1 Introduction

Two centuries lie between the publication of Euler's 'Principes généraux du mouvement des fluides' and the wide-spread application of mathematical models. During this time, engineers – who had in the course of more than a thousand years acquired a large practical know-how and learned to design by rules of experience – gradually began to appreciate the theories introduced by mathematicians. Hand in hand with this abstract treatment of water movement, a need arose for series of systematic experiments. This need was satisfied by the work of many scientists.

As well as adapting theories for practical purposes and making full use of the tools at his disposal, the engineer is faced by another, new challenge: that of executing modern works of advanced technology for an increasingly critical society in which scientists of many disciplines ponder over issues which have previously been the uncontested territories of the engineer. The authors of this book recognize this challenge because each of them has participated in multidisciplinary project teams, created *ad hoc* to solve a particular set of problems. They have not, however, gone into questions of an interdisciplinary nature; they have restricted themselves to the compilation of design tools which have not yet been presented in a comprehensive manner.

The authors have tried to present the current state of affairs on the transport of sediment and the morphological implications thereof and to indicate the applicability of these theories for the river engineer. In addition it was felt that in situ measurements and the processing of these measurements were indispensable tools which required new presentation. Mathematical models and scale models (sometimes called physical models) have also been treated. Finally, the practical river engineer who has to use models for specific projects will find solutions to a number of problems in the last part of this book.

The natural state of a river and the use that is to be made of it are seldom in harmony, the more so when advanced society increases its demands on nature. As a result river works are carried out to change the various aspects of a river so that more benefit – or less damage – can be achieved. The works cause changes in the *river bed* including the banks, changes in the *discharge* or changes in the *water level*. These three main groups of river works are treated in Part 5, preceded by theoretical considerations in the other parts of this book.

Changes to the river bed are invariably made to help solve erosion or sedimentation problems in particular areas. These problems may concern lengths of a few meters or hundreds of kilometers. The process of erosion or siltation may take hours to take effect or it may take centuries to reach an equilibrium. The area may concern a river bank or bridge pier to be protected against erosion, a channel to be deepened for navigation, a bifurcation to be altered to give a different distribution of water over its channels, the degradation of an entire river behind a large reservoir, etc. All these problems are concerned with the morphology of the river bed. The river works that are associated with their solution – if they can be solved – can be split into temporary or repeated works and permanent works. An example will illustrate the distinction. Suppose that the depth in a particular section of a river has to be increased. Dredging may solve the problem. However, after a few months or maybe a year, the area will probably have silted up again and the remedial measure will have to be repeated. On the other hand the bed could be confined by groynes to achieve a permanent deepening of the channel. In this case a new equilibrium – at other widths and depths than before the measure was carried out – will be reached between the confined river stretch and the unchanged upstream parts, whereas in the former case the difference in sediment transport capacities between the dredged section – where the sediment transport capacity decreases because of the larger profile – and the upstream river means that the river will eventually revert to its original state. Both for repeated operations and for permanent works it is necessary to know the amount of sediment transported by the river, the transport capacity in various profiles and the time it takes for a change to occur. It is also important to know to what distance, and by what time, the disturbance caused by the temporary or permanent work will travel in the upstream and/or in the downstream direction.

Much the same questions have to be answered for the other two groups of river works: those concerning the changes in discharge or in water level. Both groups of measures have to deal with the natural dependence of the river waters on rainfall. Because the patterns of rainfall and runoff seldom coincide with human requirements, systems of regulation are devised, for example: the control of floods by temporary storage in reservoirs; the increase of water depths by construction of a series of weirs. The immediate effects of these works on discharges and/or water levels are apparent, but the morphological consequences, not only in the vicinity of the works, but also further upstream or downstream, must also be appreciated and quantified.

In addition to these three groups of works the river engineer is increasingly confronted with quality aspects of the water, and sometimes of the sediment. There is little he can do when confronted with the actual situation at a particular river section unless he can take measures at the source of the pollution: sewage and other wastes. For a general understanding of pollution problems and the mechanics of water-borne organisms with respect to substances carried by water, relevant sections have been included at various places in the book. They are, however, restricted in size and depth because the book is primarily concerned with the three types of river works mentioned above.

Ice problems are not treated in this book and the reader is referred to IAHR-PIANC (1974), Laszloffy (1956) and G. P. Williams (1959, 1970). Vegetation or sudd problems – of which some aspects are similar to ice problems – are not discussed either.

The *uses* or *purposes* of a river and the *measures* needed to achieve this usage, or an improvement for an existing usage, have been summarized in Table 1.1-1. The table is not exhaustive, neither in 'use' nor in 'measure', its main purpose being to introduce the reader to various aspects of river engineering treated in this book. As shown in the table, there is sometimes more than one measure which can be used to achieve a particular purpose or part of it. Some measures are also of secondary importance to the purpose (labelled 2) and some measures (labelled 3) may be necessary as a result of the operation. A few comments on the table follow:

(i) Defensive measures against floods are not 'uses' of a river in a strict sense, but the meaning will be understood. It is obvious that one either has to build a levee – which must be protected against scour – and/or do something about the flood height.

(ii) Rectification of the channel includes the cutting of meanders; rectification in the flood plain includes measures to increase storage and/or flow capacity.

(iii) For navigation quite a number of improvements are shown. They vary in degree of effectiveness and cost.

(iv) Hydropower requires the availability of sufficient discharge, preferably in quantities which can be adjusted, and the creation of head.

(v) Irrigation and water supply withdraw water from the river; part of it may return elsewhere, usually changed in quality. For large amounts, large in comparison with the river discharges, discharge control may be necessary. A weir may also be required at the point of withdrawal. The point of withdrawal itself must be

Table 1.1-1 River uses and measures to achieve them
1 Measure to achieve the required use
2 Measure of secondary importance for the use
3 Measure which might be necessary as result of the operation

	Bed regulation								Discharge and water level regulation		Quality control
Measure	repeated dredging	temporary construction in river bed	fixation of bottom	elimination of obstacles from low-water bed	channel rectification and fixation	channel constriction	revetments and groynes	rectification in the flood plains	reservoirs	weirs	quality control works
Use of river											
Flood control					1		3	1	1		
Navigation	1	1	2	1	1	1	3		1	1	
Hydropower									1	1	
Irrigation and water supply			3				3		1	2	
Waste discharge											1
Bank protection			2		1		1				
Cooling water						3	2				1
Commercial sand dredging	1		3								
River crossings		1					3	2			
Control of sea water intrusions			2						2	2	

stable and bank protection may be necessary. Sediment problems in the river itself (sudden decrease of sediment transport capacity because of water withdrawal) and/or after the withdrawal point (sand traps may be necessary) have to be solved.

(vi) Cooling water and some other uses mentioned hereafter have been listed separately, mainly to show that there are more uses than the four big ones mentioned above. Temperature problems, which are expected gradually to become serious in some rivers, are, of course, a particular type of waste discharge problem.

(vii) A peculiar river use is large-scale commercial sand dredging which occurs in some countries – as far apart as the Netherlands and Japan – to the extent that remedial measures have to be taken.

(viii) For bridge piers anti-erosion measures are usually required. They fall under the heading river crossings, to which pipelines across a river channel also belong. For pipeline construction it is useful to know how long (in time) a dredged trench perpendicular to the river axis will last.

(ix) With the increasing use made of fresh water, the intrusion of sea water into estuaries becomes a problem which is sometimes aggravated by channel deepening for navigation purposes. Remedial measures against intrusion are often by-products of other river works such as discharge control works and/or water level control works. It usually happens that more than one purpose is served, particularly when discharge control or water level control works are carried out. However, not all uses require complementary measures and sometimes a choice between conflicting interests has to be made.

In order to describe the necessary 'measures' and find an engineering solution it is necessary to know the behaviour of both water and sediment. The engineer used to rely on rule of thumb and later on on experimental laws based on the statistical evaluation of numerous observations. To a large extent the experimental laws are still his main tools. This book, however, tries to point out the physical basis of water and sediment behaviour in Part 2; this is translated into mathematical descriptions which are further elaborated in Part 4.

It would be ideal if there were a universal law governing the time-space relation of water and sediment. If there is, it has not yet been formulated and one has instead to make do with a number of equations, each of which has particular schematizations for the description of a particular phenomenon. As a result of the schematization, each equation is an approximation of the physical phenomenon and it is important to know the limits of applicability and the accuracy of the calculations. The introduction to water and sediment movement given in Part 2 considers these two important points – *applicability* and *accuracy* – in some detail.

The first chapter of Part 2 shows how, starting from the basic equations of conservation of mass and conservation of momentum, various cases of water movement can be schematized and made accessible for analytical or numerical solutions. The underlying assumption is that the movement of a body of water is determined by the action of several forces upon it: gravity forces, boundary friction forces, viscous friction forces, turbulent friction forces and inertial forces. All these forces can be defined in one way or another, leading to mathematical descriptions of the water movement. These descriptions cannot be used to solve problems in their general form. The first chapter of Part 2 shows how to schematize in order to solve a particular problem of water movement. Because it is assumed that the movement is determined by the action of forces of which the existence is certain, the physical process of water movement and its theoretical treatment is called *deterministic*.

The description of sediment movement is also deterministic, and the sediment formulae (Part 2: Subsection 3.3.3) are all based on essentially the same assumptions about the action of forces on particles – though simplified – as used for the movement of water.

However, it appears that the movement of *a* water or *a* sediment particle cannot be described in this manner because there is a degree of *uncertainty* as to the action of the forces on the particle and as to the movement of the particle as a result of these forces. Such a process is called *stochastic* instead of deterministic. This stochastic character is also apparent on a much larger scale in morphological features such as meanders (*see* Part 2: Chapter 4) which *cannot*, with certainty, be predicted to appear in a specific shape at a specific place at a specific time. The stochastic nature of morphological processes gives another meaning to the earlier mentioned point of accuracy.

The stochastic character of the movement of a small water particle was already appreciated in the theories of water movement, where it is described as turbulence. However, the features of turbulence have been averaged in time so that the stochastic element disappears in all the water and sediment movement equations of Part 2: Chapter 2. This *process of averaging* is an important facet of river engineering. Whilst for turbulence it is concerned with averaging in time; averaging in space is necessary for other purposes. This is not only considered in Part 2, but also in Part 3 where the time-period, the frequency and the location of measurements are all discussed.

The fact that water and sediment theories use average values underlines the importance of the *time-scales*. These differ greatly between water and sediment processes. A minute suffices to average flow velocity at a particular point. The average bed load, however, is determined by the time it takes for one or two ripples or dunes to pass the point of observation – this may take hours. This difference in speed is also reflected in the adaptability to changes. Flood waves pass in a matter of hours or days; the propagation of a disturbance in water level is measured in meters per second. A disturbance in the bed, however, travels at a speed of a few meters per day or per week. This difference leads to a different sort of mathematical schematization (*see* Part 4: Subsection 2.4.2) and is, of course, of interest in particular engineering solutions. For example, the dredging of a pipe-laying trench across a river relies on the slowness of the morphological processes, as does the efficiency of repeated dredging for a greater navigational depth; the use made of backwater curves caused by the operation of weirs in a matter of minutes or hours would be much more problematic if the bottom were to adapt to a new equilibrium at the same speed. On the other hand, the slowness of morphological processes may be the cause of additional work. For example, permanent deepening of the river bed by groynes confining the river section may take so long that dredging work is necessary to help nature establish an equilibrium by the desired time.

Time-scale is not the only difference between water and sediment processes; it will be noted that quite a few solutions to sediment problems are still elusive. Whilst the physical-mathematical descriptions of flowing water are reasonably successful, those of sediment transport in suspension do not always show fair agreement with measurements (*see* Part 2: Subsection 3.3.2); there are no physical-mathematical descriptions of bed load that have led to formulae suitable for practical use. It should further be understood that all descriptions of sediment movement are *solely* concerned with *non-cohesive materials*; the behaviour of clays with respect to flowing water cannot yet be described in physical-mathematical terms. For the description of non-cohesive bed load movement, only *experimental* formulae exist, tested in a statistical manner (*see* Part 2: Subsection 3.3.3). Now bed load is primarily responsible for many of the scouring and erosion problems with which the river engineer is confronted. It is, therefore, not surprising that the majority of problems treated in Part 5 are tackled with simple experimental transport formulae even when the conditions applied (for instance, non-steady state) are not quite correct. When applying these formulae the river engineer will be quicker to realize that he is overstepping their applicability if he has absorbed the contents of Part 2. Sections of this book which are not yet readily applicable to our practical problems should also give the engineer more insight into the background of the processes.

Quite often there is more than one method to solve a particular problem. The authors have emphasized the *physical* approach because they are of the opinion that in this approach the applicability and accuracy can be better determined than with an *empirical* approach (*see also* Part 1: Section 2.3). Then there is the choice between mathematical models and scale models. A number of different characteristics, as set out in Part 4, determine their usage. One model may suit a particular problem better than the other; when both types are equally applicable the speed and cost may become decisive factors.

For the reasons given above this book is *not a manual*, although quite a number of practical problems are treated, and solutions given. It is intended to show where the present theoretical knowledge stands, where there are useful connections with practical problems and where the gap has yet to be bridged.

The fact that an engineer has to solve a problem which is not of his own making – as does the mathematician – or to which he cannot neatly set suitable boundary conditions – unlike the laboratory researcher – means that he has to know as much as possible about his problem. This can only be achieved by *measurements in prototype*, in nature. The authors cannot overstress the importance of this point. If the engineer concludes that the data collection is inadequate for the treatment of his problem, he must return to the field: inadequate data remain inadequate unless supplied with additional new data. This is not a revolutionary idea and the actual techniques of measurement in prototype are widely known. It was felt, however, that the question of what to achieve by the measurements merited separate treatment in this book: it is necessary to establish parameters for formulae and it is also necessary to bridge the gap – if possible – between the theoretical approach and practical application. The reason behind the measurements determines the accuracy needed, and this is discussed in some detail. It is also useful to know the background of the physical processes as described in Part 2 before setting out on a measurement programme: one may measure something different from what one wants to measure if one does not have sufficient knowledge of the physical process being investigated.

The reason that the authors have presented the three main items, measurements, physical-mathematical schematizations and practical applications, in one book is that there are so many links between them. It has been the intention to show that the river engineer has to familiarize himself with the totality rather than a particular facet.

2 River characteristics

2.1 The channel

Rivers vary in appearance from trickles running through gullies to mighty channels suitable for ocean-going vessels.

To start with, the world's largest river, the Amazon River in Brazil, is in a class by itself. In July 1963 its discharge was measured at Obidos, 800 km from the mouth. It was 212×10^3 $m^3 s^{-1}$. The width of the river was 2300 m and the maximum depth 60 m. The cross-section was U-shaped and measured 115×10^3 m^2. The average velocity was 1.9 $m s^{-1}$ and the maximum velocity 2.3 $m s^{-1}$. The catchment area at Obidos measures 5×10^6 km^2. The maximum discharge during the period of observations was estimated to be 280×10^3 $m^3 s^{-1}$, occurring in 1953 (Div. De Aguas, 1964). One fifth of the total discharge of the world's rivers runs through the Amazon River and its dimensions are baffling by any standard.

The second largest river with respect to discharge is the Congo which carries only one fifth the discharge of the Amazon. Compared with the Amazon, the Rhine in Europe is a mere trickle; and even the mighty Mississippi carries less than 10% of that of the Amazon. Yet the velocity of the Amazon is a normal 2 $m s^{-1}$, the enormous discharge apparently being accommodated by the shape of the river bed so that the velocity is neither much greater nor much smaller than normally encountered in rivers running through similar sediment.

In spite of the large quantities of water discharged, the Amazon does not carry the largest amount of sediment. That doubtful quality is reserved for the Hwang Ho, or Yellow River, which carries almost 2×10^9 tons of sediment to the sea annually, whilst the Amazon delivers half that amount.

Not only the total sediment load but also the sediment delivery rate (the amount of sediment discharged through a given cross-section of the river per unit of time per unit of area of the watershed) varies considerably. While the topography and vegetation cover keep the values to less than 10 tons km^{-2} per annum in some catchment areas (Dnjepr, Loire, Rhine, Ob, Yenesey) the steep mountain slopes, erodable soils and human occupation which have destroyed the natural vegetation cover result in delivery rates of over 1000 tons km^{-2} per annum in other catchment areas (Yellow River, and a number of small rivers).

Reflections of this kind raise the question of which variables govern the shape of a river. It appears that the total sediment discharge is of less importance than the bed material discharge – the latter being a function of the river flow (*see* Part 2: Subsection 3.1.4 and Chapter 4). In a simplified form there are nine variables describing the morphological processes. If the main direction x is taken in addition to the time-variable t, the other seven variables are the discharge Q, the sediment transport (bed material discharge) S, the channel width B, the channel depth h, the energy gradient i, a parameter describing the sediment simplified as 'the' diameter D and a parameter describing the roughness of the river bed expressed by the Chézy coefficient C. There are only 4 basic equations available: the equations of continuity and motion describing water and sediment movement in terms of x and t. Hence 5 variables must be known in order to determine the other 4.

In addition to, say, Q, S and D two more parameters are needed to obtain a solution. Considerable effort is being made to predict C (*see* Part 2: Subsection

3.2.5) but even if these efforts are completely successful, one of the other parameters must still be known. Now a river in its natural state does not provide an additional parameter, or in other words, the deterministic approach to describe the channel of a river fails because there is one equation too few (*see* Part 2: Section 4.1). It follows that when one parameter, for instance the width, is fixed by human interference, one-dimensional morphological problems can be given a physical-mathematical treatment. Most bed regulation works (Part 5: Chapter 2) fall under this category.

It will be clear that the primary *function* of a river channel is the conveyance of water and sediment. This will be further described in general terms in the next three sections. It should be appreciated that this primary function cannot be stopped. Nor can the long-term average be changed by measures carried out in the river bed. Thus alterations in space and time can only be made within the context of an ultimate equilibrium. Whereas the equilibrium of local scour at a groyne or a bank can usually be well taken care of, problems in connection with the equilibrium state of morphological processes of long duration are sometimes pushed aside to be solved later. Yet, weirs which initially stop part of the sediment transport must ultimately pass the average load; reservoirs inevitably silt up sooner or later. Because many of the larger river works are quite young from a morphological point of view, the river channel and river valley are still in the process of adapting to a new equilibrium. Here the engineer is confronted with problems which touch on those dealt with by geo-morphologists.

At the moment the ability of a river to form a channel cannot be explained on physical grounds; and neither can the peculiarity of splitting into more than one channel. This is a common feature in deltaic areas, where the deposition of sediment is probably the cause of the bifurcations. Sometimes it also occurs in higher river sections, when the width-depth ratio is large. Just how large this ratio can be is not usually shown on typical drawings of cross-sections because normally a river is drawn at a very distorted scale, where the width is considerably contracted with respect to the depth. Because of difficulties in showing particular features, a cross-section is hardly ever presented as in Fig. 1/2.1: a river channel of 500 m width at

Fig. 1/2.1 River channel

bank-full stage, with an average depth of 5 m drawn at an undistorted scale. There are many rivers where the width-depth ratio is even larger and it is useful to keep this picture in mind when schematizing the problem in hand.

The most conspicuous aspect of a river channel, apart from its size, is the amount of water it carries. This is best shown in a hydrograph; a few examples are shown in Figs. 1/2.2 and 1/2.3. A monsoon-type river such as the Benue River shows a peak during the rainy season; it is almost empty at the end of the dry season. Individual showers are not reflected in the Makurdi hydrograph because the catchment area is so large that the influence of various showers is evened out. For a tributary with a small catchment area, however, individual showers appear in the hydrograph as shown in the example of the Benue tributary, the Faro River. Figure 1/2.3 shows that a monsoon-type river has a very regular annual hydrograph, with a distinct period of flood and a period of low flow. On the contrary a river in an area where the rainfall is mainly determined by depressions, for instance the Rhine, has a hydrograph with unpredictable highs and lows.

Changes in discharge cause changes in water level in a river channel. At very high discharges a river channel overflows its banks on to the adjacent land. This periodically flooded land is called the flood plain. Whilst in the upper reaches the flood plains are usually narrow or even non-existent, in the lower reaches of a river the flood plains can be tens of kilometers wide. In areas with population pressures the flood plains are usually reduced in width by dikes. Problems arising from the necessity to keep the waters permanently in the confined area are treated in Part 5:

Fig. 1/2.2 Hydrographs of the Benue and Faro Rivers

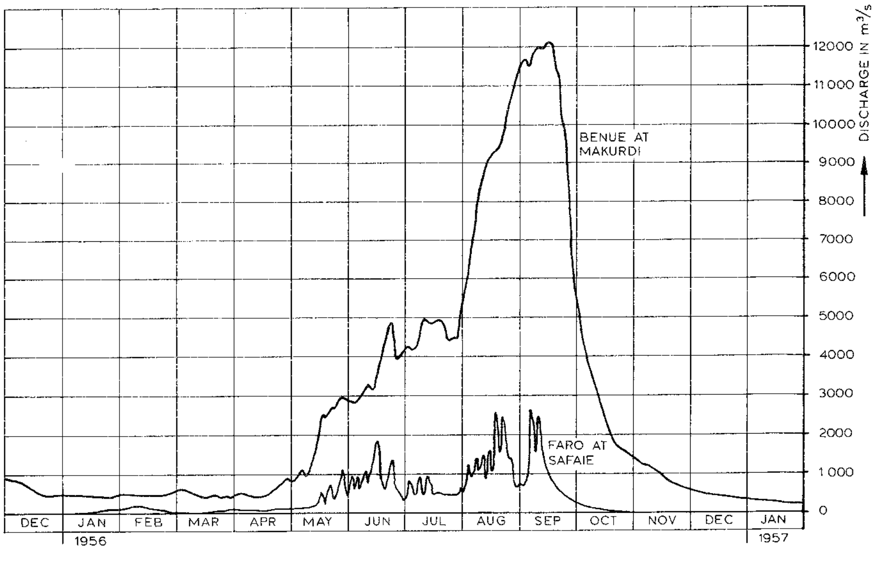
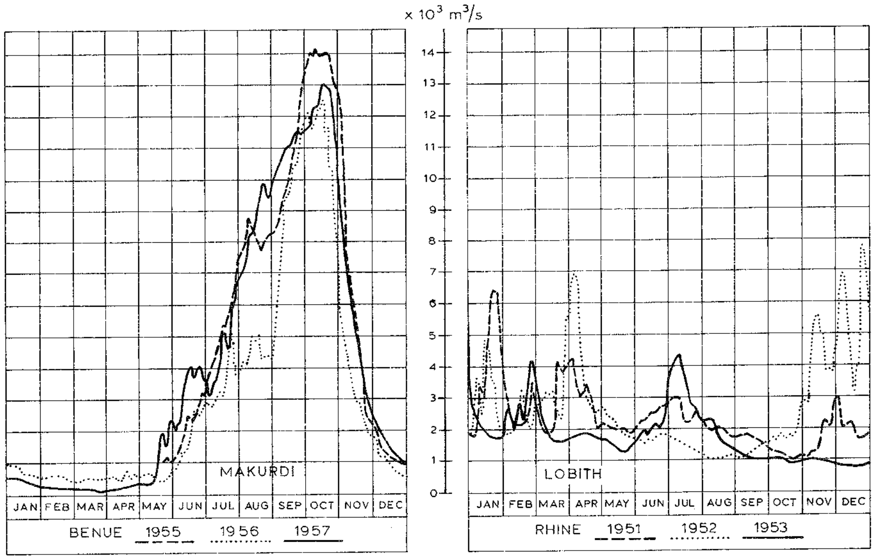


Fig. 1/2.3 Hydrographs of the River Benue and the Rhine



Sections 6.1 and 2.4. When the channel is full but does not spill on to the flood plains, it is said to be at bank-full stage. At lower discharges, sand banks gradually appear and at the lowest discharges the river runs through the low-water channel, meandering between sand banks. The variety of appearances of one channel causes problems for the user (*see* Part 5: Chapter 6) and for the engineer (*see*, for example, Part 2: Subsection 3.4.5); remedial measures which can be carried out by discharge control or water level control are set out in Part 5: Chapters 3 and 4.

2.2 The catchment area

The main river flowing to the sea or to an inland lake is fed by numerous tributaries and also by small gullies through which water trickles from rain, snow, ice or from a subsurface source. The area which is so drained is called the drainage area, drainage basin or catchment area. Usually this definition suffices. There are instances, however, where the boundaries of the subsurface drainage system do not coincide with the boundaries of the surface drainage system. Eagleson (1970) calls the combined surface and subsurface system the drainage basin and calls the surface system the catchment, whilst he defines the catchment area as the horizontal projection of the area enclosed by the catchment boundary.

A catchment can be described in terms of size, topography, geology, vegetation cover and surface drainage pattern. The basis for the description can be a geological viewpoint; information useful to the river engineer can be obtained from textbooks such as that written by Legget (1962). Another way to describe a catchment area is put forward by Eagleson (1970) and Scheidegger (1970), who put geomorphological features into figures and formulae.

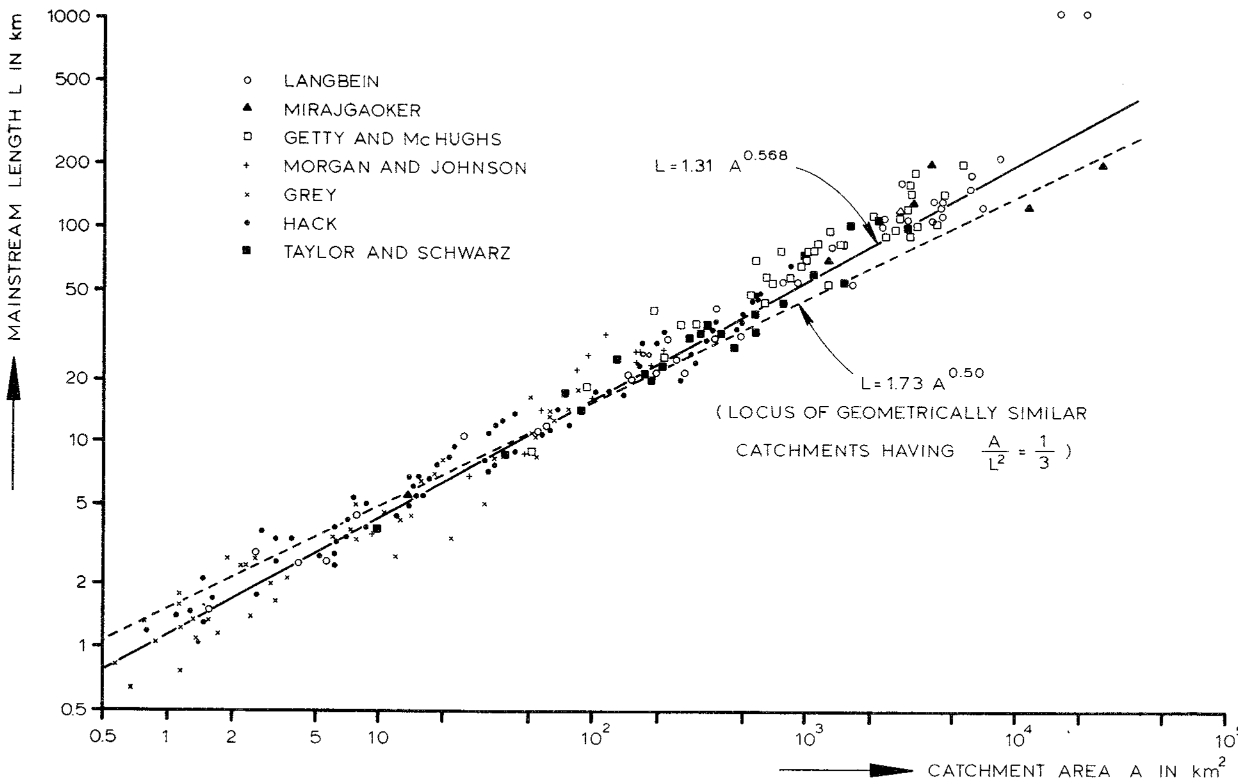


Fig. 1/2.4 Correlation between catchment area and mainstream length (after Eagleson, 1970)

The main characteristic of a catchment is its area. An analysis of the area A as a function of its mainstream length L is given by Eagleson (1970) as presented in Fig. 1/2.4. A further analysis of the catchment topography includes the shape. Eagleson introduces the largest width B of a catchment and expresses the shape in two ways:

the catchment planform factor $m = \frac{A}{BL}$ and

the catchment aspect ratio $a = \frac{B}{L}$;

hence $\frac{A}{L^2} = m \times a$.

The dotted line in Fig. 1/2.4 shows the relationship between A and L. It appears that larger catchments are usually somewhat more elongated than smaller ones, but there is on the whole a fair similarity in shape. The similarity of the shape of catchments is greatest within the same catchment: sub-catchments and main catchment often have similar characteristics. This is the reason why the aspect ratios of sub-catchments and of the main catchment tend to be the same.

The river and its tributaries have also been investigated by geo-morphologists with respect to the network of which they form a part. The so-called morphometric system of Horton (1945), as elaborated by Strahler (1957, 1964), describes the catchment area in terms of the stream network. The linear aspect of the network is analysed in a topological manner, i.e. the interconnections of the system are considered and a stream ordering is made. The system gives no information about lengths, shapes and orientation of the channels.

Strahler specifies the smallest channels as being of order one. When two channels of order one meet, a channel segment of order two is formed, and so on. Definition of the smallest channel, as distinct from no channel, depends to a certain extent on the interpretation of the analyst and on the scale of maps used for the analysis (Leopold *et al.*, 1964). The number of branches (segments) of order one, two, etc. (N_1, N_2, N_3, . . . N_i)provide an insight into the degree of branching, or bifurcation, by the ratios N_1/N_2, N_2/N_3, etc. When the bifurcation ratio is large, the basin has many small channels and relatively few big ones. The hydrograph of such a catchment area can be expected to be flatter than the hydrograph of a basin with a small bifurcation ratio, other elements being equal.

In Fig. 1/2.5, the number of branches are $N_1 = 27$, $N_2 = 9$, $N_3 = 3$, and $N_4 = 1$. The bifurcation ratios are $N_1/N_2 = N_2/N_3 = N_3/N_4 = 3$.

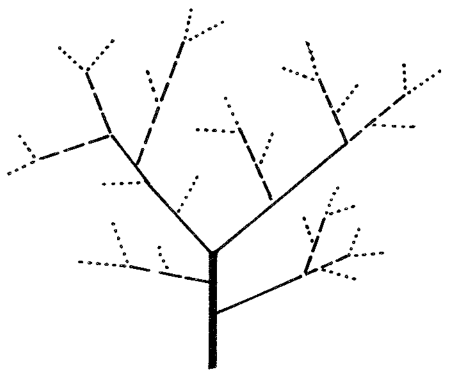


Fig. 1/2.5 Orders of stream channels

Such a net, where the bifurcation ratios within the net are equal, is called a Horton net. Many rivers appear, indeed, to have approximately constant bifurcation ratios and hence are Horton nets. The variation of bifurcation ratios between different river basins appears to be small except when peculiar geological formations dominate the basin shapes. Ranges of 2 to 5 have been cited by Horton (1945) and Strahler (1957), whilst Leopold *et al.* (1964) states that among many samples in the United States the bifurcation ratio tends to be 3.5. For stream lengths and drainage areas of a river basin, ordered in the same way, similar empirical laws have been obtained (Strahler, 1964). It appears that the empirical laws show a close resemblance to those obtained from random-generated synthetic networks (Scheidegger, 1970).

The description of a catchment in the ways shown could be very useful to the river engineer if conclusions on, say, a hydrograph or on sediment discharge could be drawn from them. This is not yet possible. However, these exercises do add to the general understanding of a river basin. Moreover, the methods may facilitate the detection of analogies. When *in situ* measurements are scarce, similar cases where more details are known can be used; the analysis from the literature cited can be applied. Of course, other aspects such as soils, slopes and rainfall pattern must be taken into account too.

2.3 Rainfall — runoff

It has already been stated in Section 2.1 that the most conspicuous feature of a river channel, apart from its size, is the hydrograph. A *hydrograph* is a time-series of water level data or discharge data. The primary data consist of water level observations and discharge measurements from which a stage discharge rating curve is established (see Part 3: Chapter 6). The amount of this information time-wise depends on the period of water level observations. Because these data are of a stochastic nature, and the engineer often requires information on extreme high or extreme low water, long time-series are needed. Now existing water level observations can only be extended if a great deal of time (years) is available and, therefore, recourse to already existing and longer time-series of related events is sought. Because rainfall data are usually available in longer time-series than water level observations, one then tries to establish the relation between rainfall and discharge.

There is a large amount of literature on this subject because it has proved impossible to describe the process of rainfall turning into runoff in terms of physical laws supplemented by a reasonable quantity of physical data of the catchment area. This is because of the complexity of river basins.

In 1932 Sherman introduced the unit hydrograph method with the object of determining the 'design flood'. The method is described in text books on hydrology (e.g. Chow, 1964). The measured hydrograph is split in an arbitrary way: one part being the base flow, which is assumed to consist mainly of groundwater flow from the catchment into the river and the surface runoff which reaches the river through stream channels. The hydrograph less base flow is correlated with that part of the rainfall which contributes directly to the surface runoff. The method is linear, which means that the principle of superposition applies; in other words that twice the input produces twice the output.

Whilst the simple unit hydrograph method has produced useful results with respect to storm runoff and design floods, it has a tendency to underestimate the higher floods and overestimate the smaller ones (Amorocho and W. E. Hart, 1964) and does not simulate a complete hydrograph with sufficient accuracy. Investigators have therefore tried to introduce more physical meanings into the empirical methods. This has led to the *parametric hydrology*, defined by Nash (1967) as 'the description of the hydrological behaviour of a basin by means of parametric values, and the empirical study of the relationship of these parameters one to another and to the physical characteristics of the basin and the use of these relations in providing estimates of magnitudes and frequencies of occurrences of hydrological events'.

The parametric values, describing physical elements such as infiltration, moisture, storage, etc., in terms of coefficients and functions, are estimated on the basis of experience and intuition. They are subsequently tested and adjusted in successive output (flow) simulations. A number of these conceptual models have been developed. For a review the reader is referred to Fleming (1975). As an example the Stanford Watershed Model is mentioned (Crawford and Linsley, 1964 and 1966). This model, which is non-linear, enables hydrologists not only to produce, from rainfall figures, a synthetic hydrograph that closely resembles the measured hydrograph, but also to predict changes in the hydrograph resulting from changes in the catchment area, for example urbanization, stream channel changes, and various land use practices.

Investigations of a complex nature whereby physical laws are introduced in an otherwise empirical methodology are sometimes referred to as *systems synthesis*. The combination of empirical and physical approaches is not restricted to hydrology and, although the reader will understand what is meant by this terminology, a more precise description may be useful.

An *empirical approach* is the investigation of correlations between parameters using only input and output data. The input and output data are obtained from observations, from measurements. Pure empiricism cannot exist because the establishment and ordering of parameters presupposes some physical notion. However, empiricism does not make use of physical laws.

A *physical approach* is the investigation of correlations between parameters using physical laws. It should be noted that a law is a simplification, an approximation, of the actual circumstances. Furthermore, the coefficients of the physical laws must be established by means of measurements in order to use the laws for quantitative purposes. A good introduction to physical laws in hydrology is given by Scheidegger (1970) and by Eagleson (1970). The UNESCO series 'Studies and reports in hydrology' provide the reader with much information on field measurements (Toebes and Ouryvaev, 1970).

The first object of parametric hydrology is to determine the relation between rainfall and runoff. As in the Stanford Watershed Model this relationship can be used to investigate changes in the hydrograph due to changes in the catchment area. An introduction to the effects of watershed changes is given by W. L. Moore and Morgan (1969).

As mentioned earlier, the rainfall–runoff relationship, in combination with long time-series of rainfall data, can be used to calculate long time-series of discharge data when observed discharges (water levels plus rating curve) are of too short a duration for the solution of a particular problem. When still longer time-series are required, *data generation* techniques can be applied. First the deterministic elements (evolving according to a fixed mechanism) and stochastic elements (evolving entirely or in part according to a random mechanism) are separated.

The stochastic elements are then increased in number with data generation techniques: Monte Carlo Method, Markov Process (R. T. Clark, 1973; Fiering and Jackson, 1971; Maas *et al.*, 1966; Yevjevich, 1972a and b). Data generation does not produce additional information, but increases the size of the original sample whilst preserving the basic properties of the sample such as the average and the variance. The long time-series which are the result of this process are useful when *simulating* the effect of a set of external conditions, thereby testing the validity or the applicability of a certain solution to technical problems. It is sometimes felt that these techniques might transform inadequate data into adequate data by some sleight-of-hand. This is not true: inadequate remains inadequate. It is true, however, that the techniques aim at wringing the maximum amount of information from the (few) data and that they present the data in a form which is useful to the engineer when investigating alternative solutions for a complex problem. Useful suggestions for further reading on mathematical modelling in hydrology are given by Dawdy and Kalinin (1971).

Many data for use in the description of the physical processes of the transition of rainfall into runoff have been collected by a great number of investigators. Much of their activity is carried out in representative basins and in experimental basins.

A *representative basin* is a catchment area which is assumed to be hydrologically similar to a much larger catchment area. They are usually between one and 250 km^2 in size. An *experimental basin* is a catchment area which is assumed to be homogeneous with respect to topography, soil and vegetation. They are usually much smaller than representative basins and measure only a few km^2. Experimental basins are used for basic research and the study of the effect of changes of one or more basin characteristics or parameters.

Representative basins serve as basic areas of study for the larger catchments which they represent. They are used to study the physical processes of the rainfall–runoff relation (and other processes in the hydrological cycle), the effects of physical changes, and hydrological prediction techniques, including the extension of series of records.

It is difficult to select basins which are sufficiently representative and it is even more difficult to find natural experimental basins which are really homogeneous. A good ‘state of the art’ on representative and experimental basins is presented by Toebes and Ouryvaev (1970).

The methods and investigations mentioned above require time, organization and money. If the investigations have not been made already, and if the problem can be solved without them, the engineer should do just that. For example, if only a rough average annual discharge figure is required, use can be made of graphs prepared by Brenken (1959) who established a relation between annual precipitation and annual runoff for ten climatic zones using data from a large number of catchments all over the world.

This section contains no more than an indication of some aspects of hydrology. Yet it is an important subject for the river engineer. The authors do not go into the matter further because there are a number of useful textbooks, some of which have been mentioned above. There is also a great deal of information published under the aegis of the UNESCO by contributors to the International Hydrological Decade.

2.4 Sediment yield

The engineering problems concerned with sediment movement are treated in this book in some detail, in particular the movement of the coarser, non-cohesive sediments (sands). Sediment is partly of mineral and partly of organic origin. The mineral part originates from the decomposition of rock. Large pieces of rock have the same mineral composition as the mother rock but further weathering usually causes a separation of the minerals and eventually each sediment particle is of a homogeneous composition. For example, granite becomes sand and clay. Some rock components dissolve in water or react with dissolved acids (humus, HCO_3) to form soluble chemicals. The most durable mineral is quartz, which may decrease in size (sand) but retains its chemical identity SiO_2. Clays are the weathering products of silicates: feldspars, hornblende, micas and other silicates.

Sediments can be divided into two groups: cohesive and non-cohesive. Clays, the finest sediments, belong to the first group; sands and coarser sediments to the second. The distinction is usually made by particle size, as shown in Table 2.4-1. Reference can also be made to Part 2: Subsection 3.1.2.

Table 2.4-1 Particle size classification

British Standards and M.I.T.		American Geophysical Union	
Clay	<2 μm	Clay	<1/256 mm
Fine silt	2–6 μm	Silt	1/256–1/16 mm
Medium silt	6–20 μm	Very fine sand	1/16–1/8 mm
Coarse silt	20–60 μm	Fine sand	1/8–1/4 mm
Fine sand	60–200 μm	Medium sand	1/4–1/2 mm
Medium sand	200–600 μm	Coarse sand	1/2–1 mm
Coarse sand	600 μm–2 mm	Very coarse sand	1–2 mm
Fine gravel	2 mm–6 mm	Very fine gravel	2–4 mm
Medium gravel	6 mm–20 mm	Fine gravel	4–8 mm
Coarse gravel	20 mm–60 mm	Medium gravel	8–16 mm
Cobbles	60 mm–200 mm	Coarse gravel	16–32 mm
		Very coarse gravel	32–64 mm
		Small cobbles	64–128 mm
		Large cobbles	128–256 mm
		Boulders	>256 mm

The erosion products of a catchment area are washed over the fields and through stream channels to the river whereby they eventually leave the catchment area. The manner in which erosion takes place has led to the following classification (Trask, 1950; ASCE, 1970):

- sheet erosion: the wearing away of a thin surface layer of the land. The formation of channels small enough to be smoothed by normal cultivation methods (rill erosion) also falls under this heading.
- gully erosion: the removal of soil by concentrated flow, resulting in channels that cannot be removed by normal cultivation methods.
- stream channel erosion: erosion of the river banks and scouring of the river bed.
- mass movement of soil by creep, landslides, slumps and avalanches.

The total sediment outflow from a catchment area passing a control station for that catchment area is called the *sediment yield*. It can either be expressed in tons per annum, in tons per square kilometre per annum, or in m^3 per square kilometre per annum. The latter denomination is the average denundation or degradation speed of the catchment area in mm per thousand years. Sediment yield expressed in tons or $m^3\ km^{-2}$ per annum is also referred to as sediment production rate or as specific annual degradation.

Table 2.4-2 shows some water and sediment characteristics of 38 rivers. The figures are very approximate; different sources may give a variation of up to factor 2 in sediment yield. The denundation speed in mm $year^{-1}$ is calculated from the figures tons $year^{-1}$ assuming a density of 1.4.

The denundation speed is lowest in flat overgrown areas with temperate or cold climates and in deserts where there is no water to transport erosion products. Table 2.4-2 shows that the denundation speed of the catchment areas of the Ob, Yenesey, Lena, St. Lawrence, Dnjepr, Rhine, Vistula and Oder is in the order of a few mm per thousand years. At the other end of the scale the Ganges and Hwang Ho have over one mm per year. The latter rivers carry the erosion products of a catchment area with a strong relief covered with fine, erodible material (see Corbel, 1959). In some small catchment areas the denundation speed can be even higher due to peculiar local circumstances. As an example, Table 2.4-2 shows the Waipapa catchment area in New Zealand with a denundation speed of 5 mm per year. Rutten (1917) reported 4 mm per year for certain areas of Java in Indonesia.

Table 2.4-2 Water and sediment discharges of 38 rivers

River	Station	Catchment area 10^6 km²	Discharge: Water $m^3 s^{-1}$	Water mm $yr.^{-1}$	Sediment 10^6 ton $yr.^{-1}$	Sediment 10^{-3} mm $yr.^{-1}$	Sediment as ppm of discharge (mg l^{-1})
Amazon	mouth	7.0	100 000	450	900	90	290
Mississippi	mouth	3.9	18 000	150	300	55	530
Congo	mouth	3.7	44 000	370	70	15	50
La Plata/Parana	mouth	3.0	19 000	200	90	20	150
Ob	mouth	3.0	12 000	130	16	4	40
Nile	delta	2.9	3 000	30	80	15	630
Yenissei	mouth	2.6	17 000	210	11	3	20
Lena	mouth	2.4	16 000	210	12	4	25
Amur	mouth	2.1	11 000	160	52	15	150
Yangtse Kiang	mouth	1.8	22 000	390	500	200	1 400
Wolga	mouth	1.5	8 400	180	25	10	100
Missouri	mouth	1.4	2 000	50	200	100	3 200
Zambesi	mouth	1.3	16 000	390	100	50	200
St Lawrence	mouth	1.3	14 000	340	3	2	7
Niger	mouth	1.1	5 700	160	40	25	220
Murray-Darling	mouth	1.1	400	10	30	20	2 500
Ganges	delta	1.0	14 000	440	1 500	1 000	3 600
Indus	mouth	0.96	6 400	210	400	300	2 000
Orinoco	mouth	0.95	25 000	830	90	65	110
Orange River	mouth	0.83	2 900	110	150	130	1 600
Danube	mouth	0.82	6 400	250	67	60	330
Mekong	mouth	0.80	15 000	590	80	70	170
Hwang Ho	mouth	0.77	4 000	160	1 900	1 750	15 000
Brahmaputra	Bahadurabad	0.64	19 000	940	730	800	1 200
Dnjepr	mouth	0.46	1 600	110	1.2	2	25
Irrawaddi	mouth	0.41	13 000	1 000	300	500	750
Rhine	delta	0.36	2 200	190	0.72	1	10
Magdalena (Colombia)	Calamar	0.28	7 000	790	220	550	1 000
Vistula (Poland)	mouth	0.19	1 000	160	1.5	5	50
Kura (USSR)	mouth	0.18	580	100	37	150	2 000
Chao Phya (Thailand)	mouth	0.16	960	190	11	50	350
Oder (Germany/Poland)	mouth	0.11	530	150	0.13	1	10
Rhone (France)	mouth	0.096	1 700	560	10	75	200
Po (Italy)	mouth	0.070	1 500	670	15	150	300
Tiber (Italy)	mouth	0.016	230	450	6	270	850
Ishikari (Japan)	mouth	0.013	420	1 000	1.8	100	140
Tone (Japan)	Matsudo	0.012	480	1 250	3	180	200
Waipapa (New-Zealand)	Kanakanala	0.0016	46	900	11	5 000	7 500

Human interference sometimes causes a large increase in denundation speed. For example strip mining in Kentucky raised the denundation rate to about 7 mm per year (a sediment yield of over 10 000 ton km^{-2} per annum), whilst the sediment yield in unmined areas of the same catchment was about 10 ton km^{-2} per annum (ASCE, 1970).

The speed of erosion usually varies from one point to another, and when particles move from an area of great erodibility to an area of smaller erodibility, the second area will silt up (aggradate). Thus part of the sediment yield of the former area does not pass through. It follows that the sediment yield of a catchment area is usually smaller than the sum of the sediment yields of its sub-systems. This is expressed as a percentage or a ratio between the sediment yield of the whole catchment area and the total on-site erosion in that area: the *sediment delivery ratio*. Whilst the sediment delivery ratio of small areas approaches 100%, the sediment delivery ratios of large areas can be lower than 10% (ASCE, 1970). Very approximate average figures are 30% for one square mile, 10% for 100 square miles and 5% for 500 square miles. For larger areas figures as low as 3 to 4% are given by Lopatin (1962).

Whilst the denundation speed describes the overall erosion of the catchment area, the river engineer is usually more interested in the total amount of solids and in the sediment yield as a function of the water discharge. Table 2.4-2 shows examples of these and it is clear that the Hwang Ho emerges as the muddiest river in the world in terms of total sediment yield as well as sediment per unit of water discharge. Rivers with small amounts of sediment (less than 100 ppm) are generally those in areas of temperate and cold climates with flat slopes. However, in tropical areas with high rainfalls the sediment yield also need not be great. For example, the Congo River, with 37 cm runoff per year, carries only 50 mg l^{-1} sediment because the catchment area is heavily wooded and flat. On the other hand, many large Chinese and South-East Asian rivers in semi-tropical and tropical areas do carry large amounts of silt. At the other end of the (water) scale are the rivers in semi-arid and arid areas. Some of these also carry relatively large amounts of sediment: the Missouri River with 5 cm runoff carries 3200 ppm sediment and the Murray-Darling River (1 cm runoff), 2500 ppm. It will be clear that a variety of factors determine the sediment transport.

The figures of Table 2.4-2 are approximate averages and are only given as indicative figures. More extensive information is given by other authors such as Fournier (1969) and Holeman (1968) who present classified summaries of sediment yields of various drainage areas. These are useful when investigating the need for sediment yield measurements for specific engineering purposes in a catchment of which little or no data are available. In that case the lists may provide comparable material. One should be careful, however, to compare areas with similar characteristics (soils, topography, vegetation, climate and size).

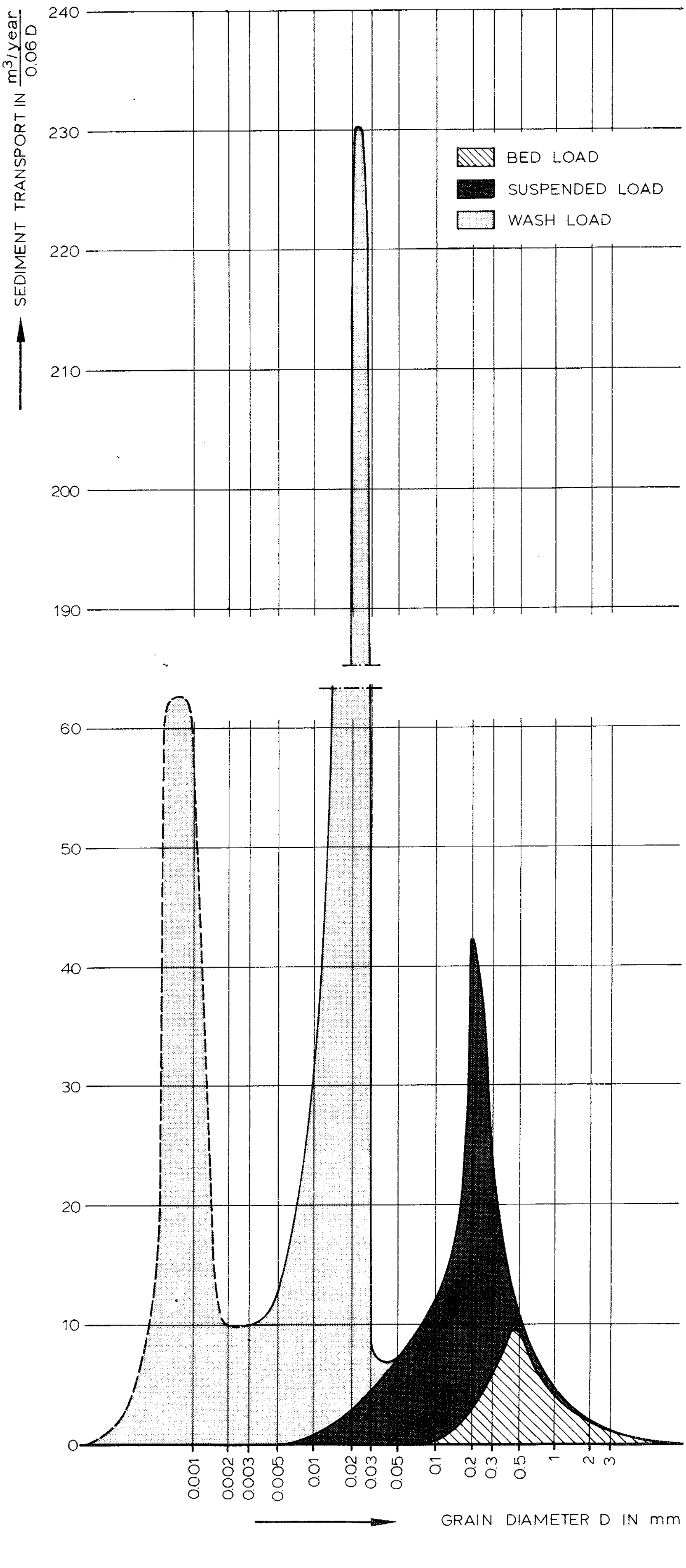
Although sediment yield is a function of many variables, some investigators have tried to narrow down their field of investigation by concentrating on the main parameters. Langbein and Schumm (1958) arrived at an annual sediment yield per unit area expressed in terms of effective rainfall. Although they carefully point out the possibility of bias in their figures, later authors often produce their graph without these comments. It is interesting to note that the precipitation figures used by Langbein and Schumm show a uniform relation with the vegetation cover so that the same graph describing sediment yield as a function of rainfall also describes sediment yield as a function of vegetation cover. Fleming (1969), who agrees with the findings in general, adds more information on vegetation cover. Douglas (1967), however, questions not only the quantities but also the shape of the sediment yield-rainfall relationship and suggests that the data of Langbein and Schumm originate from too specific an area. Fournier (1960) uses data from a large variety of sources and introduces a formula for sediment yield based on the rainfall and the topography of the catchment area. All these methods produce area distribution patterns of annual sediment yield. The actual values, however, should be regarded with caution and, where possible, checked with field measurements.

The field measurements of sediment yields of small catchment areas have provided information of a more detailed nature than has the analysis of large catchment areas. Of the small catchment areas, more uniform physical data are available and it has been possible to quantify soil losses in terms of soil erodibility, cropping pattern, rainfall intensity and topography (ASCE, 1970; Toebes and Ouryvaev, 1970).

No distinction has yet been made in the manner in which the sediment is transported. This distinction, however, is important since the type of transportation has a bearing on the design of river structures. A division is made between bed material load and wash load. Bed material load refers to the sediment which is picked up from the river bed and moved either along the bed (bed load) or in suspension. Wash load refers to sediment which originates from other areas of the catchment area, is finer than the bed material, and is carried through the river in suspension. There is a relation between the water discharge and the bed material load, but there is no relation between the water discharge and the wash load (*see* Part 2: Subsection 3.1.4).

The quantity of suspended load is in many cases much greater than that of bed load. An illustration is given in Fig. 1/2.6, showing the sediment transport of the River Niger at Baro in 1957. The dotted line showing the third peak is based on only a few observations; the two other peaks in the figure are usual for rivers of this type. The figure shows an annual average but there are large seasonal variations,

Fig. 1/2.6 Sediment transport at Baro on the River Niger (after NEDECO, 1959)



particularly in the percentage of suspended load. For example, the silt concentration in the Niger is 50 ppm during low water, rising sharply during the first floods to several hundred ppm and decreasing again thereafter (see also Leopold *et al.*, 1964). The amount of silt in the river depends on the conditions in the catchment upstream rather than those of the river section observed.

Whereas the amount of total sediment transport is the measure for denundation speed, siltation of reservoirs and accretion in delta-formations, the much smaller amounts of bed load are of prime importance to river structures since they influence the foundation conditions.