an artificial control has been installed. A small permanent canal may be constructed on which a portable weir may be used to gauge the low flows. Alternatively a small temporary canal may be used and a miniature current meter employed to measure velocities.

Sometimes a second water level recorder is required with a natural scale to record the lowest water levels, or discharge measurements are made at regular intervals and by interpolation between them a complete recession is established.

13.16 MEASUREMENT OF FLOOD FLOWS

Flood flows too great to be measured by current meter may also be measured by the slope-area method (see Chapter 5). To determine the flow by this method it is necessary to approach as closely as possible the hydraulic conditions necessary for the application of the Manning formula. The measurement reach should be as rectilinear as possible, the cross-section within the reach should vary as little as possible and the bed slope should be fairly regular. The reach should be of sufficient length for the slope to be significant. High water staff gauges require to be installed upstream and downstream of the measuring reach at a distance apart equal to at least 75 times the mean depth of the anticipated flood (see Chapter 5). It is usually wise to duplicate these staff gauges with crest-stage gauges, all gauges being levelled-in to convenient bench marks.

The uncertainty in the result of a slope-area measurement depends to a significant extent on the uncertainty in the measurement of slope and the uncertainty in the value used for Manning's n. A suitable precision level should be used to install staff gauges and preferably one with an automatic level setting device, especially if, as is often the case in hydrology, the operator is not a professional surveyor. The slope measured should be that of the surface water slope at the flood peak. If the staff gauges are at the same datum, the difference in readings divided by the distance between them is equal to the slope. The advantage of the slope-area method is its ability to obtain a measurement of discharge of past floods by using flood marks or traces. This is an important hydrological facility in arid zones.

Flow is calculated from the Manning formula as follows:

$$Q = \frac{1}{n} R_{\mathrm{h}}^{2/3} S^{1/2} A$$

where Q is the discharge ($\mathrm{m^3\,s^{-1}}$); S the slope (in fraction form); R_{h} the hydraulic radius (m); A the wetted area ($\mathrm{m^2}$); and n is the coefficient of roughness. For values of n see ISO 1070 and Benson (1968).

13.17 INVESTIGATION OF FLOOD LEVELS

There are many arid zones or even desert zones where permanent villages exist. Rural populations are often greatly motivated by flood flows as a result of the damage they cause to their fields and homes. Life goes on close to watercourses the more arid the region and 'valley civilization' is one form of life based on the oasis. These valleys are not always majestic rivers like the Nile, but more frequently ill-fated wadis. As far as possible, the investigation should be followed on a regional plan at least within the framework of a drainage basin, which permits comparisons and verifications which are always fruitful (regional enquiry). When possible it is a good idea to return to the same village several times and to question the largest number of witnesses possible, using different interpreters where this is feasible (local enquiry).

The local enquiry may centre on just the greatest known flood, but it may go further and seek to gather information about all the most significant flood flows. Attempts are made therefore to establish chronology. The memory of river dwellers is often excellent concerning this type of event, but is typically that of the countryman. It is always very difficult to discern chronology, even for relatively recent events (over a period of about 10 years, for example). The date of a flood (the year at least) may only be learned accurately if it coincides with some event which stands out in the life of a witness, the birth of a child for instance, departure on military service, or if it marks something special in village life or even some event of political interest for the country (war especially).

The regional enquiry is not always solely a series of local enquiries, it may appeal to other sources of information, administrative archives, newspaper articles, travellers' accounts, and so on, and naturally data from regularly observed stations, if sufficiently old-established ones exist.

The local enquiry should be concerned with both chronology and levels of the flood flows. For this aspect of the enquiry it is necessary to consider diverse evidence and places of observation. For the greatest flood in living memory (providing that it is not too far back, say not more than 20 or 30 years) it frequently happens that good agreement of evidence is obtained. It is customary to have the flood levels pointed out on both banks of the watercourse, but with exceptions the most coherent indications provided are for the one on which the village is sited. For each level indication it is necessary to make a careful examination of its location and surroundings and more particularly the local conditions of flow.

At the time of the local enquiry a topographical survey is made on the terrain and the checking of bed variation, particularly of cross-section profiles, takes on greater importance the more historical the flood. During one enquiry, it was observed at one site that all the cultivated terraces had disappeared increasing the width of the apparent bed from a few metres to more than 100 m.

In uninhabited regions it is possible to refer to ancient traces, but one obviously needs to be cautious. The best traces may be observed in gorges, in the shape of continuous lines over vertical rocky walls; these traces are extremely varied in nature. Some information may occasionally be extracted from considering levels of erosion of banks which are relatively free from crumbling. Alluvium deposits may also furnish some indications. Frequent mention is made of cases of clay deposits or silt in the rock fissures and hollow trees. These elements must be carefully examined and their origin duly criticized. This involves flair and common sense, as scarcely any general methodology exists. Fairly frequently one observes deposits of floating debris which is relatively and sometimes even extremely coarse in texture. The location of some of this, in caves or holes hollowed out in the rocky walls of gorges, is at such a depth that there are difficulties of interpretation. Flood marks of this kind are rarely able to serve as a basis for serious evaluation.

13.18 DILUTION GAUGING

If a chemical is injected into a river with a flow rate q and concentration c it will become diluted in the river water if sufficient mixing is present. If C is the concentration of the chemical in the river then, from Chapter 4,

$$Q = q\frac{c}{C}$$

where Q is the discharge.

This method is used for measuring relatively low to medium discharges. However, faced with the considerable difficulties in current meter gauging, which are so often encountered in arid or semi-arid regions, the dilution method has been applied to the measurement of floods.

The high sediment load, however, the rapid variation in flow during a flood and occasionally the quality of the water, are technical obstacles to the use of this method. Nevertheless it has been possible in certain instances to overcome these problems and in Madagascar a discharge of some 2200 $m^3 s^{-1}$ was measured with sodium dichromate to an acceptable degree of uncertainty. However, the method requires specialized staff which are rarely available in arid regions. For this reason tests carried out in the north and south of the Sahara scarcely reached the operational stage. In addition the cost of the large amount of dichromate required was most discouraging. It is possible, however, in a country which has both semi-arid and arid regions to form a specialized team which could be sent in emergency to a gauging station where there could be stored a permanent stock of chemical for dilution gauging. Even so, the major technical difficulty is still the rapid change in discharge during a flood.

13.19 MEASUREMENT OF CHANGE IN BED LEVEL DURING FLOODS

If the natural bed is unstable or if it has not been artificially stabilized, it is necessary to be able to determine its actual level at the time of the flood peak. This may be performed by burying a sounding weight of about 25 kg in the alluvium, to a depth greater than it is expected the bed will attain at the time of maximum scouring. To this weight a chain is fastened which will just reach the bed level prior to the flood. In order that the chain can be recovered again, it is lengthened by means of a cord to which is attached a float. Up to a dozen of these devices are installed in the cross-section. The section of chain which is cleared by the flood by removal of the surrounding alluvium follows the direction of the current and takes up a position approximately at a right angle to the remaining buried portion of the chain. The entire chain is buried once again by alluvium as the flow subsides. The chain may finally be exposed from each of the devices by digging and the minimum bed level ascertained. The same result may be obtained by burying a pile of bricks in the bed, the layers of top bricks being washed away by the current.

The measurement of depths in arid regions, however, generally pose special problems where beds are changing and are unstable. Frequently if the bed configuration is altered with each flood flow the mean depth remains the same and, except for low flows, the calibration curve remains unchanged. However, in some cases a violent flood may gouge out the bed by several metres and it may then be necessary to wait some years in order to establish the same cross-section profile which existed prior to the flood. This phenomenon is experienced in the semi-arid region of Madagascar and on many rivers in the arid and semi-arid regions of North Africa. An example of such a flood on the Wadi Zeroud occurred during a period of four days in September 1969, where the surface velocities exceeded 8 m s^{-1} and the bed levels during the flood varied from about +1.7 m to about −10 m.

13.20 CONCLUSIONS

Every endeavour is made in arid regions to apply standard methods of hydrometric principles and practices. The problems and difficulties in applying these methods, however, are considerable. Physical problems such as abnormal site conditions, hydrographic degeneration, mobile beds and rapid flow variation are severe, while staffing problems, security of installations and mobility in difficult terrain present formidable obstacles for hydrometric measurements. Nevertheless the economic development of these regions depends to a large extent on their investment in hydrometry, so that their water resources may be exploited for the benefit of the community.

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